Pr

Heat Treater's Guide

actices and Procedures for Irons and Steels

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PREFACE

The success of the 1982 edition of the *Heat Treater's Guide: Standard Practices and Procedures for Steel* is largely a tribute to its editors who came up with a unique, easy-to-use format. They packaged practical, how-to information in brief articles (typically less than a page) on each of the 280 standard AISI grades of carbon, alloy, tool, and stainless steels available at the time.

Brevity was further promoted by standardizing the information presented in each article, namely: chemical composition, alternative U.S. and foreign grades, characteristics related to heat treating, forging practice (where applicable), recommended heat treating practice, and recommended processing sequence.

The concept is carried forward in this new edition. In preparing for it, all existing articles were reviewed and updated where necessary, i.e., new AISI-UNS chemical compositions replace obsolete compositions, RH grades of steel are identified, and aerospace practice for heat treating carbon and alloy steels is presented. Other changes include:

- Steels not covered in the prior edition are added to the mix, i.e., ultrahigh strength steels, cast irons (gray, ductile, and malleable types), and P/M steels (ferrous, stainless steel, and tool steel types).
- Topics not in the '82 edition are addressed, such as the use of statistical process control in heat treating, and practical applications of the computer in heat treating.
- New information is also provided by a number of short articles that focus on major trends and current developments in heat treating practice. this information is in support of topics that are part of the standard format, i.e., normalizing, annealing, surface hardening, quenching/quenchants, tempering, cold/cryogenic treatments, and furnace atmospheres.
- The number of steels represented in standard format articles has been increased from 280 to around 350.
- Also new to this edition are more than 50 short articles on timely topics ranging from back-to-the basics look at causes of distortion and cracking in quenching to a survey of all available surface hardening processes.
- Access to articles is improved by restyled contents pages.

Table of Contents

Heat Treating Processes and Related Technology

Introduction

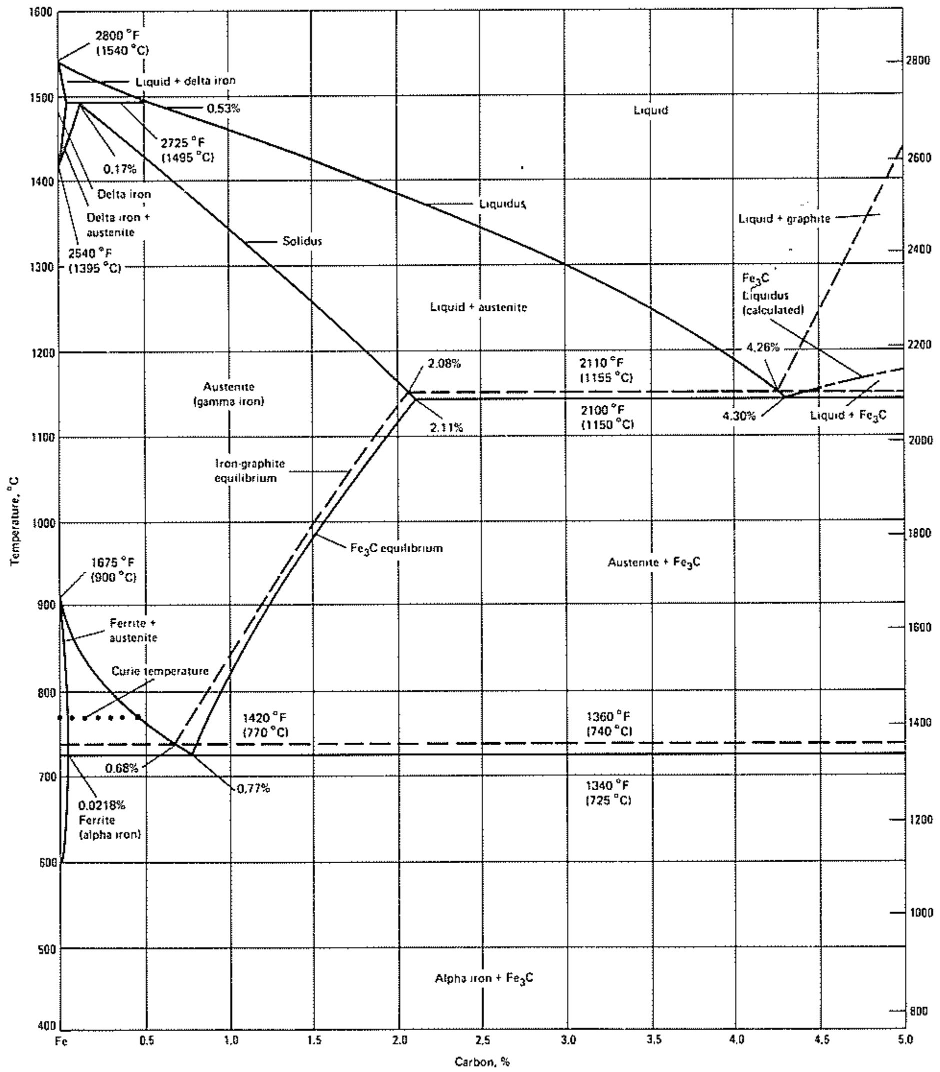
Heat treating is defined as heating and cooling a solid metal or alloy in such a way as to obtain desired conditions or properties.

Reasons for heat treating include the following:

- Remove stresses, such as those developed in processing a part
- Refine the grain structure of the steel used in a part
- Add wear resistance to the surface of a part by increasing its hardness, and, at the same time, increase its resistance to impacts by maintaining a soft, ductile core
- Beef up the properties of an economical grade of steel, making it possible to replace a more expensive steel and reduce material costs in a given application
- Increase toughness by providing a combination of high tensile strength and good ductility to enhance impact strength
- Improve the cutting properties of tool steels
- Upgrade electrical properties
- Change or modify magnetic properties

The focus in this chapter is on heat treatments and the technology associated with getting the desired result.

Iron-carbon equilibrium diagram



First, key components of the heat treating process are summarized in stracts on:

Normalizing
Annealing
Stress relieving
Surface hardening
Quenching/quenchants
Tempering
Cold/cryogenic treatments
Furnace atmospheres

Second, practical, how-to information is provided by overview articles on:

- Causes of distortion and cracking in quenching
- Stress relief heat treating
- Furnace atmospheres
- Cold and cryogenic treatments of steel
- Representative applications of heat treating furnaces
- Statistical process control of heat treating operations
- Practical applications of the computer in heat treating

leat Treating Processes

ormalizing

The term normalize does not characterize the nature of this process. More curately, it is a homogenizing or grain refining treatment, with the aim ing uniformity in composition throughout a part. In the thermal sense, rmalizing is an austenitizing heating cycle followed by cooling in still or ightly agitated air. Typically, work is heated to a temperature of approxi-ately 55 °C (100 °F) above the upper critical line of the iron-iron carbide ase diagram, and the heating portion of the process must produce a mogeneous austenitic phase. The actual temperature used depends upon e composition of the steel; but the usual temperature is around 870 °C 600 °F). Because of characteristics inherent in cast steel, normalizing is mmonly applied to ingots prior to working, and to steel castings and rgings, prior to hardening. Air hardening steels are not classified as rmalized steels because they do not have the normal pearlitic microstruc-re typical of normalized steels.

nnealing

A generic term denoting a treatment consisting of heating to and holding a suitable temperature, followed by cooling at a suitable rate; used imarily to soften metals and to simultaneously produce desired changes other properties or in microstructures. Reasons for annealing include nprovement of machinability, facilitation of cold work, improvement in echanical or electrical properties, and to increase dimensional stability. ferrous alloys, annealing usually is done above the upper critical tem-erature, but time-temperature cycles vary widely in maximum tempera-re and in cooling rate, depending on composition of the steel, condition the steel, and results desired. When the term is used without qualifica-on, full annealing is implied. When the only purpose is relief of stresses, e process is called stress relieving or stress relief annealing.

In full annealing steel is heated 90 to 180 °C (160 to 325 °F) above the $_3$ for hypoeutectoid steels and above the A_1 for hypereutectoid steels, and ow cooled, making the material easier to cut and to bend. In full anneal-g, the rate of cooling must be very slow, to allow the formation of coarse earlite. In process annealing, slow cooling is not essential because any oling rate from temperatures below A_1 results in the same microstructure nd hardness.

tress Relieving

Residual stresses can be created in a number of ways, ranging from ingot rocessing in the mill to the manufacture of the finished product. Sources iclude rolling, casting, forging, bending, quenching, grinding, and weld-g. In the stress relief process, steel is heated to around 595 °C (1105 °F), nsuring that the entire part is heated uniformly, then cooled slowly back room temperature. Procedure is called stress relief annealing, or simply ress relieving. Care must be taken to ensure uniform cooling, especially hen a part has varying section sizes. If the cooling rate is not constant and niform, new residual stresses, equal to or greater than existing originally, an be the result. Residual stresses in ferritic steel cause significant reduc-tion in resistance to brittle fracture. If a steel, such as austenitic stainless steel, is not prone to brittle fracture, residual stresses can cause stress-corrosion cracking (SCC). Warping is the common problem.

Surface Hardening

These treatments, numbering more than a dozen, impart a hard, wear resistant surface to parts, while maintaining softer, tough interior which gives resistance to breakage due to impacts. Hardness is obtained through quenching, which provides rapid cooling above a steel's transformation temperature. Parts in this condition can crack if dropped. Ductility is obtained via tempering. The hardened surface of the part is referred to as the case, and its softer interior is known as the core.

Gas carburizing is one of the most widely used surface hardening processes. Carbon is added to the surface of low-carbon steels at temperatures ranging from 850 to 950 °C (1560 to 1740 °F). At these temperatures austenite has high solubility for carbon. In quenching, austenite is replaced by martensite. The result is a high-carbon, martensitic case. Carburizing steels for case hardening usually have carbon contents of approximately 0.2%. Carbon content of a carburized case is usually controlled between 0.8 to 1% carbon. Other methods of case hardening low-carbon steels include cyaniding, ferritic nitrocarburizing, and carbonitriding.

Quenching/Quenchants

Steel parts are rapidly cooled from the austenitizing or solution treating temperature, typically from within the range of 815 to 870 °C (1500 to 1600 °F). Stainless and high-alloy steels may be quenched to minimize the presence of grain boundary carbides or to improve the ferrite distribution, but most steels, including carbon, low-alloy, and tool steels, are quenched to produce controlled amounts of martensite in the microstructure. Objectives are to obtain a required microstructure, hardness, strength, or toughness, while minimizing residual stresses, distortion, and the possibility of cracking. The ability of a quenchant to harden steel depends upon the cooling characteristics of the quenching medium. Quenching effectiveness is dependent upon steel composition, type of quenchant, or quenchant use conditions. The design of a quenching system and its maintenance are also keys to success.

Quenching Media

Selection here depends on the hardenability of the steel, the section thickness and shape involved, and the cooling rates needed to get the desired microstructure. Typically, quenchants are liquids or gases.

Common liquid quenchants are:

- Oil that may contain a variety of additives
- Water
- Aqueous polymer solutions
- Water that may contain salt or caustic additives

Most common gaseous quenchants are inert gases, including helium, argon, and nitrogen. They are sometimes used after austenitizing in a vacuum.

A number of other quenching media and methods are available, including fogs, sprays, quenching in dry dies and fluidized beds. In addition, some processes, such as electron-beam hardening and high frequency pulse hardening are self-quenching. Very high temperatures are reached in the fraction of a second, and metal adjoining the small, localized heating area acts as a heat sink, resulting in ultrarapid cooling.

Tempering

In this process, a previously hardened or normalized steel is usually heated to a temperature below the lower critical temperature and cooled at a suitable rate, primarily to increase ductility and toughness, but also to increase grain size of the matrix. Steels are tempered by reheating after hardening to obtain specific values of mechanical properties and to relieve quenching stresses and ensure dimensional stability. Tempering usually follows quenching from above the upper critical temperature.

Most steels are heated to a temperature of 205 to 595 °C (400 to 1105 °F) and held at that temperature for an hour or more. Higher temperatures increase toughness and resistance to shock, but reductions in hardness and strength are tradeoffs. Hardened steels have a fully martensitic structure, which is produced in quenching. A steel containing 100% martensite is in its strongest possible condition, but freshly quenched martensite is brittle. The microstructure of quenched and tempered steel is referred to as tempered martensite.

Martempering of Steel. The term describes an interrupted quench from the austenitizing temperature of certain alloy, cast, tool, and stainless steels. The concept is to delay cooling just above martensitic transformation for a period of time to equalize the temperature throughout the piece. Minimizing distortion, cracking, and residual stress is the payoff. The term is not descriptive of the process and is better described as marquenching. The microstructure after martempering is essentially primary martensite that is untempered and brittle.

Austempering of Steel. Ferrous alloys are isothermally transformed at a temperature below that for pearlite formation and above that of martensite formation. Steel is heated to a temperature within the austenitizing range, usually 790 to 915 °C (1455 to 1680 °F); then quenched in a bath maintained at a constant temperature, usually in the range of 260 to 400 °C (500 to 750 °F); allowed to transform isothermally to bainite in this bath; then cooled to room temperature. Benefits of the process are increased ductility, toughness, and strength at a given hardness; plus reduced distortion that lessens subsequent machining time, stock removal, sorting, inspection, and scrap. Austempering also provides the shortest possible overall time cycle to through harden within the hardness range of 35 to 55 HRC. Savings in energy and capital investment are realized.

Maraging Steels. These highly alloyed, low-carbon, iron-nickel martensites have an excellent combination of strength and toughness that is superior to that of most carbon hardened steels, and are alternatives to hardened carbon steels in critical applications where high strength and good toughness and ductility are required. Hardened carbon steels derive their strength from transformation hardening mechanisms, such as martensite and bainite formation, and the subsequent precipitation of carbides during tempering. Maraging steels, by contrast, get their strength from the formation of a very low-carbon, tough, and ductile iron-nickel martensite, which can be further strengthened by subsequent precipitation of intermetallic compounds during age hardening. The term marage was suggested by the age hardening of the martensitic structure.

Cold and Cryogenic Treatment of Steel

Cold treatment can be used to enhance the transformation of austenite to martensite in case hardening and to improve the stress relief of castings and machined parts. Practice identifies –84 °C (–120 °F) as the optimum cold treatment temperature. By comparison, cryogenic treatment at a temperature of around –190 °C (–310 °F), improves certain properties beyond the capability of cold treatment.

Furnace Atmospheres. Atmospheres serve a variety of functions: acting as carriers for elements used in some heat treating processes, cleaning surfaces of parts being treated in other processes, and providing a protective environment to guard against adverse effects of air when parts are exposed to elevated temperatures. Principal gases and vapors are air, oxygen, nitrogen, carbon dioxide and carbon monoxide, hydrogen, hydrocarbons (i.e., methane, propane, and butane), and inert gases, such as argon and helium.

Causes of Distortion and Cracking during Quenching

This problem usually is the result of an imbalance in internal residual stresses that can lead to cracking, ranging from microcracking to bulk failure of a part, Ref 1.

Factors, singly or in combination, that can influence the nature and extent of shape distortion during quenching include:

- Steel composition and hardenability
- Geometry of part
- Mechanical handling
- Type of quenching fluid
- Temperature of quenchant
- Condition of quenchant
- Circulation (agitation) of quenchant

Composition and Hardenability

The quenchant selected should:

1. Just exceed the critical cooling rate of the steel used
2. Provide a low cooling rate in the M_s to M_f transformation range

Compromises in cooling rate often are necessary to accommodate a range of steels with a range of cooling rate.

Part Geometry

Two considerations here:

1. Quenching at the slowest possible speed as dictated by thickest section of the part
2. Or resorting to hot oil quenching techniques (more later)

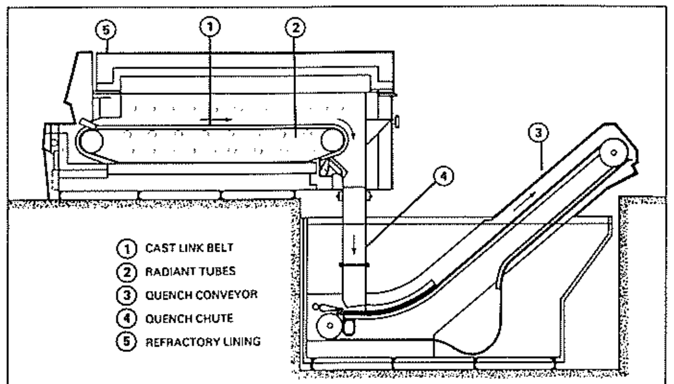
Mechanical Handling

Care is advised because steel in the austenitic condition is only one-tenth as strong as it is at room temperature. Avoid dropping parts into the bottom of a quench tank; and when continuous furnaces are used, quench chute design can cause damage when thin section parts strike pick-up slots in conveyor systems (see Figure).

Type of Quenching Fluid

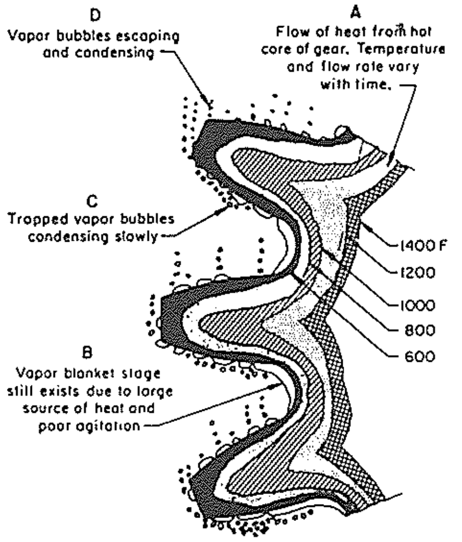
The importance of the characteristics of a quenchant during the three stages of cooling (vapor phase, boiling phase, and convection phase) is illustrated by an example involving precision auto transmission gears (see Figure). During oil quenching, vapor retention in tooth roots, combined with the onset of boiling on flanks can cause "unwinding" of thin section gears. Use of accelerated oils with special additives that reduce the stability

Schematic continuous heat treatment installation. Ref 1



A typical arrangement of a quenching system in a continuous belt or cast link furnace.

Vapor retention in gear tooth roots during oil quenching. Ref 1



f the vapor phase and promote boiling is one remedy. Greater uniformity ı cooling is the payoff.

;onvection Phase Characteristics

A temperature of 300 °C (570 °F) generally is accepted as the norm for ɔoling in this phase because it is within the M_s-M_f temperature range of a ɯmber of different engineering steels, and therefore a critical considera- on in controlling distortion.

Typical values for several types of quenchants are as follows:

uenchant	Cooling rate at 300 °C (570 °F) °C/s
ormal speed oil	5-15
ccelerated oil	10-15
ɔlymers	
PAG (polyalkylene glycol)	30-80
ACR (sodium polyacrylate)	10-25
PVP (polyvinyl pyrrolidene)	10-25
PEO (polyethyl oxazolene)	10-30

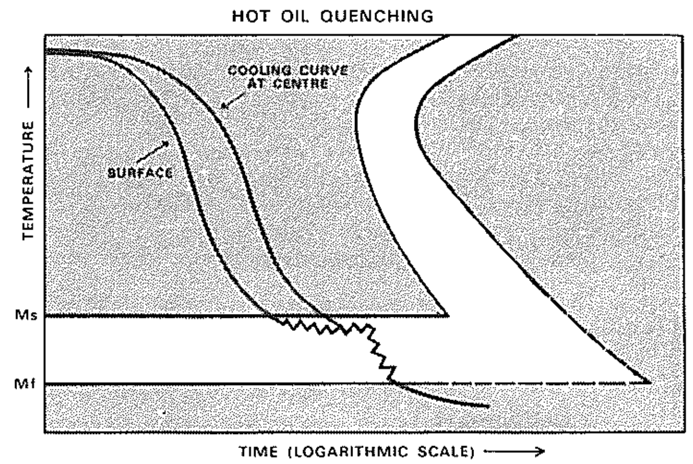
Example: Because PAG (a polymer quenchant) has higher cooling rates than oils in the convection phase, parts are more susceptible to distortion. Use of PAG requires careful consideration to steel hardenability, part section size(s), and surface finishes. By comparison, other polymer quenchants (ACR, PVP, PEO) have cooling rates similar to those of oils, which means they can be applied in treating critical alloy steel parts outside the scope of PAG quenchants, which are suitable in quenching plain carbon, low-alloy, carburized steels, or higher alloy steel parts with thick section sizes.

Quenchant Temperature

In conventional quenching, the surface and thinner sections of a part cool to the M_s temperature and are beginning to transform while center and thicker sections are still in the soft, austenitic condition. This means that when soft sections begin to transform, their changes in volume are restricted by the hard, brittle martensite previously formed on surfaces and thin sections, creating stresses that can lead to distortion or to quench cracking.

Hot oil quenching, a two-step process, is one remedy. Parts are first quenched in specially formulated oils, usually at temperatures within the range of 120 to 200 °C (250 to 390 °F), depending on part complexity and tendency to distort. Holding time at the temperature chosen is based on the time required to obtain a uniform temperature throughout a part. In the next step, parts are removed from the oil and cooled slowly in a furnace containing an atmosphere (see Figure).

Hot oil quenching techniques to reduce distortion. Ref 1



An alternative is marquenching in hot oil (150 to 200 °C, or 300 to 390 °F). The M_s temperature of typical engineering steels is in the 250 to 350 °C range (480 to 660 °F).

Condition of Quenchant

Regular monitoring of the quenching fluid is preferred practice. The minimum: testing for acidity and water content of quenching oil and checking the concentration of polymer quenchants. An added control: periodic evaluation of quenching characteristics.

Increases in quenching speeds, especially in the convection phase, are a common problem. Possible causes include:

- Contamination of quenching oils with water. As little as 0.05% water can have a dramatic effect on the maximum cooling rate and on the convection phase cooling rate.
- Oxidation of mineral oils reduces the stability of the vapor phase and accelerates maximum cooling rates.
- Contamination or thermal degradation of polymer quenchants increases the cooling rate in the convection phase. Higher polymer concentrations are a partial solution.

Circulation of quenchant is important in maintaining a uniform bath temperature and in assisting the breakdown of the vapor phase. The degree of agitation has a significant influence on the cooling rates of both quenching oils and polymer quenchants.

With increases in the agitation of oil, three things happen:

- Duration of the vapor phase is shortened
- Maximum cooling rate rises
- Cooling rate in the convection phase also goes up

The last named effect adds to the risk of cracking, meaning that excessive agitation of oils should be avoided.

Agitation of polymer quenchants has a pronounced effect on the vapor phase and maximum cooling rate, but little effect on the cooling rate in the convection phase. Vigorous agitation of polymer quenchants normally is recommended to ensure uniform quenching characteristics, a practice that does not enhance the risk of cracking.

Finally, the direction of quenchant flow over the workpiece can have an influence on distortion. Reversing the direction of flow, for example, can provide relief.

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Stress Relief Heat Treating of Steel

Residual stresses are built up in a part during the course of a manufacturing sequence. Technically, a part is stressed beyond its elastic limit and plastic flow occurs.

Causes

Bending, quenching, grinding, and welding are among the major causes of the problem (see adjoining Figure).

Bending a bar during fabrication at a temperature where recovery cannot occur (as in cold forming) can cause a buildup on residual tensile stresses in one location, and a second location, 180° from the first location, will contain residual compressive stresses (Ref 1).

Quenching of thick sections results in high residual compressive stresses on the surface of a part. They are balanced by residual tensile stresses in the interior of the part (Ref 2).

Residual stresses caused by grinding can be compressive or tensile in nature, depending on the grinding operation. Such stresses tend to be shallow in depth, but they can cause warping of thin parts (Ref 3).

In welding, residual stresses are associated with steep thermal gradients inherent in the process. Stresses may be on a macro-scale over a relatively long distance or highly localized. Postweld heat treating has two objectives: relief of residual stresses and the development of a specific metallurgical structure of properties (Ref 4, 5).

Relieving Residual Stresses

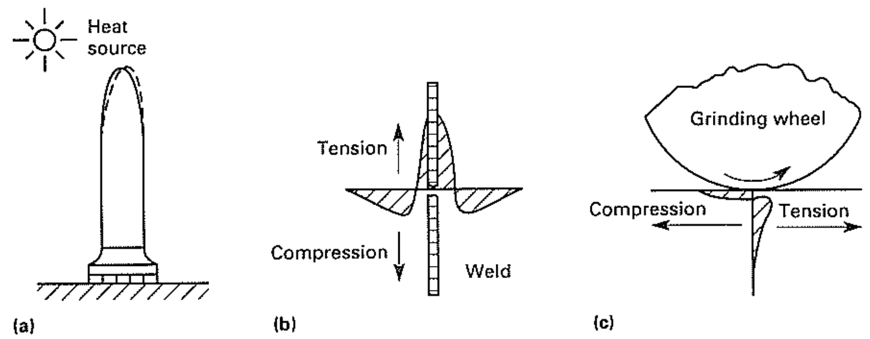
Relief is a time-temperature related phenomenon (see Figure), parametrically correlated by the Larson-Miller equation:

$$\text{Thermal effect} = T(\log t + 20)\,10^{-3}$$

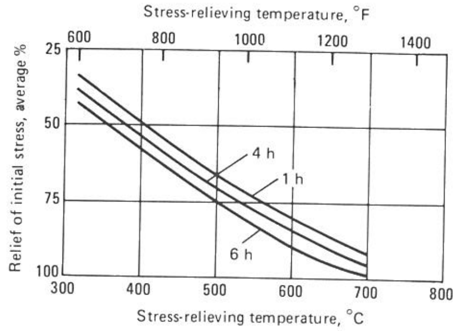
where T is the temperature (Rankin) and t is time in hours. Example: holding a part at 595 °C (1105 °F) for 6 h provides the same result as heating at 650 °C (1200 °F) for 1 h.

Other Factors. Creep resistant materials such as chromium bearing, low-alloy steel and chromium rich, high-alloy steel normally require higher stress relief temperatures than conventional low-alloy steels. Typical treatment temperatures for low-alloys are between 595 and 675 °C (1105 and 1245 °F). Temperatures required for the treatment of high alloys, by comparison, range from 900 to 1065 °C (1650 to 1950 °F).

Examples of the causes of residual stresses: (a) Thermal distortion in a structure due to heating by solar radiation. (b) Residual stresses due to welding. (c) Residual stresses due to grinding



Relationship between time and temperature in the relief of residual stresses in steel



High alloys such as austenitic stainless steels are sometimes treated at :mperatures as low as 400 °C (750 °F). But in this instance stress reduction modest. Better results are obtained at temperatures ranging from 480 to 925 °C (895 to 1695 °F). However, at the higher end of this range stress-corrosion cracking can occur (Ref 6). Solution annealing temperatures of approximately 1065 °C (1950 °F) are frequently used to reduce residual stresses in these alloys to acceptably low levels.

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'urnace Atmospheres

Properties of common gases and vapors are listed in Table 1. They clude air, oxygen, nitrogen, carbon dioxide, carbon monoxide, hydrogen, ater vapor, hydrocarbons, and inert gases. Ref 1.

Air provides atmospheres in furnaces in which protective atmospheres e not used. Air is also the major constituent in many prepared atmos- ieres. The composition of air is approximately 79% nitrogen and 21% :ygen, with trace elements of carbon dioxide. As an atmosphere, air haves like oxygen, the most reactive constituent in air.

Oxygen reacts with most metals to form oxides. It also reacts with rbon dissolved in steel, lowering surface carbon content.

Nitrogen in its molecular state is passive to ferrite and can be used as atmosphere in annealing low-carbon steels; as a protective atmosphere heat treating high-carbon steels, nitrogen must be completely dry— ıall amounts of water vapor in nitrogen cause decarburization. Molecular rogen is reactive with many stainless steels and can't be used to heat treat :m. Atomic nitrogen, which is created at normal heat treating tempera- es, is not a protective gas—it combines with iron, forming finely divided rides that reduce surface hardness.

Carbon dioxide and carbon monoxide are used in steel processing atmospheres. At austenitizing temperatures, carbon dioxide reacts with surface carbon to produce carbon monoxide, a reaction that continues until the supply of carbon dioxide is exhausted and the steel surface is free of carbon.

Hydrogen reduces iron oxide to iron. Under certain conditions, hydrogen can decarburize steel, an effect that depends on furnace temperature, moisture content (of gas and furnace), time at temperature, and carbon content of the steel.

Water vapor is oxidizing to iron and combines with carbon in steel to form carbon monoxide and hydrogen. It is reactive with steel surfaces at very low temperatures and partial pressures. It is also the principal cause of bluing during cooling cycles.

Carbon hydrocarbons are methane (CH_4), ethane (C_2H_6), propane (C_3H_8), and butane (C_4H_{10}). They impart a carburizing tendency to furnace atmospheres.

Inert gases are especially useful as protective atmospheres in the thermal processing of metals and alloys that can't tolerate the usual constituents in protective reactive metals and their alloys. Argon costs about half as much as helium, and is frequently favored; air contains approximately 0.93% argon by volume, and is recovered by liquefying air, followed by the fractionation of liquid air; helium is recovered from natural gas deposits by cryogenic methods.

ble 1 Properties of Common Gases and Vapors

s	Chemical symbol	Approximate molecular weight	Density(a) kg/m³	Density(a) lb/ft³	Specific gravity(b)
	...	28.97(c)	1.293	0.0807	1.000
monia	NH_3	17.03	0.760	0.0474	0.588
on	Ar	39.95	0.178	0.0111	1.380
bon dioxide	CO_2	44.02	1.965	0.1228	1.520
bon monoxide	CO	28.01	1.250	0.0780	0.967
ium	He	4.00	0.179	0.0112	0.138
lrogen	H_2	2.02	0.090	0.0056	0.070
hane	CH_4	16.04	0.716	0.0447	0.552
ogen	N_2	28.01	1.250	0.0780	0.968
gen	O_2	32.00	1.429	0.0892	1.105
)ane	C_3H_8	44.09	1.968	0.1229	1.522
ur dioxide	SO_2	64.06	2.860	0.1785	2.212

'tandard temperature and pressure: 0 °C (32 °F) and 760 mm Hg. (b) Relative density compared to air. (c) Because air is a mixture, it does not have a true molecular weight. This e average molecular weight of its constituents.

Table 2 Classification and Application of Principal Furnace Atmospheres

Class	Description	Common application	Nominal composition, vol % N_2	CO	CO_2	H_2	CH_4
101	Lean exothermic	Oxide coating of steel	86.8	1.5	10.5	1.2	...
102	Rich exothermic	Bright annealing; copper brazing; sintering	71.5	10.5	5.0	12.5	0.5
201	Lean prepared nitrogen	Neutral heating	97.1	1.7	...	1.2	...
202	Rich prepared nitrogen	Annealing, brazing stainless steel	75.3	11.0	...	13.2	0.5
301	Lean endothermic	Clean hardening	45.1	19.6	0.4	34.6	0.3
302	Rich endothermic	Gas carburizing	39.8	20.7	...	38.7	0.8
402	Charcoal	Carburizing	64.1	34.7	...	1.2	...
501	Lean exothermic-endothermic	Clean hardening	63.0	17.0	...	20.0	...
502	Rich exothermic-endothermic	Gas carburizing	60.0	19.0	...	21.0	...
601	Dissociated ammonia	Brazing, sintering	25.0	...	...	75.0	...
621	Lean combusted ammonia	Neutral heating	99.0	...	...	1.0	...
622	Rich combusted ammonia	Sintering stainless powders	80.0	...	...	20.0	...

Classifications of Prepared Atmospheres

The American Gas Association is the source of the following classifications:

- Class 100, exothermic base: formed by the combustion of a gas/air mixture; water vapor in the gas can be removed to get the required dew point
- Class 200, prepared nitrogen base: carbon dioxide and water vapor have been removed
- Class 300, endothermic base: formed by the reaction of a fuel gas/air mixture in a heated, catalyst filler chamber
- Class 400, charcoal base: air is passed through a bed of incandescent charcoal
- Class 500, exothermic-endothermic base: formed by the combustion of a mixture of fuel gas and air; water vapor is removed and carbon dioxide is reformed to carbon monoxide by reaction with fuel gas in a heated, catalyst filled chamber
- Class 600, ammonia base: can consist of raw ammonia, dissociated ammonia, or combusted dissociated ammonia with a regulated dew point

Subclassifications supplement the six basic classifications for prepared atmospheres—the two zeros in the latter are replaced by the two-digit numbers that follow. These atmospheres are prepared by special techniques.

- 01: prepared from a lean air and gas mixture
- 02: prepared from a rich air and gas mixture
- 03 and 04: preparation is completed within the furnace itself without the use of a special machine or generator
- 05 and 06: original base gas is subsequently passed through incandescent charcoal before admission to work chamber
- 07 and 08: raw hydrocarbon fuel gas is added to base gas before admission to work chamber
- 09 and 10: raw hydrocarbon fuel gas and raw dry anhydrous ammonia are added to base gas before admission to work chamber
- 11 and 12: combustible mixture of chlorine, hydrocarbon fuel gas and air is added to base gas before admission to work chamber
- 13 and 14: all sulfur or all sulfur and odors are removed from gas before admission to work chamber
- 15, 16, 17 and 18: lithium vapor is added to base gas before admission to work chamber
- 19 and 20: gas preparation is completed inside the furnace chamber with the addition of lithium vapor
- 21 and 22: base gas is given an additional special treatment before admission to work chamber
- 23 and 24: steam and air are added and in conjunction with a catalyst in a generator convert carbon monoxide to carbon dioxide, which is then removed
- 25 and 26: steam is added to a generator containing a catalyst, converting CH_4 to H_2 and CO_2, which is then removed

Few of the atmospheres in the subclassification category are commercially important. Principal furnace temperatures and their common applications are listed in Table 2. Potential hazards in the use of constituents in heat treating atmospheres and their functions are listed in Table 3. Physiological effects of ammonia are listed in Table 4, and physiological effects of carbon monoxide are given in Table 5.

Table 3 Potential Hazards and Functions of Heat Treating Atmosphere-Constituent Gases

Gas	Potential hazard: Flammable	Toxic	Simple asphyxiant	Atmosphere function
Nitrogen	...	...	Yes	Inert
Hydrogen	Yes	...	Yes	Strongly reducing
Carbon monoxide	Yes	Yes	...	Carburizing and mildly reducing
Carbon dioxide	...	Yes	Yes	Oxidizing and decarburizing
Natural gas	Yes	...	Yes	Strongly carburizing and deoxidizing
Ammonia	Yes	Yes	...	Strongly nitriding
Methanol	Yes	Yes	...	Carbon monoxide and hydrogen generating

Table 4 Physiological Effects of Ammonia

Concentration, ppm	Physiological effects
20	First perceptible odor
40	Slight eye irritation in a few individuals
100	Noticeable irritation of eyes and nasal passages after a few minutes of exposure
400	Severe irritation of the throat, nasal passages, and upper respiratory tract
700	Severe eye irritation; no permanent effect if the exposure is limited to less than ½ h
1700	Serious coughing, bronchial spasms; less than ½ h of exposure may be fatal
5000	Serious edema, strangulation, asphyxia; almost immediately fatal

Explosive ranges of typical atmosphere constituents are:

ınstituent	Concentration in Air %
/drogen	4.0-74
ırbon monoxide	12.5-74
ethane	5.3-14
nmonia	15.0-28
ethanol	6.7-36

xothermic-Based Atmospheres

Class 100 atmospheres of this type are widely used as lower cost ernatives to other atmospheres. They are available in two classes: rich ass 102) and lean (class 101). The rich types have moderate reducing pabilities of 10 to 21% combined carbon monoxide and hydrogen. The ın types, usually with 1 to 4% combined carbon monoxide and hydrogen, ve minimal reducing qualities.

Rich exothermic atmospheres are used mainly in the tempering of steel d sintering of powder metal compacts.

Heat treating applications of lean exothermic atmospheres are generally ıited, particularly in the treatment of ferrous metals. Exceptions include their use as intentional surface oxidizing agents or in special, low temperature operations.

Endothermic-Based Atmospheres

These atmospheres are suitable for practically all furnace processes requiring strong reducing conditions. Their most common applications are as carrier gases in gas carburizing and carbonitriding operations. Other applications include bright hardening of steel, carbon restoration in forgings and bar stock, and the sintering of powder metallurgy compacts requiring a reducing atmosphere.

Table 5 Physiological Effects of Carbon Monoxide

Concentration, ppm	Physiological effects
100	Allowable for an exposure of several hours
400	Can be inhaled for 1 h without appreciable effect
600	Causes a barely appreciable effect after 1 h of exposure
1000	Causes unpleasant symptoms, but not dangerous after 1 h
1500	Dangerous for exposure of 1 h
4000	Fatal for exposure of less than 1 h

ıble 6 Comparison of Generated Atmosphere Systems Versus Commercial Nitrogen-Based Systems

		Generated atmosphere				Nitrogen-based atmosphere				
			Nominal composition, %				Nominal composition, %			
pe of nosphere	Application	Designation	N_2	H_2	CO	Designation	N_2	H_2	CO	CH_4
ıtective	Annealing	Exothermic	70-100	0-16	0-11	Nitrogen-hydrogen	90-100	0-10	...	...
						Nitrogen-methanol	91-100	0-6	0-3	...
		Dissociated ammonia	25	75	...	Nitrogen-hydrogen	60-90	10-40	...	...
ıctive	Brazing	Exothermic	70-80	10-16	8-11	Nitrogen-hydrogen	95	5	...	...
		Dissociated ammonia	25	75	...					
	Sintering	Endothermic	40	40	20	Nitrogen-hydrogen	95	5	...	...
		Dissociated ammonia	25	75	...	Nitrogen-methanol	85	10	5	...
·bon controlled	Hardening	Endothermic	40	40	20	Nitrogen-methane	97	1	1	1
	Carburizing	Endothermic	40	40	20	Nitrogen-methanol	40	40	20	...
	Decarburizing	Exothermic	85	5	3	Nitrogen-hydrogen	90	10	...	...

ble 7 Compositions of Protective Generated Atmosphere and Commercial Nitrogen-Based Atmosphere Systems

		Furnace atmosphere analysis, %					
						Trace impurities	
plication	Input atmosphere	N_2	H_2	CO	CH_4	H_2O	CO_2
·bon steel sheet, tube, wire	Exothermic-purified	80	12	8	...	0.01	0.5
	N_2-5% H_2	95	5	...	...	0.001	...
·bon steel rod	Exothermic-purified	100	...	...	...	0.01	0.5
	Exothermic-endothermic blend	75	15	8	2	0.01	0.5
	N_2-1% C_3H_8	97	1	1	1	0.001	0.01
	N_2-5% H_2-3% CH_4	90	7	2	1	0.001	0.01
	N_2-3% CH_3OH	91	6	3	...	0.001	0.01
ɔper wire, rod	Exothermic-lean	86	...	...	...	3	11
	N_2-1% H_2	99	1	...	...	0.001	...
ıminum sheet	Exothermic-lean	86	...	...	...	3	11
	N_2	100	...	...	...	0.001	...
ınless steel sheet, wire	Dissociated ammonia	25	75	...	...	0.001	...
	H_2	...	100	...	...	0.0005	...
	N_2-40% H_2	60	40	...	...	0.0005	...
ınless steel tube	Dissociated ammonia	25	75	...	...	0.001	...
	H_2	...	100	...	...	0.0005	...
	N_2-25% H_2	75	25	...	...	0.005	...
lleable iron anneal	Exothermic-purified	98	...	2	...	0.01	0.5
	N_2-1% C_3H_8	97	1	1	1	0.001	0.2
kel-iron laminations	Dissociated ammonia	25	75	...	...	0.001	...
	N_2-15% H_2	85	15	...	...	0.001	...

Table 8 Compositions of Reactive Atmospheres for Brazing and Sintering Applications

		Furnace atmosphere analysis, %					
						Trace impurities	
Application	Input atmosphere	N_2	H_2	CO	CH_4	H_2O	CO_2
Copper braze carbon steel	Exothermic-rich	70	14	11	1	0.05	4
	Endothermic	40	39	19	2	0.05	0.1
	N_2-5% H_2	95	5	...	...	0.001	...
	N_2-3% CH_3OH	91	6	3	...	0.001	0.01
Silver braze stainless steel	Dissociated ammonia	25	75	...	...	0.001	...
	N_2-25% H_2	75	25	...	...	0.001	...
Metallize ceramics	Dissociated ammonia + H_2O	25	75	...	...	3	...
	N_2-10% H_2-2% H_2O	90	10	...	...	2	...
Glass-to-metal seal	Exothermic	75	9	7	...	3	6
	N_2-10% H_2-2% H_2O	88	10	...	...	2	...
Carbon steel sintering (6.4 to 6.8 g/cm^3, or 0.23 to 25 lb/$in.^3$ density, <0.4% C)	Endothermic	40	39	19	2	0.05	0.1
	N_2-5% H_2	95	5	...	...	0.001	...
	Endothermic	40	39	19	2	0.05	0.2
Carbon steel sintering (6.8 to 7.2 g/cm^3, or 0.25 to 0.26 lb/$in.^3$ density, >0.4% C)	N_2-endothermic	87	8	4	1	0.01	0.05
	N_2-8% CH_3OH	76	16	7	1	0.005	0.05
	N_2-8% H_2-2% CH_4	90	8	1	1	0.005	0.01
Brass, bronze sintering	Dissociated ammonia	25	75	...	...	0.001	...
	Endothermic	40	39	19	2	0.05	0.3
	N_2-10% H_2	90	10	...	...	0.001	...
Stainless steel sintering	Dissociated ammonia	25	75	...	...	0.001	...
	H_2	...	100	...	...	0.001	...
Tungsten carbide							
Sintering and brazing	Dissociated ammonia	25	75	...	...	0.001	...
Sintering	H_2	...	100	...	...	0.001	...
Presintering	N_2-20% H_2	80	20	...	...	0.001	...
Nickel sintering	Dissociated ammonia	25	75	...	...	0.001	...
	N_2-10% H_2	90	10	...	...	0.001	...

Prepared Nitrogen-Based Atmospheres

Applications in this instance extend to almost all heat treatments that do not require highly reducing atmospheres. They are not decarburizing and can be used in annealing, normalizing, and hardening of medium- and high-carbon steels; the low carbon monoxide content of lean gases makes them suitable for heat treating low-carbon steels. Because of their low dew point and virtual absence of carbon dioxide, these atmospheres (in the absence of oxygen-bearing contaminants introduced in furnace operations) are neither oxidizing or decarburizing, in contrast with exothermic-based atmospheres. In addition, they are lower in cost than all but one type of protective atmosphere: the exothermics.

Nitrogen-based atmospheres enriched with methane or other hydrocarbons are used occasionally as carrier gases in annealing, gas carburizing, and carbon restoration; but endothermic and other protective atmospheres are generally preferred for their high carbon potentials and greater ease of control.

Lean, nitrogen-based atmospheres are also used in large, semi-continuous and continuous annealing furnaces. Their rich counterparts can be used in the sintering of iron powder compacts.

Generated atmosphere systems and commercial, nitrogen-based systems are compared in Table 6.

Commercial Nitrogen-Based Atmospheres

These products fall into three major categories, based on function: protective atmospheres, reactive atmospheres, and carbon-controlled atmospheres.

Protective atmospheres prevent oxidation or decarburization during heat treatment. Typical applications include batch and continuous annealing of most ferrous metals.

Reactive atmospheres have concentrations of reactive gases greater than 5%—to reduce metal oxides or to transfer small amounts of carbon to ferrous surfaces. Hydrogen and carbon monoxide are usual reactive components. Typical applications: brazing, sintering powder metal compacts, and powder metal reduction.

Carbon-Controlled Atmospheres. Their main function is to react with steel in a controlled manner so that significant amounts of carbon can be added to or removed from the surface of a steel. Typical atmosphere components can include up to 50% hydrogen, 5 to 20% carbon monoxide, and traces (up to 3%) of carbon dioxide and water vapor.

Most common applications are carburizing and carbonitriding machined parts, neutral hardening, decarburization of electrical laminations, sintering of powder metals, and carbon restoration of hot worked or forged materials.

Advantages of commercial, nitrogen-based atmospheres include the technical viability of substituting them for generated atmospheres in most heat treating operations.

Compositions of protective generated atmospheres and commercial, nitrogen-based systems are listed in Table 7. Compositions of reactive atmospheres for brazing and sintering are given in Table 8. Compositions of carbon-controlled atmospheres for selected applications are summarized in Table 9.

Dissociated, Ammonia-Based Atmospheres

Applications include: bright heat treating of some nickel alloys and carbon steels; bright annealing of electrical components, and use as a carrier mixed gas for certain nitriding processes, including the Floe nitriding system, a method of controlling the formation of white layer.

ɔle 9 Compositions of Carbon-Controlled Atmospheres for Selected Applications

ılication	Input atmosphere	Furnace atmosphere analysis, %				Trace impurities	
		N_2	H_2	CO	CH_4	H_2O	CO_2
tral harden	Endothermic + CH_4	39	40	19	2	0.05	0.1
	N_2-2% CH_4, or 1% C_3H_8	97	1	1	1	0.001	0.01
	N_2-5% CH_3OH-1% CH_4	84	10	5	1	0.005	0.01
ɔurize	Endothermic + CH_4	37	40	18	5	0.05	0.1
	N_2-20% CH_3OH + CH_4	37	40	18	5	0.05	0.1
	N_2-17% CH_4-4% CO_2	70	16	7	7	0.005	0.05
	N_2-20% CH_4-5% H_2O	55	28	10	7	0.01	0.05
ɔonitride	Endothermic + CH_4 + NH_3	36	40	18	5	0.05	0.1
	N_2-20% CH_3OH + CH_4 + NH_3	36	40	18	5	0.05	0.1
	N_2-17% CH_4-4% CO_2 + NH_3	68	18	7	7	0.005	0.05
	N_2-20% CH_4-5% H_2O + NH_3	53	30	10	7	0.01	0.05
ıination decarburize	Exothermic + H_2O	75	9	7	...	3	6
	N_2-10% H_2-4% H_2O	83	10	1	...	3	3
	N_2-5% CH_3OH-4% H_2O	79	10	2	...	3	6

ɔle 10 Physiological Effects of Contamination of Air Ammonia in Various Concentrations

ımonia concentration r, ppm	Physiological effect
	Smallest concentration at which odor can be detected
	Maximum concentration allowable for prolonged exposure
500	Maximum concentration allowable for short exposure (½-1 h)
	Least amount causing immediate irritation to the throat
	Least amount causing immediate irritation to the eye
)	Least amount causing coughing
)-4500	Dangerous for short exposure (½ h)
)-10,000	Rapidly fatal for short exposure

his atmosphere (class 601) is a medium cost product which provides a carbon-free source of reducing gas. Typical composition: 75% hydro-, 25% nitrogen, less than 300 ppm residual ammonia. Dew point is less ı −50 °C (− 60 °F).

igh hydrogen content provides a strong deoxidizing potential, an ad-ıage in removing surface oxides or preventing oxide formation during ı temperature heat treatment. Care is advised in selecting heat process-applications that might result in unwanted hydrogen embrittlement or ace nitriding reactions.

hysiological effects of the contamination of air with ammonia in differ-concentrations are set forth in Table 10.

drogen Atmospheres

he commercially available product is 98 to 99.9% pure. All cylinder rogen contains traces of water vapor and oxygen. Methane, nitrogen, ɔon monoxide, and carbon dioxide may be present in very small ɔunts as impurities.

ydrogen is a powerful deoxidizer, and its deoxidizing potential is ted by moisture content only. Its thermal conductivity is about seven :s that of air. Its main disadvantage is that it is readily absorbed by most ımon metals, either by occlusion or by chemical composition at ele-d temperature. Absorption can result in serious embrittlement, espe-y in high-carbon steels. It may also reduce oxide inclusions in steel to ı water, which builds sufficient pressure at elevated temperatures to :e intergranular fracture of steel. Dry hydrogen will decarburize high-ɔn steels at elevated temperature by reacting with carbon to form ıane.

Table 11 Equipment Requirements for Sintering Stainless Steel Powder Metallurgy Parts in Hydrogen

Production requirements	
Load weight, kg (lb)	9 (20)
Heating cycle, min	40
Output per hour, kg (lb)	14 (30)
Equipment requirements	
Burnoff furnace	Pusher, electrically heated; forced circulation
Size of hearth, mm (in.)	255 by 150 by 915 (10 by 6 by 36)
Length of cooling chamber, m (ft)	1.8 (6)
Power, hp (kW)	27 (20)
Operating temperature, °C (°F)	425 (800)
Atmosphere, m^3/h (ft^3/h)	Dissociated ammonia, 4.2 (150)
High-heat furnace	Open chamber, electrically heated; front push, rear pull
Size of hearth, mm (in.)	255 by 610 (10 by 24) (preheating) 255 by 915 (10 by 36) (high heating)
Length of cooling chamber, mm (ft)	2.4 (8)
Power, hp (kW)	47 (35)
Operating temperature, °C (°F)	1275 (2325)

Hydrogen best suited for metallurgical purposes is made by the electrolysis of distilled water. In most heat treating procedures requiring hydrogen, water vapor and oxygen are objectionable, and hydrogen must be purified before it can be used.

Applications for dry hydrogen include the annealing of stainless steels, low-carbon steels, electrical steels, some tool steels, nickel brazing of stainless steel and heat resisting alloys, the annealing of metal powders, and the sintering of powder metal compacts.

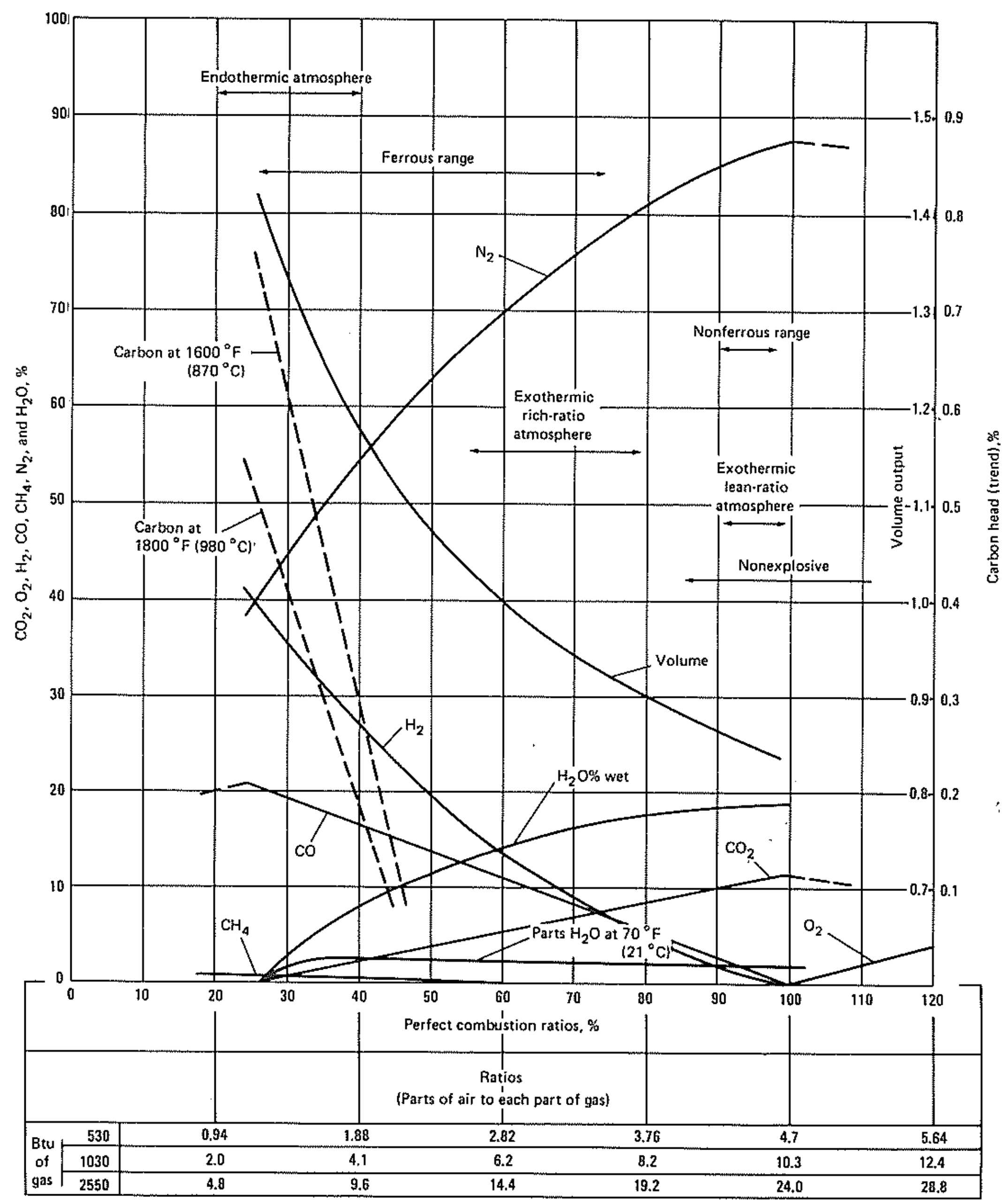
Equipment requirements for sintering stainless steel powder metallurgy parts in hydrogen are found in Table 11.

Steam Atmospheres

Scale-free tempering and stress relieving of ferrous metals in the temperature range of 345 to 650 °C (655 to 1200 °F) are among the applications here. Steam causes a thin, hard, and tenacious blue-black oxide to form on a metal surface. The film, approximately 0.00127 to 0.008 mm (0.00005 to 0.0003 in.) thick, improves properties of various metal parts.

Steam treating decreases the porosity of sintered iron compacts and provides increased compressive strength and resistance to wear and corrosion. Steam penetrates the pores of compacts and forms the oxide internally as well as on the surface. The oxide seals pores and partially fills voids.

Exothermic and Endothermic Furnace Atmospheres. Source: Electric Furnace Co.



Cast iron and steel parts, treated at 345 °C (655 °F) or higher, have increased resistance to wear and corrosion.

Before parts are processed their surfaces must be clean and oxide-free, to permit the formation of a unique coating. To prevent condensation and rusting, steam should not be admitted until workpiece surfaces are above 100 °C (210 °F). Air must be purged from the furnace before the temperature exceeds 425 °C (795 °F), to prevent the formation of a brown coating instead of the desired blue-black coating.

Charcoal-Based Atmospheres

These atmospheres (AGA classes 402 and 421) are on the way to becoming obsolete. Their main use currently is by small manufacturing plants wanting a generator low in initial cost and for intermittent use. Principal uses today are in the manufacture of malleable iron castings and as atmospheres in small toolroom, heat treating furnaces.

Exothermic-Endothermic-Based Atmospheres

These atmospheres (classes 501 and 502) are re-formed exothermic-based types and are less reducing than conventional endothermic-based atmospheres. Potentially, they can be substituted for exothermic, endothermic, and nitrogen-based atmospheres in virtually all applications for which any one of the three atmospheres is recommended. Also, they are used as carrier gas in carburizing and carbonitriding.

uipment requirements for hardening small parts made of 1070 steel in ıermic-endothermic atmospheres are provided in Table 12.

ıospheres for Backfilling and ≥nching in Vacuum

ckfilling with a cooling gas in a vacuum furnace speeds up the cooling Other uses of backfilling include: suppressing the vaporization of oil tegral quench vacuum furnaces and providing an atmosphere for ırizing and nitriding.

:rt gases, nitrogen, and hydrogen (rarely) are used for cooling; con- ıants in cooling gases must be held to a minimum to maintain the ce integrity of workpieces and to avoid damage to furnace parts.

ckfilling and forced circulation increase cooling rates, aid in harden- ınd in some instances are used to anneal metal alloys. Cooling gas is ly introduced into a vacuum chamber at the end of the high tempera- ;oaking period.

cuum furnaces can be used for carburizing by the injection of any one veral atmospheres that induce carburizing at appropriate temperatures. gen enriched with a hydrocarbon gas is most frequently used. rburizing is normally carried out in the range of 870 to 980 °C (1600 '95 °F). In the carburizing and diffusion process, surface carbon :nt of 1% or more is formed initially. The high-carbon case is then sed in vacuum to the desired surface content and case depth.

Carburizing Atmospheres

ıydrocarbon gas that is ionized by a high voltage system in a vacuum uitable atmosphere for this process. Methane is frequently used. The :ss is faster than conventional atmosphere carburizing, and surface ın content approaches saturation. For carbon control, other diluting : are added.

AISI 1018 steel can be ion carburized to a depth of 1.0 mm (0.040 /ith a 10 min cycle in an atmosphere of methane at 1.3 to 2.7 kPa (10 torr) and a temperature of 1050 °C (1920 °F). Carburizing is followed 30 min diffusion cycle in vacuum at the same temperature. About 400 ıeeded to produce the plasma.

Table 12 Equipment Requirements for Hardening Small Parts Made of 1070 Steel in an Exothermic-Endothermic Atmosphere

Production requirements	
Number of parts per load	2625
Weight of each part, kg (lb)	0.0069 (0.015)
Maximum net weight of load, kg (lb)	18 (40)
Production rate, kg (lb)	7.5 loads (135, or 300) per h
Equipment requirements	
Hardening furnace	Gas-fired radiant-tube single-row pusher type with automatic quench
Size of hearth, m (ft)	0.9 (3) wide by 2.9 (9½) long
Heat input, W/h (Btu/h)	2.2×10^5 Watts (7.5×10^5)
Operating temperature, °C (°F)	900 (1650)
Capacity of generator, m^3/h (ft^3/h)	68 (2400)
Type of atmosphere	Class 502
Capacity of oil-quench tank, L (gal)	1250 (330)
Type of oil, °C (°F)	Fast, 180 (360) flash point
Temperature of oil, °C (°F)	70 (160) (controlled)
Oil agitation	Medium

Ion Nitriding Atmospheres

The process is similar to that of ion carburizing, except that the atmosphere gas generates nitrogen ions, and the process is carried out at lower temperatures. Suitable sources for nitrogen ions are ammonia or mixtures of hydrogen and nitrogen. A typical cycle of 8 h at 510 °C (950 °F) with a mixture of 75% hydrogen and 25% nitrogen at a pressure of 0.9 kPa (7 torr) and a current density of 0.8 mA/cm^2 will produce a nitrided case of 0.30 mm (0.012 in.) in AISI 4140 steel. About 400 V is needed to generate the plasma.

Reference

1. *ASM Metals Handbook*, Vol 4, 10th ed, ASM International

›ld and Cryogenic Treatment of Steel

mmon practice for cold treatment is regarded to be –84 °C (–120 °F). 'ogenic treating, parts are chilled to approximately –190 °C (–310 °F).

ıefits from cold treatment range from enhancing transformation from nite to martensite to improving the stress relief of castings and ma- d parts. In each case, even greater gains are realized via cryogenic nent.

d Treating

a rule, 1 h for each inch of cross section is adequate. All hardened treated in this manner have less tendency to develop grinding cracks grind easier after retained austenite and untempered martensite are nated—100% transformation to martensite in hardening is rare.

ıld Treating vs. Tempering. The best opportunity for maximum formation to martensite is to cold treat parts immediately after hard- ; (and before tempering) when parts cool down to room temperature, a temperature within the range for quenching. A caveat is attached to ırocedure: cracking could result. For this reason, it is important to e that the grade of steel and product design will tolerate immediate reating, rather than immediate tempering. Some steels must be transferred to a tempering furnace when they are still warm to the touch to minimize chances of cracking. Design features such as sharp corners and abrupt changes in section create stress concentrations and promote cracking.

In most instances, cold treating does not precede tempering. In several applications, tempering is followed by deep freezing and retempering without delay. Such parts as gages and pistons are treated in this manner for dimensional stability. In critical applications, multiple freeze-temper cycles are used.

In addition, in cases where retained austenite could result in excessive wear, the wear resistance for several different materials is improved, ie., tool steels; high-carbon, martensitic stainless steels, and carburized alloy steels (see adjoining table).

Process Limitations

In some applications, explicit amounts of retained austenite are considered beneficial, and treatment could be detrimental. Also, multiple tempering, rather than alternate freeze-temper cycles, is generally more practical in transforming retained austenite in high speed and high-carbon/high-chromium steels.

Hardness Testing. Lower than expected HRC values may indicate excessive retained austenite. Significant increases in hardness readings following cold treatment indicate conversions from austenite to martensite.

Precipitation-Hardening Steels. Specifications for these steels may include a mandatory deep freeze after solution treatment and prior to aging.

Shrink Fits. This result can be obtained by cooling the inner member of a complex part. Care is advised to avoid brittle cracking when the inner member is made of heat treated steel containing large amounts of retained austenite, which converts to martensite in subzero cooling.

Stress Relief. Cold treating is beneficial in stress relieving castings and machined parts of even or nonuniform cross section. Features of the treatment include:

- Transformation of all layers is accomplished when the material reaches –84 °C (–120 °F)
- The increase in volume of the outer martensite is somewhat counteracted by the initial contraction due to chilling
- Rewarm time is more easily controlled than cooling time, allowing equipment flexibility
- The expansion of the inner core due to transformation is somewhat balanced by the expansion of the outer shell
- The chilled parts are more easily handled
- The surface is unaffected by low temperature
- Parts that contain various alloying elements and that are of different sizes and weights can be chilled simultaneously

Advantages of Cold Treating

Success depends only on reaching the minimum low temperature, and there is no penalty for a lower temperature. As long as –80 °C (–115 °F) is reached transformation takes place. Reversal is not caused by additional chilling. Also, materials with different compositions and different configurations can be chilled at the same time, even though each may have a different high temperature transformation point.

Cryogenic Treatment

A typical treatment consists of a slow cool-down rate (2.5 °C/min equivalent to 4.5 °F/min) from ambient temperature to the temperature of liquid nitrogen. When the material reaches approximately 80 K (–315 °F), it is soaked for an appropriate time (generally 24 h). Then the part is removed from the liquid nitrogen and allowed to warm to room temperature in ambient air. The temperature-time plot for this treatment is shown in the adjoining Figure. By using gaseous nitrogen in the cool-down cycle, temperatures can be controlled accurately, to avoid thermal shock.

Single cycle tempering usually is the next step—to improve impact resistance, although double or triple tempering cycles are sometimes used for the same reason.

Kinetics of Cryogenic Treatment

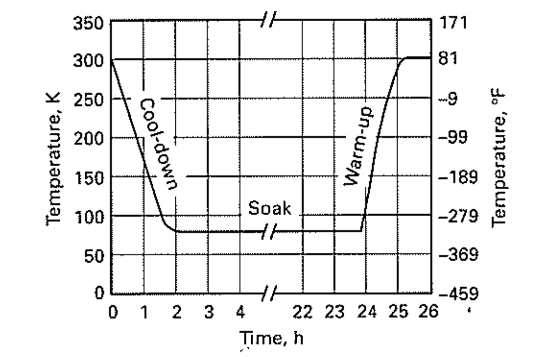
According to one theory with this treatment, transformation of retained austenite is nearly complete—a conclusion that has been verified by x-ray diffraction measurements. Another theory is based on strengthening a material via the precipitation of submicroscopic carbides. An added benefit is said to be a reduction in internal stresses in the martensite developed during carbide precipitation. Lower interior stresses may also reduce tendencies to microcrack.

Wear Resistance as a Function of Cryogenic Soak Temperature for Five High-Carbon Steels

Alloy	Untreated	Wear resistance, R_W(a) Soaked –84 °C (–120 °F)	–190 °C (–310 °F)
52100	25.2	49.3	135
D2	224	308	878
A2	85.6	174.9	565
M2	1961	2308	3993
O1	237	382	996

(a) $R_W = FV/WH_V$, where F is the normal force in newtons, N, pressing the surfaces together; V is the sliding velocity in mm/s; W is the wear rate in mm^3/s; and H_V is the Vickers hardness in MPa. R_W is dimensionless. Source: Ref 3

Plot of temperature vs. time for the cryogenic treatment process. Source: Ref 2



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1. *ASM Metals Handbook*, Heat Treating, Vol 4, 10th ed., ASM International
2. R.F. Barron and R.H. Thompson, Effect of Cryogenic Treatment on Corrosion Resistance, in *Advances in Cryogenic Engineering*, Vol 36, Plenum Press, 1990, p 1375-1379
3. R.F. Barron, "How Cryogenic Treatment Controls Wear," 21st Inter-Plant Tool and Gage Conference, Western Electric Company, Shreveport, LA, 1982

Representative Applications of Heat Treating Furnaces

Representative applications of 36 different types of heat treating furnaces, reported by suppliers of equipment, are listed in this section. Ref 1.

Soaking Pit Furnaces

Normalizing
Stress relieving
Reheating

Batch or In-and-Out Furnaces

Normalizing
Annealing
Aging

Carburizing (diffusion phase)
Stress relieving

ox Furnaces

Annealing
Tempering
Hardening
Normalizing
Stress relieving
Aging
Carburizing
Malleabilizing
Solution heat treating

arbon Bottom Furnaces

Annealing, i.e., coatings
Hardening
Normalizing
Malleabilizing
Stress relieving
Carburizing
Tempering
Spheroidizing
Homogenizing

t Furnaces

Annealing, including long cycle annealing of ferrous parts
Hardening
Tempering
Normalizing
Stress relieving
Steam treating
Homogenizing
Carburizing
Carbonitriding
Carbon restoration
Bluing
Nitriding
Solution heat treating

ell and Hood Furnaces

Hardening
Nitriding
Aging
Bluing
Tempering
Stress relieving
Solution heat treating

evating Hearth Furnaces

Solution heat treating
Hardening
Aging
Malleabilizing
Tempering
Annealing
Stress relieving
Lab work

tegral Quench Furnaces

Case hardening
Neutral hardening
Clean hardening

Normalizing
Carburizing
Nitrocarburizing
Carbonitriding
Annealing
Carbon restoration
Stress relieving
Austenitizing

Tip-Up Furnaces

Annealing, i.e., wire, long bars, rods, pipe
Hardening
Spheroidizing
Normalizing
Malleabilizing
Tempering
Stress relieving

Wraparound and Split Furnaces

Annealing
Stress relieving

Vertical Furnaces

Annealing
Hardening
Normalizing
Malleabilizing
Tempering
Stress relieving
Austempering
Carburizing

Continuous Slab and Billet Heating Furnaces

Solution heat treating
Homogenizing
Carburizing

Walking Beam Furnaces

Hardening
Annealing
Tempering
Stress relieving
Normalizing
Sintering stainless steel compacts

Rotary Hearth Furnaces

Hardening
Annealing
Carburizing
Carbonitriding
Carbon restoration
Malleabilizing
Tempering
Austempering

Pusher Furnaces

Annealing
Carbonitriding
Carburizing
Hardening
Normalizing
Clean hardening

Ferritic nitrocarburizing
Malleabilizing
Solution heat treating
Tempering
Stress relieving
Carbon restoration
Spheroidizing

Roller Hearth Furnaces

Solution heat treating
Stress relieving
Bluing
Spheroidizing
Tempering
Normalizing
Malleabilizing
Hardening, i.e., clean hardening
Tempering
Carburizing
Carbonitriding
Carbon restoration

Conveyor Hearth Furnaces

Tempering
Hardening, i.e., clean hardening
Carbon restoration
Annealing, i.e., bright annealing
Carbonitriding
Austempering
Carburizing
Spheroidizing
Homogenizing

Humpback Furnaces

Applications requiring hydrogen cover gas
Heat treating stainless steel
Annealing
Stress relieving
Carburizing
Hardening

Shaker Hearth Furnaces

Hardening, i.e., neutral hardening carbon steel and light case hardening
Carburizing
Carbonitriding
Stress relieving
Normalizing
Annealing
Tempering
Austempering

Rotary Hearth Furnaces

Small ferrous parts
Process and production testing
Small volume production
Hardening
Tempering
Austempering
Annealing
Carburizing
Carbon restoration
Carbonitriding

Screw Conveyor Furnaces

Hardening
Tempering
Annealing
Stress relieving

Slotted Roof, Monorail Conveyor Furnaces

Annealing, i.e., large castings, crankshafts, chains, and other long and unusually shaped parts
Hardening
Tempering
Annealing
Normalizing
Stress relieving

Ion Nitriding/Carburizing Furnaces

Nitriding, i.e., extrusions and D2 tool steels
Carburizing steel parts

Vacuum Furnaces

Annealing, i.e., bright annealing
Hardening
Tempering
Stress relieving
Carburizing
Carbonitriding
Degassing
Carbon deposition

Fluidized Bed Furnaces

Nitrocarburizing
Nitriding
Carbonitriding
Steam oxidizing
Carburizing
Hardening, bright type
Tempering

Salt Bath Pot Furnaces

Austempering
Martempering
Hardening
Tempering
Carburizing
Cyaniding

Salt Bath Furnaces: Batch Austemper System

Austempering, i.e., ductile iron, steel
Carburizing
Carbonitriding
Nitrocarburizing
Normalizing
Neutral hardening

Salt Bath Furnaces: Mesh Belt Austemper System

Austempering, i.e., ductile iron, steel
Carboaustempering steel

utral Salt Based Furnaces

ıstempering
artempering
ırdening

anide Based Salt Type Furnaces

ırburizing
ıse Hardening

rrel Furnaces

eat treating, continuous long lengths of pipe, turbine, bars, rods, billets
cluded in quench and temper lines for high grades of oil country tubing

›verleaf Furnaces

ardening
ormalizing
:mpering
arburizing
nnealing
arbonitriding
arbon restoration

ectron Beam Surface Treating Equipment

urface hardening primarily, i.e., martensitically hardenable ferrous metals

ser Heat Treating Furnaces

.nnealing

Quartz Tube Furnaces

Sintering
Heat treating

Rotating Finger Furnaces

Hardening
Normalizing
Tempering
Annealing
Stress relieving

Induction Heat Treating Systems

Hardening, i.e., surface and localized types
Tempering

Resistance Heating Systems

Aging
Stress relieving
Hardening
Annealing, i.e., bright annealing
Carbonitriding
Normalizing

Reference

1. Joseph H. Greenberg, *Industrial Thermal Processing Equipment Handbook*, ASM International, 1994

tatistical Process Control of Heat Treating Operations

tatistical process control (SPC) is being applied to advantage in heat ting shops with continuous, batch, and single part operations. (A case ory of how one shop has integrated this technology into its operations ɛported in a sidebar feature to this article. In many instances, as in this , teaming SPC with the computer is the next step). Ref 1.

:ontinuous equipment, such as rotary retorts, pusher carburizers, belt furnaces, offer the most straightforward approach to applying both istical quality control (SQC) and SPC techniques to improve process formance. The high volume of work handled by continuous equipment vides many opportunities for sampling key product characteristics. Problems can be predicted and corrective action taken in a timely manner. Also, special causes of problems are often more identifiable because process variables are steadier in continuous processes than they are in batch operations.

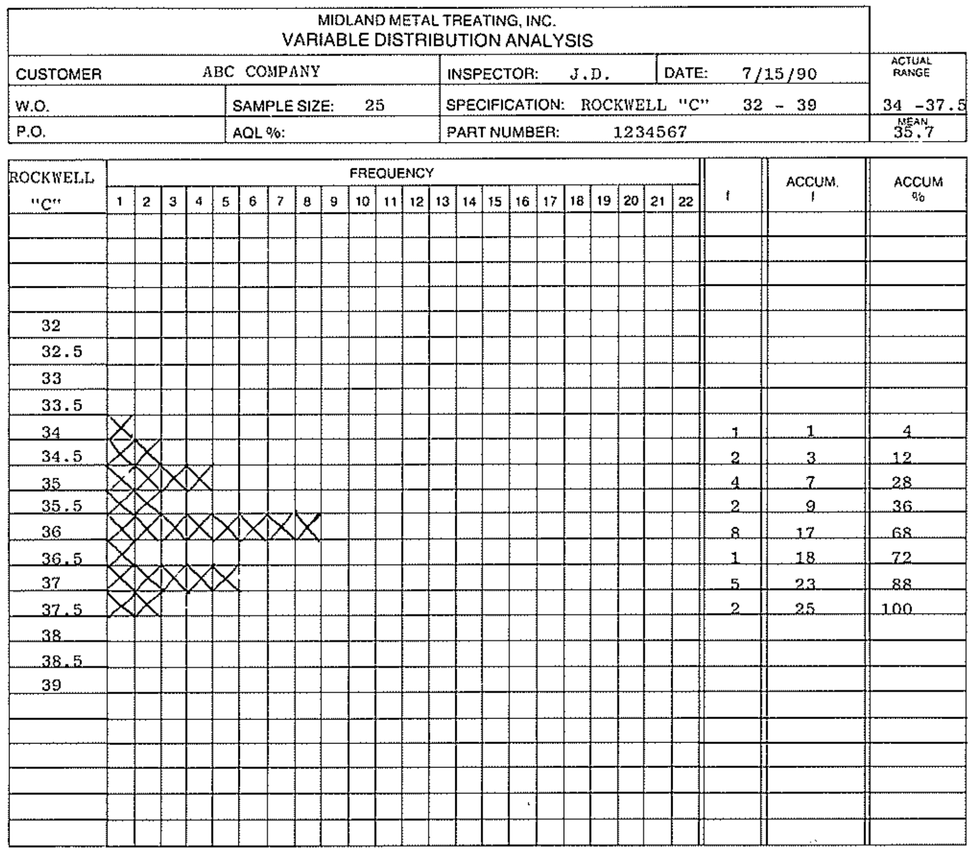
Batch operations allow a significant amount of sampling and analysis within a load. However, the only net payoff is a degree of confidence in treating an entire load. Process variables must be monitored and analyzed to ensure that the process is under control, and that there is load-to-load and day-to-day repeatability—especially when each load is different in terms of part geometry, material, and/or specification.

ıntribution of Selected Parameters to Variations in Effective Case Depth for Required 0.85 to 1.00% Surface Carbon vel at 870 °C (1600 °F) Processing Temperature

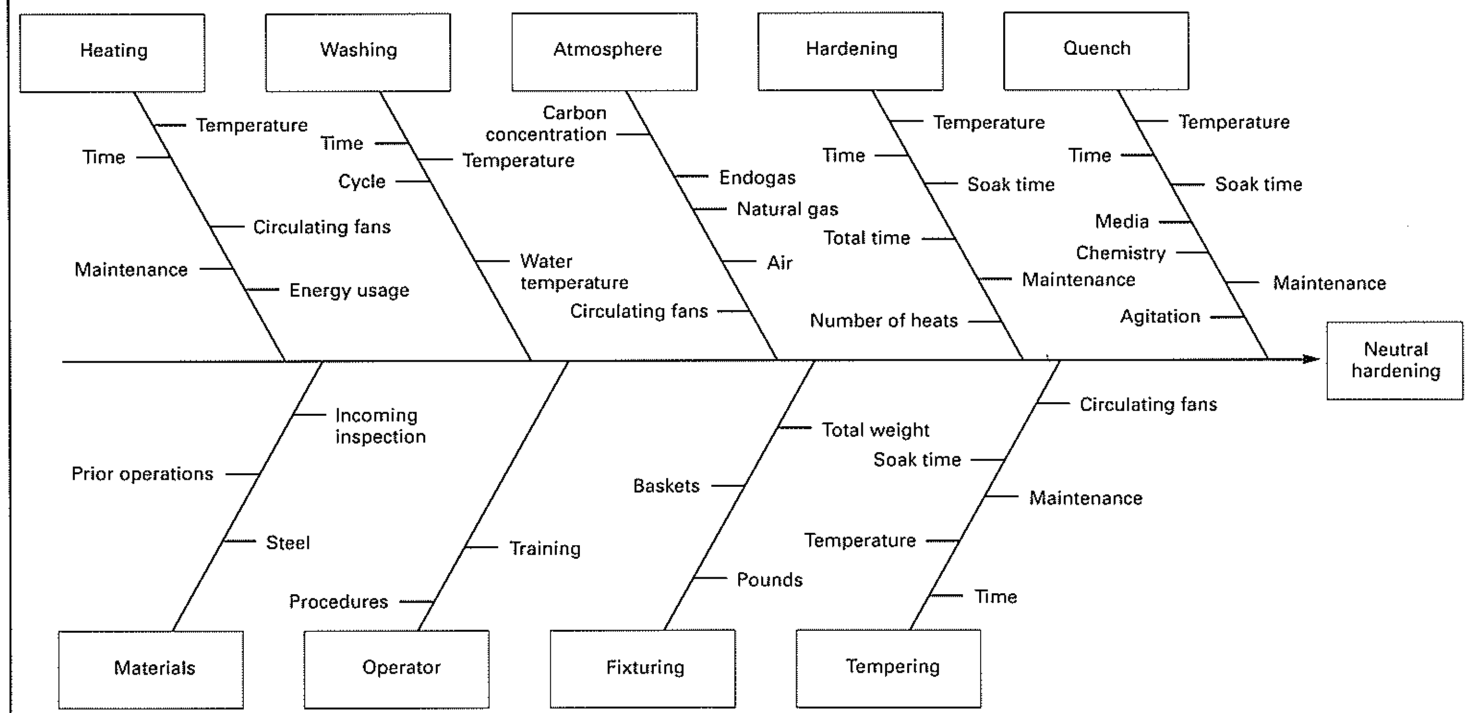
Case depth		Variation in case depth for selected parameters, % (a)											
		Temperature variation (ΔT)			Time variation (Δt)			Carbon variation (ΔC)					
								Atmosphere			Quench uniformity(b)		
		11 °C (20 °F)	28 °C (50 °F)	56 °C (100 °F)									
mm	in.				5 min	10 min	30 min	0.10%	0.15%	0.25%	0.05%	0.10%	0.20%
0.51	0.020	6	14	33	3	7	20	8	13	27	11	23	45
1.02	0.040	6	16	34	1	2	5	8	13	27	11	23	45
1.52	0.060	7	17	35	>1	1	2	8	13	27	11	23	45
2.03	0.080	9	19	36	>1	>1	1	8	13	27	11	23	45

Total process variation = $\sqrt{A^2 + B^2 + C^2 + D^2 \ldots + Z^2}$, where A, B, C, D, and Z are % variations attributed to ΔT, Δt, atmosphere ΔC, quench uniformity ΔC, and additional vari- :s, respectively (b) Variation in case carbon level when quenched to 50 HRC

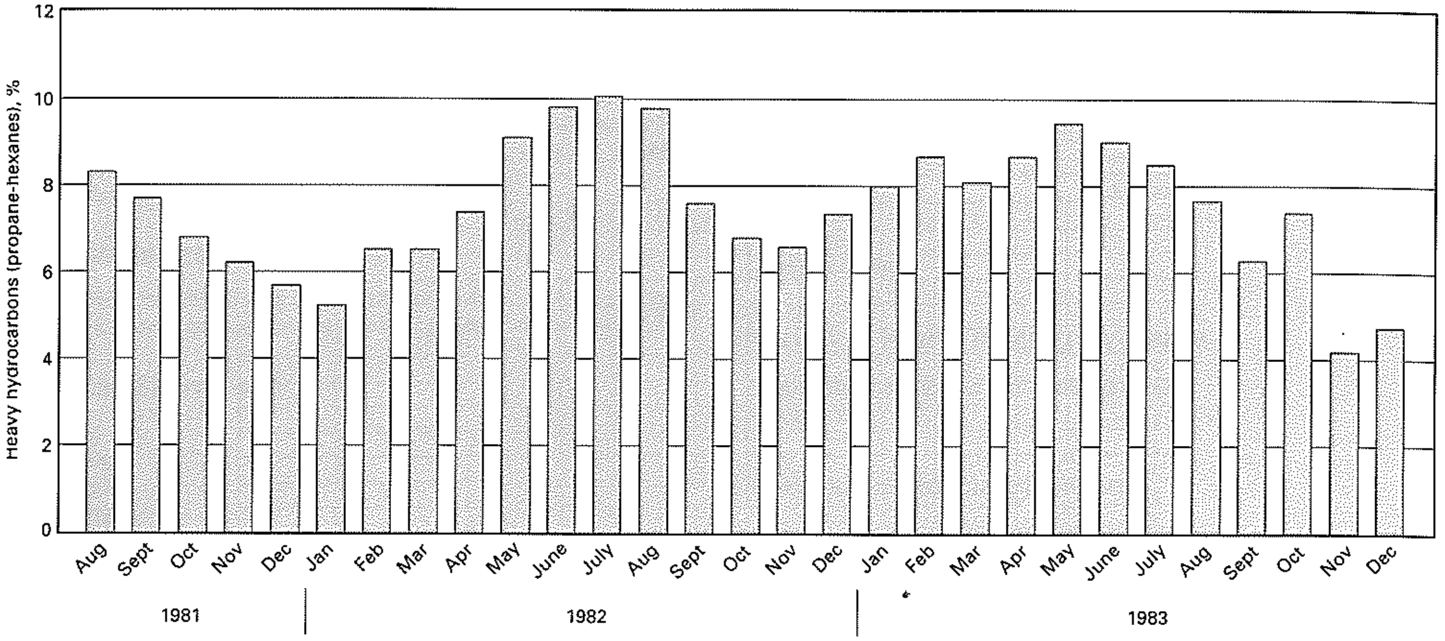
Final hardness distribution analysis for a typical quench and temper operation



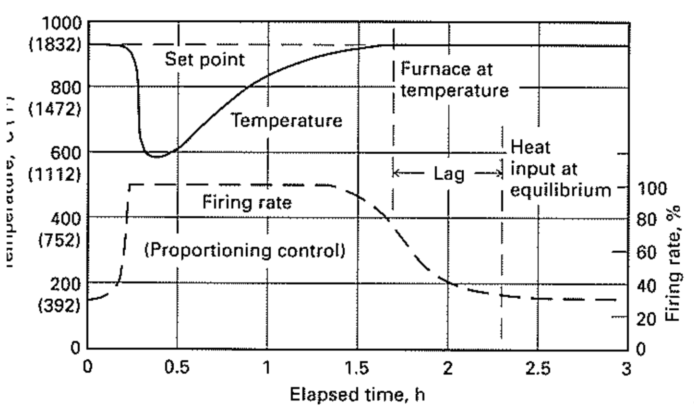
Identification of heat-treating variables for the neutral hardening process



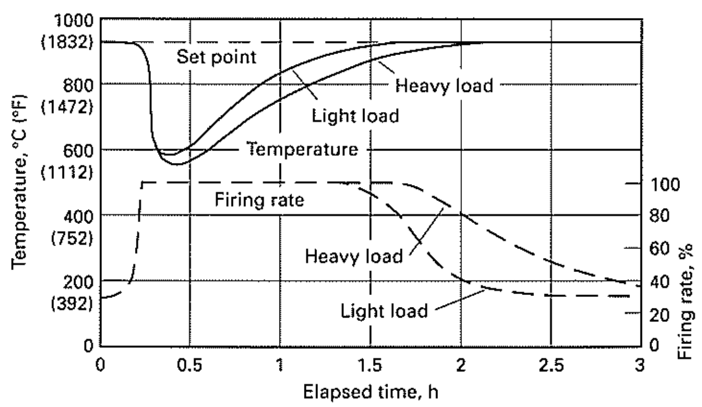
Variation in natural gas composition monitored in the Canton, OH, area over nearly a 2½-year period



Plot of furnace temperature versus elapsed time to show that heat input equilibrium lags behind attaining of setpoint temperature after furnace loading



Plot of furnace temperature versus elapsed time to show effect of load size on heat balance equilibrium



Single part treatment, as with induction or flame treating, does not nd itself to using part evaluation techniques to predict negative results. ie focus must be shifted to SPC and to the identification, monitoring, and ntrol of process variables to ensure repeatability of results. Some varibles that need to be considered are electrical power, flame temperature, an speed, coil dimension, part positioning, and quenchant temperature. ending of process variables can be utilized to determine special causes.

Process deterioration is another factor that must also be taken into count in all types of heat treating operations. The challenge is to counter ear and tear on equipment with corrective action before out-of-specification parts are produced.

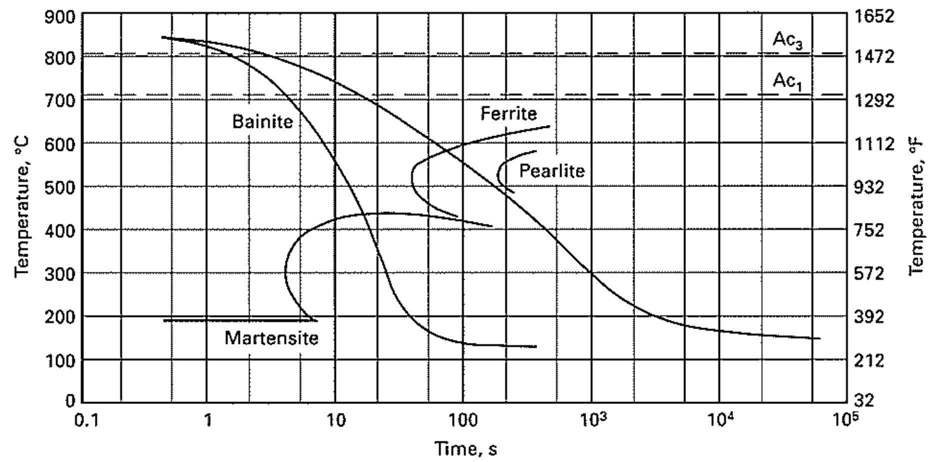
Key process variables fall into three categories: those which are controlle, those which aren't, and those which are secondary.

Controllable variables include temperature, atmosphere carbon potial, and quenchant temperature.

Uncontrollable variables include quench transfer time, temperature recovery time, and quench temperature rise. However, suitable courses of action are available. Examples follow:

- With most furnace systems, control of quench transfer time is not possible, but is often a critical parameter in producing good parts. A possible course of action is to monitor and analyze transfer time to get an early warning of trouble.
- One automatic control system compares maximum allowable transfer time needed to get the desired result with actual transfer times; an alarm is triggered when the maximum is exceeded, indicating a mechanical failure or deterioration in the system.
- Temperature recovery time can be determined, for instance, by measuring and analyzing the time taken by a batch furnace (with a standard load weight or empty) to reach set temperature. In this manner, trends, plotted on an SPC chart, may indicate a loss in furnace performance which, via investigation, could be traceable to damaged insulation, poor door seals, or heating system malfunction, for example.
- Knowing how quench temperature cycles from quench to quench can be important. Findings may trigger an investigation of the entire quenching system, which may suggest problems with quench agitation or quench cooling, for example. Furnace overloading is another possibility.

Calculated CCT diagram from actual part composition with modeled part cooling rates. Ac_1: temperature at which austenite begins to form during heating. Ac3: temperature at which transformation of ferrite to austenite is completed during heating



Secondary process variables, such as fuel consumption and additive atmosphere gas, are caused by deterioration in control loops. By monitoring gas or electrical consumption for a standardized furnace cycle and loading (or the furnace could be empty), diminished performance in the heating system can be detected.

By monitoring and trending the amount of natural gas or propane addition required to control a given carbon potential setpoint, deterioration of furnace atmosphere integrity can be detected.

Examples of parameters with an influence on effective case depth are given in an adjoining Table.

A variable distribution analysis of hardness of a job is shown in an adjoining Figure.

Heat treating variables involved in neutral hardening are given in an adjoining Figure.

Changes in natural gas composition over an extended period are plotted in an adjoining Figure.

How heat input equilibrium lags setpoint temperature after a furnace is loaded is shown in an adjoining Figure.

Effect of load size on heat balance equilibrium is indicated in an adjoining Figure.

Integrating SPC and SQC

Potentials for real time process improvement can be realized by combining the disciplines of SPC, which focus on process variables, and SQC, which focus on product quality. The computer is needed to statistically analyze data in a way that allows timely adjustment of process.

As a product characteristic (as-quenched hardness, for example) is shown to be trending away from average, a special cause, such as quench temperature, may be identified quickly. Ability to compare process variable trend charts to the product characteristic trend chart, for the same time period, offers a valuable tool for continuing improvement.

Information can be valuable even if no special cause can be identified among monitored process variables to correlate with a change in product quality. Such knowledge could lead the heat treater to an uncontrollable variable, such as material, more quickly than he could otherwise.

An example of how the computer is being utilized is shown in an adjoining Figure.

Reference

1. *Metals Handbook,* 10 ed, Vol 4, Heat Treating, ASM International

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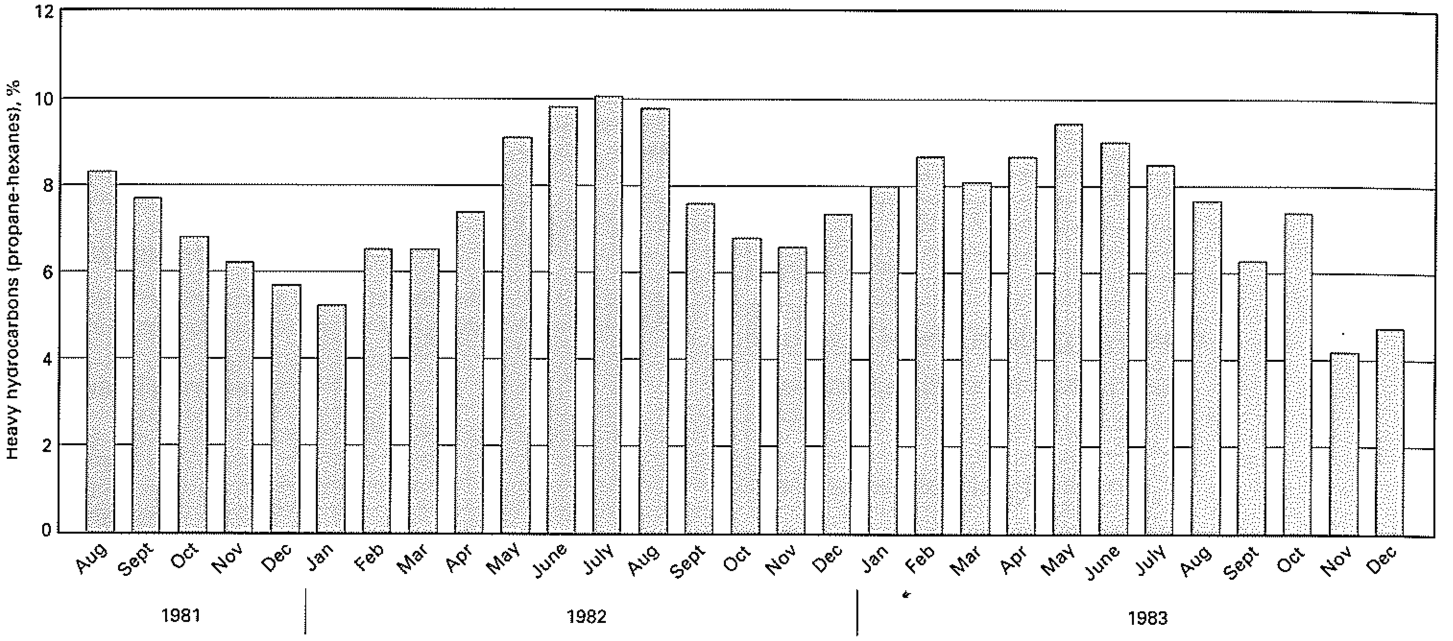

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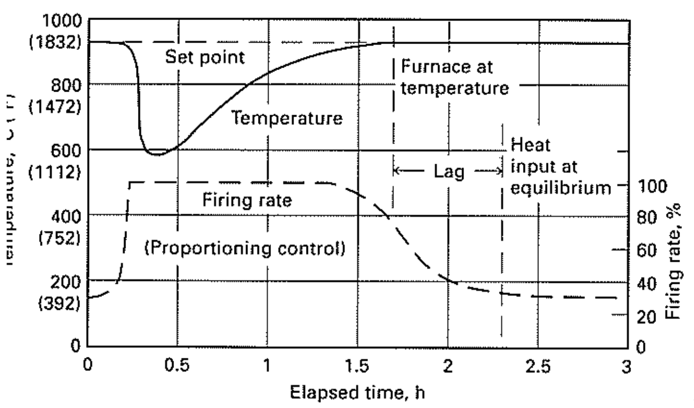

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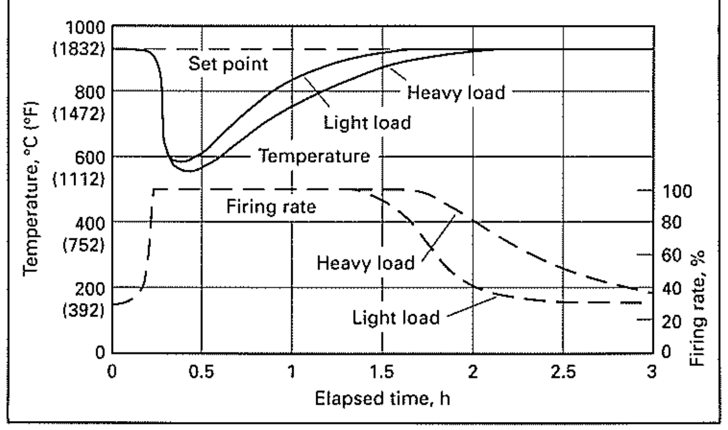

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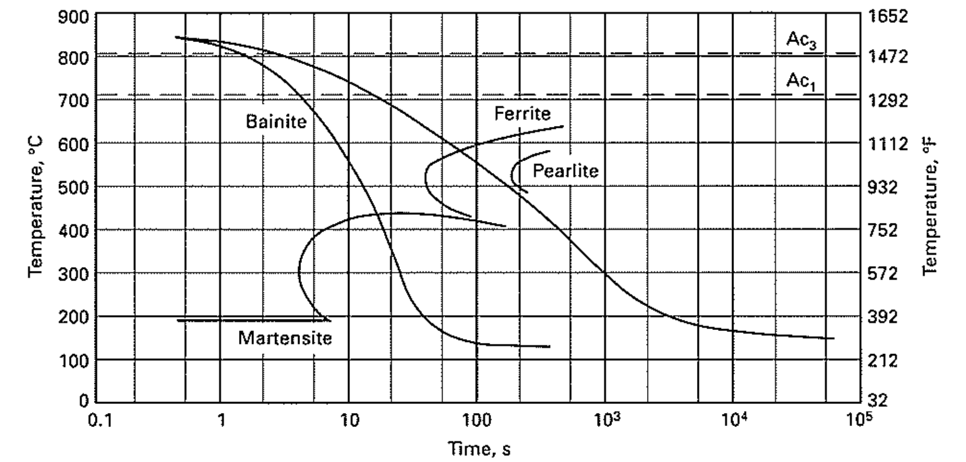

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Reference

1. *Metals Handbook,* 10 ed, Vol 4, Heat Treating, ASM International

How a Commercial Heat Treater Uses SPC and the Computer

This shop decided in 1989 to look into statistical process control (SPC) as a way to track down sources of persistent processing problems. At the time, rework jobs (in carburizing and nitriding) were running at a rate of 25 to 30 per quarter. Ref 1.

Consultants were hired to train the plant's thirty-plus employees in the application of SPC to heat treating, how to recognize out-of-control conditions, and how to react correctly to them.

Training was thorough, but stopped short of teaching how-to-be statisticians. The program consisted of 12 h in the classroom (three 4 h sessions), plus followups on the shop floor to answer questions as SPC was being installed.

The key to making SPC work, it was stressed continuously, is accuracy of data. At the same time, employees were assured that these data would be used as spotlight opportunities for improvement, not to point the finger of blame at anyone.

The First Step

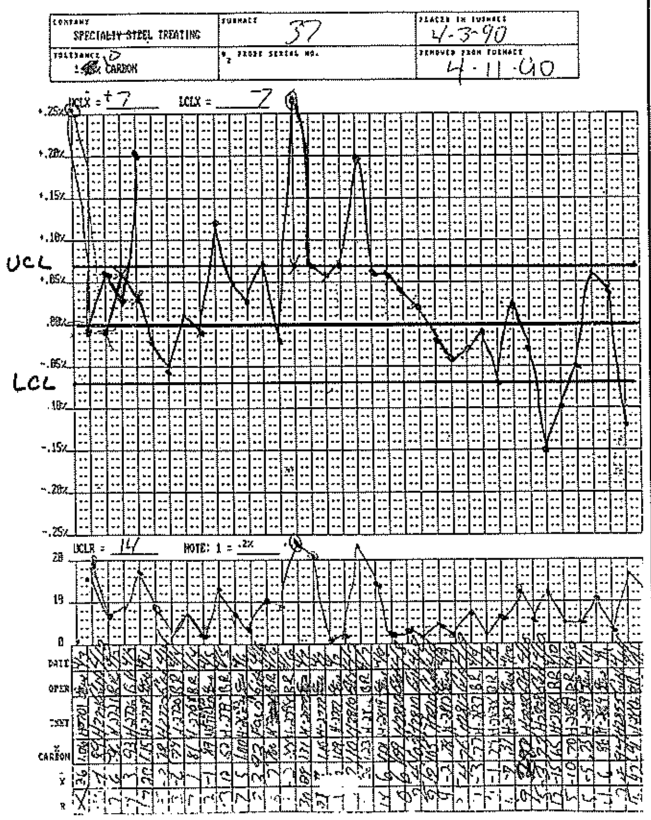
The program was started by gathering data from carburizing furnaces, using simple SPC charts. Operators used a shim shock test to compare actual carbon in the working zone compared with the level set on the furnace controller and measured with an oxygen probe.

Results fell short of expectations—a typical chart from that period is shown in an adjoining Figure. Note the large discrepancy between oxygen probe and shim shock data. A series of meetings followed, which included the quality manager, production manager, and all shop employees. In addition, furnace operators, maintenance people, and all other employees were encouraged to submit suggestions for improvements.

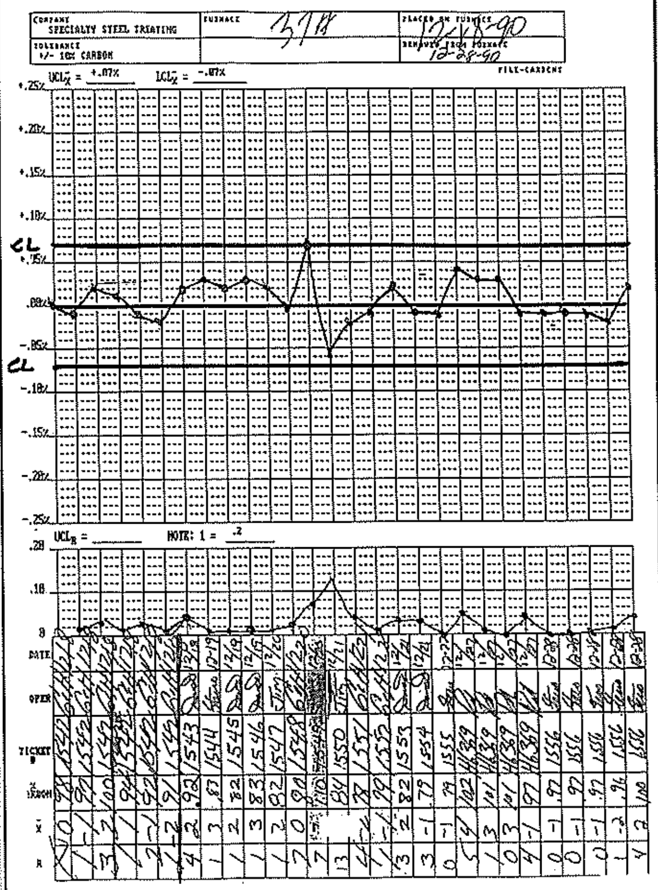
Ultimately, a decision was made to do capability studies of all carburizing and nitriding furnaces in the shop, covering, for instance, natural gas flow, air flow, nitrogen/methanol flow, load size, time in furnace, carbon control instrument settings, methods operators used to run furnaces and to correct out-of-control conditions.

Much of the inconsistency in performance, it was learned, was accounted for by differences in practice from operator to operator. To improve control here, procedures were written, based on proven strategies for correcting out-of-control conditions.

An early control chart shows large variations, with a low process capability caused by poor understanding of variables



The same furnace, eight months later, remains within control limits of ±0.07% C



With time, operators managed to keep data points closer to the target mean (for carbon potential setpoint), and control limits were set at ±0.07%. Improvement in the performance (see previous Figure) over a period of eight months is shown in the second Figure—note that control limits were maintained within 0.07%.

By 1992, reworks were down by a factor of four (see Figure). Reasons for rework, along with percentages attributable for each cause, are shown in the next Figure. Shallow case depth was the most common cause for rework, with a 23.3% rating. Cause No. 2 was operator error, accounting for 20% of all rework. For each rework, the company evaluates findings, investigates, and corrects any areas of concern.

Statistical Methods

The company now tracks performance by process capability values, C_p and C_{pk} (see Figure for definitions of these and other SPC terms). Information collected by operators is loaded into a statistical program, which produces all values needed for review by management.

A process capability study of furnace number 37 for one month is shown in an adjoining Figure. The C_{pk} is 1.41 and the process capability index (C_p) is 1.52, showing that the natural variation in the process is less than the maximum acceptable range for the product. One year earlier, this furnace had a C_{pk} value of 0.55 and a C_p value of 0.63.

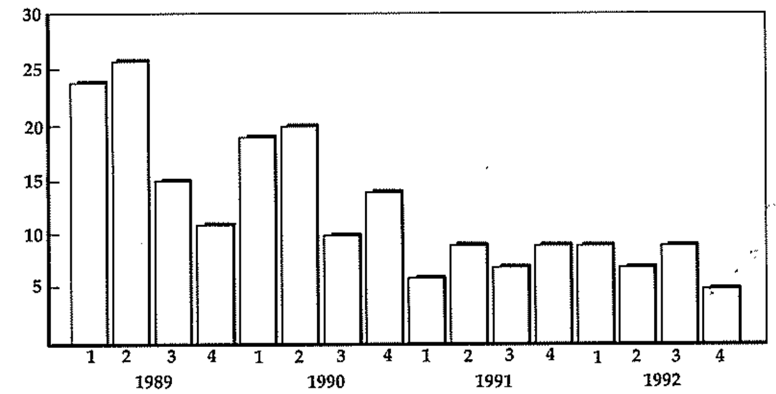
The company performs a Pareto analysis (see previous Figure for definition) for all rework. Reasons for rework, the furnace, and the operators are recorded.

The Next Step

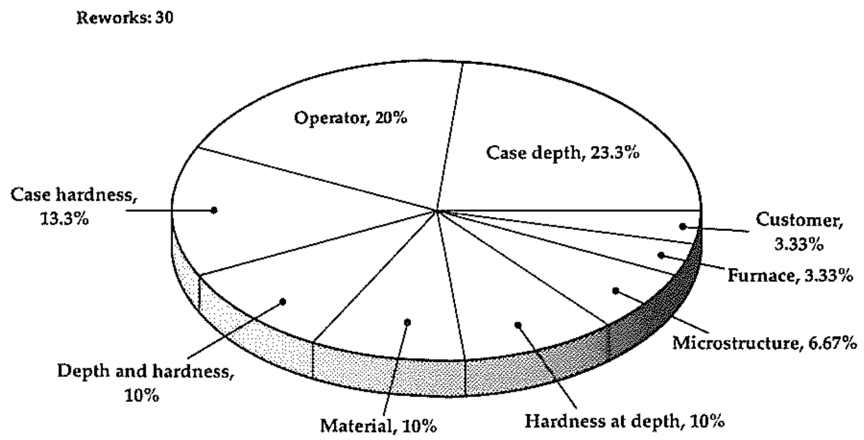
The company has computerized all carburizers and oil hardening furnaces with atmosphere and temperature controllers. With these controllers, furnace operation and final results are much more consistent than before.

Controllers are also programmable. Operators simply input the correct program number to control all parameters related to the carburizing cycle, ensuring that all temperature and carbon potential

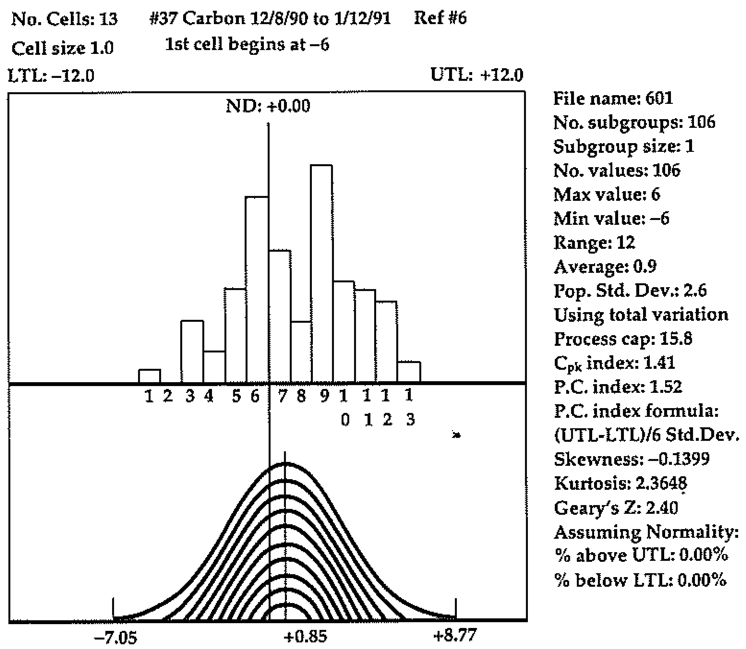
Tighter control and more-predictable process results have reduced the number of reworks required by a factor of four



Shallow case depth and operator error were the most common reasons for rework in 1992 (30 reworks total)



Process capability study for December 1990 shows that this furnace is well within the required ranges of carbon potential after improved process control. A year before, this furnace had a C_{pk} of 0.55 and C_p of 0.63



SPC Terminology

Mean, $\bar{x}$: The central value in the range of process variables, also known as the average. It is calculated by adding all readings and dividing by the total number of readings.

Standard deviation, σ: A measure of the spread of data values that is, the how far the data varies from the mean. It is calculated by the formula

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$$

where x_i is the value of data point number i, $\bar{x}$ is the mean, and n is the total number of data points.

Control limits: Upper and lower control limits are defined as three times the standard deviation (3σ) from the mean ($\bar{x}$) of a process variable. Statistically, 99% of readings should fall within these control limits, unless there is a change in the process.

Control chart: A graph used to record the readings of process variables. Each point in an x chart is typically an average of four or more readings. Each point in an R chart is the difference between the highest and lowest readings (range). Trends in control chart data can be signs of trouble. Examples include a point outside the control limits, seven consecutive points drifting in the same direction, or fewer than two-thirds of the points within the middle third of the chart.

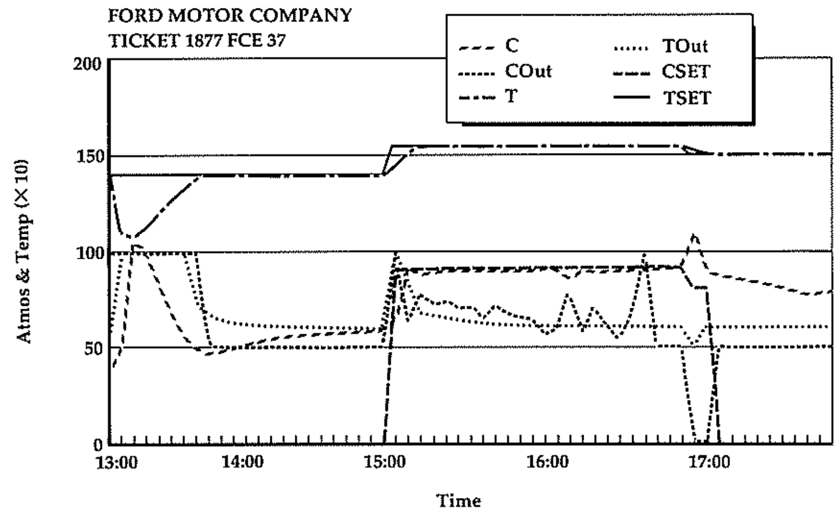
Natural variation: Process variable fluctuations that are beyond the control of the operator. The only way to reduce the amount of natural variation is to improve the process.

Pareto analysis: A process used to identify what J.M. Juran calls the "vital few projects" for which quality improvement is justified; that is, those which contain the bulk of the opportunity for improvement. Named for Italian economist Vilfredo Pareto (1848-1923).

Process capability index, C_p: The product specification or tolerance range divided by six times the standard deviation. C_p indicates whether the process is able to meet the customer's requirements. A value less than one indicates that natural variation will produce results that are out of spec.

Actual Process Capability Index, C_{pk}: A stricter index than C_p. C_{pk} measures centering as well as the amount of natural variation. It is defined as the difference between the process mean and its closest specification limit, divided by 3σ.

Example of how computer is utilized



setpoints are accurate, and that soak times and ramps (if needed) are the same from job to job. The controller sounds an alarm at the end of each soak. Alarms also sound if parameters deviate from any programmed settings.

A supervisory computer continuously monitors all variables of each heat treat process. This system stores all parameters of the carburizing cycle, such as carbon potential setting, actual carbon potential as seen by the oxygen probe, furnace temperature setpoints, actual temperature, millivolts, and reference numbers. These data can be viewed either at the completion of a job or at a later time for troubleshooting.

The computer system is useful in developing new cycles, reducing idle time, and troubleshooting. Charts and graphs can be produced using any of the information, which is less time-consuming than locating roll charts. A typical example of such a chart is shown in an adjoining Figure.

Reference

1. "Statistical Process Control Improves Heat Treating," *Advanced Materials & Processes*, Aug 1993

Practical Applications of the Computer in Heat Treating

A quick overview of available simulation software for on-line programs that control processes and those that assist in decision-making and process analysis is provided by the adjoining Table, which also lists and describes available databases developed by computers.

Software programs can be subdivided as follows:

- Property prediction programs
- Process planning programs
- Material selection programs and their databases
- Programs for special technical and economic programs related to heat-treating, such as energy consumption for a given process or calculating the expense of a heat treatment
- Finite element analysis for modeling the effects of quench severity or distortion and dimensional control of parts

Simulation modeling with the computer can be subdivided thusly:

- Static models based on empirical formulas
- Dynamic models based on differential equations or differential equation systems
- Programs with both static and dynamic models

Static models are based on simple empirical formulas that can be derived by physical principles and observation or from statistical methods. Generally, regression analysis is used in statistical modeling.

Example: Formulation or prediction of Jominy hardenability from austenitic grain size and chemical composition (Ref 1-3).

Dynamic models are based on the solution of differential equations, differential equation systems, or finite element analysis.

Examples of the differential equation approach: predicting carbon and nitrogen profiles (Ref 4-6) phenomenological models that describe the transformation of austenite under nonisothermal conditions (Ref 7-11).

Finite element analysis is used, for example, to predict residual stress and distortion (Ref 12-14) and in determining suitable quenchants (gas, oil, or water) for a given alloy (Ref 12).

xamples of Available Computer Programs and Databases Pertaining to Steel Selection, Microstructure, Properties, nd Heat-Treatment Technologies

ame of the software	Availability	Features
omputerized materials properties storage, retrieval, and use		
lat.DB	ASM International, U.S.A.	Materials data base management program containing the designations, chemical compositions, forms (sheet, bar and so forth), and properties (up to 40 properties). It is designed to select alloys on the basis of many characteristics
QUIST 2.0	SACIT Steel Advisory Centre for Industrial Technologies, Hungary	Contains the chemical compositions, mechanical properties, application fields, and the international comparison (equivalent steels) of 6500 standard steels from 18 countries
ıatabase SteelMaster	Dr. P. Sommer Werkstofftechnik GmbH, Germany	Contains compositions, mechanical properties, heat-treatment parameters, CCT diagrams, tempering charts for commonly used German structural and tool steels. The heat-treatment technologies designed by the user of the software can be stored and retrieved
ERITUS	Matsel Systems Ltd., Great Britain	This data base provides engineers with up-to-date information about materials ranging from traditional metals to new polymers. The range of information: mechanical and physical properties, environmental resistance, material forms, processing methods, trade names, and standards
,META	SACIT Steel Advisory Centre for Industrial Technologies, Hungary	This data base of individual measured steel properties contains data collected from laboratories of industry quality control departments. The range of data: steel designation, heat number, dimensions of the machine part, composition, heat treatment of the part, results of tensile tests, impact test results, measured Jominy curve of the heat, and other tests. The system makes statistical analysis of the data
:OR	SACIT Steel Advisory Centre for Industrial Technologies, Hungary	KOR is a corrosion information system, which contains a data base of 300 corrosive media, more than 15 000 individual corrosion dataset, 150 metallic structural materials, and 200 isocorrosion diagrams. Structural material selection is possible according to prescribed mechanical, physical, technological properties, or it is possible to find a suitable resisting material for a corrosive medium with given temperature and concentration. The system will also accept the user's own data
:omputer programs for calculation of processes occurring in steels during heat treatment		
'REDIC & TECH	SACIT Steel Advisory Centre for Industrial Technologies, Hungary	Simulates the cooling, transformation of austenite in cylindrical, plate-shaped workpieces, Jominy specimens made of case-hardenable and quenched and tempered low-alloy steels and calculates the microstructure and mechanical properties in any location of the cross section of the workpiece taking into account the actual chemical composition, dimensions, austenitizing temperature, durations, cooling intensity of quenchant, tempering temperature, and time. The same program works as technology planning program if the prescribed mechanical properties and composition are given
\C3	Marathon Monitors Ltd., Great Britain	Hardenability model designed to predict the response to quenching of through-hardening and carburized low-alloy steels in terms of microstructure and hardness distribution
:ETIM-SICLOP	Centre Technique des Industries Mechaniques PROGETIM, France	Contains a steel data base for the selection of structural and tool steels and calculates the mechanical properties along the cross section of workpieces
;teCal	Comline Engineering Software, Great Britain and ASM International	Calculates the heat-treatment response and properties of low-alloy steels from composition
'REVERT	Creusot-Loire Industries, France	Calculates the microstructure and mechanical properties of quenched and tempered low-alloy steels from composition and heat-treating parameters
:HAT	International Harvester Company, U.S.A.	CHAT is a two-part system for selecting the optimum steel composition to be used where heat treating is performed to develop required engineering properties
MINITECH	Minitech Limited, Canada	The Minitech Alloy Steel Information System consists of twelve computer programs which generate a series of hardenability-related properties of steels, such as Jominy curves, hardenability bands, mechanical properties of hot rolled products, hardness distributions for quenched and tempered and carburized products
PREDCARB	SACIT Steel Advisory Centre for Industrial Technologies, Hungary	This computer program determines the gas carburizing technology and calculates the carbon profile and hardness distribution in the case and core on the basis of chemical composition, dimensions of the workpiece, cooling intensity of the quenchant, prescribed characteristics of the case
SIMULAN	Lammar, Ensam Bordeaux, France	Simulates the gas carburization and induction hardening process, and calculates the carbon and the hardness profile
CARBCALC	Marathon Monitors Ltd., Great Britain	Simulates the carburizing reactions between a steel and surrounding atmosphere. It calculates the carbon profile
CARBODIFF	Process Electronic, Germany	Monitoring of carbon profile during carburizing and prediction of hardness distribution after quenching of case-hardened steels
Carbo-O-Proof	Ipsen Industries Ltd., U.S.A.	This software is able to optimize the carburizing process, calculates continuously the carbon profile, and regulates the process in accordance with program target values
SYSWELD	Framasoft, Great Britain	This system is based on finite-element technique and simulates the transformation processes in steel during heat treatment or welding. The program calculates the temperature distribution, microstructure, hardness, and stresses

Examples of programs based on finite element analysis include:

- CONTA program—for calculating surface heat fluxes (Ref 13)
- TOPAZ 2D program—for calculating temperatures (Ref 14)
- NIKE 2D program—for calculating stresses (Ref 15)

State of the Art Uses of Computer Simulation

General overviews of the subject are found in Ref 16 and 17.

Database systems containing the main characteristics of several metal alloys are being marketed. Information that can be retrieved from them include chemical composition, mechanical characteristics, and continuous cooling transformation (CCT) curves. Databases can be loaded with the results of user process planning.

Example: Research workers at Minitech Ltd (Canada) designed a software package to estimate such properties as weldability, phase diagrams, and hardenability of low-, medium-, and high-carbon steels (Ref 16).

Example: Chrysler Corporation developed an interactive system that makes it possible for designers and technologists to get material information on their own local computer terminals (Ref 16).

Example: Utilization of databases of measured steel properties is discussed in Ref 18.

The CETIM Institute (France) has developed a program for the planning of heat treatment technology and for steel selection. An essential part of the software is a database containing chemical composition, mechanical properties, and Jominy curves of the most often used quenched and tempered and case hardened steels as a function of section size (Ref 19).

Hardenability prediction has been of longstanding theoretical and practical interest (Ref 20-24).

In applying a static model, Murry et al. (Ref 25) developed a computing method for predicting the hardness of cylindrical workpieces along their cross section after quenching. Input data are: chemical composition, austenite grain size, geometrical characteristics, and cooling time from 700 to 400 °C (1290 to 750 °F).

Creusot-Loire (Ref 16 and 26) used nonlinear multiple regression analysis to derive a series of formulas for the estimation of critical cooling rates from 700 °C (1290 °F). The steelmaker also published equations to calculate as-quenched and tempered hardness from chemical composition and cooling rate from 700 °C (1290 °F).

Starting from a thermodynamic basis, researchers at McMaster University (Hamilton, Ontario, Canada) developed methods for the computer-aided determination of equilibrium diagrams of multicomponent steel alloys and for the calculation of starting curves (incubation time) of isothermal transformation diagrams as well (Ref 17, 23, 27). They also investigated the tempering process and developed usable computer programs for the prediction of hardenability and its application in steelmaking.

Programs for material selection and/or analysis of heat treatment processes usually contain a system for property or hardenability prediction. Liscic and Filetin (Ref 21, 22), for example, published a computerized process designing a system for the heat treatment of quenched and tempered steels. The system is suitable for the determination of technological parameters (austenitization and tempering temperatures), knowing the steel type and required properties.

More sophisticated models based on finite element analysis are being investigated as a way of modeling distortion and analyzing quenching methods (Ref 12).

Analysis of residual stresses and distortion generally involves finite element analysis of internal stresses developed during transformation sequences. Typical examples are given in Ref 12, 38-40.

A method of calculating transformation sequences in quenched steels is found in Ref 41.

A software package has been developed for the prediction of residual stresses in case hardened steels by tracing the transformation of the case and core of the workpiece (Ref 42 and 43).

Simulation of Case Hardening. New type models predict carbon and nitrogen profiles during and after gas carburizing and nitriding (Ref 5, 6, 28-34). In this field, calculation methods can be used to model case depth and hardness profiles (Ref 30, 35, 36). Ingham and Clarke developed a computerized method of predicting the microstructure and hardness profile of case hardened parts. Methods of microstructure prediction are described in Ref 8 and 37.

A description of how a commercial heat treater is using SQC, SPC, and the computer is found in the article, "Statistical Process Control in Heat Treating Operations," preceding this one.

This article is based on article, "Computerized Properties Prediction and Technology Planning in Heat Treatment of Steel," ASM Metals Handbook, Heat Treating, Vol 4, 10 ed., *Heat Treating Handbook,* ASM International.

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Guidelines for the Heat Treatment of Steel

Introduction

Articles in this chapter address the hands-on aspects of:

- Normalizing
- Annealing
- Surface hardening
- Quenching/quenchants (articles on eight conventional processes and 17 other processes)
- Tempering (including articles on martempering and austempering)

The Normalizing Process

This process is often considered from both thermal and microstructural standpoints.

In the thermal sense, normalizing is an austenitizing heating cycle, followed by cooling in still or agitated air. Typical normalizing temperatures for many standard steels are given in an accompanying Table.

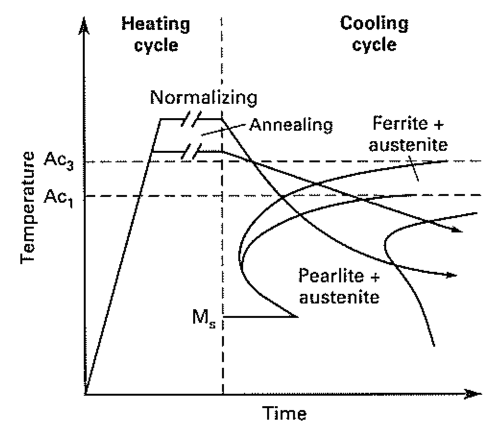
In terms of microstructure, areas that contain about 0.8% C are pearlitic. Those low in carbon are ferritic.

Range of Applications

All standard, low-carbon, medium-carbon, and high-carbon wrought steels can be normalized, as well as many steel castings. Many weldments are normalized to refine the structure within the weld-affected zone, and maraging steels either can't be normalized or are not usually normalized. Tool steels are generally annealed by the supplier.

Reasons for normalizing are diverse: for example, to increase or decrease strength and hardness, depending on the thermal and mechanical history of the product.

Comparison of time-temperature cycles for normalizing and full annealing. The slower cooling of annealing results in higher temperature transformation to ferrite and pearlite and coarser microstructures than does normalizing. Source: Ref 1



In addition, normalizing functions may overlap with or be confused with annealing, hardening, and stress relieving. Normalizing is applied, for example, to improve the machinability of a part, or to refine its grain structure, or to homogenize its grain structure or to reduce residual stresses. Time-temperature cycles for normalizing and full annealing are compared in an adjoining Figure.

Castings are homogenized by normalizing to break up or refine their dendritic structure and to facilitate a more even response to subsequent hardening.

Wrought products may be normalized, for example, to help reduce banded grain structure due to hot rolling and small grain size due to forging.

Details of three applications are given in adjoining Table, including mechanical properties in the normalized and tempered condition.

Normalizing and tempering can be substituted for conventional hardening when parts are complex in shape or have sharp changes in section. Otherwise, in conventional hardening such parts would be susceptible to cracking, distortion, or excessive dimensional changes in quenching.

Rate of cooling in normalizing generally is not critical. However, when parts have great variations in section size, thermal stresses can cause distortion.

Time at temperature is critical only in that it must be sufficient to cause homogenization. Generally, a time that is sufficient to complete austenitization is all that is required. One hour at temperature, after a furnace has recovered, per inch of part thickness, is standard.

Rate of cooling is significantly influenced by amount of pearlite, its size, and spacing of pearlite lamellae. At higher cooling rates more pearlite forms and lamellae are finer and more closely spaced. Both the increase in pearlite and its greater fineness result in higher strength and hardness. Lower cooling rates mean softer parts. Cooling rates can be enhanced with fans to increase the strength and hardness of parts, or to reduce the time required, following the furnace operation, for sufficient cooling to allow workpieces to be handled.

After parts cool uniformly through their cross section to black heat below Ar_1, they may be water or oil quenched to reduce total cooling time. Cooling center material in heavy sections to black heat can take considerable time.

Carbon Steels

Steels containing 0.20% C or less usually are not treated beyond normalizing. By comparison, medium- and high-carbon steels are often tempered

Typical Normalizing Temperatures for Standard Carbon and Alloy Steels

Grade	Temperature(a) °C	°F	Grade	Temperature(a) °C	°F	Grade	Temperature(a) °C	°F	Grade	Temperature(a) °C	°F
Plain carbon steels			**Standard alloy steels (continued)**			**Standard alloy steels (continued)**			**Standard alloy steels (continued)**		
1015	915	1675	4027	900	1650	4817	925	1700	8645	870	1600
1020	915	1675	4028	900	1650	4820	925	1700	8650	870	1600
1022	915	1675	4032	900	1650	5046	870	1600	8655	870	1600
1025	900	1650	4037	870	1600	5120	925	1700	8660	870	1600
1030	900	1650	4042	870	1600	5130	900	1650	8720	925	1700
1035	885	1625	4047	870	1600	5132	900	1650	8740	925	1700
1040	860	1575	4063	870	1600	5135	870	1600	8742	870	1600
1045	860	1575	4118	925	1700	5140	870	1600	8822	925	1700
1050	860	1575	4130	900	1650	5145	870	1600	9255	900	1650
1060	830	1525	4135	870	1600	5147	870	1600	9260	900	1650
1080	830	1525	4137	870	1600	5150	870	1600	9262	900	1650
1090	830	1525	4140	870	1600	5155	870	1600	9310	925	1700
1095	845	1550	4142	870	1600	5160	870	1600	9840	870	1600
1117	900	1650	4145	870	1600	6118	925	1700	9850	870	1600
1137	885	1625	4147	870	1600	6120	925	1700	50B40	870	1600
1141	860	1575	4150	870	1600	6150	900	1650	50B44	870	1600
1144	860	1575	4320	925	1700	8617	925	1700	50B46	870	1600
Standard alloy steels			4337	870	1600	8620	925	1700	50B50	870	1600
1330	900	1650	4340	870	1600	8622	925	1700	60B60	870	1600
1335	870	1600	4520	925	1700	8625	900	1650	81B45	870	1600
1340	870	1600	4620	925	1700	8627	900	1650	86B45	870	1600
3135	870	1600	4621	925	1700	8630	900	1650	94B15	925	1700
3140	870	1600	4718	925	1700	8637	870	1600	94B17	925	1700
3310	925	1700	4720	925	1700	8640	870	1600	94B30	900	1650
			4815	925	1700	8642	870	1600	94B40	900	1650

(a) Based on production experience, normalizing temperature may vary from as much as 28 °C (50 °F) below, to as much as 55 °C (100 °F) above, indicated temperature. The steel should be cooled in still air from indicated temperature.

Typical Applications of Normalizing and Tempering of Steel Components

Part	Steel	Heat treatment	Properties after treatment	Reason for normalizing
Cast 50 mm (2 in.) valve body, 19 to 25 mm (¾ to 1 in.) in section thickness	Ni-Cr-Mo	Full annealed at 955 °C (1750 °F), normalized at 870 °C (1600 °F), tempered at 665 °C (1225 °F)	Tensile strength, 620 MPa (90 ksi); 0.2% yield strength, 415 MPa (60 ksi); elongation in 50 mm, or 2 in., 20%; reduction in area, 40%	To meet mechanical-property requirements
Forged flange	4137	Normalized at 870 °C (1600 °F), tempered at 570 °C (1060 °F)	Hardness, 200 to 225 HB	To refine grain size and obtain required hardness
Valve-bonnet forging	4140	Normalized at 870 °C (1600 °F) and tempered	Hardness, 220 to 240 HB	To obtain uniform structure, improved machinability, and required hardness

after normalizing, i.e., to get specific properties such as lower hardness prior to straightening, cold working, or machining.

Alloy Steels

Forgings, rolled products, and alloy steel castings are often normalized as a conditioning treatment before final heat treatment. Normalizing also refines grain structures in forgings, rolled products, and castings that have been cooled nonuniformly from high temperatures.

Some alloys require more care in heating to prevent cracking from thermal shock. They also require long soaking times because of lower austenitizing and solution rates for carbon. Cooling rates in air to room temperature for many alloys must be carefully controlled. Some alloys are forced air cooled from the normalizing temperature to develop specific mechanical properties.

Forgings

When forgings are normalized prior to carburizing or before hardening and tempering, the upper range of normalizing temperatures is used. But when normalizing is the final heat treatment, the lower temperature range is used. Small forgings are typically normalized as-received from the forge shop.

Large, open die forgings are usually normalized in batch furnaces pyrometrically controlled to a narrow temperature range.

Low-carbon steel forgings containing 0.25% C or less are seldom normalized.

Multiple Treatments. Carbon and low alloy steel forgings with large dimensions are double normalized when forging temperatures are extremely high (Ref 2) to obtain, for example, a uniform fine grain structure to get specific properties such as impact strength to subzero temperatures.

Bar and Tubular Products

Normalizing is not necessary and may be inadvisable when properties of these products obtained in the finishing stages of hot mill operation are close to those produced in normalizing. But reasons for normalizing bar and tube are generally the same as those that apply to other steel products.

Castings

In industrial practice, castings may be normalized in car bottom, box, pit, and continuous furnaces. Heat treatment principles are standard for all these furnaces.

When higher alloy castings, such as C5, C12, and WC9, are loaded, furnace temperatures should be controlled to avoid thermal shock that could cause metal failure. A safe loading temperature in this instance is in the range of 315 to 425 °C (600 to 795 °F). Lower alloy grades tolerate furnace temperatures as high as 650 °C (1200 °F). Carbon and low-alloy steel castings can be charged at normalizing temperatures.

After charging, furnace temperatures are increased at a rate of approximately 225 °C (400 °F) per h, until the normalizing temperature is reached. Depending on steel composition and casting configuration, the heating rate may be reduced to approximately 28 to 55 °C (50 to 100 °F) per h, to avoid cracking. Extremely large castings may be heated more slowly to prevent the development of extreme temperature gradients.

After normalizing temperature is reached, castings are soaked for a period that ensures complete austenitization and carbide solution.

After soaking, parts are unloaded and allowed to cool in still air. Use of fans, air blasts, or other means of speeding up the cooling process should be avoided.

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Annealing of Steel

In this process, steels are heated to a specific temperature, held at that temperature for a specific time, then cooled at a specific rate.

Generally, in treating plain carbon steels, a ferrite-pearlite microstructure is produced (see adjoining Figure). Softening is the primary reason for annealing. Other important applications are to facilitate cold work or machining, to improve mechanical or electrical properties, or to promote dimensional stability.

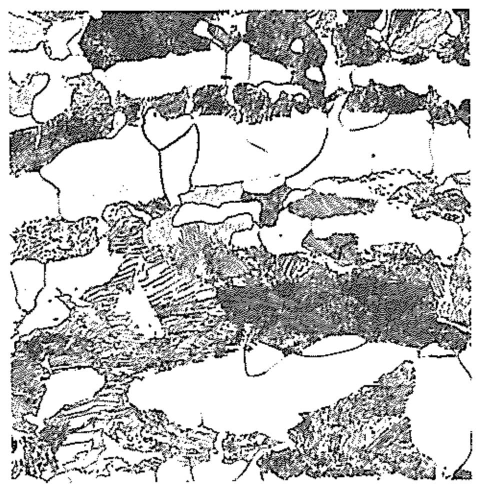
Annealing Cycles

Cycles fall into three categories, based on heating temperatures and cooling methods (see accompanying table):

- Subcritical annealing—the maximum temperature may be below the lower critical temperature, A_1
- Intercritical annealing—the maximum temperature is above A_1, but below the upper critical temperature, A_3, for hypoeutectic steels, or A_{cm} for hypereutectic steels
- Full annealing—the maximum temperature is above A_3

Austenite is present at temperatures above A_1, so cooling practice (see Table) through transformation is a critical factor in getting the desired microstructure and properties. Steels heated above A_1 are subjected to slow, continuous cooling, or to isothermal treatment at a temperature below A_1, at which transformation to the microstructure wanted can occur in a reasonable time. In some applications, two or more annealing cycles are combined or used in succession to get a specified result.

A fully annealed 1040 steel showing a ferrite-pearlite microstructure. Etched in 4% picral plus 2% nital. 500x



Subcritical Annealing

Austenite is not formed in this type of treatment. The prior condition of a steel is modified by such processes as recovery, recrystallization, grain growth, and agglomeration of carbides. The prior history of a steel is important in subcritical annealing.

In treating as-rolled or forged hypoeutectoid steels containing ferrite and pearlite, the hardnesses of both constituents can be adjusted. But if substantial softening is the objective, times at temperature can be excessively long. Subcritical annealing is most effective on hardened or cold worked steels, which recrystallize readily to form new ferrite grains. The rate of softening increases rapidly as the temperature approaches A_1. A more detailed discussion of subcritical annealing is found in Ref 1.

Intercritical Annealing

Austenite begins to form when the temperature of the steel exceeds A_1. Carbon solubility rises abruptly (nearly 1%) near the A_1 temperature. In hypoeutectoid steels, the equilibrium structure in the intercritical range between A_1 and A_3 consists of ferrite and austenite, and above A_3, the structure becomes totally austenitic. But the equilibrium mixture of ferrite and austenite is not obtained immediately. For example, the rate of solution for a typical eutectoid steel is shown in an accompanying Figure.

In hypereutectoid steels, carbide and austenite coexist in the intercritical range between A_1 and A_{cm}. The most homogeneous structure developed at higher austenitizing temperatures tends to promote lamellar carbide structures on cooling, while lower austenitizing temperatures result in less homogenous austenite, which promotes the formation of spheroidal carbides.

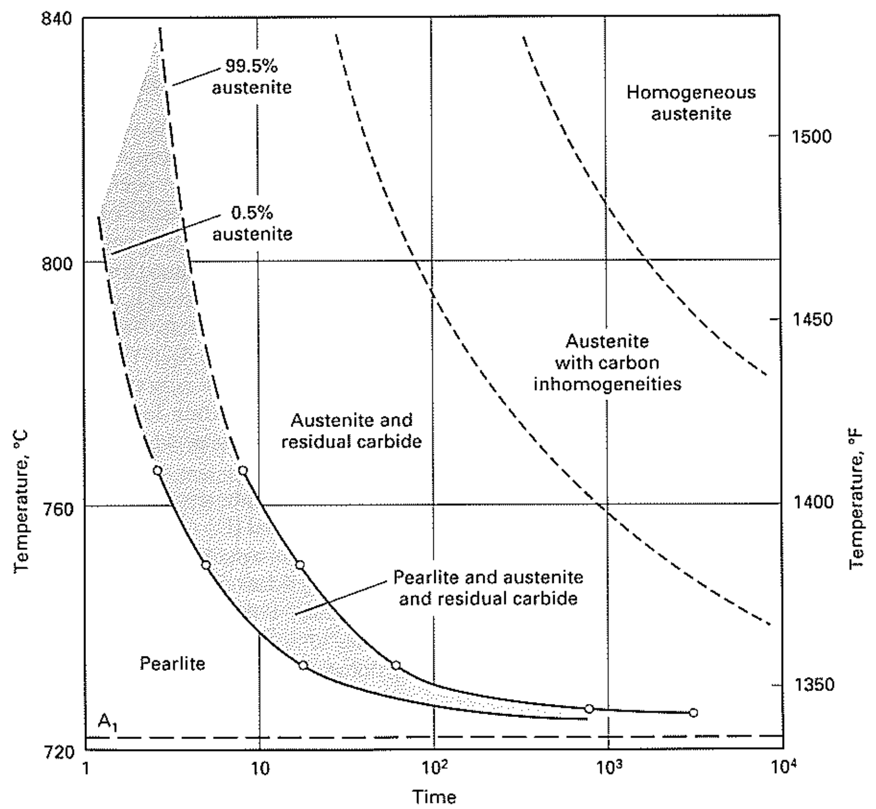
Temperature-time plots showing the progress of austenite formation under isothermal (IT) or continuous transformation (CT) conditions many steels have been published (Ref 2, 3).

Cooling After Full Transformation. After complete transformation to austenite, little else of metallurgical consequence can occur during cooling to room temperature. Extremely slow cooling can cause some agglomeration of carbides, and, consequently, some slight additional softening of the steel; but in this case, such slow cooling is less effective than high-temperature transformation. This means there is no reason for slow cooling after transformation is completed and cooling from the transformation temperature may be as rapid as is feasible to minimize the time needed for the operation.

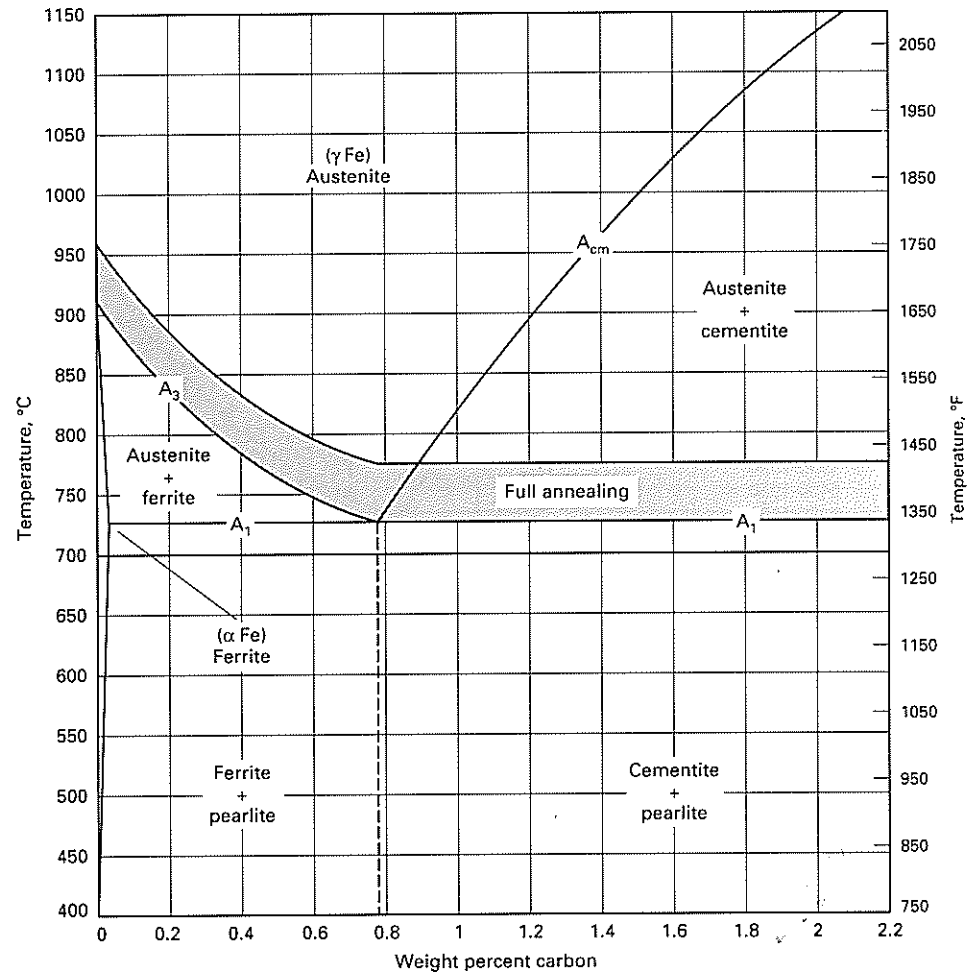
Approximate Critical Temperatures for Selected Carbon and Low-alloy Steels

	Critical temperatures on heating at 28 °C/h (50 °F/h)				Critical temperatures on cooling at 28 °C/h (50 °F/h)			
	Ac_1		Ac_3		Ar_3		Ar_1	
Steel	°C	°F	°C	°F	°C	°F	°C	°F
1010	725	1335	875	1610	850	1560	680	1260
1020	725	1335	845	1555	815	1500	680	1260
1030	725	1340	815	1495	790	1450	675	1250
1040	725	1340	795	1460	755	1395	670	1240
1050	725	1340	770	1415	740	1365	680	1260
1060	725	1340	745	1375	725	1340	685	1265
1070	725	1340	730	1350	710	1310	690	1275
1080	730	1345	735	1355	700	1290	695	1280
1340	715	1320	775	1430	720	1330	620	1150
3140	735	1355	765	1410	720	1330	660	1220
4027	725	1340	805	1485	760	1400	670	1240
4042	725	1340	795	1460	730	1350	655	1210
4130	760	1395	810	1490	755	1390	695	1280
4140	730	1350	805	1480	745	1370	680	1255
4150	745	1370	765	1410	730	1345	670	1240
4340	725	1335	775	1425	710	1310	655	1210
4615	725	1340	810	1490	760	1400	650	1200
5046	715	1320	770	1420	730	1350	680	1260
5120	765	1410	840	1540	800	1470	700	1290
5140	740	1360	790	1450	725	1340	695	1280
5160	710	1310	765	1410	715	1320	675	1250
52100	725	1340	770	1415	715	1320	690	1270
6150	750	1380	790	1450	745	1370	695	1280
8115	720	1300	840	1540	790	1450	670	1240
8620	730	1350	830	1525	770	1415	660	1220
8640	730	1350	780	1435	725	1340	665	1230
9260	745	1370	815	1500	750	1380	715	1315

Austenitizing rate-temperature curves for commercial plain carbon eutectoid steel. Prior treatment was normalizing from 875 °C (1605 °F); initial structure, fine pearlite. First curve at left shows beginning of disappearance of pearlite; second curve, final disappearance of pearlite; third curve, final disappearance of carbide; fourth curve, final disappearance of carbon concentration gradients.



The iron-carbon binary phase diagram showing region of temperatures for full annealing (Ref 4)



Recommended Temperatures and Cooling Cycles for Full Annealing of Small Carbon Steel Forgings

Data are for forgings up to 75 mm (3 in.) in section thickness. Time at temperature usually is a minimum of 1 h for sections up to 25 mm (1 in.) thick; ½ h is added for each additional 25 mm (1 in.) of thickness.

	Annealing temperature		Cooling cycle(a)				
			°C		°F		Hardness
Steel	°C	°F	From	To	From	To	range, HB
1018	855-900	1575-1650	855	705	1575	1300	111-149
1020	855-900	1575-1650	855	700	1575	1290	111-149
1022	855-900	1575-1650	855	700	1575	1290	111-149
1025	855-900	1575-1650	855	700	1575	1290	111-187
1030	845-885	1550-1625	845	650	1550	1200	126-197
1035	845-885	1550-1625	845	650	1550	1200	137-207
1040	790-870	1450-1600	790	650	1450	1200	137-207
1045	790-870	1450-1600	790	650	1450	1200	156-217
1050	790-870	1450-1600	790	650	1450	1200	156-217
1060	790-845	1450-1550	790	650	1450	1200	156-217
1070	790-845	1450-1550	790	650	1450	1200	167-229
1080	790-845	1450-1550	790	650	1450	1200	167-229
1090	790-830	1450-1525	790	650	1450	1200	167-229
1095	790-830	1450-1525	790	655	1450	1215	167-229

(a) Furnace cooling at 28 °C/h (50 °F/h)

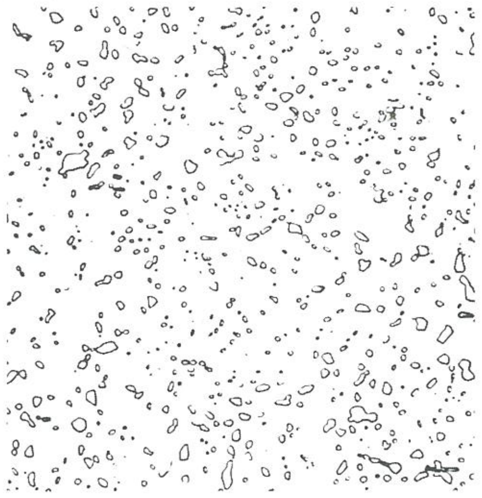
Recommended Annealing Temperatures for Alloy Steels (Furnace Cooling)

AISI/SAE Steel	Annealing temperature °C	Annealing temperature °F	Hardness (max), HB
1330	845-900	1550-1650	179
1335	845-900	1550-1650	187
1340	845-900	1550-1650	192
1345	845-900	1550-1650	…
3140	815-870	1500-1600	187
4037	815-855	1500-1575	183
4042	815-855	1500-1575	192
4047	790-845	1450-1550	201
4063	790-845	1450-1550	223
4130	790-845	1450-1550	174
4135	790-845	1450-1550	…
4137	790-845	1450-1550	192
4140	790-845	1450-1550	197
4145	790-845	1450-1550	207
4147	790-845	1450-1550	…
4150	790-845	1450-1550	212
4161	790-845	1450-1550	…
4337	790-845	1450-1550	…
4340	790-845	1450-1550	223
50B40	815-870	1500-1600	187
50B44	815-870	1500-1600	197
5046	815-870	1500-1600	192
50B46	815-870	1500-1600	192
50B50	815-870	1500-1600	201
50B60	815-870	1500-1600	217
5130	790-845	1450-1550	170
5132	790-845	1450-1550	170
5135	815-870	1500-1600	174
5140	815-870	1500-1600	187
5145	815-870	1500-1600	197
5147	815-870	1500-1600	197
5150	815-870	1500-1600	201
5155	815-870	1500-1600	217
5160	815-870	1500-1600	223
51B60	815-870	1500-1600	223
50100	730-790	1350-1450	197
51100	730-790	1350-1450	197
52100	730-790	1350-1450	207
6150	845-900	1550-1650	201
81B45	845-900	1550-1650	192
8627	815-870	1500-1600	174
8630	790-845	1450-1550	179
8637	815-870	1500-1600	192
8640	815-870	1500-1600	197
8642	815-870	1500-1600	201
8645	815-870	1500-1600	207
86B45	815-870	1500-1600	207
8650	815-870	1500-1600	212
8655	815-870	1500-1600	223
8660	815-870	1500-1600	229
8740	815-870	1500-1600	202
8742	815-870	1500-1600	…
9260	815-870	1500-1600	229
94B30	790-845	1450-1550	174
94B40	790-845	1450-1550	192
9840	790-845	1450-1550	207

Supercritical or Full Annealing

Full annealing, a common practice, is obtained by heating hypoeutectoid steels above the upper critical temperature, A_3. In treating these steels (they are less than 0.77% in carbon content), full annealing takes place in the austenite region at the annealing temperature. However, in hypereutectoid steels (they are above 0.77% in carbon content), annealing takes place above the A_1 temperature, which is the dual phase austenite region. In an adjoining Figure, the annealing temperature range for full annealing is superimposed on an iron-carbon, binary phase diagram.

Spheroidized microstructure of 1040 steel after 21 h at 700 °C (1290 °F). 4% picral etch. 1000×



Austenitizing Time and Dead Soft Steel. Hypereutectoid steels can be made extremely soft by holding for long periods at austenitizing temperatures; there is little effect on hardness, i.e., at a change from 241 to 229 HB, the effect on machining or cold forming properties may be substantial.

Annealing Temperatures

In specifying many annealing operations, it isn't necessary to go beyond stating that the steel should be cooled in the furnace from a designated austenitizing temperature. Temperatures and associated hardnesses for simple annealing of carbon steels are given in an adjoining Table; requirements for alloy steels are in another Table.

Heating cycles in the upper austenitizing temperature ranges shown in the Table for alloy steels should result in pearlitic structures. At lower temperatures, structures should be predominately spheroidized. Most steels can be annealed by heating to the austenitizing temperature then cooling in the furnace at a controlled rate, or cooling rapidly to, and holding at, a lower temperature for isothermal transformation. With either procedure, hardnesses are virtually the same. However, isothermal transformation takes considerably less time.

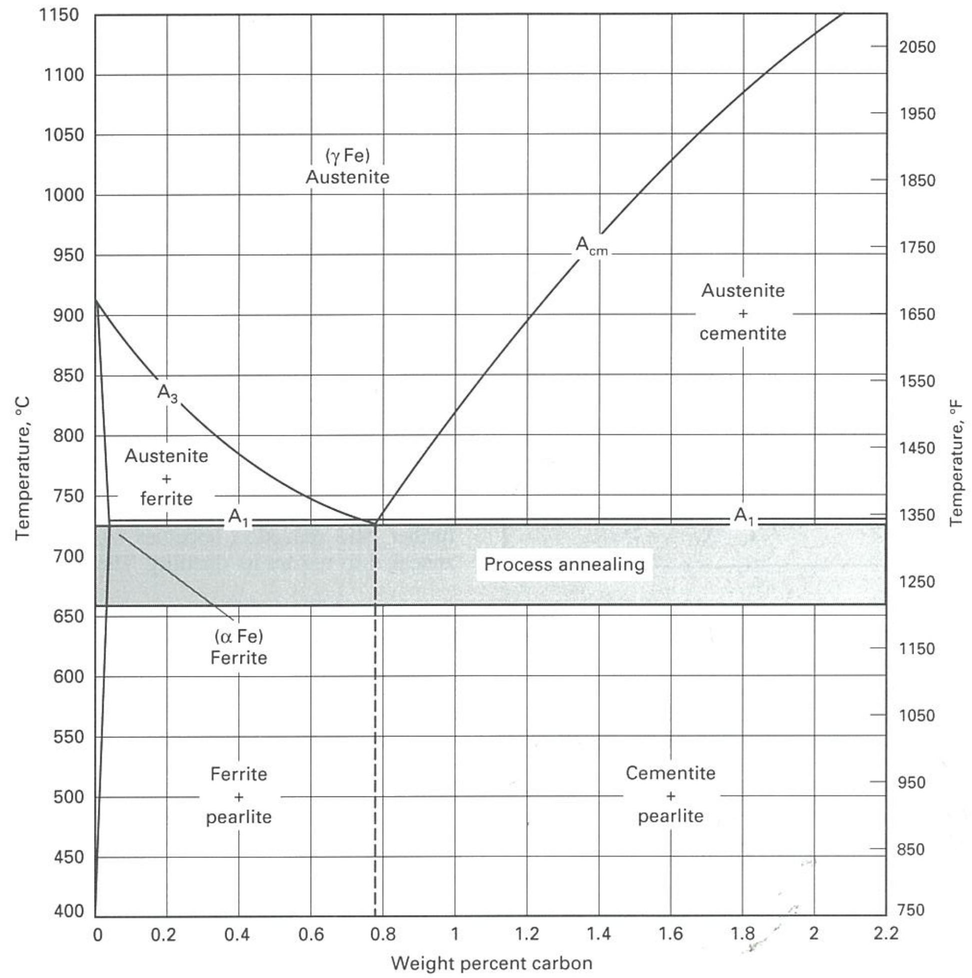
Spheroidizing

This treatment is usually chosen to improve cold formability. Other applications include improving the machinability of hypereutectoid steels and tool steels. This microstructure is used in cold forming because it lowers the flow stress of the materials. Flow stress is determined by the proportion and distribution of ferrite and carbides. Ferrite strength depends on its grain size and rate of cooling. The formability of steel is significantly affected by whether carbides are in the lamellae or spheroid condition.

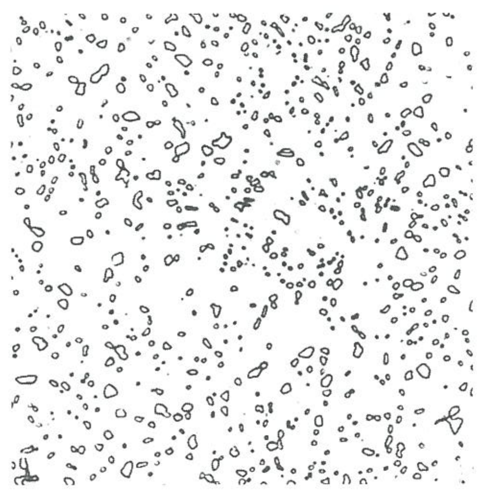
Steels may be heated and cooled to produce globular carbides in a ferritic matrix. An adjoining Figure shows 1040 steel in the fully spheroidized condition. Spheroidization can take place by using the following methods:

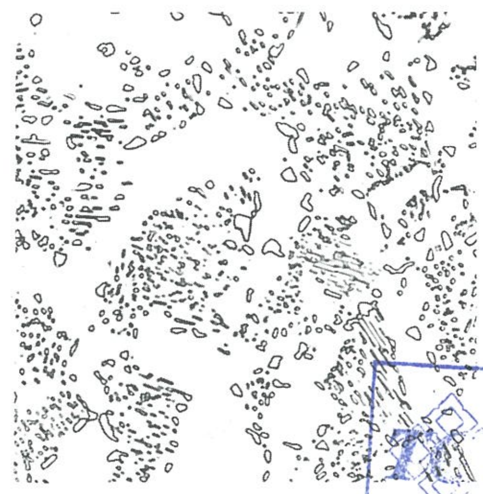
- Prolonged holding at a temperature just below the Ac_1
- Heating and cooling alternately between temperatures that are just above Ac_1 and just below Ar_1
- Heating to a temperature just above Ac_1, and then either cooling very slowly in the furnace, or holding at a temperature just above Ar_1
- Cooling at a suitable rate from the minimum temperature at which all carbide is dissolved to prevent the reformation of carbide networks, then reheating in accordance with the first or second methods described

The iron-carbon binary phase diagram showing region of temperatures for spheroidizing (Ref 4)

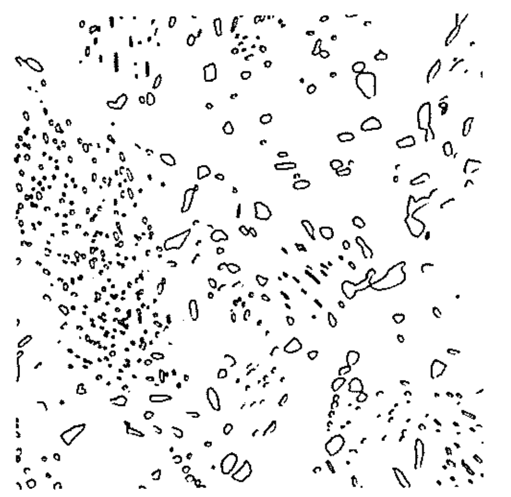


Effect of prior microstructure on spheroidizing a 1040 steel at 700 °C (1290 °F) for 21 h. (a) Starting from a martensitic microstructure (as-quenched). (b) Starting from a ferrite-pearlite microstructure (fully annealed). Etched in 4% picral plus 2% nital. 1000×


(a)


(b)

The extent of spheroidization at 700 °C (1290 °F) for 200 h for the 1040 steel starting from a ferrite-pearlite microstructure etched in 4% picral. 1000×



previously (applicable to hypereutectoid steel containing a carbide network)

The range of temperatures for spheroidizing hypoeutectoid and hypereutectoid steels is shown in an adjoining Figure. Rates of spheroidizing depend somewhat on prior microstructures, and are the greatest for quenched structures in which the carbide phase is fine and dispersed (see Figures). Prior cold work also increases the rate of the spheroidizing reaction in a subcritical spheroidizing treatment.

For full spheroidization, temperatures either slightly above Ac_1 or about midway between Ac_1 and Ac_3 are used. Low-carbon steels are seldom spheroidized for machining because in this condition they are excessively soft and gummy, and produce long, tough chips in cutting. Generally, spheroidized low-carbon steel can be severely deformed.

Hardness after spheroidization depends on carbon and alloy content. Increasing carbon or alloy content, or both, results in an increase in as-spheroidized hardness, which generally ranges from 163 to 212 HB (see adjoining Table).

Process Annealing

As a steel's hardness goes up during cold working, ductility drops and further cold reduction becomes so difficult that the material must be annealed to restore its ductility. The practice is referred to as in-process

Recommended Temperatures and Time Cycles for Annealing of Alloy Steels

Steel	Austenitizing temperature, °C	Austenitizing temperature, °F	Conventional cooling(a): Temperature °C From	°C To	°F From	°F To	Cooling rate °C/h	Cooling rate °F/h	Time, h	Isothermal method(b): Cool to °C	Cool to °F	Hold, h	Hardness (approx), HB
To obtain a predominantly pearlitic structure(c)													
1340	830	1525	735	610	1350	1130	10	20	11	620	1150	4.5	183
2340	800	1475	655	555	1210	1030	8.5	15	12	595	1100	6	201
2345	800	1475	655	550	1210	1020	8.5	15	12.7	595	1100	6	201
3120(d)	885	1625	...	...	...	...	...	...	...	650	1200	4	179
3140	830	1525	735	650	1350	1200	10	20	7.5	660	1225	6	187
3150	830	1525	705	645	1300	1190	10	20	5.5	660	1225	6	201
3310(e)	870	1600	...	...	...	...	...	...	...	595	1100	14	187
4042	830	1525	745	640	1370	1180	10	20	9.5	660	1225	4.5	197
4047	830	1525	735	630	1350	1170	10	20	9	660	1225	5	207
4062	830	1525	695	630	1280	1170	8.5	15	7.3	660	1225	6	223
4130	855	1575	765	665	1410	1230	20	35	5	675	1250	4	174
4140	845	1550	755	665	1390	1230	15	25	6.4	675	1250	5	197
4150	830	1525	745	670	1370	1240	8.5	15	8.6	675	1250	6	212
4320(d)	885	1625	...	...	...	...	...	...	...	660	1225	6	197
4340	830	1525	705	565	1300	1050	8.5	15	16.5	650	1200	8	223
4620(d)	885	1625	...	...	...	...	...	...	...	650	1200	6	187
4640	830	1525	715	600	1320	1110	7.6	14	15	620	1150	8	197
4820(d)	...	...	...	...	...	...	...	...	...	605	1125	4	192
5045	830	1525	755	665	1390	1230	10	20	8	660	1225	4.5	192
5120(d)	885	1625	...	...	...	...	...	...	...	690	1275	4	179
5132	845	1550	755	670	1390	1240	10	20	7.5	675	1250	6	183
5140	830	1525	740	670	1360	1240	10	20	6	675	1250	6	187
5150	830	1525	705	650	1300	1200	10	20	5	675	1250	6	201
52100(f)	...	...	...	...	...	...	...	...	...	...	...	...	...
6150	830	1525	760	675	1400	1250	8.5	15	10	675	1250	6	201
8620(d)	885	1625	...	...	...	...	...	...	...	660	1225	4	187
8630	845	1550	735	640	1350	1180	10	20	8.5	660	1225	6	192
8640	830	1525	725	640	1340	1180	10	20	8	660	1225	6	197
8650	830	1525	710	650	1310	1200	8.5	15	7.2	650	1200	8	212
8660	830	1525	700	655	1290	1210	8.5	15	8	650	1200	8	229
8720(d)	885	1625	...	...	...	...	...	...	...	660	1225	4	187
8740	830	1525	725	645	1340	1190	10	20	7.5	660	1225	7	201
8750	830	1525	720	630	1330	1170	8.5	15	10.7	660	1225	7	217
9260	860	1575	760	705	1400	1300	8.5	15	6.7	660	1225	6	229
9310(e)	870	1600	...	...	...	...	...	...	...	595	1100	14	187
9840	830	1525	695	640	1280	1180	8.5	15	6.6	650	1200	6	207
9850	830	1525	700	645	1290	1190	8.5	15	6.7	650	1200	8	223

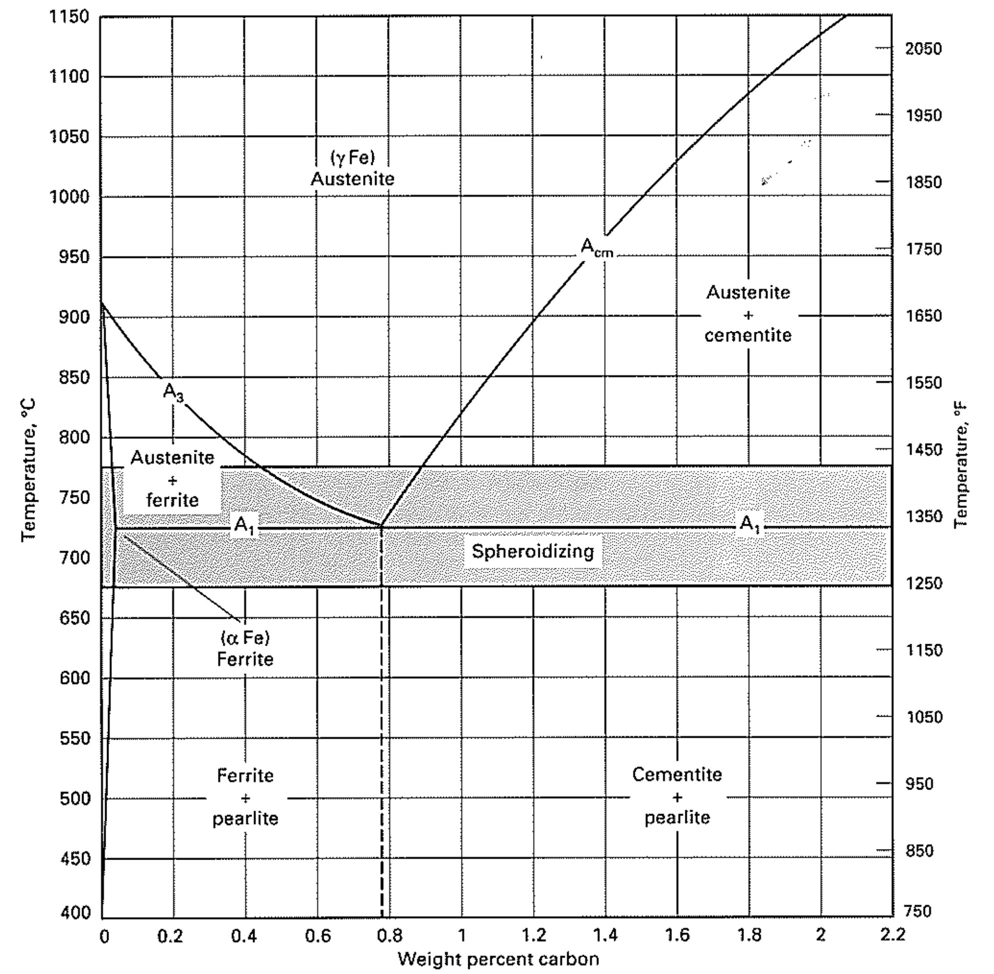
(continued)

Recommended Temperatures and Time Cycles for Annealing of Alloy Steels (continued)

Steel	Austenitizing temperature, °C	Austenitizing temperature, °F	Conventional cooling(a): Temperature °C From	°C To	°F From	°F To	Cooling rate °C/h	Cooling rate °F/h	Time, h	Isothermal method(b): Cool to °C	Cool to °F	Hold, h	Hardness (approx), HB
To obtain a predominantly ferritic and spheroidized carbide structure													
1320(d)	805	1480	...	...	...	...	...	...	...	650	1200	8	170
1340	750	1380	735	610	1350	1130	5	10	22	640	1180	8	174
2340	715	1320	655	555	1210	1030	5	10	18	605	1125	10	192
2345	715	1320	655	550	1210	1020	5	10	19	605	1125	10	192
3120(d)	790	1450	...	...	...	...	...	...	...	650	1200	8	163
3140	745	1370	735	650	1350	1200	5	10	15	660	1225	10	174
3150	750	1380	705	645	1300	1190	5	10	11	660	1225	10	187
9840	745	1370	695	640	1280	1180	5	10	11	650	1200	10	192
9850	745	1370	700	645	1290	1190	5	10	11	650	1200	12	207

(a) The steel is cooled in the furnace at the indicated rate through the temperature range shown. (b) The steel is cooled rapidly to the temperature indicated and is held at that temperature for the time specified. (c) In isothermal annealing to obtain pearlitic structure, steels may be austenitized at temperatures up to 70 °C (125 °F) higher than temperatures listed. (d) Seldom annealed. Structures of better machinability are developed by normalizing or by transforming isothermally after rolling or forging. (e) Annealing is impractical by the conventional process of continuous slow cooling. The lower transformation temperature is markedly depressed, and excessively long cooling cycles are required to obtain transformation to pearlite. (f) Predominantly pearlitic structures are seldom desired in this steel.

The iron-carbon binary phase diagram showing region of temperature for process annealing (Ref 4)



annealing or simply process annealing. In most cases, a subcritical treatment is adequate and the least costly procedure. The term process annealing, without further qualification, refers to the subcritical treatment. The range of temperatures normally used are shown in an adjoining Figure.

It is often necessary to call for process annealing when parts are cold formed by stamping, heading, or extrusion. Hot worked, high-carbon and alloy steels are also process annealed to prevent them from cracking and to soften them for shearing, turning, and straightening. The process usually consists of heating to a temperature below Ac_1, soaking for an appropriate time, then cooling—usually in air. Generally, heating to a temperature between 10 and 22 °C (20 and 40 °F) below Ac_1 produces the best combination of microstructure, hardness, and mechanical properties. Temperature controls are necessary only to prevent heating above Ac_1, which would defeat the purpose of annealing.

When the sole purpose is to soften for such operations as cold sawing and cold shearing, temperatures are usually well below Ac_1, and close control isn't necessary.

Annealed Structures for Machining

Different combinations of microstructure and hardness are important for machining. Optimum microstructures for machining steels with different carbon contents are usually as follows:

Carbon, %	Optimum microstructure
0.06-0.20	As-rolled (most economical)
0.20-0.30	Under 75 mm (3 in.) diameter, normalized; 75 mm diameter and over, as-rolled
0.30-0.40	Annealed, to produce coarse pearlite, minimum ferrite
0.o0-0.60	Coarse lamellar pearlite to coarse spheroidized carbides
0.60-1.00	100% spheroidized carbides, coarse to fine

Type of machining operation must also be taken into consideration, i.e., in machining 5160 steel tubing in a dual operation (automatic screw machines, plus broaching of cross slots), screw machine operations were the easiest with thoroughly spheroidized material, while a pearlite structure was more suitable for broaching. A semispheroidized structure proved to be a satisfactory compromise—a structure that can be obtained by austenitizing at lower temperatures, and sometimes at higher cooling rates, than those used to get pearlitic structures. In the last example, the 5160 tubing was heated to 790 °C (1455 °F) and cooled to 650 °C (1200 °F), at 28 °C (50 °F) per h. When this grade of steel is austenitized at about 775 °C (1425 °F), results are more spheroidization and less pearlite.

Medium-carbon steels are harder to carburize than high-carbon steels, such as 1095 and 52100. In the absence of excess carbides to nucleate and promote the spheroidization reaction, it is more difficult to get complete freedom from pearlite in practical heat-treating operations.

At lower carbon levels, structures consisting of coarse pearlite in a ferrite matrix are the most machinable. With some alloy steels, the best way of getting this type of structure is to heat well above Ac_3 to establish coarse austenite grain size, then holding below Ar_1 to allow coarse, lamellar pearlite to form. The process is sometimes referred to as cycle annealing or lamellar annealing.

Annealing of Forgings

Forgings are most often annealed to facilitate subsequent operations—usually machining or cold forming. The method of annealing is determined by the kind and amount of machining or cold forming to be done, as well as type of material being processed.

Annealing Bar, Rod, Wire

Significant tonnages of these products are subjected to treatments that lower hardness and prepare the steels for subsequent cold working and/or machining. Short time, subcritical annealing is often enough to prepare low-carbon steels (up to 0.20% C) for cold working. Steels higher in carbon and alloy content require spheroidization to get maximum ductility.

Annealing of Plate

These products are occasionally annealed to facilitate forming or machining operations. Plate is usually annealed at subcritical temperatures, and long annealing times are generally avoided. Maintaining flatness of large plate can be a significant problem.

Annealing of Tubular Products

Mechanical tubing is frequently machined or formed. Annealing is a common treatment. In most instances, subcritical temperatures and short annealing times are used to lower hardness. High-carbon grades such as 52100 generally are spheroidized prior to machining. Tubular products made in pipe mills rarely are annealed, and are used in the as-rolled, the normalized, or quenched and tempered conditions.

References

1. B.R. Banerjee, Annealing Heat Treatments, *Met. Prog.*, Nov 1980, p 59
2. *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, American Society for Metals, 1977
3. M. Atkins, *Atlas for Continuous Cooling Transformation Diagrams for Engineering Steels*, American Society for Metals, in cooperation with British Steel Corporation, 1980
4. G. Krauss, *Steels: Heat Treatment and Processing Principles*, ASM International, 1989

Surface Hardening Treatments

In the articles that follow, overviews of 16 surface hardening processes are presented. They include, in the order that follows:

- Induction hardening
- Flame hardening
- Gas carburizing
- Pack carburizing
- Liquid carburizing and cyaniding
- Vacuum carburizing
- Plasma (ion) carburizing
- Carbonitriding
- Gas nitriding
- Liquid nitriding
- Plasma (ion) nitriding
- Gaseous and plasma nitrocarburizing
- Fluidized bed hardening
- Boriding
- Laser surface hardening
- Electron beam surface hardening

For more detailed information and hundreds of references, see the *ASM Metals Handbook, Heat Treating*, Vol 4, 10 ed., ASM International, 1991.

Induction Hardening

Steels are surface hardened and through-hardened, tempered, and stress relieved by using electromagnetic induction as a source of heat. Heating times are unusually rapid—typically a matter of seconds, Ref 1.

Characteristics

In designing treatments, consideration must be given to the workpiece materials, their starting condition, the effect of rapid heating on the Ac_3 or Ac_{cm} temperatures, property requirements, and equipment used.

Many problems associated with furnace processes are avoided. Rate of heating is limited only by the power rating of the alternating current supply. Surface problems such as scaling and decarburization and the need for protective atmospheres often can be bypassed because heating is so fast. Heating is also energy efficient—as high as 80 percent. In gas fired furnaces, by comparison, a fairly substantial amount of consumed energy in hot gases is lost as they exit the furnace.

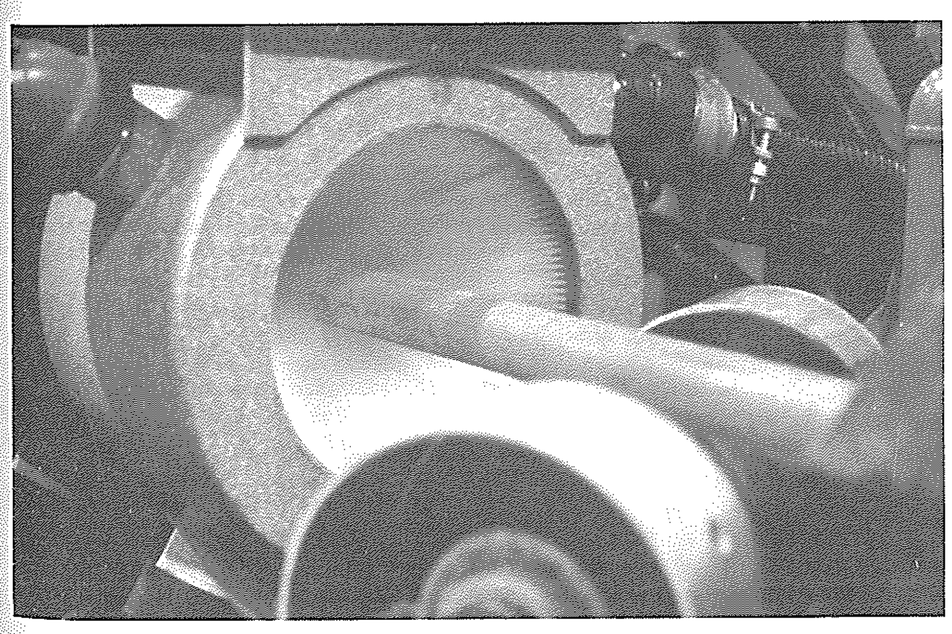
However, the process seldom competes with gas or oil-based processes in terms of energy costs alone. Savings emanate from other sources:

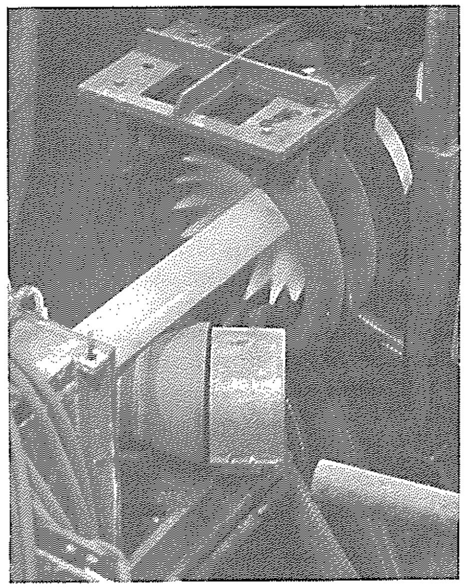
Operating and Production Data for Progressive Induction Tempering

Section size			Fre-quency(a),	Power(a),	Total heating	Scan time		Work temperature				Production rate		Inductor input(b)	
								Entering coil		Leaving coil					
mm	in.	Material	Hz	kW	time, s	s/cm	s/in.	°C	°F	°C	°F	kg/h	lb/h	kW/cm²	kW/in.²
Rounds															
13	½	4130	9600	11	17	0.39	1	50	120	565	1050	92	202	0.064	0.41
19	¾	1035 mod	9600	12.7	30.6	0.71	1.8	50	120	510	950	113	250	0.050	0.32
25	1	1041	9600	18.7	44.2	1.02	2.6	50	120	565	1050	141	311	0.054	0.35
29	1⅛	1041	9600	20.6	51	1.18	3.0	50	120	565	1050	153	338	0.053	0.34
49	1 15/16	14B35H	180	24	196	2.76	7.0	50	120	565	1050	195	429	0.031	0.20
Flats															
16	⅝	1038	60	88	123	0.59	1.5	40	100	290	550	1449	3194	0.014	0.089
19	¾	1038	60	100	164	0.79	2.0	40	100	315	600	1576	3474	0.013	0.081
22	⅞	1043	60	98	312	1.50	3.8	40	100	290	550	1609	3548	0.008	0.050
25	1	1043	60	85	254	1.22	3.1	40	100	290	550	1365	3009	0.011	0.068
29	1⅛	1043	60	90	328	1.57	4.0	40	100	290	550	1483	3269	0.009	0.060
Irregular shapes															
17.5-33	11/16–1 5/16	1037 mod	9600	192	64.8	0.94	2.4	65	150	550	1020	2211	4875	0.043	0.28
17.5-29	11/16–1⅛	1037 mod	9600	154	46	0.67	1.7	65	150	425	800	2276	5019	0.040	0.26

(a) Power transmitted by the inductor at the operating frequency indicated. For converted frequencies, this power is approximately 25% less than the power input to the machine, because of losses within the machine. (b) At the operating frequency of the inductor

Examples of quench rings for continuous hardening and quenching of tubular members. Courtesy of Ajax Magnethermic Corp.





Power Densities Required for Surface Hardening Of Steel

Frequency, KHz	Depth of hardening(a) mm	Depth of hardening(a) in.	Input(b)(c) Low(d) kW/cm²	Low(d) kW/in.²	Optimum(e) kW/cm²	Optimum(e) kW/in.²	High(f) kW/cm²	High(f) kW/in.²
500	0.381-1.143	0.015-0.045	1.08	7	1.55	10	1.86	12
	1.143-2.286	0.045-0.090	0.46	3	0.78	5	1.24	8
10	1.524-2.286	0.060-0.090	1.24	8	1.55	10	2.48	16
	2.286-3.048	0.090-0.120	0.78	5	1.55	10	2.33	15
	3.048-4.064	0.120-0.160	0.78	5	1.55	10	2.17	14
3	2.286-3.048	0.090-0.120	1.55	10	2.33	15	2.64	17
	3.048-4.064	0.120-0.160	0.78	5	2.17	14	2.48	16
	4.064-5.080	0.160-0.200	0.78	5	1.55	10	2.17	14
1	5.080-7.112	0.200-0.280	0.78	5	1.55	10	1.86	12
	7.112-8.890	0.280-0.350	0.78	5	1.55	10	1.86	12

(a) For greater depths of hardening, lower kilowatt inputs are used. (b) These values are based on use of proper frequency and normal overall operating efficiency of equipment. These values may be used for both static and progressive methods of heating; however, for some applications, higher inputs can be used for progressive hardening. (c) Kilowattage is read as maximum during heat cycle. (d) Low kilowatt input may be used when generator capacity is limited. These kilowatt values may be used to calculate largest part hardened (single-shot method) with a given generator. (e) For best metallurgical results. (f) For higher production when generator capacity is available

Approximate Power Densities Required for Through-Heating of Steel for Hardening, Tempering, or Forming Operations

Frequency(a), Hz	Input(b) 150-425 °C (300-800 °F) kW/cm²	150-425 °C kW/in.²	425-760 °C (800-1400 °F) kW/cm²	425-760 °C kW/in.²	760-980 °C (1400-1800 °F) kW/cm²	760-980 °C kW/in.²	980-1095 °C (1800-2000 °F) kW/cm²	980-1095 °C kW/in.²	1095-1205 °C (2000-2200 °F) kW/cm²	1095-1205 °C kW/in.²
60	0.009	0.06	0.023	0.15	(c)	(c)	(c)	(c)	(c)	(c)
180	0.008	0.05	0.022	0.14	(c)	(c)	(c)	(c)	(c)	(c)
1000	0.006	0.04	0.019	0.12	0.08	0.5	0.155	1.0	0.22	1.4
3000	0.005	0.03	0.016	0.10	0.06	0.4	0.085	0.55	0.11	0.7
10 000	0.003	0.02	0.012	0.08	0.05	0.3	0.070	0.45	0.085	0.55

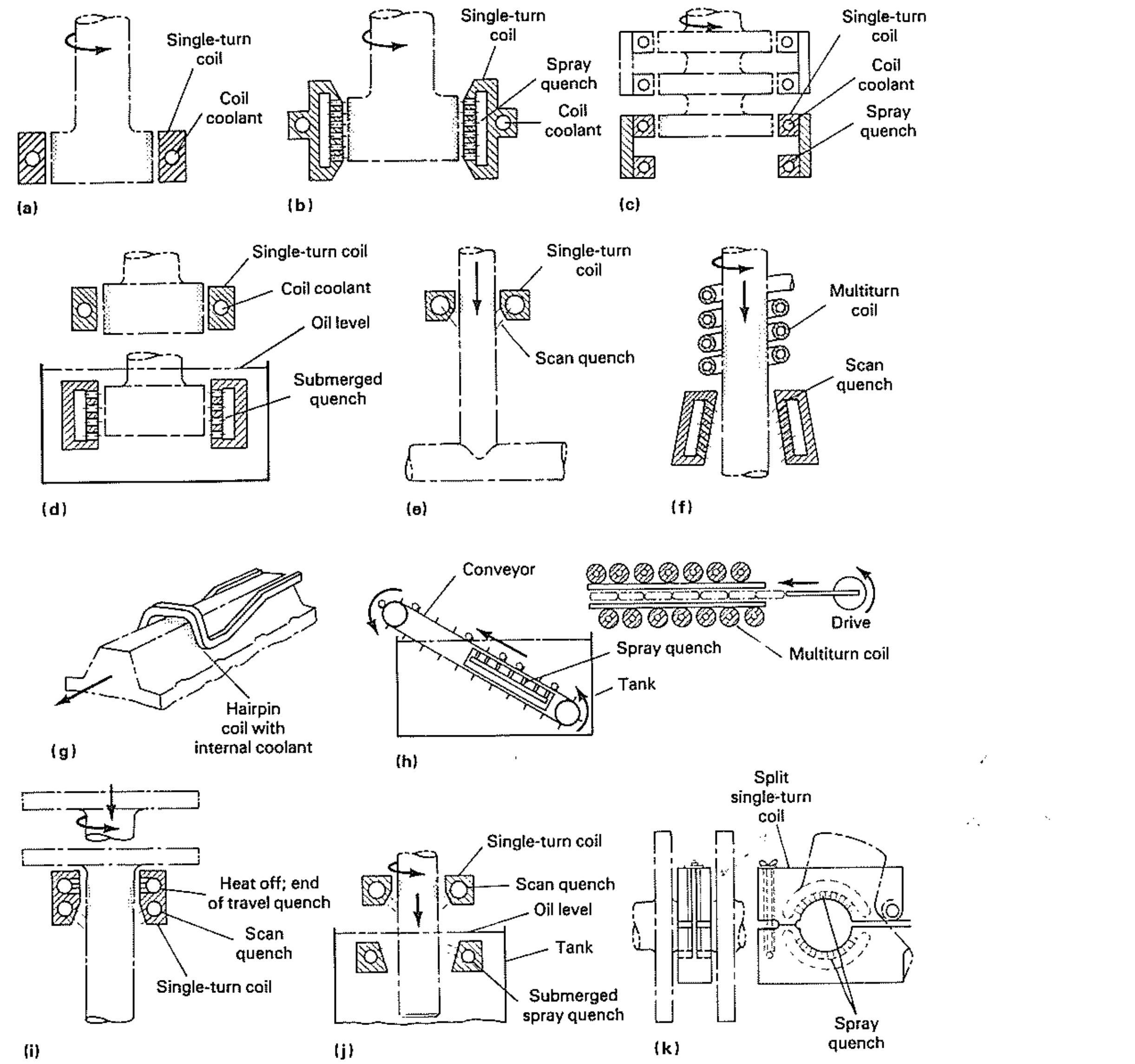
(a) The values in this table are based on use of proper frequency and normal overall operating efficiency of equipment. (b) In general, these power densities are for section sizes of 13 to 50 mm (½ to 2 in.). Higher inputs can be used for smaller section sizes, and lower inputs may be required for larger section sizes. (c) Not recommended for these temperatures

Typical Operating Conditions for Progressive Through-Hardening of Steel Parts by Induction

Section size mm	Section size in.	Material	Frequency(a), Hz	Power(b), kW	Total heating time, s	Scan time s/cm	Scan time s/in.	Work temperature Entering coil °C	Entering coil °F	Leaving coil °C	Leaving coil °F	Production rate kg/h	Production rate lb/h	Inductor input(c) kW/cm²	Inductor input(c) kW/in.²
Rounds															
13	½	4130	180	20	38	0.39	1	75	165	510	950	92	202	0.067	0.43
			9600	21	17	0.39	1	510	950	925	1700	92	202	0.122	0.79
19	¾	1035 mod	180	28.5	68.4	0.71	1.8	75	165	620	1150	113	250	0.062	0.40
			9600	20.6	28.8	0.71	1.8	620	1150	955	1750	113	250	0.085	0.55
25	1	1041	180	33	98.8	1.02	2.6	70	160	620	1150	141	311	0.054	0.35
			9600	19.5	44.2	1.02	2.6	620	1150	955	1750	141	311	0.057	0.37
29	1⅛	1041	180	36	114	1.18	3.0	75	165	620	1150	153	338	0.053	0.34
			9600	19.1	51	1.18	3.0	620	1150	955	1750	153	338	0.050	0.32
49	1 15/16	14B35H	180	35	260	2.76	7.0	75	165	635	1175	195	429	0.029	0.19
			9600	32	119	2.76	7.0	635	1175	955	1750	195	429	0.048	0.31
Flats															
16	⅝	1038	3000	300	11.3	0.59	1.5	20	70	870	1600	1449	3194	0.361	2.33
19	¾	1038	3000	332	15	0.79	2.0	20	70	870	1600	1576	3474	0.319	2.06
22	⅞	1043	3000	336	28.5	1.50	3.8	20	70	870	1600	1609	3548	0.206	1.33
25	1	1036	3000	304	26.3	1.38	3.5	20	70	870	1600	1595	3517	0.225	1.45
29	1⅛	1036	3000	344	36.0	1.89	4.8	20	70	870	1600	1678	3701	0.208	1.34
Irregular shapes															
17.5-33	11/16–1 5/16	1037 mod	3000	580	254	0.94	2.4	20	70	885	1625	2211	4875	0.040	0.26

(a) Note use of dual frequencies for round sections. (b) Power transmitted by the inductor at the operating frequency indicated. This power is approximately 25% less than the power input to the machine, because of losses within the machine. (c) At the operating frequency of the inductor

Eleven basic arrangements for quenching induction-hardened parts. See text for details.



shortened processing times, reduced labor, and the ability to heat treat in a production line or in automated systems, for example. Surface hardening and selective hardening can be energy competitive because only a small part of the metal is heated.

In addition, with induction heating it often is possible to substitute a plain carbon steel for a more expensive alloy steel. Short heating times make it possible to use higher austenitizing temperatures than those in conventional heat-treating practice.

Less distortion is another consideration. This advantage is due to the support given by the rigid, unheated core metal and uniform, individual handling during heating and quenching cycles.

Operating Information

Power densities for surface hardening are given in an adjoining Table.

Approximate power densities needed for through-heating of steel for hardening and tempering are given in an adjoining Table.

Typical operating conditions for progressive through-hardening are given in an adjoining Table.

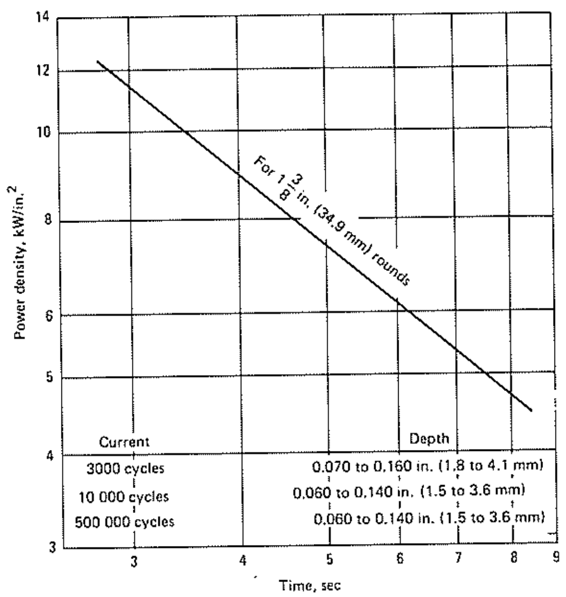
Operating and production data for progressive induction tempering are given in an adjoining Table.

Frequency and power selection influence case depth. A shallow, fully hardened case ranging in depth from 0.25 mm to 1.5 mm (0.010 to 0.060 in.) provides good resistance to wear for light to moderately loaded parts. At this level, depth of austenitizing can be controlled by using frequencies on the order of 10 KHz to 2 MHz, power densities to the coil of 800 to 8000 W/cm^2 (5 to 50 kW/in.^{2}) and heating times of not more than a few seconds.

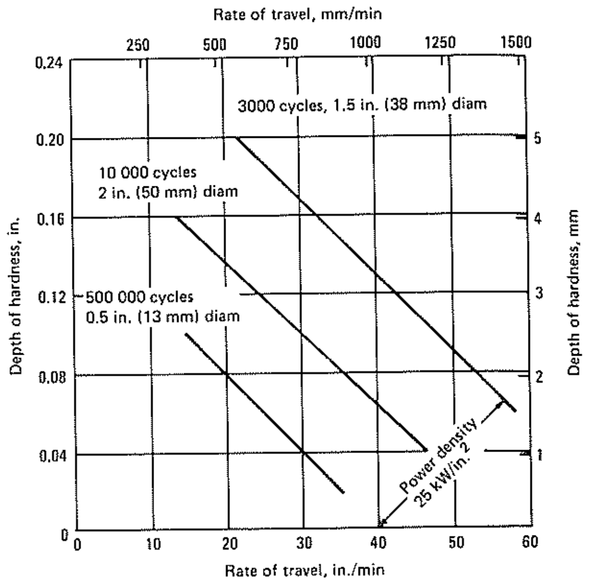
For parts subjected to heavy loads, especially cyclic bending, torsion, or brinneling, case depths must be thicker, i.e., 1.5 to 6.4 mm (0.60 to 0.250 in.). To get this result, frequencies range from 10 KHz down to 1 KHz; power densities are on the order of 80 to 1550 W/cm^2 (1/2 to 10 kW/in.^{2}), and heating times are several seconds.

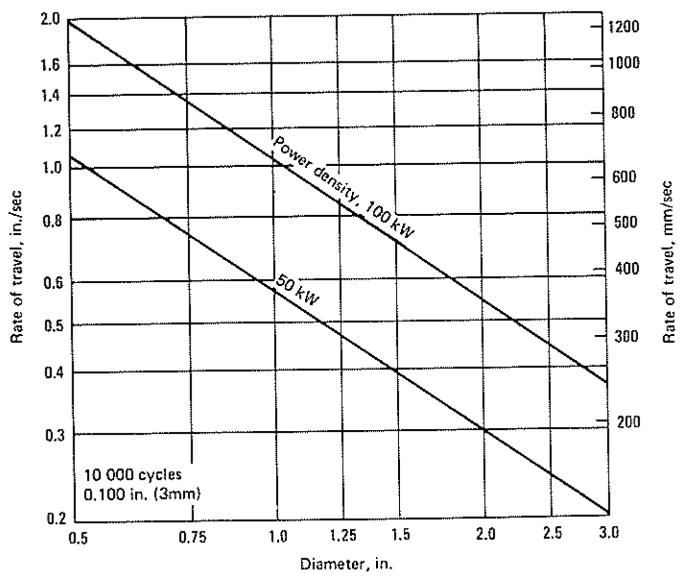
Selective hardening is possible, as is in volume surfacing hardening, in which parts are austenitized and quenched to greater than usual depths. Depth of hardness up to 25 mm (1 in.) measuring over 600 HB has been obtained with a 1 percent carbon, 1.3 to 1.6 percent chromium steel that has been water quenched. Frequencies range from 60 Hz to 1 KHz. Power

Power Input for Static Hardening. Slope of graph indicates that 35 to 40 kW-sec/in.^{2} (5 to 6 kW-sec/cm^2) is correct power input for static hardening most steels. Source: Park-Ohio Industries



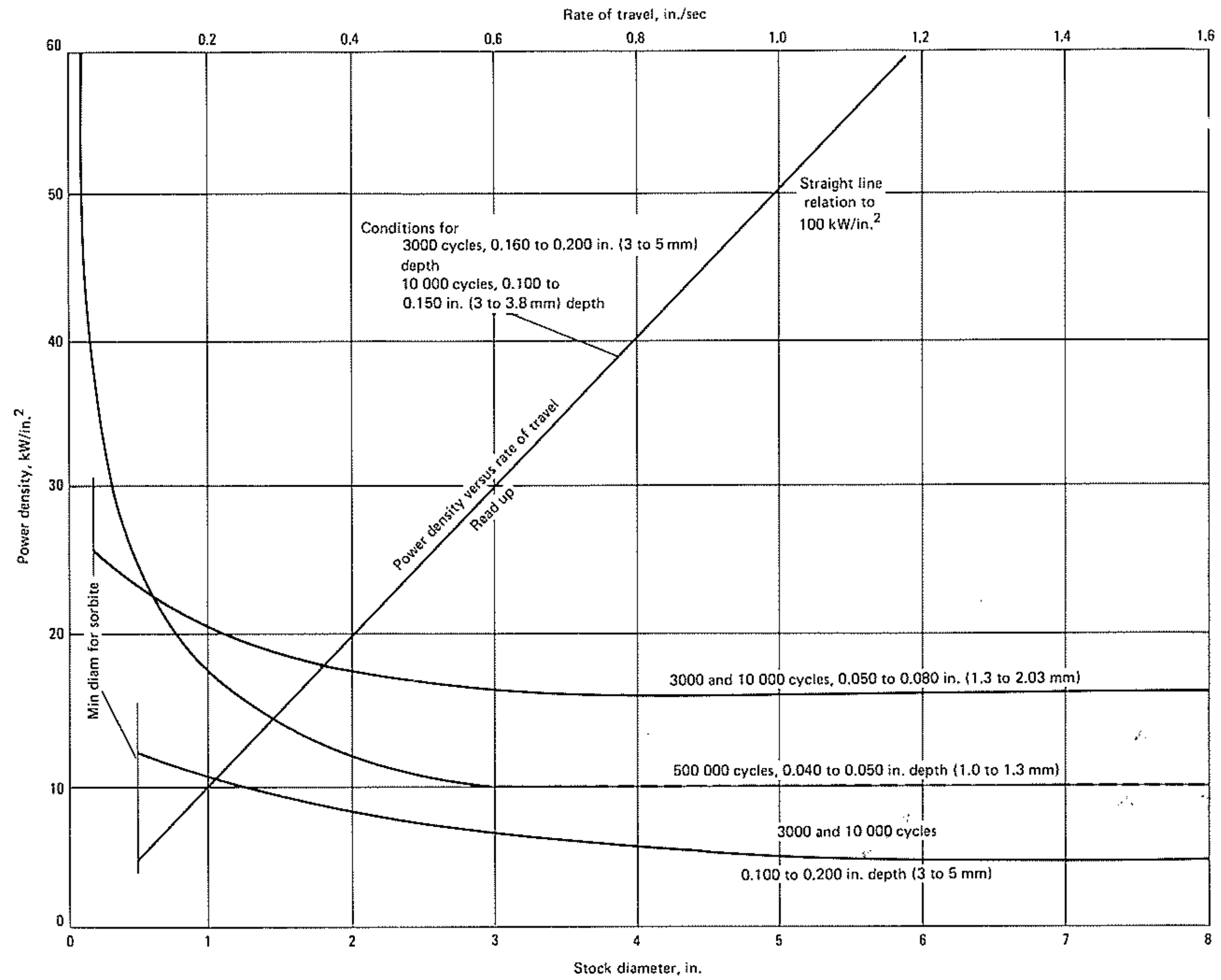
Straight-Line Relationships Between Depth of Hardness and Rate of Travel for Surface Hardening by Induction of Long Bars Progressively. Source: Park-Ohio Industries

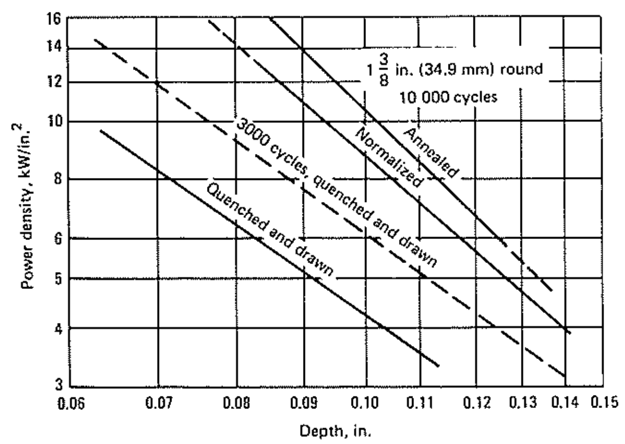




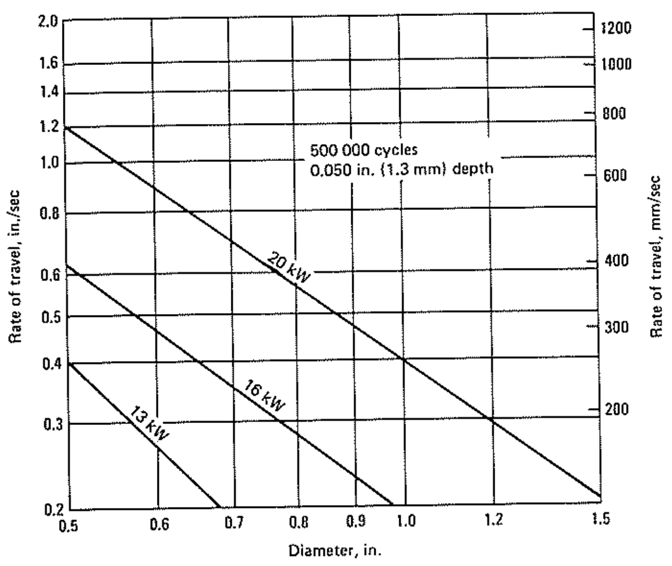
Effect of Varying Power Density on Progressive Hardening. Power density at 10 000 cycles. Case, 0.100 in. (2.54 mm) deep. Source: Park-Ohio Industries

Minimum Power Density Versus Stock Diameter for Static Hardening and Versus Rate of Travel for Progressive Hardening. Source: Park-Ohio Industries





Influence of Prior Structure on Power Requirements for Surface Hardening. Prior structure consists of fine microconstituents. Source: Park-Ohio Industries



Effect of Varying Power Density on Progressive Hardening. Power density at 500 000 cycles. Case, 0.050 in. (1.27 mm) deep. Source: Park-Ohio Industries

densities are expressed in a fraction of $kW/in.^2$. Heating times run from about 20 to 140 s.

Through-hardening is obtained in the medium frequencies (180 Hz to 10 KHz). In some instances, two frequencies may be used, a lower one to preheat the steel to a subcritical temperature, followed by a higher frequency to obtain the full austenitizing temperature.

Tempering with induction heating is highly efficient. The two most common types of quenching systems are spray quench rings (see Figure) and immersion techniques. Eleven other systems are shown in an adjoining Figure.

Water and oil are the most frequently used quenching media. Oil typically is used for high hardenability parts or for those subject to distortion and cracking. Polyvinyl alcohol solutions and compressed air also are commonly used, i.e., the former where parts have borderline hardenability, where oil does not cool fast enough, and where water causes distortion or cracking. Compressed air quenching is used for high hardenability, surface hardened steels from which little heat needs to be removed.

Applications

The process is applied mostly to hardenable grades of steel; some carburizing and slow cooled parts often are reheated in selected areas by induction heating.

Typical applications include:

- Medium-carbon steels, such as 1030 and 1045, for parts such as auto driveshafts and gears
- High-carbon steels, such as 1070, for parts such as drill and rock bits and hand tools
- Alloy steels for such parts as bearings, valves, and machine tool parts

Reference

1. *ASM Metals Handbook, Heat Treating,* Vol 4, 10th ed., ASM International, 1991, p 164

Flame Hardening

In this process, a thin surface shell of a steel part is heated rapidly to a temperature above the critical point of the steel. After the structure of the shell becomes austenitic, the part is quenched quickly, transforming the austenite to martensite. The quench must be fast enough to bypass the pearlite and bainite phases. In some applications, self-quenching and self-tempering are possible, Ref 1. (See articles on other self-quenching processes—electron beam, laser, and high frequency, pulse hardening—elsewhere in this chapter.)

Characteristics

Hardening is obtained by direct impingement of a high-temperature flame or by high-velocity combustion product gases. The flame is produced by the combustion of a mixture of fuel gas and oxygen or oil. The mixture is burned in flame heads; depth of hardness ranges from approximately 0.8 to 6.4 mm (0.03125 to 0.25 in.), depending on the fuels used, design of the flame head, duration of heating, hardenability of the workpiece, the quenching medium, and quenching method.

Flame hardening differs from true case hardening in that hardness is obtained by localized heating.

The process generally is selected for wear resistance provided by high levels of hardness. Other available gains include improvements in bending properties, torsional strength, and fatigue life.

Comparative benefits of flame hardening, induction hardening, nitriding, carbonitriding, and carburizing are summarized in an adjoining Table.

Operating Information

Methods of flame hardening include these types: spot (or stationary), progressive, spinning, and combination progressive-spinning. Spot and progressive spinning are depicted in a Figure, spinning methods in a second Figure.

Fuel Gases Used for Flame Hardening

Gas	Heating value MJ/m³	Heating value Btu/ft³	Flame temperature With oxygen °C	Flame temperature With oxygen °F	Flame temperature With air °C	Flame temperature With air °F	Usual ratio of oxygen to fuel gas	Heating value of oxy-fuel gas mixture MJ/m³	Heating value of oxy-fuel gas mixture Btu/ft³	Normal velocity of burning mm/s	Normal velocity of burning in./s	Combustion intensity(a) mm/s × MJ/m³	Combustion intensity(a) in./s × Btu/ft³	Usual ratio of air to fuel gas
Acetylene	53.4	1433	3105	5620	2325	4215	1.0	26.7	716	535	21	14 284	15 036	12
City gas	11.2-33.5	300-900	2540	4600	1985	3605	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)
Natural gas (methane)	37.3	1000	2705	4900	1875	3405	1.75	13.6	364	280	11	3 808	4 004	9.0
Propane	93.9	2520	2635	4775	1925	3495	4.0	18.8	504	305	12	5 734	6 048	25.0
MAPP	90	2406	2927	5301	1760	3200	3.5	20.0	535	381	15	7 620	8 025	22

(a) Product of normal velocity of burning multiplied by heating value of oxy-fuel gas mixture. (b) Varies with heating value and composition

Procedure for Spin Flame Hardening the Small Converter Gear Hub

Preliminary operation

Turn on water, air, oxygen, power, and propane. Line pressures: water, 220 kPa (32 psi); air, 550 kPa (80 psi); oxygen, 825 kPa (120 psi); propane, 205 kPa (30 psi). Ignite pilots.

Loading and positioning

Mount hub on spindle. Hub is held in position by magnets. Flame head previously centered in hub within 0.4 mm (1/64 in.). Distance from flame head to inside diameter of gear teeth, approximately 7.9 mm (5/16 in.)

Cycle start

Spindle with hub advances over flame head and starts to rotate. Spindle speed, 140 rpm

Heating cycle

Propane and oxygen solenoid valves open (oxygen flow delayed slightly). Mixture of propane and oxygen ignited at flame head by pilots. Check propane and oxygen gages for proper pressure. Adjust flame by regulating propane. Heating cycle controlled by timer. Time predetermined to obtain specified hardening depth

Heating cycle (continued)

Propane and oxygen solenoid valves close (propane flow delayed slightly). Spindle stops rotating and retracts. Hub stripped from spindle by ejector plate. Machine ready for recycling

Propane regulated pressure, 125 kPa (18 psi); oxygen regulated pressure, 550 kPa (80 psi); oxygen upstream pressure, 400 kPa (58 psi); oxygen downstream pressure, 140 kPa (20 psi). Flame velocity (approximate), 135 m/s (450 ft/s). Gas consumptions (approximate); propane, 0.02 m^3 (0.6 ft^3) per piece; oxygen, 0.05 m^3 (1.9 ft^3) per piece. Total heating time, 9.5 s

Flame port design: 12 ports per segment; 10 segments; port size, No. 69 (0.74 mm, or 0.0292 in.), with No. 56 (1.2 mm, or 0.0465 in.) counterbore

Quench cycle

Hub drops into quench oil, is removed from tank by conveyor. Oil temperature, 54 ± 5.6 °C (130 ± 10 °F); time in oil (approximate), 30 s

Hardness and pattern aim

Hardness, 52 HRC minimum to a depth of 0.9 mm (0.035 in.) maximum above root of gear teeth

Shallow hardness patterns of less than 3.2 mm (0.125 in.) deep can be obtained only with oxy-gas fuels. When specified hardnesses are deeper, oxy-fuels or air-gas fuels may be used. Time-temperature depth relationships for various fuel gases used in the spot (stationary), spinning, and progressive methods are shown in an adjoining Figure.

Burners and Related Equipment. Burners vary in design, depending on whether oxy-fuel or air-fuel gas mixtures are used. Flame temperatures of the air-fuel mixtures are considerably lower than those of oxy-fuel mixtures (see Table).

Flame heads for oxy-fuel gas are illustrated in an adjoining Figure, while those for air-fuel gas are shown in a second Figure.

Operating Procedures and Control. The success of many applications depends largely on the skill of the operator.

Procedures for two applications are summarized in adjoining tables.

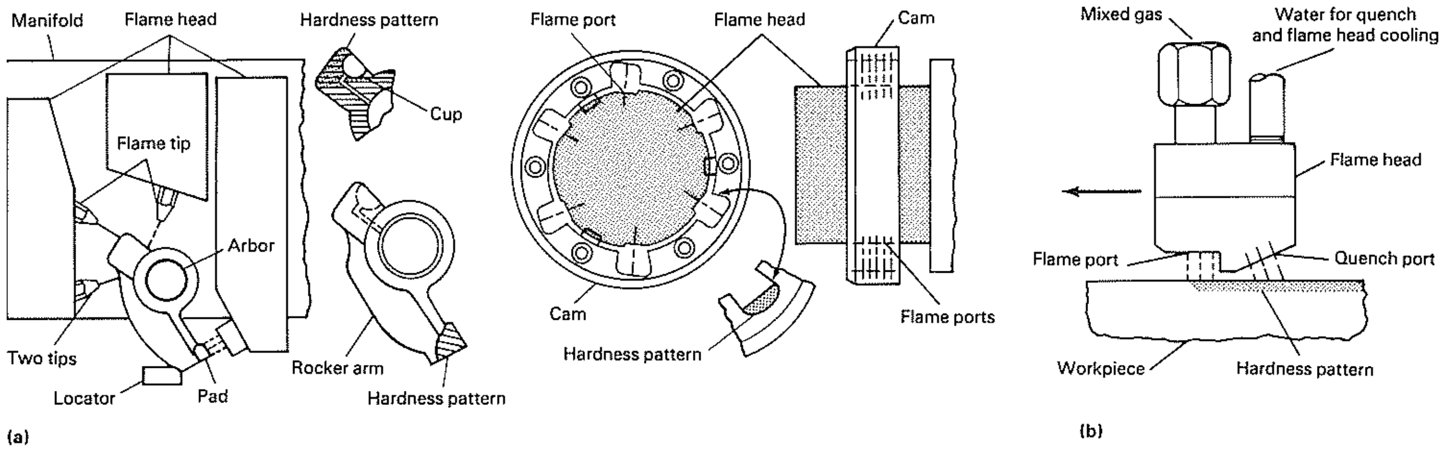
Preheating. Difficulties in getting the required surface hardness and hardness penetration in treating parts large in cross section often can be overcome by preheating. When available power or heat input is limited, depth of hardness can also be increased by preheating. Results in one application are shown in an adjoining Figure.

Quenching Methods and Equipment. Method and type of quenchant vary with the flame hardening method used. Immersion quenching generally is the choice in spot hardening, but spray quenching is an alternative. In quenching after progressive heating, the spray used is integrated into the flame head. However, for steels high in hardenability, a separate spray-quench sometimes is used. Parts heated by the spinning method are quenched several ways. In one, for example, the heated part is

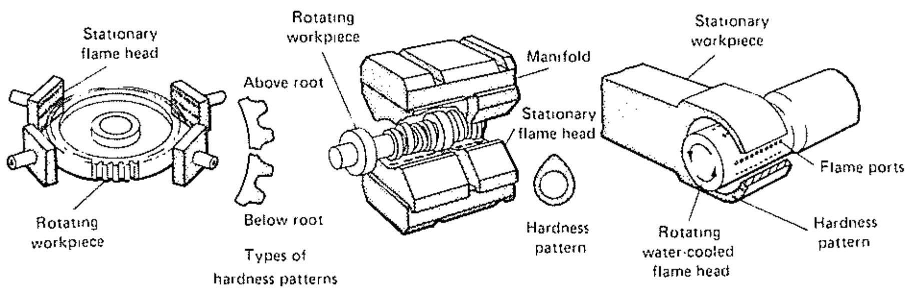
Relative Benefits of Five Hardening Processes

Carburizing	Hard, highly wear-resistant surface (medium case depths); excellent capacity for contact load; good bending fatigue strength; good resistance to seizure; excellent freedom from quench cracking; low-to-medium-cost steels required; high capital investment required
Carbonitriding	Hard, highly wear-resistant surface (shallow case depths); fair capacity for contact load; good bending fatigue strength; good resistance to seizure; good dimensional control possible; excellent freedom from quench cracking; low-cost steels usually satisfactory; medium capital investment required
Nitriding	Hard, highly wear-resistant surface (shallow case depths); fair capacity for contact load; good bending fatigue strength; excellent resistance to seizure; excellent dimensional control possible; good freedom from quench cracking (during pretreatment); medium-to-high-cost steels required; medium capital investment required
Induction hardening	Hard, highly wear-resistant surface (deep case depths); good capacity for contact load; good bending fatigue strength; fair resistance to seizure; fair dimensional control possible; fair freedom from quench cracking; low-cost steels usually satisfactory; medium capital investment required
Flame hardening	Hard, highly wear-resistant surface (deep case depths); good capacity for contact load; good bending fatigue strength; fair resistance to seizure; fair dimensional control possible; fair freedom from quench cracking; low-cost steels usually satisfactory; low capital investment required

Spot (stationary) and progressive methods of flame hardening. (a) Spot (stationary) method of flame hardening a rocker arm and the nternal lobes of a cam; quench not shown. (b) Progressive hardening method



Spinning methods of flame hardening. In methods shown at left and at center, the part rotates. In method at right, the flame head rotates. Quench not shown

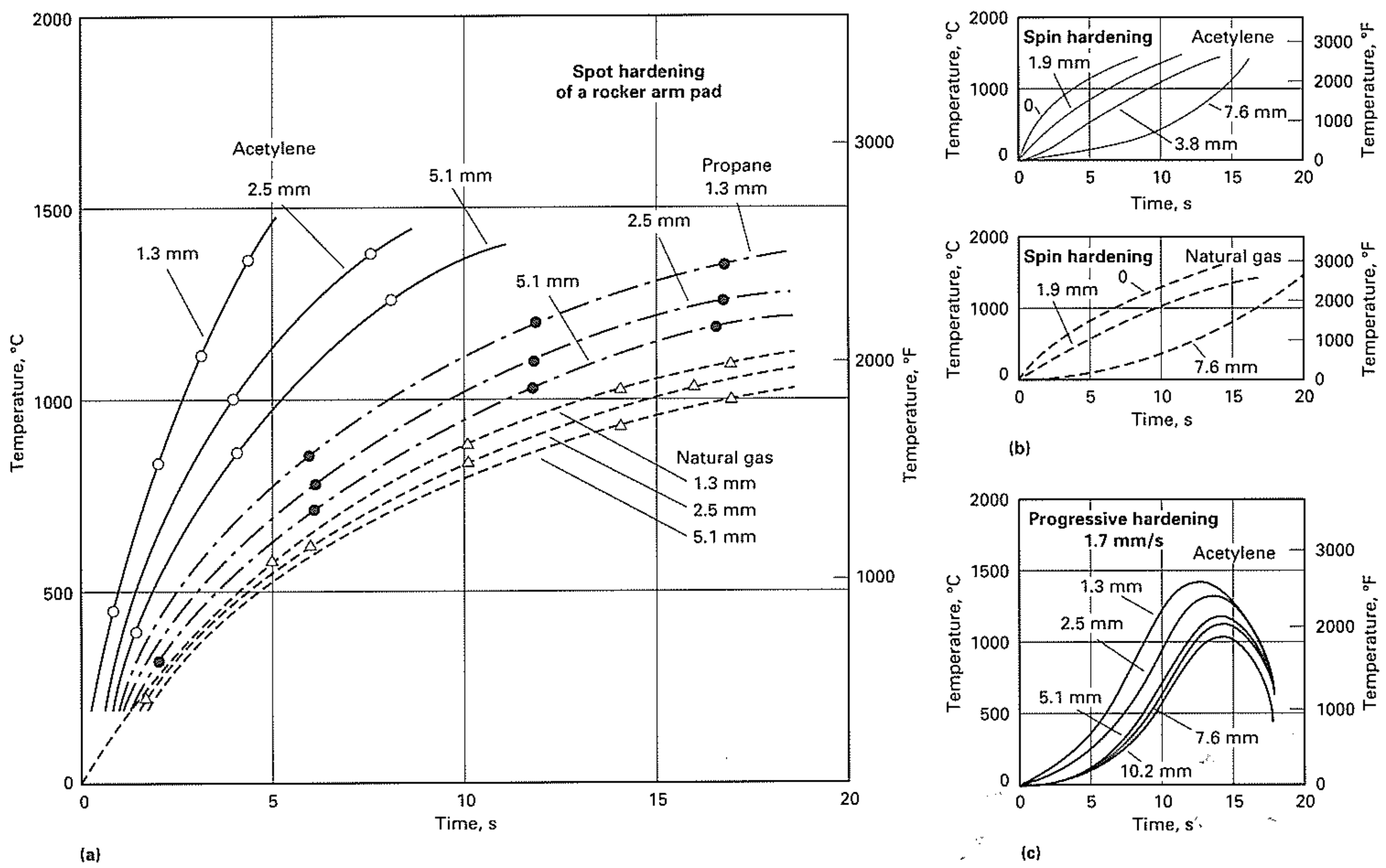


esponse of Steels and Cast Irons to Flame Hardening

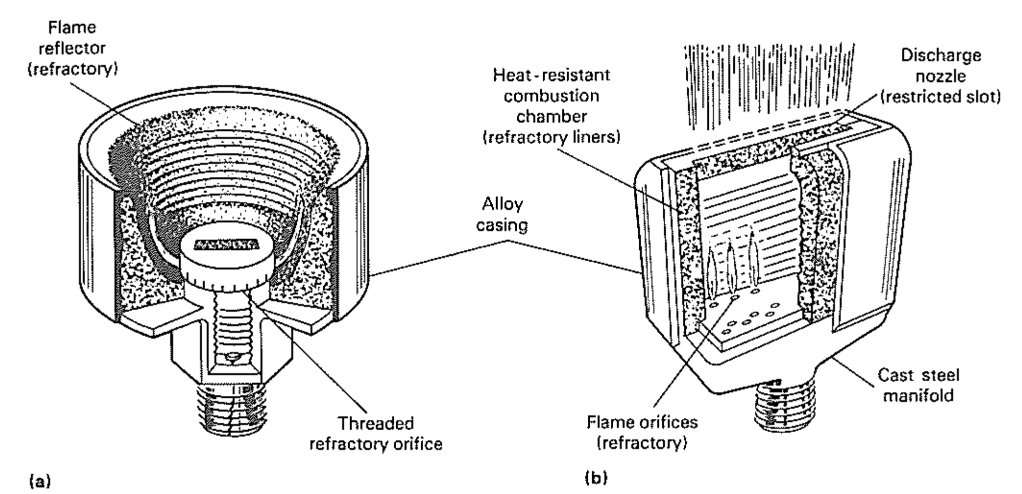
aterial	Typical hardness, HRC, as affected by quenchant Air(a)	Oil(b)	Water(b)
ain carbon steels			
25-1035	...	...	33-50
40-1050	...	52-58	55-60
55-1075	50-60	58-62	60-63
80-1095	55-62	58-62	62-65
25-1137	...	...	45-55
38-1144	45-55	52-57(c)	55-62
46-1151	50-55	55-60	58-64
arburized grades of plain carbon steels(d)			
10-1020	50-60	58-62	62-65
08-1120	50-60	60-63	62-65
lloy steels			
40-1345	45-55	52-57(c)	55-62
40-3145	50-60	55-60	60-64
50	55-60	58-62	63-65
63	55-60	61-63	63-65
30-4135	...	50-55	55-60
40-4145	52-56	52-56	55-60
47-4150	58-62	58-62	62-65
37-4340	53-57	53-57	60-63
47	56-60	56-60	62-65
40	52-56	52-56	60-63
Alloy steels (continued)			
52100	55-60	55-60	62-64
6150	...	52-60	55-60
8630-8640	48-53	52-57	58-62
8642-8660	55-63	55-63	62-64
Carburized grades of alloy steels(d)			
3310	55-60	58-62	63-65
4615-4620	58-62	62-65	64-66
8615-8620	...	58-62	62-65
Martensitic stainless steels			
410, 416	41-44	41-44	...
414, 431	42-47	42-47	...
420	49-56	49-56	...
440 (typical)	55-59	55-59	...
Cast irons (ASTM classes)			
Class 30	...	43-48	43-48
Class 40	...	48-52	48-52
Class 45010	...	35-43	35-45
50007, 53004, 60003	...	52-56	55-60
Class 80002	52-56	56-59	56-61
Class 60-45-15	...	...	35-45

) To obtain the hardness results indicated, those areas not directly heated must be kept relatively cool during the heating process. (b) Thin sections are susceptible to cracking when ienched with oil or water. (c) Hardness is slightly lower for material heated by spinning or combination progressive-spinning methods than it is for material heated by progressive stationary methods. (d) Hardness values of carburized cases containing 0.90 to 1.10% C

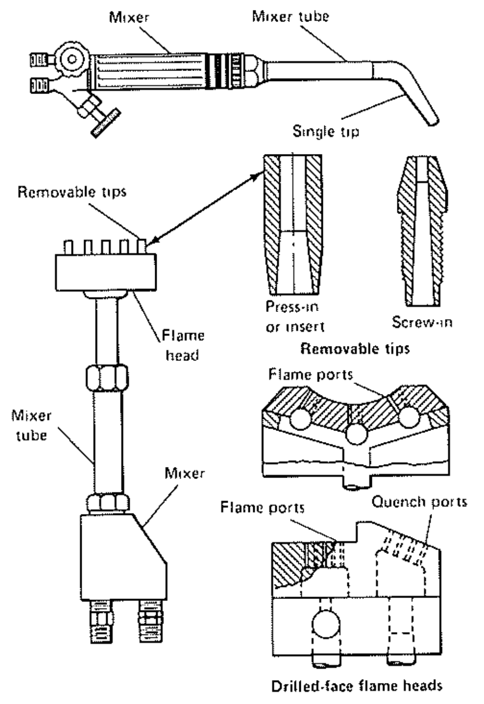
Calculated time-temperature-depth relationships for spot (stationary), spinning, and progressive flame hardening. Depth of hardness given in millimeters



Typical burners for use with air-fuel gas. (a) Radiant type. (b) High-velocity convection type (not water cooled)



Flame heads for use with oxy-fuel gas



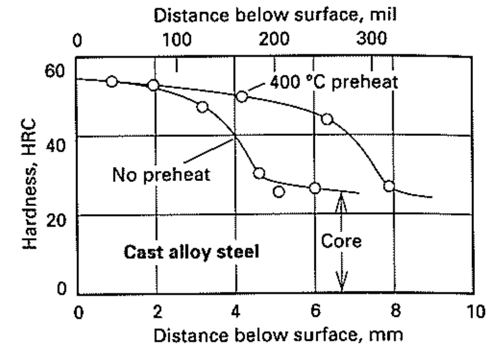
removed from the heating area and quenched by immersion in a separate tank.

Quenching Media. Water, dilute polymer solutions, and brine solutions are used. Oils are not: they should not be allowed to come into contact with oxygen, or to contaminate equipment.

In many types of flame hardening (excluding through hardening) self-quenching speeds up cooling. The mass of cold metal underneath the heated layer withdraws heat, so cooling rates are high compared with those in conventional quenching. During progressive hardening of gear teeth made of medium-carbon steels, such as 4140, 4150, 4340, and 4610, for instance, the combination of rapid heating and the temperature gradient between the surface and interior of a gear results in a self-quench. Results are similar to those obtained with oil.

Tempering. Flame hardened parts usually are tempered, with parts responding as they do when they are hardened by other methods. Standard procedures, equipment, and temperatures may be used. If parts are too large to be treated in a furnace, they can be flame tempered. Also, large parts hardened to depths of about 6.4 mm (0.25 in.) can be self-tempered by residual heat in the part; hardening stresses are relieved and tempering in a separate operation may not be necessary.

Effect of preheating on hardness gradient in a ring gear



Progressive Flame Hardening of Ring Gear Teeth

Workpiece

Bevel ring gear made of 8742 steel with 90 teeth. Diametral pitch, 1.5; face width, 200 mm (8 in.); outside diameter, 1.53 m (60.412 in.)

Mounting

Gear mounted on holding fixture to within 0.25 mm (0.010 in.) total indicator runout

Flame heads

Two 10 hole, double-row, air-cooled flame heads, one on each side of tooth. Flame heads set 3.2 mm (1/8 in.) from tooth

Operating conditions

Gas pressures. Acetylene, 69 kPa (10 psi); oxygen, 97 kPa (14 psi)
Speed. 1.9 mm/s (4.5 in./min). Complete cycle (hardening pass, overtravel at each end, index time, preheat return stroke on next tooth), 2.75 min
Indexing. Index every other tooth. Index four times before immersing in coolant.
Coolant. Mixture of soluble oil and water, at 13 °C (55 °F)
Hardness aim. 53 to 55 HRC

Applications

Flame hardened plain carbon steels, carburized grades of plain carbon steels, alloy steels, martensitic stainless steels, and cast irons that are flame hardened are listed in an adjoining Table.

Reference

1. *ASM Metals Handbook, Heat Treating,* Vol 4, 10th ed., ASM International, 1991, p 268

Gas Carburizing

In this process, carbon is dissolved in the surface layers of parts at the temperatures required to produced an austenitic microstructure in low-carbon steels. Austenite is subsequently converted to martensite by quenching and tempering, Ref 1.

Characteristics

This is the most important carburizing process commercially. The gradient in carbon content below the surface of a part produced in the process causes a gradient in hardness; resulting surface layers are strong and resistant to wear. The source of carbon is a carbon-rich furnace atmosphere, including gaseous hydrocarbons, such as methane, propane, and butane, or vaporized hydrocarbon liquids. Low-carbon steels exposed to these atmospheres carburize at temperatures of 850 °C (1560 °F) and above.

Operating Information

In present practice, carbon content in furnace atmospheres is controlled for two reasons:

- To hold final carbon concentration at the surface of parts below the solubility limit in austenite
- To minimize sooting of the furnace atmosphere

Endothermic gas, the usual carrier, plays a dual role: it acts as a diluent and accelerates the carburizing reaction at the surface of parts.

Parts, trays, and fixtures should be thoroughly cleaned before they are charged into the furnace—often in hot alkaline solutions. In some shops, these furnace components are heated to 400 °C (750 °F) before carburizing to remove traces of organic contaminants.

Key process variables are temperature, time, and composition of the atmosphere. Other variables are degree of atmosphere circulation and the alloy content of parts.

Temperature. The rate of diffusion of carbon in austenite determines the maximum rate at which carbon can be added to steel. The rate increases significantly with increasing temperature. The rate of carbon addition at 925 °C (1695 °F) is about 40 percent higher than it is at 870 °C (1600 °F). At this temperature, the carburizing rate is reasonably rapid and the deterioration of furnace components, especially alloy trays and fixtures, is not excessive. When deep cases are specified, temperatures as high as 966 °C (1770 °F) sometimes are used to shorten carburizing times.

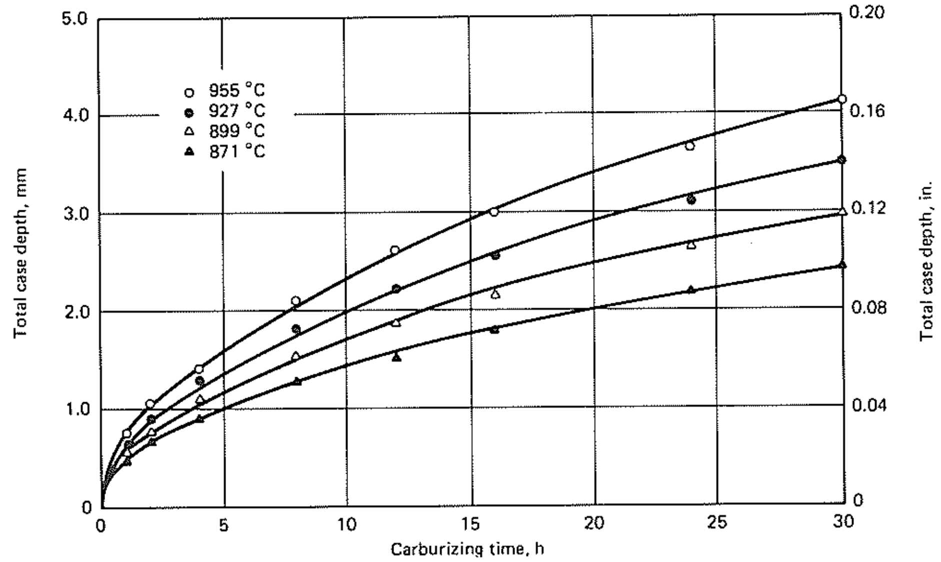
For consistent results, temperatures must be uniform throughout the workload. The desired result can be obtained, for example, with continuous furnaces with separate preheat chambers.

Time. The combined effect of time and temperature on total case depth is shown in an adjoining Figure. The relationship of carburizing time and increasing carburizing temperature is shown in a second Figure.

Dimensional Control. To keep heat-treating times as short as possible, parts should be as close to final dimensions as possible. A number of other factors also have an influence on distortion, including:

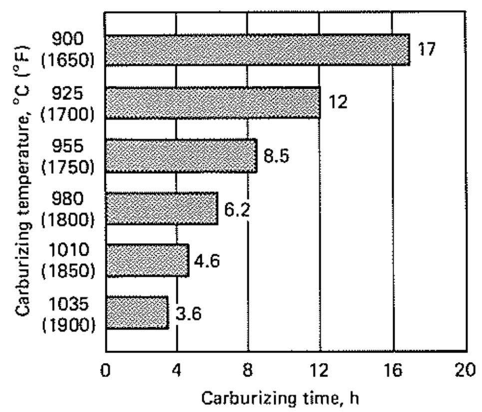
- Residual stresses put into parts prior to heat treating
- Shape changes caused by heating too rapidly

Plot of total case depth versus carburizing time at four selected temperatures. Graph based on data in table



Time, h	871 °C (1600 °F) mm	871 °C (1600 °F) in.	899 °C (1650 °F) mm	899 °C (1650 °F) in.	927 °C (1700 °F) mm	927 °C (1700 °F) in.	955 °C (1750 °F) mm	955 °C (1750 °F) in.
1	0.46	0.018	0.53	0.021	0.64	0.025	0.74	0.029
2	0.64	0.025	0.76	0.030	0.89	0.035	1.04	0.041
4	0.89	0.035	1.07	0.042	1.27	0.050	1.30	0.051
8	1.27	0.050	1.52	0.060	1.80	0.071	2.11	0.083
12	1.55	0.061	1.85	0.073	2.21	0.087	2.59	0.102
16	1.80	0.071	2.13	0.084	2.54	0.100	2.97	0.117
24	2.18	0.086	2.62	0.103	3.10	0.122	3.66	0.144
30	2.46	0.097	2.95	0.116	3.48	0.137	4.09	0.161

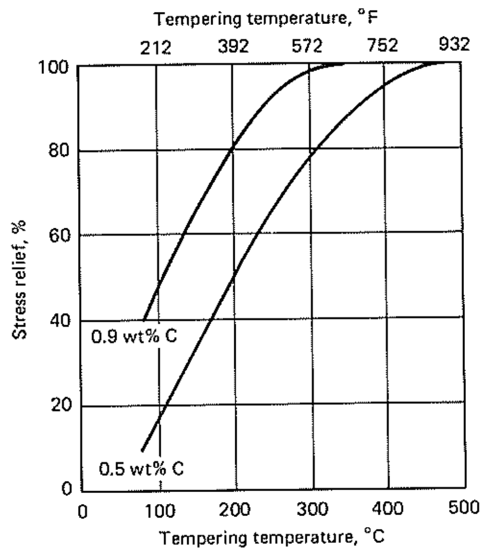
Reducing effect of increased process temperature on carburizing time for 8620 steel. Case depth: 1.5 mm (0.060 in.)



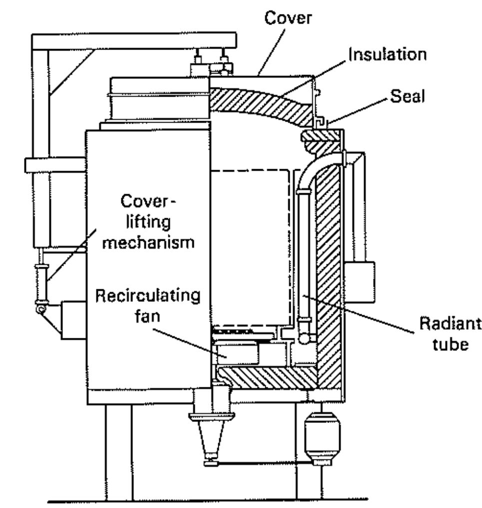
Properties of Air-Combustible Gas Mixtures

Gas	Autoignition temperature °C	Autoignition temperature °F	Flammable limits in air, vol %
Methane	540	1005	5.4-15
Propane	466	870	2.4-9.5
Hydrogen	400	750	4.0-75
Carbon monoxide	609	1130	12.5-74
Methanol	385	725	6.7-36

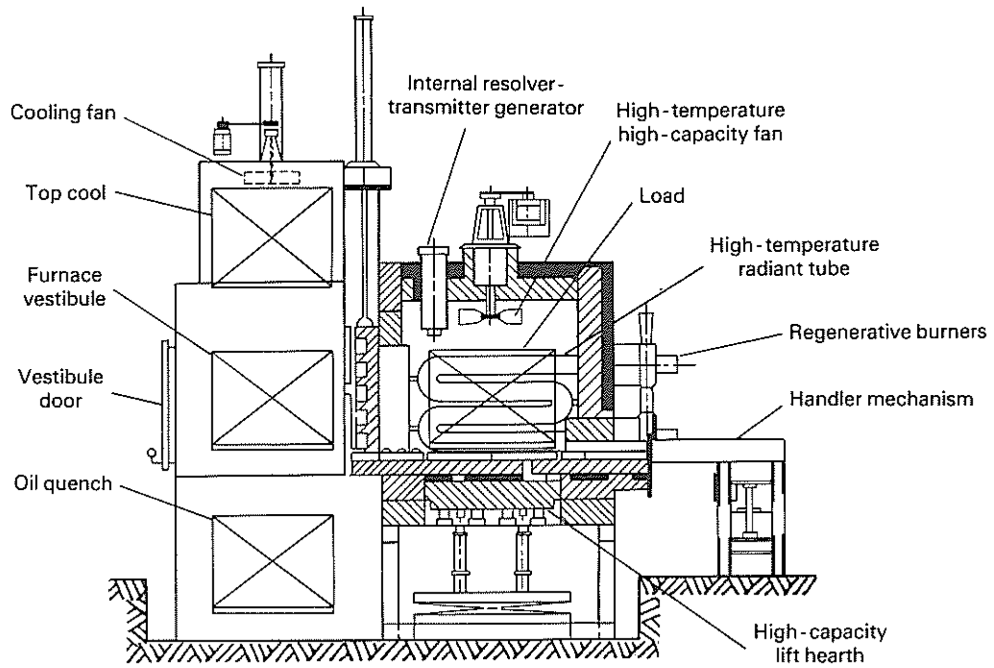
Plot of stress relief versus tempering temperatures held for 1 h for two carbon concentrations in austenite



A pit batch carburizing furnace. Dashed lines outline location of workload.



A high-productivity gas-fired integral quench furnace



- The manner in which parts are stacked or fixtured in carburizing and quenching
- Severity of quenching

Quenchants include brine or caustic solutions, aqueous polymers, oils, and molten salt.

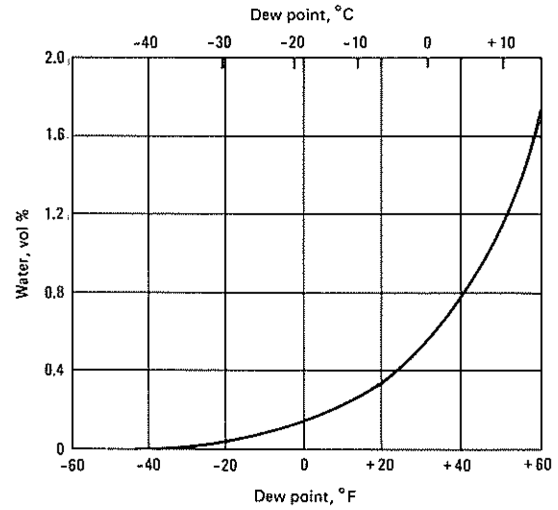
In some industries, parts are carburized at 927 °C (1700 °F) or above, cooled slowly to ambient temperature, then reheated at 843 °C (1550 °F), then quenched. Benefits include refinement in microstructure and limiting the amount of retained austenite in the case.

Tempering. Density changes during tempering affect the relief of residual stresses produced in carburizing. An adjoining Figure shows the effect of tempering for 1 h at various temperatures on stress relief. Stress relief occurs at lower tempering temperatures as the amount of carbon dissolved in austenite is increased.

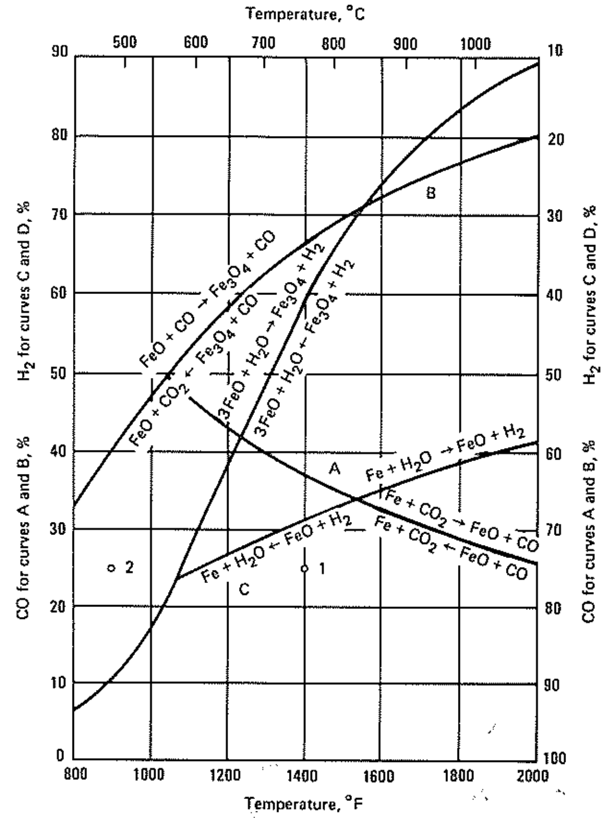
Selective Carburizing. Some gears, for example, are carburized only on teeth, splines, and bearing surfaces. Stopoffs include copper plating and ceramic coatings.

Safety Precautions. The atmospheres used are highly toxic and highly inflammable. When combined with air, explosive gas mixtures are

Relation Between Dew Point and Moisture Content of Gases. Hydrogen can be purified by a room-temperature catalytic reaction that combines oxygen with hydrogen, forming water. Then, all water vapor is removed by drying to a dew point of −60 °F (−51 °C).



Iron Oxides from CO_2 or H_2O. Data point 1: an atmosphere consisting of 75 H_2 and 25 H_2O will reduce scale on iron (FeO or Fe_3O_4) at 1400 °F (760 °C). Data point 2: same atmosphere will scale metal at 900 °F (480 °C)

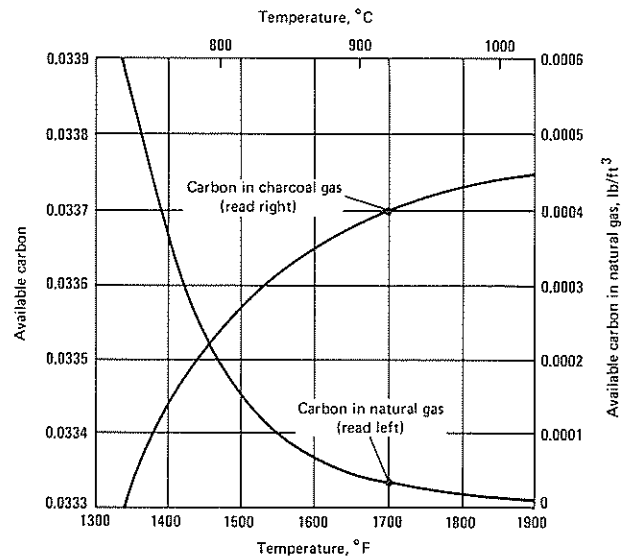


Composition of Carburizing Steels

Steel	Composition, % C	Mn	Ni	Cr	Mo	Other
Carbon steels						
1010	0.08-0.13	0.30-0.60	...	...	...	(a), (b)
1018	0.15-0.20	0.60-0.90	...	...	...	(a), (b)
1019	0.15-0.20	0.70-1.00	...	...	...	(a), (b)
1020	0.18-0.23	0.30-0.60	...	...	...	(a), (b)
1021	0.18-0.23	0.60-0.90	...	...	...	(a), (b)
1022	0.18-0.23	0.70-1.00	...	...	...	(a), (b)
1524	0.19-0.25	1.35-1.65	...	...	...	(a), (b)
1527	0.22-0.29	1.20-1.50	...	...	...	(a), (b)
Resulfurized steels						
1117	0.14-0.20	1.00-1.30	...	...	...	0.08-0.13 S
Alloy steels						
3310	0.08-0.13	0.45-0.60	3.25-3.75	1.40-1.75	...	(b), (c)
4023	0.20-0.25	0.70-0.90	...	...	0.20-0.30	(b), (c)
4027	0.25-0.30	0.70-0.90	...	...	0.20-0.30	(b), (c)
4118	0.18-0.23	0.70-0.90	...	0.40-0.60	0.08-0.15	(b), (c)
4320	0.17-0.22	0.45-0.65	1.65-2.00	0.40-0.60	0.20-0.30	(b), (c)
4620	0.17-0.22	0.45-0.65	1.65-2.00	...	0.20-0.30	(b), (c)
4815	0.13-0.18	0.40-0.60	3.25-3.75	...	0.20-0.30	(b), (c)
4820	0.18-0.23	0.50-0.70	3.25-3.75	...	0.20-0.30	(b), (c)
5120	0.17-0.22	0.70-0.90	...	0.70-0.90	...	(b), (c)
5130	0.28-0.33	0.70-0.90	...	0.80-1.10	...	(b), (c)
8617	0.15-0.20	0.70-0.90	0.40-0.70	0.40-0.60	0.15-0.25	(b), (c)
8620	0.18-0.23	0.70-0.90	0.40-0.70	0.40-0.60	0.15-0.25	(b), (c)
8720	0.18-0.23	0.70-0.90	0.40-0.70	0.40-0.60	0.20-0.30	(b), (c)
8822	0.20-0.25	0.75-1.00	0.40-0.70	0.40-0.60	0.30-0.40	(b), (c)
9310	0.08-0.13	0.45-0.65	3.00-3.50	1.00-1.40	0.08-0.15	(b), (c)
Special alloys						
CBS-600	0.16-0.22	0.40-0.70	...	1.25-1.65	0.90-1.10	0.90-1.25 Si
CBS-1000M	0.10-0.16	0.40-0.60	2.75-3.25	0.90-1.20	4.00-5.00	0.40-0.60 Si
Alloy 53	0.10	0.35	2.00	1.00	3.25	0.15-0.25 V 1.00 Si, 2.00 Cu, 0.10 V

(a) 0.004 P max, 0.05 S max. (b) 0.15-0.35 Si. (c) 0.035 P max, 0.04 S max

Available Carbon (the Weight of Carbon Obtained for Carburizing from a Given Gas at a Given Temperature). Charcoal gas analyzes 20 CO, 80 N_2. Natural gas is principally methane. Data point 1: at 1700 °F (925 °C), the available carbon in charcoal gas is 0.0000272 lb/ft³ (0.004357 kg/m³). Data point 2: in natural gas, there is 1200 times as much or 0.0337 lb/ft³ (0.5398 kg/m³)



formed. Properties of air-combustible gas mixtures are given in an adjoining Table.

Carburizing Equipment. Both batch and continuous furnaces are used. Among batch types, pit and horizontal furnaces are the most common in service. A pit furnace is illustrated in an adjoining Figure. A disadvantage of the pit type is that when parts are direct quenched, they must be moved in air to the quenching equipment. The adherent black scale developed on parts with this practice may have to be removed by shot blasting or acid pickling. Horizontal batch furnaces with integral quenching facilities are an alternative (see Figure).

Continuous furnaces used in carburizing include mesh belt, shaker hearth, rotary retort, rotary hearth, roller hearth, and pusher types.

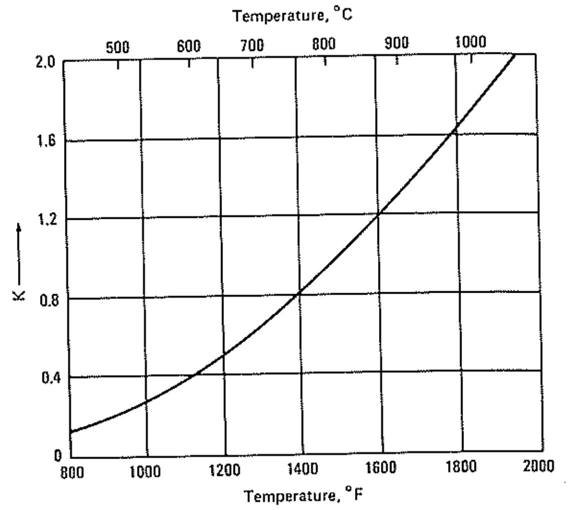
Applications

Carbon steel, resulfurized steel, and alloy steel applications are listed in an adjoining Table.

Reference

1. *ASM Metals Handbook, Heat Treating,* Vol 4, 10th ed., ASM International, 1991, p 312

Water Gas Reaction, $CO + H_2O \leftrightarrow CO_2 + H_2$. Variation of equilibrium constant K with temperature. K is independent of pressure, since there is no volume change in this reaction.



Pack Carburizing

In this process, carbon monoxide derived from a solid compound decomposes at the metal surface into nascent carbon and carbon dioxide. Carbon is absorbed into the metal; carbon dioxide immediately reacts with carbonaceous material in the solid carburizing compound to produce fresh carbon monoxide. Carbon monoxide formation is enhanced by energizers or catalysts such as barium carbonate, calcium carbonate, potassium carbonate, and sodium carbonate present in the carburizing compound. Energizers facilitate the reduction of carbon dioxide with carbon to form carbon monoxide, Ref 1.

Characteristics

Both gas carburizing and liquid carburizing have labor cost advantages over this process. This disadvantage may be offset in jobs requiring additional steps, such as cleaning and the application of protective coatings in carburizing stopoff operations.

Other considerations favor pack carburizing:

- A wide variety of furnaces may be used because the process produces its own contained environment
- It is ideally suited for slow cooling from the carburizing temperature
- It offers a wider selection of stopoff techniques than gas carburizing for selective carburizing techniques

On the other side of the ledger, pack carburizing is less clean and less convenient to use than the other carburizing processes. In addition:

- It isn't well suited for shallow case depths where depth tolerances are strict
- It is labor intensive
- It takes more processing time than gas or liquid carburizing because of the heating time and cooling time required by the extra thermal mass associated with the solid carburizing compound and the metal container used
- It isn't suited for direct quenching or quenching in dies

Operating Information

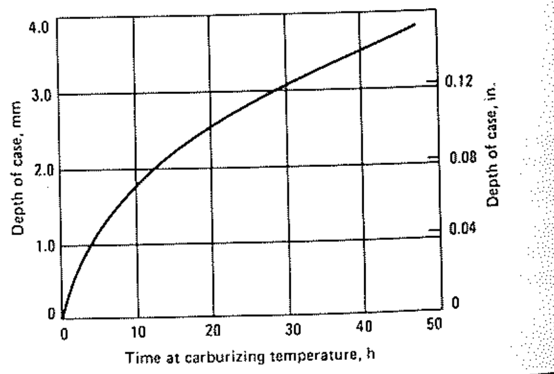
The common commercial carburizing compounds are reusable and contain 10 to 20 percent alkali or alkaline earth metal carbonates bound to hardwood charcoal, or to coke by oil, tar, or molasses. Barium carbonate is the chief energizer, usually accounting for 50 to 70 percent of total carbonate content.

Process Control. Two parameters are unique to the process:

- Case depth may vary within a given furnace due to dissimilar thermal histories within the carburizing containers
- Distortion of parts during carburizing may be reduced because compound can be used to support workpieces

Carbon potential of the atmosphere generated by the compound, as well as the carbon content obtained at the surface of the work, increase directly with an increase in the ratio of carbon monoxide to carbon dioxide.

Effect of time on case depth at 925 °C (1700 °F)



Typical Applications of Pack Carburizing

Part	Dimensions(a)				Weight		Steel	Carburizing			
	OD		OA					Case depth to 50 HRC		Temperature	
	mm	in.	mm	in.	kg	lb		mm	in.	°C	°F
Mine-loader bevel gear	102	4.0	76	3.0	1.4	3.1	2317	0.6	0.024	925	1700
Flying-shear timing gear	216	8.5	92	3.6	23.6	52.0	2317	0.9	0.036	900	1650
Crane-cable drum	603	23.7	2565	101.0	1792	3950	1020	1.2	0.048	955	1750
High-misalignment coupling gear	305	12.0	152	6.0	38.5	84.9	4617	1.2	0.048	925	1700
Continuous-miner drive pinion	127	5.0	127	5.0	5.4	11.9	2317	1.8	0.072	925	1700
Heavy-duty industrial gear	618	24.3	102	4.0	150	331	1022	1.8	0.072	940	1725
Motor-brake wheel	457	18.0	225	8.9	104	229	1020	3.0	0.120	925	1700
High-performance crane wheel	660	26.0	152	6.0	335	739	1035	3.8	0.150	940	1725
Calender bull gear	2159	85.0	610	24.0	5885	12 975	1025	4.0	0.160	955	1750
Kiln-trunnion roller	762	30.0	406	16.0	1035	2280	1030	4.0	0.160	940	1725
Leveler roll	95	3.7	794	31.3	36.7	80.9	3115	4.0	0.160	925	1700
Blooming-mill screw	381	15.0	3327	131.0	2950	6505	3115	5.0	0.200	925	1700
Heavy-duty rolling-mill gear	914	36.0	4038	159.0	11 800	26 015	2325	5.6	0.220	955	1750
Processor pinch roll	229	9.0	5385	212.0	1700	3750	8620	6.9	0.270	1050	1925

(a) OD, outside diameter; OA, overall (axial) dimension

Operating temperatures normally run from 815 to 955 °C (1500 to 1750 °F). However, temperatures as high as 1095 °C (2005 °F) are used.

The rate of change in case depth at a given temperature is proportional to the square root of time. This means the rate of carburization is highest at the beginning of the cycle and gradually diminishes as the cycle continues.

Case Depth. Even with good process control, it is difficult to hold case depth variation below 0.25 mm (0.010 in.) from maximum to minimum in a given furnace load, assuming a carburizing temperature of 925 °C (1695 °F). The effect of time on case depth is shown in an adjoining Figure.

Furnaces are commonly of the box, car bottom, and pit types. Temperature uniformity must be controllable within ±5 °C (±99 °F).

Containers normally are made of carbon steel, aluminum coated carbon steel, or iron-nickel-chromium, heat-resisting alloys.

Packing. Intimate contact between compound and workpiece is not necessary, but with proper packing the compound provides good support for workpieces.

Applications

Typical applications for pack carburizing are listed in the adjoining Table.

Reference

1. *ASM Metals Handbook, Heat Treating,* Vol 4, 10th ed., ASM International, 1991, p 325

Liquid Carburizing and Cyaniding

Both are salt bath processes. In liquid carburizing, cyanide or noncyanide salt baths are used. Cyaniding is a liquid carbonitriding process. It differs from liquid carburizing because it requires a higher percentage of cyanide and the composition of the case produced is different. Cases produced in the carburizing process are lower in nitrogen and higher in carbon than cases produced in cyaniding. Cyanide cases are seldom deeper than 0.25 mm (0.010 in.); carburizing cases can be as deep as 6.35 mm (0.250 in.). For very thin cases, low-temperature liquid carburizing baths may be used in place of cyaniding, Ref 1.

Liquid carburizing. Parts are held at a temperature above Ac_1 in a molten salt that introduces carbon and nitrogen, or carbon, into the metal being treated. Diffusion of the carbon from the surface toward the interior produces a case that can be hardened, usually by fast quenching, from the bath.

Cyaniding. In this process, steel is heated above Ac_1 in a bath containing alkali cyanides and cyanates, and its surfaces absorb both carbon and nitrogen from the molten bath.

Compositions and Properties of Sodium Cyanide Mixtures

Mixture grade designation	Composition, wt %			Melting point		Specific gravity	
	NaCN	$NaCO_3$	NaCl	°C	°F	25 °C (75 °F)	860 °C (1580 °F)
96-98(a)	97	2.3	Trace	560	1040	1.50	1.10
75(b)	75	3.5	21.5	590	1095	1.60	1.25
45(b)	45.3	37.0	17.7	570	1060	1.80	1.40
30(b)	30.0	40.0	30.0	625	1155	2.09	1.54

(a) Appearance: white crystalline solid. This grade contains 0.5% sodium cyanate (NaNCO) and 0.2% sodium hydroxide (NaOH); sodium sulfide (Na_2S) content, nil. (b) Appearance: white granular mixture

pical Applications of Liquid Carburizing In Cyanide Baths

rt	Weight kg	Weight lb	Steel	Depth of case mm	Depth of case in.	Temperature °C	Temperature °F	Time, h	Quench	Subsequent treatment	Hardness, HRC
rbon steel											
apter	0.9	2	CR	1.0	0.040	940	1720	4	AC	(a)	62-63
ɔor, tapered	0.5	1.1	1020	1.5	0.060	940	1720	6.5	AC	(a)	62-63
shing	0.7	1.5	CR	1.5	0.060	940	1720	6.5	AC	(a)	62-63
: block	3.5	7.7	1020	1.3	0.050	940	1720	5	AC	(a)	62-63
	1.1	2.5	CR	1.3	0.050	940	1720	5	AC	(a)	59-61
;k	1.4	3	1020	1.3	0.050	940	1720	5	(b)	(b)	56-57
ınge	0.03	0.06	1020	0.4-0.5	0.015-0.020	845	1550	4	Oil	(c)	55 min(d)
ge rings, knurled	0.09	0.2	1020	1.5	0.060	940	1720	6.5	AC	(a)	62-63
ld-down block	0.9	2	CR	1.0	0.040	940	1720	4	AC	(a)	62-63
ert, tapered	4.75	10.5	1020	1.3	0.050	940	1720	5	AC	(a)	62-63
ver	0.05	0.12	1020	0.13-0.25	0.005-0.010	845	1550	1	Oil	(c)	(e)
ık	0.007	0.015	1018	0.13-0.25	0.005-0.010	845	1550	1	AC	...	...
ıte	0.007	0.015	1010	0.25-0.4	0.010-0.015	845	1550	2	Oil	(c)	(e)
ıg	0.7	1.6	CR	1.5	0.060	940	1720	6.5	AC	(a)	62-63
ıg gage	0.45	1	1020	1.5	0.060	940	1720	6.5	AC	(a)	62-63
dius-cutout roll	7.7	17	CR	1.5	0.060	940	1720	6.5	AC	(a)	62-63
rsion-bar cap	0.05	0.1	1022	0.02-0.05	0.001-0.002	900	1650	0.12	Caustic	(f)	45-47
sulfurized steel											
shing	0.04	0.09	1118	0.25-0.4	0.010-0.015	845	1550	2	Oil	(c)	(e)
sh sleeve	3.6	8	1117	1.1	0.045	915	1675	7	AC	(g)	58-63
;k	0.0009	0.002	1118	0.13-0.25	0.005-0.010	845	1550	1	Brine	(c)	(e)
ive shaft	3.6	8	1117	1.1	0.045	915	1675	7	AC	(h)	58-63
ıide bushing	0.2	0.5	1117	0.75	0.030	915	1675	5	(j)	...	58-63
ıt	0.04	0.09	1113	0.13-0.25	0.005-0.010	845	1550	1	Oil	(c)	(e)
ı	0.003	0.007	1119	0.13-0.25	0.005-0.010	845	1550	1	Oil	(c)	(e)
ıg	0.007	0.015	1113	0.075-0.13	0.003-0.005	845	1550	0.5	Oil	(c)	(e)
ck	0.34	0.75	1113	0.13-0.25	0.005-0.010	845	1550	1	Oil	(c)	(e)
ıller	0.01	0.03	1118	0.25-0.4	0.010-0.015	845	1550	2	Oil	(c)	(e)
rew	0.003	0.007	1113	0.075-0.13	0.003-0.005	845	1550	0.5	Oil	(c)	(e)
aft	0.08	0.18	1118	0.25-0.4	0.010-0.015	845	1550	2	Oil	(c)	(e)
ring seat	0.009	0.02	1118	0.25-0.4	0.010-0.015	845	1550	2	Oil	(c)	(e)
ɔp collar	0.9	2	1117	1.1	0.045	925	1700	6.5	AC	(g)	60-63
ıd	0.007	0.015	1118	0.13-0.25	0.005-0.010	845	1550	1	Oil	(c)	(e)
ılve bushing	0.02	0.05	1117	1.3	0.050	915	1675	8	AC	(g)	58-63
ılve retainer	0.45	1	1117	1.1	0.045	915	1675	7	(j)	...	58-63
asher	0.007	0.015	1118	0.25-0.4	0.010-0.015	845	1550	2	Oil	(c)	(e)
loy steel											
:aring races	0.9-36	2-80	8620	2.3	0.090	925	1700	14	AC	(g)	61-64
:aring rollers	0.20	0.5	8620	2.3	0.090	925	1700	14	AC	(g)	61-64
ɔupling	0.03	0.06	8620	0.25-0.4	0.010-0.015	845	1550	2	Oil	(c)	(e)
:ankshaft	0.9	2	8620	1.0	0.040	915	1675	6.5	AC	(h)	60-63
:ar	0.34	0.75	8620	1.0	0.040	915	1675	6	AC	(g)	60-63
	0.03	0.06	8620	0.075-0.13	0.003-0.005	845	1550	0.5	Oil	(c)	(e)
ler shaft	0.45	1	8620	0.75	0.030	915	1675	5	(i)	...	58-63
ntle	4.5-86	10-190	8620	1.5	0.060	925	1700	12	(i)	...	58-63
ston	0.20	0.5	8620	1.3	0.050	915	1675	8	AC	(g)	60-63
unger	0.45-82	1-180	8620	1.3	0.050	915	1675	8	(i)	...	58-63
am	2.3-23	5-50	8620	1.1	0.045	915	1675	7	(i)	...	58-63
etainer	0.0009	0.002	9317	0.1-0.2	0.004-0.008	845	1550	0.33	Oil	(j)	(e)
ɔool	0.45-54	1-120	8620	1.3	0.050	925	1700	7	(i)	...	58-63
hrust cup	0.20	0.5	8620	1.1	0.045	915	1675	7	(i)	...	58-63
hrust plate	5.4	12	8620	2.3	0.090	925	1700	14	AC	(g)	60-64
niversal socket	1.8	4	8620	1.5	0.060	915	1675	10	AC	(g)	58-63
alve	0.01	0.03	8620	0.4-0.5	0.015-0.020	845	1550	4	Oil	(j)	60 min(d)
alve seat	0.20	0.5	8620	1.1	0.045	915	1675	7	AC	(g)	60-63
/ear plate	0.45-3.6	1-8	8620	1.3	0.050	915	1675	7	AC	(g)	60-63

ı) Reheated at 790 °C (1450 °F), quenched in caustic, tempered at 150 °C (300 °F). (b) Transferred to neutral salt at 790 °C (1450 °F), quenched in caustic, tempered at 175 °C (350 ᵋF). (c) Tempered at 165 °C (325 °F). (d) Or equivalent. (e) File-hard. (f) Tempered at 205 °C (400 °F). (g) Reheated at 845 °C (1550 °F), quenched in salt at 175 °C (350 °F). (h) eheated at 775 °C (1425 °F), quenched in salt at 195 °C (380 °F). (i) Quenched directly in salt at 175 °C (350 °F). (j) Tempered at 165 °C (325 °F) and treated at –85 °C (–120 °F)

Liquid Carburizing

Characteristics

The case produced is comparable to one obtained in gas carburizing in an atmosphere containing some ammonia. In addition, cycle times are shorter because heat up is faster, due to the excellent heat transfer characteristics of the salt bath solution.

Operating Information

Most of these baths contain cyanide. Both nitrogen and carbon are introduced into the case. A noncyanide process uses a special grade of carbon, rather than cyanide, as the source of carbon. These cases contain only carbon as the hardening agent.

Low-temperature (for light cases) and high-temperature (for deep cases), cyanide-containing carburizing baths are available. In addition to operating temperatures, cycle times can also be different.

Low-Temperature Baths. Typical operating temperatures range from 845 to 900 °C (1555 to 1650 °F). Baths generally are of the accelerated cyanogen type. Operating compositions of liquid carburizing baths are listed in Table 1. Baths usually are operated with a protective carbon cover. Cases that are 0.13 to 0.25 mm (0.005 to 0.010 in.) deep contain substantial amounts of nitrogen.

High-Temperature Baths. Operating temperatures usually are in the range of 900 to 955 °C (1650 to 1750 °F). Rapid carbon penetration may be obtained at operating temperatures between 980 and 1040 °C (1795 to 1905 °F). Cases range from 0.5 to 3.0 mm (0.020 to 0.120 in.) deep. The most important application of this process is for the rapid development of cases 1 to 2 mm (0.040 to 0.080 in.) deep. These baths contain cyanide and a major amount of barium chloride (see Table).

Applications

Typical applications of liquid carburizing in cyanide baths are listed in an adjoining Table.

Operating Compositions of Liquid Carburizing Baths

Constituent	Composition of bath, %: Light case, low temperature 845-900 °C (1550-1650 °F)	Composition of bath, %: Deep case, high temperature 900-955 °C (1650-1750 °F)
Sodium cyanide	10-23	6-16
Barium chloride	...	30-55(a)
Salts of other alkaline earth metals(b)	0-10	0-10
Potassium chloride	0-25	0-20
Sodium chloride	20-40	0-20
Sodium carbonate	30 max	30 max
Accelerators other than those involving compounds of alkaline earth metals(c)	0-5	0-2
Sodium cyanate	1.0 max	0.5 max
Density of molten salt	1.76 g/cm³ at 900 °C (0.0636 lb/in.³ at 1650 °F)	2.00 g/cm³ at 925 °C (0.0723 lb/in.³ at 1700 °F)

(a) Proprietary barium chloride-free deep-case baths are available. (b) Calcium and strontium chlorides have been employed. Calcium chloride is more effective, but its hygroscopic nature has limited its use. (c) Among these accelerators are manganese dioxide, boron oxide, sodium fluoride, and sodium pyrophosphate.

Effect of Sodium Cyanide Concentration on Case Depth in 1020 Steel Bars

Samples are 25.4 mm diam (1.0 in. diam) bars that were cyanided 30 min at 815 °C (1500 °F).

NaCN in bath, %	Depth of case mm	Depth of case in.
94.3	0.15	0.0060
76.0	0.18	0.0070
50.8	0.15	0.0060
43.0	0.15	0.0060
30.2	0.15	0.0060
20.8	0.14	0.0055
15.1	0.13	0.0050
10.8	0.10	0.0040
5.2	0.05	0.0020

Noncyanide Liquid Carburizing

A special grade of carbon is used in place of cyanide as the source for carbon. Carbon particles are dispersed in the molten salt by mechanical agitation with one or more simple propeller stirrers. The chemical reaction is thought to be adsorption of carbon monoxide on carbon particles. Carbon monoxide is generated by a reaction between carbon and carbonates in the salt bath. Carbon monoxide is presumed to react with steel surfaces in a manner similar to that in pack carburizing.

Operating Information

Operating temperatures usually are higher than those for cyanide-type baths. The common range is about 900 to 955 °C (1650 to 1750 °F). Case depths and carbon gradients are in the same range as those for high-temperature, cyanide-type salts. Carbon content is slightly lower than that of standard carburizing baths containing cyanide.

Faster carbon penetration is obtained by using operating temperatures above 950 °C (1740 °F). Noncyanide baths are not adversely affected at this temperature because no cyanide is present to break down and cause carbon scum or frothing. Parts quenched after treatment contain less retained austenite than those quenched following cyanide carburization.

Applications

Typical applications of liquid carburizing in noncyanide baths are listed in an adjoining Table.

Cyaniding (Liquid Carbonitriding)

Operating Information

In this instance, sodium cyanide is used instead of the more expensive potassium cyanide. The active hardening agents (carbon monoxide and nitrogen) are produced directly from sodium cyanide.

A sodium cyanide mixture such as grade 30 (containing 30 percent NaCN, 40 percent Na_2CO_3, and 30 percent NaCl) generally is the choice for production applications (see Table showing compositions). A 30 percent cyanide bath operating at 815 to 850 °C (1500 to 1560 °F) produces a 0.13 mm (0.005 in.) case containing 0.65 percent carbon at the surface in min. Similar case depths can be obtained with sodium cyanide in ting 1020 steel. The effect of sodium cyanide on case depth in treating steel is in an adjoining Table.

plications

file hard, wear-resistant surface is produced on ferrous parts. The hard e is produced in quenching in mineral oil, paraffin-base oils, water, or brine. The case contains less carbon and more nitrogen than those developed in liquid carburizing.

Reference

1. *ASM Metals Handbook, Heat Treating,* Vol 4, 10th ed., ASM International, 1991, p 329

acuum Carburizing

n this process, steel is austenitized in a rough vacuum, carburized in a tial pressure of hydrocarbon gas, diffused in a rough vacuum, then enched in oil or gas, Ref 1.

haracteristics

Benefits of the process include:

- Excellent uniformity and repeatability due to the degree of process control inherent in the process
- mproved mechanical properties due to a lack of intergranular oxidation
- Reduced cycle times due to higher processing temperatures

Operating Information

A continuous vacuum carburizing furnace is pictured in an adjoining Figure. Furnaces usually are designed for vacuum carburizing, with or without vacuum quenching capability. Controls and plumbing are modified to accommodate the process.

Heat and Soak Step. Steel is first heated to the desired carburizing temperature (typically in the range of 845 to 1040 °C (1555 to 1905 °F). Soaking follows at that temperature, but only long enough to get temperature uniformity throughout the part.

In this step, surface oxidation must be prevented, and any surface oxides present must be reduced. In a graphite-lined heating chamber with graphite heating elements, for example, a rough vacuum in the range of 13 to 40 Pa (0.1 to 0.3 torr) usually is satisfactory.

Boost Step. The result here is carbon absorption by the austenite to the limit of carbon solubility in austenite at the processing temperature for the steel being treated. The operation in this instance is backfilling the vacuum chamber to a partial pressure with either a pure hydrocarbon gas, such as methane or propane, or a mixture of hydrocarbon gases.

A minimum partial pressure of the gas is needed to ensure rapid carburizing of the austenite. Minimum partial pressure varies with carburizing temperature, gas composition, and furnace construction. Typical partial pressures vary between 1.3 and 6.6 kPa (10 to 150 torr) in furnaces of graphite construction and 13 to 25 kPa (100 to 200 torr) in furnaces of ceramic construction.

Diffusion Step. In this instance, carbon is diffused inward from the carburized surface, resulting in a lower surface carbon content (relative to the limit of carbon solubility in austenite at the carburizing temperature) and a more gradual case/core transition. Diffusion usually is in a rough vacuum of 67 to 135 kPa (0.5 to 1.0 torr) at the carburizing temperature.

Oil Quenching Step. Steel is directly quenched in oil, usually under a partial pressure of nitrogen.

When temperatures are higher than those in conventional atmosphere carburizing, requirements usually call for cooling to a lower temperature and stabilizing at that temperature prior to quenching.

If a reheating step is needed for grain refinement, the steel is gas quenched from the diffusion temperature to room temperature, usually under partial pressure of nitrogen. Reheating usually consists of austenitizing in the range of 790 to 845 °C (1455 to 1555 °F), followed by oil quenching.

Carburizing Gas Circulation. For uniform case depths the chief requirements are:

- Temperature uniformity of ±8 °C (±14 °F) or better
- Uniform circulation of carburizing gas

High-Temperature Vacuum Carburizing

Typical atmosphere furnace construction generally limits maximum carburizing temperatures to about 955 °C (1750 °F). Vacuum furnaces permit higher carburizing temperatures, with correspondingly reduced cycle times.

The process can significantly reduce overall cycle times required to get effective case depths in excess of 0.9 to 1.0 mm (0.030 to 0.040 in.). There is no advantage for lower case depths. In an adjoining Table, the times needed to get 0.9 to 1.0 mm (0.030 to 0.040 in.) case depths with vacuum carburizing at 900 °C (1650 °F) and 1040 °C (1905 °F) for an AISI 8620 steel are compared.

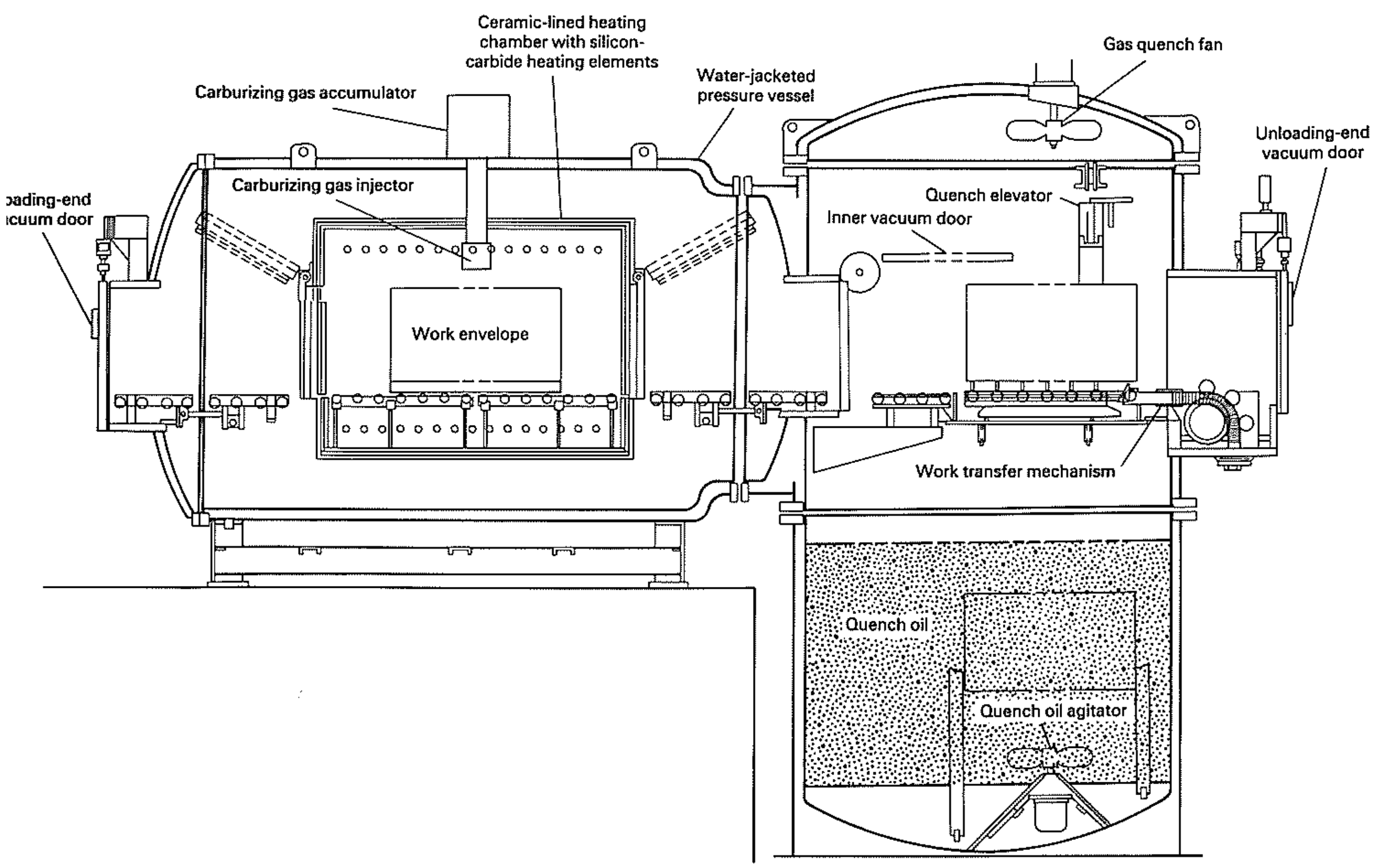
Applications

The process is well suited to process the more highly alloyed, high-performance grades of carburizing steels and the moderately alloyed grades being used. Gas pressure quenching in vacuum opens up opportunities for treating high-performance, low distortion gearing.

Reference

1. *ASM Metals Handbook, Heat Treating,* Vol 4, 10th ed., ASM International, 1991, p 348

continuous ceramic vacuum-carburizing furnace



Comparison of Time Required to Obtain a 0.9 mm (0.035 in.) and 1.3 mm (0.050 in.) Effective Case Depth in an AISI 8620 Steel at Carburizing Temperatures of 900 °C (1650 °F) and 1040 °C (1900 °F)

Effective depth		Carburizing temperature		Time, min								
mm	in.	°C	°F	Heating to carburizing temperature	Soaking prior to carburizing	Boost	Diffusion	Gas quench to 540 °C (1000 °F)	Reheat to 845 °C (1550 °F)	Soak at 845 °C (1550 °F)	Oil quench	Total
0.9	0.035	900	1650	78	45	101	83	(a)	(a)	(a)	15	>322
		1040	1900	90	30	15	23	20	22	60	15	275
1.3	0.050	900	1650	78	45	206	169	(a)	(a)	(a)	15	>513
		1040	1900	90	30	31	46	20	22	60	15	314

(a) Not available

Plasma (Ion) Carburizing

This is basically a vacuum process utilizing glow discharge technology to introduce carbon bearing ions to steel surfaces for subsequent diffusion below the surfaces, Ref 1.

Characteristics

The process has several advantages over gas and atmosphere carburizing:

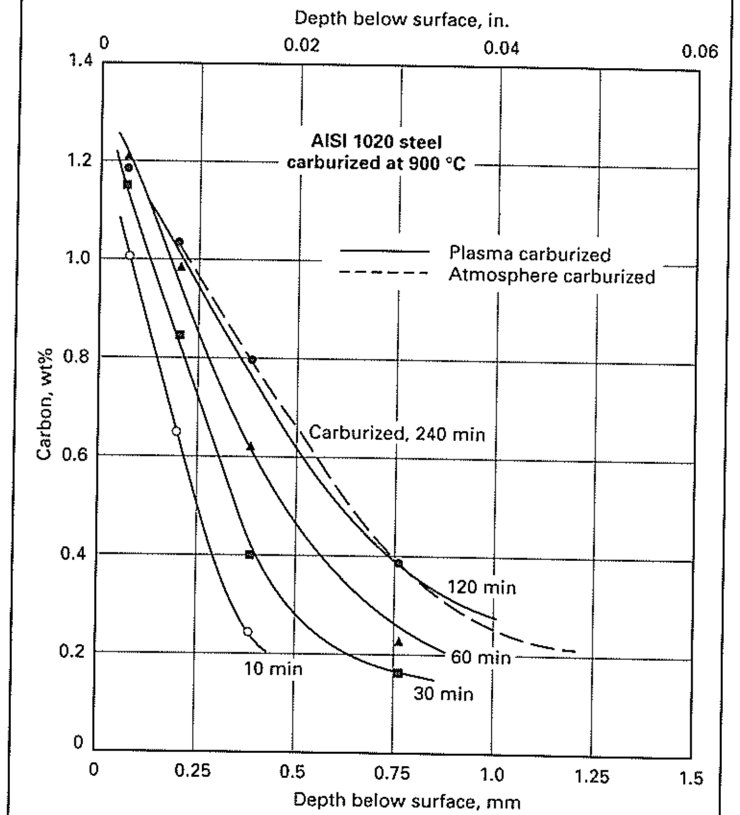
- Higher carburizing rates
- Higher operating temperatures
- Improved case uniformity
- Blind hole penetration
- Insensitivity to steel composition

Carburizing rates are higher because the process involves several steps in the dissociation process that produce active soluble carbon. With methane, for example, active carbon can be formed due to the ionizing effect of the plasma. Carburizing rates of plasma and atmosphere carburizing are compared in an adjoining Figure. Note that the results obtained in atmosphere carburizing for 240 min at 900 °C (1650 °F) were obtained with the plasma process in half the time.

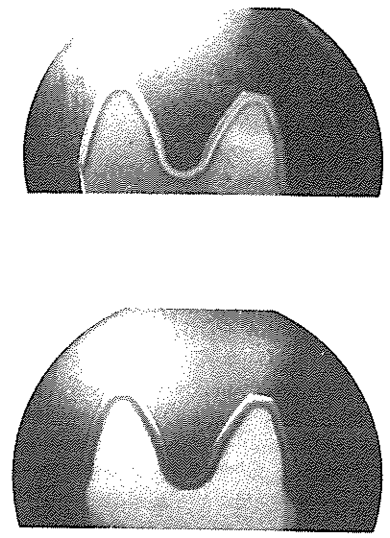
In some applications, higher temperatures are permissible because the process takes place in an oxygen-free vacuum.

Improvements in uniformity of case depth in gear tooth profiles are shown in an adjoining Figure. Results obtained with the plasma process at 980 °C (1795 °F) and those obtained with atmosphere carburizing at the same temperature are compared.

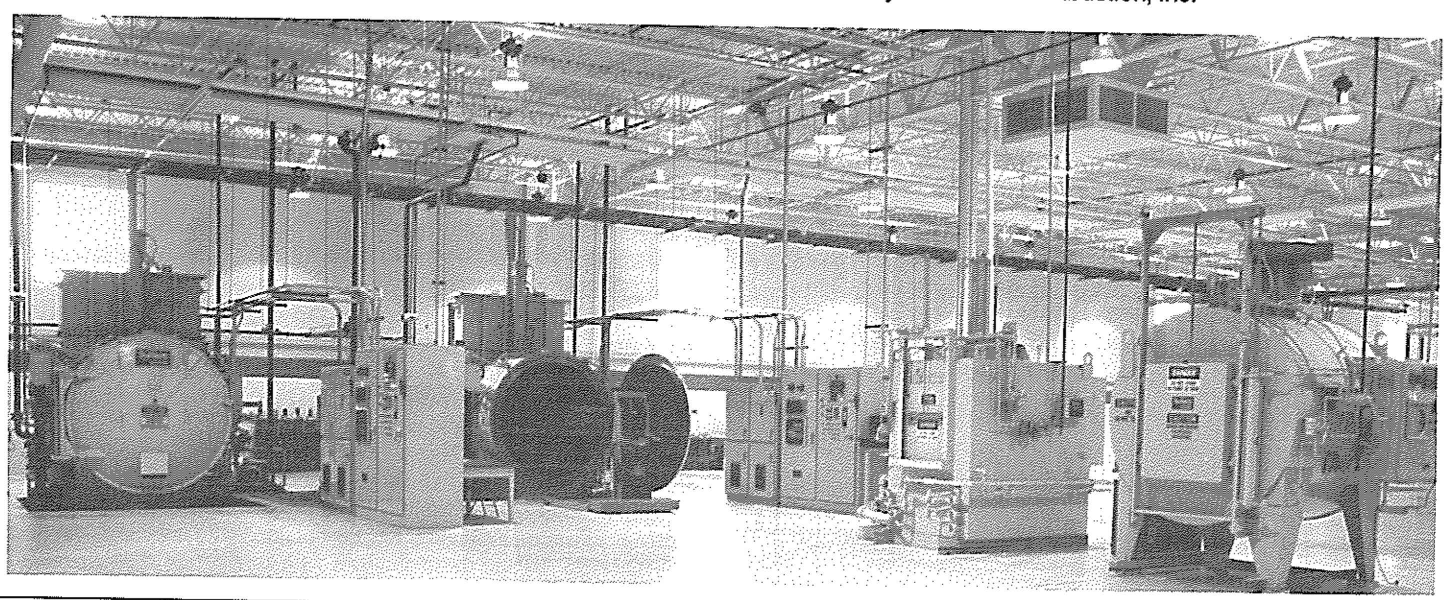
Carbon concentration profiles in AISI 1020 steel after ion carburizing for 10, 20, 30, 60, and 120 min at 900 °C (1650 °F). Carbon profile after atmosphere carburizing for 240 min at 900 °C (1650 °F) shown for comparison



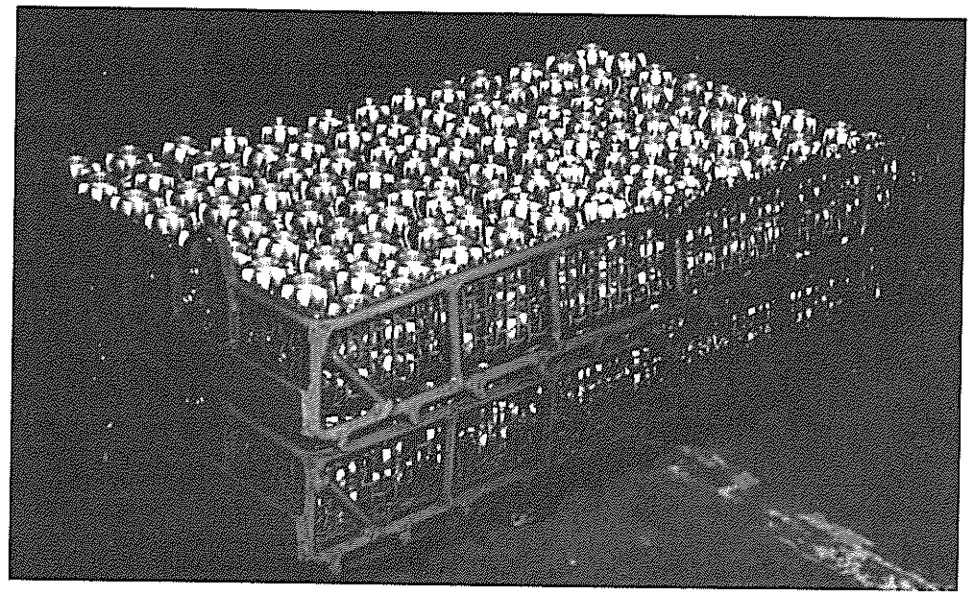
Comparing uniformity of case depth over gear-tooth profiles. (a) Ion carburized at 980 °C (1800 °F). (b) Atmosphere carburized in a 980 °C (1800 °F) boost-diffuse cycle. Case depth in (a) exhibits more consistency, particularly in the root of the gear profile. Courtesy of Surface Combustion, Inc.


(a)
(b)

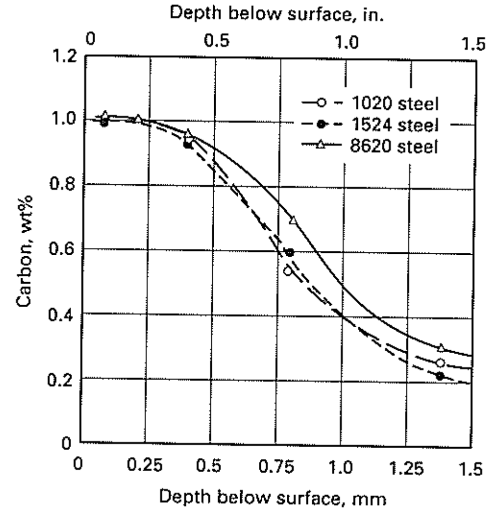
Production installation of two dual-chamber ion carburizing furnaces. Courtesy of Surface Combustion, Inc.



Racked array of universal-joint components ready for ion carburizing. Two stacked fixtures constitute one furnace load of 1500 parts. Courtesy of Dana Corporation



Carbon concentration profiles in three carburizing steels after ion carburizing illustrating insensitivity to steel composition. Data are based on a boost-diffuse cycle of ion carburizing at 1040 °C (1900 °F) for 10 min followed by diffusion for 30 min at 1000 °C (1830 °F).



The ion carburizing rate for a given steel is quite insensitive to alloy composition, as shown in an adjoining Figure. The process is also insensitive to the hydrocarbon gas used as a source of carbon.

A two-chamber ion carburizing furnace is shown in an adjoining Figure.

As in other carburizing processes, time and temperature are the parameters that determine surface carbon and case depth. Temperature, and indirectly time, determine grain size and mechanical properties. Higher operation temperatures are used to speed up diffusion rates.

After a time/temperature cycle is established, operating pressure is chosen, which can be any value, provided the plasma covers the parts and no hollow cathode effect is evident; a low pressure usually is chosen, in the range of 130 to 670 Pa (1 to 5 torr). Optimum uniformity in carburizing is obtained in this range.

The gas may be any hydrocarbon. The simplest and most commonly used is CH_4 (methane). Propane (C_3H_8) is also used.

To be successful in plasma carburizing, the plasma envelope must surround the parts, meaning that parts must be fixtured, or positioned so that they do not touch each other (see Figure). In the figure, gears are stacked in layers separated by a woven wire screen between layers.

Applications

The range of applications includes 1020, 1524, and 8620 steels.

Reference

1. *ASM Metals Handbook, Heat Treating,* Vol 4, 10th ed., ASM International, 1991, p 353

Carbonitriding

This is a modified form of gas carburizing, rather than a form of nitriding. The modification: ammonia is combined with the gas carburizing atmosphere to add nitrogen to the carburized case as it is being produced. Nascent nitrogen is at the work surfaces. Ammonia dissociates in the furnace atmosphere; nitrogen diffuses into the steel simultaneously with carbon, Ref 1.

Characteristics

Carbonitriding is similar to liquid cyaniding in terms of its effects on steel. The process is often substituted for liquid cyaniding because of problems in the disposal of cyanide-bearing water. Case characteristics of carburized and nitrided parts are also different; carburized cases normally do not contain nitrogen, and nitrided cases are primarily nitrogen, while carbonitrided cases contain both carbon and nitrogen.

Ability to produce hard, wear-resistant cases, which are generally in the range of 0.075 to 0.75 mm (0.003 to 0.030 in.), is the typical reason for selecting this process. Cases have better hardenability than carburized types (nitrogen increases the hardenability of steel); nitrogen is also an austenite stabilizer, and high nitrogen levels can result in retained austenite, particularly in alloy steels.

Economies can be realized with carbonitriding and quenching in the production of hard cases within a specific case depth range and for either carbon or low-alloy steel. With oil quenching, full hardness with less distortion can be obtained, or in some cases, with gas quenching, using a protective atmosphere as the quenching medium.

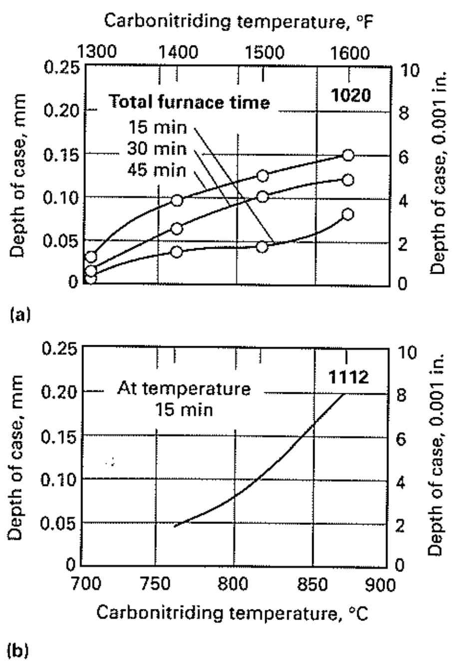
Another plus: carburizing and carbonitriding often are combined to get deeper case depths and better performance in service than are possible with carbonitriding alone.

Effect of Material/Variables on the Possibility of Void Formation in Carbonitrided Cases

Material/processing variables(a)	Possibility of void formation
Temperature increase	Increased
Longer cycles	Increased
Higher case nitrogen levels	Increased
Higher case carbon levels	Increased
Aluminum-killed steel	Increased
Increased alloy content of steel	Decreased
Severe prior cold working of material	Increased
Ammonia addition during heat-up cycle	Increased

(a) All other variables held constant

Effects of temperature and of duration of carbonitriding on effective case depth. Both sets of data were obtained in the same plant. Note that upper graph (for 1020 steel) is in terms of total furnace time, whereas bottom graph (for 1112 steel) is for 15 min at temperature.

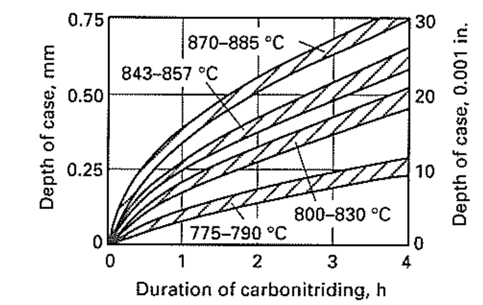


Operating Information

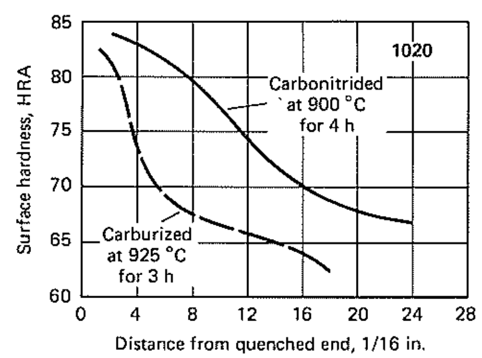
Industrial practice for time and temperature is indicated in an adjoining Figure, which shows the effects of time and temperature on effective depth (as opposed to total case depth).

Effects of total furnace time on the case depth of 1020 steel is shown in adjoining Figure (a). Specimens were heated to 705, 760, 815, and 870 °C

Results of a survey of industrial practice regarding effects of time and temperature on effective case depth of carbonitrided cases



End-quench hardenability curve for 1020 steel carbonitrided at 900 °C (1650 °F) compared with curve for the same steel carburized at 925 °C (1700 °F). Hardness was measured along the surface of the as-quenched hardenability specimen. Ammonia and methane contents of the inlet carbonitriding atmosphere were 5%; balance, carrier gas.

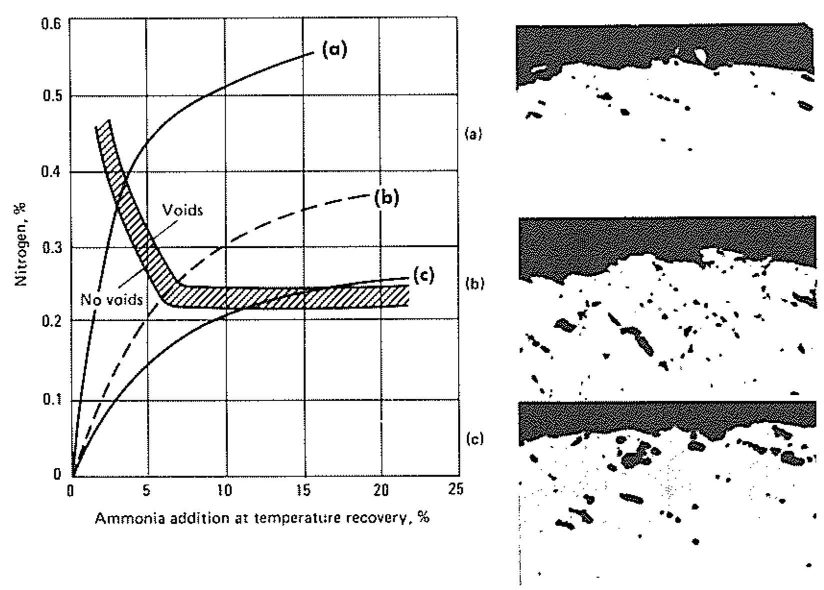


Typical Applications and Production Cycles For Carbonitriding

Part	Steel	Case depth, mm	Case depth, 0.001 in.	Furnace temperature, °C	Furnace temperature, °F	Total time in furnace	Quench
Carbon steels							
Adjusting yoke, 25 by 9.5 mm (1 by 0.37 in.)	1020	0.05-0.15	2-6	775 and 745	1425 and 1375	64 min	Oil
Bearing block, 64 by 32 by 3.2 mm (2.5 by 1.3 by 0.13 in.)	1010	0.05-0.15	2-6	775 and 745	1425 and 1375	64 min	Oil
Cam, 2.3 by 57 by 64 mm (0.1 by 2.25 by 2.5 in.)	1010	0.38-0.45	15-18	855	1575	2½ h	Oil
Cup, 13 g (0.46 oz)	1015	0.08-0.13	3-5	790	1450	½ h	Oil
Distributor drive shaft, 125 mm OD by 127 mm (5 by 5 in.)	1015	0.15-0.25	6-10	815 and 745	1500 and 1375	108 min	Gas(a)
Gear, 44.5 mm diam by 3.2 mm (1.75 by 0.125 in.)	1213(b)	0.30-0.38	12-15	855	1575	1¾ h	Oil(c)
Hex nut, 60.3 by 9.5 mm (2.4 by 0.37 in.)	1030	0.15-0.25	6-10	815 and 745	1500 and 1375	64 min	Oil
Hood-latch bracket, 6.4 mm diam (0.25 in.)	1015	0.05-0.15	2-6	775 and 745	1425 and 1375	64 min	Oil
Link, 2 by 38 by 38 mm (0.079 by 1.5 by 1.5 in.)	1022	0.30-0.38	12-15	855	1575	1½ h	Oil
Mandrel, 40 g (1.41 oz)	1117	0.20-0.30	8-12	845	1550	1½ h	Oil
Paper-cutting tool, 410 mm long	1117	~0.75	~30	...	...	...	...
Segment, 2.3 by 44.5 by 44.5 mm (0.09 by 1.75 by 1.75 in.)	1010	0.38-0.45	15-18	855	1575	2½ h	Oil
Shaft, 4.7 mm diam by 159 mm (0.19 by 6.25 in.)	1213(b)	0.30-0.38	12-15	815	1500	2½ h	Gas(a)(d)
Shift collar, 59 g (2.1 oz)	1118	0.30-0.36	12-14	775	1430	5½ h	Oil(e)
Sliding spur gear, 66.7 mm OD (2.625 in.)	1018	0.38-0.50	15-20	870	1600	2 h(f)	Oil(g)
Spring pin, 14.3 mm OD by 114 mm (0.56 by 4.5 in.)	1030	0.25-0.50	10-20	815 and 745	1500 and 1375	144 min	Oil
Spur pinion shaft, 41.3 mm OD (1.625 in.)	1018	0.38-0.50	15-20	870	1600	2 h(f)	Oil(h)
Transmission shift fork, 127 by 76 mm (5 by 3 in.)	1040	0.25-0.50	10-20	815 and 745	1500 and 1375	162 min	Gas(a)
Alloy steels							
Helical gear, 82 mm OD (3.23 in.)	8617H	0.50-0.75	20-30	845	1550	6 h(f)	Oil(g)
Input shaft, 1.2 kg (2.6 lb)	5140	0.30-0.35	12-14	775	1430	5½ h	Oil(e)
Pinion gear, 0.2 kg (0.44 lb)	4047	0.30-0.35	12-14	775	1430	5½ h	Oil(e)
Ring gear, 0.9 kg (2 lb)	4047	0.20-0.30	8-10	760	1400	9 h	Oil(i)
Segment, 1.4 by 83 mm (0.055 by 3.27 in.)	8617	0.18-0.25	7-10	815	1500	1½ h	Gas(a)
Spur pinion shaft, 63.5 mm OD by 203 mm (2.5 by 8 in.)	5140H	0.05-0.20	2-8	845	1550	1 h(f)	Oil(j)
Stationary gear plate, 0.32 kg (0.7 lb)	5140	0.30-0.35	12-14	775	1430	5½ h	Oil(e)
Transmission main shaft sleeve, 38 mm OD by 25 mm (1.5 by 2 in.)	8622	0.15-0.25	6-10	815 and 745	1500 and 1375	108 min	Gas(a)
Transmission main shaft washer, 57 mm OD by 6.4 mm (2.25 by 0.25 in.)	8620	0.25-0.50	10-20	815 and 745	1500 and 1375	162 min	Gas(a)

(a) Modified carbonitriding atmosphere. (b) Leaded. (c) Tempered at 190 °C (375 °F). (d) Tempered at 150 °C (300 °F). (e) Tempered at 165 °C (325 °F). (f) Time at temperature. (g) Oil at 150 °C (300 °F); tempered at 150 °C (300 °F) for 1 h. (h) oil at 150 °C (300 °F) tempered at 260 °C (500 °F) for 1 h. (i) Tempered at 175 °C (350 °F). (j) Oil at 150 °C (300 °F); tempered at 230 °C (450 °F) for 2 h. OD, outside diameter

Effect of ammonia additions on nitrogen content and formation of subsurface voids in foils. (a) 850 °C (1560 °F) 0.29% CO_2. (b) 925 °C (1695 °F) 0.13% CO_2. (c) 950 °C (1740 °F) 0.10% CO_2



(1300, 1400, 1500, and 1600 °F). An adjoining Figure (b) shows total case depths obtained with 1112 steel held at 15 min at temperatures between 750 and 900 °C (1380 and 1650 °F).

Depth of Case.

- Case depths of 0.025 to 0.075 mm (0.001 to 0.003 in.) commonly are put on thin parts requiring wear resistance under light loads.
- Case depths up to 0.75 mm (0.030 in.) are applied to parts such as cams for resistance to high compressive loads.
- Case depths of 0.63 to 0.75 mm (0.025 to 0.030 in.) are applied to shafts and gears subjected to high tensile or compressive stresses, or contact loads.
- Medium-carbon steel with hardnesses of 40 to 45 HRC normally require less case depth than steels with core hardnesses of 20 HRC or below.
- Low-alloy steels with medium-carbon content, i.e., those used in transmission gears for autos, often have minimum case depths of 0.2 mm (0.008 in.).

Hardenability of Case. Case hardenability is significantly greater when nitrogen is added by carbonitriding than when the same steel is only carburized (see Figure). This opens up the use of steels that could not have uniform hardness if they were only carburized and quenched.

When core properties are not important, carbonitriding permits the use of low-carbon steels that cost less and may provide better machinability or formability.

Because of the hardenability effect of nitrogen, the process makes it possible to oil quench such steels as 1010, 1020, and 1113 to obtain martensitic case structures.

Void Formation. Case structures may contain subsurface voids or porosity if processing conditions are not adjusted properly (see Figure). The problem is related to excessive ammonia additions. Factors that contribute to the problem are summarized in an adjoining Table.

Furnaces. Almost any furnace suitable for gas carburizing can be adapted for carbonitriding.

Atmospheres generally are a mixture of carrier gas, enriching gas, and ammonia. Basically, the required atmosphere can be obtained by adding 2 to 12 percent ammonia to a standard gas-carburizing atmosphere.

Quenching. Whether parts are quenched in water, oil, or gas depends on allowable distortion, metallurgical requirements, case or core hardness, and type of furnace used.

Tempering. Many shallow case parts are used without tempering. Nitrogen in the case increases resistance to softening—the degree depending on the amount of nitrogen in the case.

Applications

Applications are more restricted than those for carburizing. The process is largely limited to case depths of approximately 0.75 mm (0.03 in.). Typical applications and production cycles for a number of steels are listed in an adjoining Table.

On the plus side, resistance to softening during tempering is markedly superior to that of a carburized surface. Other benefits include residual stress patterns, metallurgical structure, fatigue and impact strength at specific hardness levels, and the effects of alloy composition on case and core hardness characteristics. In many applications, properties equivalent to those obtained in carburizing alloy steels can be obtained with less expensive grades of steel.

On the minus side, a carbonitrided case usually contains more retained austenite than a carburized case of the same carbon content. However, the amount of retained austenite can be significantly reduced by cooling quenched parts to –40 to –100 °C (–40 to –150 °F).

P/M Applications. The process is widely used in treating ferrous powder parts. Parts may or may not be copper infiltrated prior to carbonitriding.

The process is effective in case hardening compacts made of electrolytic powders which are difficult to harden by carburizing. To avoid such problems, parts are treated at 790 to 815 °C (1455 to 1500 °F). Lower rates of diffusion at these temperatures permit control of case depth and allow the buildup of adequate carbon in the case. The presence of nitrogen provides sufficient hardenability to allow oil quenching.

File hard cases (with microhardness equivalent to 60 HRC) with predominately martensitic structures can be consistently obtained.

Parts usually are tempered even though there is little danger of cracking untempered pieces. However, there is a reason for tempering: it facilitates tumbling and deburring operations.

Reference

1. *ASM Metals Handbook, Heat Treating,* Vol 4, 10th ed., ASM International, 1991, p 376

Gas Nitriding

In this process, nitrogen is introduced into the surface of a solid ferrous alloy at a temperature below Ac_1 in contact with a nitrogen gas, usually ammonia, Ref 1.

Characteristics

A hard case is produced without quenching. Benefits of the process include:

- High surface hardness
- Improved resistance to wear and galling
- Improved fatigue life
- Improved corrosion resistance (stainless steel is an exception)

In addition, distortion and deformation are less than they are in carburizing and other conventional hardening processes. Best results are obtained with steels containing one or more of the nitride-forming alloying elements—aluminum, chromium, vanadium, tungsten, and molybdenum. Other alloying elements such as nickel, copper, silicon, and manganese have little, if any, effect on nitriding characteristics. Alloys containing 0.85 to 1.50 percent aluminum yield the best results (see Table).

Nitriding downgrades the corrosion resistance of stainless steel because of its chromium content. On the upside, surface hardness is increased and resistance to abrasion is improved.

Operating Information

The nitriding temperature for all steels is 495 to 565 °C (925 to 1050 °F).

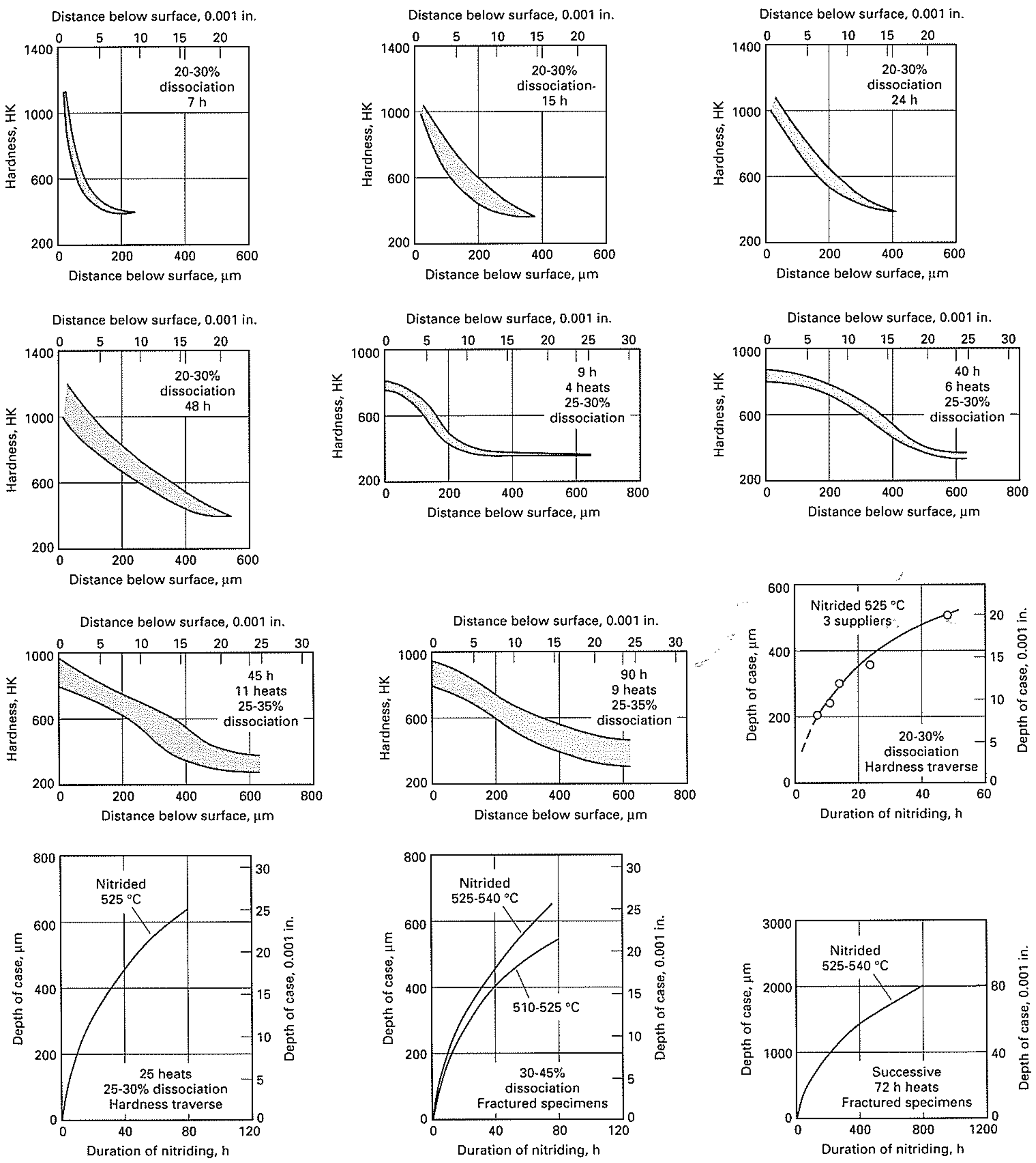
All hardenable steels must be hardened and tempered prior to nitriding. The minimum tempering temperature usually is at least 30 °C (55 °F) above the maximum nitriding temperature.

Either a single- or double-stage process may be used in nitriding with anhydrous ammonia.

The operating temperature of the single-stage process is in the range of about 495 to 525 °C (925 to 975 °F). A brittle, nitrogen-rich layer, called the white layer, is produced on the surface of the case.

Reducing white layer thicknesses is a benefit of the double-stage process—also called the Floe process. Nitriding applications for both processes are listed in an adjoining table. White layers produced in the single- and double-stage processes are compared in an adjoining Figure. Examples of where nitriding eliminates production or service problems with parts case hardened by other methods are found in an adjoining Table.

Hardness gradients and case depth relations for single-stage nitrided aluminum-containing SAE 7140 steel



Nitriding Applications and Procedures

Part	Dimensions or weight of part	Steel	Nitriding time, h
Single-stage nitriding			
Hydraulic barrel	50 mm (2 in.) OD, 19 mm (3/4 in.) ID, 150 mm (6 in.) long	AMS 6470	48
Trigger for pneumatic hammer	...	AMS 6470	40
Governor push button	6 mm (1/4 in.) diam	AMS 6470	30
Tachometer shaft	380 mm (15 in.) long	AMS 6475	25
Helical timing gear	205 mm (8 in.) OD (4.5 kg or 10 lb)	4140	24
Gear	50 mm (2 in.) OD, 6 mm (1/4 in.) thick	4140	24
Generator shaft	25 mm (1 in.) OD, 355 mm (14 in.) long	4140	24
Rotor and pinion for pneumatic drill	22 mm (7/8 in.) diam	4140	9
Sleeve for pneumatic tool clutch	38 mm (1 1/2 in.) diam	4140	9
Marine helical transmission gear	635 mm (25 in.) OD (227 kg or 500 lb)	4142	32
Oil-pump gear	50 mm (2 in.) OD, 180 mm (7 in.) long	4340	25
Loom shuttle	150 mm by 25 mm by 25 mm (6 in. by 1 in. by 1 in.)	410 stainless	8
Double-stage nitriding			
Ring gear for helicopter main transmission	380 mm (15 in.) OD, 350 mm (13.8 in.) ID, 64 mm (2.5 in.) long	AMS 6470(a)	60(b)
Aircraft cylinder barrel	180 mm (7 in.) OD, 305 mm (12 in.) long	AMS 6470	35(c)
Bushing	10 kg (23 lb)	AMS 6470	90
Cutter spindle	3 kg (7 lb)	AMS 6470	45
Plunger	75 mm (3 in.) OD, 1525 mm (60 in.) long	AMS 6475	72
Crankshaft	205 mm (8 in.) OD (journals), 4 m (13 ft) long	4130	65
Piston ring	150 mm (6 in.) OD, 4.25 m (14 ft) long	4130	65
Clutch	1 kg (2 lb)	4140	45
Double helical gear	50 kg (108 lb)	4140	97
Feed screw	4 kg (9 lb)	4140	45
Pumper plunger	0.5 kg (1 lb)	4140	127
Seal ring	9.5 kg (21 lb)	4140	90
Stop pin	3 kg (7 lb)	4140	90
Thrust collar	3.6 kg (8 lb)	4140	90
Wear ring	40 kg (87 lb)	4140	90
Clamp	7 kg (15 lb)	4150	90
Die	21 kg (47 lb)	4340	90
Gib	10 kg (23 lb)	4340	49
Spindle	122 kg (270 lb)	4340	90
Torque gear	62.5 kg (138 lb)	4340	90
Wedge	1.8 kg (4 lb)	4340	42
Pumper plunger	1.4 kg (3 lb)	420 stainless	127

Note: OD, outer diameter; ID, inner diameter. (a) Vacuum melted. (b) 9 h at 525 °C (975 °F), 51 h at 545 to 550 °C (1015 to 1025 °F). (c) 6 h at 525 °C (975 °F), 29 h at 565 °C (1050 °F)

Examples of Parts for Which Nitriding Proved Superior to Other Case-hardening Processes for Meeting Requirements

Part	Requirement	Material and process originally used	
Gear	Good wear surface and fatigue properties	Carburized 3310 steel 0.4 to 0.6 mm (0.017 to 0.025 in.) case	
High-speed pinion (on gear motor)	Provide teeth with minimum (equivalent) hardness of 50 HRC	8620 steel gas carburized at 900 °C (1650 °F) to 0.5 mm (0.02 in.) case, direct quenched from 845 °C (1550 °F), and tempered at 205 °C (400 °F)	
Bushings (for conveyor rollers handling abrasive alkaline material)	High surface hardness for abrasion resistance; resistance to alkaline corrosion	Carburized bushings	
Spur gears (in train of power gears; 10-pitch, tip modified)	Sustain continuous Hertz stress of 1035 MPa (150 ksi) (overload of 1550 MPa, or 225 ksi), continuous Lewis stress of 275 MPa (40 ksi) (overload of 725 MPa, or 105 ksi)(c)	Carburized AMS 6260	
		Resultant problem	**Solution**
Gear	Good wear surface and fatigue properties	Difficulty in obtaining satisfactory case to meet a reliability requirement	AMS 6470 substituted for 3310 and double-stage nitrided for 25 h
High-speed pinion (on gear motor)	Provide teeth with minimum (equivalent) hardness of 50 HRC	Distortion in teeth and bore caused high rejection rate	4140 steel, substituted for 8620, was heat treated to 255 HB; parts were rough machined, finish machined, nitrided(a)
Bushings (for conveyor rollers handling abrasive alkaline material)	High surface hardness for abrasion resistance; resistance to alkaline corrosion	Service life of bushings was short because of scoring	Substitution of Nitralloy 135 type G (resulfurized) heat treated to 269 HB and nitrided(b)
Spur gears (in train of power gears; 10-pitch, tip modified)	Sustain continuous Hertz stress of 1035 MPa (150 ksi) (overload of 1550 MPa, or 225 ksi), continuous Lewis stress of 275 MPa (40 ksi) (overload of 725 MPa, or 105 ksi)(c)	Gears failed because of inadequate scuff resistance, also suffered property losses at high operating temperatures	Substitution of material of H11 type, hardened and multiple tempered (3 h + 3 h) to 48 to 52 HRC, then double-stage nitrided(d)

(a) Single-stage nitrided at 510 °C (950 °F) for 38 h. Cost increased 5%, but rejection rate dropped to zero. (b) Single-stage nitrided at 510 °C (950 °F) for 38 h. Case depth was 0.46 mm (0.018 in.), and hardness was 94 HR15-N; parts had three times the service life of carburized parts. (c) Must withstand operating temperatures to 290 °C (550 °F). (d) 15 h at 515 °C (960 °F) (15 to 25% dissociation); then 525 °C (980 °F) (80 to 83% dissociation). Effective case depth (to 60 HRC), 0.25 to 0.4 mm (0.010 to 0.015 in.); case hardness, 67 to 72 HRC (converted from Rockwell 15-N scale)

The first stage of the double-stage process is the same as that for the single-stage process, except for time (see Table). The operating temperature in the second stage may be the same as that in the first stage, or it may be increased from 550 to 565 °C (1020 to 1050 °F). The higher temperature increases case depth.

Prior to nitriding, parts should be thoroughly cleaned (typically with vapor degreasing) after they are hardened and tempered.

Furnace Purging. After loading and sealing the furnace at the start of the nitriding cycle, air must be purged from the retort before the furnace is heated above 150 °C (300 °F). Purging prevents oxidation of workpieces and furnace components. When ammonia is the purging atmosphere, purging avoids the production of a potentially explosive mixture. Nitrogen is the preferred quenching medium.

Under no circumstances should ammonia be introduced into a furnace containing air at 330 °C (625 °F) because of the explosion hazard. Furnaces should also be purged at the conclusion of the nitriding cycle, during the cool-down period. At this time, it is common practice to remove any ammonia in the retort with nitrogen.

Emergency Purging. If the ammonia supply is cut off during the nitriding cycle or a supply line breaks, air can be sucked into the furnace—the greatest danger is during the cooling cycle. The common safety measure is an emergency purging system that pumps dry nitrogen or an oxygen-free, generated gas and maintains a safe pressure.

Case Depth Control. Case depth and case hardness vary with the duration of the nitriding cycle and other process conditions. Hardness gradients and case depths obtained in treating SAE 7140 (AMS 6470) as a function of cycle time and nitriding conditions are indicated in an adjoining Figure.

Equipment. Several designs are in common use, including the vertical retort furnace (see Figure), bell type movable furnace, box furnace, and tube retorts. Most furnaces are of the batch type.

Furnace fixtures are similar in design to those used in gas carburizing. Ammonia and dissociated products can react chemically with material in retorts, fans, work baskets, and fixtures. Alloys containing a high percentage of nickel and chromium normally are used in furnace parts and fixtures (see Table).

Ammonia Supply. Anhydrous liquid ammonia (refrigerator grade, 99.98 percent NH_3 by weight) is used.

Applications

The list of applications includes:

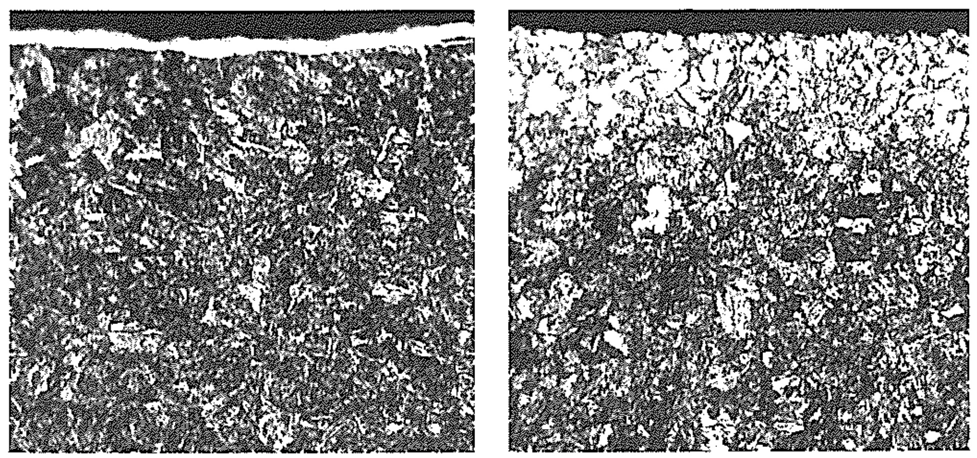
- Aluminum containing, low-alloy steels (see Table)
- Medium-carbon, chromium-containing, low-alloy steels of the 4100, 4300, 5100, 6100, 8600, 8700, and 9800 series
- Hot-work die steels containing 5 percent chromium, such as H11, H12, and H13
- Low-carbon, chromium-containing, low-alloy steels of the 3300, 8600, and 9300 series
- Air-hardening tool steels, such as A-2, A-6, D-2, D-3, and S-7

Nominal Composition and Preliminary Heat-Treating Cycles for Aluminum-Containing Low-Alloy Steels Commonly Gas Nitrided

Steel			Composition, %								Austenitizing temperature(a)		Tempering temperature(a)	
SAE	AMS	Nitralloy	C	Mn	Si	Cr	Ni	Mo	Al	Se	°C	°F	°C	°F
...	...	G	0.35	0.55	0.30	1.2	...	0.20	1.0	...	955	1750	565-705	1050-1300
7140	6470	135M	0.42	0.55	0.30	1.6	...	0.38	1.0	...	955	1750	565-705	1050-1300
...	6475	N	0.24	0.55	0.30	1.15	3.5	0.25	1.0	...	900	1650	650-675	1200-1250
...	...	EZ	0.35	0.80	0.30	1.25	...	0.20	1.0	0.20	955	1750	565-705	1050-1300

(a) Sections up to 50 mm (2 in.) in diameter, quenched in oil; larger sections may be water quenched

Microstructure of quenched and tempered 4140 steel after (a) gas nitriding for 24 h at 525 °C (975 °F) with 20 to 30% dissociation and (b) gas nitriding for 5 h at 525 °C (975 °F) with 20 to 30% dissociation followed by a second stage of 20 h at 565 °C (1050 °F) with 75 to 80% dissociation. Both specimens were oil quenched from 845 °C (1550 °F), tempered for 2 h at 620 °C (1150 °F), and surface activated with manganese phosphate before nitriding. (a) Structure after single-stage nitriding 0.005 to 0.0075 mm (0.0002 to 0.0003 in.) white surface layer (Fe_2N), iron nitride, and tempered martensite. (b) The high second-stage dissociation caused absence of white layer, and the final structure had a diffused nitride layer on a matrix of tempered martensite. Both 2% nital, 400×



(a) (b)

ecommended Materials for Parts and Fixtures in itriding Furnaces

/laterials are recommended on the basis of maximum operating emperature of 565 °C (1050 °F).

art	Material Wrought	Cast
etorts(a)	Type 330; Inconel 600	Not usually cast
ans	Type 330; Inconel 600	35-15 or equivalent
rays, baskets, fixtures	Types 310, 330; Inconel 600	35-15 or equivalent
hermocouple protection tube	Type 330; Inconel 600	Not usually cast

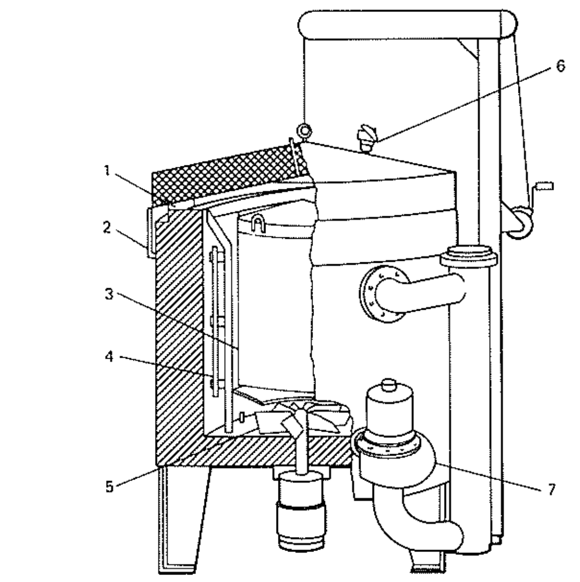
a) Periodic inspection of austenitic stainless steel retorts is mandatory because of em-rittlement after long exposures to nitriding. Retorts of 18-8 stainless steel lined with igh-temperature glass have been used successfully.

- High-speed steels, such as M-2 and M-4
- Nitronic stainless steels, such as 30, 40, 50, and 60
- Ferritic and martensitic stainless steels of the 400 and 500 series
- Austenitic stainless steels in the 200 and 300 series
- PH stainless steels, such as 13-8 PH, 15-5 PH, 17-7 PH, A-286, AM 350, and AM 355

As stated previously, gas nitriding reduces the corrosion resistance of tainless steels. However, all of these steels can be nitrided to some degree. 'rior to nitriding, some surface preparations unique to stainless steel are ecessary. Primarily, the chromium oxide film that provides corrosion rotection must be removed by such processes as dry honing, wet blasting, nd pickling. The treatment must precede placing workpieces into the urnace. In addition, all parts must be perfectly clean and free of embedded oreign particles.

Special nitriding processes include pressure nitriding, bright ni-riding, pack nitriding, ion (plasma) nitriding, and vacuum nitrocarburiz-ng.

Vertical retort nitriding furnace. 1, gasket; 2, oil seal; 3, work basket; 4, heating elements; 5, circulating fan; 6, thermocouple; and 7, cooling assembly. At end of cycle, a valve is opened and fan (not shown) incorporated in the external cooler circulates atmosphere through the water-jacketed cooling manifold.



Reference

1. *ASM Metals Handbook, Heat Treating,* Vol 4, 10th ed., ASM International, 1991, p 387

Liquid Nitriding

Processing takes place in a molten salt bath at the gas nitriding operating emperature—510 to 580 °C (950 to 1075 °F). The case hardening medium a molten, nitrogen-bearing, fused-salt bath containing either cyanides or yanates, Ref 1.

haracteristics

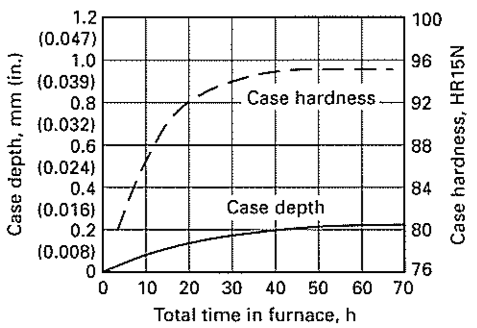
Bath compositions are similar to those in liquid carburizing and cy-niding. However, liquid cyaniding has an operating temperature lower an the critical transformation temperature. This means it is possible to eat finished parts because dimensional stability can be maintained in quid carburizing.

The process also improves surface wear resistance and the endurance mit in fatigue. Also, the corrosion resistance of many steels is improved. enerally, the process is not suitable where applications require deep cases nd hardened cores.

Gas nitriding and liquid nitriding have common applications. Gas nitrid-ng may have the edge where heavier case depths and dependable stopoffs re specified. Four examples of conversions from other processes to liquid itriding are summarized in an adjoining Table.

The process has become the generic term for a number of different fused-alt bath processes, all of which are carried out at the subcritical transfor-nation temperature. The basic processes are identified in an adjoining able. A typical commercial bath is a mixture of sodium and potassium salts. Cyanide-free salt compositions are available. They have gained wide acceptance within the heat-treating industry because they contribute substantially to the alleviation of a potential source of pollution.

Results of liquid pressure nitriding on type 410 stainless steel (composition, 0.12C-0.45Mn-0.41Ni-11.90Cr; core hardness, 24 HRC)

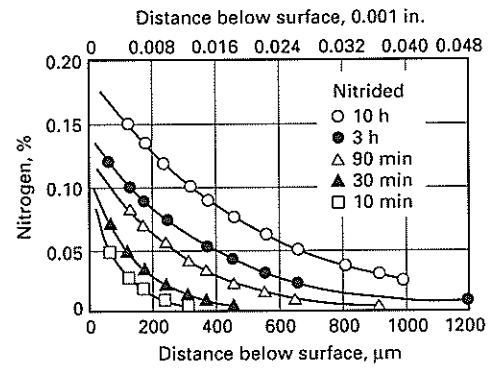


Automotive Parts for Which Liquid Nitriding Proved Superior to Other Case-Hardening Processes for Meeting Service Requirements

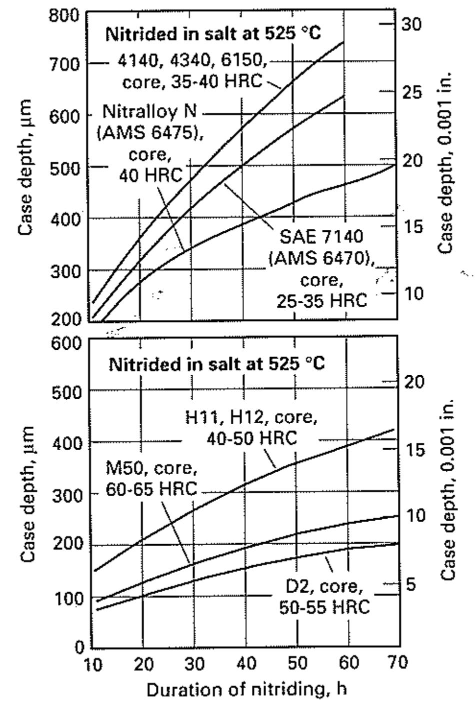
Component	Requirement	Material and process originally used	Resultant problem	Solution
Thrust washer	Withstand thrust load without galling and deformation	Bronze, carbonitrided 1010 steel	Bronze galled, deformed; steel warped	1010 steel nitrided 90 min in cyanide-cyanate bath at 570 °C (1060 °F) and water quenched(a)
Shaft	Resist wear on splines and bearing area	Induction harden through areas	Required costly inspection	Nitride for 90 min in cyanide-cyanate salt bath at 570 °C (1060 °F)
Seat bracket	Resist wear on surface	1020 steel, cyanide treated	Distortion; high loss in straightening(b)	1020 nitrided 90 min in cyanide-cyanate salt bath and water quenched(c)
Rocker arm shaft	Resist water on surface; maintain geometry	SAE 1045 steel, rough ground, induction hardened, straightened, finish ground, phosphate coated	Costly operations and material	SAE 1010 steel liquid-nitrided 90 min in low-cyanide fused salt at 570 to 580 °C (1060 to 1075 °F)(d)

(a) Resulted in improved product performance and extended life, with no increase in cost. (b) Also, brittleness. (c) Resulted in less distortion and brittleness, and elimination of scrap loss. (d) Eliminated finish grinding, phosphatizing, and straightening

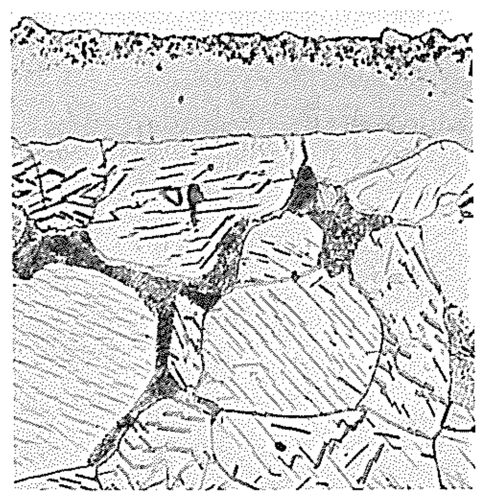
Nitrogen gradients in 1015 steel as a function of time of nitriding at 565 °C (1050 °F), using the aerated bath process



Depth of case for several chromium-containing low-alloy steels, aluminum-containing steels, and tool steels after liquid nitriding in a conventional salt bath at 525 °C (975 °F) for up to 70 h



Nitrided case and diffusion zone produced by cyanide-cyanate liquid nitriding. The characteristic needle structure is seen only after a 300 °C (570 °F) aging treatment.



Liquid nitriding processes include liquid pressure nitriding, aerated bath nitriding, and aerated, low-cyanide nitriding.

Results in liquid pressure nitriding type 410 stainless steel are found in an adjoining Figure.

Results in aerated salt bath nitriding a 1015 steel part are shown in an adjoining Figure.

A nitrided case and diffusion zone obtained in cyanide-cyanate liquid nitriding are shown in an adjoining Figure.

Operating Information

Important procedures include:

- Initial preparation and heating of the salt bath
- Aging of molten salts, when required

- Analysis and maintenance of baths

Practically all steels must be quenched and tempered for core properties before nitrided or stress relieved for distortion.

Prior heat treatment requirements are similar to those for gas nitriding. Parts are hardened prior to nitriding. Tempering temperatures should be no lower than the nitriding temperature, and preferably, slightly higher.

Starting Baths. Baths basically are sodium and potassium cyanides, or sodium and potassium cyanates. Cyanide, the active ingredient, is oxidized to cyanate by aging. The commercial salt mixture of 60 to 70 percent sodium salts and 30 to 40 percent potassium salts is melted at 540 to 595 °C (1000 to 1105 °F). During melting, a cover should be placed over the retort to guard against spattering or explosion of the salt, unless equipment is completely hooded and vented. Salts must be dry before placing them in the retort; entrapped moisture can cause eruption when the salt is heated. Baths are heated internally or externally.

Bath Maintenance. All work placed in the bath should be thoroughly cleaned and free of surface oxide. Either acid pickling or abrasive cleaning prior to nitriding is recommended. Finished parts should be preheated prior to immersion in the bath to rid them of surface moisture.

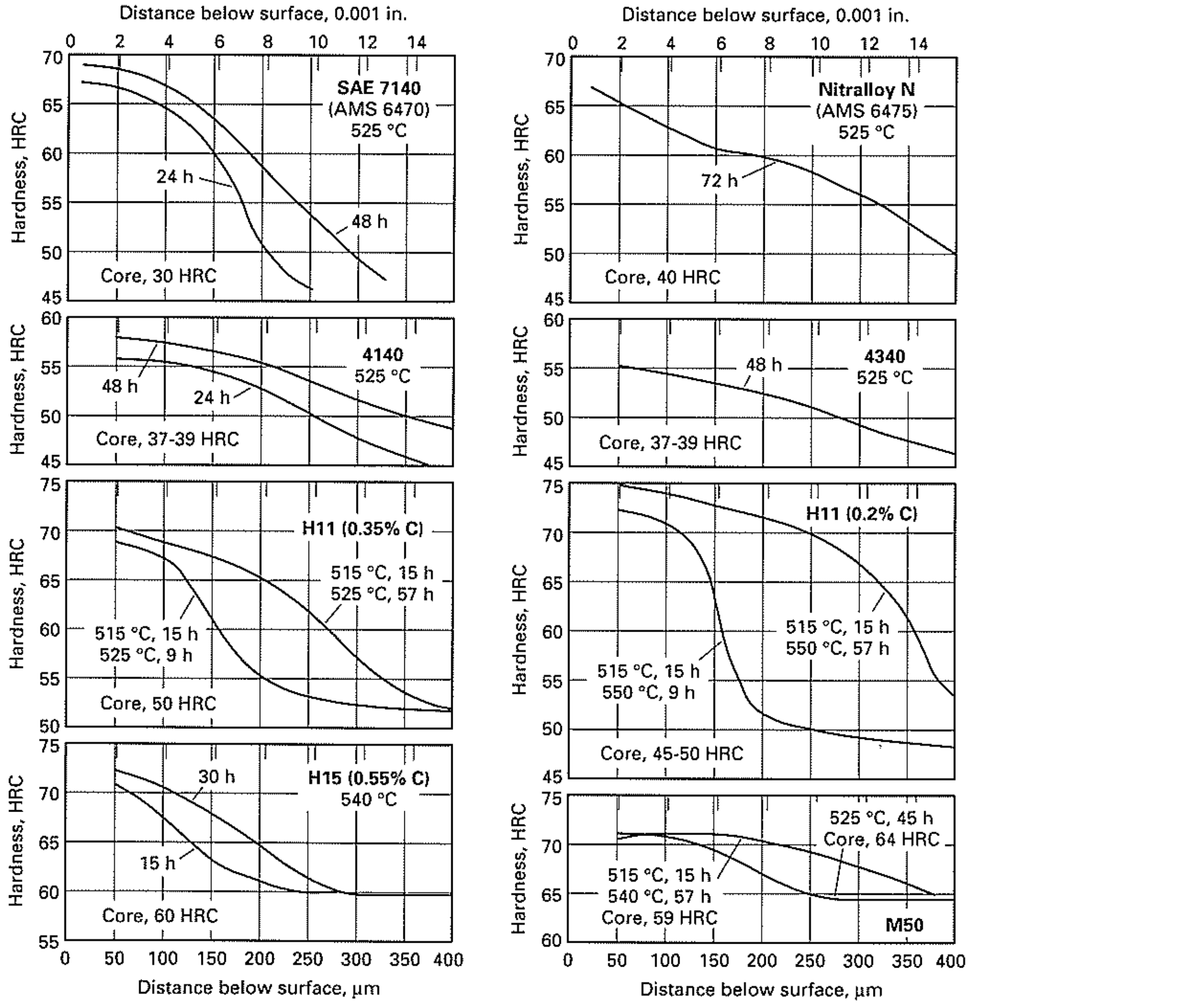
Safety. Compounds containing sodium cyanide or potassium cyanide or both can be handled safely with the proper equipment and must be neutralized by chemical means before discharge. These compounds are highly toxic. Great care should be taken to avoid taking them internally, or allowing them to be absorbed through skin abrasions. Another hazard is caused by contact between the compounds and mineral acids. Hydrogen cyanide gas, an extremely toxic product, is produced. Exposure can be fatal.

Equipment. Salt bath furnaces may be heated by gas, oil, or electricity, and essentially are similar in design to furnaces used in other processes. Batch furnaces are the most common, but continuous operations are feasible.

Liquid Nitriding Processes

Process identification	Operating range composition	Chemical nature	Suggested post treatment	Operating temperature °C	Operating temperature °F	U.S. patent number
Aerated cyanide-cyanate	Sodium cyanide (NaCN), potassium cyanide (KCN) and potassium cyanate (KCNO), sodium cyanate (NaCNO)	Strongly reducing	Water or oil quench; nitrogen cool	570	1060	3,208,885
Casing salt	Potassium cyanide (KCN) or sodium cyanide (NaCN), sodium cyanate (NaCNO) or potassium cyanate (KCNO), or mixtures	Strongly reducing	Water or oil quench	510-650	950-1200	
Pressure nitriding	Sodium cyanide (NaCN), sodium cyanate (NaCNO)	Strongly reducing	Air cool	525-565	975-1050	
Regenerated cyanate-carbonate	Type A: Potassium cyanate (KCNO), potassium carbonate (K_2CO_3)	Mildly oxidizing	Water, oil, or salt quench	580	1075	4,019,928
	Type B: Potassium cyanate (KCNO), potassium carbonate (K_2CO_3), 1-10 ppm, sulfur (S)	Mildly oxidizing	Water, oil quench, or salt quench	540-575	1000-1070	4,006,643

Hardness gradients for several alloy and tool steels nitrided in salt by the liquid pressure process. Rockwell C hardness values are converted from Knoop hardness measurements made using a 500 g load. Temperatures are nitriding temperatures.



Applications

Data in an adjoining Figure show depth of case obtained in a number of steels treated in a conventional liquid nitriding bath at 525 °C (975 °F) for up to 70 h. Effective cyanide content of the bath was 30 to 35 percent and cyanate content was 15 to 20 percent. Before being nitrided, all parts were tempered to the core hardnesses indicated in the Figure previously cited. Steels treated included three chromium-containing, low-alloy steels (4140, 4340, and 6150); two aluminum-containing nitriding steels (SAE 7140 and 6475); and four tool steels (H11, H12, M50, and D2).

An adjoining Figure presents data on core hardnesses obtained in liquid pressure nitriding several alloy and tool steels: SAE 7140, AMS 6475, 4140, 4340; and medium carbon H11, H15, and M50. In this instance, case depths and hardnesses are comparable to those obtained in single-stage gas nitriding.

In treating high-speed steel cutting tools with liquid nitriding, cases have a lower nitrogen content and are more ductile than those produced in gas nitriding.

Reference

1. *ASM Metals Handbook, Heat Treating,* Vol 4, 10th ed., ASM International, 1991, p 410

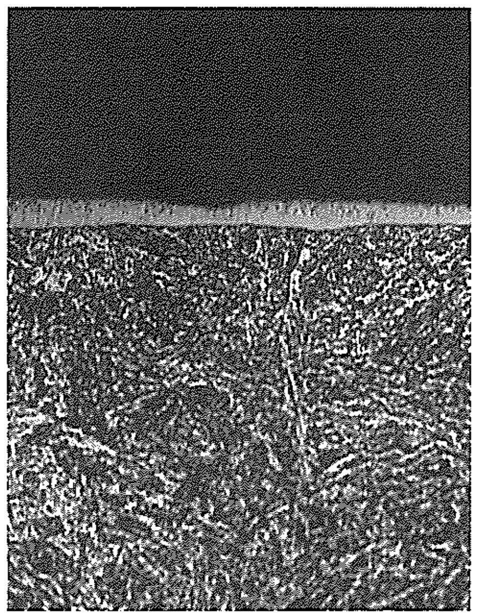
Plasma (Ion) Nitriding

In this vacuum process, nascent (elemental) nitrogen is introduced to the surfaces of workpieces for subsequent diffusion into the metal. High voltage electrical energy forms a plasma through which nitrogen atoms are accelerated to impinge on workpieces. Ion bombardment heats workpieces, cleans surfaces, and provides active nitrogen (Ref 1).

Characteristics

The process, in comparison with conventional gas nitriding, provides more precise control of nitrogen supply at the workpiece surface. Another advantage: ability to select either an epsilon (ε) or gamma (γ) monophase layer, or prevent white layer formation entirely. A compound layer on quenched and tempered 4140 is shown in an adjoining Figure. The diffusion zone in type 416 stainless steel is shown in another Figure. A third Figure shows typical gas compositions and resulting metallurgical configu-

Compound layer of γ′ (Fe_4N) on the ion-nitrided surface of quenched and tempered 4140 steel. The γ′ compound layer is supported by a diffused case, which is not observable in this micrograph. Nital etched. 500×



Observable diffusion zone on the unetched (white) portion of an ion-nitrided 416 stainless steel. Nital etched. 500×

rations. The process is replacing carbonitriding for better dimensional control and the reduction or elimination of machining after heat treating.

Operating Information

A typical ion nitriding vessel is depicted in an adjoining Figure. Operating temperatures are in the range of 375 to 650 °C (705 to 1200 °F). At the lower temperature, the amount of residual stress relief is minimized. Because loads are gas cooled, they do not experience distortion from temperature gradients or from martensitic formation.

After work is heated to the desired temperature, process gas is admitted at a flow rate determined by the load surface area. Pressure is regulated in the 1 to 10 torr range by a control valve just upstream from the vacuum pump. Process gas is normally a mixture of nitrogen, hydrogen, and occasionally, small amounts of methane.

Cooling is by backfilling with nitrogen or other inert gases, and by recirculating the gas from the load to a cold surface, such as a cold wall.

Prior microstructure can influence response to nitriding. For alloy steels, a quenched and tempered structure is believed to get optimum results. Tempering temperatures should be 15 to 25 °C (25 to 45 °F) higher than the anticipated nitriding temperature to minimize further tempering of the core during the nitriding process.

Hardness profiles for typical ion nitrided alloys are shown in an adjoining Figure.

Applications

Response to ion nitriding depends heavily on the presence of strong, nitride-forming elements. Plain carbon steels can be treated, but cases aren't significantly harder than the cores.

Steels in the Nitralloy series with about 1 percent aluminum and 1 to 1.5 percent chromium are the premier applications. Other suitable applications include:

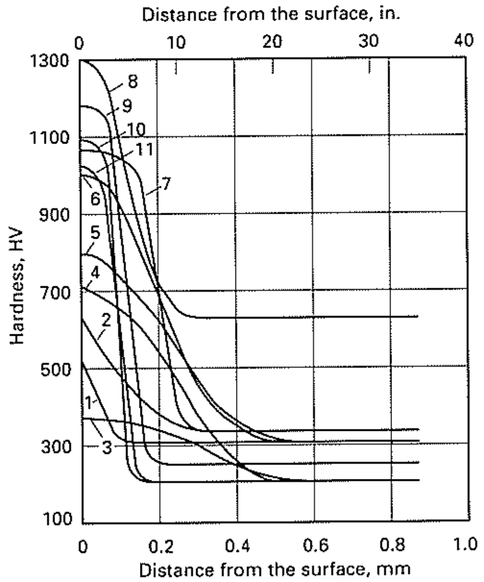
- Chromium-bearing alloys, ie., 4100, 4300, 5100, 6100, 8600, 8700, 9300, and 9800 series
- Most tool and die steels, stainless steels, and PH alloys
- P/M parts (due to porosity, cleaning is a critical requirement)
- Cast iron wear parts

Gears, crankshafts, cylinder liners, and pistons are regarded as excellent applications.

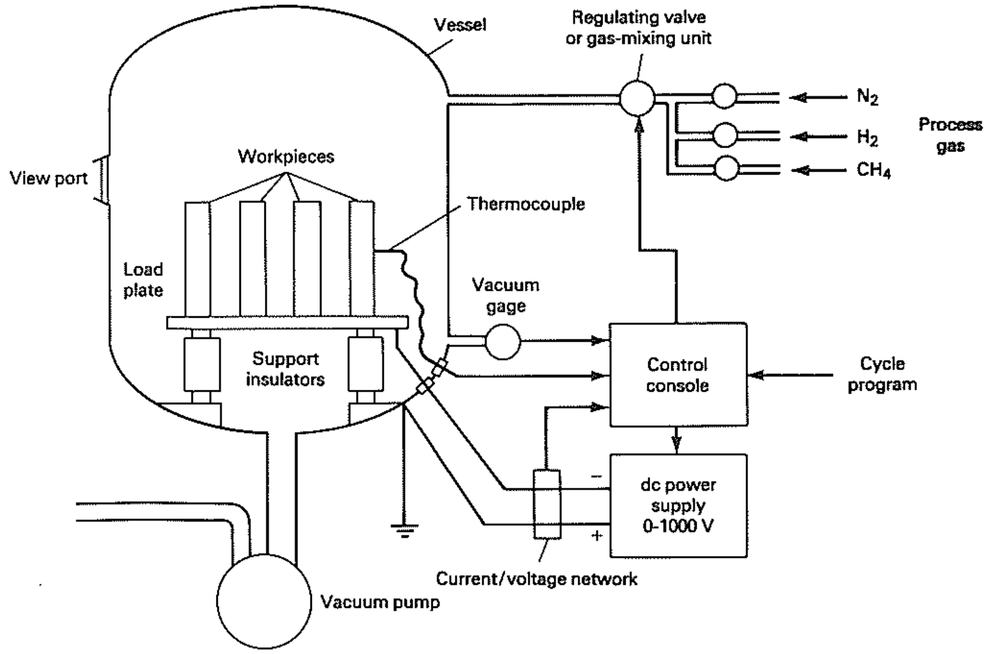
Reference

1. *ASM Metals Handbook, Heat Treating,* Vol 4, 10th ed., ASM International, 1991, p 420

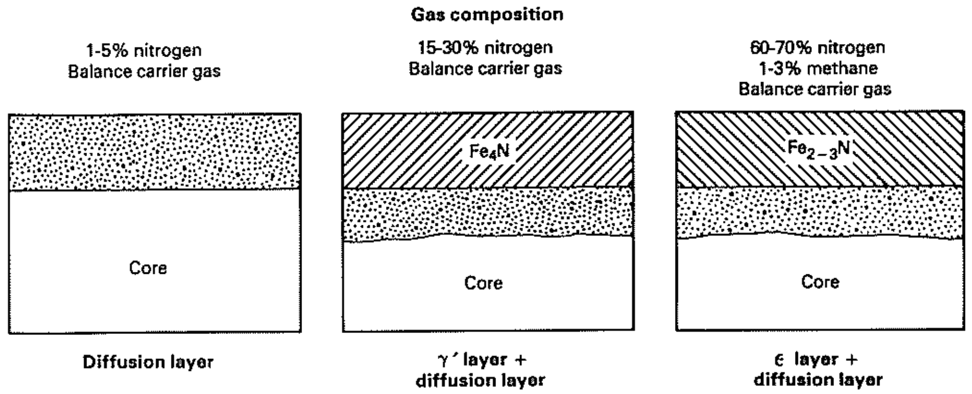
Hardness profile for various ion-nitrided materials. 1, gray cast iron; 2, ductile cast iron; 3, AISI 1040; 4, carburizing steel; 5, low-alloy steel; 6, nitriding steel; 7, 5% Cr hot-work steel; 8, cold-worked die steel; 9, ferritic stainless steel; 10, AISI 420 stainless steel; 11, 18-8 stainless steel



Typical ion-nitriding vessel



Typical gas compositions and the resulting metallurgical configurations of ion-nitrided steel



Gaseous and Plasma Nitrocarburizing

In the gaseous process, carbon and nitrogen are introduced into a steel, producing a thin layer of iron carbonitride and nitrides. This is the white layer, or compound layer, with an underlying diffusion zone containing dissolved nitrogen and iron or alloy nitrides. Gas processes include Nitemper, Alnat-N, black nitrocarburizing, and austenitic nitrocarburizing. White layers formed in gaseous nitrocarburizing are shown in an adjoining Figure.

Plasma nitrocarburizing is a variant of glow discharge plasma nitriding (see article in this chapter). The microstructure produced in EN 408 steel is shown in an adjoining Figure.

Characteristics (Both Processes)

Improving resistance to scuffing is a common benefit of the compound layer produced with these processes. In addition, fatigue properties are enhanced when nitrogen is retained in solid solution in the diffusion zone beneath the compound layer.

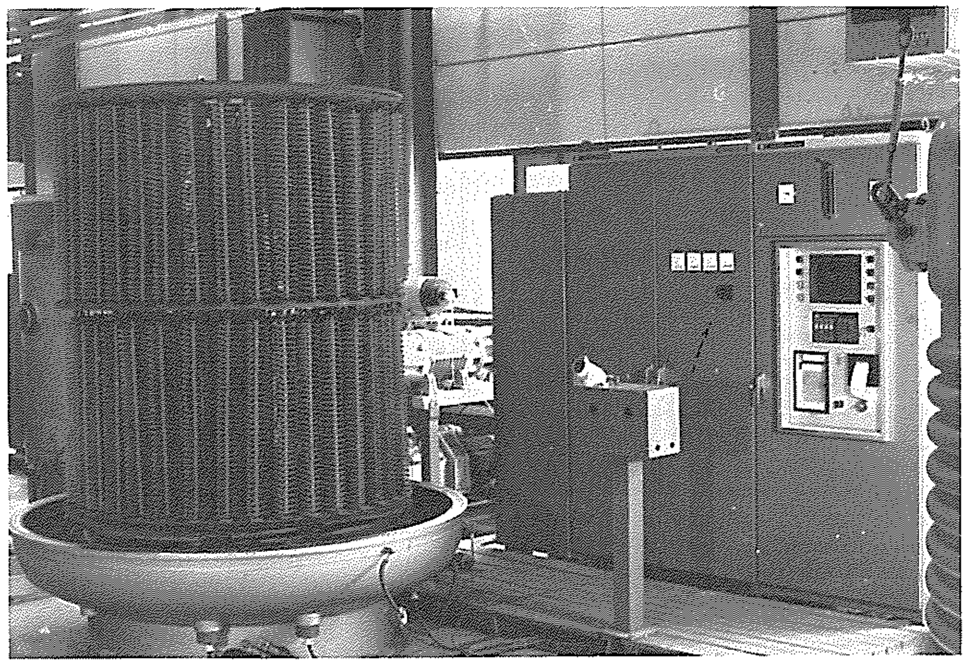
Gaseous Processes

Operating Information. Parts usually are treated at a temperature of 570 °C (1060 °F), which is just below the austenitic range for the Fe-N system. Treatment times usually run 1 to 3 h.

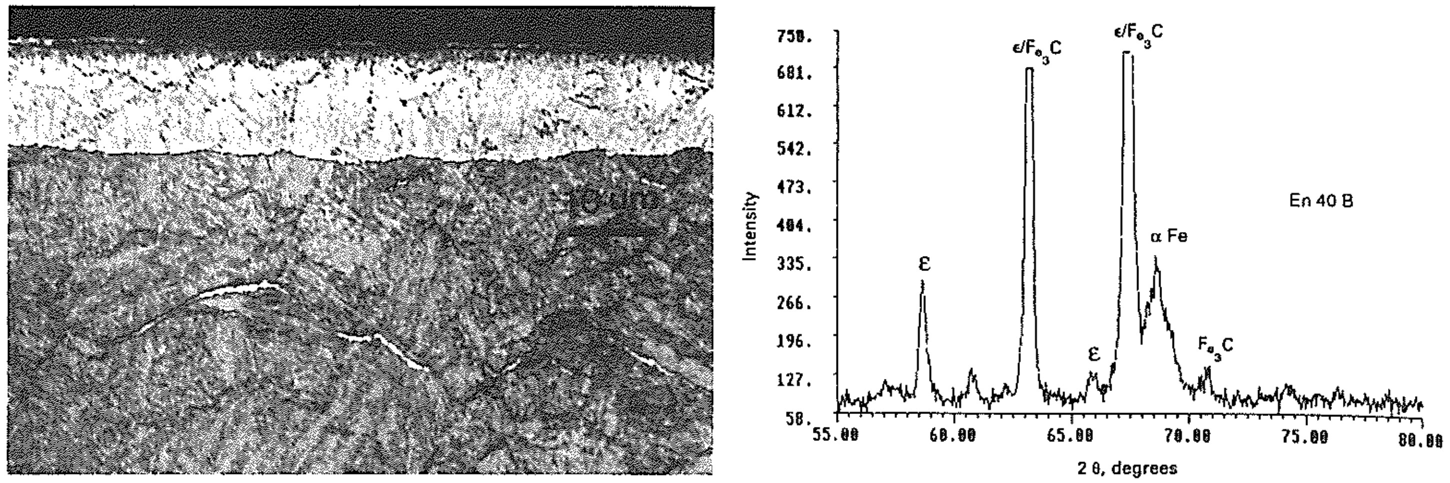
To get optimum results, surfaces must be free of contaminants, such as oxides, scale, oil, and decarburization. Vapor degreasing is adequate in most applications.

Preliminary heat treatments include simple stress relieving and tempering to increase core strength. Both stress relief and tempering should be at temperatures at least 25 °C (45 °F) above the nitrocarburizing temperature to prevent changes in core properties during nitrocarburizing.

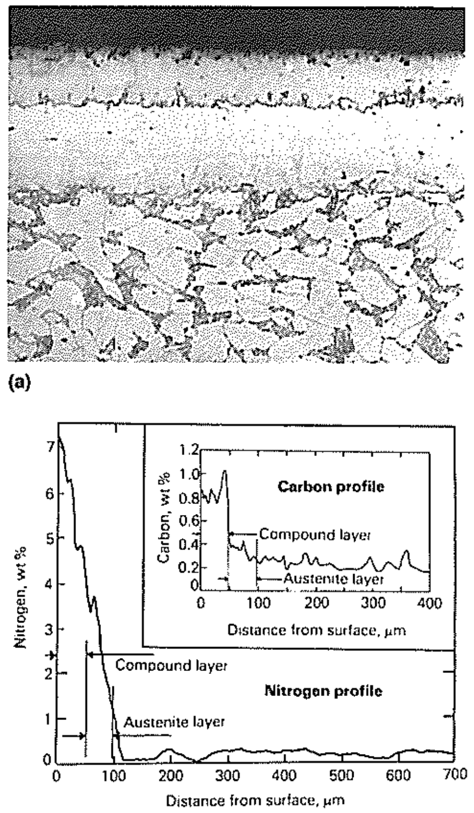
Plasma nitrocarburizing installation for heat treating a load of 3000 automotive seat rails. Source: Klockner IONON GmbH



Microstructure (a) of a plasma nitrocarburized EN40B steel sample with (b) the corresponding x-ray diffraction pattern.



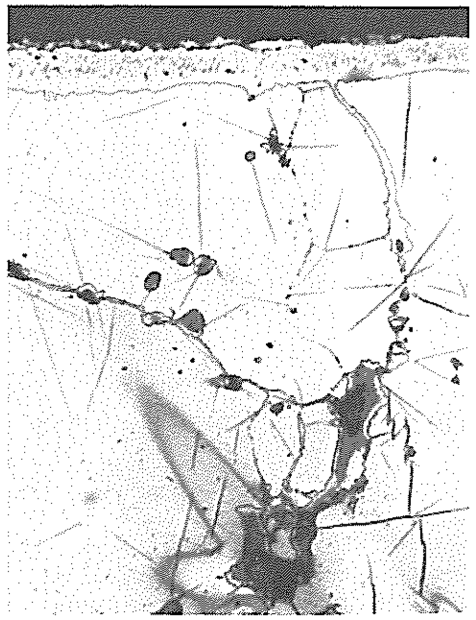
Structural characteristics of an austenitic nitrocarburized material. (a) Micrograph of EN32 steel nitrocarburized for 1 h at 700 °C (1290 °F) in ammonia/endothermic gas with 15% residual ammonia and oil quenched. (b) Carbon and nitrogen profiles for EN32 nitrocarburized for 1 h at 700 °C (1290 °F) in ammonia/endothermic gas with 15% residual NH_3



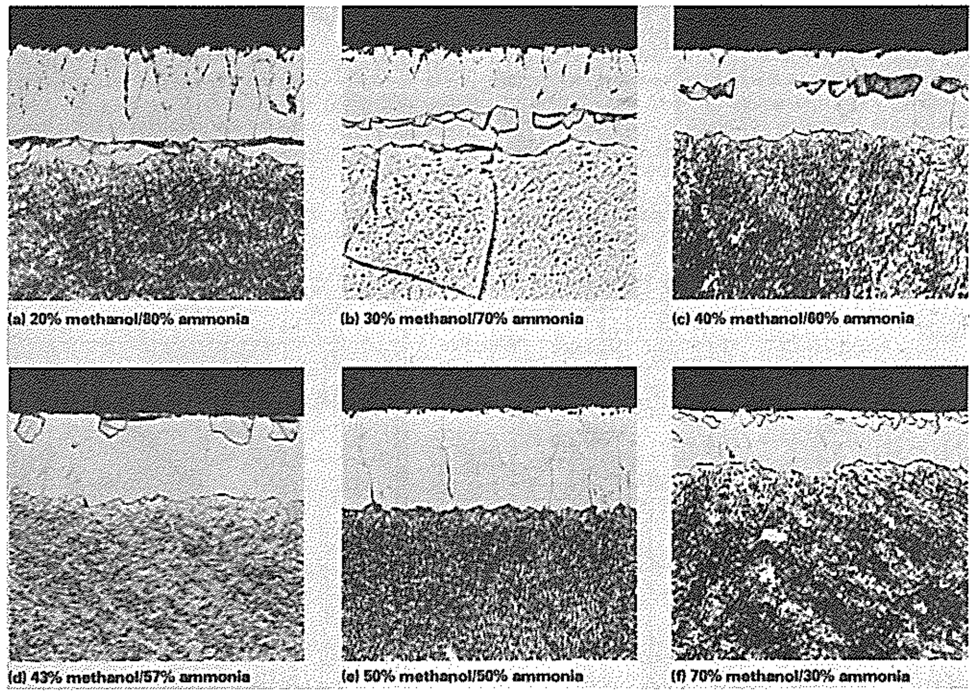
Production Applications of Austenitic Nitrocarburizing

Austenitic nitrocarburizing treatment type	Applications
Alpha Plus (0.125 mm, or 0.005 in., underlying case)	Clutch plates, levers, gears, bushes, thin pressings
Alpha Plus (0.25 mm, or 0.010 in., underlying case)	Gears, levers, pulleys, liners
Beta (0.60 mm, or 0.025 in., underlying case)	Machine slideways, guide bars, gears, sprockets, pins, bushes, water-pump parts, liners, jigs/fixtures, bearings

Microstructure of a plasma nitrocarburized P/M steel (SINT-D35) with a compound layer thickness of 10 μm. Source: Klockner IONON GmbH



Compound layers formed on iron by gaseous nitrocarburizing in various methanol ammonia ratios. Quenched samples, all shown at 80× (a, c, d, e, and f etched in alcoholic ferric chloride and hydrochloric acid with iodine; b, etched in nital with ferric chloride)



Batch furnaces with integral oil quenches are ideally suited for the process. The hot chamber temperature should be controllable to within ±5 °C (±9 °F) at 570 °C (1060 °F). For safety reasons gas leaks in the furnace and around doors must be minimized.

Nitemper Process. Sealed quench furnaces normally are used. Atmospheres consist of 50 percent ammonia and 50 percent endogas. Treatment temperature is 570 °C (1060 °F). Treatment times usually run between 1 and 3 h. Parts are oil quenched, or cooled under recirculated protective gas.

Alnat-N Process. Nitrous oxide in the atmosphere enhances the rate of compound layer formation through the indirect presence of oxygen. Another feature is claimed for this patented process: it is possible to eliminate the addition of a carburizing gas to the basic ammonia/nitrous oxide/nitrogen mixture. Carbon is incorporated into the compound layer by diffusion from the matrix material.

Black Nitrocarburizing. This process was first used as a cosmetic treatment for gaseous nitrocarburized parts for the hydraulic industry. It has since been found that the application of the process can be extended to improving the fatigue, wear, and corrosion properties of mild steels.

Austenitic Nitrocarburizing. In this process, the treatment temperature makes it possible to get partial transformation of the matrix to austenite via enrichment with nitrogen. The reason for this is to get around the main disadvantage of ferritic nitrocarburizing: in treating plain carbon steel there is no significantly hardened case below the compound layer. This means resistance of a part to horizontal (contact) stresses is restricted. In the process, the subsurface (but not the entire cross section) is transformed to iron-carbon-nitrogen austenite, which is subsequently transformed to tempered martensite and bainite, with a hardness in the range of 750 to 900 HV (see adjoining Figure and Table).

Plasma Process

Operating Information. Atmospheres in this instance are mixtures of hydrogen, nitrogen, and carbon-bearing gas. Treatment temperature is 570 °C (1060 °F). The compound layer measures >5 μm; surface hardness runs around 350 HV. Parts are cooled under controlled vacuum conditions.

Applications. The plasma equipment shown in an adjoining Figure has been treating seat slider rails for autos for a number of years without significant technical or metallurgical problems. Applications include low-alloy, chromium-bearing steels, some plain carbon steels, and, recently, sintered P/M parts, replacing the salt bath process (see adjoining Figure).

Reference

1. *ASM Metals Handbook, Heat Treating,* Vol 4, 10th ed., ASM International, 1991, p 425

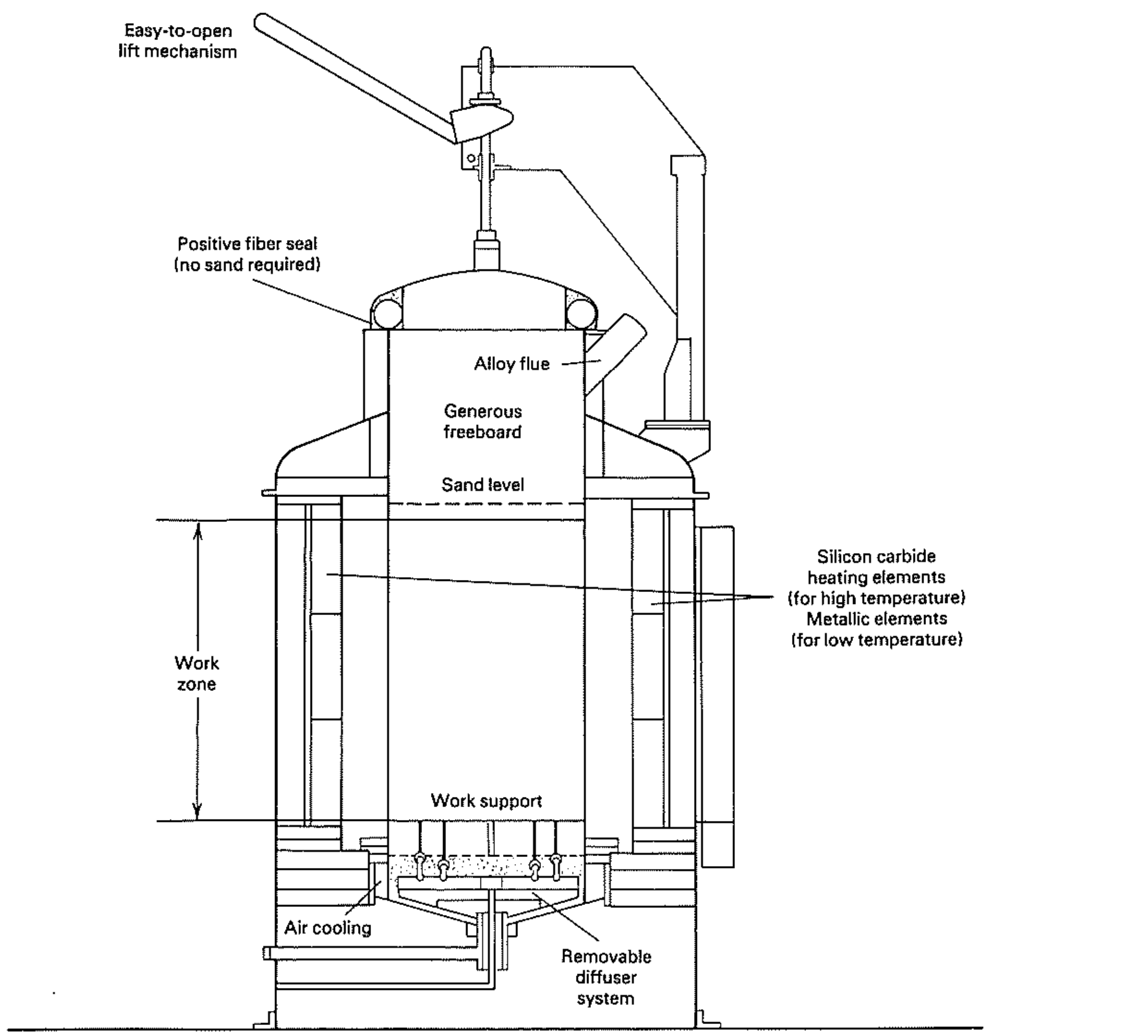
Fluidized Bed Hardening

Steel parts are nitrocarburized, carburized, and carbonitrided in fluid bed furnaces. The process also is used in quenching (see article in this chapter). In heat-treating applications, a bed of dry, finely divided (80 mesh to 180 μm) particles, typically aluminum oxide, is made to behave like a liquid by a moving gas fed upward through a diffusor or distributor into the bed of the furnace.

Characteristics

Fluidized beds, using atmospheres made up of ammonia, natural gas, nitrogen, and air or similar combinations, are capable of doing low-temperature nitrocarburizing. Results are equivalent to those with conventional salt bath processes or other atmosphere processes. High-speed steel tools

Fluidized-bed furnace with external heating by electrical resistance elements



oxynitrided in a fluidized bed have properties similar to those of tools treated by the more conventional gas processes. In carburizing and carbonitriding, results can be similar to those obtained with conventional atmosphere processes. In an adjoining Figure, results in treating SAE 8620 steel are compared with those obtained in gas carburizing. An effective case depth of 1 mm (0.04 in.) was obtained in 1.5 h.

Advantages of the process include:

- Carburizing is rapid because treatment temperatures are high
- Temperature uniformity is ensured
- Furnaces are tight; upward pressure of gases minimizes leakage of air
- Part finishes are uniform

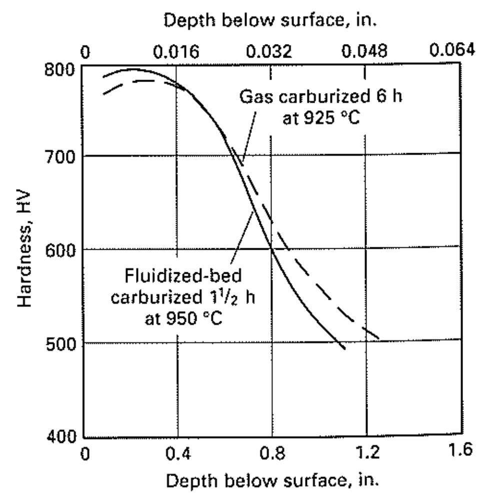
Operating Information

The carbon potential of the atmosphere varies with the air-to-gas ratio. For each hydrocarbon gas (typically propane, methane, or vaporized methanol) a relationship can be established. Furnaces are equipped with ports and probes to facilitate necessary measurements.

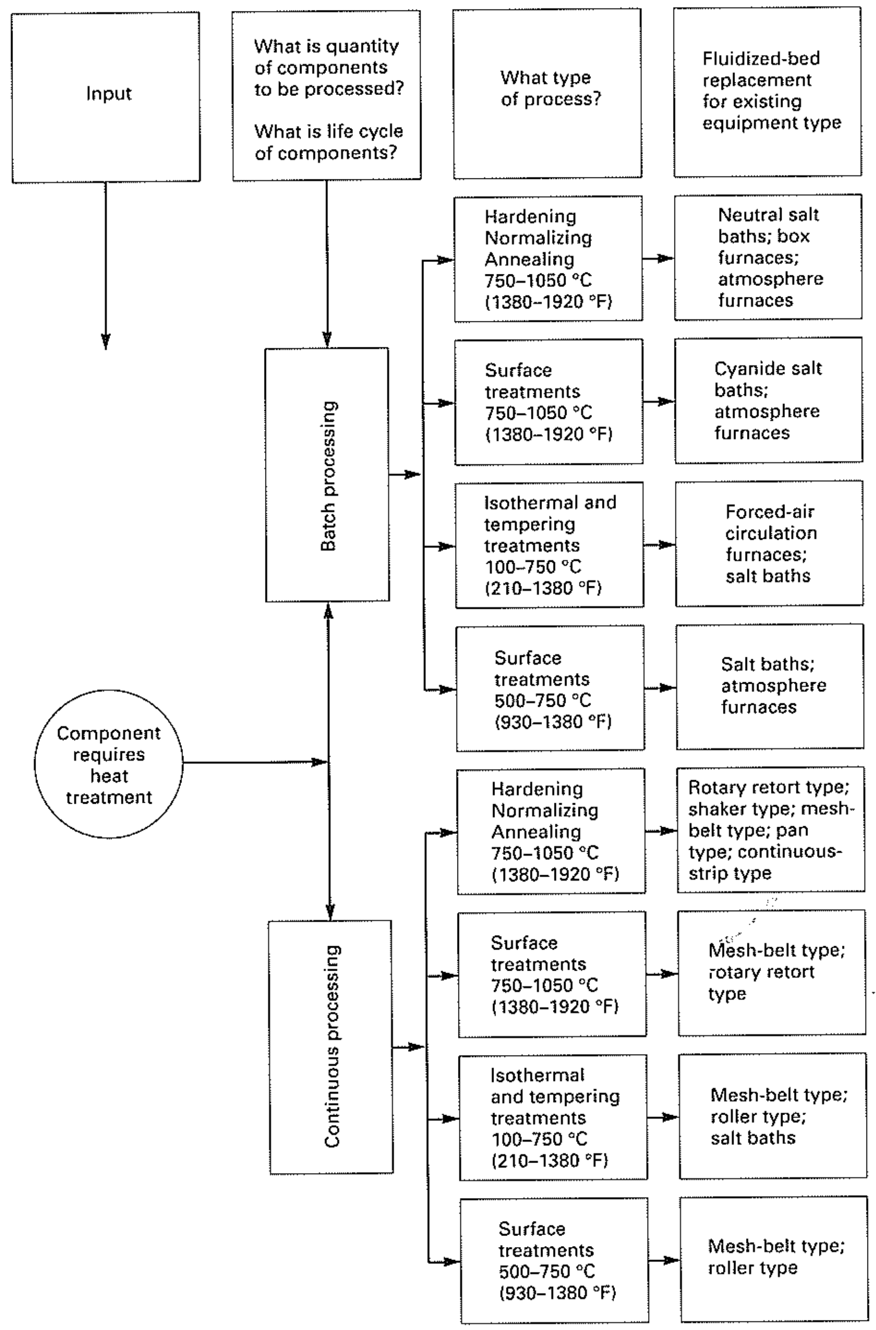
Dense phase furnaces are the most widely used in heat treating. In this instance, parts are submerged in a bed of fine, solid particles held in suspension, without any particle entrainment, by a flow of gas. Several methods of heating are available, including external-resistance-heated beds (see Figure); external-combustion-heated beds, submerged-combustion beds, internal-combustion, gas-fired beds; and two-stage, internal-combustion, gas-fired beds.

Operational Safety. As with all forms of gas heating, accepted safety devices are incorporated into the majority of today's furnaces.

Comparison of hardness profiles obtained by fluidized-bed and conventional gas carburizing. SAE 8620 steel, rehardened from 820 °C (1510 °F)



Fluidized-bed applications; decision model



Applications

Applications of fluidized beds and those of competing processes are listed in an adjoining Figure. Note that the information includes operating temperatures.

Reference

1. *ASM Metals Handbook, Heat Treating,* Vol 4, 10th ed., ASM International, 1991, p 484

Boriding (Boronizing) Process

This is a thermomechanical surface hardening process which is applied to a number of ferrous materials. During boriding, the diffusion and subsequent absorption of boron atoms into the metallic lattice on the surface of workpieces form initial boron compounds, Ref 1.

Characteristics

The process has advantages over conventional case hardened parts. One is extremely high hardness (between 1450 and 5000 HV) with high melting points of constituent phases (see Table). Typical surface hardness values are compared with those of other treatments in an adjoining Table. In addition, a combination of high surface hardness and low surface coefficients of the borided layer helps in combating several types of wear, i.e., adhesion, tribo-oxidation, abrasion, and surface fatigue.

On the negative side, boriding techniques lack flexibility and are labor intensive, making the process less cost effective than other thermomechanical treatments, such as gas carburizing and plasma nitriding.

Alternative processes include gas boriding, plasma boriding, fluidized bed boriding, and multicomponent boriding. A diagram of a fluidized bed for boriding is shown in an adjoining Figure.

Typical Surface Hardness of Borided Steels Compared with Other Treatments and Hard Materials

Material	Microhardness, kg/mm² or HV
Boride mild steel	1600
Borided AISI H13 die steel	1800
Borided AISI A2 steel	1900
Quenched steel	900
Hardened and tempered H13 die steel	540-600
Hardened and tempered A2 die steel	630-700
High-speed steel BM42	900-910
Nitrided steels	650-1700
Carburized low-alloy steels	650-950
Hard chromium plating	1000-1200
Cemented carbides, WC + Co	1160-1820 (30 kg)
$Al_2O_3 + ZrO_2$ ceramic	1483 (30 kg)
$Al_2O_3 + TiC + ZrO_2$ ceramic	1738 (30 kg)
Sialon ceramic	1569 (30 kg)
TiN	2000
TiC	3500
SiC	4000
B_4C	5000
Diamond	>10 000

Operating Information

Well-cleaned material is heated in the range of 700 to 1000 °C (1290 to 1830 °F) for 1 to 12 h in contact with a boronaceous solid powder, paste, liquid, or gaseous medium.

In the multicomponent process, conventional boronizing is followed by applying one or more metallic elements, such as aluminum, silicon, chromium, vanadium, or titanium (see Table). The operating temperature ranges from 850 to 1050 °C (1560 to 1920 °F). It is a two-step process:

1. Boriding by conventional methods, such as pack, paste, and electrolytic salt bath techniques
2. Diffusing metallic elements through the powder mixture or borax-based melt into the borided surfaces. With the pack method, sintering of particles is avoided by passing argon or hydrogen into the reaction chamber. The microstructure of a borochromtitanized alloy steel is shown in an adjoining Figure.

Melting Point and Microhardness of Different Boride Phases Formed During Boriding of Different Substrate Materials

Substrate	Constituent phases in the boride layer	Microhardness of layer, HV or kg/mm²	Melting point °C	Melting point °F
Fe	FeB	1900-2100	1390	2535
	Fe_2B	1800-2000	...	...
Co	CoB	1850	...	...
	Co_2B	1500-1600	...	...
	Co_3B	700-800	...	...
Co-27.5 Cr	CoB	2200 (100 g)(a)	...	...
	Co_2B	~1550 (100 g)(a)	...	...
	Co_3B(?)	700-800	...	...
Ni	Ni_4B_3	1600	...	...
	Ni_2B	1500	...	...
	Ni_3B	900	...	...
Inco 100	...	1700 (200 g)(b)	...	...
Mo	Mo_2B	1660	2000	3630
	MoB_2	2330	~2100	~3810
	Mo_2B_5	2400-2700	2100	3810
W	W_2B_5	2600	2300	4170
Ti	TiB	2500	~1900	3450
	TiB_2	3370	2980	5395
Ti-6Al-4V	TiB		...	...
	TiB_2	3000 (100 g)(a)	...	...
Nb	NbB_2	2200	3050	5520
	NbB_4		...	...
Ta	Ta_2B		3200-3500	5790-6330
	TaB_2	2500	3200	5790
Hf	HfB_2	2900	3250	5880
Zr	ZrB_2	2250	3040	5500
Re	ReB	2700-2900	2100	3810

(a) 100 g load. (b) 200 g load

Multicomponent Boriding Treatments

Reference	Multicomponent boriding technique	Media type	Media composition(s), wt%	Process steps investigated(a)	Substrate(s) treated	Temperature, °C (°F)
61	Boroaluminizing	Electrolytic salt bath	3-20% Al_2O_3 in borax	S	Plain carbon steels	900 (1650)
62	Boroaluminizing	Pack	84% B_4C + 16% borax	S	Plain carbon steels	1050 (1920)
			97% ferroaluminum + 3% NH_4Cl	B-Al		
				Al-B		
2	Borochromizing	Pack	5% B_4C + 5% KBF_4 + 90% SiC (Ekabor II)	S	Plain carbon steels	Borided at 900 (1650) Chromized at 1000 (1830)
				B-Cr		
			78% ferrochrome + 20% Al_2O_3 + 2% NH_4Cl	Cr-B		
2	Borosiliconizing	Pack	5% B_4C + 5% KBF_4 + 90% SiC (Ekabor II)	B-Si	0.4% Steel	900-1000 (1650-1830)
			100% Si	Si-B		
2	Borovanadizing	Pack	5% B_4C + 5% KBF_4 + 90% SiC (Ekabor II)	B-V	1.0% C steel	Borided at 900 (1650) Vanadized at 1000 (1830)
			60% ferrovanadium + 37% Al_2O_3 + 3% NH_4Cl			

(a) S, simultaneous boriding and metallizing; B-Si, borided and then siliconized; Al-B, aluminized and then borided

Proven Applications for Borided Ferrous Materials

Substrate material AISI	BSI	DIN	Application
		St37	Bushes, bolts, nozzles, conveyer tubes, base plates, runners, blades, thread guides
1020	...	C15 (Ck15)	Gear drives, pump shafts
1043	...	C45	Pins, guide rings, grinding disks, bolts
		St50-1	Casting inserts, nozzles, handles
1138	...	45S20	Shaft protection sleeves, mandrels
1042	...	Ck45	Swirl elements, nozzles (for oil burners), rollers, bolts, gate plates
		C45W3	Gate plates
W1	...	C60W3	Clamping chucks, guide bars
D3	...	X210Cr12	Bushes, press tools, plates, mandrels, punches, dies
C2	...	115CrV3	Drawing dies, ejectors, guides, insert pins
		40CrMnMo7	Gate plates, bending dies
H11	BH11	X38CrMoV51	Plungers, injection cylinders, sprue
H13	...	X40CrMoV51	Orifices, ingot molds, upper and lower dies and matrices for hot forming, disks
H10	...	X32CrMoV33	Injection molding dies, fillers, upper and lower dies and matrices for hot forming
D2	...	X155CrVMo121	Threaded rollers, shaping and pressing rollers, pressing dies and matrices
		105WCr6	Engraving rollers
D6	...	X210CrW12	Straightening rollers
S1	~BS1	60WCrV7	Press and drawing matrices, mandrels, liners, dies, necking rings
D2		X165CrVMo12	Drawing dies, rollers for cold mills
L6	BS224	56NiCrMoV7	Extrusion dies, bolts, casting inserts, forging dies, drop forges
		X45NiCrMo4	Embossing dies, pressure pad and dies
O2	~BO2	90MnCrV8	Molds, bending dies, press tools, engraving rollers, bushes, drawing dies, guide bars, disks, piercing punches
E52100	...	100Cr6	Balls, rollers, guide bars, guides
		Ni36	Parts for nonferrous metal casting equipment
		X50CrMnNiV229	Parts for unmagnetizable tools (heat treatable)
4140	708A42 (En19C)	42CrMo4	Press tools and dies, extruder screws, rollers, extruder barrels, non-return valves
4150	~708A42 (CDS-15)	50CrMo4	Nozzle base plates
4317	...	17CrNiMo6	Bevel gears, screw and wheel gears, shafts, chain components
5115	...	16MnCr5	Helical gear wheels, guide bars, guiding columns
6152	...	50CrV4	Thrust plates, clamping devices, valve springs, spring contacts
302	302S25 (En58A)	X12CrNi188	Screw cases, bushes
316	~316S16 (En58J)	X5CrNiMo1810	Perforated or slotted hole screens, parts for the textile and rubber industries
		G-X10CrNiMo189	Valve plugs, parts for the textile and chemical industries
410	410S21 (En56A)	X10Cr13	Valve components, fittings
420	~420S45 (En56D)	X40Cr13	Valve components, plunger rods, fittings, guides, parts for chemical plants
		X35CrMo17	Shafts, spindles, valves
Gray and ductile cast iron			Parts for textile machinery, mandrels, molds, sleeves

Quenching and Tempering. Borided steels are quenched in air, oil, salt baths, and aqueous polymers.

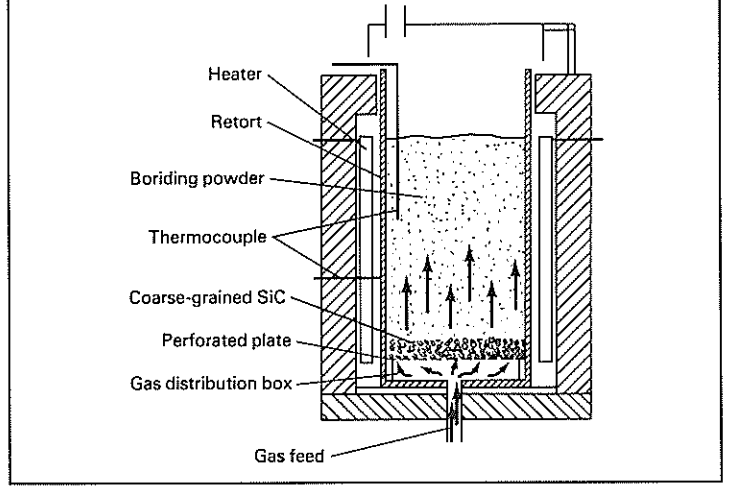
Applications

Many ferrous materials can be borided, including structural steels, tool steels, stainless steels, cast steels, Armco CP iron, gray and ductile irons, and ferrous P/M materials. Proven applications are shown in an adjoining Table.

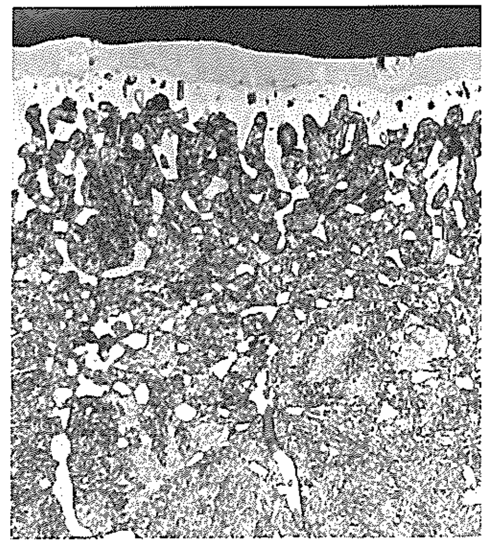
Air-hardening steels can be simultaneously hardened and borided; water-hardening steels are not borided because of the susceptibility of the boride layer to thermal shock.

Also excluded are resulfurized and leaded steels (because of tendencies toward case spalling and case cracking), and nitrided steels (due to their sensitivity to cracking).

Diagram of a fluidized bed for boriding



Microstructure of the case of a borochromtitanized construction alloy steel



Reference

1. *ASM Metals Handbook, Heat Treating,* Vol 4, 10th ed., ASM International, 1991, p 437

Laser Surface Hardening

A laser heats the surface of a part to its austenitic temperature. The laser beam is a beam of light, is easily controlled, requires no vacuum, and does not generate combustion products. However, complex optics are required, and coatings are required on surfaces to be hardened because of the low infrared absorption of the steel, Ref 1.

Characteristics

Lasers are effective in selective hardening of wear and fatigue prone areas of irregularly shaped machine components such as camshafts and crankshafts. Distortion is low. Lasers are not efficient from an energy utilization standpoint. Energy efficiency may be as low as 10 percent.

Operating Information

This surface hardening process is not fundamentally different from conventional through hardening of ferrous materials. In both instances, increased hardness and strength are obtained by quenching the material from the austenite region to form hard martensite. With laser hardening, however, only a thin surface layer is heated to the austenitizing temperature prior to quenching, leaving the interior of the workpiece essentially unaffected. Because ferrous materials are fairly good conductors of heat, it is necessary to use very intense heat fluxes to heat the surface layer to austenitizing temperatures without unduly affecting the bulk temperature of the workpiece.

In laser surface hardening, as in the electron beam process and high frequency, pulse hardening methods (see article on these self-quenching processes in this chapter), a quenching medium is not needed. Self-quenching occurs when the cold interior of the workpiece is a large enough heat sink to quench the hot surface by heat conduction fast enough to allow the formation of martensite on the surface.

Applications

More than 50 applications of the process have been reported. Materials include plain carbon steels (1040, 1050, 1070), alloy steels (4340, 52100), tool steels, and cast irons (gray, ductile, and malleable types). Reported case depths on steels run from 250 to 750 μm; those on cast irons about 1000 μm.

Reference

1. *ASM Metals Handbook, Heat Treating,* Vol 4, 10th ed., ASM International, 1991, p 286

Electron Beam Hardening

This is a short surface hardening process for martensitically hardenable ferrous materials. Energy for austenitizing is provided by electron beams, Ref 1.

Characteristics

Extremely low hardening distortion and relatively low energy consumption give the metallurgist an alternative to conventional hardening processes. In some instances, the technique is competitive with case hardening and induction hardening processes.

Operating Information

Typical hardening depths range from 0.1 to 1.5 mm (0.004 to 0.006 in.). Rapid cooling of austenite to martensite occurs through self-quenching (see article on process in this chapter). To accommodate self-quenching, workpiece thickness should be at least 5 to 10 times the depth of austenitizing.

Applications

Carbon, alloy, and tool steel applications are listed in the adjoining Table.

Reference

1. *ASM Metals Handbook, Heat Treating,* Vol 4, 10th ed., ASM International, 1991, p 297

Steels Commonly Used in Electron Beam Hardening Applications

Material			Composition, wt%											
AISI	UNS No.	DIN(a)	C	Si	Mn	P	S	Cr	Mo	Ni	V	Al	Cu	Ti
Carbon and low alloy														
4140	G41400	42 CrMo 4	0.38-0.45	0.17-0.37	0.50-0.80	0.035 max	0.035 max	0.90-1.20	0.15-0.25	0.30 max	0.06 max	...	...	...
1340	G13400	42 MnV 7	0.38-0.45	0.17-0.37	1.60-1.90	0.035 max	0.035 max	0.30 max	0.10 max	0.30 max	0.07-0.12	...	...	...
E52100	G52986	100 Cr 6	0.95-1.05	0.17-0.37	0.20-0.45	0.027 max	0.020 max	1.30-1.65	...	0.30 max	...	...	0.25	...
1015	G10150	C 15	0.12-0.19	0.17-0.37	0.35-0.65	0.040 max	0.040 max	0.50 max	0.10 max	0.30 max	...	...	...	...
1045	G10450	C 45	0.42-0.50	0.17-0.37	0.50-0.80	0.040 max	0.040 max	0.50 max	0.10 max	0.30 max	...	...	...	...
1070	G10700	Ck 67	0.65-0.72	0.25-0.50	0.60-0.80	0.035 max	0.035 max	0.35 max	...	0.35 max	...	...	0.35	...
...	...	55 Cr 1	0.52-0.60	0.17-0.37	0.5-0.8	0.035 max	...	0.2-0.5	...	0.3 max	...	0.02-0.05	0.3 max	0.015
...	...	50 CrV 4	0.47-0.55	0.4 max	0.7-1.1	0.035	0.03 max	0.9-1.2	...	...	...	...	...	0.1-0.2
Tool steels														
O2	T31502	90 MnV 8	0.85-0.95	0.15-0.35	1.80-2.00	0.030 max	0.030 max	...	...	...	0.07-0.12	...	...	...
W1	T72301	C 100 W1	0.95-1.04	0.15-0.30	0.15-0.25	0.020 max	0.020 max	0.20 max	...	0.20 max(b)	...	...	...	...

(a) Deutsche Industrie-Normen. (b) 0.25 max Cu

Steel Quenching Technology

Introduction

"Quenching is one of the least understood of the various heat treating technologies," in the words of a world authority on the subject, George E. Totten of Union Carbide Chemical & Plastics Co., Inc.

Other dimensions of the problem are identified in the following quotes from other experts:

- "Quenching is critically important, but often the neglected part of heat treating."
- "Quenching is the most critical part of the hardening process... [it] must be designed to extract heat from the hot workpiece at a rate required to produce the desired microstructure, hardness, and residual stresses."
- "Distortion is perhaps one of the biggest problems in heat treating... little information on the subject has been published."

The subject was introduced in the previous chapter by two articles on the subject: "Causes of Distortion and Cracking in Quenching" and "Stress Relief Heat Treating."

In this section, the topic is surveyed in depth in eight articles on conventional quenching processes:

- Air quenching
- Water quenching
- Oil quenching
- Polymer quenching
- Molten salt quenching
- Brine quenching
- Caustic quenching
- Gas quenching

In addition, 17 alternative methods of quenching are discussed in articles:

- Austempering
- Martempering
- Isothermal quenching
- Aus-bay quenching
- Spray quenching
- Fog quenching
- Cold die quenching
- Press quenching
- Vacuum quenching
- Fluidized bed quenching
- HIP quenching
- Ultrasonic quenching
- Quenching in electric and magnetic fields
- Quenching flame and induction hardened parts
- Self-quenching processing—electron beam hardening, laser hardening, and high frequency pulse hardening

References

1. George E. Totten, preface to ASM Conference Proceedings, "Quenching and Distortion Control," ASM International, '92
2. Totten et al, "Handbook of Quenchants and Quenching Technology," ASM International, '93

Air Quenching Process

Air is the oldest, most common, least expensive quenching medium, Ref 1.

Characteristics of Process

Air, a gas high in nitrogen, cools by extended vapor phase cooling.

Operating Information

As with other quenchants, heat transfer rates are dependent on flow rate—in this instance, flow rate of air past the hot part (see Figure). Cooling can be speeded up by increasing the velocity of air flow, but the accelerated rate is not sufficient to quench harden many steels. The ability of air to harden plain carbon steels drops dramatically with increasing carbon content (see Figure).

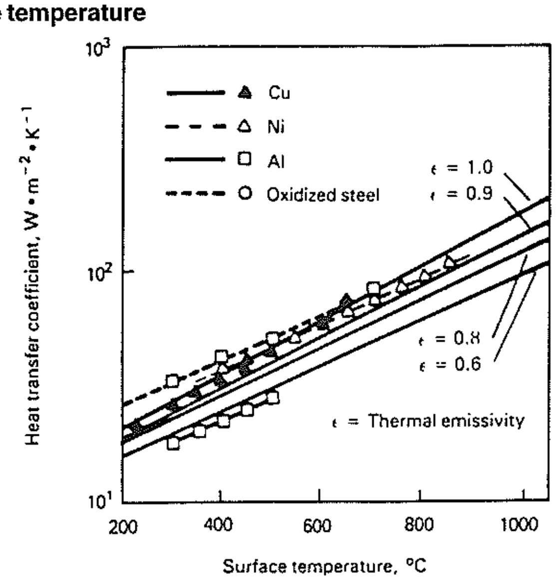
Application Range

Air is used in quenching steel and several nonferrous metals. The comparative heat transfer coefficients of different metals as a function of surface temperature are shown in an adjoining Figure. To get optimal hardness, it is often necessary to use a more active quenching medium, such as brine or oil.

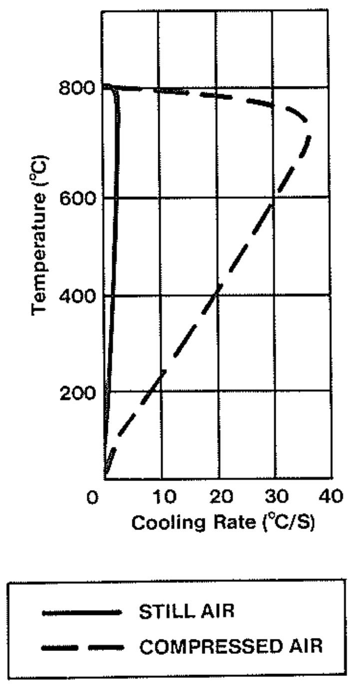
Reference

1. Totten et al, *Handbook of Quenchants and Quenching Technology,* ASM International, 1993

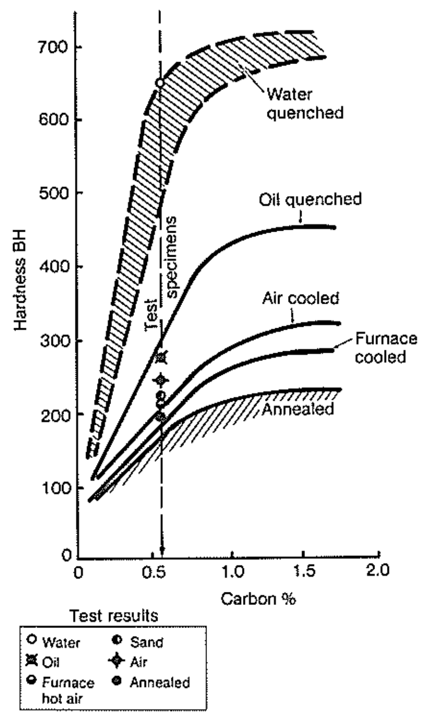
Heat transfer coefficients for air cooling as a function of surface temperature



Cooling capacities of still and compressed air



Hardness values obtained with different quenching media



Water Quenching Process

Like air, water is an old, common, inexpensive quenchant (Ref 1). It is applied in several ways: in straight, immersion quenching; in a special, double-step, hot water quenching process; and in conjunction with polymer quenchants and with brine quenchants.

Characteristics of Process

Water, especially cold water, is one of the most severe quenching media available. Vigorously agitated water produces a cooling rate approaching the maximum with liquid quenchants (Ref 2). As water temperature rises, the vapor phase is prolonged and the maximum rate of cooling drops sharply (see Figure).

Operating Information

Generally, good results are obtained in straight immersion quenching by maintaining water temperatures in the range of 15 to 25 °C (60 to 75 °F) and by agitating water to velocities greater than 0.25 m/s (50 ft/min). Water temperature, agitation of water, and amount of contamination in the water must be controlled. The comparative cooling properties of hard water and distilled water are indicated in an adjoining Figure.

The detrimental effect of temperature dependence and vapor phase stability can be minimized (Ref 3) by:

- Maintaining water at a low temperature through cooling
- Vigorous agitation to disperse the vapor blanket
- Addition of an organic salt (see Brine Quenching)

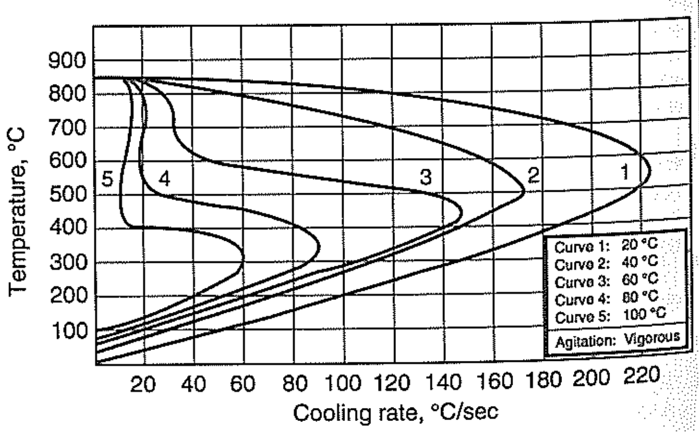
Double-step, hot water quenching is a possible alternative to lead patenting of steel wire. It consists of:

- Heating wire to 920 to 950 °C (1690 to 1740 °F) and immersing into boiling hot water for an appropriate time
- Removing wire from water and air cooling (Ref 1)

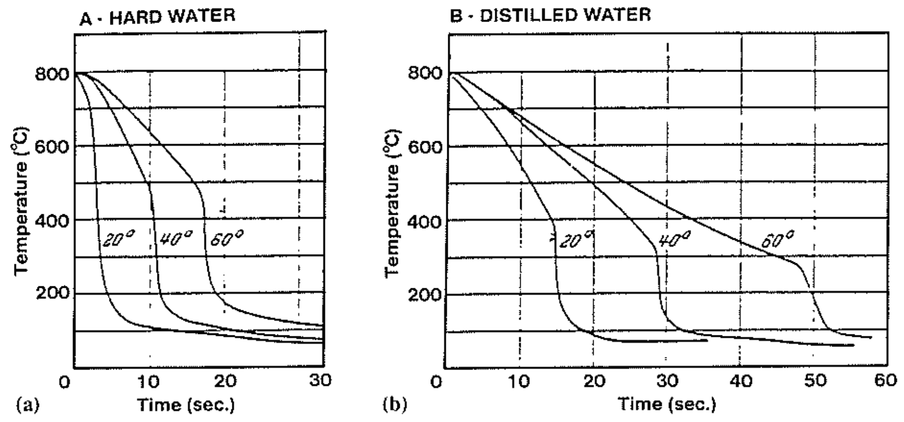
Application Range

Water is the choice where a severe quench does not result in excessive distortion and cracking. Use generally is restricted to quenching simple, symmetrical parts made of shallow hardening grades of steel. Other applications include austenitic stainless steels and other metals that have been solution treated at elevated temperatures.

Effect of temperature on quenching properties of water. Source: E.F. Houghton & Co.



Cooling curves for hard water and distilled water



References

1. Totten et al., *Handbook of Quenchants and Quenching Technology,* ASM International, 1993
2. *ASM Metals Handbook, Heat Treating,* Vol 4, 10th ed., ASM International, 1991
3. *Houghton on Quenching,* E.F. Houghton & Co., Valley Forge, PA

Oil Quenching Process

All modern quenching oils are based on mineral oil, usually paraffin based, and do not contain fatty oils.

Usage of oils opens up a number of options for the heat treater:

- Normal-speed oil for treating steels high in hardenability
- Medium-speed oils for medium hardenability steels
- High-speed oils for treating low hardenability steels and for other applications
- Hot oil quenching (also called marquenching or martempering) provides another option
- Water-washable quenching oils: for removing oils on treated parts with plain water

Characteristics of Process

Oils are characterized in various ways, depending upon operating requirements. Quenching speed and operating temperature are among these considerations.

The importance of quenching speed is that it influences hardness and depth of hardening. Cooling rate curves for normal-, medium-, and high-speed quenching oils are shown in an adjoining Figure (Ref 1). Cooling curves for different quenchants are given in an adjoining Figure (Ref 2).

Almost all quenching oils produce lower quenching rates than water or brine solutions, but they remove heat from workpieces more uniformly than water normally does, meaning less likelihood of distortion and cracking (Ref 3).

Temperature of operation is important because it influences:

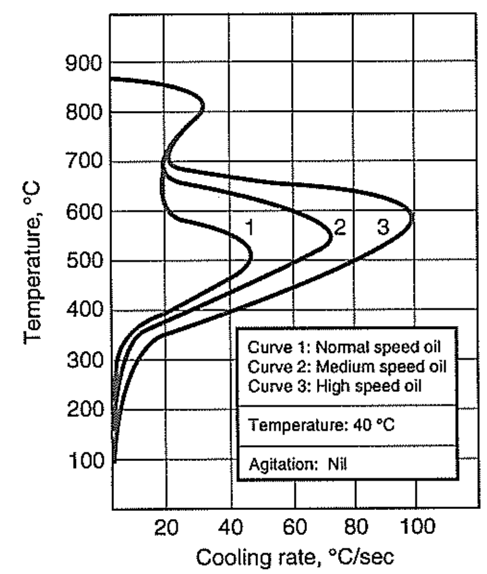
- Oil life
- Quenching speed
- Viscosity of oil
- Distortion of workpieces

Effect of temperature on quenching speed for a hot quenching oil is shown in an adjoining Figure (Ref 1).

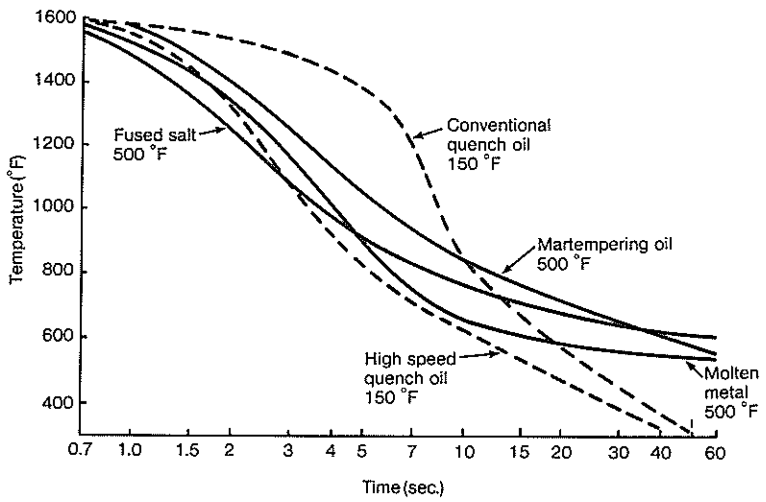
Changes in viscosity can indicate oxidation and thermal degradation, or the presence of contaminants. In general, viscosity goes up as an oil degrades and can result in changes in quenching speed.

Flash point, another consideration, is the lowest temperature at which oil vapors ignite in the presence of an ignition source; it is important because

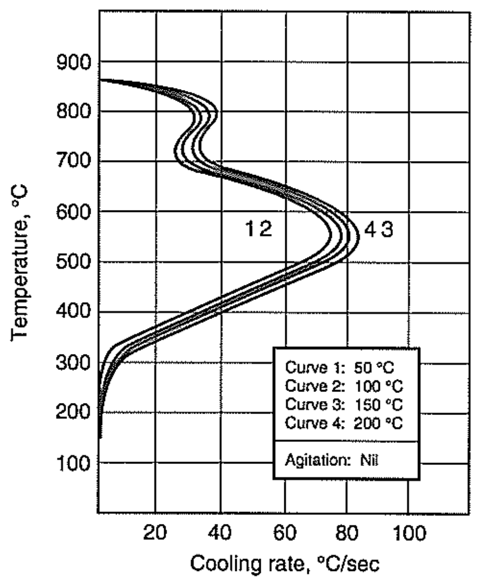
Cooling rate curves for quenching oils. Source: E.F. Houghton & Co.



Cooling rates for different quenchants



Effect of temperature on quenching speed of hot oil. Source: E.F. Houghton & Co.



Characteristics of Quenching Oils

Type of oil	Bath temperature °C	Bath temperature °F	Flash point °C	Flash point °F	Typical viscosity at 40 °C (100 °F), SUS	GM quenchometer (nickel ball) time, s	Hot-wire test, A
Conventional	<65	<150	170	340	105	16.0	30
Accelerated	<120	<250	180	355	94	10	39
Marquenching	<200	<400	300	570	700	30	30

Use Temperatures for Marquenching Oils

Viscosity at 40 °C (100 °F), SUS	Minimum flash point °C	Minimum flash point °F	Use temperature: Open air °C	Open air °F	Protective atmosphere °C	Protective atmosphere °F
250-550	220	430	95-150	200-300	95-175	200-350
700-1500	250	480	120-175	250-350	120-205	250-400
2000-2800	290	550	150-205	300-400	150-230	300-450

it is related to the maximum safe operating temperature—usually 40 to 50 °C (74 to 90 °F) below the open cup flash point for oil.

Operating Information

Data on the use temperatures for conventional, accelerated, and marquenching oils are given in an adjoining Table and use temperatures for marquenching oils are given in a second Table (Ref 2).

Applications based on oil speed are as follows:

- Normal-speed oils: used where the hardenability of a steel is high enough to provide specified mechanical properties with slow cooling. Typical applications are highly alloyed steels and tool steels
- Medium-speed oils: typical applications are medium- to high-hardenability steels
- High-speed quenching oils: for low hardenability alloys, carburized and carbonitrided parts, and medium hardenability steel parts large in cross section that require very high rates of cooling to get maximum mechanical properties

Hot oil quenching: for applications where it is desirable to keep distortion and cracking to a minimum. It is a two-step operation:

- Operating temperature generally of the oil is 100 to 200 °C (210 to 390 °F).
- Operating temperature is held until the temperature throughout the workpiece is uniform.
- Workpieces are then air cooled to ambient temperature.

References

1. *Houghton on Quenching,* E.F. Houghton & Co., Valley Forge, PA
2. Totten et al., *Handbook of Quenchants and Quenching Technology,* ASM International, 1993
3. *ASM Metals Handbook, Heat Treating,* Vol 4, 10th ed., ASM International, 1991

Polymer Quenchants

Around 20 different aqueous polymers, it's reported, have been used in quenching steels (Ref 1). They include:

- Polyvinyl alcohol (PVA)
- Polyalkylene glycol (PAG)
- Sodium polyacrylate (ACR)
- Polyvinyl pyrrolidone (PVP)
- Polethyl oxazoline (PEO)

PAG is No. 1 in usage today

Characteristics

Inverse solubility in water is a key characteristic of a number of polymer quenchants, including PAG's, because this phenomenon modifies the conventional, three-stage quenching mechanism, providing flexibility in cooling rate. These polymers are completely soluble in water at room temperature, but insoluble at elevated temperatures, ranging from 60 to 90 °C (140 to 195 °F).

When a hot part is first immersed in a quenchant bath, the quenchant in the immediate vicinity of the hot metal surfaces becomes insoluble and deposits itself on the part in the form of a polymer-rich film.

The film acts as an insulator, which slows down cooling to a rate analogous to that of oil in the vapor phase. In a number of applications, the quenching rates of aqueous polymers are intermediate between those of water and oil (see adjoining Table).

In stage 2 of cooling (boiling phase), the film eventually collapses and the quenchant comes into contact with the hot metal, resulting in nucleate boiling and high heat extraction rates.

In the final stage, cooling is by conduction and convection into the liquid. When metal surface temperatures fall below the inversion temperature, i.e., 75 s, the polymer redissolves and forms a homogeneous polymer-water mixture.

Operating Information

Cooling rates can be tailored to requirements by changing the concentration of the solution, quenchant temperature, and degree of agitation of the bath.

Concentration influences film thickness; with increasing concentration, the maximum rate of cooling and the cooling rate in the convection phase drop (see Figure). Agitation of the quenchant has little effect during the film stage.

Wettability of workpiece surfaces is improved with 5% solutions of PAG, which is beneficial to quench uniformity. At this concentration, problems with soft spotting associated with water quenching are avoided.

Concentrations in the 10 to 20% range accelerate cooling rates to the level of fast quenching oils. These concentrations are suitable for quenching low hardenability steels requiring maximum mechanical properties.

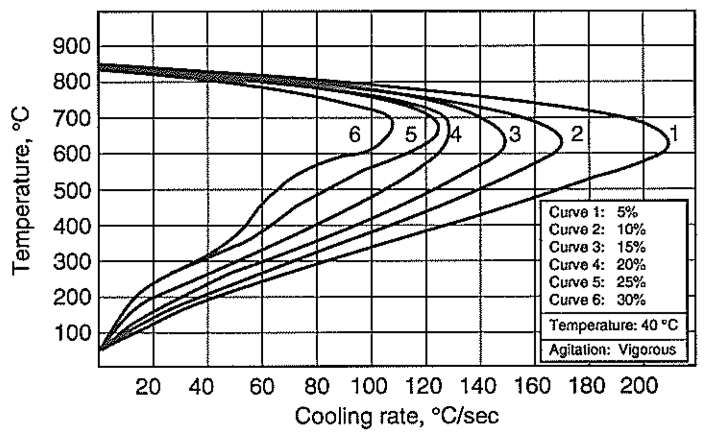
Concentrations of 20 to 30% boost cooling rates suitable for a wide range of through hardening and case hardening steels.

Bath temperature has an influence on the quenching speed of solutions. The effects of three different temperatures on a 25% PAG concentration with vigorous agitation is shown in an adjoining Figure. The maximum cooling rate decreases with increasing temperature. PAG solutions must be

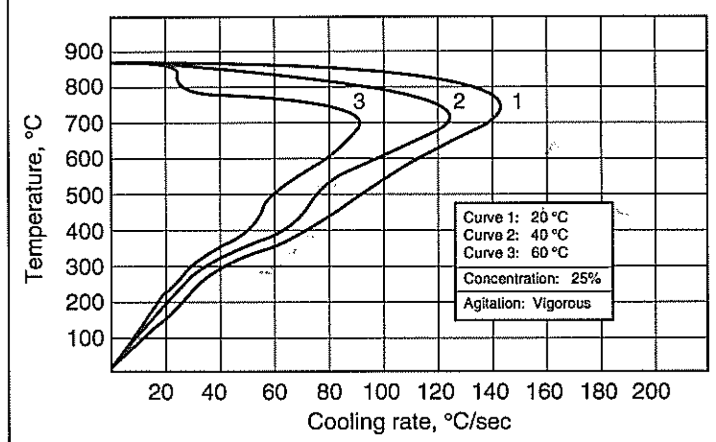
Typical Quench Severities Achievable with Various Media

Quenchant	Grossmann *H* factor
Oil	0.25-0.8
Polymer	0.2-1.2
Water	0.9-2.0
Brine	2.0-5.0

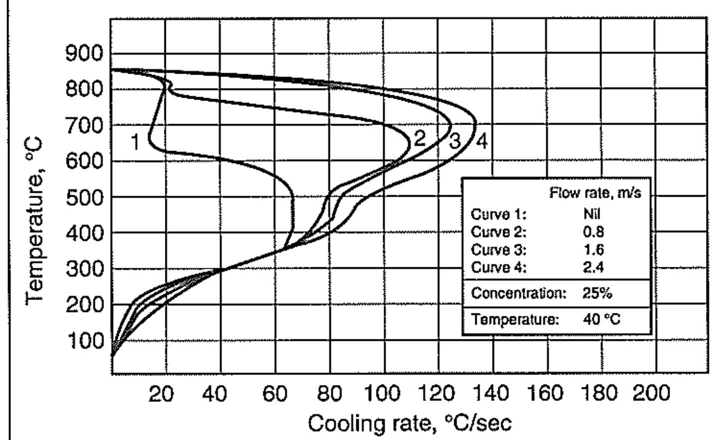
Effect of PAG concentration on quenching characteristics



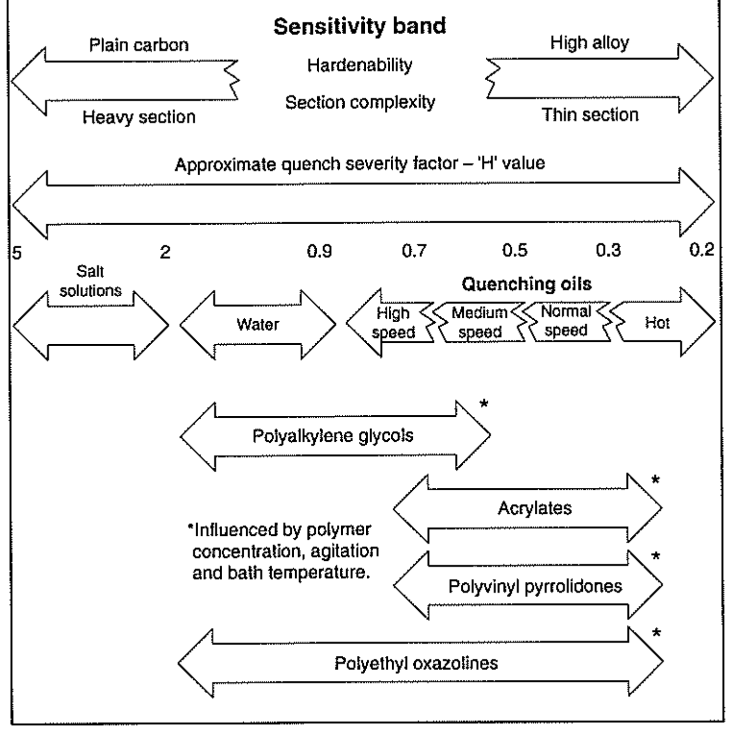
Effect of PAG-water temperature on quenching characteristics



Effect of agitation on quenching characteristics of PAG solution



Sensitivity band for quenchant selection



cooled to prevent them from reaching the inversion temperature. A maximum operating temperature of approximately 55 °C (130 °F) normally is recommended.

Agitation has an important effect on all polymer quenchants, by ensuring a uniform temperature distribution within the bath; it also affects cooling rate (see Figure). As the severity of agitation increases, the duration of the vapor phase (film phase) is shortened and eventually disappears. During the convection phase, agitation has comparatively little effect.

PAG's are used in immersion quenching of steel parts, in induction hardening, and in spray quenching. Applications of other polymers include forgings, open tank quenching of high hardenability steels, use in integral quenching furnaces, patenting of high-carbon steel wire and rod, and in quenching railroad rails.

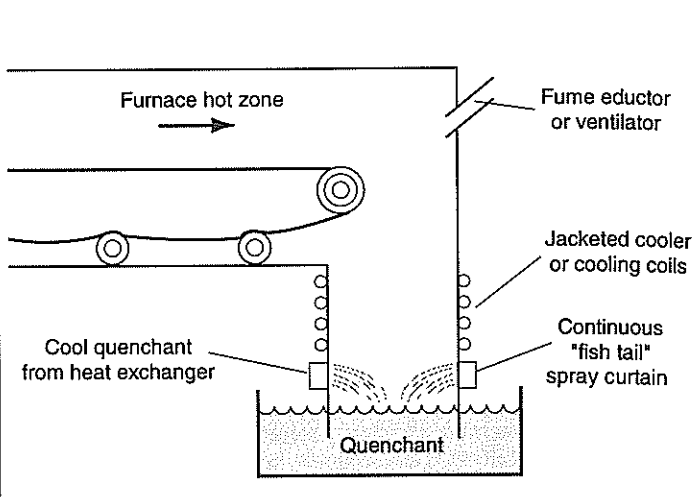
Guidelines for Selecting Polymers

Considerations generic to polymer quenchants include:

- Material composition
- Section size of workpiece
- Type of furnace
- Quenching system design
- Method of quenching
- Distortion control

Material composition and section size play critical roles in quenchant selection (see Figure). Note that this figure provides guidelines for selecting polymer quenchants based on such considerations as hardenability of the steel, section size, quench severity factors, and polymer selection per applications. Alloy content influences hardenability, which determines the quenching speed needed to get a specified hardness and other properties.

Spray curtain in quenching chute



Section size and complexity affect quenching speed requirements. Heavy section parts are quenched faster than those with thin sections to get equivalent results.

Furnaces used in oil quenching may require modification for polymer quenching, and certain precautions are observed.

The design of integral quench furnaces, for example, may require modification to minimize the possible effects of water vapor in furnace atmospheres. Changes include ensuring a good inner door seal and the maintenance of positive gas pressure in the hot zone.

Spray curtains are needed in the quenching chutes of continuous furnaces to prevent contamination of the furnace atmosphere with water vapor (see Figure).

A precaution: polymer quenching of steel parts previously treated in salt baths generally is not recommended due to the effects of the carryover of high-temperature salt.

Aqueous polymer quenchants are recommended for parts treated in induction heating.

Quenching system design can have an influence on quenching characteristics. Examples include design features relating to agitation, method of circulating quenchants, and fluid temperature controls.

Method of quenching can directly affect cooling rates and the results obtained in quenching.

Direct Quenching. This technique is commonly used in quenching with aqueous polymers in many different types of furnaces.

Time or Interrupted Quenching. This technique is used to change the cooling rate during quenching, i.e., quenching a large forging in water for a specified time, then transferring the workpiece to a polymer quenchant to reduce cooling in the convection phase. An alternative practice, used to reduce quench cracking and distortion, is to quench first in a polymer solution, followed by an air quench.

In spray quenching quenchant characteristics are influenced by the volume and pressure of the quenchant and by spray nozzle design.

Distortion control is needed in quenching thin or complex section workpieces. Use of a slower quenchant is one of the control techniques.

References

1. Totten et al., *Handbook of Quenchants and Quenching Technology*, ASM International, 1993
2. *Houghton on Quenching*, E.F. Houghton & Co., Valley Forge, PA

Molten Salt Quenching Process

These salts usually are the medium of choice for high-temperature quenching. They are either binary or ternary mixtures of potassium nitrate (KNO_3), sodium nitrite ($NaNO_2$), and sodium nitrate ($NaNO_3$), Ref 1.

Characteristics

Minimum quenching temperatures depend on the melting point of the salt mixture, which depends on the composition of the mixture (see Figure); the ratio of the salt mixture may also affect the viscosity of the medium, which, in turn, affects cooling.

Operating Information

Quenching temperatures of the bath range from 140 to 600 °C (285 to 1110 °F), but salt melting points as low as 80 °C (175 °F) can be obtained with additions of up to 10% water.

Control of bath temperature is critical (see Table). Salt baths are subject to potential explosive degradation at temperatures above 600 °C (1110 °F). Care is also advised in making water additions, because they are accompanied by spattering of the molten salt. In one safety procedure, additions are made very slowly and bath temperatures are held below 175 °C (345 °F). An automatic additive device and probe monitoring system (see Figure) is an alternative. Controlled additions of specific amounts of salt are made in a temperature range of 180 to 250 °C (355 to 480 °F).

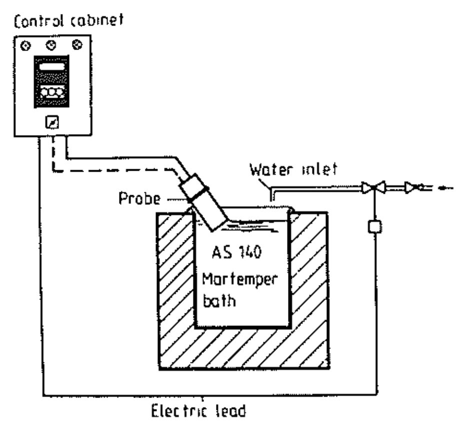
Another consideration: salt can absorb water from a humid environment at room temperature when a quenching system is not in use. Before normal operations are resumed, heating the bath to 95 °C (205 °F) until all water is removed is a general recommendation.

Effect of Salt Temperature on Quench Severity(a)

Salt temperature, °C	Salt temperature, °F	Grossmann H factor, in.$^{-1}$ Center	Grossmann H factor, in.$^{-1}$ Surface
195	385	0.46	0.63
200	390	0.45	0.65
230	450	0.40	0.65
270	515	0.45	0.64
295	560	0.41	0.57
350	660	0.43	0.58

(a) A KNO_3-$NaNO_2$ salt with a melting point of 135 °C (275 °F) was used with no agitation.

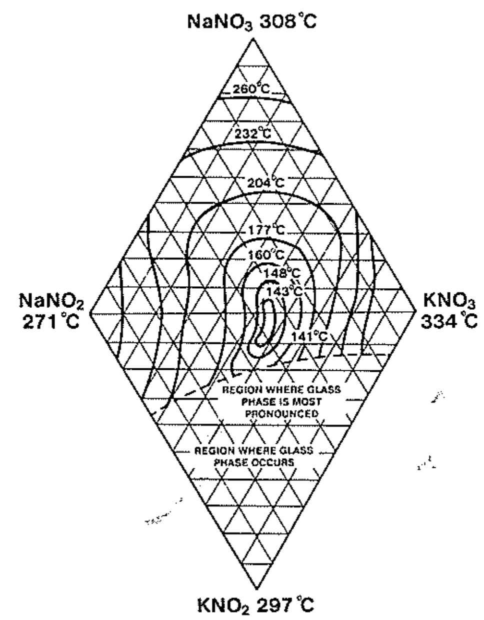
Degussa system for adding water to molten salt



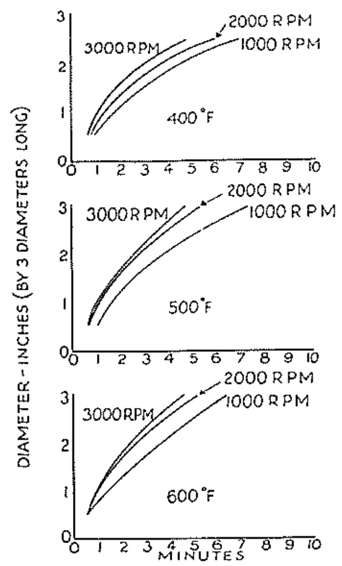
Like all quenchants, the heat extraction capabilities of molten salt depend on the agitation rate of the bath (see Figure). Agitation is applied in several ways. One approach is shown in an adjoining Figure.

In heat treating it is common for steel to be austenitized in a high-temperature salt bath composed of a binary blend of $KNO_3/NaNO_3$, or a ternary chloride blend, such as KCl/LiCl/NaCl. When austenitization is completed, the workpiece is quenched in a lower temperature, ternary blend of $KNO_2/NaNO_2/NaNO_3$.

Freezing points of ternary alkali nitrate-nitrite mixtures given in percent



Effect of agitation on quench severity of molten salt



Application Range

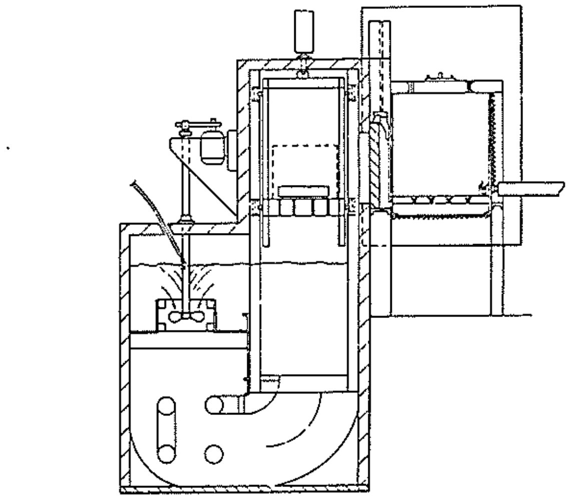
Molten salt quenching applications include:

- Martempering and austempering (see items on both subjects in this chapter)
- Quenching high-alloy steels
- Quenching high-speed steel tools, to minimize scaling, distortion, and cracking
- Quenching steels such as spring wire to reduce the risk of cracking during martensitic formation
- Quenching to enhance the formation of high-temperature transformation products, such as bainite and ferrite.

Reference

1. Totten et al., *Handbook of Quenchants and Quenching Technology,* ASM International, 1993

Dual impeller salt bath agitation system



Brine Quenching Process

The term refers to aqueous solutions containing different percentages of salts such as sodium chloride (NaCl) or calcium chloride (CaCl).

Characteristics

Cooling rates are higher than those of water for the same degree of agitation, or, alternately, less agitation is needed to get a given cooling rate. Higher cooling rates reduce the possibility of steam, the cause of soft spots in quenching, but higher cooling rates generally increase the likelihood of distortion and cracking. Use of baffling patterns on quench tanks and propeller agitation may be needed in quenching very lower hardenability steels (Ref 2).

In quenching, minute salt crystals are deposited on the surfaces of workpieces. Localized high temperatures cause crystals to fragment violently, creating turbulence that destroys the vapor phase, resulting in very high cooling rates.

Operating Information

Brine concentration is expressed in several ways (see Table). Both sodium chloride and sodium hydroxide, the latter a caustic solution, are covered in the Table.

Brine concentrations up to 24 percent progressively reduce the vapor phase, but such concentrations generally are considered impractical. A 10 percent solution of NaCl is quite effective in hardening. The relationship of brine concentration to hardness is indicated in an adjoining Figure. It is necessary to monitor brine concentration to get reproducible results in quenching.

Cooling properties are not seriously affected by small variations in the operating temperatures. Brines can be used at temperatures near that of boiling water, but their maximum cooling power is at a temperature of approximately 20 °C (70 °F). Effects of temperature on cooling power are indicated in an adjoining Figure.

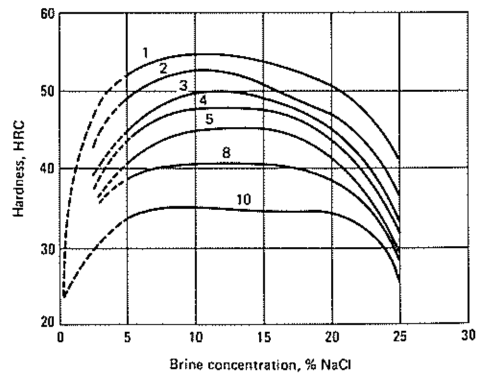
Sludge and scale should be removed from baths periodically. They can clog pumps and recirculating systems and reduce cooling rates. Excess water reduces solution strength and cooling power.

Relation of Brine Density to Brine Concentration (Ref 2)

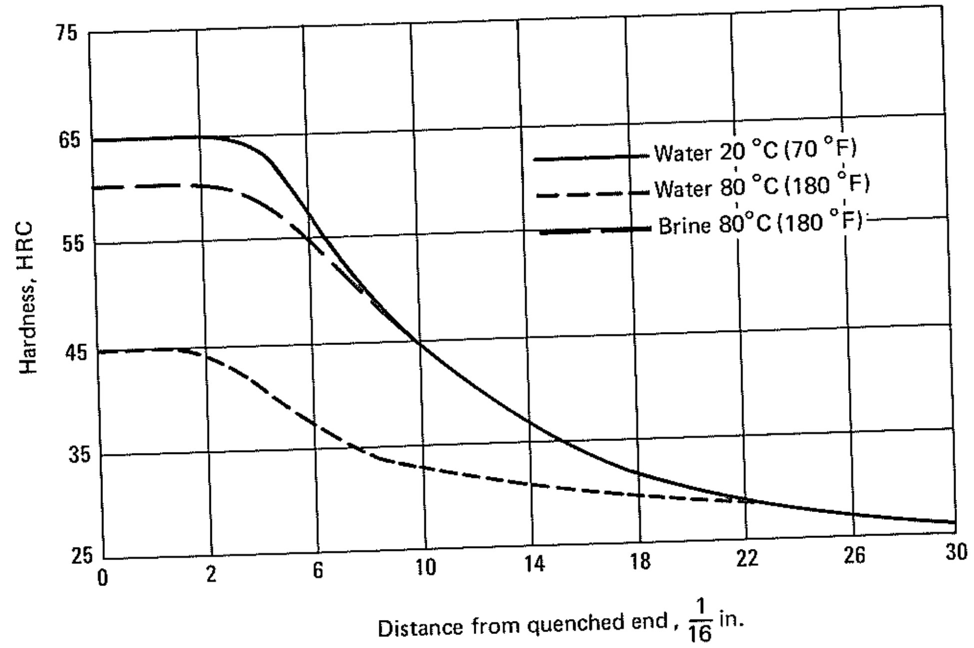
	Specific gravity		Salt concentration	
Salt, %	Direct reading hydrometer	°Bé(a)	g/L	lb/gal
NaCl solutions				
4	1.0268	3.8	41.1	0.343
6	1.0413	5.8	62.4	0.521
8	1.0559	7.7	84.5	0.705
9	1.0633	8.7	95.9	0.800
10	1.0707	9.6	107.1	0.894
12	1.0857	11.5	130.3	1.087
NaOH solutions				
1	1.0095	1.4	10.1	0.0842
2	1.0207	2.9	20.4	0.1704
3	1.0318	4.5	31.0	0.2583
4	1.0428	6.0	41.7	0.3481
5	1.0538	7.4	52.7	0.4397

(a) °Bé, Baumé; specific gravity for liquids heavier than water is 145/(145 – *n*), where *n* is reading on Bé scale in °Bé

Relation of hardness to brine concentration when still-quenching, end quench specimens 90 °C (195 °F) brine solution. Number above curves indicate distance from quenched end in units of 1/16 in. (Ref 2).



Relation of hardness to distance from quenched end of specimens quenched in water and brine. Cooling power of brine is greater than that of water at 80 °C (175 °F) (Ref 2).



References

1. Totten et al., *Handbook of Quenchants and Quenching Technology,* ASM International, 1993
2. *ASM Metals Handbook, Heat Treating,* Vol 4, 10th ed., ASM International, 1991

Caustic Quenching Process

The most common alternative to sodium chloride quenching is aqueous sodium hydroxide (a caustic) in concentrations ranging from 5 to 10 percent (Ref 1).

Characteristics

Cooling rates are similar to those of sodium chloride at high surface temperatures. Slower cooling rates than those available with sodium chloride are obtained in the martensitic transformation temperatures for many steels (<350 °C, or 660 °F), which would be expected to reduce susceptibility to cracking.

Operating Information

The effect of NaOH concentration on cooling rate, at a bath temperature of 20 °C (70 °F), is shown in an adjoining Figure. The effects of 1 to 5 percent concentrations of NaOH are shown in an adjoining Table. In practice, aqueous solutions are in the 5 to 10 percent range.

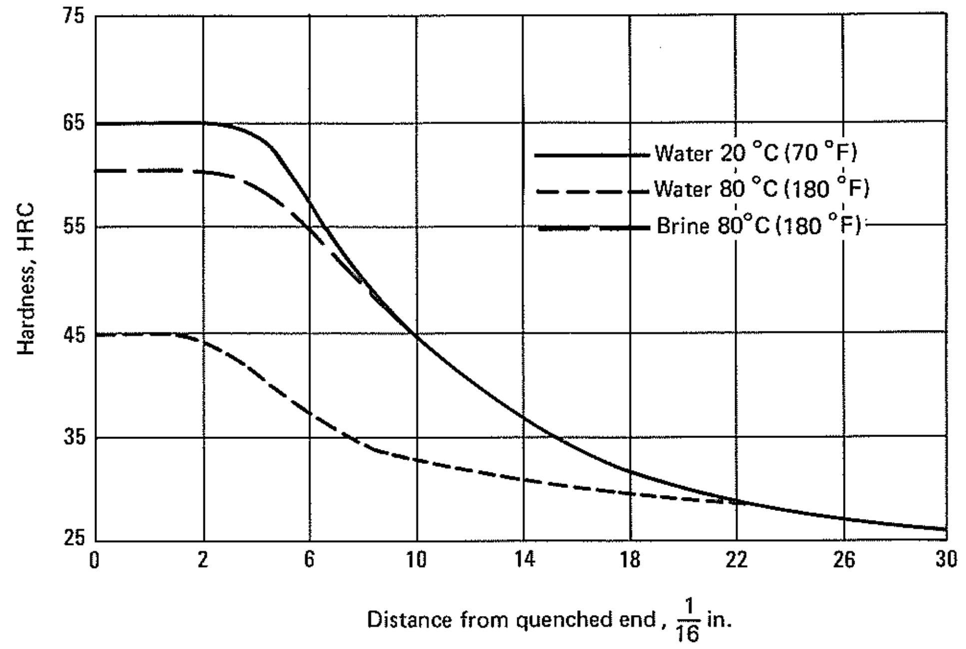
Comparatively, NaCl solutions are considered to be safer, less costly, and easier to handle than NaOH solutions. The main shortcoming of the latter is that its high alkalinity is harmful to human skin (Ref 2).

Relation of Brine Density to Brine Concentration of NaCl and NaOH Solutions

	Specific gravity		Salt concentration	
Salt, %	Direct reading hydrometer	°Bé(a)	g/L	lb/gal
NaCl solutions				
4	1.0268	3.8	41.1	0.343
6	1.0413	5.8	62.4	0.521
8	1.0559	7.7	84.5	0.705
9	1.0633	8.7	95.9	0.800
10	1.0707	9.6	107.1	0.894
12	1.0857	11.5	130.3	1.087
NaOH solutions				
1	1.0095	1.4	10.1	0.08[illegible]
2	1.0207	2.9	20.4	0[illegible]
3	1.0318	4.5	31.0	
4	1.0428	6.0	41.7	
5	1.0538	7.4	52.7	

(a) °Bé, Baumé; specific gravity for liquids heavier than water *n* is reading on Bé scale in °Bé

Effect of NaOH concentration on cooling rate



References

1. Totten et al., *Handbook of Quenchants and Quenching Technology,* ASM International, 1993
2. *ASM Metals Handbook, Heat Treating,* Vol 4, 10th ed., ASM International, 1991

Gas Quenching Process

Atmospheres containing some hydrogen or helium are commonly used. Nitrogen is among the alternatives. Gases are also used in vacuum quenching.

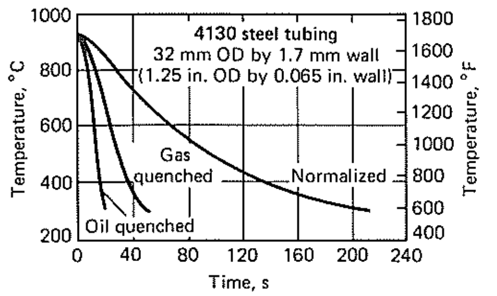
Characteristics

Cooling rates are faster than those in still air and slower than those obtained with oil. Austenitized workpieces are placed directly in the quenching zone and heat is extracted by a fast-moving stream of gas (Ref 1).

Operating Information

The cooling rate of the metal being treated is related to surface area and mass of a part, as well as the type, pressure, and velocity of the cooling gas.

Cooling curves in quenching 4130 steel in gas, oil, and still air (normalizing)

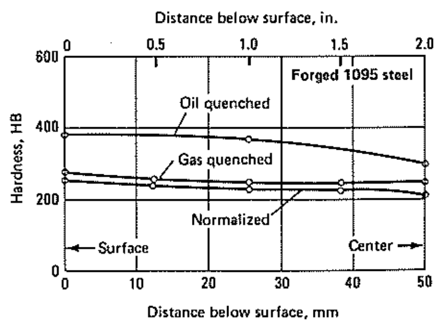


Cooling rate is adjusted and controlled by altering the type, pressure, and velocity of the gas.

In quenching, large volumes of gas are directed through nozzles or vanes to impinge on the workpiece. After the gas absorbs heat from the hot workpiece, it is cooled by being passed through water-cooled or refrigerated coils. Recirculating fans return gas to the nozzles, through which they are again directed at the workload.

Quenching units are of the batch or continuous types, and the former are most commonly used.

Brinnel hardness of forged, 1095 steel disks 100 mm (4 in. thick) after oil quenching, gas quenching (forced air), and cooling in still air (normalizing)



Application Range

In some instances quenching in still gas is too slow and oil quenching is not desirable for such reasons as distortion, cost, handling problems, or insufficient final hardness. Quenching in a fast-moving stream of gas is a compromise.

The process is used, for example, in hardening aircraft tubing, steels that are not air hardenable, and tool steels.

Data on quenching 4130 aircraft tubing are found in an adjoining Figure.

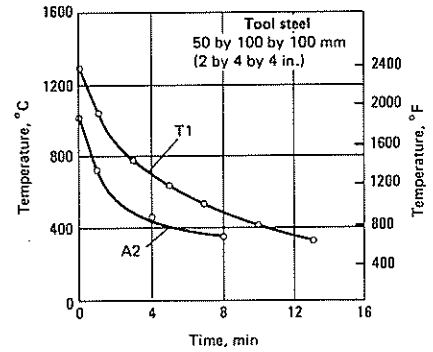
Data on steel that is not air hardenable (forged 1095 steel in this instance) are presented in an adjoining Figure.

In the tool steel example, A2 and T1, in the form of solid blocks 50 by 100 by 100 mm (2 by 4 by 4 in.), were gas quenched with cylinder nitrogen in a vacuum furnace. Cooled gas was admitted to the chamber at 69 kPa (10 psig). As indicated in an adjoining Figure, A2 was cooled from 1010 to 345 °C (1850 to 655 °F) in 8 min, and T1 was cooled from 1290 to 345 °C (2355 to 655 °F) in 13 min. In both instances, cooling rates were suitable for maximum hardness.

Reference

1. *ASM Metals Handbook, Heat Treating,* Vol 4, 10th ed., ASM International, 1991

Surface cooling curves for blocks made of types 11 and A2 tool steels quenched from austenitizing temperatures by cooled nitrogen in a vacuum furnace



Other Quenchants/Processes

ntroduction

A number of alternatives to standard quenchants/processes are available, ıcluding:

- Vacuum quenching
- Self-quenching processes (high frequency, pulse hardening; electron beam process, and laser process)
- Fluidized bed quenching
- Ultrasonic quenching
- HIP quenching
- Spray quenching
- Fog quenching
- Cold die quenching
- Quenching in an electric or magnetic field

In addition, some processes are uniquely suited for quenching parts surface hardened in a specific process, such as quenchants for flame and induction hardened workpieces.

/acuum Quenching

Parts can be quenched in vacuum furnaces, but heat transfer rates are ːlatively slow (5.7 W/m^2 · K, or 3.6 Btu/h · °F) in comparison with those f oil, helium, nitrogen, and air (see adjoining Table and Figure, Ref 1).

;haracteristics of Process

Alternative quenches must be used to make vacuum quenching viable.)ther media include oil, aqueous polymers, and gas. Gas is the most ommonly used. In fact, the fastest growing technology in heat treating is as quenching in a vacuum furnace (Ref 1).

)perating Information, Quenching with Gas

In this procedure, the furnace is pressurized with gas after the heat ·eating step is completed—this is called backfilling.

The two main factors affecting quench severity are gas velocity and gas ressure (see adjoining Figures).

Gas quenching usually is done with nitrogen, argon, helium, or hydro-en. Physical properties of quenching gases are listed in an adjoining Table. ːecently developed applications are based on gas mixtures, such as nitro-en/helium. Gas blending is a cost-effective way of getting heat transfer ates greater than those available with helium alone.

High pressure gas quenching (helium at a pressure of 20 bar) can produce uench severities comparable to those of conventional, recirculated oil. At ·ery high pressures (hydrogen at 50 bar) heat transfer coefficients are ;reater than those of water.

;omparison of Heat Transfer Coefficients of Various /ledia

)uenchant	Heat transfer coefficient(λ), W/m^2 · K
;as, recirculated (1000 mbar N_2)	100-150
;as, overpressure, high velocity	300-400
ːalt bath (550 °C, or 1020 °F)	350-450
'luidized bed	400-500
ːtationary oil (20-80 °C, or 70-175 °F)	1000-1500
ːecirculated oil (20-80 °C, or 70-175 °F)	1800-2200
Vater (15-25 °C, or 60-75 °F)	3000-3500

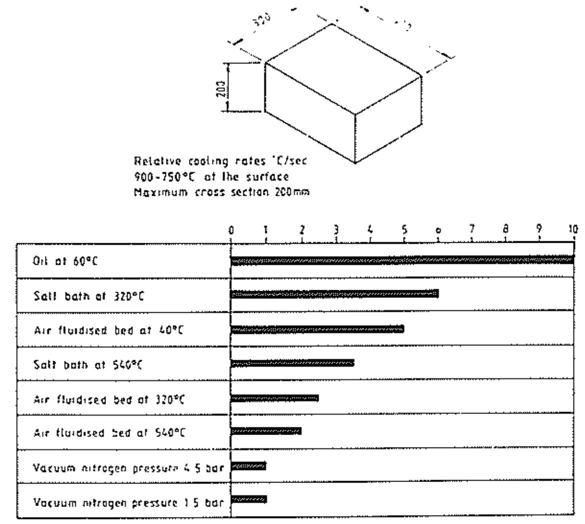
Vacuum Quenching in Oil

With the exception of relatively high pressure (>20 bar) gas quenching, quench severities with gas are limited to those up to, but usually not including, conventional oil. When lower hardenability alloys are heat treated in vacuum furnaces, more quench severity is needed, which is the niche for oil.

Reference

1. Totten et al., *Handbook of Quenchants and Quenching Technology,* ASM International, 1993

Quench severities of different media

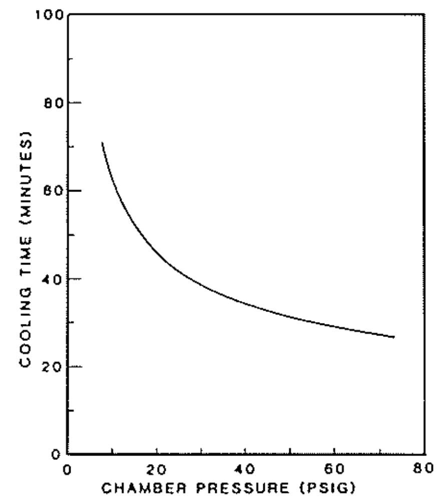


Physical Properties of Quenching Gases

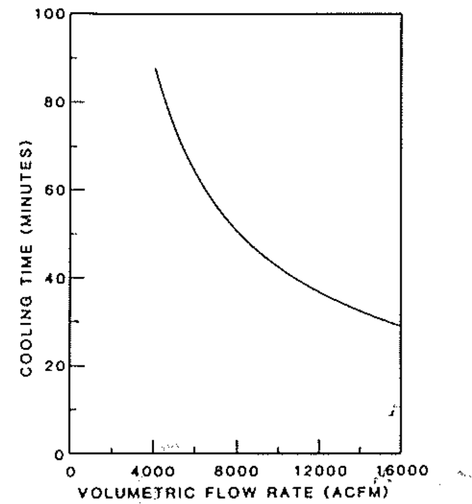
Property	Quenching gas: Argon	Nitrogen	Helium	Hydrogen
Density, kg/m^3 at 15 °C/1 bar	1.6687	1.170	0.167	0.0841
Density ratio, *w/r*, to air	1.3797	0.967	0.138	0.0695
Molar mass, kg/mol	39.948	28.0	4.0026	2.0158
Specific heat(a), kJ/kg · K	0.5204	1.041	5.1931	14.3
Thermal conductivity(a), W/m · K	177×10^{-4}	259×10^{-4}	1500×10^{-4}	1869×10^{-4}
Dynamic viscosity(a), N · s/m^2	22.6×10^{-6}	17.74×10^{-6}	19.68×10^{-6}	892×10^{-6}

(a) Gas conditions: 25 °C, 1 bar. Source: Ref 62

Effect of chamber pressure at constant volumetric rate on cooling time



Effect of volumetric flow rate of gas at constant density on cooling time



Self-Quenching Processes

In this category are high frequency pulse hardening (Ref 1), electron beam, and laser processes (Ref 2).

Self-quenching occurs when the cold interior of a workpiece is a sufficiently large heat sink to quench hot surfaces by heat conduction to the interior at a rate fast enough to allow martensite to form at the surface.

Heat sources are the laser, electron beam, and inductive electric heating.

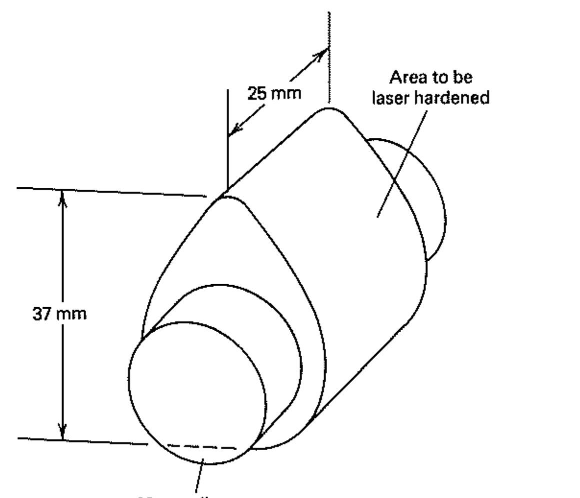
In pulse hardening with induction heating, for example, power density is up to about 300 W/mm^2, and heat treatment is in the millisecond range (Ref 1). With each process, areas treated are small and part size can be a restriction.

Applications

Lasers. Materials hardened include plain carbon steels (1040, 1050, 1070), alloy steels (4340, 52100), tool steels, and cast irons (gray, ductile, and malleable). Examples include selective hardening of irregularly shaped parts like camshafts and crankshafts, which are subject to wear and have fatigue-prone areas (see adjoining Figure, Ref 2).

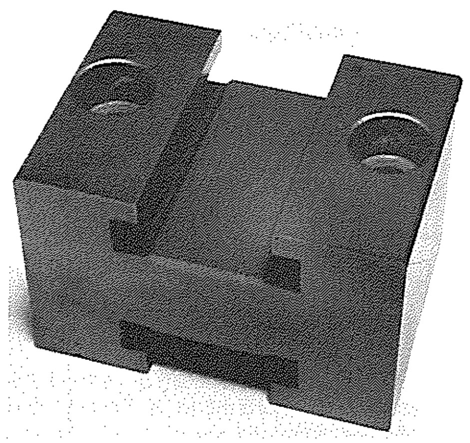
Electron Beam. Commonly used steels are listed in an adjoining Table. Typical parts are shown in an adjoining Figure (Ref 2).

Area treated on ductile iron camshaft is indicated (Ref 2)

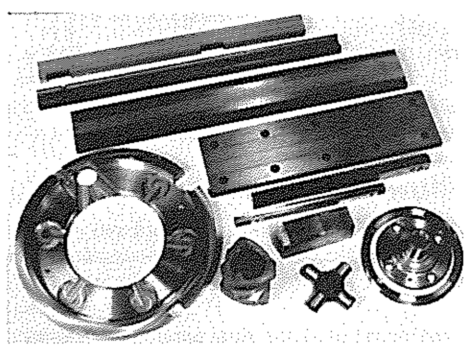


Pulse Hardening. Selectively hardened parts include saws (in an ad-
ining Figure, Ref 1), circular saw blades, and punching tools, plus
ecision engineering components for the electrical and textile industries
ee Figure, Ref 1). Also, this process produces very fine, acicular struc-
res that add corrosion resistance to a part.

Typical components heat treated with electron beam hardening method. (a) Rollerbearing element support. (b) Selected components used for both linear and rotary motion applications. Courtesy of Chemnitzer Werkzeugmaschinen GmbH (Ref 2)



(a)

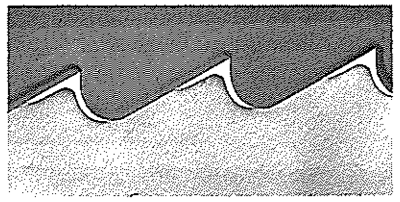


(b)

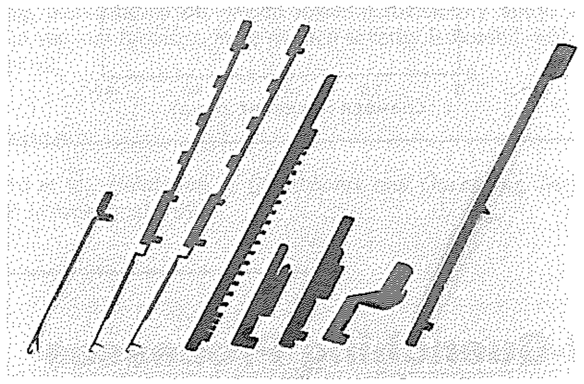
References

1. G. Plöger, "HF Pulse Hardening in the Millisecond Range," ASM Conference Proceedings, *Quenching and Distortion Control,* ASM International, 1992
2. *ASM Metals Handbook, Heat Treating,* Vol 4, 10th ed., ASM International, 1991

Hardened teeth on band saw blade (Ref 1)



Samples of textile industry parts (Ref 1)



teels Commonly Used in Electron Beam Hardening Applications

Material			Composition, wt%											
ISI	UNS No.	DIN(a)	C	Si	Mn	P	S	Cr	Mo	Ni	V	Al	Cu	Ti
arbon and low alloy														
140	G41400	42 CrMo 4	0.38-0.45	0.17-0.37	0.50-0.80	0.035 max	0.035 max	0.90-1.20	0.15-0.25	0.30 max	0.06 max	...	...	...
340	G13400	42 MnV 7	0.38-0.45	0.17-0.37	1.60-1.90	0.035 max	0.035 max	0.30 max	0.10 max	0.30 max	0.07-0.12	...	...	...
52100	G52986	100 Cr 6	0.95-1.05	0.17-0.37	0.20-0.45	0.027 max	0.020 max	1.30-1.65	...	0.30 max	...	...	0.25	...
)15	G10150	C 15	0.12-0.19	0.17-0.37	0.35-0.65	0.040 max	0.040 max	0.50 max	0.10 max	0.30 max	...	...	...	...
)45	G10450	C 45	0.42-0.50	0.17-0.37	0.50-0.80	0.040 max	0.040 max	0.50 max	0.10 max	0.30 max	...	...	...	...
)70	G10700	Ck 67	0.65-0.72	0.25-0.50	0.60-0.80	0.035 max	0.035 max	0.35 max	...	0.35 max	...	...	0.35	...
.	...	55 Cr 1	0.52-0.60	0.17-0.37	0.5-0.8	0.035 max	...	0.2-0.5	...	0.3 max	...	0.02-0.05	0.3 max	0.015
.	...	50 CrV 4	0.47-0.55	0.4 max	0.7-1.1	0.035	0.03 max	0.9-1.2	...	...	...	...	...	0.1-0.2
ool steels														
2	T31502	90 MnV 8	0.85-0.95	0.15-0.35	1.80-2.00	0.030 max	0.030 max	...	...	...	0.07-0.12	...	...	...
'1	T72301	C 100 W1	0.95-1.04	0.15-0.30	0.15-0.25	0.020 max	0.020 max	0.20 max	...	0.20 max(b)	...	...	...	...

) Deutsche Industrie-Normen. (b) 0.25 max Cu

Fluidized Bed Quenching

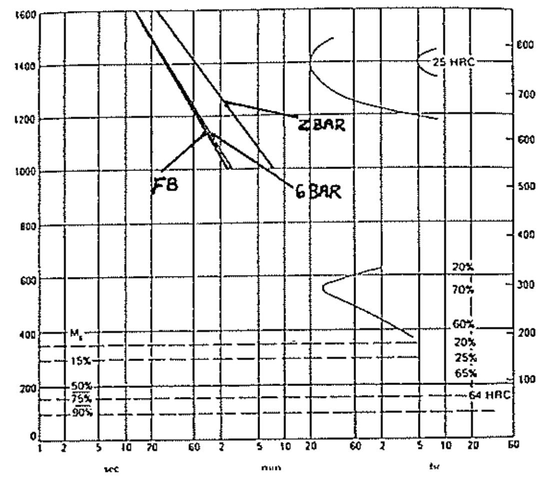
Nitrogen and air are common quenching media. Other quenchants are argon, carbon dioxide, helium, or hydrogen. Critical variables are rate of fluidizing gas flow and thermal conductivity of the gas.

Characteristics of Process

Control over quenching with this process compares favorably with that of other liquid quenchants. The heat transfer mechanism is uniform throughout the entire temperature range, and is dominated by the properties of the gas phase. Quench rates are reproducible, do not degrade with time, and can be adjusted within wide limits and operate over a wide temperature range (Ref 1).

The quenching or heat treating rate can be adjusted by altering operating conditions of the fluid bed. Variables include particle size and volume (aluminum oxide is preferred), rate of fluidizing gas flow, and the thermal conductivity of the gas. Nitrogen usually is the choice. Quench severities are between those of still air and slow air.

Comparisons of quenching rates for fluidized beds operating on nitrogen, and vacuum furnaces operating at 2 bar and 6 bar quench pressures at temperatures up to 575 °C (1065 °F)



In comparison with other heat treating/quenching processes, the fluid bed is less sensitive to load density and part geometry. Because of the liquidlike characteristics of the fluid bed, parts are surrounded by aluminum oxide particles, and the high heat capacity of aluminum oxide does not require complete gas flow over all surfaces because heat is removed by conduction.

Operating Information

In treating H-11 and H-13 forging dies the following procedure was used (Ref 1):

- Preheat work to 595 °C (1105 °F)
- Austenitize at 1040 °C (1905 °F)
- Step quench at 595 °C (1105 °F)
- Fluid bed quench at ambient temperature for 5 to 7 min at approximately 290 °C (555 °F)
- Air cool to room temperature

A second, two-stage process: quenching in helium first, followed by quenching in nitrogen. Application: austempering 4340, medium carbon steel tools, replacing salt processing, i.e., austenitizing at 920 °C (1690 °F) and quenching into salt at 320 °C (610 °F), then holding for 30 min. For the two-stage process, the quench temperature was reduced from 330 °C (625 °F) to 295 °C (565 °F).

Step No. 1: Short pulse (30 to 60 s) of helium to drive the load past the nose of the cooling curve. (In treating 4340, the first 10 s of the cooling curve is critical). Beyond this point allowable time is increased.

Step No. 2: Gas is switched from helium to nitrogen for the remainder of the cycle.

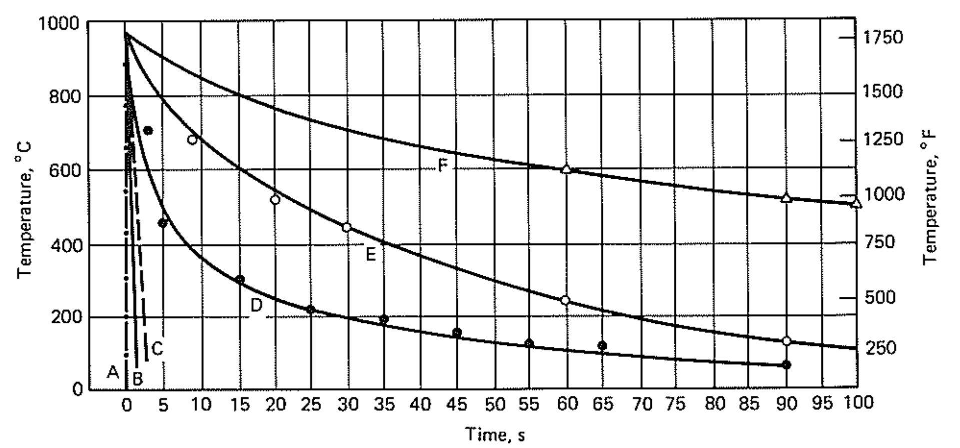
In cases where hardness values in fluidized bed quenching are slightly lower than those of the other quenchants, higher hardness can be obtained by slightly decreasing fluidized bed temperatures.

Range of Applications

Standard and special fluid bed processes are available. Air hardening tool steels, for example, are within the range of the former, while medium and low alloy steels are among the applications of the latter.

Standard Process. Performance of this process in treating air hardening tool steels is said to compare favorably with that of high pressure gas quenching in a vacuum furnace. In this instance, two critical factors are: the quench rate must be severe enough to effect full metallurgical transformation of thick sections, while not causing severe distortion or cracking.

Comparison of results in quenching and normalizing with: A, salt solution; B, agitated water; C, still water; D, oil; E, fluidized bed; F, normalized. Specimens were 12.6 mm (0.50 in.) diameter bars.



)uenching rates for the fluid bed process and those for high pressure gas uenching in vacuum are compared in an adjoining Figure. The fluid bed ate is slightly higher than that at 6 bar quench pressures. The material is 1-2 high speed tool steel. Other comparisons are made in a second Figure.

Special Process. The standard fluidized bed has insufficient heat ·ansfer characteristics to be useful in quenching medium to low alloy teels because the critical portion of their cooling cycle is the first 10 s, vhich precludes the application of a number of these alloys in austemper-ng, marquenching, and direct hardening. This limitation is bypassed by nodifications in the standard process. Quenching speeds are significantly igher.

The special process has two phases.

In the first phase, helium replaces nitrogen for cooling in the critical ortion of the cycle (the nose of the isothermal transformation cycle). Ielium has a gas conductivity nearly six times that of nitrogen, and the luidization rate is doubled. The helium phase takes 30 to 60 s.

In the second phase, nitrogen replaces helium for the rest of the ycle.

Example of an Application: austempering 4340 steel tools. In salt rocessing, parts were austenitized at 920 °C (1690 °F), and they were juenched in salt at 315 °C (600 °F), then held at that temperature for 30 nin. In processing with the modified fluid bed process, the austempering juenching temperature was reduced from 315 to 295 °C (600 to 565 °F). Iardness of these parts was lower than that of those treated with the salt process. The desired result was obtained by slight reductions in the fluid bed temperature.

Steel parts treated by this process and prior quenching techniques include the following:

- 52100, bearing races, oil quenched
- 4340, wood routing bits, austempered at 350 °C (660 °F)
- Modified S-2, screw driver bits austempered at 315 °C (600 °F)
- 0-1, general tooling, marquenched in salt at 210 °C (410 °F)
- Ductile iron, crankshaft, oil quenched
- 86B40, forging, oil quenched
- 5150, machined parts, oil quenched

Reference

1. A. Dinunsi, "Advances in Fluidized Bed Quenching," p 71, ASM Conference Proceedings, *Quenching and Distortion Control,* ASM International, 1992

Other References

- Totten et al., *Handbook of Quenchants and Quenching Technology,* ASM International
- *ASM Metals Handbook, Heat Treating,* Vol 4, 10th ed., ASM International

Ultrasonic Quenching

Virtually any liquid quenching medium can be used in ultrasonic quenching.

Characteristics of Process

Vapor blanket formation is readily interrupted by ultrasonic energy (see Figure).

Operating Information

Ultrasonic agitation substantially increases quench severity (see Table), but the cracking and distortion that can be caused by oil, water, or brine quenchants often are eliminated. Reductions in distortion and cracking are often accompanied by an increase in hardness.

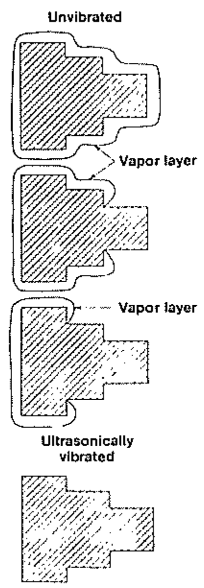
Grossmann *H* Values of Various Quenchants with and without Ultrasonic Energy

Quenchant	Grossmann *H* value
Oil	
Still quench	0.25/0.30
Violent agitation	0.80/1.10
Ultrasonic agitation	1.65
Brine	
Still quench	2.0
Violent agitation	5.0
Ultrasonic agitation	7.5
Hot salt at (400 °F)	
Still quench	0.30
Violent agitation	1.20
Ultrasonic agitation	1.80

Reference

1. Totten et al., *Handbook of Quenchants and Quenching Technology,* ASM International, 1993

Comparison of vapor blanket phases during oil quenching and ultrasonic quenching



HIP Quenching

The HIP quencher is an offshoot of the more familiar hot isostatic press used to densify metal powders and ceramics and to improve certain properties of castings.

Gas (usually argon) is the only cooling medium in HIP quenching. Rapid cooling is obtained with high pressure gas at 800 to 1800 bar. Heated gas is cooled in a heat exchanger. Gas pressure pushes gas atoms closer together, increasing the number of atoms that remove heat from steel surfaces. The heat exchanger is located in the HIP vessel outside the hot zone.

Characteristics of Process

The extremely high heat transfer coefficient of gas under high pressure makes for less variation in temperature in different areas of a part, reducing the likelihood of distortion. Characteristics of several different quenching methods are compared in an adjoining Table. The heat transfer coefficient of the process is of the same magnitude as that for the fluidized bed and about three times greater than that for the vacuum furnace (see Figure). Gas temperature is closely controlled by computer as a function of time.

Applications

Higher hardenability steels such as high speed steels and other tool steels are in the applications range of the process. Densification and heat treatment can be combined in a single operation.

References

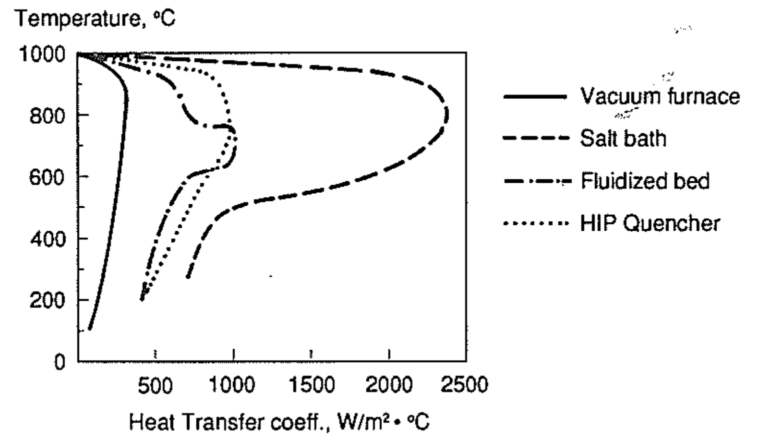
1. Bergman and Segerberg, "HIP Quencher for Efficient and Uniform Quenching," and Segerberg, ASM Conference Proceedings, *Quenching and Distortion Control,* ASM International, 1992
2. A. Traff, *Metal Powder Report,* 45 (1990), 4
3. *Industrial Quenching Oils—Determination of Cooling Characteristics—Laboratory Test Method.* Draft international standard ISO/DIS 9950, International Organization for Standardization (submitted 1988).
4. S. Segerberg, *IVF-rapport 92021,* IVF, Göteborg, Sweden

Characteristics of Four Quenching Methods

Method of quenching	Temperature of quenchant, °C	Gas	Pressure, bar
Vacuum	60	Nitrogen	4
Salt bath	230	...	...
Fluidized bed	20	Nitrogen	1
HIP quencher	Decreasing from 1000	Argon	800-1800

Ref 1

Heat transfer coefficients of different quenching methods (Ref 1)



Spray Quenching Process

High pressure streams of quenching fluids are directed onto areas of a workpiece requiring higher cooling rates. Quenchant droplets formed by the spray account for the speedup in cooling rate. Low pressure spraying, providing a flood-type flow, is preferred in quenching with some aqueous polymers. Spray nozzles are located on a quench rig. Quenching characteristics can be influenced by volume and pressure of the quenchant, as well as the design of spray nozzles.

·og Quenching Process

A fine fog or mist of liquid droplets in a gas carrier is the cooling agent. :ooling rates are lower than those in spray quenching because of the :latively low liquid content of the stream.

:old Die Quenching

Used for parts such as thin disks and long, slender rods that distort xcessively when quenched in conventional liquid media. Quenching is etween various forms of cold, flat, or shaped dies, which usually are in a ress close to austenitizing operations.

Reference

1. *ASM Metals Handbook, Heat Treating,* Vol 4, 10th ed., ASM International, 1991

;uenching in an Electric or Magnetic Field

In quenching steels in an electrical field, electrical current is passed ırough the part while it is submerged in a liquid such as oil or water.

In quenching in a magnetic field, steel is quenched into an aqueous ıspension of 10 nm magnetic particles.

:haracteristics of Process

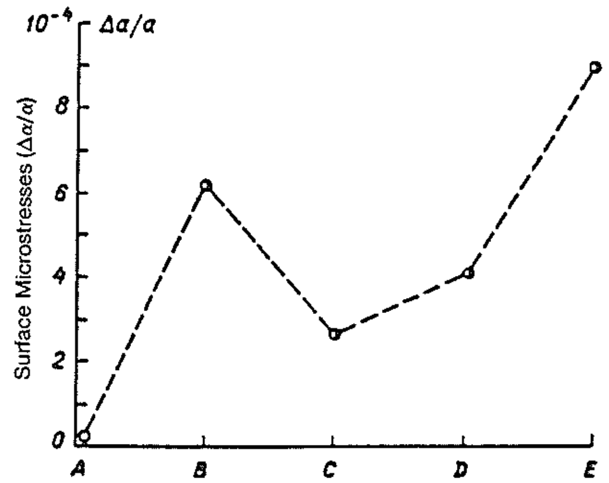
In quenching in an electrical field, uniformity of surface heat transfer is nhanced by destabilizing vapor blanket cooling by passing an electrical urrent through the workpiece.

)perating Information

It has been demonstrated, for example that the hardness of a 0.45 percent arbon steel can be increased 10 to 18 HRC, while quench-induced micro-:resses are virtually eliminated (see Figure).

Similar results have been obtained in magnetic field quenching. Cooling ıtes throughout the quench can be controlled by the concentration of ıagnetite particles and the force of the magnetic field (Ref 1,4).

Microstresses on perimeter of 0.45 percent carbon steel quenched in different media (Ref 1)



A = Unquenched Specimen
B = Water (Without Electric Field)
C = Water + Electric Field
D = Binary Mixture (Water + 012 + Electric Field)
E = Oil + Electric Field

ॊeferences

. Totten et al., *Handbook of Quenchants and Quenching Technology,* ASM International, 1993
. A.A. Skimbov, I.A. Kozhukhar, and N.N. Morar, *Sov. Eng. Appl. Electrochem,* Vol 2, 1989, p 136-138
. A.A. Skimbov, I.A. Kozhukhar, and N.N. Morar, *Elektronnaya Obrab. Mater.,* Vol 2, 1989, p 87-88
. S.N. Verkhovskii, L.I. Mirkin, and A.Ya. Simonovskii, *Fiz. Khim. Obrab. Mater.,* Vol 2, 1990, p 127-132

Quenching Flame and Induction Hardened Parts

Water is the common quenchant for flame and induction hardened workpieces. Other media are oil, soluble oil, compressed air, aqueous polymer solutions, and brine (Ref 1).

Characteristics of Process

Water is the choice unless metallurgical considerations call for less severe quenching media.

Operating Information

Open and submerged spray systems generally are used in conjunction with induction hardening. Spray orifices for water quenching are relatively small to maximize cooling rates. Different orifice sizes and spray pressures are required in quenching with aqueous polymers. High pressure and fine spray cause premature rupture of polymer films on hot metal surfaces, which reduces cooling rates. Recommended orifice sizes and fluid pressure for quenching steels from an austenitizing temperature of 845 °C (1555 °F) with polyethylene glycol (PAG) are listed in an adjoining Table (Ref 1).

Reference

1. *ASM Metals Handbook, Heat Treating,* Vol 4, 10th ed., ASM International, 1991

Recommended Orifice Sizes and Fluid Pressures for Induction Spray Systems

Type of spray(a)	Pressure(b) kPa	Pressure(b) psi	Orifice diameter mm	Orifice diameter in.
Open	<140	<20	3.2	⅛
Submerged	>275	>40	6.4	¼

(a) All of the cooling curves for the quench factor correlation were determined using AISI type 304 stainless steel probes. (b) Data for UCON (Union Carbide Chemicals and Plastics Company, Inc.) Quenchant B. Source: Ref 58

Tempering Processes/Technology

Conventional Processes

Tempering is a process in which previously hardened or normalized steel s usually heated to a temperature below the lower critical temperature and :ooled at a suitable rate, primarily to increase ductility and toughness, but .lso to increase the grain size of the matrix. Steels are tempered by eheating after hardening to obtain specific values of mechanical properties .nd also to relieve quenching stresses and to ensure dimensional stability. 'empering usually follows quenching from above the upper critical tem- ıerature; however, tempering is also used to relieve the stresses and reduce he hardness developed during welding and to relieve stresses induced by 'orming and machining.

Principal Variables

Variables that affect the microstructure and the mechanical properties of ı tempered steel include:

- Tempering temperature
- Time at temperature
- Cooling rate from the tempering temperature
- Composition of the steel, including carbon content, alloy content, and residual elements

In a steel quenched to a microstructure consisting essentially of martensite, the iron lattice is strained by the carbon atoms, producing the high hardness of quenched steels.

Under certain conditions, hardness may remain unaffected by tempering or may even be increased as a result of it. For example, tempering a hardened steel at very low tempering temperatures may cause no change in hardness but may achieve a desired increase in yield strength. Also, those alloy steels that contain one or more of the carbide-forming elements (chromium, molybdenum, vanadium, and tungsten) are capable of secondary hardening; that is, they may become somewhat harder as a result of tempering.

The tempered hardness values for several quenched steels are presented in an adjoining Table. Temperature and time are interdependent variables in the tempering process. Within limits, lowering temperature and increasing time can usually produce the same result as raising temperature and decreasing time. However, minor temperature changes have a far greater effect than minor time changes in typical tempering operations. With few exceptions, tempering is done at temperatures between 175 and 705 °C (345 and 1300 °F) and for times from 30 min to 4 h.

Structural Changes. Based on x-ray, dilatometric, and microstructural studies, there are three distinct stages of tempering, even though the temperature ranges overlap (Ref 1-4):

- Stage I: The formation of transition carbides and lowering of the carbon content of the martensite to 0.25% (100 to 250 °C, or 210 to 480 °F)
- Stage II: The transformation of retained austenite to ferrite and cementite (200 to 300 °C, or 390 to 570 °F)
- Stage III: The replacement of transition carbides and low-temperature martensite by cementite and ferrite (250 to 350 °C, or 480 to 660 °F)

An additional stage of tempering (stage IV), precipitation of finely dispersed alloy carbides, exists for high-alloy steels. It has been found that stage I of tempering is often preceded by the redistribution of carbon atoms, called autotempering or quench tempering, during quenching and/or holding at room temperature (Ref 5). Other structural changes take place because of carbon atom rearrangement preceding the classical stage I of tempering (Ref 6, 7).

Dimensional Changes. Martensite transformation is associated with an increase in volume. During tempering, martensite decomposes into a mixture of ferrite and cementite with a resultant decrease in volume as tempering temperature increases. Because a 100% martensitic structure after quenching cannot always be assumed, volume may not continuously decrease with increasing tempering temperature.

The retained austenite in plain carbon steels and low-alloy steels transforms to bainite with an increase in volume, in stage II of tempering. When certain alloy steels are tempered, a precipitation of finely distributed alloy carbides occurs, along with an increase in hardness, called secondary hardness, and an increase in volume. With the precipitation of alloy carbides, the M_s temperature (temperature at which martensite starts to form from austenite upon cooling) of the retained austenite will increase and transform to martensite during cooling from the tempering temperature.

Tempering Temperature. Several empirical relationships have been made between the tensile strength and hardness of tempered steels. The measurement of hardness commonly is used to evaluate the response of a steel to tempering. An adjoining Figure shows the effect of tempering temperature on hardness, tensile and yield strengths, elongation, and reduction in area of a plain carbon steel (AISI 1050) held at temperature for 1 h. It can be seen that both room-temperature hardness and strength decrease as the tempering temperature is increased. Ductility at ambient temperatures, measured by either elongation or reduction in area, increases with tempering temperature.

Most medium-alloy steels exhibit a response to tempering similar to that of carbon steels. The change in mechanical properties with tempering temperature for 4340 steel is shown in an adjoining Figure.

There is no decrease in ductility in the temperature range of tempered martensite embrittlement, or TME (also known as 260 °C [500 °F] embrittlement or one-step temper embrittlement) because the tensile tests are performed on smooth, round specimens at relatively low strain rates. However, in impact loading, catastrophic failure may result when alloy steel is tempered in the tempered martensite embrittlement range (260 to 370 °C, or 500 to 700 °F).

Whereas elongation and reduction in area increase continuously with tempering temperature, toughness, as measured by a notched-bar impact test, varies with tempering temperature for most steels, as shown in an adjoining Figure. Tempering at temperatures from 260 to 320 °C (500 to 610 °F) decreases impact energy to a value below that obtained at about 150 °C (300 °F). Above 320 °C (610 °F), impact energy again increases with increasing tempering temperature. Both plain carbon and alloy steels respond to tempering in this manner. The phenomenon of impact energy centered around 300 °C (570 °F) is called tempered martensite embrittlement (TME) or 260 °C (500 °F) embrittlement.

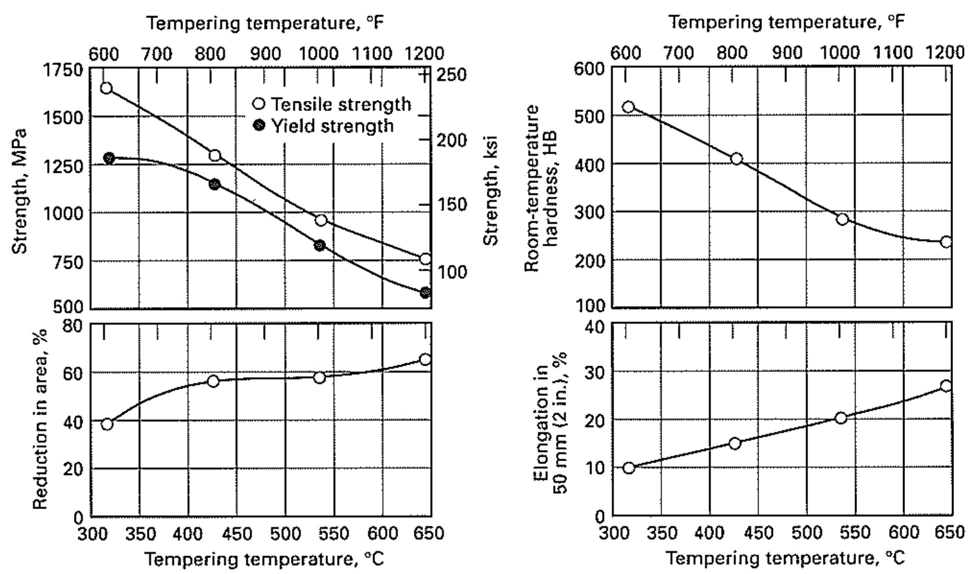
Tempering Time. The diffusion of carbon and alloying elements necessary for the formation of carbides is temperature and time dependent. The effect of tempering time on the hardness of a 0.82% C steel tempered at various temperatures is shown in an adjoining Figure. Changes in hardness are approximately linear over a large portion of the time range when the time is presented on a logarithmic scale. Rapid changes in room temperature hardness occur at the start of tempering in times less than 10 s. Less rapid, but still large, changes in hardness occur in times from 1 to 10 min, and smaller changes occur in times from 1 to 2 h. For consistency and less dependency on variations in time, components generally are tempered for 1 to 2 h. The levels of hardness produced by very short tempering cycles,

Typical Hardnesses of Various Carbon and Alloy Steels after Tempering

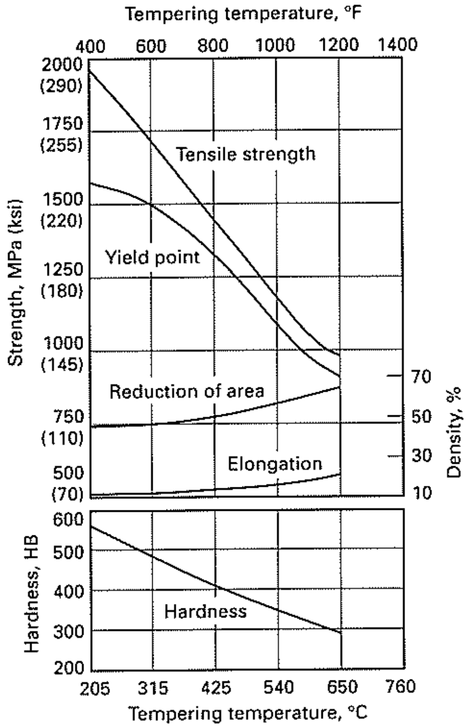
Grade	Carbon content, %	Hardness, HRC, after tempering for 2 h at 205 °C (400 °F)	260 °C (500 °F)	315 °C (600 °F)	370 °C (700 °F)	425 °C (800 °F)	480 °C (900 °F)	540 °C (1000 °F)	595 °C (1100 °F)	650 °C (1200 °F)	Heat treatment
Carbon steels, water hardening											
.030	0.30	50	45	43	39	31	28	25	22	95(a)	Normalized at 900 °C (1650 °F), water quenched from
040	0.40	51	48	46	42	37	30	27	22	94(a)	830-845 °C (1525-1550 °F); average dew point,
.050	0.50	52	50	46	44	40	37	31	29	22	16 °C (60 °F)
.060	0.60	56	55	50	42	38	37	35	33	26	Normalized at 885 °C (1625 °F), water quenched from
.080	0.80	57	55	50	43	41	40	39	38	32	800-815 °C (1475-1500 °F); average dew point,
.095	0.95	58	57	52	47	43	42	41	40	33	7 °C (45 °F)
.137	0.40	44	42	40	37	33	30	27	21	91(a)	Normalized at 900 °C (1650 °F), water quenched from
.141	0.40	49	46	43	41	38	34	28	23	94(a)	830-855 °C (1525-1575 °F); average dew point,
.144	0.40	55	50	47	45	39	32	29	25	97(a)	13 °C (55 °F)
Alloy steels, water hardening											
:330	0.30	47	44	42	38	35	32	26	22	16	Normalized at 900 °C (1650 °F), water quenched from
2330	0.30	47	44	42	38	35	32	26	22	16	800-815 °C (1475-1500 °F); average dew point,
3130	0.30	47	44	42	38	35	32	26	22	16	16 °C (60 °F)
4130	0.30	47	45	43	42	38	34	32	26	22	Normalized at 885 °C (1625 °F), water quenched from
5130	0.30	47	45	43	42	38	34	32	26	22	800-855 °C (1475-1575 °F); average dew point,
8630	0.30	47	45	43	42	38	34	32	26	22	16 °C (60 °F)
Alloy steels, oil hardening											
1340	0.40	57	53	50	46	44	41	38	35	31	Normalized at 870 °C (1600 °F), oil quenched from
3140	0.40	55	52	49	47	41	37	33	30	26	830-845 °C (1525-1550 °F); average dew point,
4140	0.40	57	53	50	47	45	41	36	33	29	16 °C (60 °F)
4340	0.40	55	52	50	48	45	42	39	34	31	Normalized at 870 °C (1600 °F), oil quenched from
4640	0.40	52	51	50	47	42	40	37	31	27	830-845 °C (1525-1575 °F); average dew point,
8740	0.40	57	53	50	47	44	41	38	35	22	13 °C (55 °F)
4150	0.50	56	55	53	51	47	46	43	39	35	Normalized at 870 °C (1600 °F), oil quenched from
5150	0.50	57	55	52	49	45	39	34	31	28	830-870 °C (1525-1600 °F); average dew point,
6150	0.50	58	57	53	50	46	42	40	36	31	13 °C (55 °F)
8650	0.50	55	54	52	49	45	41	37	32	28	Normalized at 870 °C (1600 °F), oil quenched from
8750	0.50	56	55	52	51	46	44	39	34	32	815-845 °C (1500-1550 °F); average dew point,
9850	0.50	54	53	51	48	45	41	36	33	30	13 °C (55 °F)

Data were obtained on 25 mm (1 in.) bars adequately quenched to develop full hardness. (a) Hardness, HRB

Effect of tempering temperature on room-temperature mechanical properties of 1050 steel. Properties summarized are for one heat of 1050 steel that was forged to 38 mm (1.50 in.) in diameter, then water quenched and tempered at various temperatures. Composition of heat: 0.52% C, 0.93% Mn



Effect of tempering temperature on the mechanical proper-ies of oil-quenched 4340 steel bar. Single-heat results: ladle ;omposition, 0.41% C, 0.67% Mn, 0.023% P, 0.018% S, 0.26% Si, l.77% Ni, 0.78% Cr, 0.26% Mo; grain size, ASTM 6 to 8; critical ɔoints, Ac_3, 770 °C (1420 °F); Ar_3, 475 °C (890 °F); Ar_1, 380 °C (720 'F); treatment, normalized at 870 °C (1600 °F), reheated to 800 °C 1475 °F), quenched in agitated oil; cross section, 13.46 mm 0.530 in.) diam; round treated, 12.83 mm (505 in.) diam; round ested; as-quenched hardness, 601 HB. Source: Ref 8



ıch as in induction tempering, would be quite sensitive to both the ːmperature achieved and the time at temperature.

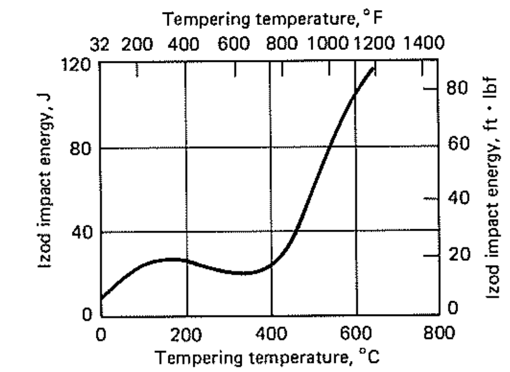
By the use of an empirical tempering parameter developed by Holloman nd Jaffe (Ref 10), the approximate hardnesses of quenched and tempered ɔw- and medium-alloy steels can be predicted. Reasonably good correla-ons are obtained except when significant amounts of retained austenite re present.

Cooling Rate. Another factor that can affect the properties of a steel is ıe cooling rate from the tempering temperature. Although tensile proper-es are not affected by cooling rate, toughness (as measured by notched-ar impact testing) can be decreased if the steel is cooled slowly through ıe temperature range from 375 to 575 °C (705 to 1065 °F), especially in teels that contain carbide-forming elements. Elongation and reduction in rea may be affected also. This phenomenon is called temper embrittle-ıent.

Carbon Content

The principal effect of carbon content is on as-quenched hardness. An djoining Figure shows the relationship between carbon content and the naximum hardness that can be obtained upon quenching. The relative lifference in hardness compared with as-quenched hardness is retained fter tempering. An adjoining Figure shows the combined effect of time, emperature, and carbon content on the hardness of three carbon-molybde-ıum steels of different carbon contents. Another Figure shows the hardness ıf these steels after tempering for 1 h, as a function of tempering tempera-ure. The effect of carbon content is evident.

Notch toughness as a function of tempering temperature for 4140 (UNS G41400) ultrahigh-strength steel tempered 1 h



Alloy Content

The main purpose of adding alloying elements to steel is to increase hardenability (capability to form martensite upon quenching from above its critical temperature). The general effect of alloying elements on tempering is a retardation of the rate of softening, especially at the higher tempering temperatures. Thus, to reach a given hardness in a given period of time, alloy steels require higher tempering temperatures than do carbon steels.

Alloying elements can be characterized as carbide forming or non-carbide forming. Elements such as nickel, silicon, aluminum, and manganese, which have little or no tendency to occur in the carbide phase, remain essentially in solution in the ferrite and have only a minor effect on tempered hardness. The carbide forming elements (chromium, molybdenum, tungsten, vanadium, tantalum, niobium, and titanium) retard the softening process by the formation of alloy carbides.

Strong carbide-forming elements such as chromium, molybdenum, and vanadium are most effective in increasing hardness at higher temperatures above 205 °C (400 °F). Silicon was found to be most effective in increasing hardness at 315 °C (600 °F). The increase in hardness caused by phosphorus, nickel, and silicon can be attributed to solid-solution strengthening. Manganese is more effective in increasing hardness at higher tempering temperatures. The carbide-forming elements retard coalescence of cementite during tempering and form numerous small carbide particles. Under certain conditions, such as with highly alloyed steels, hardness may actually increase. This effect, mentioned previously, is known as secondary hardening.

Other Alloying Effects. In addition to ease of hardening and secondary hardening, alloying elements produce a number of other effects. The higher tempering temperatures used for alloy steels presumably permit greater relaxation of residual stresses and improve properties. Furthermore, the hardenability of alloy steels requires use of a less drastic quench so that quench cracking is minimized. However, higher hardenability steels are prone to quench cracking if the quenching rate is too severe. The higher hardenability of alloy steels may also permit the use of lower carbon content to achieve a given strength level but with improved ductility and toughness.

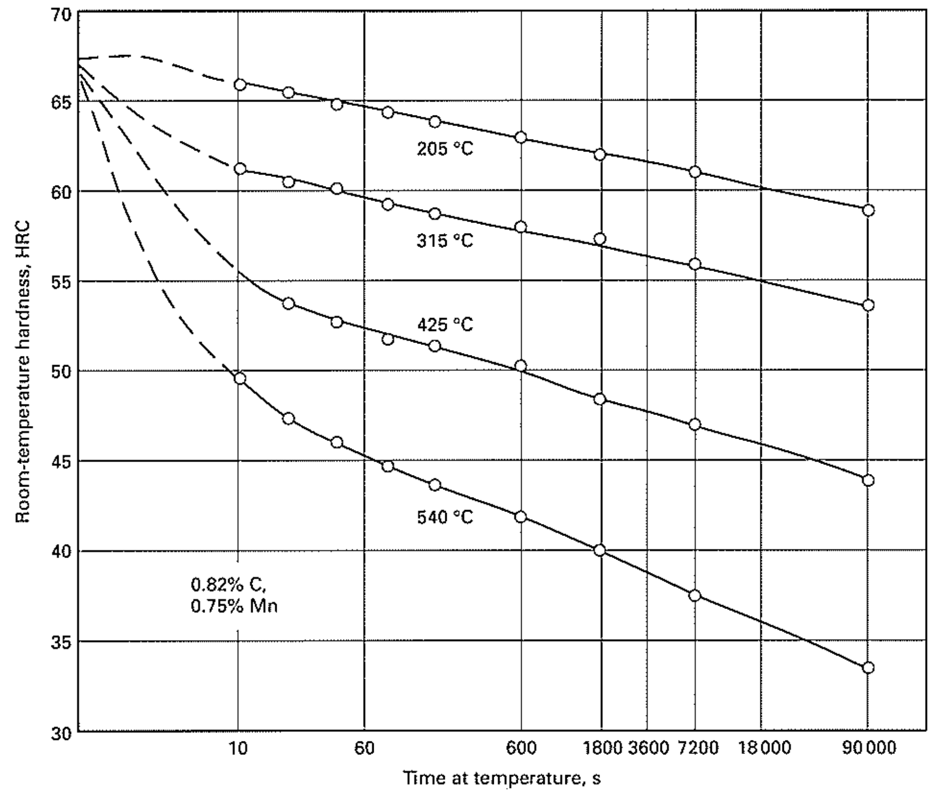
Residual Elements. The elements that are known to cause embrittlement are tin, phosphorus, antimony, and arsenic.

Tempering Procedures

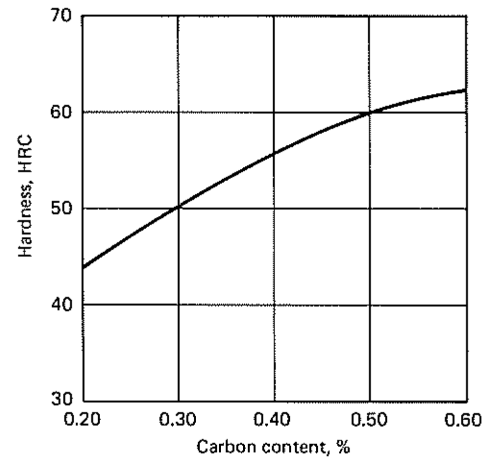
Bulk processing may be done in convection furnaces or in molten salt, hot oil, or molten metal baths. The selection of furnace type depends primarily on number and size of parts and on desired temperature. Temperature ranges, most likely reasons for use, and fundamental problems associated with four types of equipment are given in an adjoining Table.

Selective tempering techniques are used to soften specific areas of fully hardened parts or to temper areas that were selectively hardened previously. The purpose of this treatment is to improve machinability, toughness, or resistance to quench cracking in the selected zone.

Effect of time at four tempering temperatures on room-temperature hardness of quenched 0.82% C steel. Note nearly straight lines on logarithmic time scale. Source: Ref 9



Relationship between carbon content and room-temperature hardness for steels comprising 99.9% untempered martensite



Induction and flame tempering are the most commonly used selective techniques because of their controllable local heating capabilities. Immersion of selected areas in molten salt or molten metal is an alternative, but some control is sacrificed.

Special processes that provide specific properties, such as those obtained in steam treating or the use of protective atmospheres, are available.

Temperature Ranges and General Conditions of Use for Four Types of Tempering

Type of equipment	Temperature range °C	Temperature range °F	Service conditions
Convection furnace	50-750	120-1380	For large volumes of nearly common parts; variable loads make control of temperature more difficult
Salt bath	160-750	320-1380	Rapid, uniform heating; low to medium volume; should not be used for parts whose configurations make them hard to clean
Oil bath	≤250	≤480	Good if long exposure is desired; special ventilation and fire control are required
Molten metal bath	>390	>735	Very rapid heating; special fixturing is required (high density)

For certain steels, the tempering mechanism is enhanced by cyclic heating and cooling. A particularly important procedure employs cycles between subzero temperatures and the tempering temperature to increase the transformation of retained austenite. The term used for this procedure, multiple tempering, is also applied to procedures that use intermediate thermal cycles to soften parts for straightening prior to tempering.

Cracking in Processing

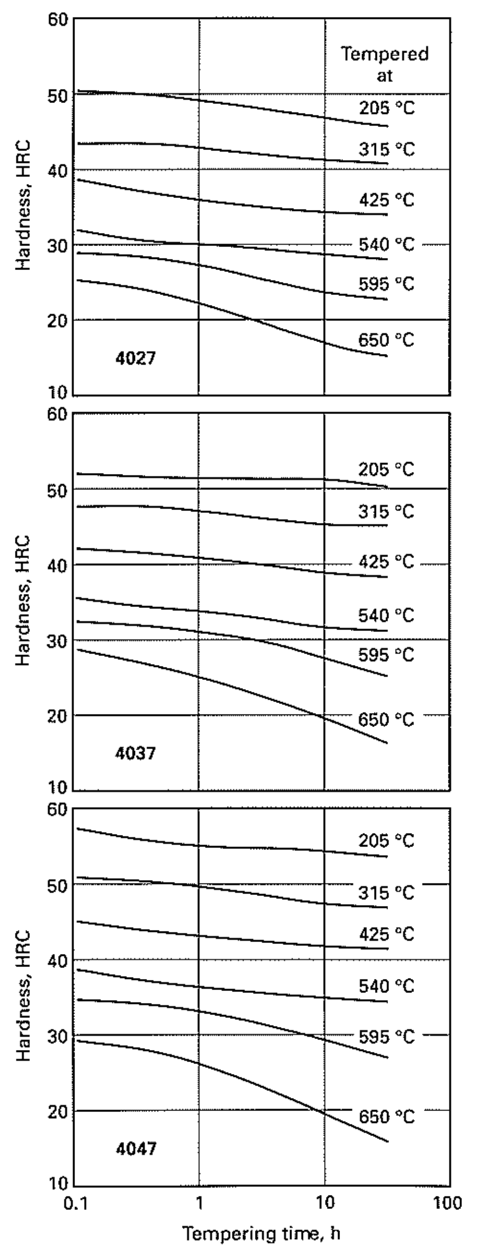
Because of their carbon or alloy contents, some steels are likely to crack if they are permitted to cool to room temperature during or immediately following the quenching operation. Causes include high tensile residual stresses generated during quenching due to thermal gradients, abrupt changes in section thickness, decarburization, or other hardenability gradients. Another potential source is cracking due to quenchant contamination and the subsequent change in quenching severity.

Accordingly, for carbon steels containing more than 0.4% C and alloy teels containing more than 0.35% C, transfer of parts to tempering furaces before they cool to below 100 to 150 °C (210 to 300 °F) is recomnended. Alternately, quenching oil may be used in tempering operation nartempering), or to avoid cooling below 125 °C (255 °F). Steels that are nown to be sensitive to this type of cracking include 1060, 1090, 1340, 063, 4150, 4340, 52100, 6150, 8650, and 9850.

Other carbon and alloy steels generally are less sensitive to this type of elayed quench cracking but may crack as a result of part configuration or urface defects. These steels include 1040, 1050, 1141, 1144, 4047, 4132, 140, 4640, 8632, 8740, and 9840. Some steels, such as 1020, 1038, 1132, 130, 5130, and 8630, are not sensitive.

Before being tempered, parts should be quenched to room temperature) ensure the transformation of most of the austenite to martensite and to achieve maximum as-quenched hardness. Austenite retained in low-alloy steels will, upon heating for tempering, transform to an intermediate structure, reducing overall hardness. However, in medium- to high-alloy steels containing austenite-stabilizing elements (nickel, for example), retained austenite may transform to martensite upon cooling from tempering, and such steels may require additional tempering (double tempering) for the relief of transformation stresses.

Effect of tempering time at six temperatures on room-temperature hardness of carbon-molybdenum steels with different carbon contents but with prior martensitic structures



Temper Embrittlement

When carbon or low-alloy steels are cooled slowly from tempering above 575 °C (1065 °F) or are tempered for extended times between 375 and 575 °C (705 and 1065 °F), a loss in toughness occurs that manifests itself in reduced notched-bar impact strength compared to that resulting from normal tempering cycles and relatively fast cooling rates.

The cause of temper embrittlement is believed to be the precipitation of compounds containing trace elements such as tin, arsenic, antimony, and phosphorus, along with chromium and/or manganese. Although manganese and chromium cannot be restricted, a reduction of the other elements and quenching from above 575 °C (1065 °F) are the most effective remedies for this type of embrittlement.

Steels that have been embrittled because of temper embrittlement can be de-embrittled by heating to about 575 °C (1065 °F), holding a few minutes, then cooling or quenching rapidly. The time for de-embrittlement depends on the alloying elements present and the temperature of reheating (Ref 11).

Blue Brittleness

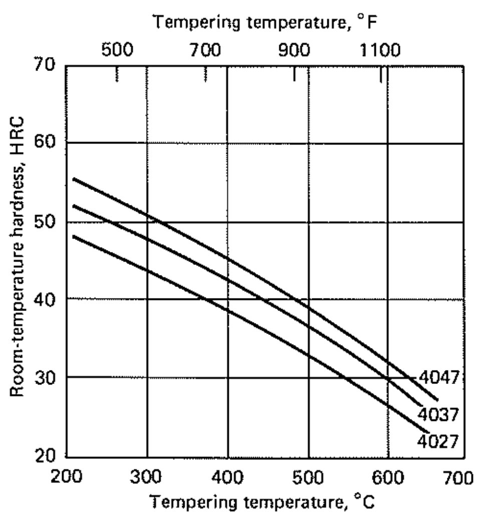
The heating of plain carbon steels or some alloy steels to the temperature range of 230 to 370 °C (445 to 700 °F) may result in increased tensile and yield strength, as well as decreased ductility and impact strength. This embrittling phenomenon is caused by precipitation hardening and is called blue brittleness because it occurs within the blue heat range.

If susceptible steels are heated within the 230 to 370 °C (445 to 700 °F) range, they may be embrittled and thus should not be used in parts subjected to impact loads.

Tempered Martensite Embrittlement

Both intergranular (Ref 13-15) and transgranular fracture modes may be observed in tempered martensite embrittlement (Ref 13, 16). The combination of the segregation of impurities such as phosphorus to the austenitic grain boundaries during austenitizing and the formation of cementite at prior austenitic grain boundaries during tempering are responsible.

Effect of carbon content and tempering temperature on room-temperature hardness of three molybdenum steels. Tempering time: 1 h at temperature



There is a loss in impact toughness for steels tempered in the temperature range of 250 to 300 °C (480 to 570 °F). Steels with lower phosphorus content have superior impact properties than steels with a higher phosphorus level. Also, impact toughness decreases with increasing carbon content (Ref 17). Generally, with steels containing either potent carbide forms such as chromium or other impurities that make them susceptible to tempered martensite embrittlement, tempering between 200 to 370 °C (390 to 700 °F) should be avoided.

Hydrogen Embrittlement

The selection of tempering temperature and the resultant hardness or plasticity must include the consideration of the potential problem of hydrogen embrittlement under these conditions: the part will be exposed to hydrogen through electroplating, phosphating, or other means, or where environmental conditions will cause the cathodic absorption of hydrogen during service.

Generally, the restricted notch ductility of steels with hardnesses above 40 HRC presents ideal conditions for the development of stress concentrations in parts containing notches or defects that would, in the presence of relatively low hydrogen concentrations, lead to failure at stresses far below the nominal tensile strength of the material. Such parts should be tempered to hardness below 40 HRC if they are to be subjected to relatively high stresses and probable exposure to hydrogen.

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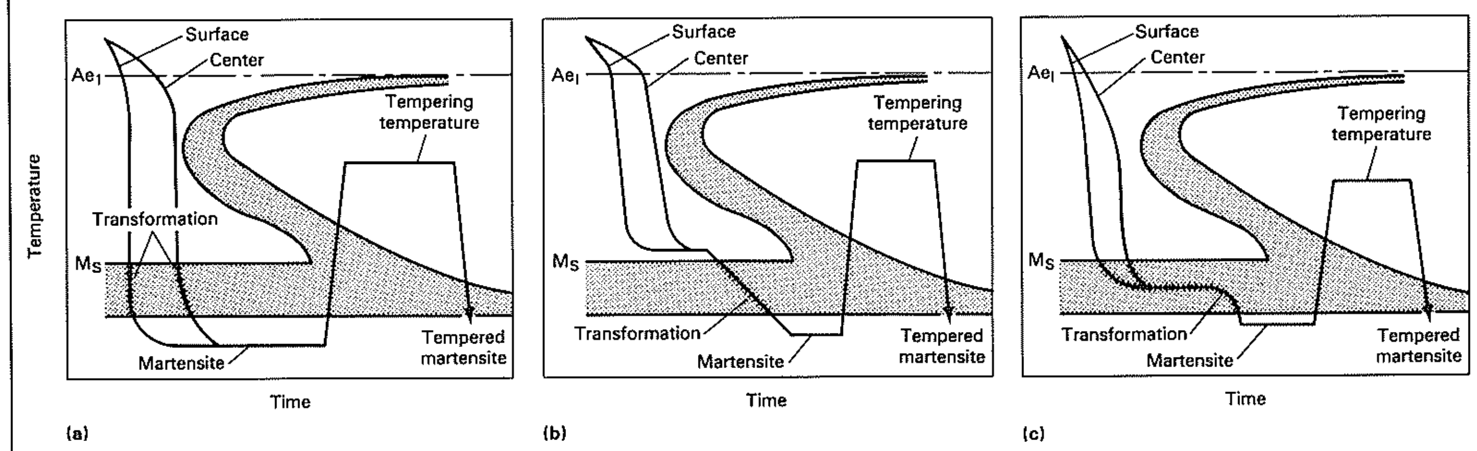
Martempering of Steel

The process entails an interrupted quench from the austenitizing temperature of certain alloy, cast, tool, and stainless steels. Cooling is delayed just above martensitic transformation for the time needed to equalize temperature throughout a part, for the purpose of minimizing distortion, cracking, and residual stress. The resulting microstructure is primarily martensitic, and is untempered and brittle (Ref 1).

Differences between conventional quenching and martempering (aka marquenching) are shown in an adjoining Figure (see a and b).

Time-temperature transformation diagrams with superimposed cooling curves showing quenching and tempering. (a) Conventional process. (b) Martempering. (c) Modified martempering



łechanical Properties of 1095 Steel Heat Treated by Two Methods

pecimen umber	Heat treatment	Hardness, HRC	Impact energy J	Impact energy ft · lbf	Elongation(a), %
	Water quench and temper	53.0	16	12	0
	Water quench and temper	52.5	19	14	0
	Martemper and temper	53.0	38	28	0
	Martemper and temper	52.8	33	24	0

) In 25 mm or 1 in.

Marquenching of wrought steel and cast iron consists of the following eps:

Quenching from the austenitizing temperature into a hot fluid medium (oil, molten salt, molten metal, or a fluidized particle bed) at a temperature usually above the martensitic range (M_s point)
Holding in the quenching medium until the temperature throughout a part is uniform
Cooling, usually in air, at a moderate rate to prevent large differences between temperatures on the outside and center of a section

During cooling to room temperature, the formation of martensite ıroughout a part is fairly uniform, which avoids excessive residual :resses. When the still-hot part is removed from the bath, it is easy to raighten or to form, and will hold its shape on subsequent cooling in a xture, or in air cooling after removal from a forming die. Following ıarquenching, parts are tempered in the same manner as conventionally uenched parts. The time lapse between martempering and tempering is ɔt so critical as it is in conventional quenching and tempering operations.

ιdvantages of Martempering

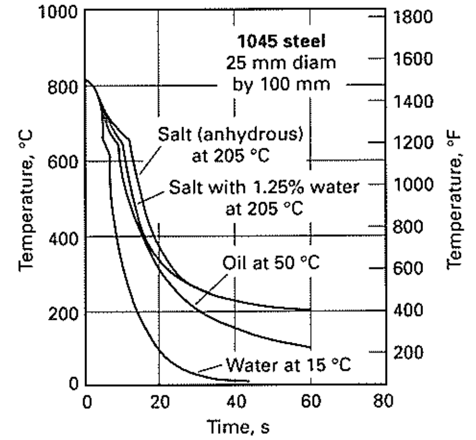
Properties of steel treated in conventional water quenching and temperıg and steel treated in martempering are compared in an adjoining Table.
In martempering residual stresses are lower than those developed in ɔnventional quenching because the greatest thermal variations come 'hile the steel is still in its relatively plastic austenitic condition and ecause final transformation and thermal changes occur throughout a part : essentially the same time.
Other advantages of the process:

Susceptibility to cracking is reduced or eliminated
When the austenitizing bath is a neutral salt and is controlled by the addition of methane or by proprietary rectifiers to maintain its neutrality, parts are protected with a residual coating of neutral salt until they are immersed in the marquench bath
Problems with pollution and fire hazards are greatly reduced if nitrate-nitrite salts are used, rather than marquenching oils
Quenching severity of molten salt is greatly enhanced by agitation and by water additions to the bath
Martempering often eliminates the need for quenching fixtures, which are required to minimize distortion in conventional quenching

łodified Martempering

The only difference between this process and standard martempering is ıe temperature of the quenching bath—it is below that of the M_s point—'hich increases the severity of the quench (see c in Figure cited preiously). This capability is important for steels with lower hardenability ıat require faster cooling to get greater depth of hardness.
When hot oil is used, the typical martempering temperature in this ıstance is 175 °C (345 °F). By comparison, molten nitrate-nitrite salt baths 'ith water additions and agitation are effective at temperatures as low as 75 °C (345 °F). The molten salt method has some metallurgical and ɔerational advantages.

Cooling curves for 1045 steel cylinders quenched in salt, water, and oil. Thermocouples were located at centers of specimens.



Martempering Media

Molten salt and hot oil are widely used. Operating temperature is the most common deciding factor in choosing between salt and oil. For oil, the upper temperature is 205 °C (400 °F). Temperatures up to 230 °C (445 °F) are an occasional exception. The range for salt is 160 to 400 °C (320 to 750 °F).

Composition and Cooling Power of Salt. A commonly used salt contains 50 to 60% potassium nitrate, 37 to 50% sodium nitrite, and 0 to 10% sodium nitrate. This salt's melting point is approximately 140 °C (285 °F); its working range is 165 to 540 °C (330 to 1000 °F). Salts with a higher melting point (they cost less than the one just described) can be used to get higher operating temperatures. Their composition: 40 to 50% potassium nitrate, 0 to 30% sodium nitrite, and 20 to 60% sodium nitrate.

The cooling power of agitated salt at 205 °C (400 °F) is about the same as that of agitated oil in conventional oil quenching. Water additions increase the cooling power of salt, as indicated by cooling curves in an adjoining Figure and hardness values in a second Figure, in which the cooling power of water is compared with that of water and three types of oil.

Salt Vs. Oil. Advantages of salt include the following:

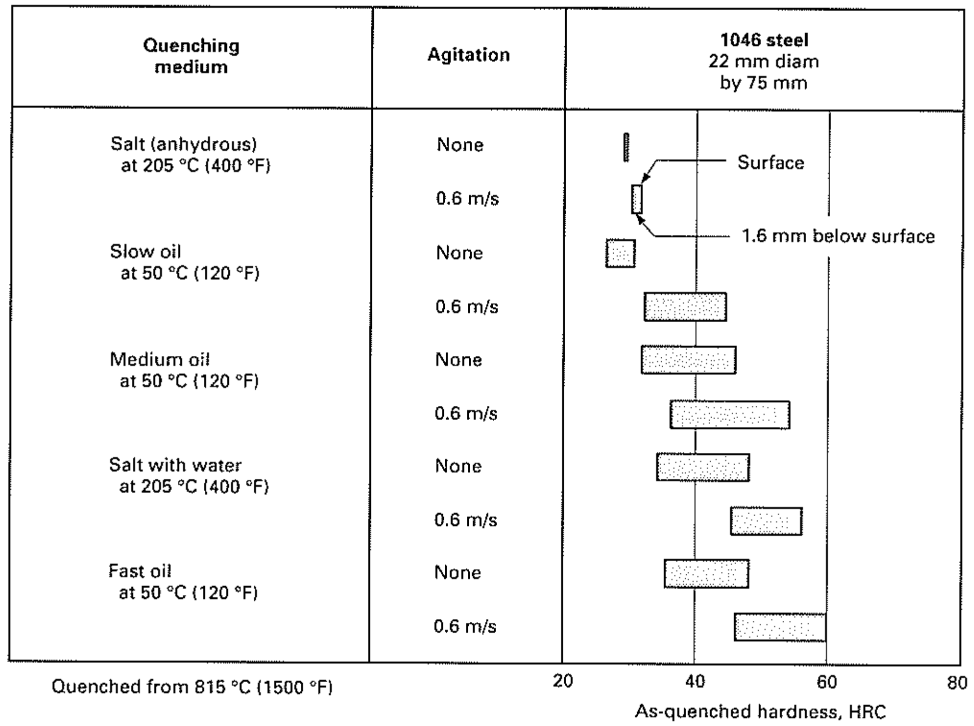
- Changes in viscosity are slight over a wide temperature range
- Salt retains its chemical stability. Replenishment, usually, is needed only to replace dragout losses
- Salt is easily washed from work with plain water

Disadvantages, salt vs. oil include the following:

- Minimum operating temperature of salt is 160 °C (320 °F)
- Quenching from cyanide-based carburizing salt is hazardous because of possible explosion; explosion and splatter can occur if wet or oily parts are immersed in high-temperature salt; and there is potential for explosive reactions when atmosphere furnaces are connected to martempering salt quenches and atmospheres are sooty
- Quenching salt can be contaminated by high-temperature, neutral salt used for heating. To maintain quench severity, sludging is required

Niche for Fluidized Beds. Marquenching applications are limited. They have the advantage of equal heat transfer throughout the entire quenching temperature range. The quench rate is reproducible, does not degrade with time, and can be adjusted within wide limits.

Effects of quenchant and agitation on hardness of 1046 steel



Physical Properties of Two Oils Used for Martempering of Steel

Property	Value, for oil with operating temperature of 95 to 150 °C (200 to 300 °F)(a)	Value, for oil with operating temperature of 150 to 230 °C (300 to 450 °F)
Flash point (min), °C (°F)	210 (410)	275 (525)
Fire point (min), °C (°F)	245 (470)	310 (595)
Viscosity, SUS, at:		
38 °C (100 °F)	235-575	...
100 °C (210 °F)	50.5-51	118-122
150 °C (300 °F)	36.5-37.5	51-52
175 °C (350 °F)	...	42-43
205 °C (400 °F)	...	38-39
230 °C (450 °F)	...	35-36
Viscosity index (min)	95	95
Acid number	0.00	0.00
Fatty-oil content	None	None
Carbon residue	0.05	0.45
Color	Optional	Optional

(a) Temperature range for modified martempering

Oils For Martempering

Properties of two commonly used oils are listed in an adjoining Table. Compounded for the process, they provide higher rates of cooling than conventional oils during the initial stage of quenching.

At temperatures between 95 to 230 °C (205 to 445 °F) quenching oil requires special handling. It must be maintained under a protective atmosphere (reducing or neutral) to prolong its life. Exposure to air at elevated temperatures speeds up the deterioration of oil. For every 10 °C above 60 °C (18 above 140 °F) the oxidation rate approximately doubles, causing the formation of sludge and acid, which can affect the hardness and color of workpieces.

Oil life can be extended and the production of clean work can be maintained by using bypass or continuous filter units containing suitable filtering media (clay, cellulose cartridge, or waste cloth). Oils should be circulated at a rate no lower than 0.9 m/s (180 ft/min) to break up excessive vapor formed during quenching.

Advantages of oil vs. salt include the following:

- Oil can be used at lower temperatures
- Oil is easier to handle at room temperature
- Dragout is less

Disadvantages of oil vs. salt include the following:

- Maximum operating temperature of oil is 230 °C (445 °F)
- Oil deteriorates with usage
- Workpieces require more time to reach temperature equalization
- Oil, hot or cold, is a fire hazard
- Soap or emulsifier is needed to wash off oil. Washers must be drained and refilled periodically. Oil wastes present disposal problems

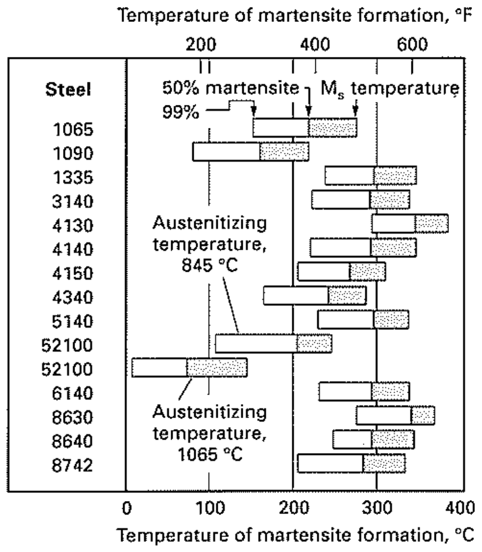
Martempering Applications

Alloy steels generally are more adaptable than carbon steels to martempering (see Figure). In general, any steel that is normally quenched in oil can be martempered. Some carbon steels that are normally water quenched can be martempered at 205 °C (400 °F) in sections thinner than 5 mm

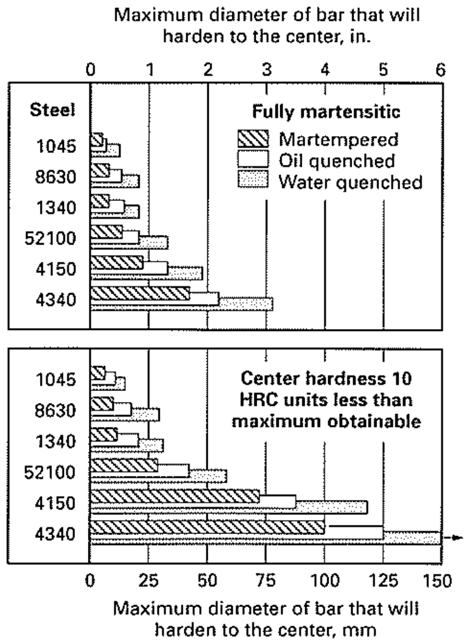
(0.1875 in.), using vigorous agitation of the martempering medium. In addition, thousands of gray cast iron parts are martempered on a routine basis.

The grades of steel that are commonly martempered to full hardness include 1090, 4130, 4140, 4150, 4340, 300M (4340M), 4640, 5140, 6150, 8630, 8640, 8740, 8745, SAE 1141, and SAE 52100. Carburizing grades such as 3312, 4620, 5120, 8620, and 9310 also are commonly martempered after carburizing. Occasionally, higher-alloy steels such as type 410 stainless are martempered, but this is not a common practice.

Temperature ranges of martensite formation in 14 carbon and low-alloy steels



Approximate maximum diameters of bars that are hardenable by martempering, oil quenching, and water quenching.

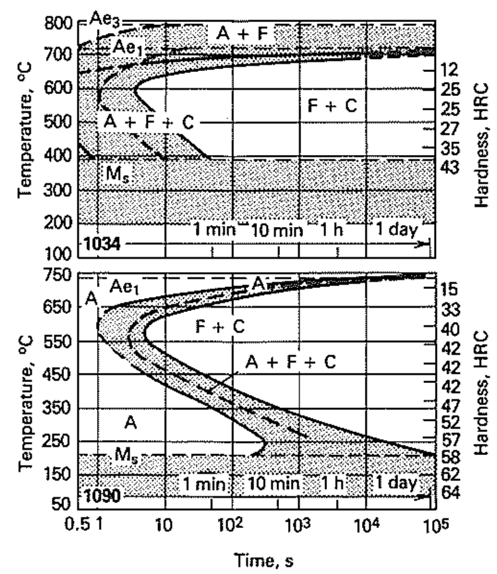


Success in martempering is based on a knowledge of the transformation characteristics (TTT curves) of the steel being considered. The temperature range in which martensite forms is especially important.

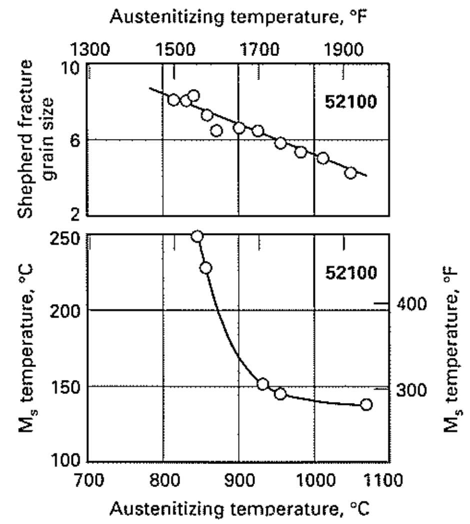
Low-carbon and medium-carbon steels 1008 through 1040 are too low in hardenability to be successfully martempered, except when carburized. The TTT curve for the 1034 steel in an adjoining Figure is characteristic of a steel that is unsuitable for martempering. Except in sections only a few thousandths of an inch thick, it would be impossible to quench the steel in hot salt or oil without encountering upper transformation products.

Borderline Grades. Some carbon steels higher in manganese content such as 1041 and 1141 can be martempered in thin sections. Low-alloy steels that have limited applications for martempering are listed (the lower-carbon grades are carburized before martempering): 1330 to 1345, 4012 to 4042, 4118 to 4137, 4422 and 4427, 4520, 5015 and 5046, 6118 and 6120, 8115.

Time-temperature transformation diagrams for 1034 and 1090 steels. The 1090 steel was austenitized at 885 °C (1625 °F) and had a grain size of 4 to 5.



Effects of austenitizing temperature on grain size and M_s temperature of 52100 steel



Most of these alloy steels are suitable for martempering in section thicknesses of up to 16 to 19 mm (0.625 to 0.75 in.). Martempering at temperatures below 205 °C (400 °F) will improve hardening response, although greater distortion may result than in martempering at higher temperatures.

Effect of Mass. The limitation of section thickness or mass must be considered in martempering. With a given severity of quench, there is a limit to bar size beyond which the center of the bar will not cool fast enough to transform entirely to martensite. This is shown in an adjoining Figure, which compares the maximum diameter of bar that can be hardened by martempering, oil quenching, and water quenching for 1045 steel and five alloy steels in various hardenabilities.

For some applications, a fully martensitic structure is unnecessary and a center hardness 10 HRC units lower than the maximum obtainable value for a given carbon content may be acceptable. By this criterion, maximum bar diameter is 25 to 300% greater than the maximum diameter that can be made fully martensitic (see lower graph in Figure just cited). Non-martensitic transformation products (pearlite, ferrite, and bainite) were observed at the positions on end-quenched bars corresponding to this reduced hardness value, as follows:

Steel	Transformation
1045	15% pearlite
8630	10% ferrite and bainite
1340	20% ferrite and bainite
52100	50% pearlite and bainite
4150	20% bainite
4340	5% bainite

Control of Process Variables

The success of martempering depends on close control of variables throughout the process. It is important that the prior structure of the material being austenitized be uniform. Also, use of a protective atmosphere (or salt) in austenitizing is required because oxide or scale will act as a barrier to uniform quenching in hot oil or salt.

Process variables that must be controlled include austenitizing temperature, temperature of martempering bath, time in martempering bath, salt contamination, water additions to salt, agitation, and rate of cooling from the martempering bath.

Austenitizing temperature is important because it controls austenitic grain size, degree of homogenization, and carbide solution, and because it affects the M_s temperature and increases grain size. (See adjoining Figure.)

Temperature control during austenitizing is the same for martempering as for conventional quenching: a tolerance of ±8 °C (±14 °F) is common. The austenitizing temperatures most commonly used for several different steels are indicated in an adjoining Table.

In most instances, austenitizing temperatures for martempering are the same as those for conventional oil quenching. Occasionally, however, medium-carbon steels are austenitized at higher temperatures prior to martempering to increase as-quenched hardness.

Salt Contamination. When parts are carburized or austenitized in a salt bath, they can be directly quenched in an oil bath operating at the martempering temperature. However, if the parts are carburized or austenitized in salt containing cyanide, they must *not* be directly martempered in salt because the two types of salts are not compatible and explosions can occur if they are mixed. Instead, one of two procedures should be used: Either air cool from the carburizing bath, wash, reheat to the austenitizing temperature for case and/or core in a chloride bath, and then martemper; or quench from the cyanide-containing bath into a neutral chloride rinse bath maintained at the austenitizing temperature and then martemper.

Temperature of the martempering bath varies considerably, depending on composition of workpieces, austenitizing temperature, and desired results. In establishing procedures for new applications, many plants begin at 95 °C (205 °F) for oil quenching, or at about 175 °C (345 °F) for salt quenching, and progressively increase the temperature until the best combination of hardness and distortion is obtained. Martempering temperatures (for oil and salt) that represent the experience of several plants are listed in the Table previously cited.

Typical Austenitizing and Martempering Temperatures for Various Steels

Grade	Austenitizing temperature		Martempering temperature			
			Oil(a)		Salt(b)	
	°C	°F	°C	°F	°C	°F
Through-hardening steels						
1024	870	1600	135	275	...	...
1070	845	1550	175	350	...	...
1146	815	1500	175	350	...	...
1330	845	1550	175	350	...	...
4063	845	1550	175	350	...	...
4130	845	1550	...	...	205-260	400-500
4140	845	1550	150	300	...	...
4140	830	1525	...	...	230-275	450-525
4340, 4350	815	1500	...	...	230-275	450-525
52100	855	1575	190	375	...	...
52100	845	1550	...	...	175-245	350-475
8740	830	1525	...	...	230-275	450-525
Carburizing steels						
3312	815	1500	...	...	175-190	350-375
4320	830	1525	...	...	175-190	350-375
4615	955	1750	190	375	...	...
4720	845	1550	...	...	175-190	350-375
8617, 8620	925	1700	150	300	...	...
8620	855	1575	...	...	175-190	350-375
9310	815	1500	...	...	175-190	350-375

(a) Time in oil varies from 4 to 20 min, depending on section thickness. (b) Martempering temperature depends on shape and mass of parts being quenched; higher temperatures in range (and sometimes above range) are used for thinner sections and more intricate parts.

Time in the martempering bath depends on section thickness and on the type, temperature, and degree of agitation of the quenching medium. The effects of section thickness and of temperature and agitation of the quench bath on immersion time are indicated in an adjoining Figure.

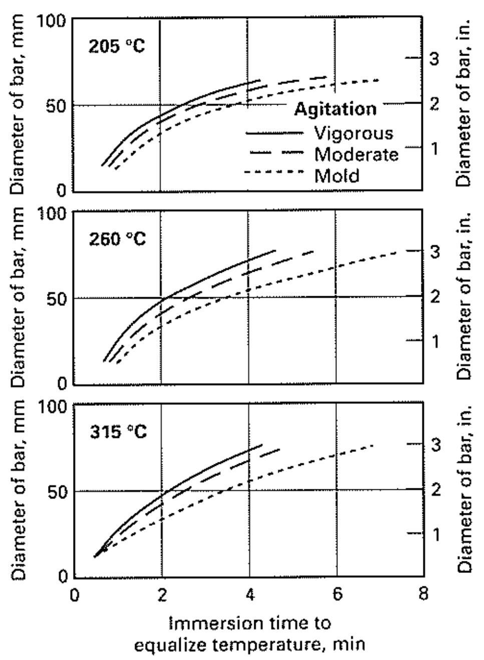
Because the object of martempering is to develop a martensitic structure with low thermal and transformation stresses, there is no need to hold the steel in the martempering bath for extended periods. Excessive holding lowers final hardness because it permits transformation to products other than martensite. In addition, stabilization may occur in medium-alloy steels that are held for extended periods at the martempering temperature.

The martempering time for temperature equalization in oil is about four to five times that required in anhydrous salt at the same temperature.

Water Additions to Salt. The quenching severity of a nitrate-nitrite salt can be increased significantly by careful addition of water. Agitation of the salt is necessary to disperse the water uniformly, and periodic additions are needed to maintain required water content. The water can be added with complete safety as follows:

- Water can be misted at a regulated rate into a vigorously agitated area of the molten bath
- In installations where the salt is pump circulated, returning salt is cascaded into the quench zone. A controlled fine stream of water can be injected into the cascade of returning salt
- The austempering bath can be kept saturated with moisture by introducing steam directly into the bath. The steam line should be trapped and equipped with a discharge to avoid emptying condensate directly into the bath
- Steam addition of water to the bath is done on baths with operating temperatures above 260 °C (500 °F)

Martempering time versus section size and agitation of quench bath for 1045 steel bars. Effects of bar diameter and agitation of quench bath on time required for centers of 1045 steel bars to reach martempering temperature when quenched from a neutral chloride bath at 845 °C (1555 °F) into anhydrous nitrate-nitrite martempering salt at 205, 260, and 315 °C (400, 500, and 600 °F). Length of each bar was three times the diameter.



Austempering of Steel

In this process, a ferrous alloy is isothermally quenched at a temperature below that of pearlite formation, Ref 1.

Workpieces are heated to a temperature within the austenitizing range, usually 790 to 915 °C (1455 to 1680 °F).

Quenching is in a bath maintained at a constant temperature, usually in a range of 260 to 400 °C (500 to 750 °F).

Parts are allowed to transform isothermally to bainite in this bath. Cooling to room temperature completes the process.

The basic differences between austempering and conventional quenching and tempering is shown schematically in an adjoining Figure. In true austempering, metal must be cooled from the austenitic temperature to the temperature of the austempering bath fast enough to ensure complete transformation of austenite to bainite.

Compositions and characteristics of salts used for austempering

	High range	Wide range
Sodium nitrate, %	45-55	0-25
Potassium nitrate, %	45-55	45-55
Sodium nitrite, %	...	25-55
Melting point (approx), °C (°F)	220 (430)	150-165 (300-330)
Working temperature range, °C (°F)	260-595 (500-1100)	175-540 (345-1000)

Treatment of hardenable cast irons is another application. In this case, a unique acicular matrix of bainitic ferrite and stable high-carbon austenite is formed.

Advantages of austempering include higher ductility, toughness, and strength at a given hardness (see Table) and reduced distortion. In addition, the overall time cycle is the shortest needed to get through hardness within the range of 35 to 55 HRC.

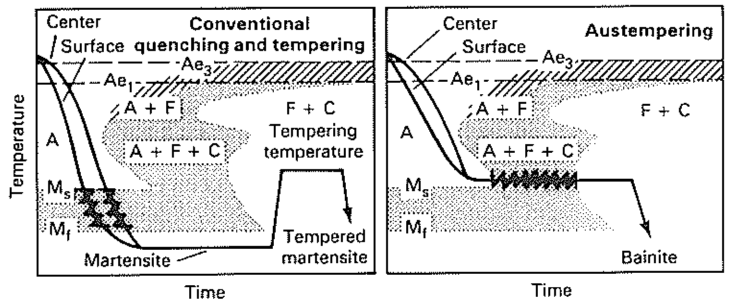
Quenching Media

Molten salt is the most commonly used. Formulations and characteristics of two typical baths are given in an adjoining Table. The high range of salt is suitable for only austempering, while the wide range type is suitable for austempering, martempering, and variations thereof. Quench severities under different conditions are compared in adjoining Table.

The quenching severity of a nitrate-nitrite salt can be boosted significantly with careful additions of water. The salt must be agitated to disperse the water uniformly. Periodic additions are needed to maintain required water content.

Water usually is added by directing a stream onto the molten salt at the agitator vortex. A protective water shroud surrounds the water spray to prevent spattering. Turbulence of the water carries it into the bath without spattering, a hazard to the operator. Water should never be added from a pail or dipper. Water is continuously evaporating from the bath at a rate which increases as hot work is quenched. The amount of water added to an

Comparison of time-temperature transformation cycles for conventional quenching and tempering and for austempering



Mechanical Properties of 1095 Steel Heat Treated by Three Methods

Specimen No.	Heat treatment	Hardness, HRC	Impact strength J	Impact strength ft · lbf	Elongation in 25 mm, or 1 in., %
1	Water quenched and tempered	53.0	16	12	...
2	Water quenched and tempered	52.5	19	14	...
3	Martempered and tempered	53.0	38	28	...
4	Martempered and tempered	52.8	33	24	...
5	Austempered	52.0	61	45	11
6	Austempered	52.5	54	40	8

open bath varies with the operating temperature of the salt, as indicated by the following recommended concentrations:

Temperature °C	Temperature °F	Water concentration, %
205	400	½ to 2
260	500	½ to 1
315	600	¼ to ½
370	700	¼

The presence of water can be visually detected by the operator because steam is released when hot work is immersed into the nitrate-nitrite salt.

Oil as Quenching Media. Usage is restricted to quenching below 245 °C (475 °F), because of oil's chemical instability, resulting in changes of viscosity at austempering temperatures.

Austempering Steels

Selection is based on the transformation characteristics of a specific steel as indicated by time-temperature-transformation (TTT) diagrams. Three important considerations are:

- Location of the nose of the TTT curve and the speed of a quench
- Time needed for complete transformation of austenite to bainite at the austempering temperature
- Location of the M_s point

Because of its transformation characteristics, 1080 carbon steel has limited applicability for austempering (see Figure). Cooling must take place in about 1 s to avoid the nose of the TTT curve to prevent transformation to pearlite on cooling. Because of this disadvantage, austempering of 1080 is limited to thin sections—the maximum is about 5 mm (0.2 in.).

On the other hand, 5140, a low-alloy steel, is well suited to the process (see TTT curves for 1080, 5140, 1034, and 9261 in an adjoining Figure). About 2 s are allowed to bypass the nose of the curve; transformation to bainite is completed within 1 to 10 min at 315 to 400 °C (600 to 750 °F). This means that sections thicker than those possible with 1080 steel are

Quench severity comparison for salt quenches

Agitation	At temperature 180 °C (360 °F)	At temperature 370 °C (700 °F)
Still and dry	0.15-0.20	0.15
Agitated and dry	0.25-0.35	0.20-0.25
Agitated with 0.5% water	0.40-0.50	0.30-0.40
Agitated with 2% water	0.50-0.60	0.50-0.60(a)
Agitated with 10% water	0.90-1.3(a)	Not possible

(a) Requires special enclosed quenching apparatus

feasible in treating 5140 and other steels with similar transformation characteristics.

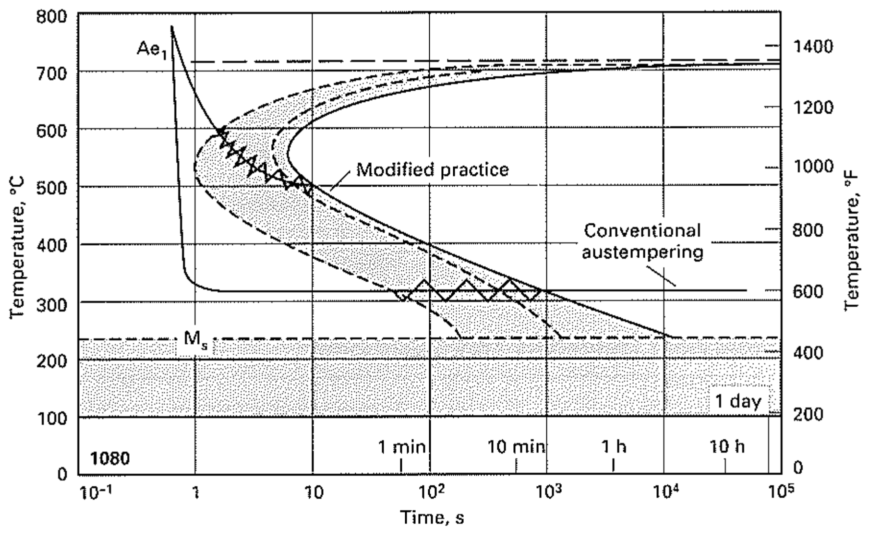
Other austempering steels include:

- Plain carbon steels containing 0.50 to 1.00% carbon and a minimum of 0.60% manganese
- High-carbon steels containing more than 0.90% carbon and, possibly, a little less than 0.60% manganese
- Some carbon steels, such as 1041, with less than 0.50% carbon and manganese in the range of 1.00 to 1.65%
- Certain low alloys, such as 5100 series alloys, that contain over 0.40% carbon, plus other steels such as 4140, 6145, and 9440

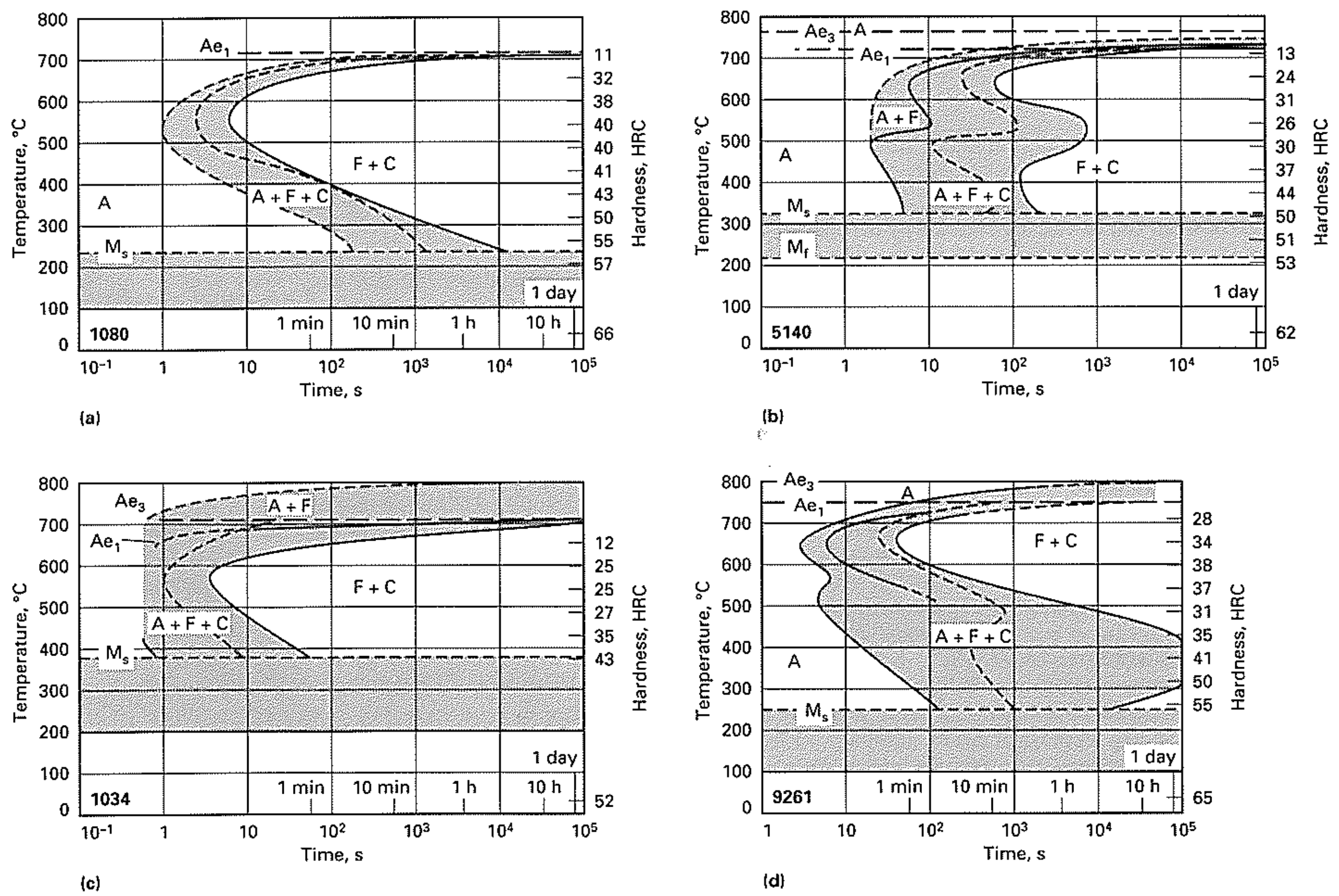
Some steels sufficient in carbon or alloy content to be hardenable are borderline or impractical because transformation at the nose of the TTT curve starts in less than 1 s, ruling out the quenching of all but thin sections in molten salt without forming some pearlite, or transformation takes excessively long times.

Chemical composition is the main determinant of the martensite start (M_s) temperature. Carbon is the most significant variable. Direct effects of other alloying elements are less pronounced, but carbide-forming elements such as molybdenum and vanadium can tie up carbon as alloy carbides and prevent complete solution of carbon.

Time-temperature transformation diagram for 1080 steel, showing difference between conventional and modified austempering. When applied to wire, the modification shown is known as patenting.



Transformation characteristics of 1080, 5140, 1034, and 9261 steels, in relation to their suitability for austempering. 1080, limited suitability for austempering because pearlite reaction starts too soon near 540 °C (1000 °F); 5140, well suited to austempering; 1034, impossible to austemper because of extremely fast pearlite reaction time at 540 to 595 °C (1000 to 1105 °F); 9261, not suited to austempering because of slow reaction to bainite at 260 to 400 °C (500 to 750 °F)



Hardness of Various Steels and Section Sizes of Austempered Parts

Steel	Section size		Salt temperature		M_s temperature(a)		Hardness, HRC
	mm	in.	°C	°F	°C	°F	
1050	3(b)	0.125(b)	345	655	320	610	41-47
1065	5(c)	0.187(c)	(d)	(d)	275	525	53-56
1066	7(c)	0.281(c)	(d)	(d)	260	500	53-56
1084	6(c)	0.218(c)	(d)	(d)	200	395	55-58
1086	13(c)	0.516(c)	(d)	(d)	215	420	55-58
1090	5(c)	0.187(c)	(d)	(d)	...	...	57-60
1090(e)	20(c)	0.820(c)	315(f)	600(f)	...	...	44.5 (avg)
1095	4(c)	0.148(c)	(d)	(d)	210(g)	410(g)	57-60
1350	16(c)	0.625(c)	(d)	(d)	235	450	53-56
4063	16(c)	0.625(c)	(d)	(d)	245	475	53-56
4150	13(c)	0.500(c)	(d)	(d)	285	545	52 max
4365	25(c)	1.000(c)	(d)	(d)	210	410	54 max
5140	3(b)	0.125(b)	345	655	330	630	43-48
5160(e)	26(c)	1.035(c)	315(f)	600(f)	255	490	46.7 (avg)
8750	3(b)	0.125(b)	315	600	285	545	47-48
50100	8(c)	0.312(c)	(d)	(d)	...	...	57-60

(a) Calculated. (b) Sheet thickness. (c) Diameter of section. (d) Salt temperature adjusted to give maximum hardness and 100% bainite. (e) Modified austempering; microstructure contained pearlite as well as bainite. (f) Salt with water additions. (g) Experimental value

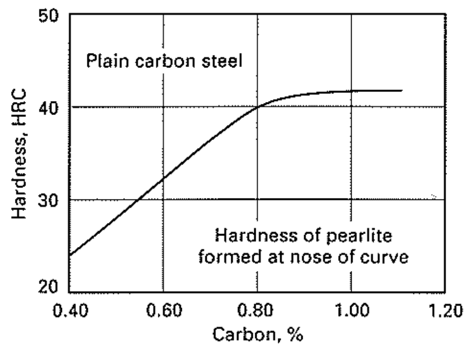
Typical Production Applications of Austempering

Parts listed in order of increasing section thickness

Part	Steel	Maximum section thickness		Parts per unit weight		Salt temperature		Immersion time, min	Hardness, HRC
		mm	in.	kg^{-1}	lb^{-1}	°C	°F		
Plain carbon steel parts									
Clevis	1050	0.75	0.030	770/kg	350/lb	360	680	15	42
Follower arm	1050	0.75	0.030	412/kg	187/lb	355	675	15	42
Spring	1080	0.79	0.031	220/kg	100/lb	330	625	15	48
Plate	1060	0.81	0.032	88/kg	40/lb	330	630	6	45-50
Cam lever	1065	1.0	0.040	62/kg	28/lb	370	700	15	42
Plate	1050	1.0	0.040	0.5 kg	¼ lb	360	675	15	42
Type bar	1065	1.0	0.040	141/kg	64/lb	370	700	15	42
Tabulator stop	1065	1.22	0.048	440/kg	200/lb	360	680	15	45
Lever	1050	1.25	0.050	...	...	345	650	15	45-50
Chain link	1050	1.5	0.060	573/kg	260/lb	345	650	15	45
Shoe-last link	1065	1.5	0.060	86/kg	39/lb	290	550	30	52
Shoe-toe cap	1070	1.5	0.060	18/kg	8/lb	315	600	60	50
Lawn mower blade	1065	3.18	0.125	1.5 kg	⅔ lb	315	600	15	50
Lever	1075	3.18	0.125	24/kg	11/lb	385	725	5	30-35
Fastener	1060	6.35	0.250	110/kg	50/lb	310	590	25	50
Stabilizer bar	1090	19	0.750	22 kg	10 lb	370	700	6-9	40-45
Boron steel bolt	10B20	6.35	0.250	100/kg	45/lb	420	790	5	38-43
Alloy steel parts									
Socket wrench	6150	...	...	0.3 kg	⅛ lb	365	690	15	45
Chain link	Cr-Ni-V(a)	1.60	0.063	110/kg	50/lb	290	550	25	53
Pin	3140	1.60	0.063	5500/kg	2500/lb	325	620	45	48
Cylinder liner	4140	2.54	0.100	15 kg	7 lb	260	500	14	40
Anvil	8640	3.18	0.125	1.65 kg	¾ lb	370	700	30	37
Shovel blade	4068	3.18	0.125	...	...	370	700	15	45
Pin	3140	6.35	0.250	100/kg	45/lb	370	700	45	40
Shaft	4140(b)	9.53	0.375	0.5 kg	¼ lb	385	725	15	35-40
Gear	6150	12.7	0.500	4.4 kg	2 lb	305	580	30	45
Carburized steel parts									
Lever	1010	3.96	0.156	33 kg	15 lb	385	725	5	30-35(c)
Shaft	1117	6.35	0.250	66/kg	30/lb	385	725	5	30-35(c)
Block	8620	11.13	0.438	132/kg	60/lb	290-315	550-600	30	50(c)

(a) Contains 0.65 to 0.75% C. (b) Leaded grade. (c) Case hardness

Effect of carbon content in plain carbon steel on the hardness of fine pearlite formed when the quenching curve intersects the nose of the time-temperature diagram for isothermal transformation



Austenitizing temperature has a significant effect on the time at which ·ansformation begins. As this temperature rises above normal (for a given teel) the nose of the TTT curve shifts to the right because of grain oarsening. Use of standard austenitizing temperatures is recommended.

;ection Thickness Limitations

Maximum section thickness is important in determining if a part is a andidate for austempering. The maximum for a 1080 steel, for instance, ; about 5 mm (0.2 in.), if the part requires a fully bainitic structure. Steels ›wer in carbon are restricted to proportionately less thicknesses. However, eavier sections can be handled if a low-carbon steel contains boron. Also, ections thicker than 5 mm (0.2 in.) are regularly austempered in production when some pearlite is tolerated (see Table that lists section thicknesses ›r specific steels).

\pplications

Austempering usually is substituted for conventional quenching and ›mpering for these reasons:

- To improve mechanical properties
- To reduce the likelihood of cracking and distortion
- To upgrade wear resistance at a given hardness
- To add resistance to subsequent embrittlement

At times, austempering is more economical than conventional quenching nd tempering—most likely when small parts are treated in an automated ›tup in competition with conventional quenching and tempering, which is three-step operation: austenitizing, quenching, and tempering. Austempering is a two-step process: austenitizing and isothermal transformation in an austempering bath.

Generally, applications are limited to parts made from small-diameter bars or from sheet or strip which is small in cross section. The process is especially suitable for the treatment of thin section, carbon steel parts calling for exceptional toughness at hardnesses between 40 and 50 HRC.

Reduction in the area of austempered, carbon steel parts usually is much greater than it is for parts conventionally quenched and tempered, as indicated in the following tabulation for 5 mm (0.180 in.) bars of 0.85% carbon, plain carbon steel:

Austempered mechanical properties	
Tensile strength, MPa (ksi)	1780 (258)
Yield strength, MPa (ksi)	1450 (210)
Reduction in area, %	45
Hardness, HRC	50
Quenched and tempered mechanical properties	
Tensile strength, MPa (ksi)	1795 (260)
Yield strength, MPa (ksi)	1550 (225)
Reduction in area, %	28
Hardness, HRC	50

In commercial austempering practice, acceptable results are obtained with parts having less than 100% bainite. In some instances, 85% bainite is satisfactory. Representative practice in a dozen plants for a variety of parts and steels is summarized in an adjoining Table.

Dimensional Control. Dimensional change in austempering usually is less than that experienced in conventional quenching and tempering. The process may be the most effective way to hold close tolerances without excessive straightening or machining after heat treating.

Modified Austempering. Modifications of the process that result in mixed pearlite/bainite structures are quite common in commercial practice.

Patenting of wire is an example. Wire or rod is continuously quenched in a bath maintained at 510 to 540 °C (950 to 1000 °F) and held for periods ranging from 10 s (for small wire) to 90 s (for rod). Result: Moderately high strength combined with high ductility.

Modified practice varies from true austempering in that the quenching rate is different; instead of being rapid enough to avoid the nose of the TTT curve, it is sufficiently slow to intersect the nose, which results in the formation of fine pearlite.

Practice is similar for plain carbon steels at hardnesses between 30 and 42 HRC. In this instance, the hardness of steel quenched at a rate that intersects the nose of the TTT curve varies with carbon content (see Figure).

Carbon & Alloy Steels Introduction

Designation System

Much study and effort have been put into providing a simplified list of steel compositions to serve the metallurgical and engineering requirements of fabricators and users of steel products. These studies have resulted in the carbon and alloy steel compositions listed in Tables 2 to 10 and are generally known as the Standard Grades.

AISI-SAE Grades

With few exceptions, steel compositions established by the American Iron and Steel Institute and the Society of Automotive Engineers (AISI and SAE) use a four-numeral series to designate the standard carbon and alloy steels, specified to chemical composition ranges. In two instances of alloy steels, a five-numeral designation is used.

In the alloy steel tables which are presented later in this section, some grades bear the prefix letter E. This denotes that the steel was made by the basic electric furnace process with special practice. In the designations of certain carbon and alloy steels, the suffix letters H and RH signify that the steel is made to comply with specific hardenability limits.

Carbon or alloy steel designations showing the letter B inserted between the second and third numerals indicate that the steel contains 0.0005 to 0.003 boron. The letter L inserted between the second and third numerals of the designation indicates that this steel contains 0.15 to 0.35 lead for improved machinability.

Table 1 represents an abbreviated listing of the AISI or SAE carbon and alloy steels. The first two digits of each series have a definite meaning, providing the approximate composition of elements other than carbon.

The last two digits of the four-numeral designations and the last three digits of the five-numeral designations indicate the approximate mean carbon content of the allowable carbon range. For example, in Grade 1035, the 35 indicates a carbon range of 0.98 to 1.10. These last digits are replaced by XX in Table 1. It is often necessary to deviate slightly from this system and to interpolate numbers for some carbon ranges and for variations in manganese, sulfur, or other elements with the same carbon range.

Table 1 Types and Approximate Percentages of Identifying Elements in Standard Carbon and Alloy Steels

Series designation	Description
Carbon steels	
10XX	Nonresulfurized, 1.00 manganese maximum
11XX	Resulfurized
12XX	Rephosphorized and resulfurized
15XX	Nonresulfurized, over 1.00 manganese maximum
Alloy steels	
13XX	1.75 manganese
40XX	0.20 or 0.25 molybdenum or 0.25 molybdenum and 0.042 sulfur
41XX	0.50, 0.80, or 0.95 chromium and 0.12, 0.20, or 0.30 molybdenum
43XX	1.83 nickel, 0.50 to 0.80 chromium, and 0.25 molybdenum
46XX	0.85 or 1.83 nickel and 0.20 or 0.25 molybdenum
47XX	1.05 nickel, 0.45 chromium, 0.20 or 0.35 molybdenum
48XX	3.50 nickel and 0.25 molybdenum
51XX	0.80, 0.88, 0.93, 0.95, or 1.00 chromium
51XXX	1.03 chromium
52XXX	1.45 chromium
61XX	0.60 or 0.95 chromium and 0.13 or 0.15 vanadium minimum
86XX	0.55 nickel, 0.50 chromium, and 0.20 molybdenum
87XX	0.55 nickel, 0.50 chromium, and 0.25 molybdenum
88XX	0.55 nickel, 0.50 chromium, and 0.35 molybdenum
92XX	2.00 silicon or 1.40 silicon and 0.70 chromium
50BXX(a)	0.28 or 0.50 chromium
51BXX(a)	0.80 chromium
81BXX(a)	0.30 nickel, 0.45 chromium, and 0.12 molybdenum
94BXX(a)	0.45 nickel, 0.40 chromium, and 0.12 molybdenum

(a) B denotes boron steel. Source: *AISI Steel Products Manual*

Table 2 Compositions of Standard Carbon H-steels and Standard Carbon Boron H-steels

Steel designation AISI or SAE	UNS No.	Chemical composition, %				
		C	Mn	P max	S max	Si
Standard carbon H-steels						
1038H	H10380	0.34-0.43	0.50-1.00	0.040	0.050	0.15-0.30
1045H	H10450	0.42-0.51	0.50-1.00	0.040	0.050	0.15-0.30
1522H	H15220	0.17-0.25	1.00-1.50	0.040	0.050	0.15-0.30
1524H	H15240	0.18-0.26	1.25-1.75(a)	0.040	0.050	0.15-0.30
1526H	H15260	0.21-0.30	1.00-1.50	0.040	0.050	0.15-0.30
1541H	H15410	0.35-0.45	1.25-1.75(a)	0.040	0.050	0.15-0.30
Standard carbon boron H-steels						
15B21H, 15B21RH	H15211	0.17-0.24	0.70-1.20	0.040	0.050	0.15-0.30
15B35H, 15B35RH	H15351	0.31-0.39	0.70-1.20	0.040	0.050	0.15-0.30
15B37H	H15371	0.30-0.39	1.00-1.50	0.040	0.050	0.15-0.30
15B41H	H15411	0.35-0.45	1.25-1.75(a)	0.040	0.050	0.15-0.30
15B48H	H15481	0.43-0.53	1.00-1.50	0.040	0.050	0.15-0.30
15B62H	H15621	0.54-0.67	1.00-1.50	0.040	0.050	0.40-0.60

(a) Standard AISI-SAE H-steels with 1.75 manganese maximum are classified as carbon steels.

̄able 3 Compositions of Standard Nonresulfurized ;arbon Steels (1.0 Manganese Maximum)

;teel lesignation ıISI or SAE	UNS No.	Chemical composition, % C	Mn	P max	S max
005(a)	G10050	0.06 max	0.35 max	0.040	0.050
006(a)	G 10060	0.08 max	0.25 max	0.040	0.050
008	G10080	0.10 max	0.30-0.50	0.040	0.050
010	G10100	0.08-0.13	0.30-0.60	0.040	0.050
012	G10120	0.10-0.15	0.30-0.60	0.040	0.050
013	G10130	0.11-0.16	0.50-0.80	0.040	0.050
015	G10150	0.13-0.18	0.30-0.60	0.040	0.050
016	G10160	0.13-0.18	0.60-0.90	0.040	0.050
017	G10170	0.15-0.20	0.30-0.60	0.040	0.050
018	G10180	0.15-0.20	0.60-0.90	0.040	0.050
019	G10190	0.15-0.20	0.70-1.00	0.040	0.050
020	G10200	0.18-0.23	0.30-0.60	0.040	0.050
021	G10210	0.18-0.23	0.60-0.90	0.040	0.050
022	G10220	0.18-0.23	0.70-1.00	0.040	0.050
023	G10230	0.20-0.25	0.30-0.60	0.040	0.050
025	G10250	0.22-0.28	0.30-0.60	0.040	0.050
026	G10260	0.22-0.28	0.60-0.90	0.040	0.050
029	G10290	0.25-0.31	0.60-0.90	0.040	0.050
030	G10300	0.28-0.34	0.60-0.90	0.040	0.050
035	G10350	0.32-0.38	0.60-0.90	0.040	0.050
037	G10370	0.32-0.38	0.70-1.00	0.040	0.050
038	G10380	0.35-0.42	0.60-0.90	0.040	0.050
039	G10390	0.37-0.44	0.70-1.00	0.040	0.050
040	G10400	0.37-0.44	0.60-0.90	0.040	0.050
042	G10420	0.40-0.47	0.60-0.90	0.040	0.050
043	G10430	0.40-0.47	0.70-1.00	0.040	0.050
044	G10440	0.43-0.50	0.30-0.60	0.040	0.050
045	G10450	0.43-0.50	0.60-0.90	0.040	0.050
046	G10460	0.43-0.50	0.70-1.00	0.040	0.050
049	G10490	0.46-0.53	0.60-0.90	0.040	0.050
050	G10500	0.48-0.55	0.60-0.90	0.040	0.050
053	G10530	0.48-0.55	0.70-1.00	0.040	0.050
055	G10550	0.50-0.60	0.60-0.90	0.040	0.050
059(a)	G10590	0.55-0.65	0.50-0.80	0.040	0.050
060	G10600	0.55-0.65	0.60-0.90	0.040	0.050
064	G10640	0.60-0.70	0.50-0.80	0.040	0.050
065	G10650	0.60-0.70	0.60-0.90	0.040	0.050
069	G10690	0.65-0.75	0.40-0.70	0.040	0.050
070	G10700	0.65-0.75	0.60-0.90	0.040	0.050
075	G10750	0.70-0.80	0.40-0.70	0.040	0.050
078	G10780	0.72-0.85	0.30-0.60	0.040	0.050
080	G10800	0.75-0.88	0.60-0.90	0.040	0.050
084	G10840	0.80-0.93	0.60-0.90	0.040	0.050
085	G10850	0.80-0.93	0.70-1.00	0.040	0.050
086(a)	G10860	0.80-0.93	0.30-0.50	0.040	0.050
090	G10900	0.85-0.98	0.60-0.90	0.040	0.050
095	G10950	0.90-1.03	0.30-0.50	0.040	0.050

ı) Standard steel grades for wire rods and wire only

ı̇etailed composition ranges will be provided for each member of each :eries in other tables which follow.

ʲnified Numbering System

The standard carbon and alloy grades established by AISI or SAE have ow been assigned designations in the Unified Numbering System (UNS) y the American Society for Testing and Materials (ASTM E527) and the ociety of Automotive Engineers (SAE J1868). In the composition tables ʻhich follow, the UNS numbers are listed along with their corresponding .ISI-SAE numbers.

The UNS number consists of a single letter prefix followed by five umerals. The prefix letter G indicates standard grades of carbon or alloy eels, while the prefix letters H and RH indicate standard grades which ıeet certain hardenability limits. The first four digits of the UNS designations usually correspond to the standard AISI-SAE designations, while the last digit (other than zero) denotes some additional composition requirement such as lead or boron. The digit is sometimes a 6, which is used to designate steels which are made by the basic electric furnace with special practices.

Table 4 Compositions of Standard Nonresulfurized Carbon Steels (Over 1.0 Manganese)

Steel designation AISI or SAE	UNS No.	Chemical composition, % C	Mn	P max	S max
1513	G15130	0.10-0.16	1.10-1.40	0.040	0.050
1522	G15220	0.18-0.24	1.10-1.40	0.040	0.050
1524	G15240	0.19-0.25	1.35-1.65	0.040	0.050
1526	G15260	0.22-0.29	1.10-1.40	0.040	0.050
1527	G15270	0.22-0.29	1.20-1.50	0.040	0.050
1541	G15410	0.36-0.44	1.35-1.65	0.040	0.050
1548	G15480	0.44-0.52	1.10-1.40	0.040	0.050
1551	G15510	0.45-0.56	0.85-1.15	0.040	0.050
1552	G15520	0.47-0.55	1.20-1.50	0.040	0.050
1561	G15610	0.55-0.65	0.75-1.05	0.040	0.050
1566	G15660	0.60-0.71	0.85-1.15	0.040	0.050

The term carbon steel does not necessarily mean that the steel does not contain any other alloying elements. There are, however, sharp restrictions on the amounts of alloy that may be contained in carbon steels. These generally agreed upon restrictions are summarized in the paragraphs which follow.

Steel is considered to be a carbon steel when no minimum content is specified or required for aluminum (except as related to deoxidization or grain size control), chromium, cobalt, columbium (niobium), molybdenum, nickel, titanium, tungsten, vanadium, zirconium, or any other element added to obtain a desired alloying effect. Further restrictions include: (a) when the specified minimum for copper does not exceed 0.40 or (b) when the maximum content specified for any of the following elements does not exceed the percentages noted: 1.65 manganese, 0.60 silicon, 0.60 copper. Boron may be added to carbon steels to improve hardenability (see Table 2).

In all carbon steels, small quantities of alloying elements or residuals, such as nickel, chromium, and molybdenum, are present. Their existence is unavoidable because they are retained from the raw materials used for melting. As a rule, small amounts of these elements have little or no meaning to the fabricator. For purposes of identity and because of the wide variations in properties, compositions of the standard carbon steels are presented in five separate tables.

Standard Nonresulfurized Grades

Compositions for 48 standard nonresulfurized grades, 1.0 manganese maximum, are given in Table 3.

Many of these grades are available with an addition of 0.15 to 0.35 lead to improve machinability. When lead is added, it is denoted by the letter L between the second and third digits. For example, a leaded grade of 1045 is denoted as 10L45.

Similarly, many of these grades are available with a boron addition. A letter B is inserted between the second and third digits, such as 10B35.

Compositions for 11 additional standard carbon steels are presented in Table 4. The essential difference between the steels listed in Table 3, assuming the same carbon content, and those listed in Table 4 is the higher manganese content of the latter group. For one grade, it is as high as 1.65, which is the borderline between carbon steels and alloy steel. Higher manganese increases hardenability. The grades listed in Table 4 may also be produced with additions of lead or boron as described above for the grades listed in Table 3.

Standard Resulfurized Carbon Steels

Compositions listed in Table 5 represent those grades of standard carbon steels which have been resulfurized, as high as 0.33 sulfur, for improved machinability. These grades are also available with lead additions for further improvement in machinability.

Table 5 Compositions of Standard Resulfurized Carbon Steels

Steel designation AISI or SAE	UNS No.	Chemical composition, % C	Mn	P max	S
1108	G11080	0.08-0.13	0.50-0.80	0.040	0.08-0.13
1110	G11100	0.08-0.13	0.30-0.60	0.040	0.08-0.13
1113	G11130	0.13 max	0.70-1.00	0.07-0.12	0.24-0.33
1117	G11170	0.14-0.20	1.00-1.30	0.040	0.08-0.13
1118	G11180	0.14-0.20	1.30-1.60	0.040	0.08-0.13
1137	G11370	0.32-0.39	1.35-1.65	0.040	0.08-0.13
1139	G11390	0.35-0.43	1.35-1.65	0.040	0.13-0.20
1140	G11400	0.37-0.44	0.70-1.00	0.040	0.08-0.13
1141	G11410	0.37-0.45	1.35-1.65	0.040	0.08-0.13
1144	G11440	0.40-0.48	1.35-1.65	0.040	0.24-0.33
1146	G11460	0.42-0.49	0.70-1.00	0.040	0.08-0.13
1151	G11510	0.48-0.55	0.70-1.00	0.040	0.08-0.13

Table 6 Compositions of Standard Rephosphorized and Resulfurized Carbon Steels

Steel designation AISI or SAE	UNS No.	Chemical composition, % C	Mn	P	S	Pb
1211	G12110	0.13 max	0.60-0.90	0.07-0.12	0.10-0.15	...
1212	G12120	0.13 max	0.70-1.00	0.07-0.12	0.16-0.23	...
1213	G12130	0.13 max	0.70-1.00	0.07-0.12	0.24-0.33	...
1215	G12150	0.09 max	0.75-1.05	0.04-0.09	0.26-0.35	...
12L14	G12144	0.15 max	0.85-1.15	0.04-0.09	0.26-0.35	0.15-0.35

Standard Rephosphorized and Resulfurized Carbon Steels

Table 6 lists compositions for four grades of carbon steels which contain higher than normal amounts of phosphorus as well as sulfur. One grade, 12L14, has been rephosphorized, resulfurized, and leaded. All of the above conditions and additions contribute to the superior machining characteristics of these grades. Any steel from this group may be produced with additions of 0.15 to 0.35 lead.

Alloy Steels

A steel is considered to be an alloy grade when the maximum of the range given for the content of alloying elements exceeds one or more of the following limits: (a) 1.65 manganese, (b) 0.60 silicon, (c) 0.60 copper. It is also considered an alloy steel when a definite minimum quantity of any of the following elements is specified or required within the limits of the recognized constructional alloy steels: (a) aluminum, (b) chromium, (c) cobalt, (d) columbium (niobium), (e) molybdenum, (f) nickel, (g) titanium, (h) tungsten, (I) vanadium, (k) zirconium, or any other alloying element added to obtain a specific alloying effect. As a rule, the total amount of alloy in these AISI-SAE Standard Grades of Alloy Steels does not exceed approximately 4.0 over and above that amount normally permitted in carbon steels.

Compositions of Standard Alloy Steels. Compositions for a total of 58 different alloy steels are listed in Table 7. It might seem that there is great similarity among grades in some instances and that the list could easily be reduced in number of grades. However, many different compositions are required to fulfill the thousands of mechanical and physical property requirements for manufactured products. The demands of fabricability and economy are also factors which must be satisfied, often with very precise chemical compositions.

Fig. 1 Relationship Between Carbon Content and Maximum Hardness. Full hardness can be obtained with as little as 0.60 C. Note data point, O

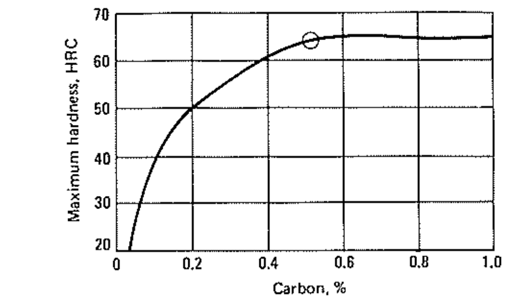
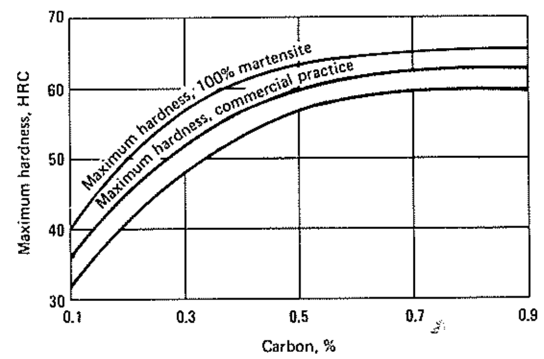


Fig. 2 Relationship Between Carbon Content and Maximum Hardness. Usually attained in commercial hardening



While the various compositions listed in Table 7 are not produced in equal quantities, each of the steels listed in this table is produced in significant quantities by numerous mills. A large number of them are also available through steel service centers.

Almost all of the 58 compositions listed in Table 7 are available with lead additions for improved machinability, and some manufacturers produce certain alloy grades as resulfurized steels, also to induce better machinability.

Compositions of Standard Boron Steels. Compositions of the standard alloy grades which contain 0.0005 to 0.003 boron are listed in Table 8. The boron provides an increase in hardenability for these steels which are relatively lean alloys.

Hardenability

Hardenability and methods for increasing this property, such as boron additions, are referred to several times within this article. However, hardenability does not necessarily mean the ability to be hardened to a certain Rockwell or Brinell value. For example, just because a given steel is capable of being hardened to 65 HRC does not necessarily mean that it has high hardenability. Also, a steel that can be hardened to only 40 HRC may have very high hardenability. Hardenability refers to capacity of hardening (depth) rather than to maximum attainable hardness.

Role of Carbon

The carbon content of a steel determines the maximum hardness attainable, with particular emphasis on the word attainable. The effect of carbon on attainable hardness is demonstrated in Fig. 1. The maximum attainable hardness requires only about 0.60 carbon. However, the data shown in Fig. 1 are actually theoretical, because they are based upon heat treating of wafer-thin sections which are cooled from their austenitizing temperature to room temperature within a matter of seconds, thus developing 100%

martensite throughout their sections. Therefore, the ideal condition shown in Fig. 1 is seldom attained in practice. Figure 2 shows a better example of hardness versus carbon content because it is a more accurate condition, one expected in commercial practice.

The most important factor influencing the maximum hardness that can be attained is mass of the metal being quenched. In a small section, the heat is extracted quickly, thus exceeding the critical cooling rate of the specific steel. The critical cooling rate is that rate of cooling which must be exceeded to prevent formation of nonmartensitic products. As section size increases, it becomes increasingly difficult to extract the heat fast enough to exceed the critical cooling rate and thus avoid formation of nonmartensitic products. A typical condition is shown in Fig. 3, which illustrates the effect of section size on surface hardness and is a good example of the mass effect. For small sections up to 13 mm (0.5 in.), full hardness of approxi-

Table 7 Compositions of Standard Alloy Steels

Steel designation AISI or SAE	UNS No.	Chemical composition, %							
		C	Mn	P max	S max	Si	Ni	Cr	Mo
1330	G13300	0.28-0.33	1.60-1.90	0.035	0.040	0.15-0.30	...	...	...
1335	G13350	0.33-0.38	1.60-1.90	0.035	0.040	0.15-0.30	...	...	...
1340	G13400	0.38-0.43	1.60-1.90	0.035	0.040	0.15-0.30	...	...	...
1345	G13450	0.43-0.48	1.60-1.90	0.035	0.040	0.15-0.30	...	...	...
4023	G40230	0.20-0.25	0.70-0.90	0.035	0.040	0.15-0.30	...	...	0.20-0.30
4024	G40240	0.20-0.25	0.70-0.90	0.035	0.035-0.050	0.15-0.30	...	...	0.20-0.30
4027	G40270	0.25-0.30	0.70-0.90	0.035	0.040	0.15-0.30	...	...	0.20-0.30
4028	G40280	0.25-0.30	0.70-0.90	0.035	0.035-0.050	0.15-0.30	...	...	0.20-0.30
4037	G40370	0.35-0.40	0.70-0.90	0.035	0.040	0.15-0.30	...	...	0.20-0.30
4047	G40470	0.45-0.50	0.70-0.90	0.035	0.040	0.15-0.30	...	...	0.20-0.30
4118	G41180	0.18-0.23	0.70-0.90	0.035	0.040	0.15-0.30	...	0.40-0.60	0.08-0.15
4130	G41300	0.28-0.33	0.40-0.60	0.035	0.040	0.15-0.30	...	0.80-1.10	0.15-0.25
4137	G41370	0.35-0.40	0.70-0.90	0.035	0.040	0.15-0.30	...	0.80-1.10	0.15-0.25
4140	G41400	0.38-0.43	0.75-1.00	0.035	0.040	0.15-0.30	...	0.80-1.10	0.15-0.25
4142	G41420	0.40-0.45	0.75-1.00	0.035	0.040	0.15-0.30	...	0.80-1.10	0.15-0.25
4145	G41450	0.43-0.48	0.75-1.00	0.035	0.040	0.15-0.30	...	0.80-1.10	0.15-0.25
4147	G41470	0.45-0.50	0.75-1.00	0.035	0.040	0.15-0.30	...	0.80-1.10	0.15-0.25
4150	G41500	0.48-0.53	0.75-1.00	0.035	0.040	0.15-0.30	...	0.80-1.10	0.15-0.25
4161	G41610	0.56-0.64	0.75-1.00	0.035	0.040	0.15-0.30	...	0.70-0.90	0.25-0.35
4320	G43200	0.17-0.22	0.45-0.65	0.035	0.040	0.15-0.30	1.65-2.00	0.40-0.60	0.20-0.30
4340	G43400	0.38-0.43	0.60-0.80	0.035	0.040	0.15-0.30	1.65-2.00	0.70-0.90	0.20-0.30
E4340	G43406	0.38-0.43	0.65-0.85	0.025	0.025	0.15-0.30	1.65-2.00	0.70-0.90	0.20-0.30
4615	G46150	0.13-0.18	0.45-0.65	0.035	0.040	0.15-0.30	1.65-2.00	...	0.20-0.30
4620	G46200	0.17-0.22	0.45-0.65	0.035	0.040	0.15-0.30	1.65-2.00	...	0.20-0.30
4626	G46260	0.24-0.29	0.45-0.65	0.035	0.040	0.15-0.30	0.70-.100	...	0.15-0.25
4720	G47200	0.17-0.22	0.50-0.70	0.035	0.040	0.15-0.30	0.90-1.20	0.35-0.55	0.15-0.25
4815	G48150	0.13-0.18	0.40-0.60	0.035	0.040	0.15-0.30	3.25-3.75	...	0.20-0.30
4817	G48170	0.15-0.20	0.40-0.60	0.035	0.040	0.15-0.30	3.25-3.75	...	0.20-0.30
4820	G48200	0.18-0.23	0.50-0.70	0.035	0.040	0.15-0.30	3.25-3.75	...	0.20-0.30
5117	G51170	0.15-0.20	0.70-0.90	0.035	0.040	0.15-0.30	...	0.70-0.90	...
5120	G51200	0.17-0.22	0.70-0.90	0.035	0.040	0.15-0.30	...	0.70-0.90	...
5130	G51300	0.28-0.33	0.70-0.90	0.035	0.040	0.15-0.30	...	0.80-1.10	...
5132	G51320	0.30-0.35	0.60-0.80	0.035	0.040	0.15-0.30	...	0.75-1.00	...
5135	G51350	0.33-0.38	0.60-0.80	0.035	0.040	0.15-0.30	...	0.80-1.05	...
5140	G51400	0.38-0.43	0.70-0.90	0.035	0.040	0.15-0.30	...	0.70-0.90	...
5150	G51500	0.48-0.53	0.70-0.90	0.035	0.040	0.15-0.30	...	0.70-0.90	...
5155	G51550	0.51-0.59	0.70-0.90	0.035	0.040	0.15-0.30	...	0.70-0.90	...
5160	G51600	0.56-0.64	0.75-1.00	0.035	0.040	0.15-0.30	...	0.70-0.90	...
E51100	G51986	0.98-1.10	0.25-0.45	0.025	0.025	0.15-0.30	...	0.90-1.15	...
E52100	G52986	0.98-1.10	0.25-0.45	0.025	0.025	0.15-0.30	...	1.30-1.60	...
6118	G61180	0.16-0.21	0.50-0.70	0.035	0.040	0.15-0.30	...	0.50-0.70	0.10-0.15 V
6150	G61500	0.48-0.53	0.70-0.90	0.035	0.040	0.15-0.30	...	0.80-1.10	0.15 V min
8615	G86150	0.13-0.18	0.70-0.90	0.035	0.040	0.15-0.30	0.40-0.70	0.40-0.60	0.15-0.25
8617	G86170	0.15-0.20	0.70-0.90	0.035	0.040	0.15-0.30	0.40-0.70	0.40-0.60	0.15-0.25
8620	G86200	0.18-0.23	0.70-0.90	0.035	0.040	0.15-0.30	0.40-0.70	0.40-0.60	0.15-0.25
8622	G86220	0.20-0.25	0.70-0.90	0.035	0.040	0.15-0.30	0.40-0.70	0.40-0.60	0.15-0.25
8625	G86250	0.23-0.28	0.70-0.90	0.035	0.040	0.15-0.30	0.40-0.70	0.40-0.60	0.15-0.25
8627	G86270	0.25-0.30	0.70-0.90	0.035	0.040	0.15-0.30	0.40-0.70	0.40-0.60	0.15-0.25
8630	G86300	0.28-0.33	0.70-0.90	0.035	0.040	0.15-0.30	0.40-0.70	0.40-0.60	0.15-0.25
8637	G86370	0.35-0.40	0.75-1.00	0.035	0.040	0.15-0.30	0.40-0.70	0.40-0.60	0.15-0.25
8640	G86400	0.38-0.43	0.75-1.00	0.035	0.040	0.15-0.30	0.40-0.70	0.40-0.60	0.15-0.25
8642	G86420	0.40-0.45	0.75-1.00	0.035	0.040	0.15-0.30	0.40-0.70	0.40-0.60	0.15-0.25
8645	G86450	0.43-0.48	0.75-1.00	0.035	0.040	0.15-0.30	0.40-0.70	0.40-0.60	0.15-0.25
8655	G86550	0.51-0.59	0.75-1.00	0.035	0.040	0.15-0.30	0.40-0.70	0.40-0.60	0.15-0.25
8720	G87200	0.18-0.23	0.70-0.90	0.035	0.040	0.15-0.30	0.40-0.70	0.40-0.60	0.20-0.30
8740	G87400	0.38-0.43	0.75-1.00	0.035	0.040	0.15-0.30	0.40-0.70	0.40-0.60	0.20-0.30
8822	G88220	0.20-0.25	0.75-1.00	0.035	0.040	0.15-0.30	0.40-0.70	0.40-0.60	0.30-0.40
9260	G92600	0.56-0.64	0.75-1.00	0.035	0.040	1.80-2.20	...	...	...

Table 8 Compositions of Standard Boron (Alloy) Steels

Steel designation AISI or SAE	UNS No.	Chemical composition, %							
		C	Mn	P max	S max	Si	Ni	Cr	Mo
50B44	G50441	0.43-0.48	0.75-1.00	0.035	0.040	0.15-0.30	...	0.40-0.60	...
50B46	G50461	0.44-0.49	0.75-1.00	0.035	0.040	0.15-0.30	...	0.20-0.35	...
50B50	G50501	0.48-0.53	0.75-1.00	0.035	0.040	0.15-0.30	...	0.40-0.60	...
50B60	G50601	0.56-0.64	0.75-1.00	0.035	0.040	0.15-0.30	...	0.40-0.60	...
51B60	G51601	0.56-0.64	0.75-1.00	0.035	0.040	0.15-0.30	...	0.70-0.90	...
81B45	G81451	0.43-0.48	0.75-1.00	0.035	0.040	0.15-0.30	0.20-0.40	0.35-0.55	0.08-0.15
94B17	G94171	0.15-0.20	0.75-1.00	0.035	0.040	0.15-0.30	0.30-0.60	0.30-0.50	0.08-0.15
94B30	G94301	0.28-0.33	0.75-1.00	0.035	0.040	0.15-0.30	0.30-0.60	0.30-0.50	0.08-0.15

Table 9 Compositions of Standard Alloy H- and RH-Steels

Steel designation AISI or SAE	UNS No.	Chemical composition, %							
		C	Mn	P max	S max	Si	Ni	Cr	Mo
1330H	H13300	0.27-0.33	1.45-2.05	0.035	0.040	0.15-0.30	...	...	...
1335H	H13350	0.32-0.38	1.45-2.05	0.035	0.040	0.15-0.30	...	...	...
1340H	H13400	0.37-0.44	1.45-2.05	0.035	0.040	0.15-0.30	...	...	...
1345H	H13450	0.42-0.49	1.45-2.05	0.035	0.040	0.15-0.30	...	...	...
3310RH		0.08-0.13	0.40-0.60	...	...	0.15-0.35	3.25-3.75	1.40-1.75	...
4027H	H40270	0.24-0.30	0.60-1.00	0.035	0.040	0.15-0.30	...	...	0.20-0.30
4027RH		0.25-0.30	0.70-0.90	...	...	0.15-0.35	...	...	0.20-0.30
4028H	H40280	0.24-0.30	0.60-1.00	0.035	0.035-0.050	0.15-0.30	...	...	0.20-0.30
4032H	H40320	0.29-0.35	0.60-1.00	0.035	0.040	0.15-0.30	...	...	0.20-0.30
4037H	H40370	0.34-0.41	0.60-1.00	0.035	0.040	0.15-0.30	...	...	0.20-0.30
4042H	H40420	0.39-0.46	0.60-1.00	0.035	0.040	0.15-0.30	...	...	0.20-0.30
4047H	H40470	0.44-0.51	0.60-1.00	0.035	0.040	0.15-0.30	...	...	0.20-0.30
4118H	H41180	0.17-0.23	0.60-1.00	0.035	0.040	0.15-0.30	...	0.30-0.70	0.08-0.15
4120H	H41200	0.18-0.23	0.90-1.20	...	...	0.15-0.35	...	0.40-0.60	0.13-0.20
4120RH		0.18-0.23	0.90-1.20	...	...	0.15-0.35	...	0.40-0.60	0.13-0.20
4130H	H41300	0.27-0.33	0.30-0.70	0.035	0.040	0.15-0.30	...	0.75-1.20	0.15-0.25
4135H	H41350	0.32-0.38	0.60-1.00	0.035	0.040	0.15-0.30	...	0.75-1.20	0.15-0.25
4137H	H41370	0.34-0.41	0.60-1.00	0.035	0.040	0.15-0.30	...	0.75-1.20	0.15-0.25
4140H	H41400	0.37-0.44	0.65-1.10	0.035	0.040	0.15-0.30	...	0.75-1.20	0.15-0.25
4142H	H41420	0.39-0.46	0.65-1.10	0.035	0.040	0.15-0.30	...	0.75-1.20	0.15-0.25
4145H	H41450	0.42-0.49	0.65-1.10	0.035	0.040	0.15-0.30	...	0.75-1.20	0.15-0.25
4145RH		0.43-0.48	0.75-1.0	...	...	...	...	0.80-1.10	0.15-0.25
4147H	H41470	0.44-0.51	0.65-1.10	0.035	0.040	0.15-0.30	...	0.75-1.20	0.15-0.25
4150H	H41500	0.47-0.54	0.65-1.10	0.035	0.040	0.15-0.30	...	0.75-1.20	0.15-0.25
4161H	H41610	0.55-0.65	0.65-1.10	0.035	0.040	0.15-0.30	...	0.65-0.95	0.25-0.35
4161RH		0.56-0.64	0.75-1.0	...	...	0.15-0.35	...	0.70-0.90	0.25-0.35
4320H	H43200	0.17-0.23	0.40-0.70	0.035	0.040	0.15-0.30	1.55-2.00	0.35-0.65	0.20-0.30
4320RH		0.17-0.22	0.45-0.65	...	...	0.15-0.35	1.65-2.00	0.40-0.60	0.20-0.30
4340H	H43400	0.37-0.44	0.55-0.90	0.035	0.040	0.15-0.30	1.55-2.00	0.65-0.95	0.20-0.30
E4340H	H43406	0.37-0.44	0.60-0.95	0.025	0.025	0.15-0.30	1.55-2.00	0.65-0.95	0.20-0.30
4620H	H46200	0.17-0.23	0.35-0.75	0.035	0.040	0.15-0.30	1.55-2.00	...	0.20-0.30
4626H	H46260	0.23-0.29	0.40-0.70	0.035	0.040	0.15-0.30	0.65-1.05	...	0.15-0.25
4720H	H47200	0.17-0.23	0.45-0.75	0.035	0.040	0.15-0.30	0.85-1.25	0.30-0.60	0.15-0.25
4815H	H48150	0.12-0.18	0.30-0.70	0.035	0.040	0.15-0.30	3.20-3.80	...	0.20-0.30
4817H	H48170	0.14-0.20	0.30-0.70	0.035	0.040	0.15-0.30	3.20-3.80	...	0.20-0.30
4820H	H48200	0.17-0.23	0.40-0.80	0.035	0.040	0.15-0.30	3.20-3.80	...	0.20-0.30
4820RH		0.18-0.23	0.50-0.70	...	...	0.15-0.35	3.25-3.75	...	0.20-0.30
5046H	H50460	0.43-0.50	0.65-1.10	0.035	0.040	0.15-0.30	...	0.13-0.43	...
5120H	H51200	0.17-0.23	0.60-1.00	0.035	0.040	0.15-0.30	...	0.60-1.00	...
5130H	H51300	0.27-0.33	0.60-1.00	0.035	0.040	0.15-0.30	...	0.75-1.20	...
5130RH		0.28-0.33	0.70-0.90	...	...	0.15-0.35	...	0.80-1.10	...
5132H	H51320	0.29-0.35	0.50-0.90	0.035	0.040	0.15-0.30	...	0.65-1.10	...
5135H	H51350	0.32-0.38	0.50-0.90	0.035	0.040	0.15-0.30	...	0.70-1.15	...
5140H	H51400	0.37-0.44	0.60-1.00	0.035	0.040	0.15-0.30	...	0.60-1.00	...
5140RH		0.38-0.43	0.70-0.90	...	...	0.15-0.35	...	0.70-0.90	...
5150H	H51500	0.47-0.54	0.60-1.00	0.035	0.040	0.15-0.30	...	0.60-1.00	...
5155H	H51550	0.50-0.60	0.60-1.00	0.035	0.040	0.15-0.30	...	0.60-1.00	...
5160H	H51600	0.55-0.65	0.65-1.00	0.035	0.040	0.15-0.30	...	0.60-1.00	...
5160RH		0.56-0.64	0.75-1.00	...	...	0.15-0.35	...	0.70-0.90	...
6118H	H61180	0.15-0.21	0.40-0.80	0.035	0.040	0.15-0.30	...	0.40-0.80	0.10-0.15

(continued)

ıble 9 Compositions of Standard Alloy H- and RH-Steels *(continued)*

eel signation ISI or SAE	UNS No.	Chemical composition, % C	Mn	P max	S max	Si	Ni	Cr	Mo
50H	H61500	0.47-0.54	0.60-1.00	0.035	0.040	0.15-0.30	...	0.75-1.20	0.15 V min
17H	H86170	0.14-0.20	0.60-0.95	0.035	0.040	0.15-0.30	0.35-0.75	0.35-0.65	0.15-0.25
20H	H86200	0.17-0.23	0.60-0.95	0.035	0.040	0.15-0.30	0.35-0.75	0.35-0.65	0.15-0.25
22H	H86220	0.19-0.25	0.60-0.95	0.035	0.040	0.15-0.30	0.35-0.75	0.35-0.65	0.15-0.25
22RH		0.20-0.25	0.70-0.90	...	...	0.15-0.35	0.40-0.70	0.40-0.60	0.15-0.25
25H	H86250	0.22-0.28	0.60-0.95	0.035	0.040	0.15-0.30	0.35-0.75	0.35-0.65	0.15-0.25
27H	H86270	0.24-0.30	0.60-0.95	0.035	0.040	0.15-0.30	0.35-0.75	0.35-0.65	0.15-0.25
30H	H86300	0.27-0.33	0.60-0.95	0.035	0.040	0.15-0.30	0.35-0.75	0.35-0.65	0.15-0.25
37H	H86370	0.34-0.41	0.70-1.05	0.035	0.040	0.15-0.30	0.35-0.75	0.35-0.65	0.15-0.65
40H	H86400	0.37-0.44	0.70-1.05	0.035	0.040	0.15-0.30	0.35-0.75	0.35-0.65	0.15-0.25
42H	H86420	0.39-0.46	0.70-1.05	0.035	0.040	0.15-0.30	0.35-0.75	0.35-0.65	0.15-0.25
45H	H86450	0.42-0.49	0.70-1.05	0.035	0.040	0.15-0.30	0.35-0.75	0.35-0.65	0.15-0.25
50H	H86500	0.47-0.54	0.70-1.05	0.035	0.040	0.15-0.30	0.35-0.75	0.35-0.65	0.15-0.25
55H	H86550	0.50-0.60	0.70-1.05	0.035	0.040	0.15-0.30	0.35-0.75	0.35-0.65	0.15-0.25
60H	H86600	0.55-0.65	0.70-1.05	0.035	0.040	0.15-0.30	0.35-0.75	0.35-0.65	0.15-0.25
20H	H87200	0.17-0.23	0.60-0.95	0.035	0.040	0.15-0.30	0.35-0.75	0.35-0.65	0.20-0.30
20RH		0.18-0.23	0.70-0.90	...	...	0.15-0.35	0.40-0.70	0.40-0.60	0.20-0.30
40H	H87400	0.37-0.44	0.70-1.05	0.035	0.040	0.15-0.30	0.35-0.75	0.35-0.65	0.20-0.30
22H	H88220	0.19-0.25	0.70-1.05	0.035	0.040	0.15-0.30	0.35-0.75	0.35-0.65	0.30-0.40
22RH		0.20-0.25	0.75-1.00	...	...	0.15-0.35	0.40-0.70	0.40-0.60	0.30-0.40
60H	H92600	0.55-0.65	0.65-1.10	0.035	0.040	1.70-2.20	...	...	...
10H	H93100	0.07-0.13	0.40-0.70	0.035	0.040	0.15-0.30	2.95-3.55	1.00-1.45	0.08-0.15
10RH		0.08-0.13	0.45-0.65	...	...	0.15-0.35	3.00-3.50	1.00-1.40	0.08-0.15

ıble 10 Compositions of Standard Boron (Alloy) H- and RH-Steels

eel signation ISI or SAE	UNS No.	Chemical composition, % C	Mn	P max	S max	Si	Ni	Cr	Mo
B40H	H50401	0.37-0.44	0.65-1.10	0.035	0.040	0.15-0.30	...	0.30-0.70	...
B40RH		0.38-0.43	0.75-1.00	...	...	0.15-0.35	...	0.40-0.60	...
B44H	H50441	0.42-0.49	0.65-1.10	0.035	0.040	0.15-0.30	...	0.30-0.70	...
B46H	H50461	0.43-0.50	0.65-1.10	0.035	0.040	0.15-0.30	...	0.13-0.43	...
B50H	H50501	0.47-0.54	0.65-1.10	0.035	0.040	0.15-0.30	...	0.30-0.70	...
B60H	H50601	0.55-0.65	0.65-1.10	0.035	0.040	0.15-0.30	...	0.30-0.70	...
B60H	H51601	0.55-0.65	0.65-1.10	0.035	0.040	0.15-0.30	...	0.60-1.00	...
B45H	H81451	0.42-0.49	0.70-1.05	0.035	0.040	0.15-0.30	0.15-0.45	0.30-0.60	0.08-0.15
B30H	H86301	0.27-0.33	0.60-0.95	0.035	0.040	0.15-0.30	0.35-0.75	0.35-0.65	0.15-0.25
B45H	H86451	0.42-0.49	0.70-1.05	0.035	0.040	0.15-0.30	0.35-0.75	0.35-0.65	0.15-0.25
B15H	H94151	0.12-0.18	0.70-1.05	0.035	0.040	0.15-0.30	0.25-0.65	0.25-0.55	0.08-0.15
B17H	H94171	0.14-0.20	0.70-1.05	0.035	0.040	0.15-0.30	0.25-0.65	0.25-0.55	0.08-0.15
B30H	H94301	0.27-0.33	0.70-1.05	0.035	0.040	0.15-0.30	0.25-0.65	0.25-0.55	0.08-0.15

ately 63 HRC is attainable. As the diameter of the quenched piece is creased, cooling rates and hardness decrease, because the critical cooling te for this specific steel was not exceeded. Thus, Fig. 3 also serves as an ccellent example of a low-hardenability steel. Plain carbon steels are iaracterized by their low hardenability, with critical cooling rates lasting ıly for brief periods. Hardenability of all steels is directly related to itical cooling rates. The longer the time of critical cooling rate, the higher e hardenability for a given steel, almost regardless of carbon content.

ole of Alloying Elements

The principal reason for using alloying elements in the standard grades steel is to increase hardenability. The alloying elements used in the andard alloy steels in Table 7 are confined to:(a) manganese, (b) silicon,) chromium, (d) nickel, (e) molybdenum, and (f) vanadium. Because of e small amounts used, boron is not usually called an alloy. Steels that ontain boron, whether they are carbon or alloy grades, are more often rmed as boron-treated steels. The use of cobalt, tungsten, zirconium, and titanium is generally confined to tool or other specialty steels. Tool steels and other highly alloyed steels are covered in other sections of this book.

Manganese, silicon, chromium, nickel, molybdenum, and vanadium all have their separate and unequal effects on hardenability. However, the individual effects of these alloying elements may be completely altered when two or more of these are used together. In periods of alloy shortages, extensive investigations were conducted, and it has been established that more hardenability can be attained with less total alloy content when two or more alloys are used together. This practice is clearly reflected in the standard steel compositions shown in Table 7. This approach not only saves alloys that are often in scarce supply, but also results in more hardenability at lower cost.

Therefore, all of the steels listed in Tables 7 and 8 have significantly greater hardenability than the carbon steels listed in Tables 3 to 6. It must be further emphasized that the hardenability varies widely among the alloy grades, which is a principal reason for the existence of so many grades.

It is obvious that hardenability is an all important factor in the discriminating selection of a steel grade for heat treated parts. A standard procedure

Fig. 3 Effect of Section Size on Surface Hardness of a 0.54 Carbon Steel. Quenched in water from 830 °C (1525 °F)

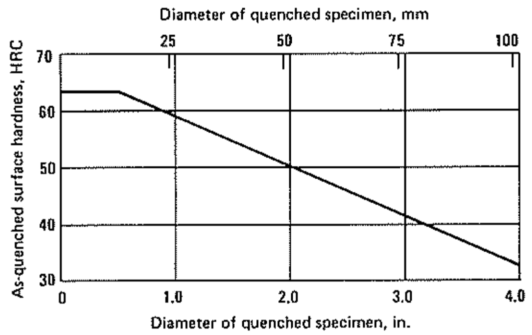
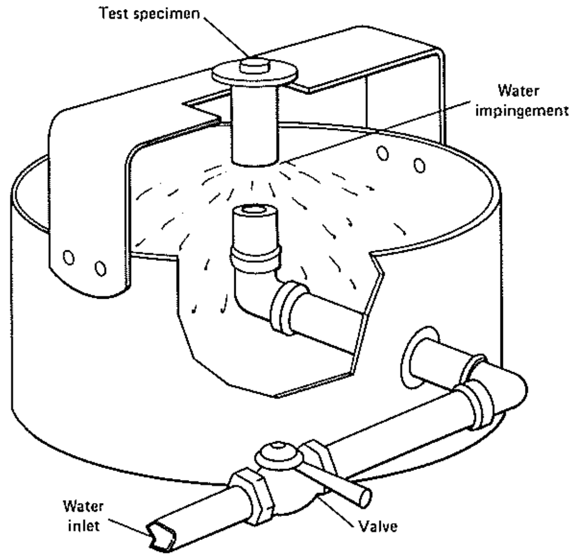


Fig. 4 Standard End-Quench (Jominy) Test Specimen and Method of Quenching in Quenching Jig



for evaluating the hardenability of steels is necessary for initial selection as well as a tool for controlling quality.

Methods for Evaluating Hardenability

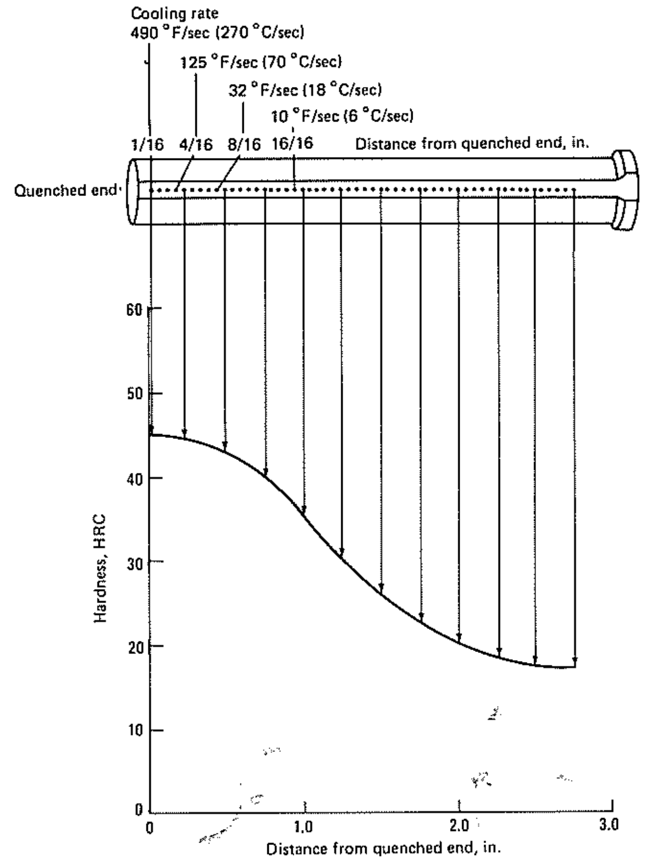
A number of hardenability tests have been devised, each having its advantages and limitations. Most of these tests are either no longer used or their use is restricted to specialized applications.

The end-quench test has proved to be the method with the highest degree of reproducibility and has thus been almost universally adopted for evaluating hardenability of virtually all standard alloy steels and for some grades of carbon steels. The test is relatively simple to perform and can produce much useful information for the designer as well as for the fabricator.

Test Bars for the End-Quench Test. Although variations are sometimes made to accommodate specific requirements, the test bars for the end-quench test are normally 25.5 mm (1 in.) in diameter by 102 mm (4 in.) long. A 25.5 mm (1 in.) diameter collar is left on one end to hold it in a quenching jig, as illustrated in Fig. 4.

In this test, the water flow is controlled by a suitable valve, so that the amount striking the end of the specimen (Fig. 4) is constant in volume and velocity. The water impinges on the end of the specimen only, then drains away. By this means, cooling rates vary from about the fastest possible on the quenched end to very slow, essentially equal to cooling in still air, on the opposite end. This results in a wide range of hardnesses along the length of the bar.

Fig. 5 Method of Developing End-Quench Curve by Plotting Hardness Versus Distance from Quenched End. Hardness plotted every quarter inch for sake of clarity, although Rockwell C readings were taken in increments of one-sixteenth inch, as shown at top of illustration



After the test bar has been quenched, two opposite and flat parallel surfaces are ground along the length of the bar to a depth of 0.381 mm (0.015 in.). Rockwell C hardness determinations are then made every 1.588 mm (0.60 in.). A specimen-holding indexing fixture is helpful for this operation for convenience as well as accuracy. Such fixtures are available as accessory attachments for conventional Rockwell testers. The next step is to record the readings and plot them on graph paper to develop a curve, as illustrated in Fig. 5. By comparing the curves resulting from end-quench tests of different grades of steel, their relative hardenability may be established. The steels having higher hardenability will be harder at a given distance from the quenched end of the specimen than steels having lower hardenability. Thus, the flatter the curve, the greater the hardenability. On the end-quench curves, hardness is not usually measured beyond approximately 51 mm (2 in.), because hardness measurements beyond this distance are seldom of any significance. At about this 51 mm (2 in.) distance from the quenched end, the effect of water on the quenched end has deteriorated, and the effect of cooling from the surrounding air has become significant. An absolutely flat curve demonstrates conditions of very high hardenability which characterize an air-hardening steel such as some of the highly alloyed tool steels, which will be discussed later in this book.

Variations in Hardenability. Because hardenability is a principal factor in steel selection and because hardenability varies over a broad range for the standard carbon and alloy steels, many grades are available.

As a rule, hardenability of the standard carbon grades is very low, although there is still a great deal of variation in hardenability among the

Fig. 6 End-Quench Hardenability Curve for 1541 Carbon Steel

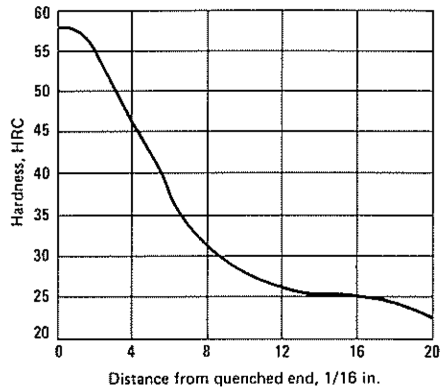
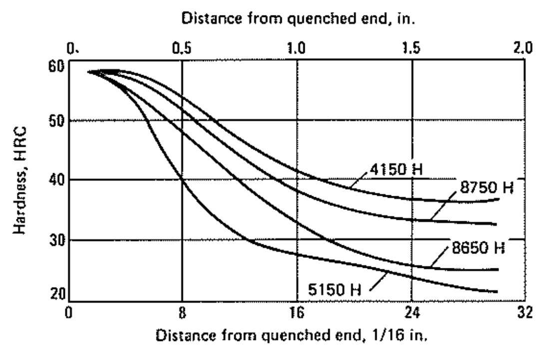


Fig. 7 Hardenability Curves for Several Alloy Steels



fferent grades. This variation depends to a great extent upon the manga-se content and sometimes to a smaller extent on the residual alloys which e sometimes present. A hardenability curve for a high-manganese grade carbon steel, 1541, is shown in Fig. 6. This curve represents near aximum hardenability that can be obtained from any standard carbon ade.

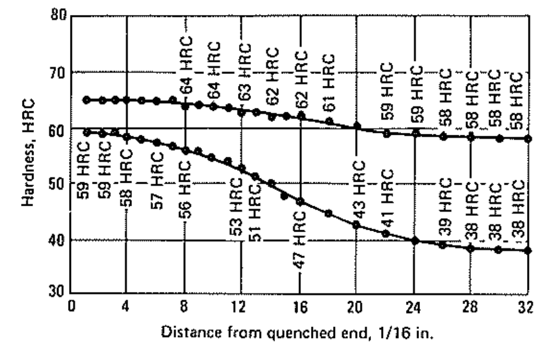
In contrast to the curve shown in Fig. 6, typical hardenability curves for ur different 0.50 carbon alloy steels are presented in Fig. 7. These data nphasize the fact that maximum attainable hardness is provided by the rbon content, while the differences in alloy content markedly affect ırdenability.

Hardenability also depends on grain size (i.e., deoxidation practice) and elting practice (i.e., BOF vs electric furnace). Electric furnace steel tends have high levels of nickel, copper, chromium, and molybdenum residu-s that improve hardenability. On the other hand, fine grained, aluminum lled steels (premium grades with respect to formability) have lower ırdenability than coarser grained, silicon killed steels.

and RH Steels

Because of the normal variations within prescribed limits of composi-on, it would be unrealistic to expect that the hardenability of a given grade ould always follow a precise curve such as shown in Fig. 6 and 7. Instead, e hardenability of any grade will vary considerably, which results in a ırdenability band such as the 4150H band in Fig. 8. This steel was ormalized at 870 °C (1600 °F), then austenitized at 845 °C (1555 °F) efore end quenching. The upper and lower curves that represent the oundaries of the hardenability band not only show the possible variation

Fig. 8 Hardenability Band for an Alloy Steel. 4150H: 0.47 to 0.54 C, 0.65 to 1.10 Mn. Normalized at 870 °C (1600 °F). Annealed at 845 °C (1555 °F)



in hardness at the quenched end, caused by the allowable carbon range of 0.47 to 0.54, but also the difference in hardenability as a result of the alloying elements being on the high or low side of the prescribed limits.

The need for hardenability data for steel users has been recognized. Cooperative work by AISI and SAE has been responsible for devising hardenability bands for a large number of carbon and alloy steels, principally the latter. Steels that are sold with guaranteed hardenability bands are known as the H-steels. The numerical parts of the designation are the same as for the other standard grades, but the suffix letter H, such as 4140H, identifies it as a steel that will meet prescribed hardenability limits.

Chemical Composition Limits

Not all of the steels listed in Tables 3 to 8 are available as H or RH steels, although most of the alloy steels can be purchased as H-grades. Tables 2, 9, and 10 list those carbon and alloy grades which are presently available as H or RH steels.

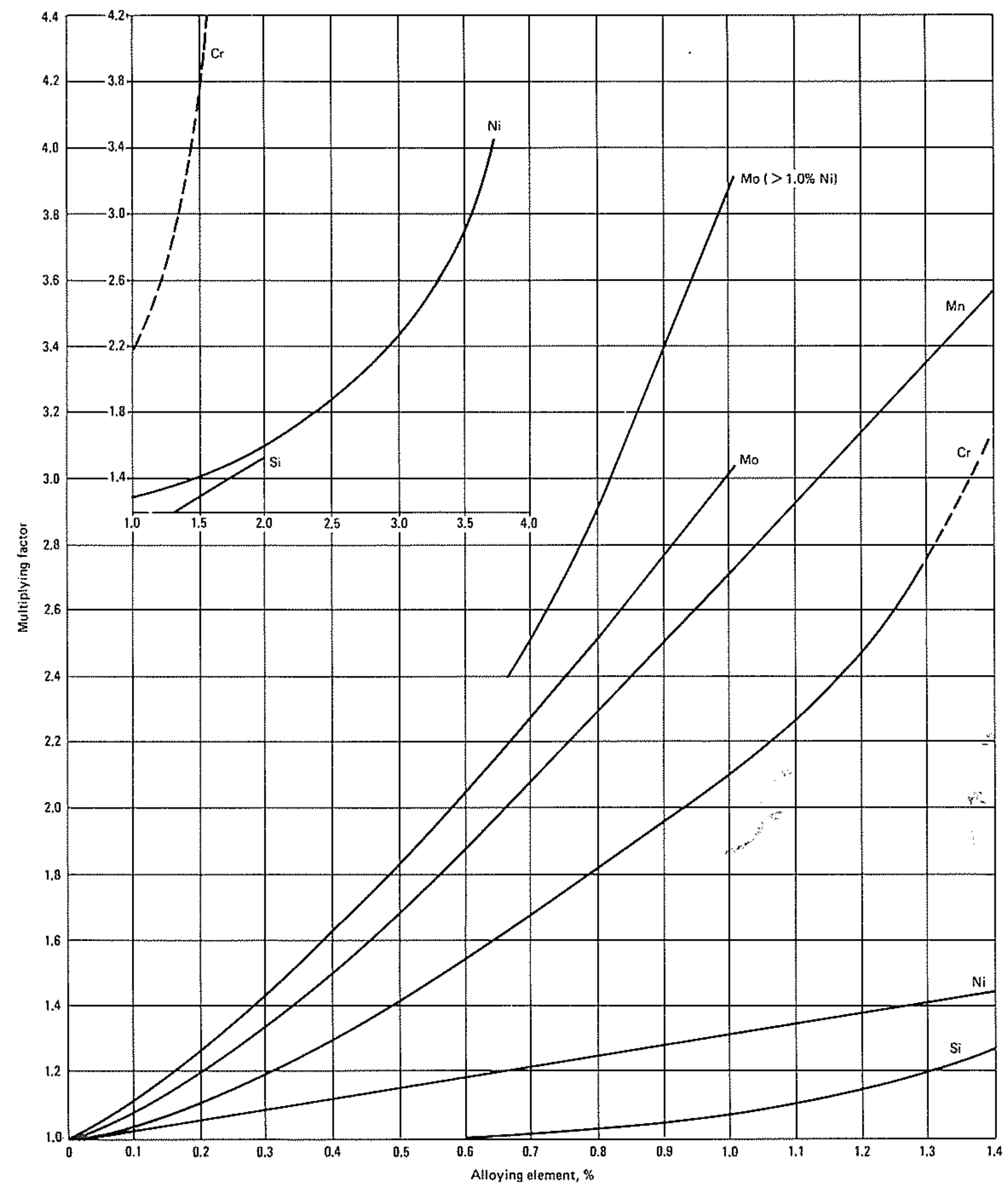
In order to give steel producers the latitude necessary in manufacturing for common hardenability limits, the chemical compositions of normal grades have been modified to form the H and RH steels. These modifications permit adjustments in manufacturing ranges of chemical composition. These adjustments correct melting practice for individual plants which might otherwise influence the hardenability bands. However, the modifications are not great enough to influence the general characteristics of the original compositions of the steels.

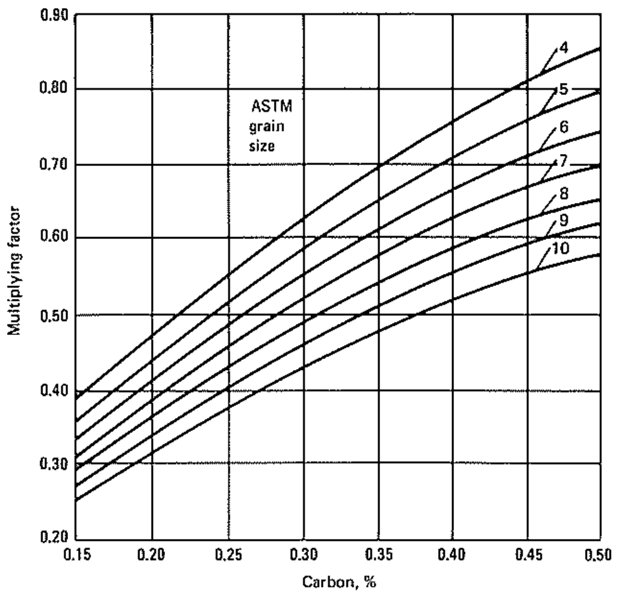
Figure 8 is presented merely as an example of a hardenability band. In the section which follows, the hardenability bands, if available, are included with heat treating and other data for individual carbon and alloy steels.

Restricted hardenability (RH) steels are defined in SAE J1868. Composition ranges are the same as those for the standard alloy grades, and hardenability bands are narrower than those for the H grades. For example, 4140 and 4140 RH have the same specified composition ranges, while 4140 H has broader ranges. The Jominy hardenability band of 4140 RH is about half the width of the 4140 band.

RH grades open the door to substantial benefits to the heat treater. A major metalworking company, for instance, had a part forged to four different dimensions. Four different procedures were required to heat treat the parts to a set of common properties. Restrictive steel chemistries eliminated the need for the four procedures and made it possible to consolidate specifications. The RH grades also made it possible to design a new specification that provides Jominy hardenability bands lying with the overlap of two older specifications. Over a five year period, this company was able to reduce its material specifications in this manner from a total of 21 down to nine.

Alloying Elements. Source: Climax Molybdenum





Carbon Plus Grain Size. Source: Climax Molybdenum

Carbon Steels (1000, 1100, 1200, and 1500 Series)

Introduction

Carbon steels are now classified in four distinct series, in accordance with the AISI system of designations: the 1000 series, which are plain carbon steels containing not more than 1.00 Mn maximum; the 1100 series, which are resulfurized carbon steels; the 1200 series, which are resulfurized and rephosphorized carbon steels; and the 1500 series, which are high-manganese (up to 1.65) carbon steels and are nonresulfurized. These four series differ in certain fundamental properties, thus justifying the series differentiation. However, in terms of their response to heat treatment, all four series can be discussed in terms of their carbon content, the principal controlling factor in heat treating. Other factors are considered for the individual steels on the pages that follow. To simplify consideration of the treatments for various applications, the steels in this discussion are classified as follows: Group I, 0.08 to 0.25 C; Group II, 0.30 to 0.50 C; Group III, 0.55 to 0.95 C. A relatively few steels, such as 1026 and 1029, can be assigned to more than one group, depending on their carbon content.

Group I (0.08 to 0.25% C). The three principal types of heat treatment used on these low-carbon steels are: (a) process treating of material to prepare it for subsequent operations; (b) treating of finished parts to improve mechanical properties; and (c) case hardening, notably by carburizing or carbonitriding, to develop a hard, wear-resistant surface. It is often necessary to process anneal drawn products between operations, thus relieving work strains in order to permit further working. This operation is normally carried out at temperatures between the recrystallization temperature and the lower transformation temperatures. The effect is to soften by recrystallization of the grain growth of ferrite. It is desirable to keep the recrystallized grain size relatively fine. This is promoted by rapid heating and short holding time at temperature. A similar practice may be used in the treatment of low-carbon, cold-headed bolts made from cold-drawn wire. Sometimes the strains introduced by cold working so weaken the heads that they break through the most severely worked portion under slight additional strain. Process annealing is used to overcome this condition. Stress relieving at approximately 540 °C (1000 °F) is more effective than annealing in retaining the normal mechanical properties of the shank of the cold-headed bolt.

Heat treating is frequently used to improve machinability. The generally poor machinability of the low-carbon steels, except those containing sulfur or other alloying elements, results principally from the fact that the proportion of free ferrite to carbide is high. This situation can be modified by putting the carbide into its most voluminous form, pearlite, and dispersing fine particles of this pearlite evenly throughout the ferrite mass. Normalizing is commonly used with success, but best results are obtained by quenching the steel in oil from 815 to 870 °C (1500 to 1600 °F). With the exception of steels containing a carbon content approaching 0.25%, little or no martensite is formed, and the parts do not require tempering.

Group II (0.30 to 0.50% C). Because of the higher carbon content, quenching and tempering become increasingly important when steels of this group are considered. They are the most versatile of the carbon steels, because their hardenability (response to quenching) can be varied over a wide range by suitable controls. In this group of steels, there is a continuous change from water-hardening to oil-hardening types. Hardenability is very sensitive to changes in chemical composition, particularly to the content of manganese, silicon, and residual elements, as well as grain size. These steels are also very sensitive to changes in section.

The medium-carbon steels should be either normalized or annealed before hardening in order to obtain the best mechanical properties after hardening and tempering. Parts made from bar stock are frequently given no treatment prior to hardening (the prior treatment having been performed at the steel mill), but it is common practice to normalize or anneal forgings.

These steels, whether hot finished or cold finished, machine reasonably well in bar stock form and are machined as received, except in the higher carbon grades and small sizes that require annealing to reduce the as-received hardness. Forgings are usually normalized to improve machinability over that encountered with the fully annealed structure. These steels are widely used for machinery parts for moderate duty. When the parts are to be machined after heat treatment, the maximum hardness is usually held to 320 HB and is frequently much lower.

In hardening, the selection of quenching medium will vary with the steel composition, the design of the part, the hardenability of the steel, and the hardness desired in the finished part. Water is the quenching medium most commonly used, because it is best known and is usually least expensive and easiest to install. Caustic soda solution (5 to 10% NaOH) is used in some instances with improved results. It is faster than water and may produce better mechanical properties in all but light sections. It is hazardous, however, and operators must be protected against contact with it. Salt solutions (brine) are often successfully used. They are not dangerous to operators, but their corrosive action on iron or steel parts or equipment is potentially serious. When the section is light or the properties required after heat treatment are not very high, oil quenching is often used. Finally, the medium-carbon steels are readily case hardened by flame or induction hardening.

Group III (0.55 to 0.95% C). Forged parts made of these steels should be annealed because:

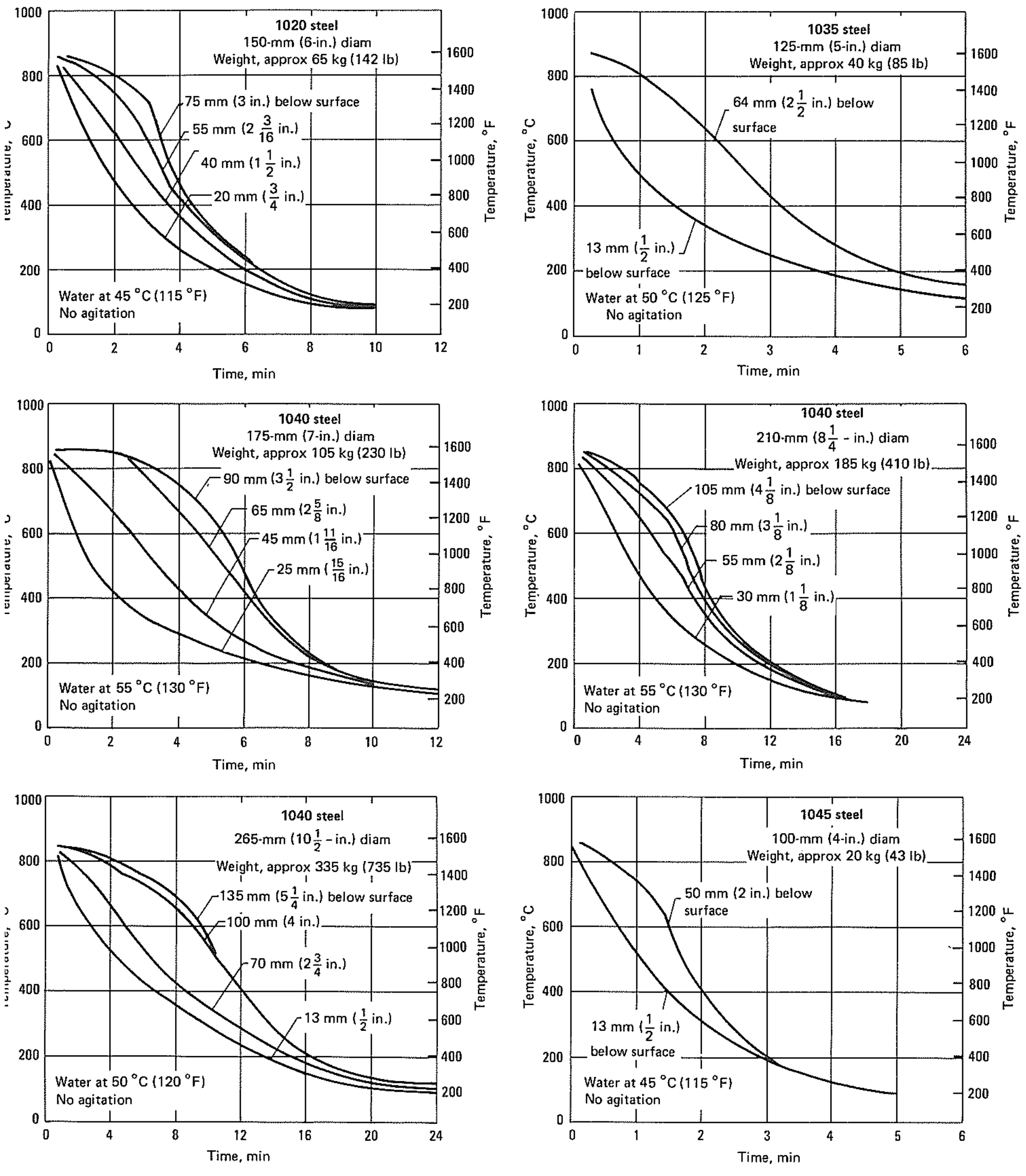
- Refinement of the forged structure is important in producing a high quality, hardened product
- The parts come from the forging operation too hard for cold trimming of the flash or for any machining operations

Ordinary annealing practice, followed by furnace cooling to approximately 600 °C (1110 °F) is satisfactory for most parts.

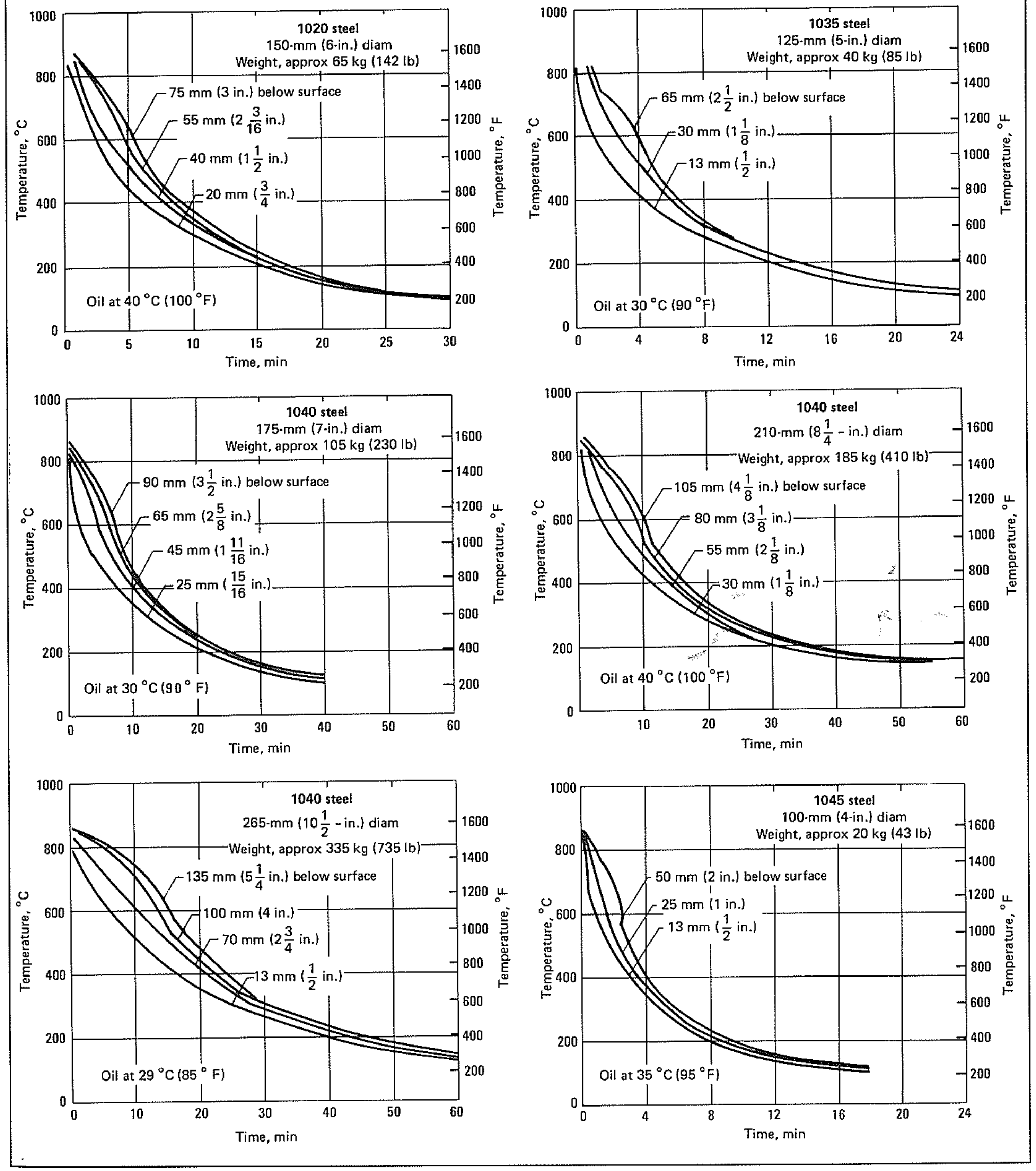
Hardening by conventional quenching is used on most parts made from steels in this group. However, special techniques are required at times. Both oil and water quenching are used: water, for heavy sections of the lower carbon steels and for cutting edges; oil, for general use. Austempering and martempering are often successfully applied. The principal advantages of such treatments are considerably reduced distortion, elimination of breakage, and, in many instances, greater toughness at high hardness.

Tools with cutting edges are sometimes heated in liquid baths to the lowest temperatures at which the part can be hardened and are then quenched in brine. The fast heating of the liquid bath plus the low temperature fail to put all of the available carbon into solution. As a result, the cutting edge consists of martensite containing less carbon than indicated by the chemical composition of the steel and containing many embedded particles of cementite. In this condition, the tool is at its maximum toughness relative to its hardness, and the embedded carbides promote long life of the cutting edge. Final hardness is 55 to 60 HRC. Steels in this group are also commonly hardened by flame or induction methods.

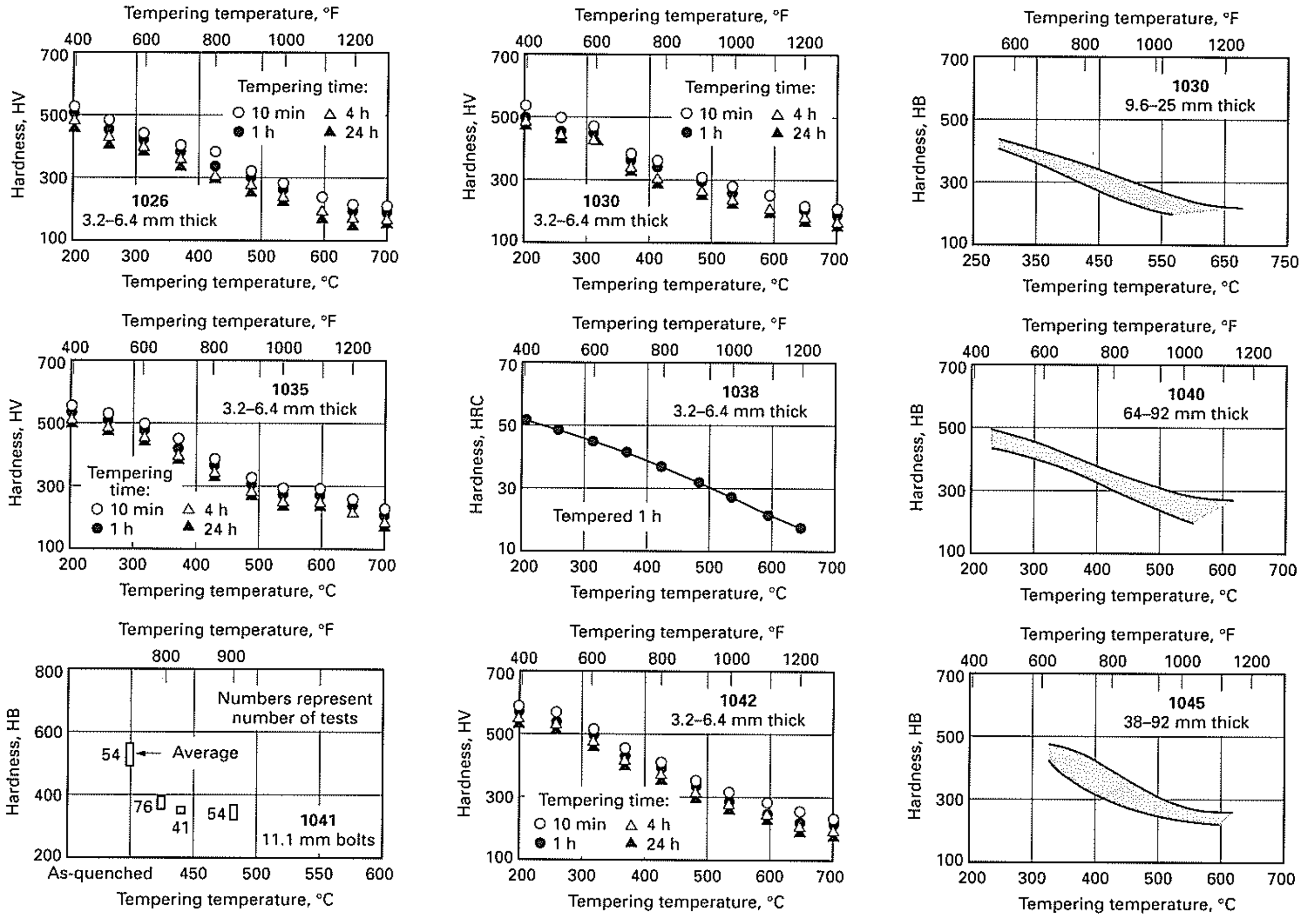
Effect of mass and section size on cooling curves obtained for the water quenching of plain carbon steels



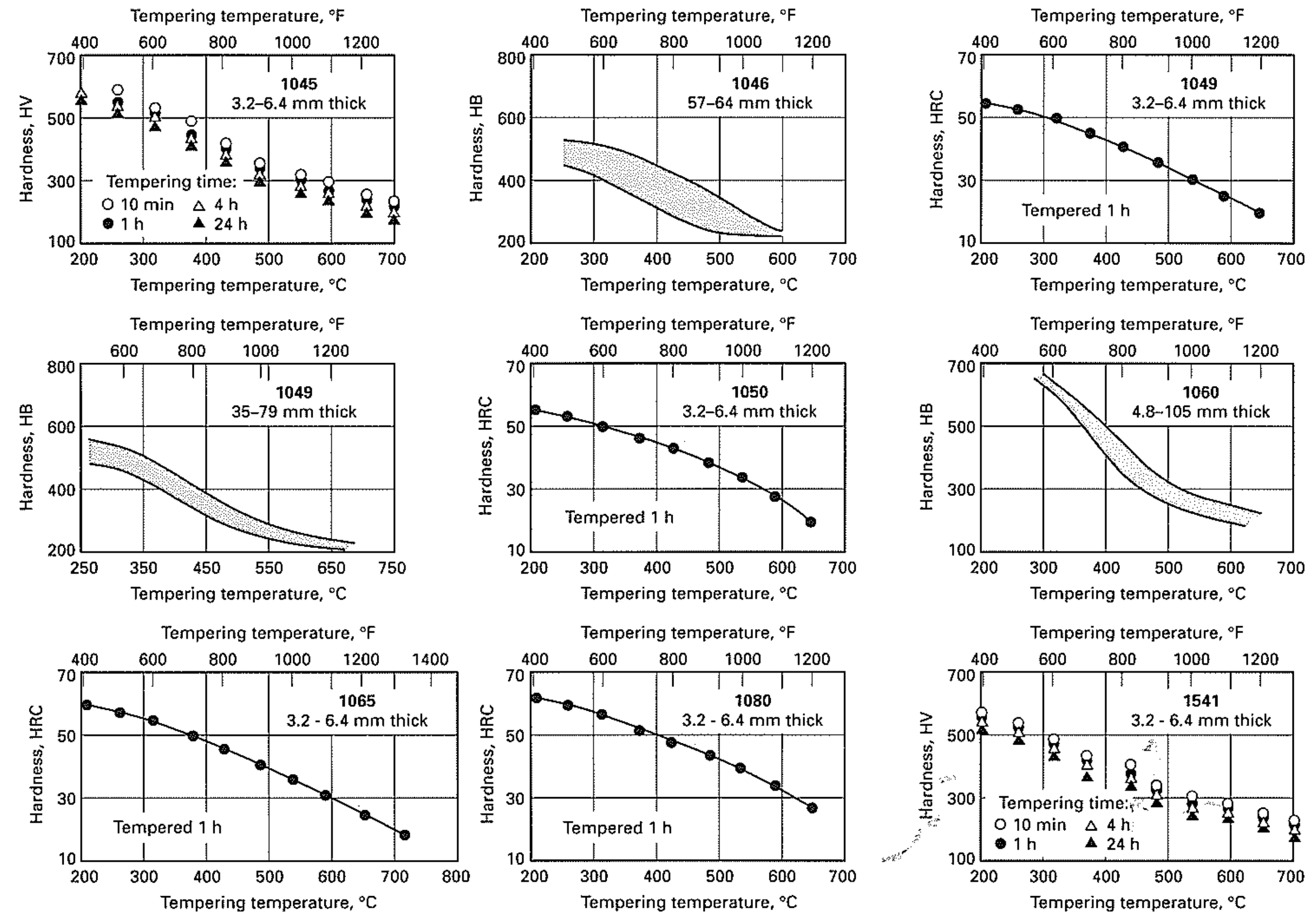
Effect of mass and section size on cooling curves obtained for the oil quenching of plain carbon steels



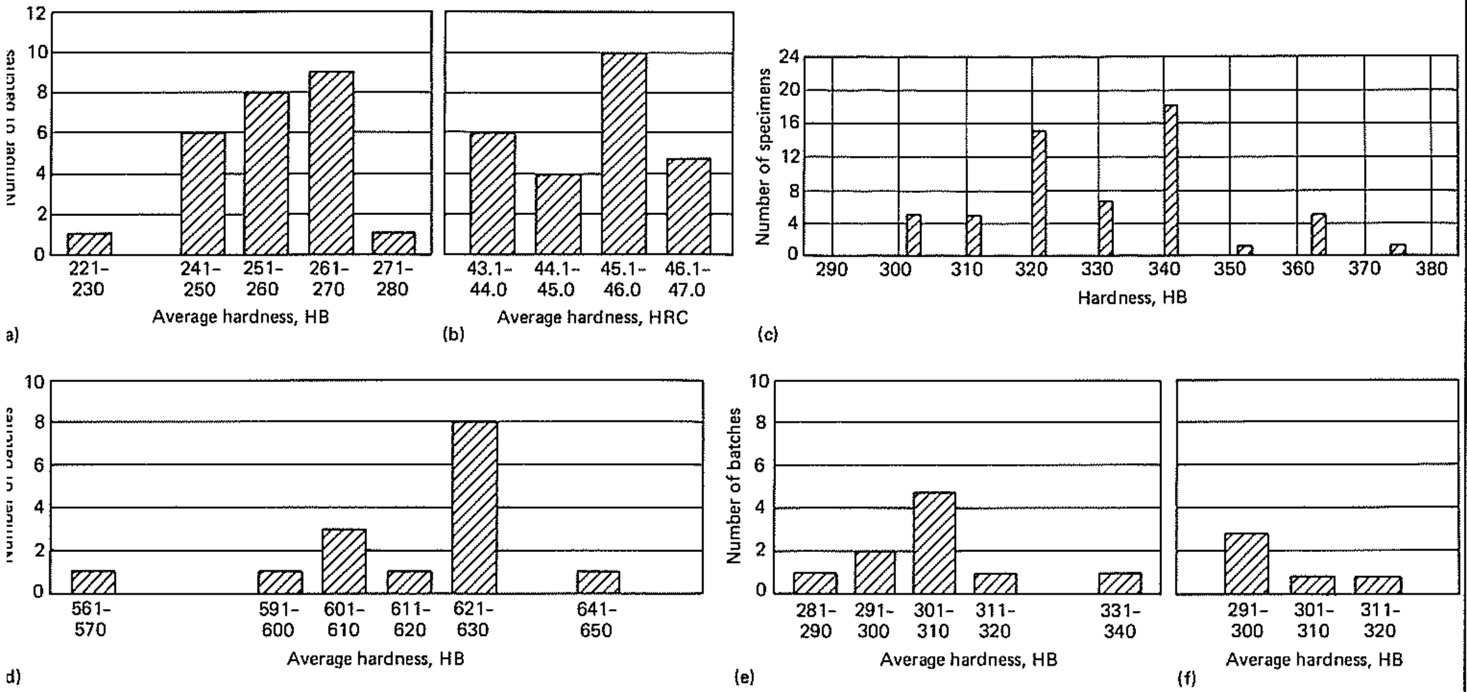
Influence of tempering temperature on room-temperature hardness of quenched carbon steels



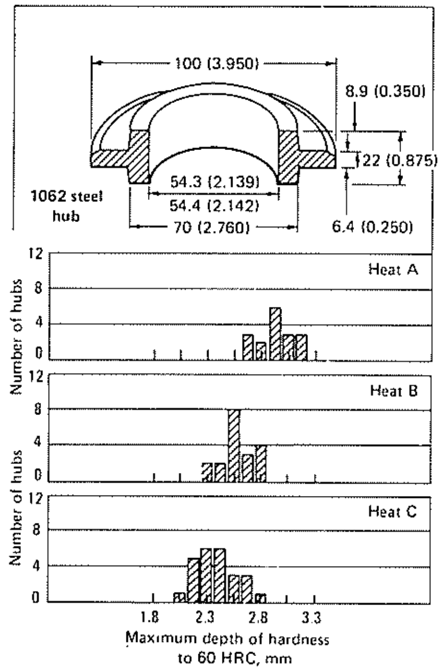
Influence of tempering temperature on room-temperature hardness of quenched carbon steels (continued)



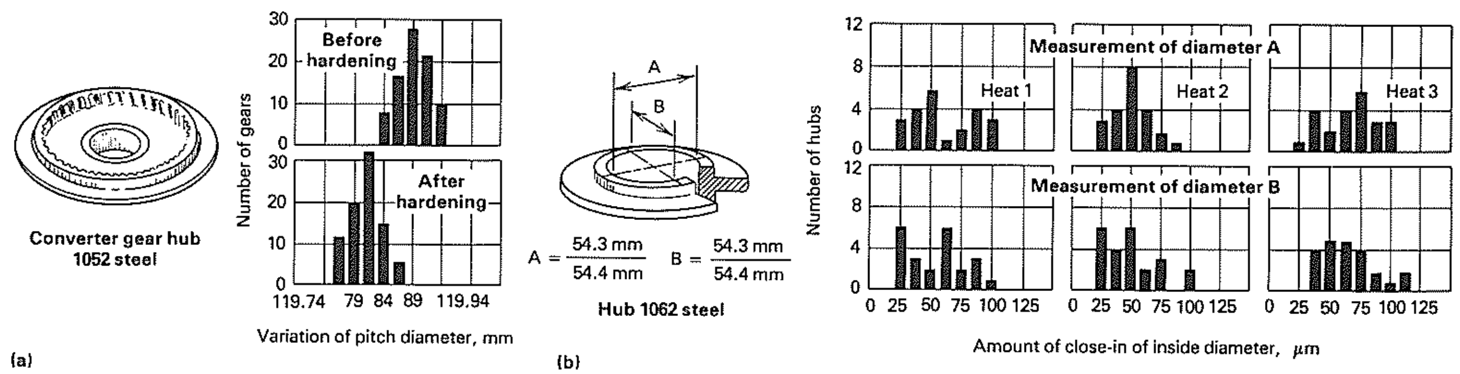
Room-temperature hardness of three carbon steels after production tempering. (a) Automotive steering-arm forgings made of fine-grain 1035 steel. Section thickness varied from 16 to 29 mm (5/8 to 1 1/8 in.). Forgings were austenitized at 825 °C (1520 °F) in oil-fired pusher conveyor furnace, held 45 min, quenched in water at 21 °C (70 °F), and tempered 45 min at 580 to 625 °C (1080 to 1160 °F) in oil-fired link-belt furnace to required hardness range of 217 to 285 HB. Hardness was checked hourly with a 5% sample; readings were taken on polished flash line of 29 mm (1 1/8 in.) section. Survey of furnace revealed temperature variation at 605 °C (1120 °F) of 8, –4 °C (15, –7 °F). Data represent forgings from four mill heats of steel and cover a 6-week period. (b) Woodworking cutting tools forged from 1045 steel. Section of cutting lip was hardened locally by gas burners that heated the steel to 815 °C (1500 °F). Tools were oil quenched and tempered at 305 to 325 °C (585 to 615 °F) for 10 min in electrically heated recirculating-air furnace to a desired hardness range of 42 to 48 HRC. Data were recorded during a 6-month period and represent forgings from 12 mill heats. (c) Plate sections, 19 to 22 mm (3/4 to 7/8 in.) thick, of 1045 steel were water quenched to a hardness range of 534 to 653 HRB and tempered 1 h at 475 °C (890 °F) in continuous roller-hearth furnaces. Data represent a 2-month production period. (d) Forged 1046 steel heated to 830 °C (1525 °F), and quenched in caustic. Forgings were heated in a continuous belt-type furnace and individually dump quenched in agitated caustic. Forgings weighed 9 to 11 kg (20 to 24 lb) each; maximum section, 38 mm (1 1/2 in.). (e) As-quenched forged 1046 steel shown in (d), tempered at 510 °C (950 °F) for 1 h. (f) As-quenched forged 1046 steel shown in (d), tempered at 525 °C (975 °F) for 1 h. Average hardness data for all but (c) obtained by calculating average of high and low extremes of hardness specification range for each batch.



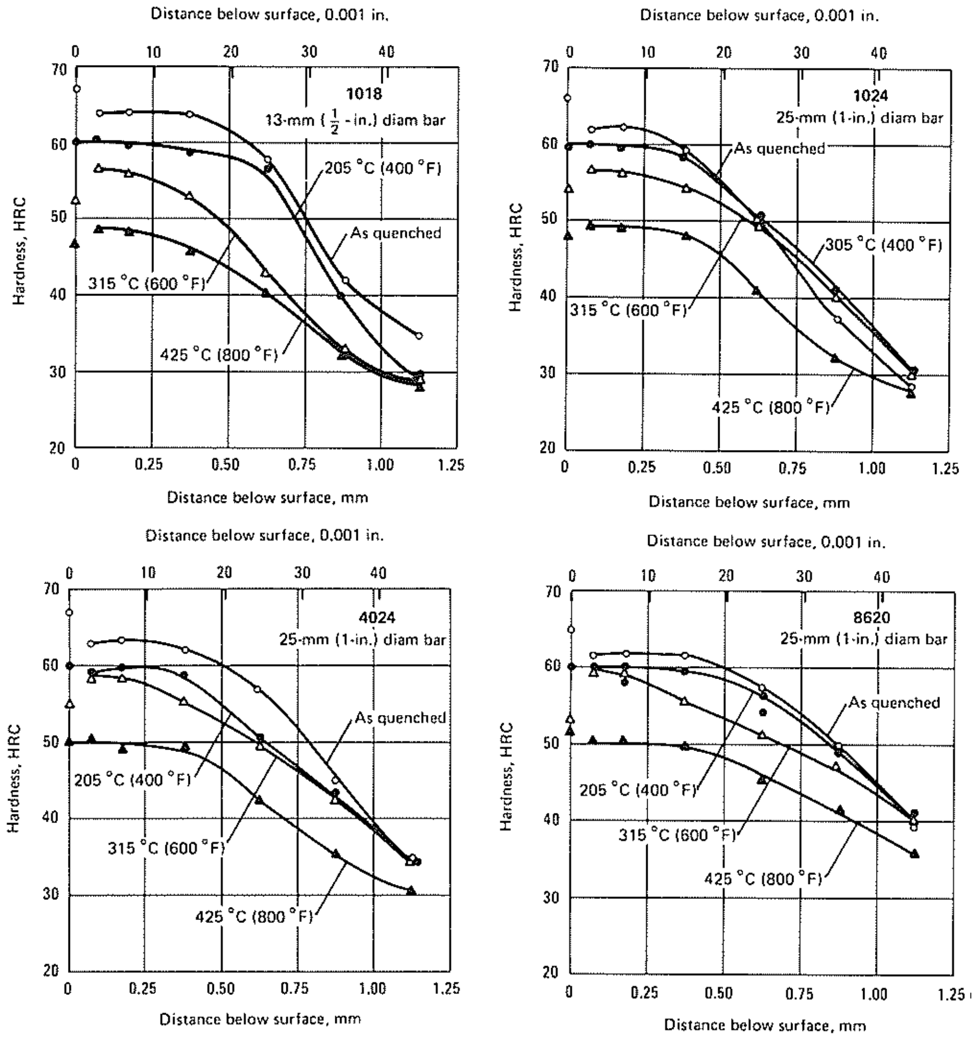
1062: Heat-to-Heat Variations in Depth of Hardness. Heat-to-heat variations in depth of hardness among three heats. Hubs were flame hardened on the inside diameter to a minimum of 59 HRC at 1.9 mm (0.075 in.) below the surface. Parts were heated 12 s and quenched in oil. Hardness was measured on cross sections of heated area.



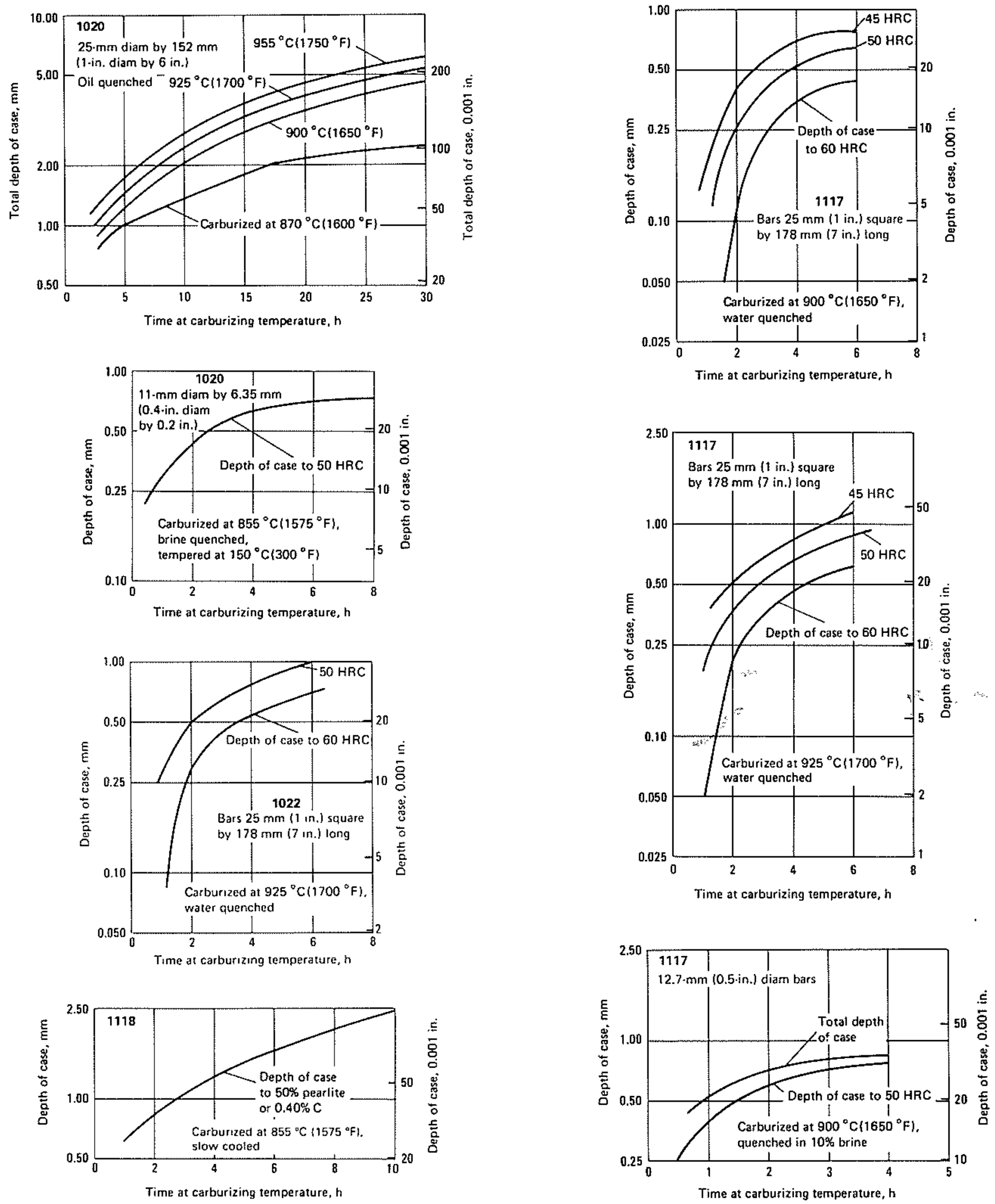
1052 and 1062: Flame hardening hubs. Distribution of dimensional change as a result of flame hardening. (a) Change in pitch diameter of converter gear hubs made of 1052 steel. Gear teeth on inside diameter were heated for a total of 9.5 s, before being quenched in oil to provide a depth of hardness of 0.9 mm (0.035 in.) above the root. (b) Close-in of inside diameters of converter hubs made of 1062 steel. Inside diameter was heated for a total of 12 s and then oil quenched to harden to 59 HRC min at a depth of 1.9 mm (0.075 in.) below the surface. Inside diameter was finish ground after hardening.



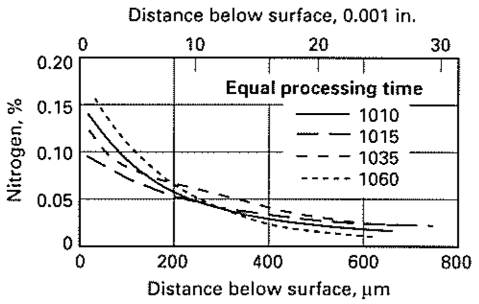
1018 and 1024: Gas carburizing. Effect of tempering on hardness of 1018 and 1024 steel. Parts were carburized at 925 °C (1700 °F) for 4.5 h, then oil quenched and tempered.



Effect of time and temperature on case depth of liquid carburized steels



Nitriding Carbon Steels. Effect of carbon content in carbon steels on the nitrogen gradient obtained in aerated bath nitriding



Typical Normalizing Temperatures for Standard Carbon Steels

Grade	Temperature(a) °C	Temperature(a) °F
Plain carbon steels		
1015	915	1675
1020	915	1675
1022	915	1675
1025	900	1650
1030	900	1650
1035	885	1625
1040	860	1575
1045	860	1575
1050	860	1575
1060	830	1525
1080	830	1525
1090	830	1525
1095	845	1550
1117	900	1650
1137	885	1625
1141	860	1575
1144	860	1575

(a) Based on production experience, normalizing temperature may vary from as much as 27 °C (50 °F) below, to as much as 55 °C (100 °F) above, indicated temperature. The steel should be cooled in still air from indicated temperature.

roperties of Selected Carbon Steels in the Hot-Rolled, Normalized, and Annealed Conditions

ISI ade(a)	Condition or treatment	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation(b), %	Reduction in area, %	Hardness, HB	Izod impact strength J	Izod impact strength ft · lbf
15	As-rolled	420	61	315	46	39.0	61	126	111	82
	Normalized at 925 °C (1700 °F)	425	62	325	47	37.0	70	121	115	85
	Annealed at 870 °C (1600 °F)	385	56	285	41	37.0	70	111	115	85
20	As-rolled	450	65	330	48	36.0	59	143	87	64
	Normalized at 870 °C (1600 °F)	440	64	345	50	35.8	68	131	118	87
	Annealed at 870 °C (1600 °F)	395	57	295	43	36.5	66	111	123	91
22	As-rolled	505	73	360	52	35.0	67	149	81	60
	Normalized at 925 °C (1700 °F)	485	70	360	52	34.0	68	143	117	87
	Annealed at 870 °C (1600 °F)	450	65	315	46	35.0	64	137	121	89
30	As-rolled	550	80	345	50	32.0	57	179	75	55
	Normalized at 925 °C (1700 °F)	525	76	345	50	32.0	61	149	94	69
	Annealed at 845 °C (1550 °F)	460	67	345	50	31.2	58	126	69	51
40	As-rolled	620	90	415	60	25.0	50	201	49	36
	Normalized at 900 °C (1650 °F)	595	86	370	54	28.0	55	170	65	48
	Annealed at 790 °C (1450 °F)	520	75	350	51	30.2	57	149	45	33
50	As-rolled	725	105	415	60	20.0	40	229	31	23
	Normalized at 900 °C (1650 °F)	750	109	430	62	20.0	39	217	27	20
	Annealed at 790 °C (1450 °F)	635	92	365	53	23.7	40	187	18	13
60	As-rolled	815	118	485	70	17.0	34	241	18	13
	Normalized at 900 °C (1650 °F)	775	113	420	61	18.0	37	229	14	10
	Annealed at 790 °C (1450 °F)	625	91	370	54	22.5	38	179	11	8
80	As-rolled	965	140	585	85	12.0	17	293	7	5
	Normalized at 900 °C (1650 °F)	1015	147	525	76	11.0	21	293	7	5
	Annealed at 790 °C (1450 °F)	615	89	380	55	24.7	45	174	7	5
95	As-rolled	965	140	570	83	9.0	18	293	4	3
	Normalized at 900 °C (1650 °F)	1015	147	505	73	9.5	14	293	5	4
	Annealed at 790 °C (1450 °F)	655	95	380	55	13.0	21	192	3	2
17	As-rolled	490	71	305	44	33.0	63	143	81	60
	Normalized at 900 °C (1650 °F)	470	68	305	44	33.5	54	137	85	63
	Annealed at 860 °C (1575 °F)	430	62	285	41	32.8	58	121	94	69
18	As-rolled	525	76	315	46	32.0	70	149	109	80
	Normalized at 925 °C (1700 °F)	475	69	315	46	33.5	66	143	103	76
	Annealed at 790 °C (1450 °F)	450	65	285	41	34.5	67	131	107	79
37	As-rolled	625	91	380	55	28.0	61	192	83	61
	Normalized at 900 °C (1650 °F)	670	97	400	58	22.5	49	197	64	47
	Annealed at 790 °C (1450 °F)	585	85	345	50	26.8	54	174	50	37

(continued)

Properties of Selected Carbon Steels in the Hot-Rolled, Normalized, and Annealed Conditions *(continued)*

AISI grade(a)	Condition or treatment	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation(b), %	Reduction in area, %	Hardness, HB	Izod impact strength J	Izod impact strength ft · lbf
1141	As-rolled	675	98	360	52	22.0	38	192	11	8
	Normalized at 900 °C (1650 °F)	710	103	405	59	22.7	56	201	53	39
	Annealed at 815 °C (1500 °F)	600	87	355	51	25.5	49	163	34	25
1144	As-rolled	705	102	420	61	21.0	41	212	53	39
	Normalized at 900 °C (1650 °F)	670	97	400	58	21.0	40	197	43	32
	Annealed at 790 °C (1450 °F)	585	85	345	50	24.8	41	167	65	48

(a) All grades are fine grained except for those in the 1100 series, which are coarse grained. (b) In 50 mm or 2 in.

Effect of Mass on Hardness of Normalized Carbon and Alloy Steels

Grade	Normalizing temperature °C	Normalizing temperature °F	Hardness, HB, for bar with diameter, mm (in.), of 13(½)	25(1)	50(2)	100(4)
Carbon steels, carburizing grades						
1015	925	1700	126	121	116	116
1020	925	1700	131	131	126	121
1022	925	1700	143	143	137	131
1117	900	1650	143	137	137	126
1118	925	1700	156	143	137	131
Carbon steels, direct-hardening grades						
1030	925	1700	156	149	137	137
1040	900	1650	183	170	167	167
1050	900	1650	223	217	212	201
1060	900	1650	229	229	223	223
1080	900	1650	293	293	285	269
1095	900	1650	302	293	269	255
1137	900	1650	201	197	197	192
1141	900	1650	207	201	201	201
1144	900	1650	201	197	192	192

Note: All data are based on single heats.

Approximate Critical Temperatures for Selected Carbon Steels

Steel	Critical temperatures on heating at 28 °C/h (50 °F/h) Ac_1 °C	Ac_1 °F	Ac_3 °C	Ac_3 °F	Critical temperatures on cooling at 28 °C/h (50 °F/h) Ar_3 °C	Ar_3 °F	Ar_1 °C	Ar_1 °F
1010	725	1335	875	1610	850	1560	680	1260
1020	725	1335	845	1555	815	1500	680	1260
1030	725	1335	815	1495	790	1450	675	1250
1040	725	1335	795	1460	755	1395	670	1240
1050	725	1335	770	1415	740	1365	680	1260
1060	725	1335	745	1375	725	1340	685	1265
1070	725	1335	730	1350	710	1310	690	1275
1080	730	1345	735	1355	700	1290	695	1280

ecommended Temperatures and Cooling Cycles for Full Annealing of Small Carbon Steel Forgings

ata are for forgings up to 75 mm (3 in.) in section thickness. Time at temperature usually is a minimum of 1 h for sections up to 25 mm (1 in.) ick; ½ h is added for each additional 25 mm (1 in.) of thickness.

eel	Annealing temperature		Cooling cycle(a)				Hardness range, HB
			°C		°F		
	°C	°F	From	To	From	To	
18	855-900	1575-1650	855	705	1575	1300	111-149
20	855-900	1575-1650	855	700	1575	1290	111-149
22	855-900	1575-1650	855	700	1575	1290	111-149
25	855-900	1575-1650	855	700	1575	1290	111-187
30	845-885	1550-1625	845	650	1550	1200	126-197
35	845-885	1550-1625	845	650	1550	1200	137-207
40	790-870	1450-1600	790	650	1450	1200	137-207
45	790-870	1450-1600	790	650	1450	1200	156-217
50	790-870	1450-1600	790	650	1450	1200	156-217
60	790-845	1450-1550	790	650	1450	1200	156-217
70	790-845	1450-1550	790	650	1450	1200	167-229
80	790-845	1450-1550	790	650	1450	1200	167-229
90	790-830	1450-1525	790	650	1450	1200	167-229
95	790-830	1450-1525	790	655	1450	1215	167-229

Furnace cooling at 28 °C/h (50 °F/h)

Approximate Grossmann Quenching Severity Factor of Various Media in the Pearlite Temperature Range

Circulation or agitation	Grossmann quench severity factor, *H*			
	Brine	Water	Oil and salt	Air
None	2	0.9-1.0	0.25-0.30	0.02
Mild	2-2.2	1.0-1.1	0.30-0.35	...
Moderate	...	1.2-1.3	0.35-0.40	...
Good	...	1.4-1.5	0.4-0.5	...
Strong	...	1.6-2.0	0.5-0.8	...
Violent	5	4	0.8-1.1	...

rossmann Numbers and Film Coefficients for Selected Quenchants

uenchant	Quenchant temperature		Quenchant velocity		Grossmann number, ($H = h/2k$)	Effective film coefficient	
	°C	°F	m/s	ft/min		w/m²·K	Btu/ft²·h·°F
ater	32	90	0.00	0	1.1	5000	880
			0.25	50	2.1	9000	1600
			0.51	100	2.7	12000	2100
			0.76	150	2.8	12000	2100
	55	130	0.00	0	0.2	1000	180
			0.25	50	0.6	2500	440
			0.51	100	1.5	6500	1100
			0.76	150	2.4	10500	1850
st oil	60	140	0.00	0	0.5	2000	350
			0.25	50	1.0	4500	790
			0.51	100	1.1	5000	880
			0.76	150	1.5	6500	1200
% polyvinyl pyrrolidone	43	110	0.00	0	0.8	3500	620
			0.25	50	1.3	6000	1100
			0.51	100	1.5	6500	1200
			0.76	150	1.8	7500	1300
onventional oil	65	150	0.51	100	0.7	3000	530
artempering oil	150	300	0.51	100	1.2	5000	880
r	27	80	0.00	0	0.05	200	35
			2.54	500	0.06	250	44
			5.08	1000	0.08	350	62

Comparison of the Cooling Power of Commercially Available Quenching and Martempering Oils According to Magnetic Quenchometer Test Results

Types of quenching oil	Oil sample	Viscosity at 40 °C (100 °F) SUS(a)	Flash point		Quenching duration from 885 °C (1625 °F) to 355 °C (670 °F), s			
					At 27 °C (80 °F)		At 120 °C (250 °F)	
			°C	°F	Ni-ball	Chromized Ni-ball	Ni-ball	Chromized Ni-ball
Conventional	1	102	190	375	22.5	27.2	...	...
	2	105	195	380	17.8	27.9	...	...
	3	107	170	340	16.0	24.8	...	...
Fast	4	50	145	290	7.0	(a)	...	...
	5	94	170	335	9.0	15.0	...	...
	6	107	190	375	10.8	17.0	...	...
	7	110	185	370	12.7	19.6	...	...
	8	120	190	375	13.3	17.8	...	...
Martempering, without speed improvers	9	329	235	455	19.2	27.6	18.4	22.1
	10	719	245	475	26.9	29.0	25.1	30.4
	11	2550	300	575	31.0	32.0	31.7	32.8
Martempering, with speed improvers	12	337	230	450	15.3	(b)	12.8	(b)
	13	713	245	475	16.4	17.9	14.0	15.6
	14	2450	300	570	19.7	17.0	15.1	15.4

(a) SUS, Saybolt universal seconds. (b) Not available

Comparison of the Ranges of Cooling Power of Commercially Available Quenching and Martempering Oils According to Magnetic Quenchometer Test Results using Pure Nickel Balls

Type of quenching oil	Quenching duration from 885 °C (1625 °F) to 355 °C (670 °F)			
	At 65 °C (150 °F)	At 120 °C (250 °F)	At 175 °C (350 °F)	At 230 °C (450 °F)
Conventional	14-22	14-22	...	...
Fast	7-14	7-14	...	...
Martempering, without speed improvers	18-34	18-34	22-38	≈47
Martempering, with speed improvers	14-20	13-18	16-22	≈33

Typical Hardnesses of Various Carbon Steels after Tempering

Grade	Carbon content, %	Hardness, HRC, after tempering for 2 h at									Heat treatment
		205 °C (400 °F)	260 °C (500 °F)	315 °C (600 °F)	370 °C (700 °F)	425 °C (800 °F)	480 °C (900 °F)	540 °C (1000 °F)	595 °C (1100 °F)	650 °C (1200 °F)	
Carbon steels, water hardening											
1030	0.30	50	45	43	39	31	28	25	22	95(a)	Normalized at 900 °C (1650 °F), water quenched from 830-845 °C (1525-1550 °F); average dew point, 16 °C (60 °F)
1040	0.40	51	48	46	42	37	30	27	22	94(a)	
1050	0.50	52	50	46	44	40	37	31	29	22	
1060	0.60	56	55	50	42	38	37	35	33	26	Normalized at 885 °C (1625 °F), water quenched from 800-815 °C (1475-1500 °F); average dew point, 7 °C (45 °F)
1080	0.80	57	55	50	43	41	40	39	38	32	
1095	0.95	58	57	52	47	43	42	41	40	33	
1137	0.40	44	42	40	37	33	30	27	21	91(a)	Normalized at 900 °C (1650 °F), water quenched from 830-855 °C (1525-1575 °F); average dew point, 13 °C (55 °F)
1141	0.40	49	46	43	41	38	34	28	23	94(a)	
1144	0.40	55	50	47	45	39	32	29	25	97(a)	

Data were obtained on 25 mm (1 in.) bars adequately quenched to develop full hardness. (a) Hardness, HRB

arbon Steels: Typical Austempering Applications

arts listed in order of increasing section thickness

rt	Steel	Maximum section thickness		Parts per unit weight		Salt temperature		Immersion time, min	Hardness, HRC
		mm	in.	kg^{-1}	lb^{-1}	°C	°F		
ain carbon steel parts									
evis	1050	0.75	0.030	770/kg	350/lb	360	680	15	42
llower arm	1050	0.75	0.030	412/kg	187/lb	355	675	15	42
ring	1080	0.79	0.031	220/kg	100/lb	330	625	15	48
ite	1060	0.81	0.032	88/kg	40/lb	330	630	6	45-50
m lever	1065	1.0	0.040	62/kg	28/lb	370	700	15	42
ite	1050	1.0	0.040	0.5 kg	¼ lb	360	675	15	42
pe bar	1065	1.0	0.040	141/kg	64/lb	370	700	15	42
bulator stop	1065	1.22	0.048	440/kg	200/lb	360	680	15	45
ver	1050	1.25	0.050	...	...	345	650	15	45-50
ain link	1050	1.5	0.060	573/kg	260/lb	345	650	15	45
oe-last link	1065	1.5	0.060	86/kg	39/lb	290	550	30	52
oe-toe cap	1070	1.5	0.060	18/kg	8/lb	315	600	60	50
wn mower blade	1065	3.18	0.125	1.5 kg	⅔ lb	315	600	15	50
ver	1075	3.18	0.125	24/kg	11/lb	385	725	5	30-35
stener	1060	6.35	0.250	110/kg	50/lb	310	590	25	50
abilizer bar	1090	19	0.750	22 kg	10 lb	370	700	6-9	40-45
ron steel bolt	10B20	6.35	0.250	100/kg	45/lb	420	790	5	38-43

/pical Operating Conditions for Through Hardening Carbon Steel Parts by Induction Process

Section size		Material	Frequency(a), Hz	Power(b), kW	Total heating time, s	Scan time		Work temperature: Entering coil		Work temperature: Leaving coil		Production rate		Inductor input(c)	
m	in.					s/cm	s/in.	°C	°F	°C	°F	kg/h	lb/h	kW/cm^2	$kW/in.^2$
unds															
	¾	1035 mod	180	28.5	68.4	0.71	1.8	75	165	620	1150	113	250	0.062	0.40
			9600	20.6	28.8	0.71	1.8	620	1150	955	1750	113	250	0.085	0.55
	1	1041	180	33	98.8	1.02	2.6	70	160	620	1150	141	311	0.054	0.35
			9600	19.5	44.2	1.02	2.6	620	1150	955	1750	141	311	0.057	0.37
	1⅛	1041	180	36	114	1.18	3.0	75	165	620	1150	153	338	0.053	0.34
			9600	19.1	51	1.18	3.0	620	1150	955	1750	153	338	0.050	0.32
ats															
	⅝	1038	3000	300	11.3	0.59	1.5	20	70	870	1600	1449	3194	0.361	2.33
	¾	1038	3000	332	15	0.79	2.0	20	70	870	1600	1576	3474	0.319	2.06
	⅞	1043	3000	336	28.5	1.50	3.8	20	70	870	1600	1609	3548	0.206	1.33
	1	1036	3000	304	26.3	1.38	3.5	20	70	870	1600	1595	3517	0.225	1.45
	1⅛	1036	3000	344	36.0	1.89	4.8	20	70	870	1600	1678	3701	0.208	1.34
regular shapes															
.5-33	11/16–15/16	1037 mod	3000	580	254	0.94	2.4	20	70	885	1625	2211	4875	0.040	0.26

) Note use of dual frequencies for round sections. (b) Power transmitted by the inductor at the operating frequency indicated. This power is approximately 25% less than the power put to the machine, because of losses within the machine. (c) At the operating frequency of the inductor

Operating and Production Data for Progressive Induction Tempering

Section size		Material	Frequency, Hz	Power(a), kW	Total heating time, s	Scan time		Work temperature: Entering coil		Work temperature: Leaving coil		Production rate		Inductor input(b)	
mm	in.					s/cm	s/in.	°C	°F	°C	°F	kg/h	lb/h	kW/cm^2	$kW/in.^2$
Rounds															
19	¾	1035 mod	9600	12.7	30.6	0.71	1.8	50	120	510	950	113	250	0.050	0.32
25	1	1041	9600	18.7	44.2	1.02	2.6	50	120	565	1050	141	311	0.054	0.35
29	1⅛	1041	9600	20.6	51	1.18	3.0	50	120	565	1050	153	338	0.053	0.34
Flats															
16	⅝	1038	60	88	123	0.59	1.5	40	100	290	550	1449	3194	0.014	0.089
19	¾	1038	60	100	164	0.79	2.0	40	100	315	600	1576	3474	0.013	0.081
22	⅞	1043	60	98	312	1.50	3.8	40	100	290	550	1609	3548	0.008	0.050
25	1	1043	60	85	254	1.22	3.1	40	100	290	550	1365	3009	0.011	0.068
29	1⅛	1043	60	90	328	1.57	4.0	40	100	290	550	1483	3269	0.009	0.060
Irregular shapes															
17.5-33	11/16–15/16	1037 mod	9600	192	64.8	0.94	2.4	65	150	550	1020	2211	4875	0.043	0.28
17.5-29	11/16–1⅛	1037 mod	9600	154	46	0.67	1.7	65	150	425	800	2276	5019	0.040	0.26

(a) Power transmitted by the inductor at the operating frequency indicated. For converted frequencies, this power is approximately 25% less than the power input to the machine, because of losses within the machine. (b) At the operating frequency of the inductor

1062: Spot Flame Hardening of a Free-Wheel Cam

Preliminary operation

Turn on water, air, oxygen, power, and propane. Line pressures: water, 205 kPa (30 psi); air, 550 kPa (80 psi); oxygen, 825 kPa (120 psi); propane, 205 kPa (30 psi). Ignite pilots.

Loading and positioning

Mount cam on flame head. Cam positioned on locating plate and two wear pads, and against three locating pins that are integral parts of flame head. Distance from flame head to cam surface, approximately 7.9 mm (5/16 in.)

Cycle start and heating cycle

Propane and oxygen solenoid valves open (oxygen flow delayed slightly). Mixture of propane and oxygen ignited at flame heads by pilots. Check propane and oxygen pressures. Adjust flame by regulating propane. Heating cycle controlled by timer. Time predetermined to obtain specified hardening depth. Propane and oxygen solenoid valves close (propane flow delayed slightly). Ejector plate (air operated) advances and strips cam from flame head.

Propane regulated pressure, 125 kPa (18 psi); oxygen regulated pressure, 585 kPa (85 psi); oxygen upstream pressure, 425 kPa (62 psi); oxygen downstream pressure, 110 kPa (16 psi). Flame velocity (approximate), 135 m/s (450 ft/s). Gas consumption (approximate): propane, 0.01 m^3 (0.4 ft^3) per piece; oxygen, 0.04 m^3 (1.3 ft^3) per piece. Total heating time, 11 s

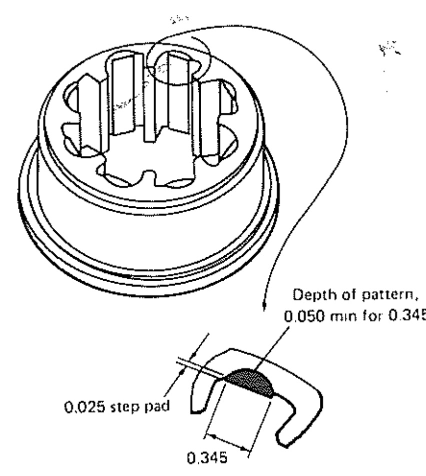
Flame port design: nine ports per row; eight rows; port size, No. 69 (0.74 mm, or 0.0292 in.), with No. 56 (1.2 mm, or 0.0465 in.) counterbore

Quench cycle

Cam drops into quench oil, is removed from tank by conveyor. Oil temperature, 54 ± 5.6 °C (130 ± 10 °F). Time in oil (approximate), 30 s

Hardness and pattern aim

Hardness, 60 HRC minimum at surface and 59 HRC minimum at a depth of 1.3 mm (0.050 in.) below surface, for width of 8.8 mm (0.345 in.) on cam roller surface. Dimensions below given in inches



Hardness pattern

Flame Hardening Response of Carbon Steels

Material	Typical hardness, HRC, as affected by quenchant: Air(a)	Oil(b)	Water (b)
Plain carbon steels			
1025-1035	...	...	33-50
1040-1050	...	52-58	55-60
1055-1075	50-60	58-62	60-63
1080-1095	55-62	58-62	62-65
1125-1137	...	...	45-55
1138-1144	45-55	52-57(c)	55-62
1146-1151	50-55	55-60	58-64
Carburized grades of plain carbon steels(d)			
1010-1020	50-60	58-62	62-65
1108-1120	50-60	60-63	62-65

(a) To obtain the hardness results indicated, those areas not directly heated must be kept relatively cool during the heating process. (b) Thin sections are susceptible to cracking when quenched with oil or water. (c) Hardness is slightly lower for material heated by spinning or combination progressive-spinning methods than it is for material heated by progressive or stationary methods. (d) Hardness values of carburized cases containing 0.90 to 1.10% C

Gas Carburizing: Carburizing Steel Compositions

Steel	Composition, %: C	Mn	Ni	Cr	Mo	Other
Carbon steels						
1010	0.08-0.13	0.30-0.60	...	...	...	(a), (b)
1018	0.15-0.20	0.60-0.90	...	...	...	(a), (b)
1019	0.15-0.20	0.70-1.00	...	...	...	(a), (b)
1020	0.18-0.23	0.30-0.60	...	...	...	(a), (b)
1021	0.18-0.23	0.60-0.90	...	...	...	(a), (b)
1022	0.18-0.23	0.70-1.00	...	...	...	(a), (b)
1524	0.19-0.25	1.35-1.65	...	...	...	(a), (b)
1527	0.22-0.29	1.20-1.50	...	...	...	(a), (b)
Resulfurized steels						
1117	0.14-0.20	1.00-1.30	...	...	...	0.08-0.13 S

(a) 0.04 P max, 0.05 S max. (b) 0.15-0.35 Si

Effect of Cyaniding Temperatures and Time on Case Depth and Carbon and Nitrogen Contents

Material thickness, 2.03 mm (0.080 in.); cyanide content of bath, 20 to 30%

Steel	Case depth after cyaniding for: 15 min, mm	15 min, in.	100 min, mm	100 min, in.	Analysis after 100 min at temperature(a): Carbon, %	Nitrogen, %
Cyanided at 760 °C (1400 °F)						
1008	0.038	0.0015	0.152	0.006	0.68	0.51
1010	0.038	0.0015	0.152	0.006	0.70	0.50
1022	0.051	0.0020	0.203	0.008	0.72	0.51
Cyanided at 845 °C (1550 °F)						
1008	0.076	0.0030	0.203	0.008	0.75	0.26
1010	0.076	0.0030	0.203	0.008	0.77	0.28
1022	0.089	0.0035	0.254	0.010	0.79	0.27

(a) Carbon and nitrogen contents were determined from analysis of the outermost 0.076 mm (0.003 in.) of cyanided cases.

Liquid Carburizing Carbon Steels in Cyanide Baths

Typical application of carbon steel and resulfurized steel

Part	Weight, kg	Weight, lb	Steel	Depth of case, mm	Depth of case, in.	Temperature, °C	Temperature, °F	Time, h	Quench	Subsequent treatment	Hardness, HRC
Carbon steel											
Adapter	0.9	2	CR	1.0	0.040	940	1720	4	AC	(a)	62-63
Arbor, tapered	0.5	1.1	1020	1.5	0.060	940	1720	6.5	AC	(a)	62-63
Bushing	0.7	1.5	CR	1.5	0.060	940	1720	6.5	AC	(a)	62-63
Die block	3.5	7.7	1020	1.3	0.050	940	1720	5	AC	(a)	62-63
	1.1	2.5	CR	1.3	0.050	940	1720	5	AC	(a)	59-61
Disk	1.4	3	1020	1.3	0.050	940	1720	5	(b)	(b)	56-57
Flange	0.03	0.06	1020	0.4-0.5	0.015-0.020	845	1550	4	Oil	(c)	55 min(d)
Gage rings, knurled	0.09	0.2	1020	1.5	0.060	940	1720	6.5	AC	(a)	62-63
Hold-down block	0.9	2	CR	1.0	0.040	940	1720	4	AC	(a)	62-63
Insert, tapered	4.75	10.5	1020	1.3	0.050	940	1720	5	AC	(a)	62-63
Lever	0.05	0.12	1020	0.13-0.25	0.005-0.010	845	1550	1	Oil	(c)	(e)
Link	0.007	0.015	1018	0.13-0.25	0.005-0.010	845	1550	1	AC	...	...
Plate	0.007	0.015	1010	0.25-0.4	0.010-0.015	845	1550	2	Oil	(c)	(e)
Plug	0.7	1.6	CR	1.5	0.060	940	1720	6.5	AC	(a)	62-63
Plug gage	0.45	1	1020	1.5	0.060	940	1720	6.5	AC	(a)	62-63
Radius-cutout roll	7.7	17	CR	1.5	0.060	940	1720	6.5	AC	(a)	62-63
Torsion-bar cap	0.05	0.1	1022	0.02-0.05	0.001-0.002	900	1650	0.12	Caustic	(f)	45-47
Resulfurized steel											
Bushing	0.04	0.09	1118	0.25-0.4	0.010-0.015	845	1550	2	Oil	(c)	(e)
Dash sleeve	3.6	8	1117	1.1	0.045	915	1675	7	AC	(g)	58-63
Disk	0.0009	0.002	1118	0.13-0.25	0.005-0.010	845	1550	1	Brine	(c)	(e)
Drive shaft	3.6	8	1117	1.1	0.045	915	1675	7	AC	(h)	58-63
Guide bushing	0.2	0.5	1117	0.75	0.030	915	1675	5	(i)	...	58-63
Nut	0.04	0.09	1113	0.13-0.25	0.005-0.010	845	1550	1	Oil	(c)	(e)
Pin	0.003	0.007	1119	0.13-0.25	0.005-0.010	845	1550	1	Oil	(c)	(e)
Plug	0.007	0.015	1113	0.075-0.13	0.003-0.005	845	1550	0.5	Oil	(c)	(e)
Rack	0.34	0.75	1113	0.13-0.25	0.005-0.010	845	1550	1	Oil	(c)	(e)
Roller	0.01	0.03	1118	0.25-0.4	0.010-0.015	845	1550	2	Oil	(c)	(e)
Screw	0.003	0.007	1113	0.075-0.13	0.003-0.005	845	1550	0.5	Oil	(c)	(e)
Shaft	0.08	0.18	1118	0.25-0.4	0.010-0.015	845	1550	2	Oil	(c)	(e)
Spring seat	0.009	0.02	1118	0.25-0.4	0.010-0.015	845	1550	2	Oil	(c)	(e)
Stop collar	0.9	2	1117	1.1	0.045	925	1700	6.5	AC	(g)	60-63
Stud	0.007	0.015	1118	0.13-0.25	0.005-0.010	845	1550	1	Oil	(c)	(e)
Valve bushing	0.02	0.05	1117	1.3	0.050	915	1675	8	AC	(g)	58-63
Valve retainer	0.45	1	1117	1.1	0.045	915	1675	7	(i)	...	58-63
Washer	0.007	0.015	1118	0.25-0.4	0.010-0.015	845	1550	2	Oil	(c)	(e)

(a) Reheated at 790 °C (1450 °F), quenched in caustic, tempered at 150 °C (300 °F). (b) Transferred to neutral salt at 790 °C (1450 °F), quenched in caustic, tempered at 175 °C (350 °F). (c) Tempered at 165 °C (325 °F). (d) Or equivalent. (e) File-hard. (f) Tempered at 205 °C (400 °F). (g) Reheated at 845 °C (1550 °F), quenched in salt at 175 °C (350 °F). (h) Reheated at 775 °C (1425 °F), quenched in salt at 195 °C (380 °F). (i) Tempered at 165 °C (325 °F) and treated at –85 °C (–120 °F)

Liquid Carburizing Carbon Steels in Noncyanide Baths

Typical applications of carbon steels

Part	Weight, kg	Weight, lb	Steel	Case depth, mm	Case depth, in.	Temperature, °C	Temperature, °F	Time, h	Quench	Subsequent treatment	Hardness, HRC
Production tools	0.5-2.0	1.1-4.4	1018	0.375	0.015	925	1700	0.5-1.0	Brine	...	50-60
Bicycle forks	1.4	3.1	1017(a)	0.05-0.08	0.002-0.003	925	1700	0.085	Brine	Temper at 425 °C (795 °F)	60
Shift lever and ball	~1.5	~3.3	1040, 1017(b)	0.25	0.010	925	1700	0.67	Air cool 30 s in brine	...	File hard
Clock screws and studs	0.005	0.011	1006, 1113	0.08-0.10	0.003-0.004	955	1750	0.2	Brine	...	62-64
Flat head screws	0.015	0.033	1122	0.15	0.006	925	1700	0.33	Molten salt, 290 °C (550 °F)	...	56

(a) Partial immersion. (b) Carburizer brass braze

Flame Hardening Response of Carbon Steels

Material	Typical hardness, HRC, as affected by quenchant Air(a)	Oil(b)	Water (b)
Plain carbon steels			
1025-1035	...	...	33-50
1040-1050	...	52-58	55-60
1055-1075	50-60	58-62	60-63
1080-1095	55-62	58-62	62-65
1125-1137	...	...	45-55
1138-1144	45-55	52-57(c)	55-62
1146-1151	50-55	55-60	58-64
Carburized grades of plain carbon steels(d)			
1010-1020	50-60	58-62	62-65
1108-1120	50-60	60-63	62-65

(a) To obtain the hardness results indicated, those areas not directly heated must be kept relatively cool during the heating process. (b) Thin sections are susceptible to cracking when quenched with oil or water. (c) Hardness is slightly lower for material heated by spinning or combination progressive-spinning methods than it is for material heated by progressive or stationary methods. (d) Hardness values of carburized cases containing 0.90 to 1.10% C

Gas Carburizing: Carburizing Steel Compositions

Steel	Composition, % C	Mn	Ni	Cr	Mo	Other
Carbon steels						
1010	0.08-0.13	0.30-0.60	...	...	...	(a), (b)
1018	0.15-0.20	0.60-0.90	...	...	...	(a), (b)
1019	0.15-0.20	0.70-1.00	...	...	...	(a), (b)
1020	0.18-0.23	0.30-0.60	...	...	...	(a), (b)
1021	0.18-0.23	0.60-0.90	...	...	...	(a), (b)
1022	0.18-0.23	0.70-1.00	...	...	...	(a), (b)
1524	0.19-0.25	1.35-1.65	...	...	...	(a), (b)
1527	0.22-0.29	1.20-1.50	...	...	...	(a), (b)
Resulfurized steels						
1117	0.14-0.20	1.00-1.30	...	...	...	0.08-0.13 S

(a) 0.04 P max, 0.05 S max. (b) 0.15-0.35 Si

Effect of Cyaniding Temperatures and Time on Case Depth and Carbon and Nitrogen Contents

Material thickness, 2.03 mm (0.080 in.); cyanide content of bath, 20 to 30%

Steel	Case depth after cyaniding for: 15 min, mm	15 min, in.	100 min, mm	100 min, in.	Analysis after 100 min at temperature(a) Carbon, %	Nitrogen, %
Cyanided at 760 °C (1400 °F)						
1008	0.038	0.0015	0.152	0.006	0.68	0.51
1010	0.038	0.0015	0.152	0.006	0.70	0.50
1022	0.051	0.0020	0.203	0.008	0.72	0.51
Cyanided at 845 °C (1550 °F)						
1008	0.076	0.0030	0.203	0.008	0.75	0.26
1010	0.076	0.0030	0.203	0.008	0.77	0.28
1022	0.089	0.0035	0.254	0.010	0.79	0.27

(a) Carbon and nitrogen contents were determined from analysis of the outermost 0.076 mm (0.003 in.) of cyanided cases.

Liquid Carburizing Carbon Steels in Cyanide Baths

Typical application of carbon steel and resulfurized steel

Part	Weight kg	Weight lb	Steel	Depth of case mm	Depth of case in.	Temperature °C	Temperature °F	Time, h	Quench	Subsequent treatment	Hardness, HRC
Carbon steel											
Adapter	0.9	2	CR	1.0	0.040	940	1720	4	AC	(a)	62-63
Arbor, tapered	0.5	1.1	1020	1.5	0.060	940	1720	6.5	AC	(a)	62-63
Bushing	0.7	1.5	CR	1.5	0.060	940	1720	6.5	AC	(a)	62-63
Die block	3.5	7.7	1020	1.3	0.050	940	1720	5	AC	(a)	62-63
	1.1	2.5	CR	1.3	0.050	940	1720	5	AC	(a)	59-61
Disk	1.4	3	1020	1.3	0.050	940	1720	5	(b)	(b)	56-57
Flange	0.03	0.06	1020	0.4-0.5	0.015-0.020	845	1550	4	Oil	(c)	55 min(d)
Gage rings, knurled	0.09	0.2	1020	1.5	0.060	940	1720	6.5	AC	(a)	62-63
Hold-down block	0.9	2	CR	1.0	0.040	940	1720	4	AC	(a)	62-63
Insert, tapered	4.75	10.5	1020	1.3	0.050	940	1720	5	AC	(a)	62-63
Lever	0.05	0.12	1020	0.13-0.25	0.005-0.010	845	1550	1	Oil	(c)	(e)
Link	0.007	0.015	1018	0.13-0.25	0.005-0.010	845	1550	1	AC	...	...
Plate	0.007	0.015	1010	0.25-0.4	0.010-0.015	845	1550	2	Oil	(c)	(e)
Plug	0.7	1.6	CR	1.5	0.060	940	1720	6.5	AC	(a)	62-63
Plug gage	0.45	1	1020	1.5	0.060	940	1720	6.5	AC	(a)	62-63
Radius-cutout roll	7.7	17	CR	1.5	0.060	940	1720	6.5	AC	(a)	62-63
Torsion-bar cap	0.05	0.1	1022	0.02-0.05	0.001-0.002	900	1650	0.12	Caustic	(f)	45-47
Resulfurized steel											
Bushing	0.04	0.09	1118	0.25-0.4	0.010-0.015	845	1550	2	Oil	(c)	(e)
Dash sleeve	3.6	8	1117	1.1	0.045	915	1675	7	AC	(g)	58-63
Disk	0.0009	0.002	1118	0.13-0.25	0.005-0.010	845	1550	1	Brine	(c)	(e)
Drive shaft	3.6	8	1117	1.1	0.045	915	1675	7	AC	(h)	58-63
Guide bushing	0.2	0.5	1117	0.75	0.030	915	1675	5	(i)	...	58-63
Nut	0.04	0.09	1113	0.13-0.25	0.005-0.010	845	1550	1	Oil	(c)	(e)
Pin	0.003	0.007	1119	0.13-0.25	0.005-0.010	845	1550	1	Oil	(c)	(e)
Plug	0.007	0.015	1113	0.075-0.13	0.003-0.005	845	1550	0.5	Oil	(c)	(e)
Rack	0.34	0.75	1113	0.13-0.25	0.005-0.010	845	1550	1	Oil	(c)	(e)
Roller	0.01	0.03	1118	0.25-0.4	0.010-0.015	845	1550	2	Oil	(c)	(e)
Screw	0.003	0.007	1113	0.075-0.13	0.003-0.005	845	1550	0.5	Oil	(c)	(e)
Shaft	0.08	0.18	1118	0.25-0.4	0.010-0.015	845	1550	2	Oil	(c)	(e)
Spring seat	0.009	0.02	1118	0.25-0.4	0.010-0.015	845	1550	2	Oil	(c)	(e)
Stop collar	0.9	2	1117	1.1	0.045	925	1700	6.5	AC	(g)	60-63
Stud	0.007	0.015	1118	0.13-0.25	0.005-0.010	845	1550	1	Oil	(c)	(e)
Valve bushing	0.02	0.05	1117	1.3	0.050	915	1675	8	AC	(g)	58-63
Valve retainer	0.45	1	1117	1.1	0.045	915	1675	7	(i)	...	58-63
Washer	0.007	0.015	1118	0.25-0.4	0.010-0.015	845	1550	2	Oil	(c)	(e)

(a) Reheated at 790 °C (1450 °F), quenched in caustic, tempered at 150 °C (300 °F). (b) Transferred to neutral salt at 790 °C (1450 °F), quenched in caustic, tempered at 175 °C (350 °F). (c) Tempered at 165 °C (325 °F). (d) Or equivalent. (e) File-hard. (f) Tempered at 205 °C (400 °F). (g) Reheated at 845 °C (1550 °F), quenched in salt at 175 °C (350 °F). (h) Reheated at 775 °C (1425 °F), quenched in salt at 195 °C (380 °F). (i) Tempered at 165 °C (325 °F) and treated at −85 °C (−120 °F)

Liquid Carburizing Carbon Steels in Noncyanide Baths

Typical applications of carbon steels

Part	Weight kg	Weight lb	Steel	Case depth mm	Case depth in.	Temperature °C	Temperature °F	Time, h	Quench	Subsequent treatment	Hardness, HRC
Production tools	0.5-2.0	1.1-4.4	1018	0.375	0.015	925	1700	0.5-1.0	Brine	...	50-60
Bicycle forks	1.4	3.1	1017(a)	0.05-0.08	0.002-0.003	925	1700	0.085	Brine	Temper at 425 °C (795 °F)	60
Shift lever and ball	~1.5	~3.3	1040, 1017(b)	0.25	0.010	925	1700	0.67	Air cool 30 s in brine	...	File hard
Clock screws and studs	0.005	0.011	1006, 1113	0.08-0.10	0.003-0.004	955	1750	0.2	Brine	...	62-64
Flat head screws	0.015	0.033	1122	0.15	0.006	925	1700	0.33	Molten salt, 290 °C (550 °F)	...	56

(a) Partial immersion. (b) Carburizer brass braze

Carbonitriding Carbon Steels

Typical applications and production cycles

Part	Steel	Case depth		Furnace temperature		Total time in furnace	Quench
		mm	0.001 in.	°C	°F		
Carbon steels							
Adjusting yoke, 25 by 9.5 mm (1 by 0.37 in.)	1020	0.05-0.15	2-6	775 and 745	1425 and 1375	64 min	Oil
Bearing block, 64 by 32 by 3.2 mm (2.5 by 1.3 by 0.13 in.)	1010	0.05-0.15	2-6	775 and 745	1425 and 1375	64 min	Oil
Cam, 2.3 by 57 by 64 mm (0.1 by 2.25 by 2.5 in.)	1010	0.38-0.45	15-18	855	1575	2½ h	Oil
Cup, 13 g (0.46 oz)	1015	0.08-0.13	3-5	790	1450	½ h	Oil
Distributor drive shaft, 125 mm OD by 127 mm (5 by 5 in.)	1015	0.15-0.25	6-10	815 and 745	1500 and 1375	108 min	Gas(a)
Gear, 44.5 mm diam by 3.2 mm (1.75 by 0.125 in.)	1213(b)	0.30-0.38	12-15	855	1575	1¾ h	Oil(c)
Hex nut, 60.3 by 9.5 mm (2.4 by 0.37 in.)	1030	0.15-0.25	6-10	815 and 745	1500 and 1375	64 min	Oil
Hood-latch bracket, 6.4 mm diam (0.25 in.)	1015	0.05-0.15	2-6	775 and 745	1425 and 1375	64 min	Oil
Link, 2 by 38 by 38 mm (0.079 by 1.5 by 1.5 in.)	1022	0.30-0.38	12-15	855	1575	1½ h	Oil
Mandrel, 40 g (1.41 oz)	1117	0.20-0.30	8-12	845	1550	1½ h	Oil
Paper-cutting tool, 410 mm long	1117	~0.75	~30	...	...	...	...
Segment, 2.3 by 44.5 by 44.5 mm (0.09 by 1.75 by 1.75 in.)	1010	0.38-0.45	15-18	855	1575	2½ h	Oil
Shaft, 4.7 mm diam by 159 mm (0.19 by 6.25 in.)	1213(b)	0.30-0.38	12-15	815	1500	2½ h	Gas(a)(d)
Shift collar, 59 g (2.1 oz)	1118	0.30-0.36	12-14	775	1430	5½ h	Oil(e)
Sliding spur gear, 66.7 mm OD (2.625 in.)	1018	0.38-0.50	15-20	870	1600	2 h(f)	Oil(g)
Spring pin, 14.3 mm OD by 114 mm (0.56 by 4.5 in.)	1030	0.25-0.50	10-20	815 and 745	1500 and 1375	144 min	Oil
Spur pinion shaft, 41.3 mm OD (1.625 in.)	1018	0.38-0.50	15-20	870	1600	2 h(f)	Oil(h)
Transmission shift fork, 127 by 76 mm (5 by 3 in.)	1040	0.25-0.50	10-20	815 and 745	1500 and 1375	162 min	Gas(a)

(a) Modified carbonitriding atmosphere. (b) Leaded. (c) Tempered at 190 °C (375 °F). (d) Tempered at 150 °C (300 °F). (e) Tempered at 165 °C (325 °F). (f) Time at temperature. (g) Oil at 150 °C (300 °F): tempered at 150 °C (300 °F); for 1 h. (h) Oil at 150 °C (300 °F); tempered at 260 °C (500 °F) for 1 h

Applications for Boride Carbon Steels

Substrate material AISI	BSI	DIN	Application
		St37	Bushes, bolts, nozzles, conveyer tubes, base plates, runners, blades, thread guides
1020	...	C15 (Ck15)	Gear drives, pump shafts
1043	...	C45	Pins, guide rings, grinding disks, bolts
		St50-1	Casting inserts, nozzles, handles
1138	...	45S20	Shaft protection sleeves, mandrels
1042	...	Ck45	Swirl elements, nozzles (for oil burners), rollers, bolts, gate plates

Nonresulfurized Carbon Steels (1000 Series)

1005

Chemical Composition. AISI and UNS: 0.06 C max, 0.35 Mn max, 0.040 P max, 0.050 S max; (standard steel grade for wire rod and wire only)

Recommended Heat Treating Practice

Case Hardening. Can be carbonitrided

1006

Chemical Composition. AISI and UNS: 0.08 C max, 0.25 Mn max, 0.040 P max, 0.050 S max; (standard steel grade for wire rod and wire only)

Recommended Heat Treating Practice

Case Hardening. Carbonitriding and liquid carburizing are suitable processes

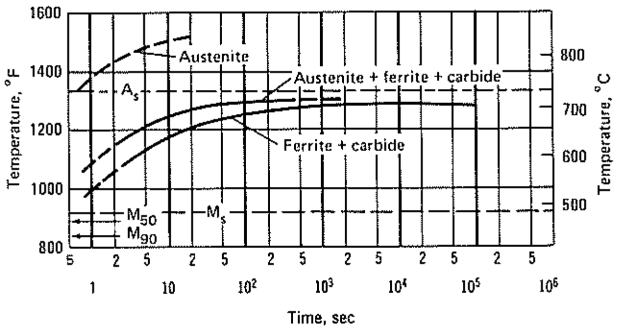
1008

Chemical Composition. AISI and UNS: 0.10 C max, 0.30 to 0.50 Mn, 0.040 P max, 0.050 S max. **UNS G10080 and AISI-SAE1008 standard composition ranges and limits:** 0.10 C max, 0.25 to 0.50 Mn

Similar Steels (U.S. and/or Foreign). UNS G10080; ASTM A108, A510, A519, A545, A549, A575, A576; FED QQ-S-637 (C1008), QQ-S-698 (C1008); MIL SPEC MIL-S-11310 (CS1008); SAE J403, J412, J414; (Ger.) DIN 1.0204; (Ital.) UNI CB 10 FU

Characteristics. Extremely ductile in the normalized or annealed condition and often subjected to severe cold reduction. Has excellent cold formability and is readily welded by any of the well-known welding processes. Brazing results also excellent, which accounts for widespread use of furnace brazing in producing assemblies. Machinability is extremely poor

1008: Isothermal Transformation Diagram. Containing 0.06 C, 0.43 Mn; austenitized at 915 °C (1680 °F). Grain size, 7. Martensite transformation temperatures are estimates.



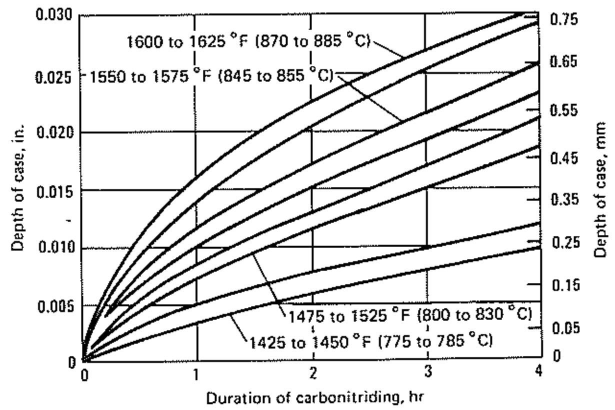
Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). This will restore the microstructure, which consists of a few pearlite plates dispersed among grains of blocky ferrite

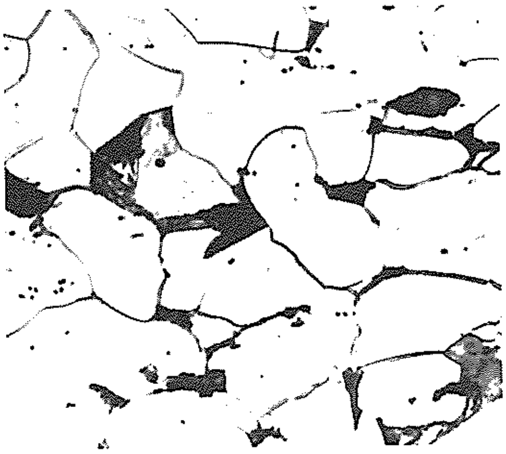
Annealing. When clean surfaces are required, heat to approximately 910 °C (1670 °F) in a lean exothermic atmosphere. Cool in the cooler section of a continuous furnace. Microstructure following this treatment essentially the same as that obtained after normalizing

Tempering. Although the vast majority of parts case hardened by carbonitriding are not tempered, they can be rendered less brittle by tempering

1008: Carbonitriding

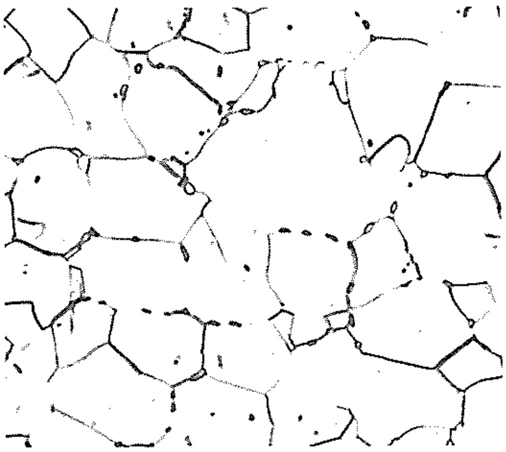


1008: Microstructures. (a) Aluminum-killed 1008 steel, normalized after 60% cold reduction to a final thickness of 0.8 mm (0.03 in.). The ferritic structure contains fine pearlite (dark areas) at the grain boundaries. 4% nital. 1000×. (b) Same as (a), except process annealed at 595 °C (1105 °F) after normalizing. Ferritic structure contains some fine pearlite and some spheroidized cementite at the grain boundaries. 4% nital. 1000×. (c) Same as (a), except process annealed at 705 °C (1300 °F) after normalizing. The ferritic structure contains some cementite particles at the grain boundaries. 4% nital. 1000×



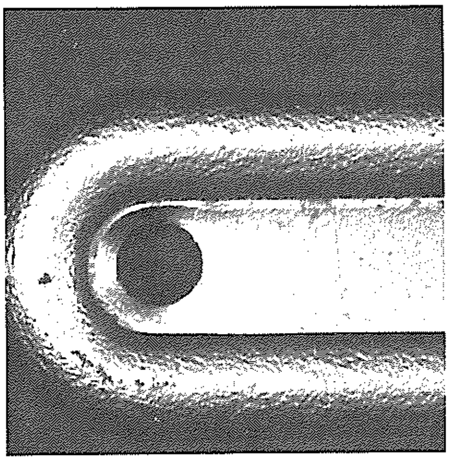
(a)

(b)

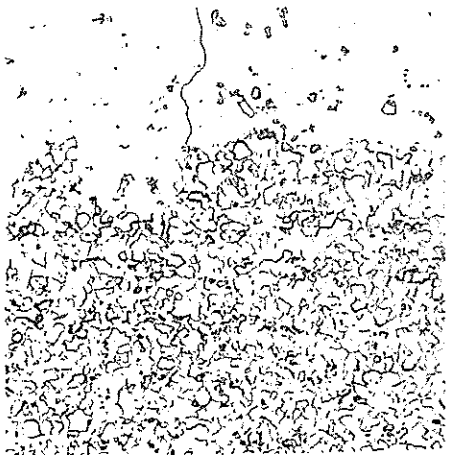


(c)

1008: Rimmed 1008 steel part, formed from sheet, with surface roughness (orange peel). Not polished, not etched. Actual size



1008: Rimmed 1008 Steel Parts. Magnified cross section shows the coarse surface grain that caused the orange peel. nital. 50×



t 150 to 205 °C (300 to 400 °F) without appreciable loss of surface ıardness

Case Hardening. Hard, wear-resisting surfaces can be obtained on parts by carbonitriding. Depth of case developed depends upon time and emperature. Carbonitride at 760 °C (1400 °F) to 870 °C (1600 °F). Atmosphere usually comprised of an enriched carrier gas from an endothermic generator, plus about 10% anhydrous ammonia. Case depths usually ange from approximately 0.008 to 0.25 mm (0.003 to 0.010 in.). Maximum surface hardness usually obtained by oil quenching directly from the carbonitriding temperature. Cyanide or cyanide-free liquid salt baths and gas carburizing may also be used for equivalent results. Temperatures, time at temperature, and quenching practice also approximately the same

Process Annealing. Heating to 600 °C (1110 °F) will recrystallize cold worked structures; often used as an intermediate anneal prior to further cold working

1010

Chemical Composition. AISI and UNS: 0.08 to 0.13 C, 0.30 to 0.60 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). UNS G10100; AMS 5040, 5042, 5044, 5047, 5053; ASTM A108, A510, A519, A545, A549, A575, A576; MIL SPEC MIL-S-11310 (CS1010); SAE J403, J412, J414; (Ger.) DIN 1.1121; (Fr.) AFNOR XC 10; (Jap.) JIS S 10 C, S 12 C 9 CK

Characteristics. Extremely ductile in the normalized or annealed condition and often subjected to severe cold reduction, accounting for excellent cold formability. However, as the carbon content increases the cold formability decreases, slightly reducing the severity it can withstand in cold forming. Weldability and brazing results are excellent. Machinability is poor

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Cool in still air

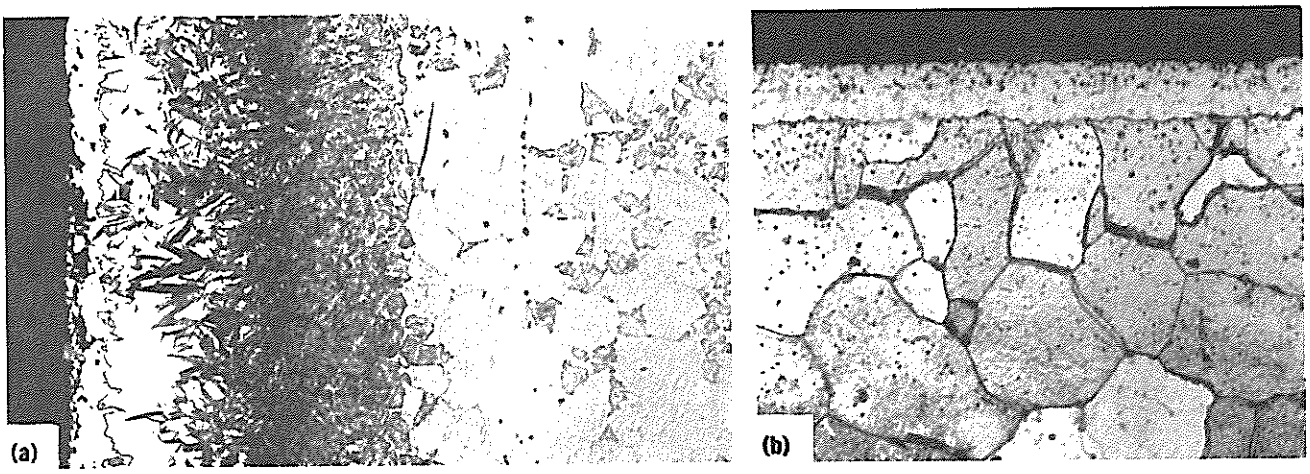
Annealing. For clean surfaces, heat to approximately 910 °C (1670 °F) in a lean exothermic atmosphere. Cool in the cooler section of a continuous furnace

Tempering. Optional. Tempering at 150 to 205 °C (300 to 400 °F) reduces brittleness without appreciable loss of surface hardness

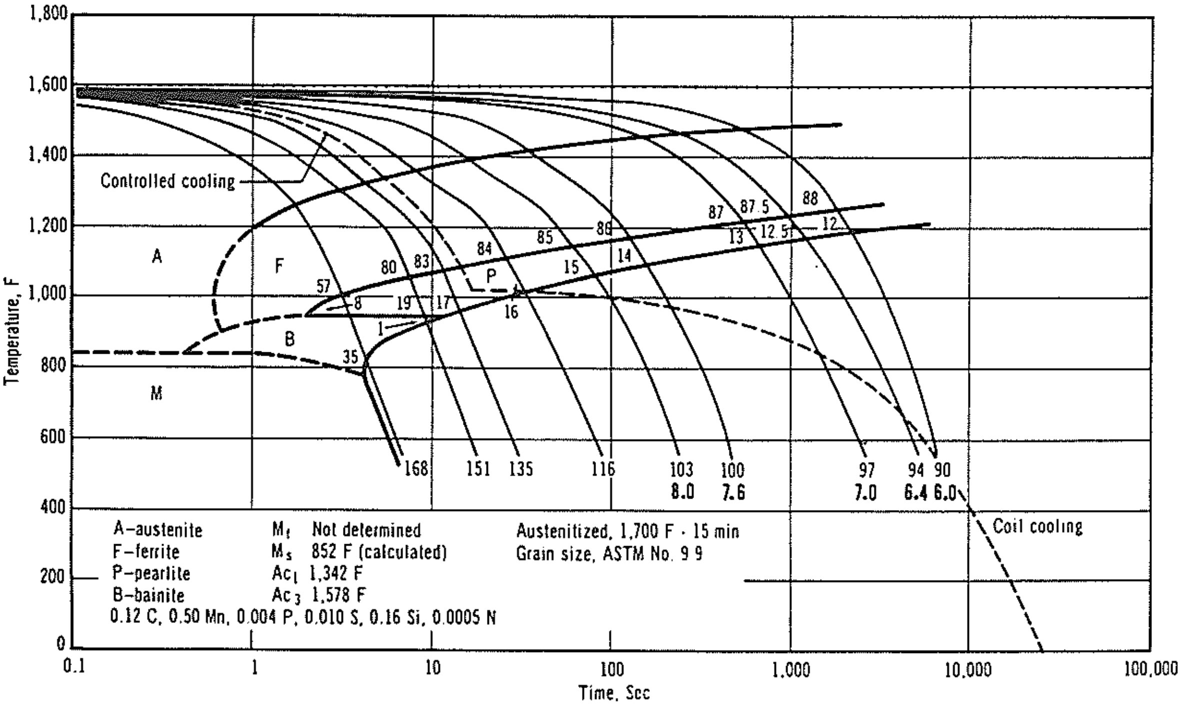
Case Hardening. Carbonitride at 760 to 870 °C (1400 to 1600 °F) in an enriched endothermic carrier gas, plus about 10% anhydrous ammonia. Case depths range from 0.076 to 0.254 mm (0.003 to 0.01 in.). Oil quenching directly from carbonitriding temperature provides maximum surface hardness. Salt baths produce similar results. Flame hardening, austempering, and liquid carburizing are alternative processes

Process Annealing. Heating to 600 °C (1110 °F) will recrystallize cold worked structures; often used as an intermediate anneal prior to further cold working

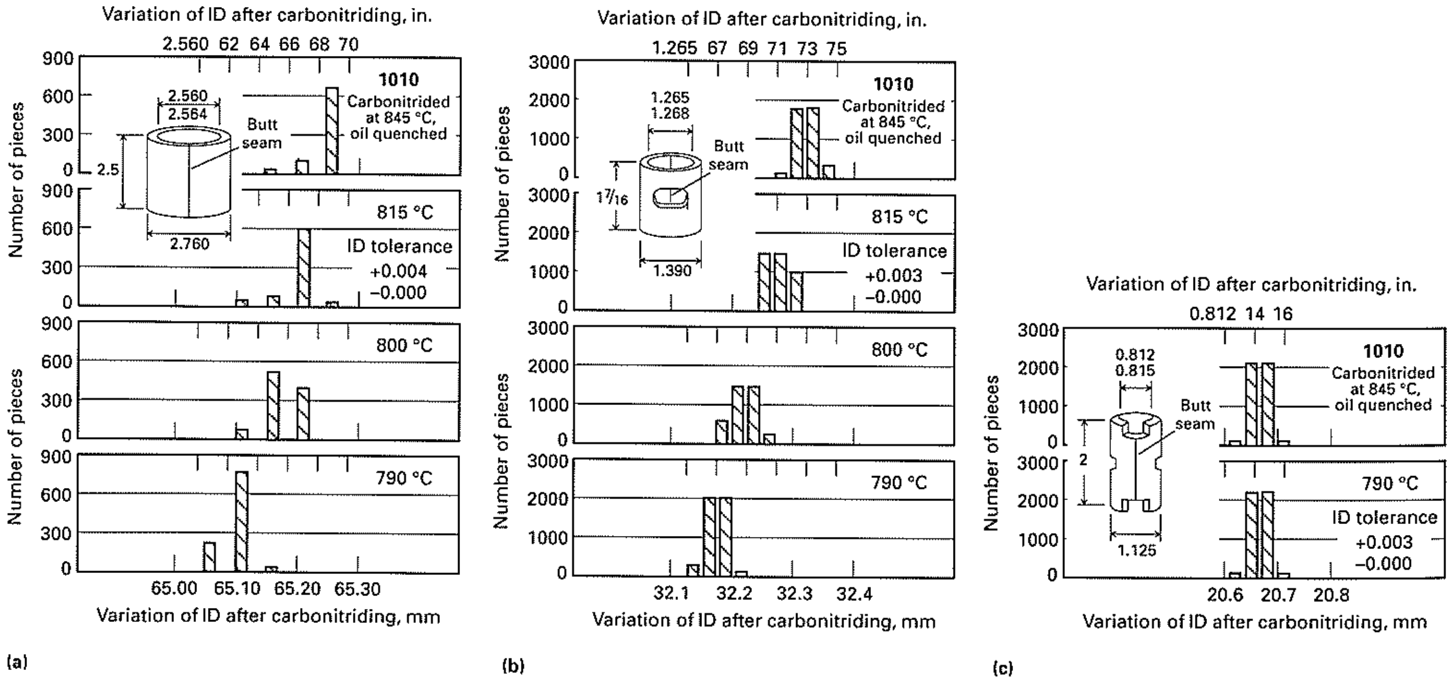
1010: Microstructures. (a) Nital, 200×. Carbonitrided at 790 °C (1455 °F) and oil quenched, showing a high-carbon, low-nitrogen case. Core (right half of micrograph) is predominantly ferrite. (b) 2% nital, 700×. Liquid nitrided 1 h at 570 °C (1060 °F) in aerated nitriding salt bath. Nitrided layer, 0.0076 mm (0.0003 in.) deep. Core structure, blocky ferrite and grain-boundary carbide. No transition zone evident

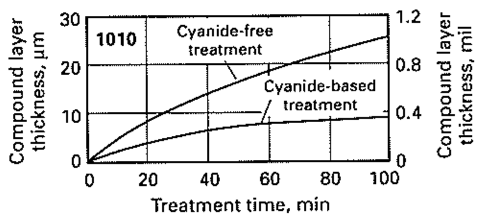


1010: Time-Temperature Diagram. Composition: 0.12 C, 0.50 Mn, 0.16 Si, 0.004 P, 0.010 S, 0.0005 N. Austenitized at 925 °C (1695 °F) for 15 min. Grain size: 9.9. Source: Atlas of Time-Temp. Diagrams for Irons and Steels



1010: Carbonitriding. Effect of carbonitriding temperature on dimensional stability of three 1010 steel production parts. Parts were carbonitrided to produce a case depth of 0.13 to 0.20 mm (0.005 to 0.008 in.) with minimum surface hardness of 89 HR15N. Gas ratios and dew points were essentially the same for all temperatures. Time at temperature was 15 to 45 min, depending on temperature. ID, inside diameter. Part dimensions and tolerances given in inches





1010: Cyanide-noncyanide Treatments. Comparison of compound zone thickness produced by low-cyanide and cyanide-based treatments containing sulfur

1012

Chemical Composition. AISI and UNS: 0.10 to 0.15 C, 0.30 to 0.60 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). UNS G10120; ASTM A510, A519, A545, A549, A575, A576; MIL SPEC MIL-S-11310 (CS1012); SAE J403, J412, J414

Characteristics. Extremely ductile in the normalized or annealed condition and often subjected to severe cold reduction, accounting for excellent cold formability. However, as the carbon content increases the cold formability decreases, slightly reducing the severity it can withstand in cold forming. Therefore, this steel is best suited for production of stampings, where the amount of drawing is minimal. Weldability and brazing results are excellent. Machinability is poor

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Cool in still air

Annealing. For clean surfaces, heat to approximately 885 °C (1625 °F) in a lean exothermic atmosphere. Cool in the cooler section of a continuous furnace

Case Hardening. Carbonitride at 760 to 870 °C (1400 to 1600 °F) in an enriched endothermic carrier gas, plus about 10% anhydrous ammonia. Case depths range from 0.076 to 0.254 mm (0.003 to 0.01 in.). Oil quenching directly from carbonitriding temperature provides maximum surface hardness. Salt baths produce similar results. Flame hardening is an alternative process

1013

Chemical Composition. AISI and UNS: 0.11 to 0.16 C, 0.50 to 0.80 Mn, 0.040 P max, 0.050 S max

Recommended Heat Treating Practice

Case Hardening. Flame hardening and carbonitriding are suitable processes

1015

Chemical Composition. AISI and UNS: 0.13 to 0.18 C, 0.30 to 0.60 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). UNS G10150; AMS 5060; ASTM A510, A519, A545, A549, A575, A576, A659; FED QQ-S-698 (C1015); MIL SPEC MIL-S-16974; SAE J403, J412, J414; (Ger.) DIN 1.1141; (Fr.) AFNOR X C 15, X C 18; (Jap.) JIS S 15 C, S 17 C, S 15 CK; (Swed.) SS_{14} 1370

Characteristics. Sometimes considered a borderline grade of steel. Carbon content is high for best cold formability and slightly low compared with grades of carbon steel used for most carburizing applications. Excellent forgeability, reasonably good cold formability, and excellent weldability. Machinability is relatively poor compared with the 1100 and 1200 grades

Forging. Heat to 1290 °C (2355 °F). Do not forge below 925 °C (1695 °F)

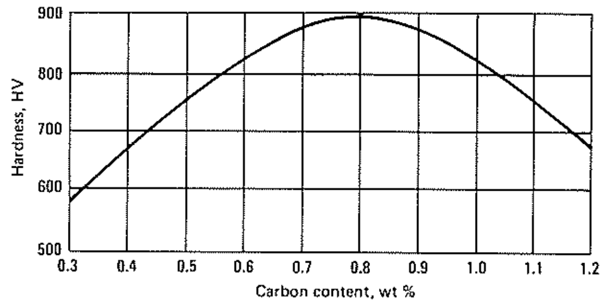
Recommended Heat Treating Practice

Normalizing. Heat to 915 °C (1680 °F). Air cool

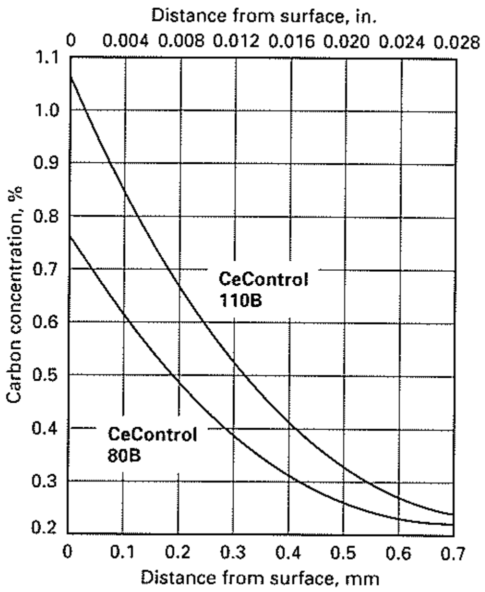
Annealing. Heat to 885 °C (1625 °F). Cool slowly, preferably in a cooler or by furnace cooling

Hardening. May be case hardened by carburizing. (See procedure for 1020.) More often, it is subjected to light case hardening by carbonitriding or casing in a liquid bath. (See procedure for 1008 steel.) Flame hardening, gas nitriding, and electron beam hardening are alternative processes. In many instances, forgings of this grade are used in service either as forged or as forged and normalized

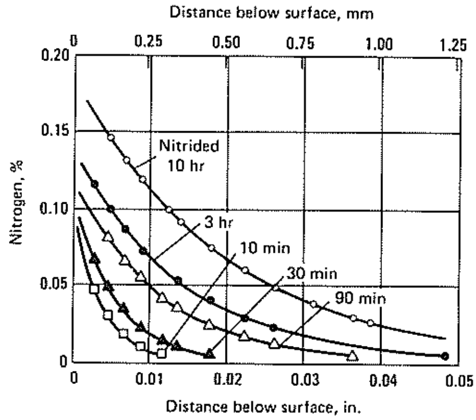
1015: Maximum Case Hardness vs Carbon Content



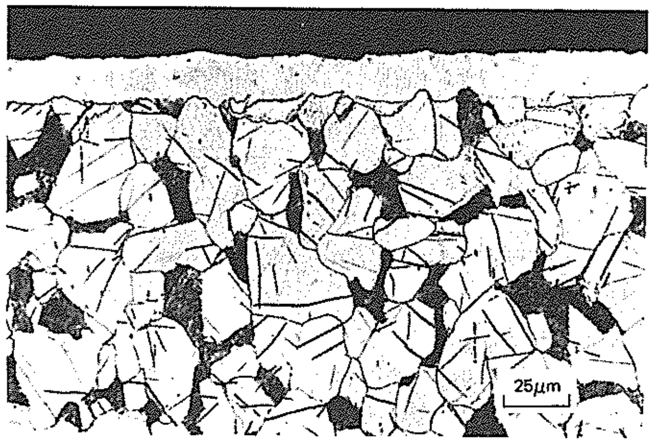
1015: Liquid Carburizing. Plots of carbon concentration versus carbon penetration for 1015 steels that were carburized at 930 °C (1705 °F) for 1 h with two different Durofer process base salt regenerators



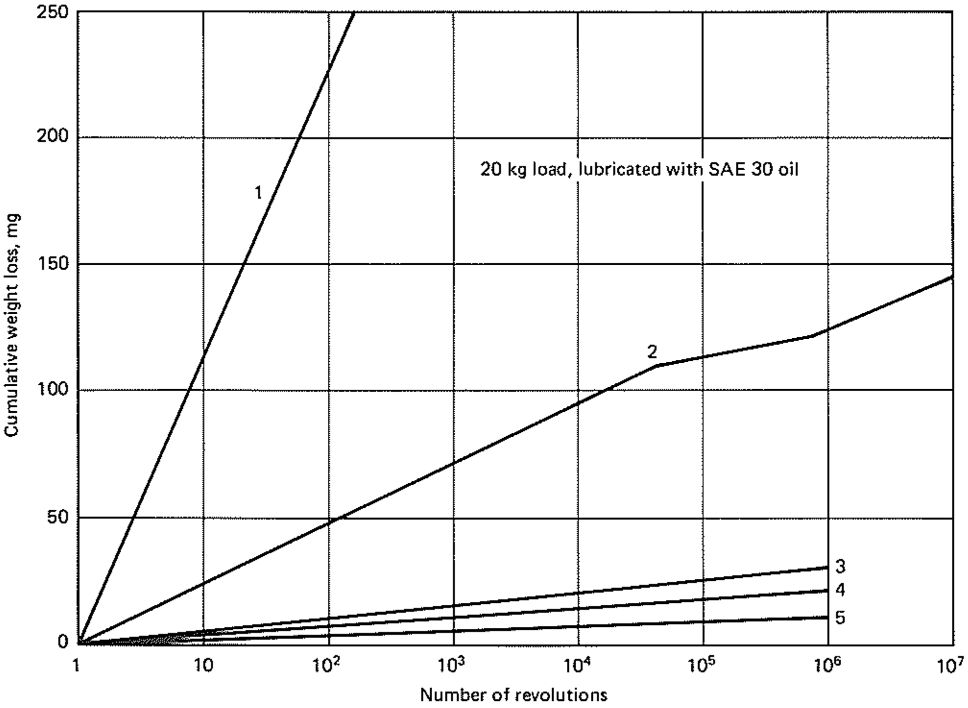
1015: Nitriding. At 565 °C (1050 °F), using aerated bath process



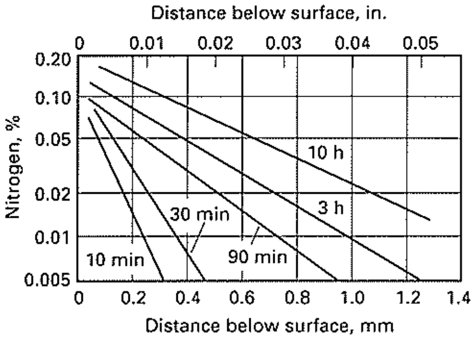
1015: Microstructure. The metallographic appearance of AISI 1015 material after a 2-h vacuum-nitrocarburizing treatment in an ammonia/methane mixture with 1% oxygen addition



1015: Gas Nitriding. Comparative Amsler wear tests on AISI 1015 after various ferritic nitrocarburizing treatments. 1, untreated; 2, cyanide-based salt bath nitrocarburizing with sulfur; 3, subatmospheric oxynitrocarburizing; 4, gaseous nitrocarburizing; and 5, cyanide-based salt bath nitrocarburizing (treatment 1)



1015: Liquid Nitriding. Nitrogen diffusion in AISI 1015 steel



1016

Chemical Composition. **AISI and UNS:** 0.13 to 0.18 C, 0.60 to 0.90 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). UNS G10160; ASTM A108, A510, A513, A545, A548, A549, A576, A659; MIL SPEC MIL-S-866; SAE J403, J412, J414; (Ger.) DIN 1.0419

Characteristics. Carbon content is high for best cold formability and slightly low compared with the grades of carbon steel used for most carburizing applications. Excellent forgeability, reasonably good cold formability and excellent weldability. Machinability is relatively poor compared with the 1100 and 1200 grades

Forging. Heat to 1290 °C (2355 °F). Do not forge below 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Air cool

Annealing. Heat to 885 °C (1625 °F). Cool slowly, preferably in a cooler or by furnace cooling

Hardening. May be case hardened by carburizing. (See procedure for 1020.) More often, it is subjected to light case hardening by carbonitriding or casing in a liquid bath. (See procedure for 1008 steel.) Flame hardening is an alternative process. In many instances, forgings of this grade are used in service either as forged or as forged and normalized

1017

Chemical Composition. **AISI and UNS:** 0.15 to 0.20 C, 0.30 to 0.60 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). UNS G10170; ASTM A108, A510, A513, A519, A544, A549, A575, A576, A659; MIL SPEC MIL-S-11310 (CS 1017); SAE J403, J412, J414; (Ger.) DIN 1.1141; (Fr.) AFNOR X C 15, X C 18; (Jap.) JIS S 15 C, S 17 C, S 15 CK; (Swed.) SS14 1370

Characteristics. Excellent forgeability, reasonably good cold formability and excellent weldability. As carbon content increases, strength also increases, accompanied by a small decrease in cold formability. Machinability is relatively poor compared with the 1100 and 1200 grades

Forging. Heat to 1275 °C (2325 °F). Do not forge below 910 °C (1670 °F)

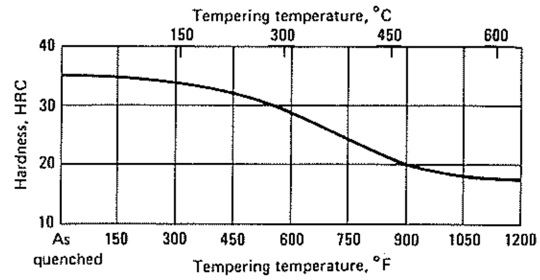
Recommended Heat Treating Practice

Normalizing. Heat to 885 °C (1625 °F). Air cool

Annealing. Heat to 885 °C (1625 °F). Cool slowly, preferably in a cooler or by furnace cooling

Hardening. May be case hardened by carburizing. (See procedure for 1020.) More often, it is subjected to light case hardening by carbonitriding or casing in a liquid bath. (See procedure for 1008 steel.) Flame hardening is an alternative process. In many instances, forgings of this grade are used in service either as forged or as forged and normalized

1017 Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure (no case hardening)



1018

Chemical Composition. **AISI and UNS:** 0.15 to 0.20 C, 0.60 to 0.90 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). UNS G10180; AMS 5069; ASTM A108, A510, A513, A519, A544, A545, A548, A549, A576, A659; MIL SPEC MIL-S-11310 (CS1018); SAE J403, J412, J414

Characteristics. Excellent forgeability, reasonably good cold formability, and excellent weldability. As carbon content increases, strength also increases, accompanied by a small decrease in cold formability. Machinability is relatively poor compared with the 1100 and 1200 grades. The slightly higher manganese (compared with 1017) provides a slight increase in strength in the normalized or annealed condition. Higher manganese also provides for a mild increase of hardenability for case hardened parts

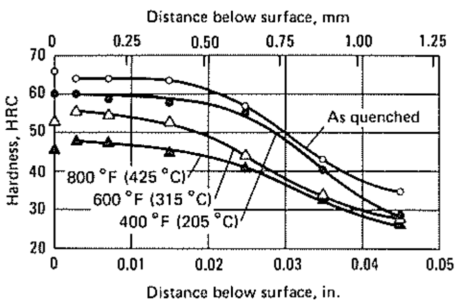
Forging. Heat to 1275 °C (2325 °F). Do not forge below 910 °C (1670 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Air cool

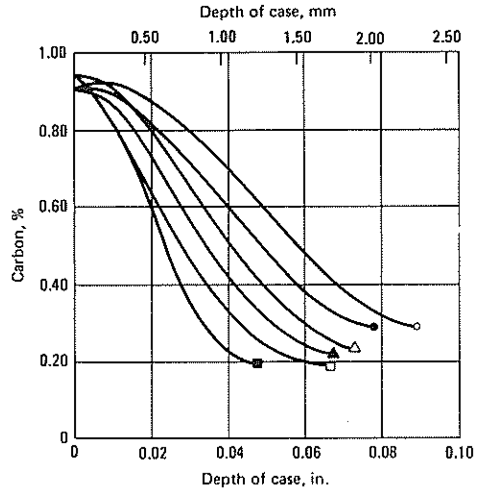
Annealing. Heat to 885 °C (1625 °F). Cool slowly, preferably in a cooler or by furnace cooling

Hardening. May be case hardened by liquid or gas carburizing, or by flame hardening. (See procedure for 1020.) Quenchants include aqueous polymers. More often, it is subjected to light case hardening by carbonitriding or casing in a liquid bath. (See procedure for 1008 steel.) In many instances, forgings of this grade are used in service either as forged or as forged and normalized. Grade 1018 is used to a considerable extent for carburizing to deep case depths



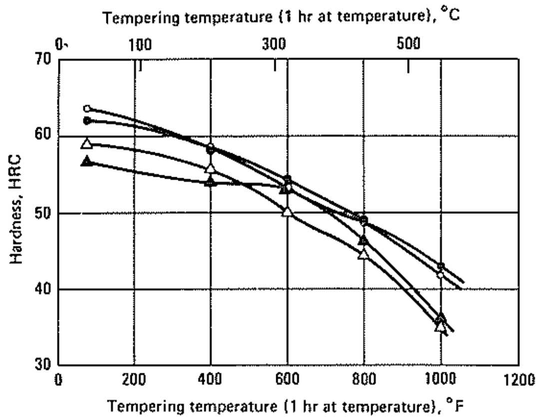
1018: Carburized, Oil Quenched, and Tempered. 12.7-mm (0.5-in.) diam bar, carburized at 925 °C (1695 °F) for 4 1/2 h, oil quenched, and tempered at indicated temperatures

1018: Carburizing Temperature vs Depth of Case. Treated 3 h at temperature. Endothermic gas atmosphere, enriched with natural gas. Carbon potential automatically controlled by dew point method, producing 0.90 to 0.95% surface carbon.



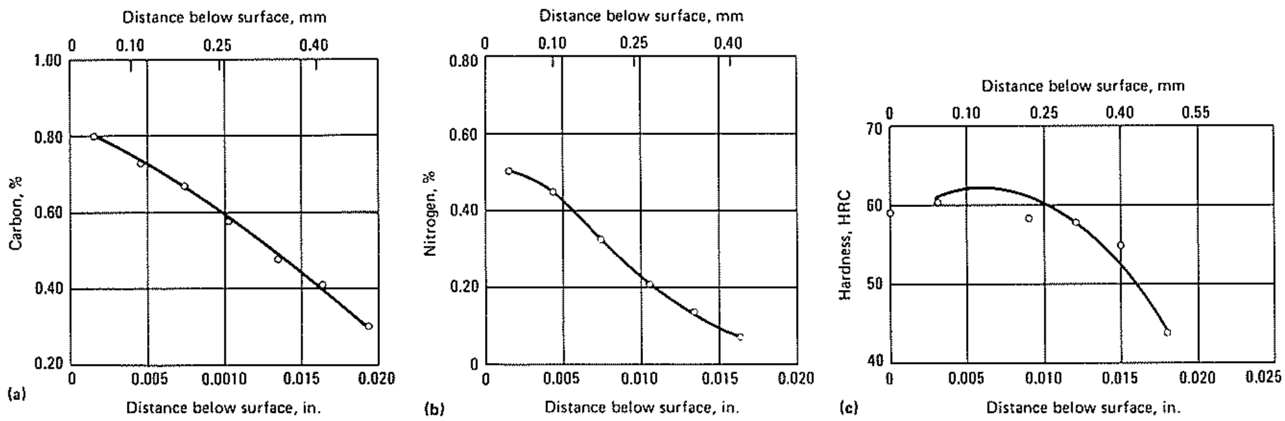
Symbol	Carburizing temperature °F	Carburizing temperature °C	Dew point °F	Dew point °C
○	1950	1065	−7 to −5	−22 to −21
●	1900	1040	−2 to 0	−19 to −18
△	1850	1010	+2 to +14	−17 to −10
▲	1800	980	+6 to +9	−14 to −13
□	1750	955	+11 to +13	−12 to −10
■	1700	925	+14 to +15	−10 to −9

1018: Hardness vs Tempering Temperature. Decrease of surface hardness with increasing tempering temperature. Rockwell C converted from Rockwell 30-N. Carbonitrided 2 1/2 h

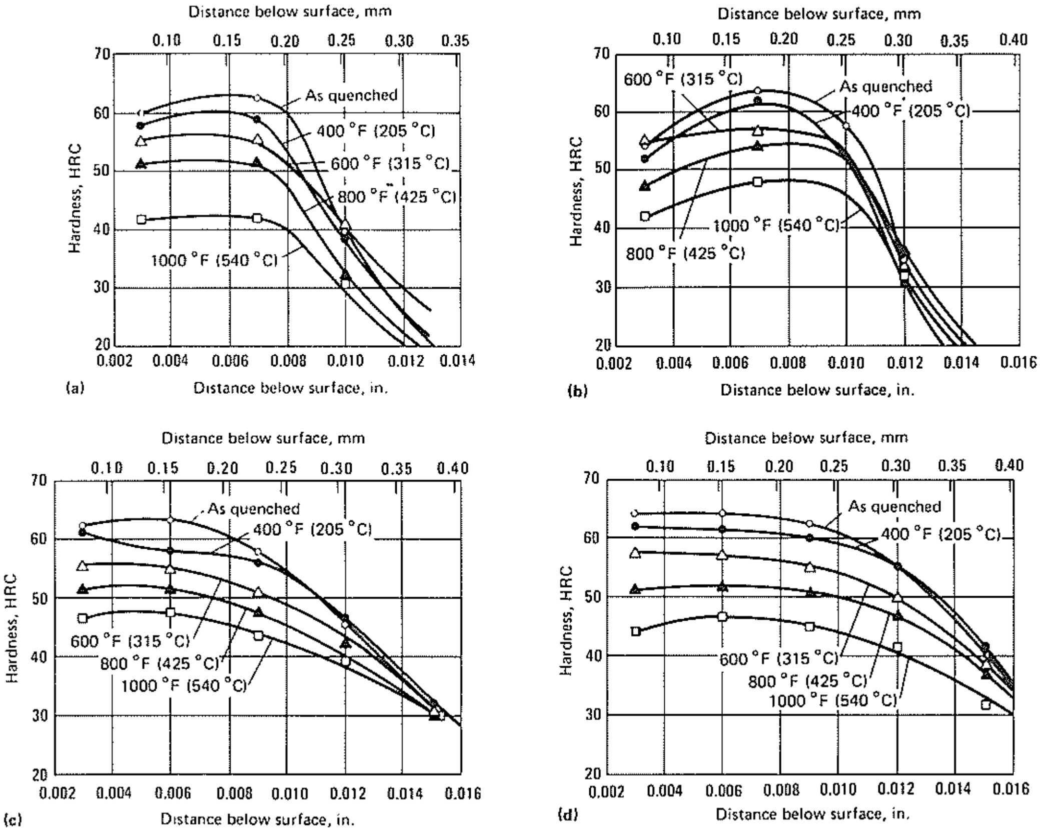


Symbol	Tempering temperature °F	Tempering temperature °C	NH_3, %
○	1550	845	5
●	1550	845	10
△	1450	790	5
▲	1450	790	10

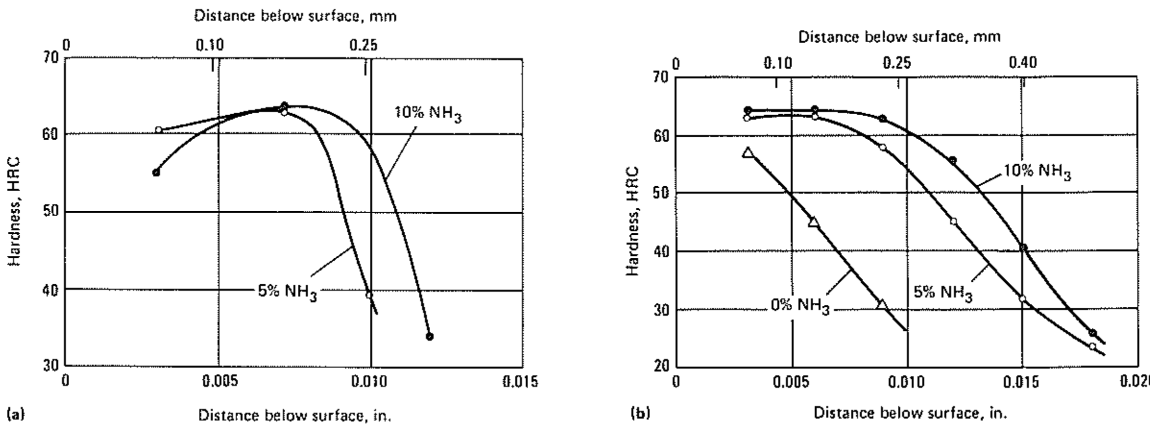
1018: Carbon, Nitrogen, and Hardness Gradients. Carbonitrided at 845 °C (1555 °F), 4 h. Oil quenched at 55 °C (130 °F). Hardness converted from Tukon

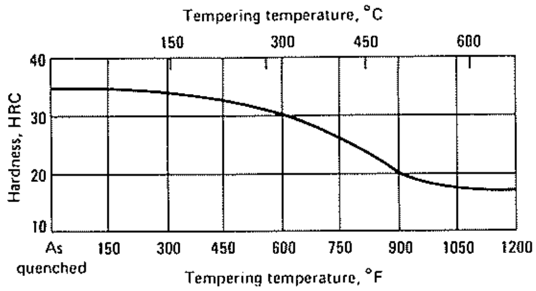


1018: Effect of Tempering Temperature on Hardness Gradients. Tempered 1 h at temperature. Rockwell C hardness converted from Vickers. (a) Carbonitrided at 790 °C (1455 °F) , 2 1/2 h; 5% NH_3. (b) Carbonitrided at 790 °C (1450 °F), 2 1/2 h; 10% NH_3. (c) Carbonitrided at 845 °C (1555 °F), 2 1/2 h; 5% NH_3. (d) Carbonitrided at 845 °C (1555 °F), 2 1/2 h; 10% NH_3



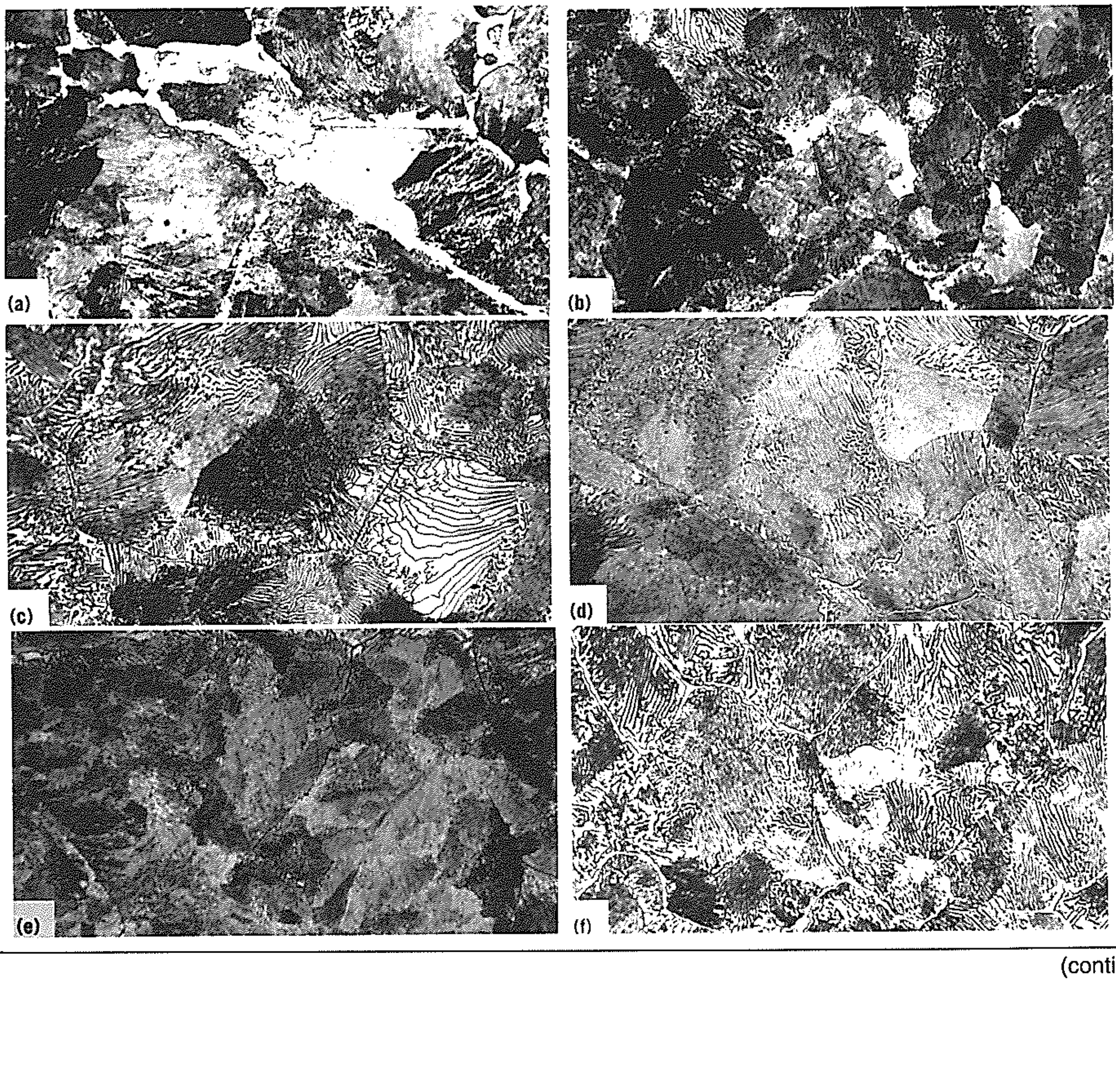
1018: Effect of Ammonia in Carbonitriding Gas on Hardness Gradient. (a) Carbonitrided at 790 °C (1450 °F), 2 1/2 h. (b) Carbonitrided at 845 °C (1555 °F), 2 1/2 h. Hardness converted from Vickers





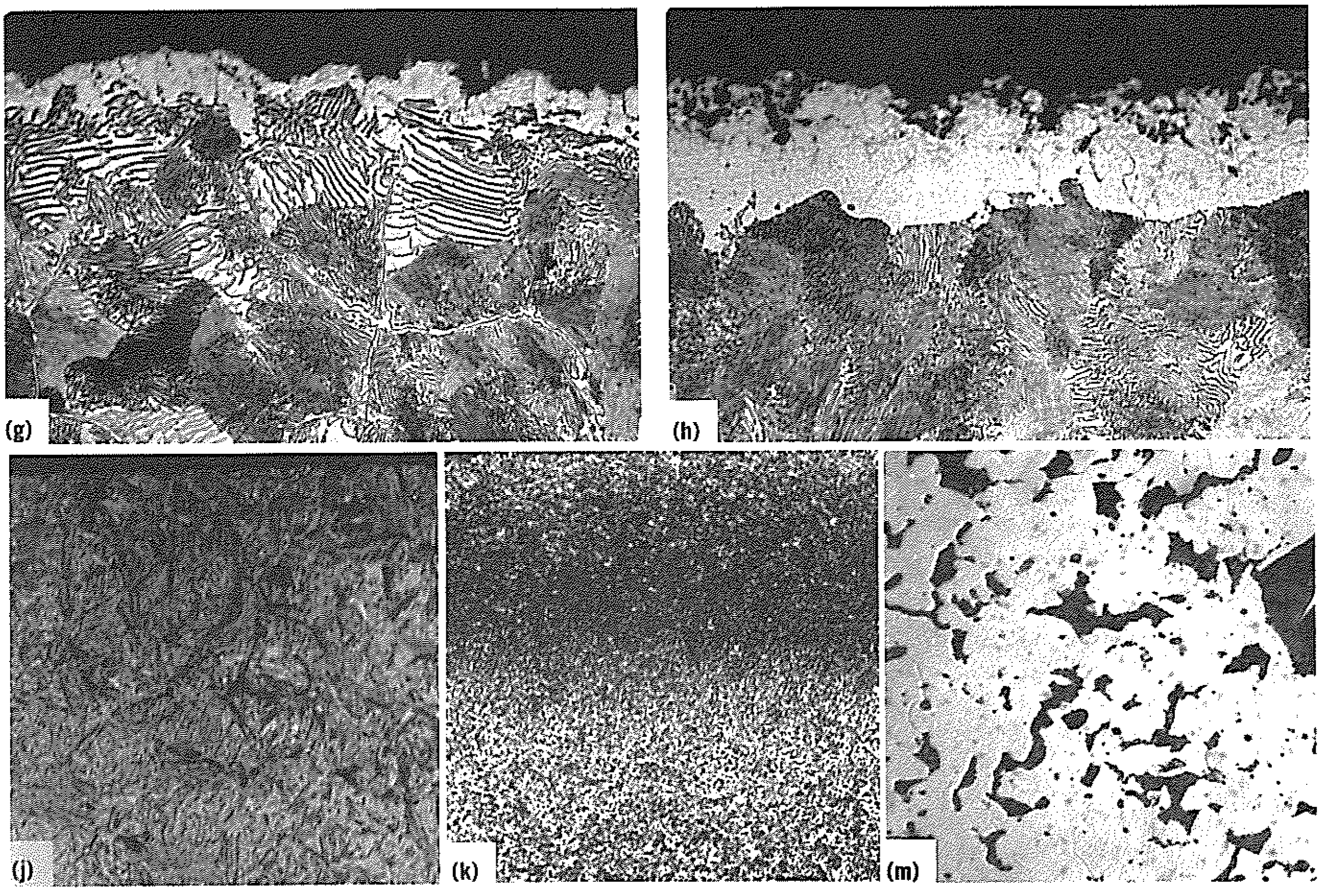
1018: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure (no case hardening)

1018: Microstructures. (a) 1% nital, 500×. Carburized 8 h. Surface carbon content, 0.60 to 0.70%. Ferrite (light areas), outlining prior austenite grain boundaries, and pearlite (dark areas). (b) 1% nital, 500×. Carburized 4 h. Surface carbon, 0.70 to 0.80%; wholly pearlitic. Below surface, dark areas are pearlite. Areas of ferrite outline prior austenite grain boundaries. (c) 1% nital, 500×. Carburized 6 h. Surface carbon, 0.90 to 1.00%. Thin film of carbide outlines prior austenite grain boundaries in matrix of pearlite. (d) 1% nital, 500×. Carburized 16 h. Surface carbon, 1.00 to 1.10%. Surface layer, carbide. Below surface, thin film of carbide outlines prior austenite grain boundaries in pearlite matrix. (e) 1% nital, 500×. Carburized 18 h in continuous furnace. Cooled under atmosphere in furnace vestibule. Partly separated layer of carbide (approximately 0.90% carbon) covers pearlite matrix. (f) 1% nital, 500×. Carburized 12 h. Surface carbon, approximately 1.10%. Carbide surface layer. Film of carbide outlines prior austenite grain boundaries in pearlite matrix



(continued)

1018: Microstructures (continued). (g) 1% nital, 500×. Gas carburized, 5 h; 925 °C (1700 °F), pit-type furnace with air leak. Furnace cooled to 540 °C (1000 °F) in 2 h 10 min. Air cooled to room temperature. Thin decarburized layer (ferrite), caused by furnace leak, covers surface. Matrix is pearlite, with carbide at prior austenite grain boundaries. (h) 1% nital, 500×. Gas carburized, furnace cooled, and cooled to room temperature under same conditions as (g), except furnace leak was more severe. Decarburized layer (ferrite) caused by leak is thicker and covers matrix of pearlite. Carbon has diffused from grain boundaries. (j) 3% nital, 200×. Carbonitrided, 4 h; 845 °C (1551 °F) in 3% ammonia. Propane, 6%; remainder, endothermic gas. Oil quenched. Cooled to −74 °C (−100 °F). Tempered 1 1/2 h at 150 °C (300 °F). Tempered martensite; some bainite. (k) Nital, 100×. Carbonitrided 4 h; 845 °C (1555 °F). Oil quenched; not tempered. Stabilized by subzero temperature. Normal case structure for carbon steel. Contains martensite, carbide particles, and small amount of retained austenite. (m) Picral, 200×. Annealed by austenitizing at 885 °C (1625 °F), 2 h. Cooled in furnace. Fully annealed structure consists of patches of pearlite (dark areas) in matrix of ferrite (light areas)



1019

Chemical Composition. AISI and UNS: 0.15 to 0.20 C, 0.70 to 1.00 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). UNS G10190; ASTM A510, A513, A519, A545, A548, A576; SAE J403, J412, J414

Characteristics. Excellent forgeability, reasonably good cold formability, and excellent weldability. As carbon content increases, strength also increases, accompanied by a small decrease in cold formability. Machinability is relatively poor compared with the 1100 and 1200 grades. The slightly higher manganese (compared with 1018) provides a slight increase in strength and hardenability

Forging. Heat to 1275 °C (2325 °F). Do not forge below 910 °C (1670 °F)

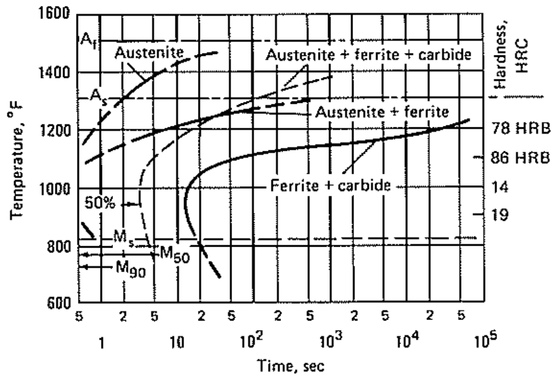
Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Air cool

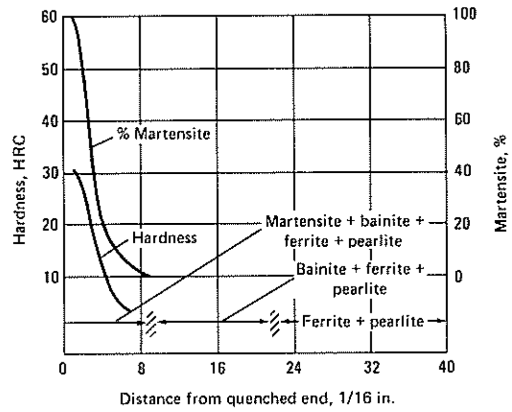
Annealing. Heat to 885 °C (1625 °F). Cool slowly, preferably in a cooler or by furnace cooling

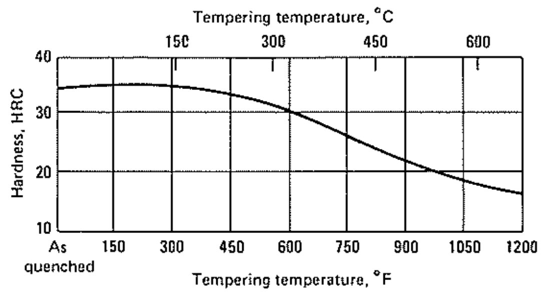
Hardening. May be case hardened by gas carburizing. (See procedure for 1020.) More often, it is subjected to light case hardening by carbonitriding or casing in a liquid bath. (See procedure for 1008 steel.) Flame hardening is an alternative process. In many instances, forgings of this grade are used in service either as forged or as forged and normalized

1019: Isothermal Transformation Diagram. Containing 0.17 C, 0.92 Mn. Austenitized at 1315 °C (2400 °F). Grain size, 0 to 2. Martensite temperatures estimated



1019: End-Quench Hardenability. 12.7 mm (0.5-in.) diam bar. 0.17 C, 0.92 Mn. Grain size, 0 to 2. Austenitized at 1315 °C (2400 °F). Quenched from 870 °C (1600 °F)





1019: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure (no case hardening)

1020

Chemical Composition. AISI and UNS: 0.18 to 0.23 C, 0.30 to 0.60 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). UNS G10200; AMS 5032, 5045; ASTM A510, A519, A544, A575, A576, A659; MIL SPEC MIL-S-11310 (CS1020); SAE J403, J412, J414; (Ger.) DIN 1.0402; (Fr.) AFNOR CC 20; (Ital.) UNI C 20; (Swed.) SS_{14} 1450; (U.K.) B.S. 040 A 20, 070 M 20

Characteristics. Most widely used of several similar grades containing about 0.20% carbon. Available in a variety of product forms. Excellent forgeability and weldability. Even with a maximum carbon content of 0.23%, no preheating or postheating required for the vast majority of welded structures. When most of the fabricating operations consist of some form of machining, this grade is not recommended because machinability is notably poor. Widely used as a carburizing steel

Forging. Heat to 1260 °C (2300 °F). Do not forge below 900 °C (1650 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Air cool

Annealing. Heat to 870 °C (1600 °F). Cool slowly, preferably in furnace

Hardening. Can be case hardened by any one of several processes, which range from light case hardening, such as carbonitriding and the others described for grade 1008, to deeper case carburizing in gas, solid, or liquid media. Most carburizing is done in a gaseous mixture of methane combined with one of several carrier gases, using the temperature range of 870 to 955 °C (1600 to 1750 °F). Carburize for desired case depth with a 0.90 carbon potential. Case depth achieved is always a function of time and temperature. For most furnaces, a temperature of 955 °C (1750 °F) approaches the practical maximum without causing excessive deterioration in the furnace. With the advent of vacuum carburizing, temperatures up to 1095 °C (2005 °F) can be used to develop a given case depth in about one half the time required at the more conventional temperature of 925 °C (1695 °F). Alternative processes are flame hardening, boriding, liquid nitriding, and plasma (ion) carburizing

Hardening After Carburizing is usually achieved using one of three procedures:

1. Quench directly into water or brine from the carburizing temperature
2. After the desired carburizing cycle has been completed, decrease the furnace temperature or use lower temperature zone of a continuous furnace to 845 °C (1555 °F) for a diffusion cycle. Quench in water or brine
3. Cool slowly to room temperature after carburizing. Reheat to 815 °C (1500 °F). Quench in water or brine

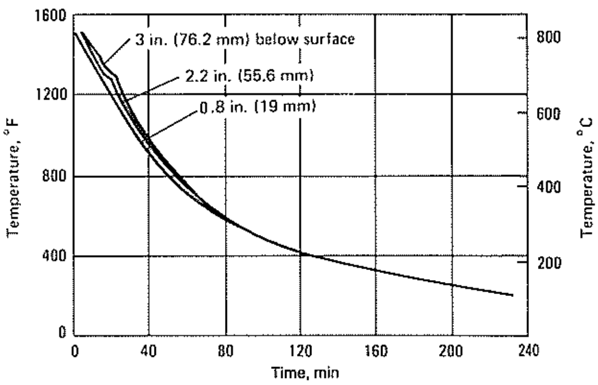
For rounds not over 6.35 to 9.53 mm (0.25 to 0.375 in.) diam, full hardness usually can be obtained by oil quenching. In carbonitriding, oil quenching will also provide full hardness. The liquid carburizing method using molten salt may also achieve relatively deep cases on 1020 and similar grades of carbon steel

empering. Although many carburized and hardened parts are placed in ervice without tempering, it is considered good practice to temper at 150 C (300 °F) or somewhat higher for 1 h if some sacrifice in hardness can e tolerated

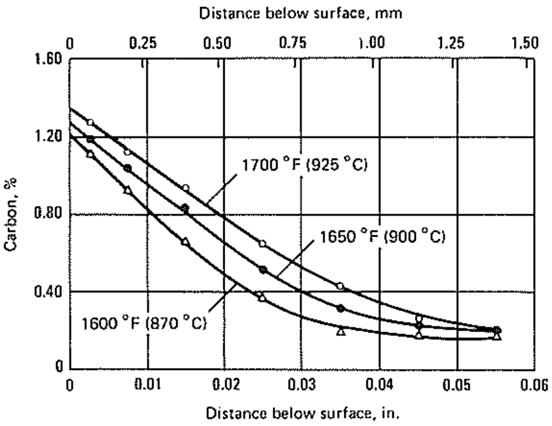
ecommended Processing Sequence

- Forge
- Normalize (omit for parts machined from bar stock)
- Rough machine and/or rough grind
- Semifinish machine and grind
- Carburize
- Lower temperature for diffusion cycle
- Quench
- Temper
- Finish grind (removing no more than 10% of the effective case per side)

1020: Normalizing. Effect of mass and section size on cooling curves obtained in still-air at 23 °C (73 °F). 152.4 mm (6 in.) diam. Approximately 64 kg (142 lb)



1020: Gas Carburizing. Carburized for 4 h in batch furnace



1020: Influence of Sodium Cyanide Concentration on Case Depth

25.4 mm (1 in.) diam bars, cyanided 30 min at 815 °C (1500 °F)

NaCN, %	Depth of case in.	Depth of case mm
94.3	0.0060	0.1524
76.0	0.0070	0.1778
50.8	0.0060	0.1524
43.0	0.0060	0.1524
30.2	0.0060	0.1524
20.8	0.0055	0.1397
15.1	0.0050	0.1270
10.8	0.0040	0.1016
5.2	0.0020	0.0508

1020: Effect of Cyaniding Temperature and Time on Depth of Case

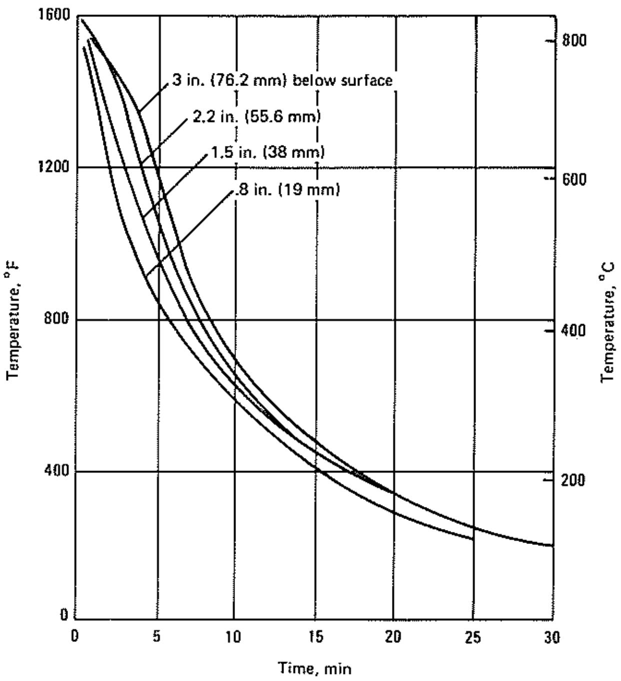
Depth of case		Cyaniding temperature	
in.	mm	°F	°C
Produced by immersion for 15 min			
0.00025	0.00635	1300	705
0.00135	0.03429	1400	760
0.00175	0.04445	1500	815
0.00320	0.08128	1600	870
Produced by immersion for 30 min			
0.00050	0.01270	1300	705
0.00250	0.06350	1400	760
0.00400	0.10160	1500	815
0.00480	0.12192	1600	870
Produced by immersion for 45 min			
0.00100	0.02540	1300	705
0.00375	0.09525	1400	760
0.00500	0.12700	1500	815
0.00600	0.15240	1600	870

1020: Effect of Cyaniding Mass on Depth of Case

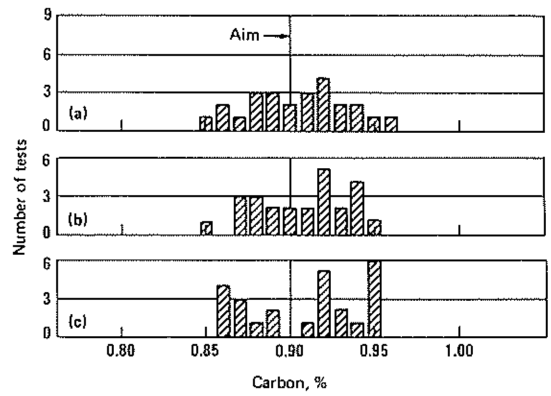
Steel cyanided at 815 °C (1500 °F)

Diameter of specimen		Case depth	
in.	mm	in.	mm
15-min immersion			
0.250	6.350	0.0045	0.1143
0.500	12.700	0.0035	0.0889
0.750	19.050	0.0030	0.0762
1.000	25.400	0.0027	0.0686
2.000	50.800	0.0025	0.0635
3.000	76.200	0.0023	0.0584
30-min immersion			
0.25	6.350	0.0045	0.1143
0.50	12.700	0.0035	0.0889
0.75	19.050	0.0030	0.0762
1.00	25.400	0.0027	0.0686
2.00	50.800	0.0025	0.0635
3.00	76.200	0.0023	0.0584

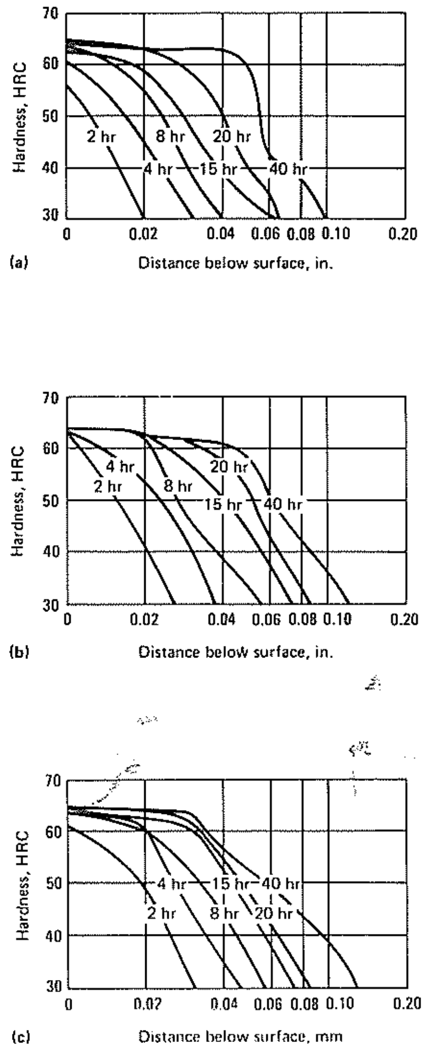
1020: Oil Quenching. Effect of mass and section size on cooling curves in oil quenching. Oil at 37 °C (99 °F). 152.4 mm (6 in.) diam. Approximately 64 kg (142 lb)



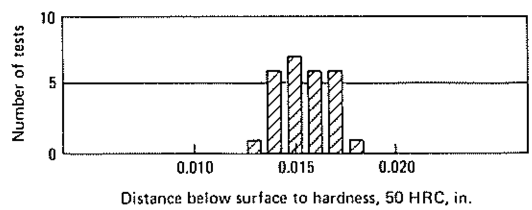
1020: Gas Carburizing. Variations of carbon content, 0.25 mm (0.010 in.) below the surface. Three similar batch furnaces (a, b, c) used. Twenty-five tests in each



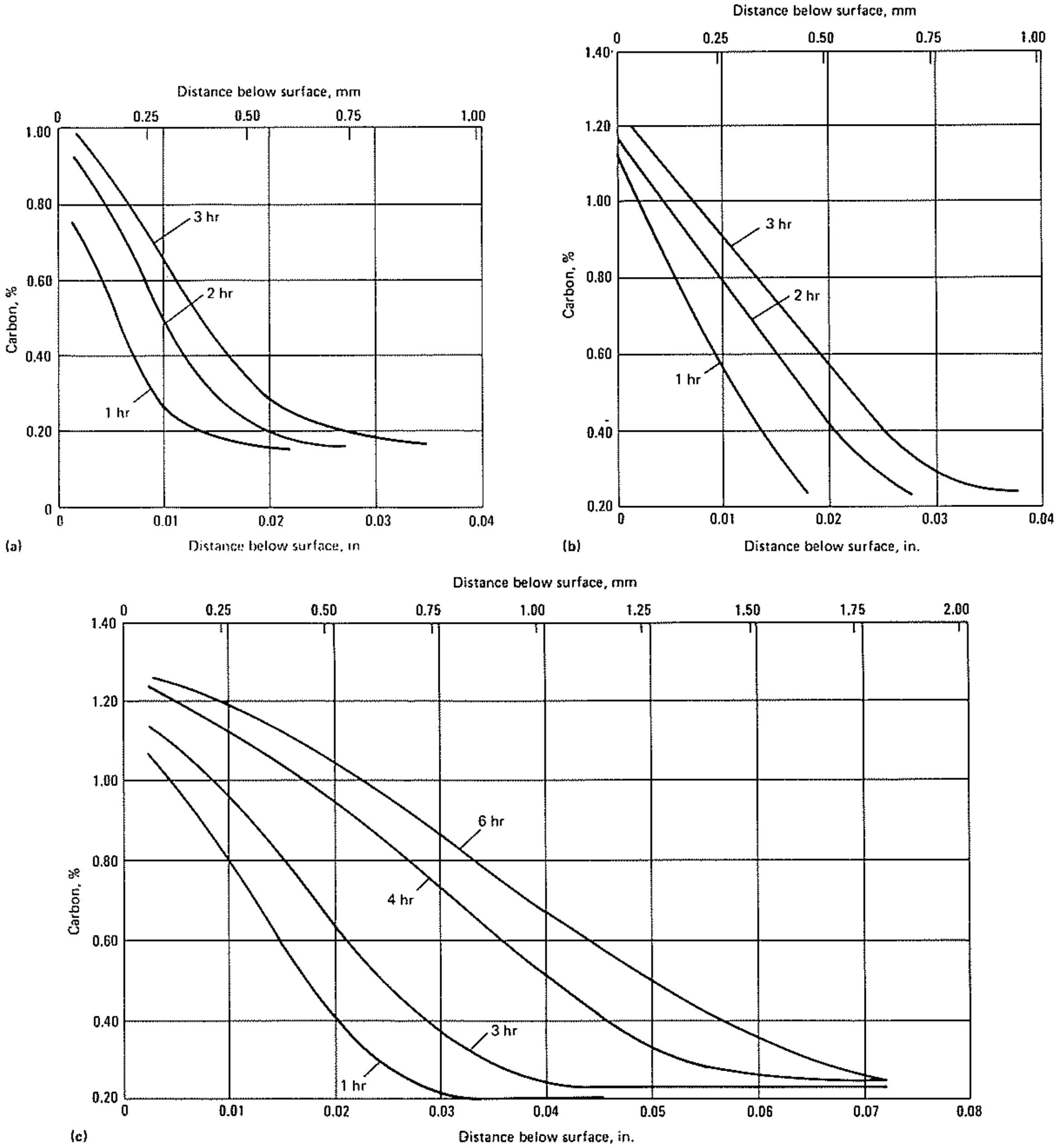
1020: Liquid Carburizing. Effect of carburizing temperature and time at temperature on case depth and case hardness gradient. Specimens 19.05 mm (0.75 in.) diam by 50.8 mm (2 in.). Liquid carburized, air cooled, reheated in neutral salt at 845 °C (1555 °F), and quenched in salt at 180 °C (355 °F). (a) Carburized at 870 °C (1600 °F). (b) 900 °C (1650 °F). (c) 925 °C (1695 °F)

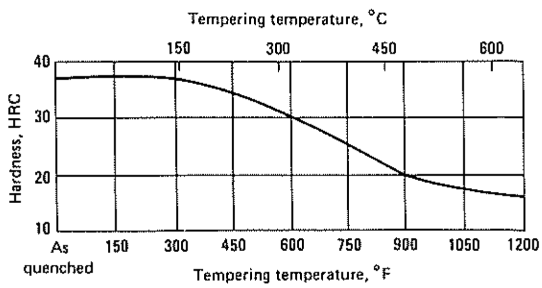


1020: Liquid Carburizing. Comparison of case depth and case hardness of 27 specimens, 11.1125 mm (0.4375 in.) diam by 6.35 mm (0.25 in.). Liquid carburized, 2 h, at 855 °C (1570 °F). Brine quenched and tempered, 150 °C (300 °F)



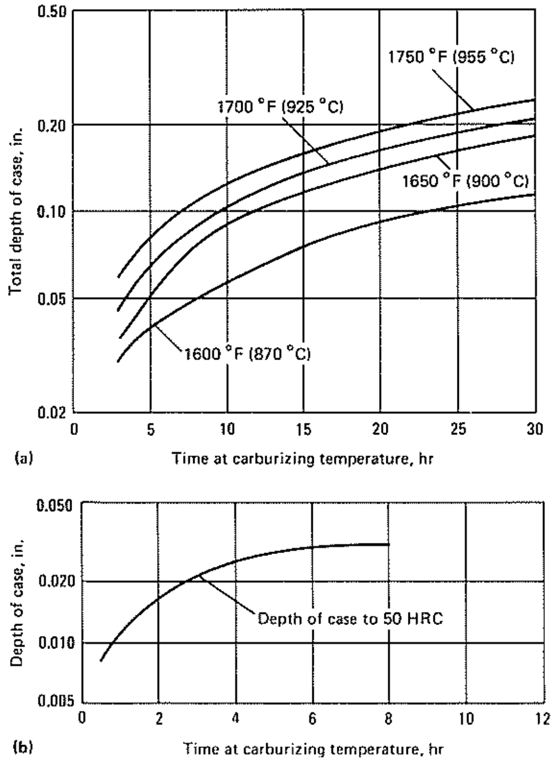
020: Liquid Carburizing. Carbon gradients produced in low- and high-temperature baths. 25.4 mm (1 in.) diam bar carburized, for time hown, at (a) 845 °C (1550 °F); (b) 870 °C (1600 °F); (c) 955 °C (1750 °F)



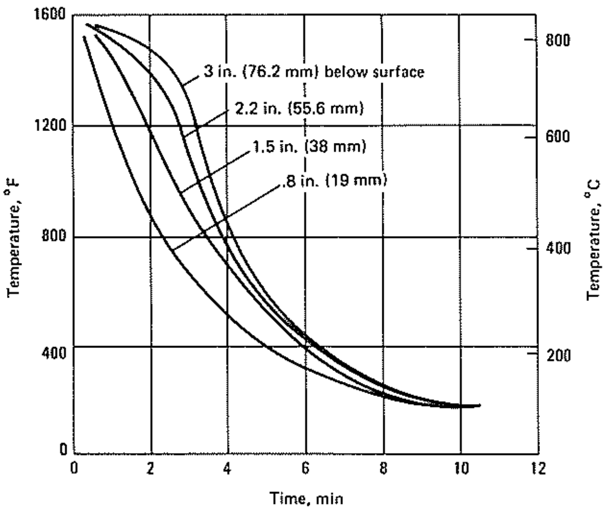


1020: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure (no case hardening)

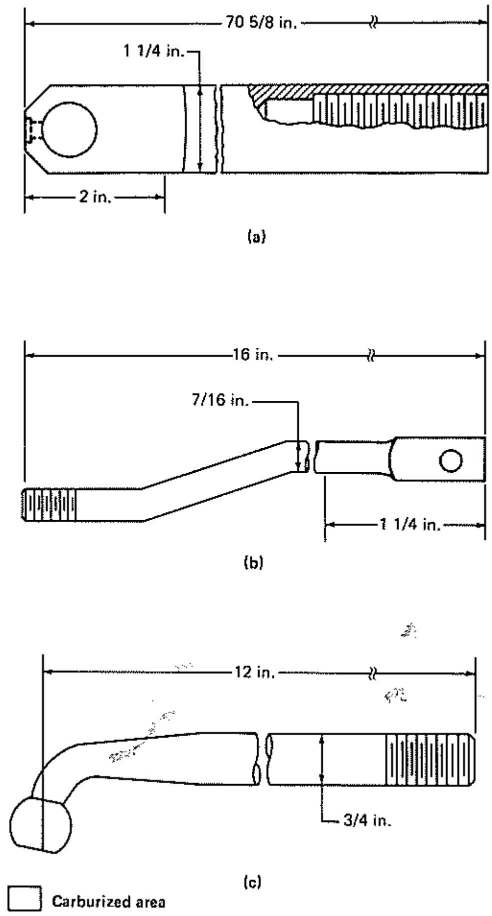
1020: Liquid Carburizing. Effect of time and temperature on case depth. (a) 25.4 mm (1 in.) outside diam by 152.4 mm (6 in.). Specimen carburized at temperature indicated. Oil quenched. (b) 11.1125 mm (0.4375 in.) diam by 6.35 mm (0.25 in.). Specimen carburized at 855 °C (1570 °F), brine quenched, and tempered at 150 °C (300 °F)



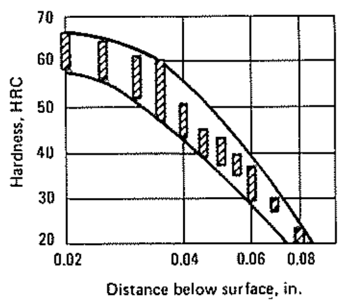
1020: Water Quenching. Effect of mass and section size on cooling curves in water quenching. Water at 46 °C (115 °F). No agitation. 152.4 mm (6 in.) diam. Approximately 64 kg (142 lb)



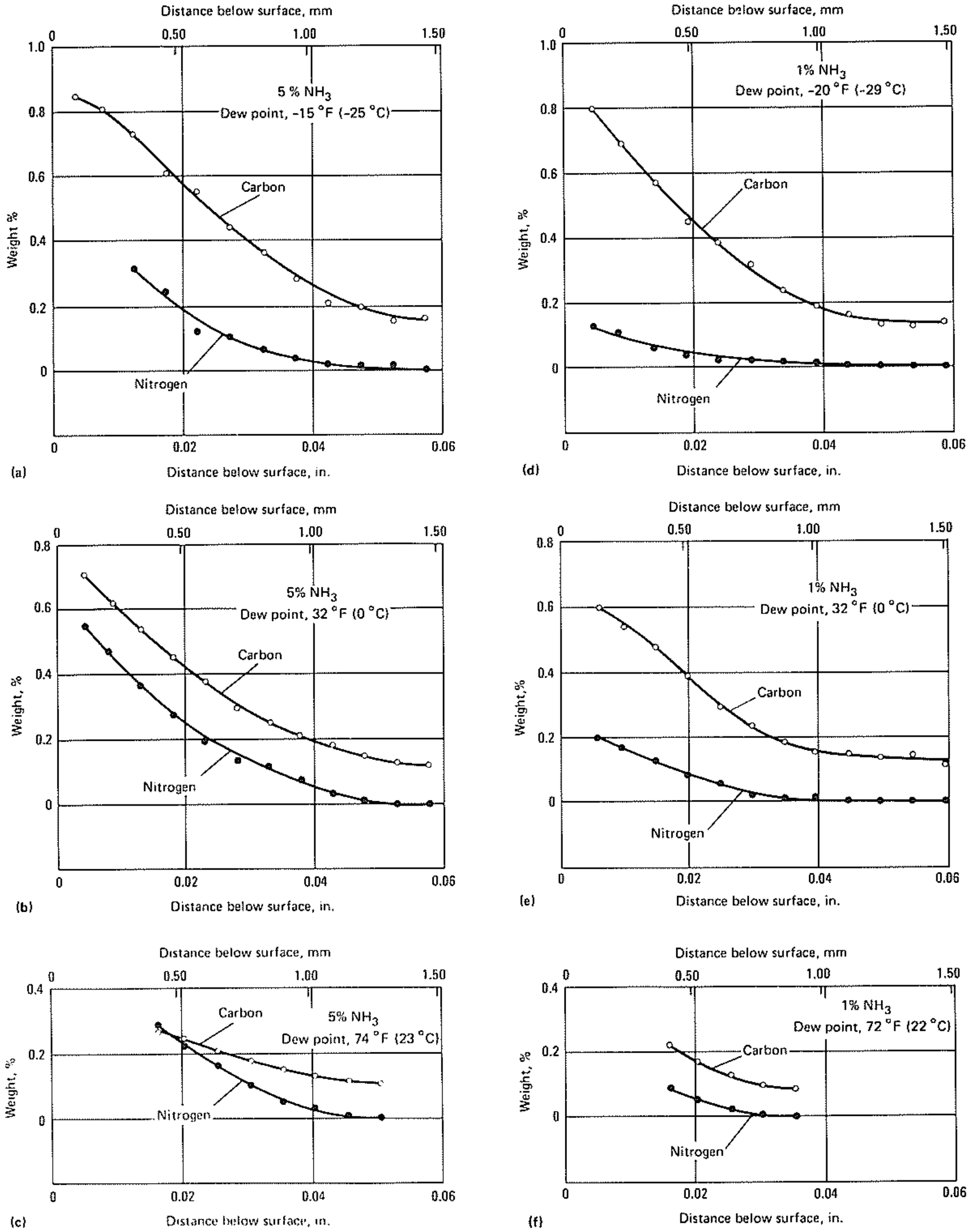
1020: Liquid Carburizing of Typical Parts. Selective carburizing by partial immersion. Only that portion to be carburized (shaded area) is immersed in bath. (a) Compression rod. Depth of case, 0.508 to 0.635 mm (0.020 to 0.025 in.). Hardness, 55 to 60 HRC. (b) Control linkage. Depth of case, 0.127 to 0.254 mm (0.005 to 0.010 in.). Hardness, 55 to 60 HRC. (c) Ball connecting rod. Depth of case, 0.254 to 0.381 mm (0.010 to 0.015 in.). Hardness, 55 to 60 HRC



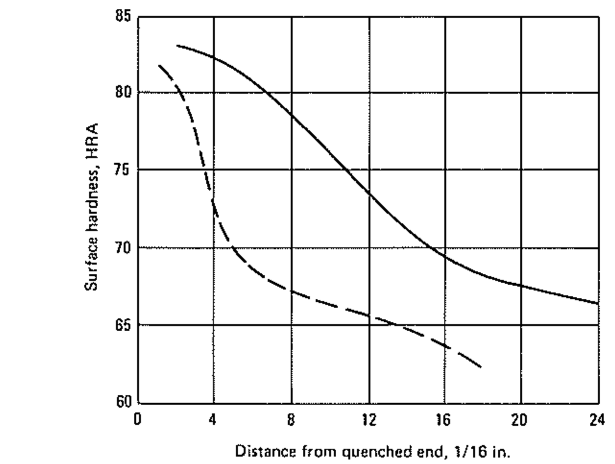
1020: Liquid Carburizing. Case hardness gradients, obtained in ten tests, showing scatter from normal variations



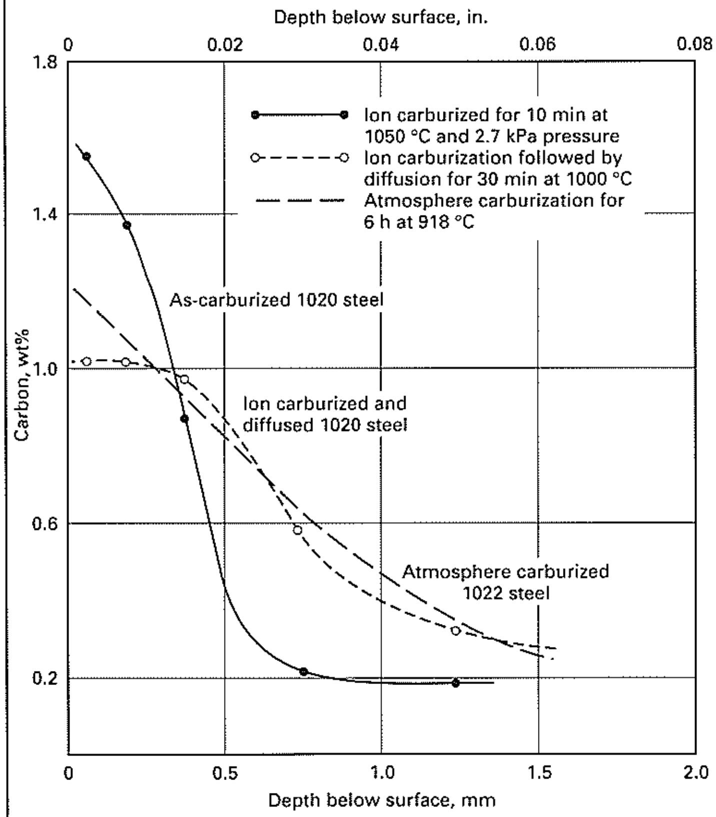
020: Gas Carbonitriding. Effects of ammonia concentration and inlet-gas dew point on carbon and nitrogen gradients. Carbonitrided at 45 °C (1555 °F), 4 h. Inlet gas: 5% methane; remainder, carrier gas. Air cooled. (a) 5% NH_3. Dew point, −26 °C (−15 °F). (b) 5% NH_3. Dew oint, 0 °C (+32 °F). (c) 5% NH_3. Dew point, +24 °C (+74 °F). (d) 1% NH_3. Dew point, −29 °C (−20 °F). (e) 1% NH_3. Dew point, 0 °C (+32 °F). f)) 1% NH_3. Dew point, +22 °C (+72 °F)



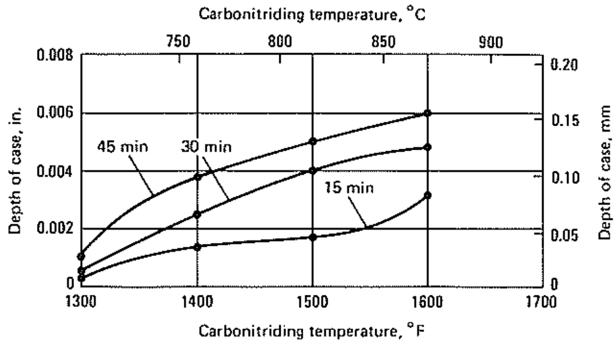
1020: End-Quench Hardenability: Carbonitriding and Carburizing. As-quenched hardenability measured along surface. Inlet carbonitriding atmosphere was 5% ammonia, 5% methane, and the remainder, carrier gas. Solid line: carbonitrided 4 h at 900 °C (1650 °F). Dotted line: carburized 3 h at 925 °C (1695 °F)



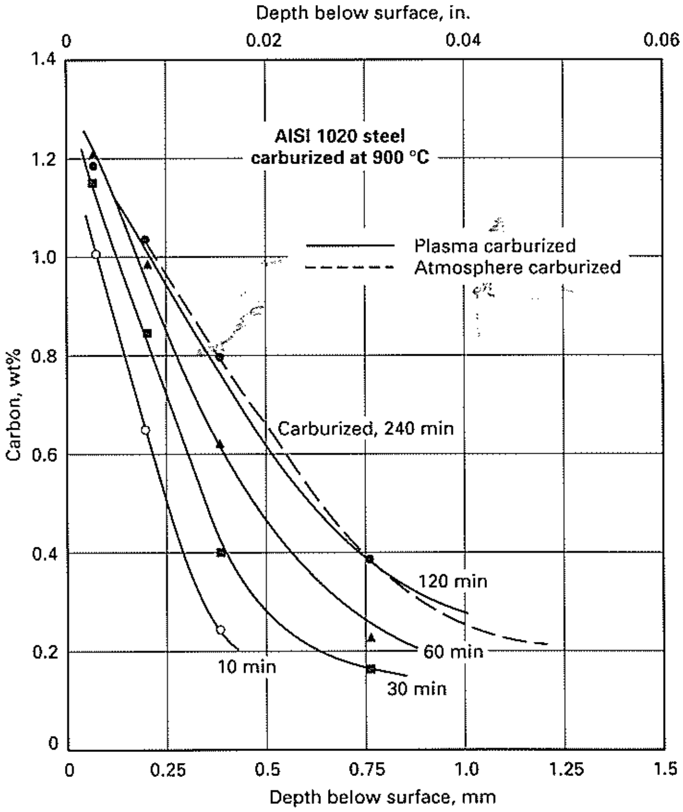
1020: Plasma (Ion) Carburizing. Carbon concentration profile in AISI 1020 steel after ion carburizing for 10 min at 1050 °C (1920 °F) followed by vacuum diffusing for an additional 30 min at 1000 °C (1830 °F). A similar carbon concentration profile is obtained by atmosphere carburizing for 6 h at 918 °C (1685 °F)



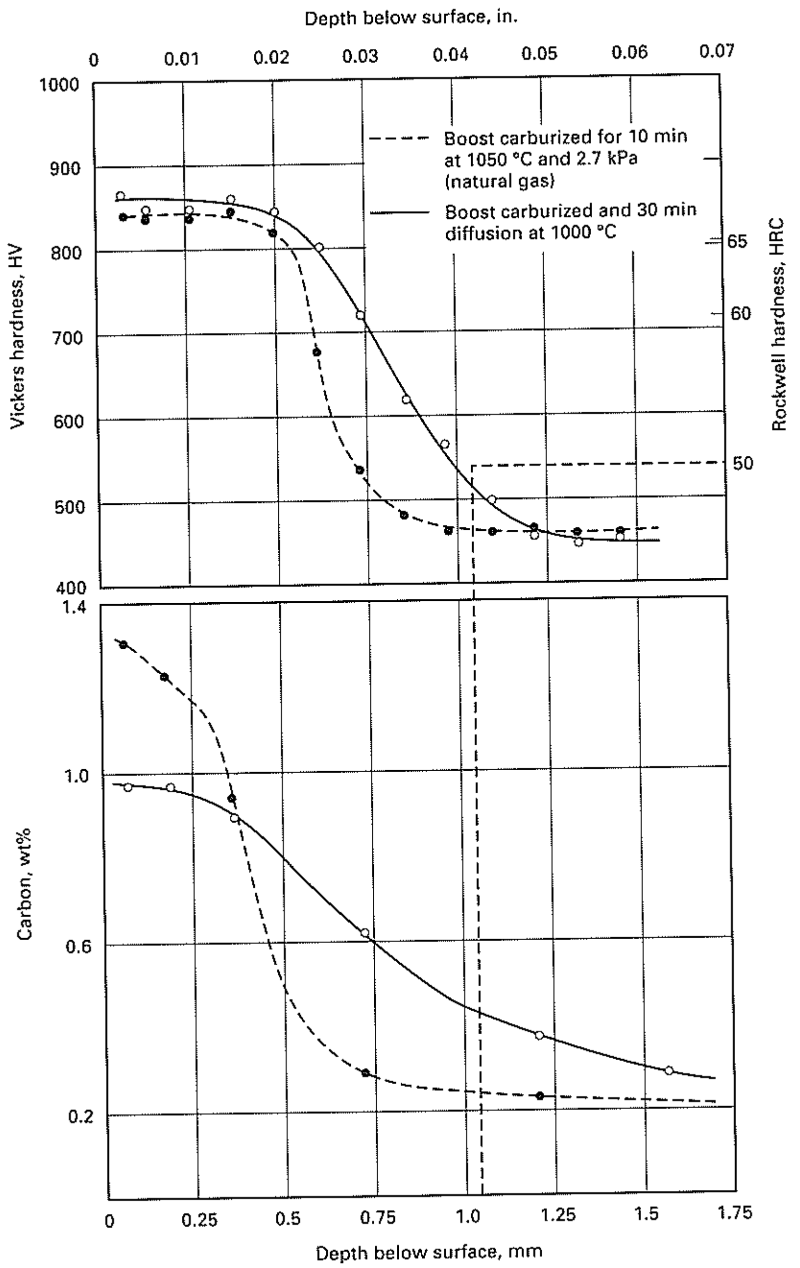
1020: Gas Carbonitriding. Effects of temperature and duration of carbonitriding on depth of case. Total furnace time indicated



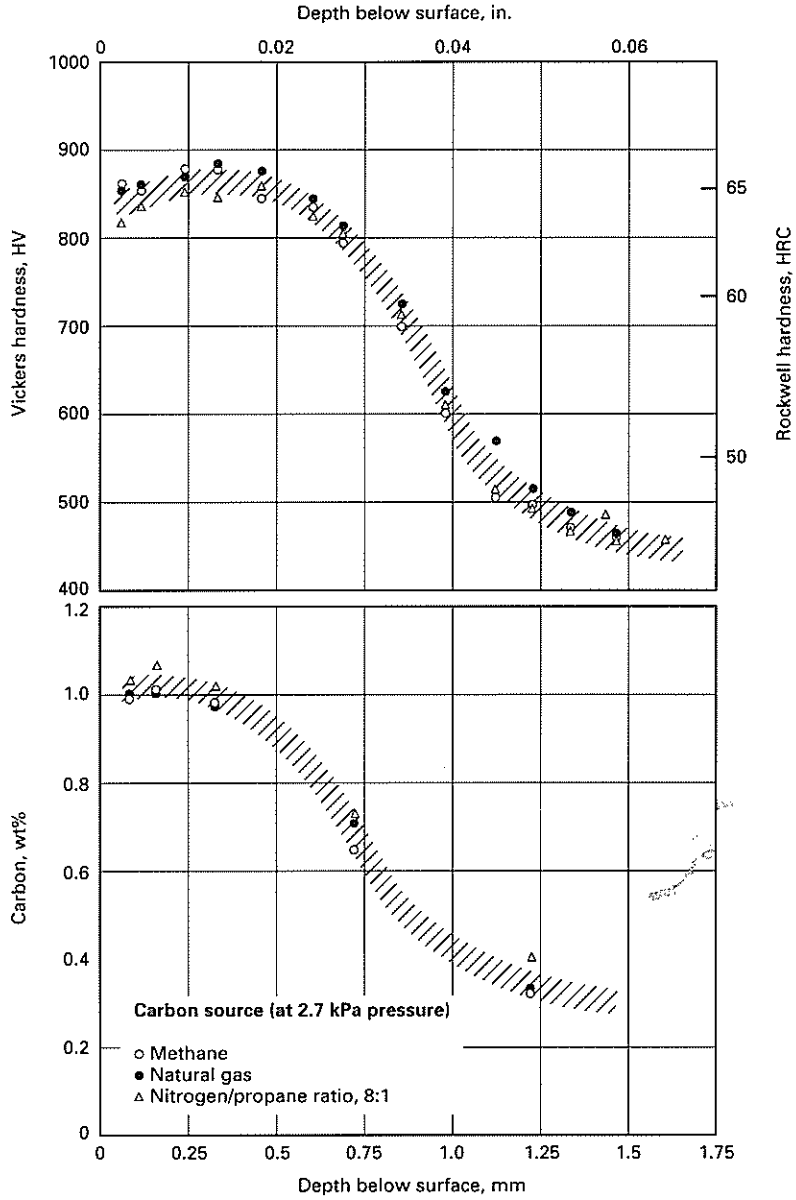
1020: Plasma (Ion) Carburizing. Carbon concentration profiles in AISI 1020 steel after ion carburizing for 10, 20, 30, 60, and 120 min at 900 °C (1650 °F). Carbon profile after atmosphere carburizing for 240 min at 900 °C (1650 °F) shown for comparison



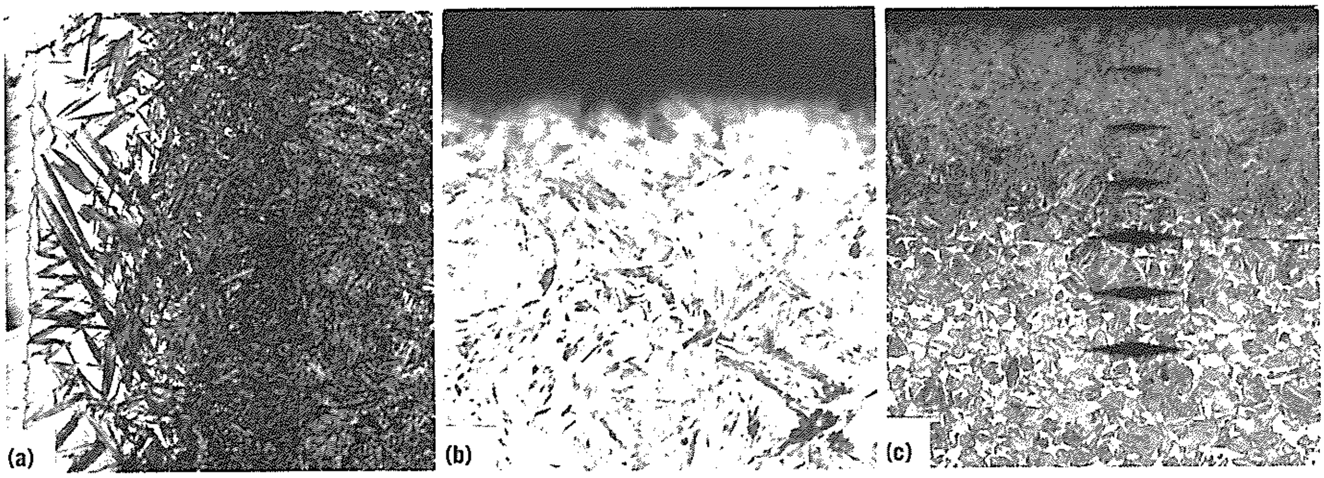
1020: Plasma (Ion) Carburizing. Carbon concentration and hardness profiles in AISI 1020 steel after ion carburizing for 10 min at 1050 °C 1920 °F) followed by additional vacuum diffusing for 30 min at 1000 °C (1830 °F). Effective case depth is indicated by dotted line



1020: Plasma (Ion) Carburizing. Carbon concentration and hardness profiles through cases on AISI 1020 steel after ion carburizing in methane, natural gas, and in 8:1 nitrogen/propane combination. Data are based on a boost-diffuse cycle of ion carburizing for 10 min at 1050 °C (1920 °F) followed by 30 min of diffusion at 1000 °C (1830 °F)



1020: Microstructures. (a) Nital, 500×. Carbonitrided and oil quenched, showing effect of too high a carbon potential. Outer white layer, ;ementite; followed by interlaced martensite needles in retained austenite. Martensite matrix on right. (b) 2% nital, 550×. Cyanided in salt ɔath, 845 °C (1555 °F), for 1 h. Water quenched. As-quenched condition shows coarse martensite with some carbide particles. Free of fer- ite. (c) 2% nital 100×. Same as (b), but lower magnification; showing case, transition, and core structures. Dark impressions are 500-g Tukon microhardness indentations, 0.0762 mm (0.003 in.) apart. Equivalent hardness, 61 HRC in case and 25.5 in core



1021

hemical Composition. AISI and UNS: 0.18 to 0.23 C, 0.60 to 90 Mn, 0.040 P max, 0.050 S max

imilar Steels (U.S. and/or Foreign). UNS G10210; ASTM 510, A519, A545, A548, A576, A659; SAE J403, J412, J414

haracteristics. Excellent forgeability and weldability. Even with a aximum carbon content of 0.23%, no preheating or postheating is re- ıired for the vast majority of welded structures. Machinability is notably ɔor. The slightly higher manganese content provides minor increases in rength and hardenability compared with 1020

orging. Heat to 1260 °C (2300 °F). Do not forge below 900 °C (1650 ᶠ)

ℓecommended Heat Treating Practice

ormalizing. Heat to 925 °C (1695 °F). Air cool

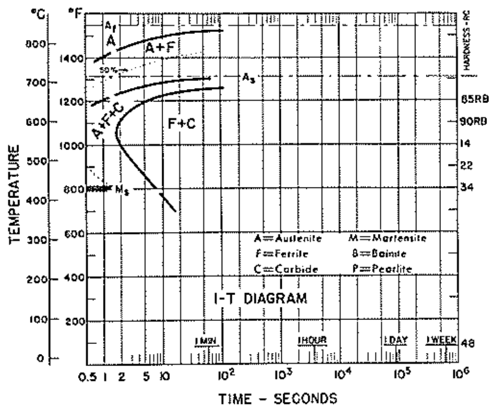
nnealing. Heat to 870 °C (1600 °F). Cool slowly, preferably in furnace

Hardening. Can be case hardened by any one of several processes, which range from light case hardening (by carbonitriding and salt bath nitriding described for grade 1008) to deeper case carburizing in gas, solid, or liquid media. (See carburizing process described for grade 1020)

Tempering. Optional. Temper at 150 °C (300 °F) for 1 h, or higher if some sacrifice of hardness can be tolerated

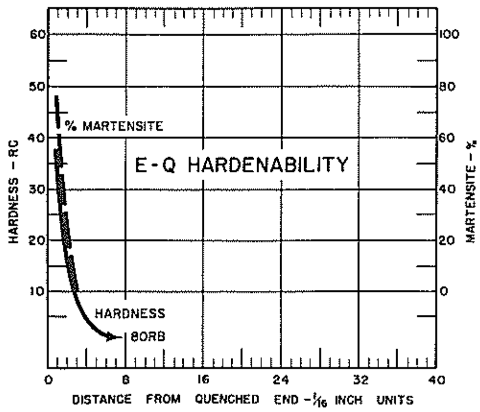
Recommended Processing Sequence

- Forge
- Normalize
- Rough machine
- Semifinish machine and grind
- Carburize
- Diffusion cycle
- Quench
- Temper
- Finish grind

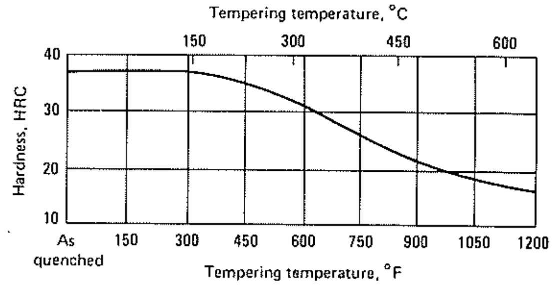


1021: Isothermal Transformation Diagram. 0.20 C, 0.81 Mn. Grain size, 8 to 9. Austenitized at 925 °C (1695 °F). Martensite temperatures, estimated

1021: End-Quench Hardenability. 12.7 mm (0.5 in.) diam bar. 0.17 C, 0.92 Mn. Grain size, 0 to 2. Austenitized at 1315 °C (2400 °F). Quenched from 870 °C (1600 °F)



1021: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure (no case hardening)



1022

Chemical Composition. **AISI and UNS:** 0.18 to 0.23 C, 0.70 to 1.00 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). UNS G10220; AMS 5070; ASTM A510, A519, A544, A545, A548, A576; MIL SPEC MIL-S-11310 (CS1020); SAE J403, J412, J414; (Ger.) DIN 1.1133; (Ital.) UNI G22 Mn 3; (Jap.) JIS SMnC 21

Characteristics. Excellent forgeability and weldability. Even with a maximum carbon content of 0.23%, no preheating or postheating is required for the vast majority of welded structures. Machinability is notably poor. High manganese content results in increased hardenability, thus permitting achievement of full hardness by oil quenching of somewhat thicker sections than 1020. Quenching can be less severe because of greater hardenability

Forging. Heat to 1260 °C (2300 °F). Do not forge below 900 °C (1650 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Air cool

Annealing. Heat to 870 °C (1600 °F). Cool slowly, preferably in furnace

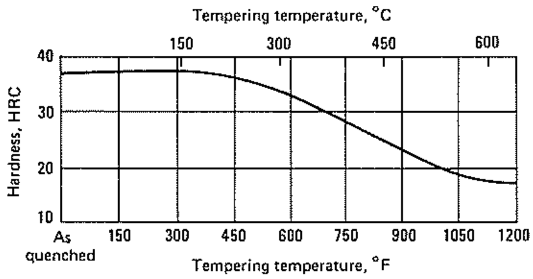
Hardening. Can be case hardened by any one of several processes, which range from light case hardening (by carbonitriding and salt bath nitriding described for grade 1008) to deeper case carburizing in gas, solid, or liquid media. (See carburizing process described for grade 1020.) Plasma (ion) carburizing is an alternative process for shallow cases. Quenchants include aqueous polymers

Tempering. Optional. Temper at 150 °C (300 °F) for 1 h, or higher if some sacrifice of hardness can be tolerated

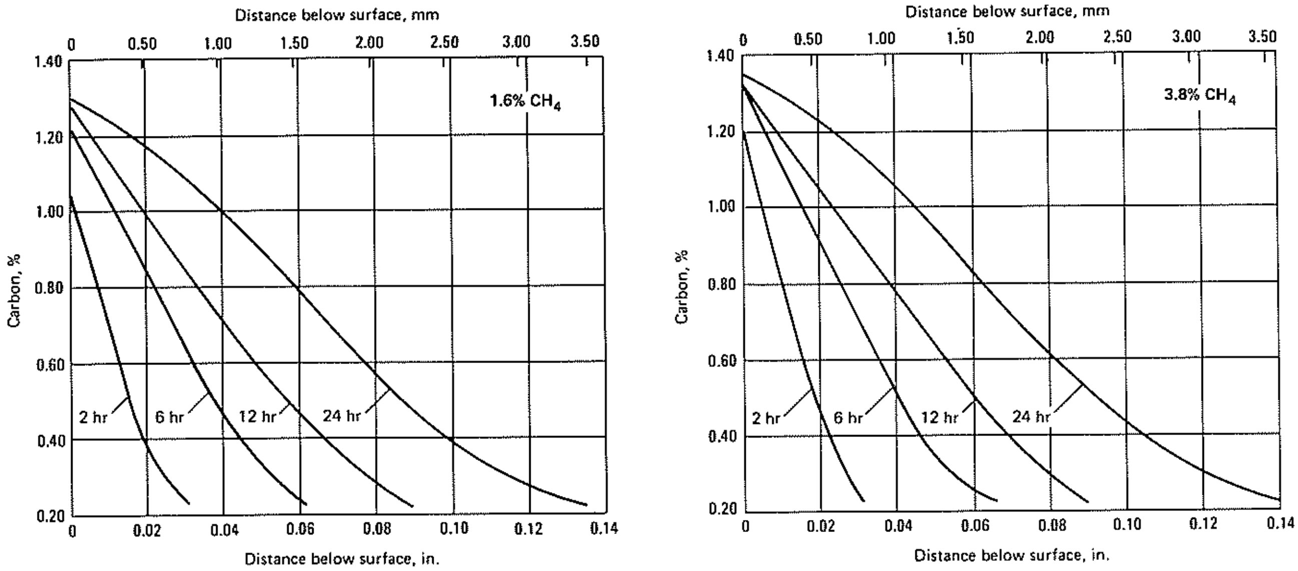
Recommended Processing Sequence

- Forge
- Normalize
- Rough machine
- Semifinish machine and grind
- Carburize
- Diffusion cycle
- Quench
- Temper
- Finish grind

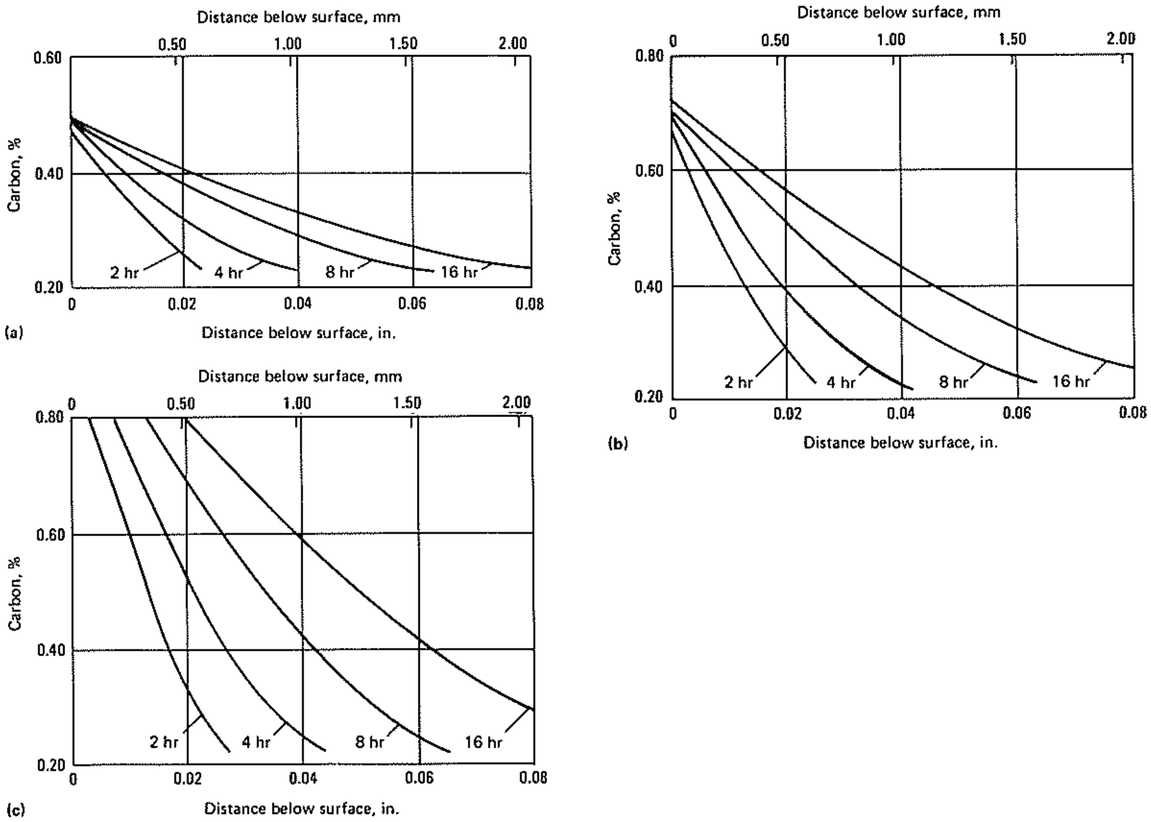
1022: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure (no case hardening)



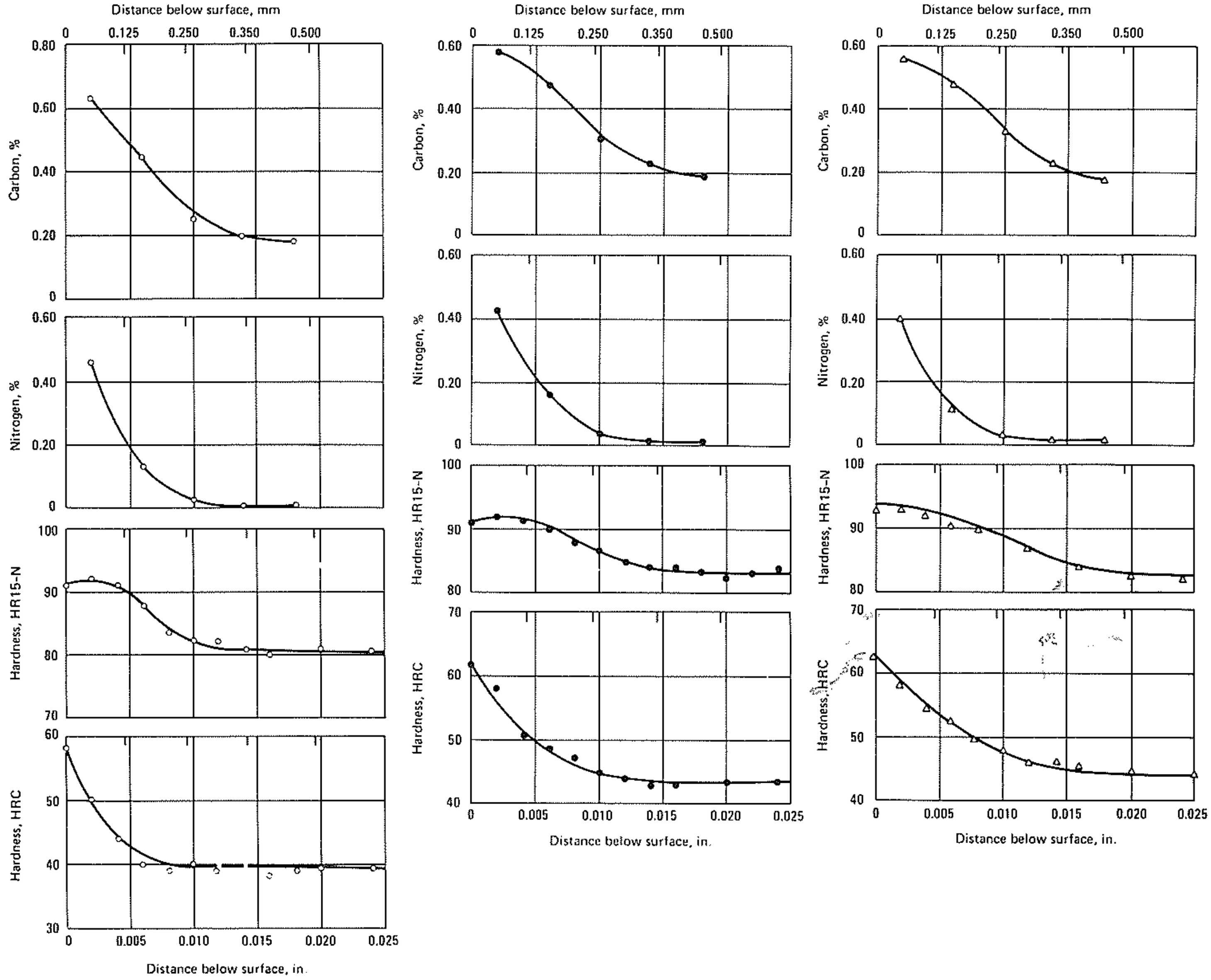
022: Gas Carburizing. Carburized at 920 °C (1690 °F) in 20% CO, 40% H_2 gas, with 1.6 and 3.8% CH_4 added

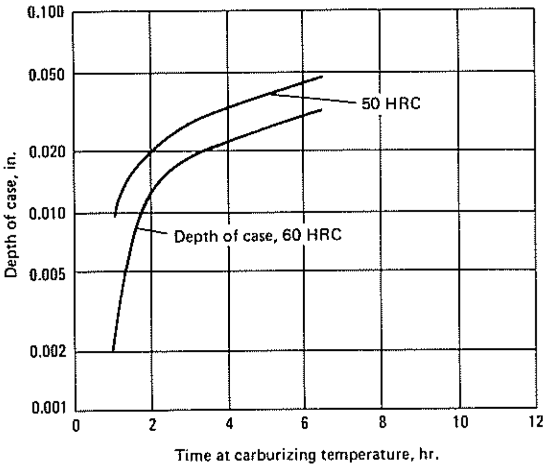


1022: Gas Carburizing. Carburized at 920 °C (1690 °F) with 20% CO, 40% H_2 gas. Contains enough H_2O to produce carbon potentials ndicated: (a) 0.50%; (b) 0.75%; (c) 1.10%



1022: Cyaniding. Effect of cyaniding bath temperature on carbon and nitrogen contents and on case hardness. Specimens heat treated 1 h in 30% NaCN bath at temperatures indicated. Composition specimens air cooled; hardness specimens, water quenched. Cyanate concentrations: O: 4.87% at 815 °C (1500 °F); ●: 3.37% at 845 °C (1555 °F); Δ: 2.71% at 870 °C (1600 °F). Note: Rockwell C measurements unreliable. Thin, brittle case incapable of supporting Rockwell C load. Dip in surface hardness on Rockwell 15-N scale (O and ●) indicative of effect of retained austenite





1022: Liquid Carburizing. Effect of time and temperature on case depth. Bars: 25.4 mm (1 in.) square by 177.8 mm (7 in.) long. Carburized at 925 °C (1695 °F). Water quenched

I023

hemical Composition. **AISI and UNS:** 0.20 to 0.25 C, 0.30 to 60 Mn, 0.040 P max, 0.050 S max

imilar Steels (U.S. and/or Foreign). UNS G10230; ASTM 510, A575, A576, A659; SAE J403, J412, J414; (Ger.) DIN 1.1151; (Fr.) FNOR XC 18 S, XC 25; (Jap.) JIS S 20 C, S 22 C, S 20 CK

haracteristics. Quite weldable. However, when carbon content is in ,e upper end of the allowable range, it becomes borderline in terms of :quiring preheating and postheating, when complex structures are being elded. Machinability is poor. Forgeability is excellent

orging. Heat to 1260 °C (2300 °F). Do not forge below 900 °C (1650 °F)

łecommended Heat Treating Practice

lormalizing. Heat to 925 °C (1695 °F). Air cool

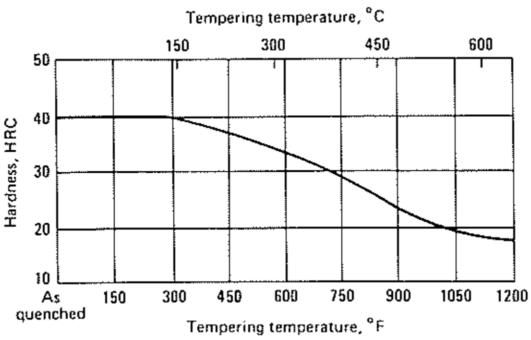
ınnealing. Heat to 870 °C (1600 °F). Cool slowly, preferably in furnace

lardening. Can be case hardened by any one of several processes, 'hich range from light case hardening (by carbonitriding and salt bath nitriding described for grade 1008) to deeper case carburizing in gas, solid, or liquid media. (See carburizing process described for grade 1020.) When carbon content is near the high end of the range, the core strength of case hardened parts will be slightly greater than that of 1020

Tempering. Optional. Temper at 150 °C (300 °F) for 1 h, or higher if some sacrifice of hardness can be tolerated

Recommended Processing Sequence

- Forge
- Normalize
- Rough machine
- Semifinish machine and grind
- Carburize
- Diffusion cycle
- Quench
- Temper
- Finish grind



1023: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure (no case hardening)

1025

Chemical Composition. AISI and UNS: 0.22 to 0.28 C, 0.30 to 0.60 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). UNS G10250; AMS 5075, 5077; ASTM A510, A512, A519, A575, A576; FED QQ-S-700 (C1025); MIL SPEC MIL-S-11310 (CS1025); SAE J403, J412, J414; (Ger.) DIN 1.1158; (Jap.) JIS S25 C, S 28 C

Characteristics. A borderline or transition grade between case hardening and direct hardening types. It is used for both. Because of higher carbon content, it is less suitable for cold forming than 1018 and 1020. Machinability is poor, because it does not contain additives for free machining. Excellent forgeability and good weldability. With the carbon near the higher side of the range, preheating and/or postheating may be required, depending upon the carbon equivalent and complexity of the weldment

Forging. Heat to 1245 °C (2275 °F). Do not forge below 900 °C (1650 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Cool in still air.

In aerospace practice, parts are normalized at 900 °C (1650 °F)

Annealing. Heat to 870 °C (1600 °F). Cool to 675 °C (1245 °F), at a rate not to exceed 28 °C (50 °F) per h.

In aerospace practice, parts are annealed at 885 °C (1625 °F) and allowed to cool to below 540 °C (1000 °F)

Direct Hardening. Austenitize at 870 °C (1600 °F). Quench in water or brine

In aerospace practice, parts are austenitized at 870 °C (1600 °F) and quenched in water

Tempering. As-quenched hardness of 400 HB can be expected for sections up to approximately 25.4 mm (1 in.). Initial hardness can be decreased as desired, by tempering. Water is quenchant. Parts may be tempered at 370 °C (700 °F) for tensile strengths in the range of 620 to 860 MPa (90 to 125 ksi)

Case Hardening. Can be case hardened by any of several processes, which range from light case hardening (by carbonitriding and salt bath nitriding described for grade 1008) to deeper case carburizing in gas, solid, or liquid media. (See carburizing process described for grade 1020.) Other processes include flame hardening and plasma (ion) carburizing. Quenchants include water and aqueous polymers.

Recommended Processing Sequence

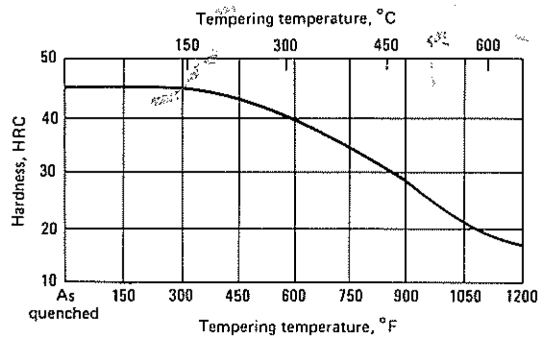
Direct Hardening

- Forge
- Normalize
- Anneal (if necessary)
- Rough machine
- Austenitize
- Quench
- Temper to desired hardness
- Finish machine

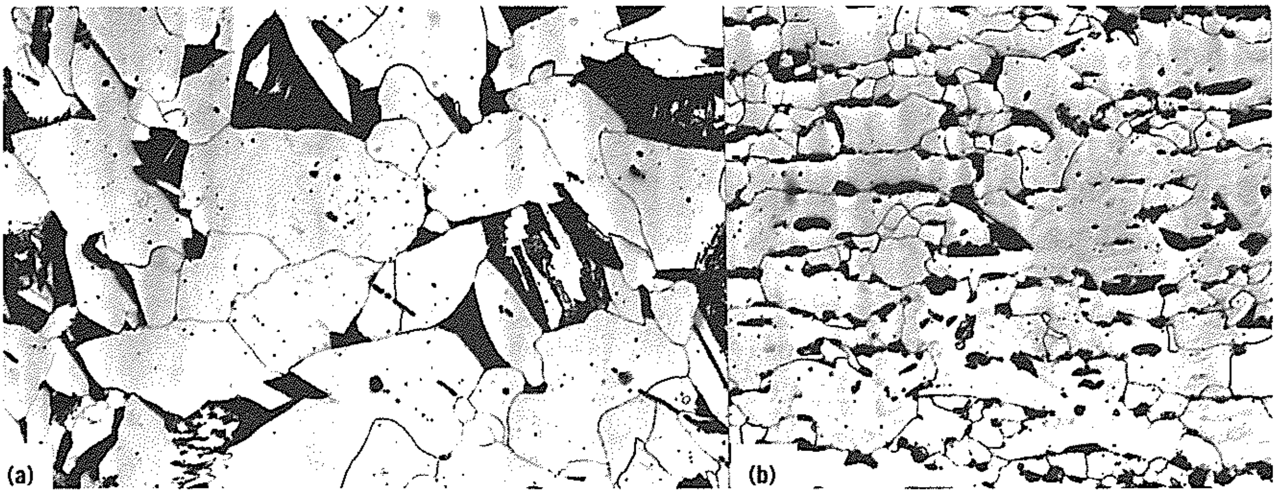
Case Hardening

- Forge
- Normalize
- Rough machine
- Semifinish machine and grind
- Carburize
- Diffusion cycle
- Quench
- Temper
- Finish grind

1025: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure (no case hardening)



1025: Microstructures. (a) Picral, 500×. Normalized by austenitizing, 1095 °C (2005 °F). Air cooled. Coarse grain structure; pearlite (black areas) in ferrite matrix (white areas). (b) Picral, 500×. Normalized by austenitizing, 925 °C (1695 °F). Air cooled. Finer grain size due to lower temperature



1026

Chemical Composition. **AISI and UNS:** 0.22 to 0.28 C, 0.60 to 0.90 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). UNS G10260; ASTM A273, A510, A519, A545, A576; SAE J403, J412, J414

Characteristics. A borderline or transition grade between case hardening and direct hardening types. It is used for both. Because of its higher carbon content, it is less suitable for cold forming than 1018 or 1020. Machinability is poor, because it does not contain additives for free machining. Excellent forgeability, and good weldability. However, the slightly higher manganese range increases hardenability, which can be significant in welding. The tendency to weld crack increases with increasing manganese, so that preheating or postheating may have to be used. Increased hardenability will permit through hardening of sections that are somewhat thicker when compared to 1025

Forging. Heat to 1245 °C (2275 °F). Do not forge below 900 °C (1650 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Cool in still air

Annealing. Heat to 870 °C (1600 °F). Cool to 675 °C (1245 °F), at a rate not to exceed 28 °C (50 °F) per h

Direct Hardening. Austenitize at 870 °C (1600 °F). Quench in water or brine

Tempering. As-quenched hardness of 400 HB can be expected for sections up to approximately 25.4 mm (1 in.). Initial hardness can be decreased as desired, by tempering

Case Hardening. Can be case hardened by any one of several processes, which range from light case hardening (by carbonitriding and salt bath nitriding described for grade 1008) to deeper case carburizing in gas, solid, or liquid media. (See carburizing process described for grade 1020.) Flame hardening is an alternative process

Recommended Processing Sequence

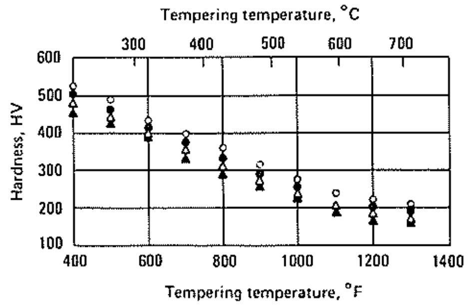
Direct Hardening

- Forge
- Normalize
- Anneal (if necessary)
- Rough machine
- Austenitize
- Quench
- Temper to desired hardness
- Finish machine

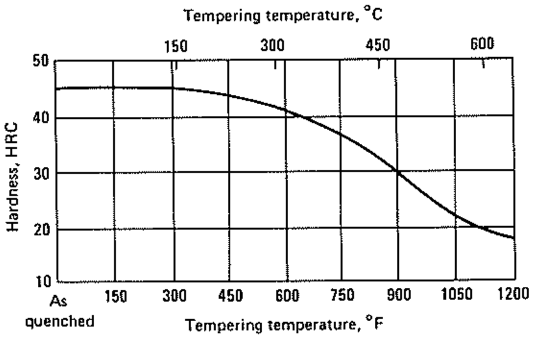
Case Hardening

- Forge
- Normalize
- Rough machine
- Semifinish machine and grind
- Carburize
- Diffusion cycle
- Quench
- Temper
- Finish grind

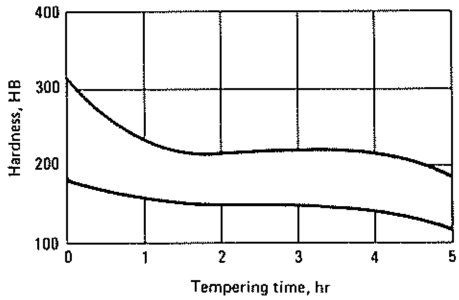
1026: Hardness vs Tempering Temperature. Specimen 3.175 mm (1/8 in.) to 6.35 mm (1/4 in.) thick. Tempering time: O: 10 min; ●: 1 h; Δ: 4 h; ▲: 24 h



1026: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure (direct hardening)



1026: Hardness vs Tempering Time. Textile machine forging, 304.8 mm (12 in.) long by 28.575 mm (1 1/8 in.) diam. Heated in pusher conveyor furnace, 900 °C (1650 °F). Water quenched. Tempered at 315 °C (600 °F) in muffle furnace. Both furnaces gas fired; no atmosphere control. Hardness measured on polished flash line



1029

Chemical Composition. **AISI and UNS:** 0.25 to 0.31 C, 0.60 to 0.90 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). UNS G10290; ASTM A273, A510, A576; SAE J403, J412

Characteristics. With few exceptions, this grade of steel is not case hardened. May be given a wear-resisting surface by quenching from a carbonitriding atmosphere. (See procedure for 1008.) As a rule, it is used either in the normalized or annealed condition or is subjected to direct hardening and tempering. While cold formability is poor compared with lower carbon grades, grade 1029 can be purchased to specific quality requirements, which permit its use for applications that require cold extrusion or cold heading. Machinability is poor. Forgeability is excellent. Can be readily welded, but preheating and postheating are generally required for steels of this carbon content

Forging. Heat to 1245 °C (2275 °F). Do not forge below 885 °C (1625 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 915 °C (1680 °F). Cool in still air

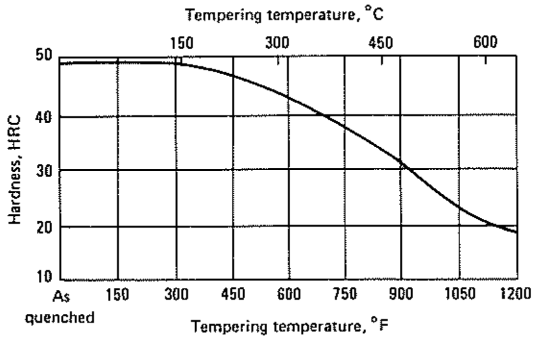
Annealing. Heat to 870 °C (1600 °F). Furnace cool to 650 °C (1200 °F), at a rate not to exceed 28 °C (50 °F) per h

Hardening. Flame hardening and carbonitriding are available surface hardening processes. Austenitize at 860 °C (1580 °F). Quench in water or brine, except for rounds under 6.35 mm (0.25 in.) diam. These may be quenched in oil for near full hardness

Tempering. Using the austenitizing practice described above, an as-quenched hardness of near 425 HB should be attained. The desired hardness can then be developed by tempering

Recommended Processing Sequence

- Forge
- Normalize
- Anneal (if necessary for machining)
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine



1029: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

1030

:hemical Composition. **AISI** and **UNS:** 0.28 to 0.34 C, 0.60 to .90 Mn, 0.040 P max, 0.050 S max

;imilar Steels (U.S. and/or Foreign). UNS G10300; ASTM .510, A512, A519, A544, A546, A576, A682; FED QQ-S-635 (C1030),)Q-S-700 (C1030); MIL SPEC MIL-S-11310 (CS1030); SAE J403, J412, 414; (W. Ger.) DIN 1.1172; (Ital.) UNI CB 35

:haracteristics. With few exceptions, used in the normalized or anealed condition, or subjected to direct hardening and tempering. Cold ɔrmability is poor compared with lower carbon grades. Machinability is oor. Forgeability is excellent. The slightly higher carbon content has some egative effect on weldability. Unless preheating and postheating practices re used, weld cracking may occur. Widely used for producing forgings and arts machined from hot rolled or cold drawn bars. Also available in cold eading quality for fabrication processes involving cold heading or cold xtrusion

:orging. Heat to 1245 °C (2275 °F). Do not forge below 885 °C (1625 °F)

?ecommended Heat Treating Practice

lormalizing. Heat to 915 °C (1680 °F). Cool in still air

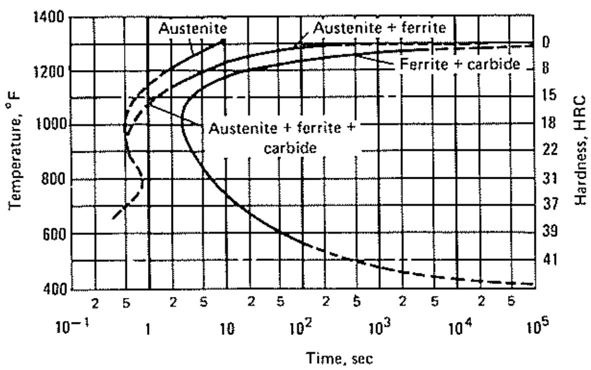
Annealing. Heat to 870 °C (1600 °F). Furnace cool to 650 °C (1200 °F) at a rate not to exceed 28 °C (50 °F) per h

Hardening. Austenitize at 860 °C (1580 °F). Surface hardening processes include flame hardening, induction hardening, carbonitriding, and plasma (ion) carburizing. Quench in water or brine, except for rounds under 6.35 mm (0.25 in.) diam. These may be quenched in oil for near full hardness

Tempering. An as-quenched hardness of near 425 HB should be attained by using the austenitizing practice described. Desired hardness can be reached by tempering

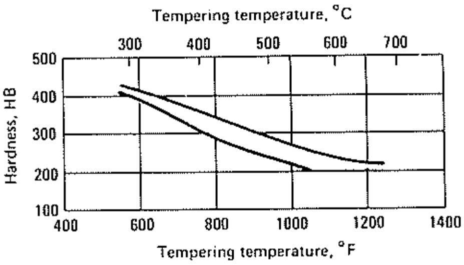
Recommended Processing Sequence

- Forge
- Normalize
- Anneal (if necessary for machining)
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

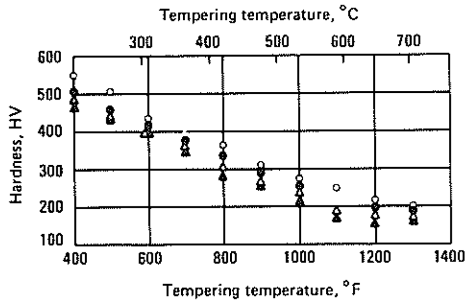


1030: Isothermal Transformation Diagram. Rolled from cast coupons. Austenitized at 905 °C (1660 °F). Grain size, 7 to 8

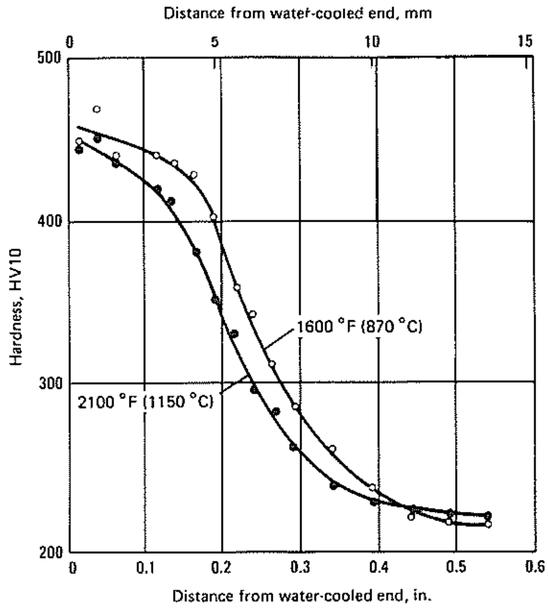
1030: Hardness vs Tempering Temperature. Specimen, 9.525 to 25.4 mm (0.375 to 1 in.) thick



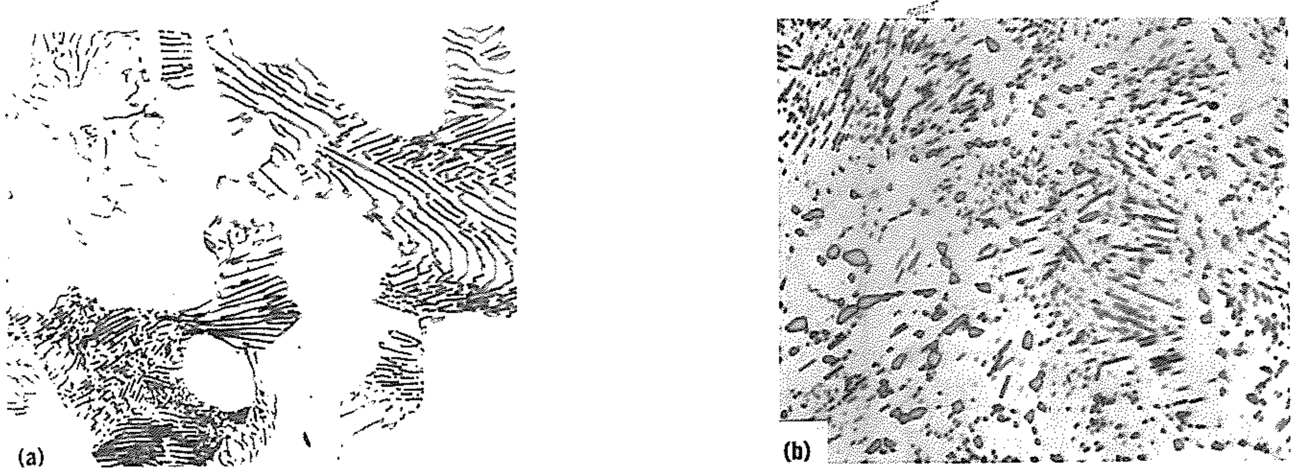
1030: Hardness vs Tempering Temperature. Specimen, 3.175 to 6.35 mm (0.125 to 0.25 in.) thick. Tempering time: O: 10 min; ●: 1 h; Δ: 4 h; ▲: 24 h



1030: End-Quench Hardenability. Effect of high-quenching temperature on hardness. Specimen contains 0.30 C, 0.10 Cr, 0.94 Mn, 0.012 P, 0.028 S, 0.18 Si. ASTM grain size, 1.8. Quenched at temperatures indicated



1030: Microstructures. (a) Picral, 1000×. Austenitized at 925 °C (1695 °F), 1 h; then 775 °C (1425 °F), 2 h 40 min; held at 710 °C (1310 °F), 4 h for isothermal transformation of austenite; brine quenched. Ferrite and coarse pearlite. (b) Picral, 1000×. Austenitized at 800 °C (1475 °F), 40 min; held at 705 °C (1300 °F), 15 min, for isothermal transformation; reheated to 710 °C (1310 °F), held 192 h. Partly spheroidized pearlite. Ferrite matrix



1035

Chemical Composition. **AISI and UNS:** 0.32 to 0.38 C, 0.60 to 0.90 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). UNS G10350; AMS 5080, 5082; ASTM A510, A519, A544, A545, A546, A576, A682; FED QQ-S-635 (C1035), QQ-S-700 (C1035); SAE J403, J412, J414; (Ger.) DIN 1.0501; (Fr.) AFNOR CC 35; (Ital.) UNI C 35; (Swed.) SS14 1550; (U.K.) B.S. 060 A 35, 080 A 32, 080 A 35, 080 A 37, 080 M 36

Characteristics. One of the most widely used medium-carbon grades for machinery parts. Available principally in bars or billets for forging. Excellent forgeability. Special quality grades available for cold heading, old forging, and cold extrusion. Because of carbon content, preheating and ostheating are required when welding. Interpass temperature must be ontrolled. Machinability is only fair. Wide range of mechanical properties an be attained by quenching and tempering

'orging. Heat to 1245 °C (2275 °F). Do not forge below 870 °C (1600 °F)

ℓecommended Heat Treating Practice

lormalizing. Heat to 915 °C (1680 °F). Cool in air.

In aerospace practice, parts are normalized at 800 °C (1650 °F)

ınnealing. Heat to 870 °C (1600 °F). Furnace cool to 650 °C (1200 °F), t a rate not to exceed 28 °C (50 °F) per h.

In aerospace practice, parts are annealed at 870 °C (1600 °F) and llowed to cool below 540 °C (1000 °F)

lardening. Austenitize at 855 °C (1570 °F). Flame hardening, induc-on hardening, austempering, liquid nitriding, and carbonitriding are suit-ble treatment processes. Quench in water or brine, except for rounds under .35 mm (0.25 in.) diam. These may be oil quenched.

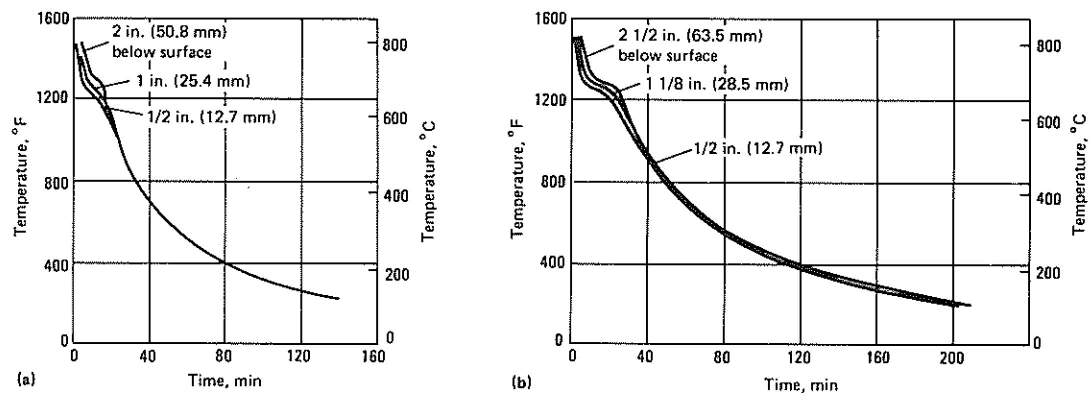
In aerospace practice, parts are austenitized at 845 °C (1555 °F) and quenched in water, polymer, or oil

Tempering. As-quenched hardness should be approximately 45 HRC. Hardness can be reduced by tempering. When quenching in water, parts may be tempered at 455 °C (850 °F) to get tensile strengths in the range of 620 to 860 MPa (90 to 125 ksi); for oil or polymer quenching, parts may be tempered at 370 °C (700 °F) to get tensile strengths in the range of 620 to 860 MPa (90 to 125 ksi)

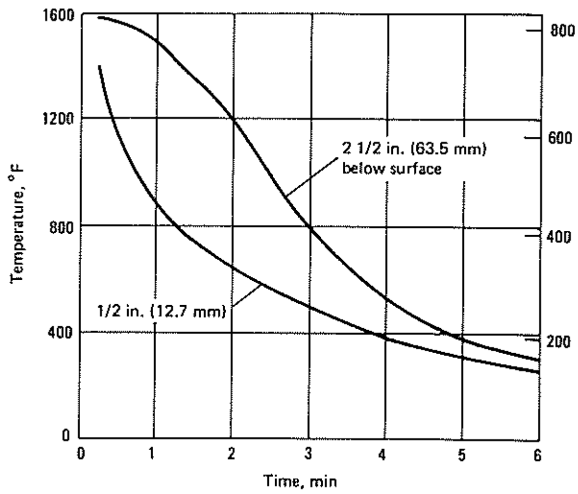
Recommended Processing Sequence

- Forge
- Normalize
- Anneal (if necessary for machining)
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

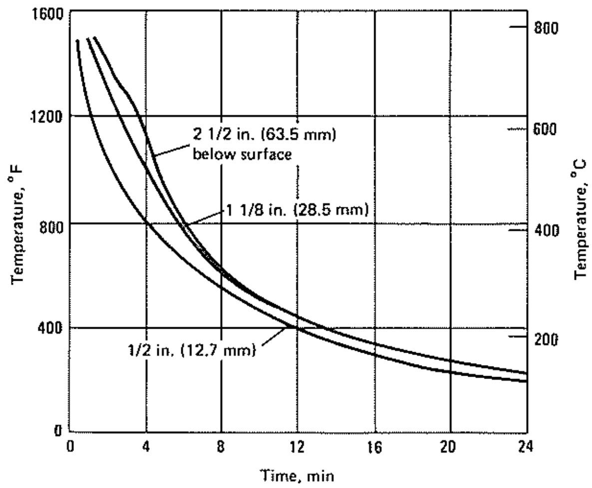
1035: Normalizing. (a) Specimen, 101.6-mm (4-in.) diam. Approximately 95 kg (43 lb). Still air at 20 °C (70 °F). (b) Specimen, 127-mm (5-in.) diam. Approximately 39 kg (85 lb). Still air at 25 °C (75 °F)



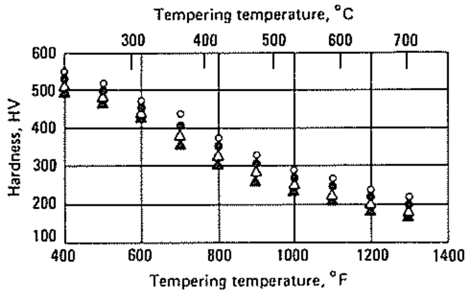
1035: Water Quenching. Specimen, 127 mm (5 in.) diam. Approximately 39 kg (85 lb). Water at 51 °C (125 °F). No agitation



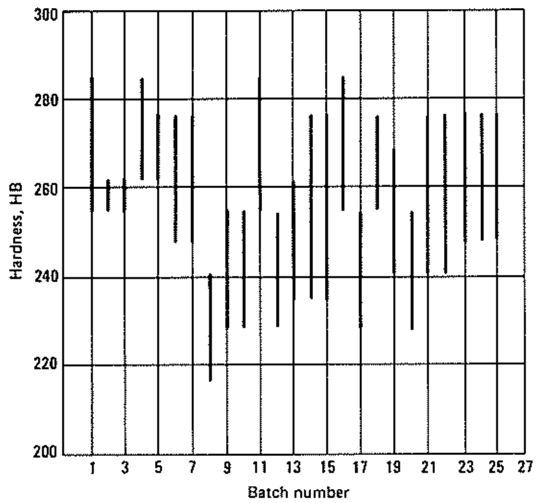
1035: Oil Quenching. Specimen, 127 mm (5 in.) diam. Approximately 39 kg (85 lb). Oil at 32 °C (90 °F)

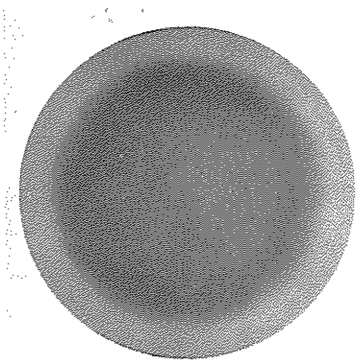


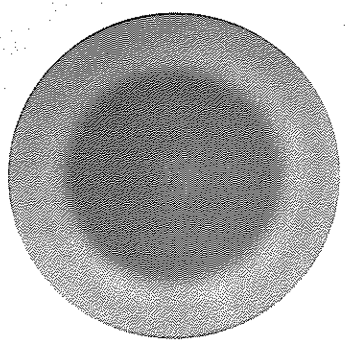
1035: Hardness vs Tempering Temperature. Specimen, 31.8 to 6.35 mm (0.125 to 0.25 in.) thick. Tempered at ○: 10 min; ●: 1 h; △: 4 h; ▲: 24 h



1035: Hardness vs Tempering Temperature. Automotive steering arm forgings. Section thickness, 15.875 to 28.575 mm (0.625 to 1.125 in.). Fine-grained steel. Forgings austenitized at 825 °C (1520 °F) in oil-fired pusher conveyor furnace. Held 45 min. Quenched in water at 20 °C (70 °F). Tempered 45 min at 580 to 625 °C (1075 to 1160 °F) in oil-fired link-belt furnace to required hardness, 217 to 285 HB. Hardness, checked hourly with 5% sample. Readings on polished flash line of 28.575 mm (1.125 in.). Furnace variation at 550 °C (1120 °F) of −9 and −21 °C (+15 and −7 °F). Four mill heats and six-week period




(a)


(b)


(c)

1035: Microstructures. (a) 1035 steel bar, austenitized 1 h at 850 °C (1560 °F), water quenched, and tempered 1 h at 175 °C (350 °F). Cross section shows light outer zone of martensite and a dark core of softer transformation products 10% nital and 1% picral. Actual size (b) 10B35 steel bar (same as 1035, except boron treated) after same heat treatment as bar shown in (a). Effect of boron on hardenability is evident from the greater depth of the martensite zone. 10% nital and 1% picral. Actual size (c) SAE 1035 modified (0.20% Al added) steel, salt bath nitrided 90 min at 580 °C (1075 °F) and water quenched. Surface layer of iron nitride over a matrix of ferrite and pearlite. 1% nital. 500×

1037

Chemical Composition. AISI and UNS: 0.32 to 0.38 C, 0.70 to 1.00 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). UNS G10370; ASTM A510, A576; SAE J403, J412, J414

Characteristics. Excellent forgeability. Special quality grades available for cold heading, cold forging, and cold extrusion. Because of the carbon content, preheating and postheating are required when welding. Interpass temperature must be controlled. Machinability is only fair. Wide range of mechanical properties can be attained by quenching and tempering. The higher manganese content provides additional hardenability. Slightly thicker sections can be fully hardened with a less severe quench, compared with parts made from 1035

Forging. Heat to 1245 °C (2275 °F). Do not forge below 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 915 °C (1680 °F). Cool in air

Annealing. Heat to 870 °C (1600 °F). Furnace cool to 650 °C (1200 °F), at a rate not to exceed 28 °C (50 °F) per h

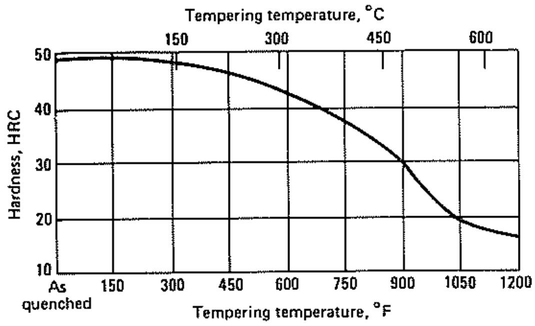
Hardening. Austenitize at 855 °C (1570 °F). Quench in water or brine, except for rounds under 6.325 mm (0.25 in.) diam. These may be oil quenched. Carbonitriding is a suitable surface hardening process

Tempering. As-quenched hardness should be approximately 45 HRC. Hardness can be reduced by tempering

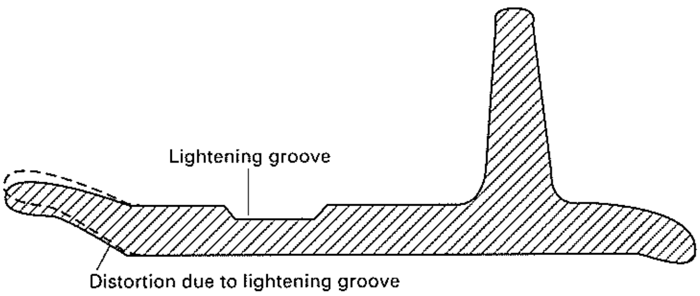
Recommended Processing Sequence

- Forge
- Normalize
- Anneal (if necessary for machining)
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

1037: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure



1037: Water-Quenched Part. Cross section of a water-quenched SAE/AISI 1037 steel track shoe with 0.25 mm (0.010 in.) distortion caused by lightening groove. Redesigning of the shoe to remove the grooves improved uniformity of the section and reduced the distortion to a maximum of 0.08 mm (0.003 in.)



1038, 1038H

Chemical Composition. 1038. AISI and UNS: 0.35 to 0.42 C, 0.60 to 0.90 Mn, 0.040 P max, 0.050 S max. **1038H. UNS H10380 and SAE/AISI 1038H:** 0.34 to 0.43 C, 0.50 to 1.00 Mn, 0.15 to 35 Si

Similar Steels (U.S. and/or Foreign). 1038. UNS G10380; ASTM A510, A544, A545, A546, A576; SAE J403, J412, J414; (Ger.) DIN 1.1176; (Fr.) AFNOR XC 38 TS. **1038H.** UNS H10380; SAE J1268; (Ger.) DIN 1.1176; (Fr.) AFNOR XC 38 TS

Characteristics. One of the most widely used carbon steels having a medium-carbon content. Most widely used for producing forgings to be used in the heat treated condition. Also available as an H steel. Welded only with the precautions used for welding of any medium-carbon steel: preheating, postheating, and control of interpass temperature

Forging. Heat to 1245 °C (2275 °F). Do not forge below 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F). Cool in air

Annealing. Heat to 855 °C (1570 °F). Furnace cool to 650 °C (1200 °F), at a rate not to exceed 28 °C (50 °F) per h

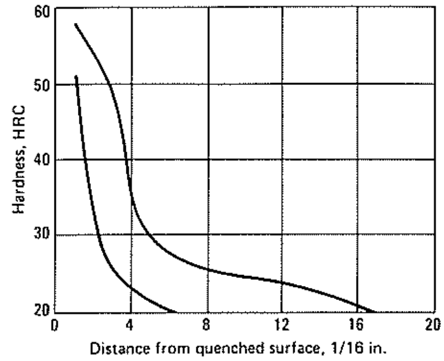
Hardening. Heat to 855 °C (1570 °F). Carbonitriding is a suitable surface hardening process. Quench in water or brine. Rounds under 6.35 mm (0.25 in.) diam may be oil quenched for full hardness

Recommended Processing Sequence

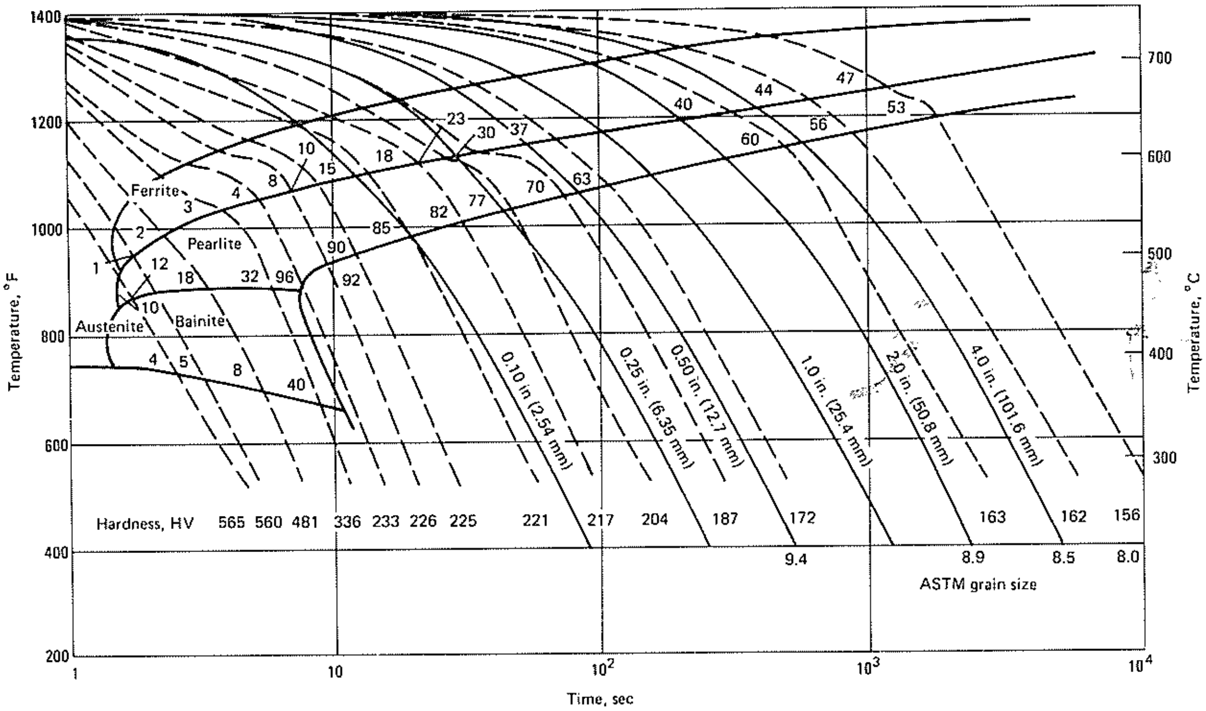
- Forge
- Normalize
- Anneal (if necessary for machining)
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

1038H: End-Quench Hardenability. Normalized at 870 °C (1600 °F). Austenitized at 845 °C (1550 °F)

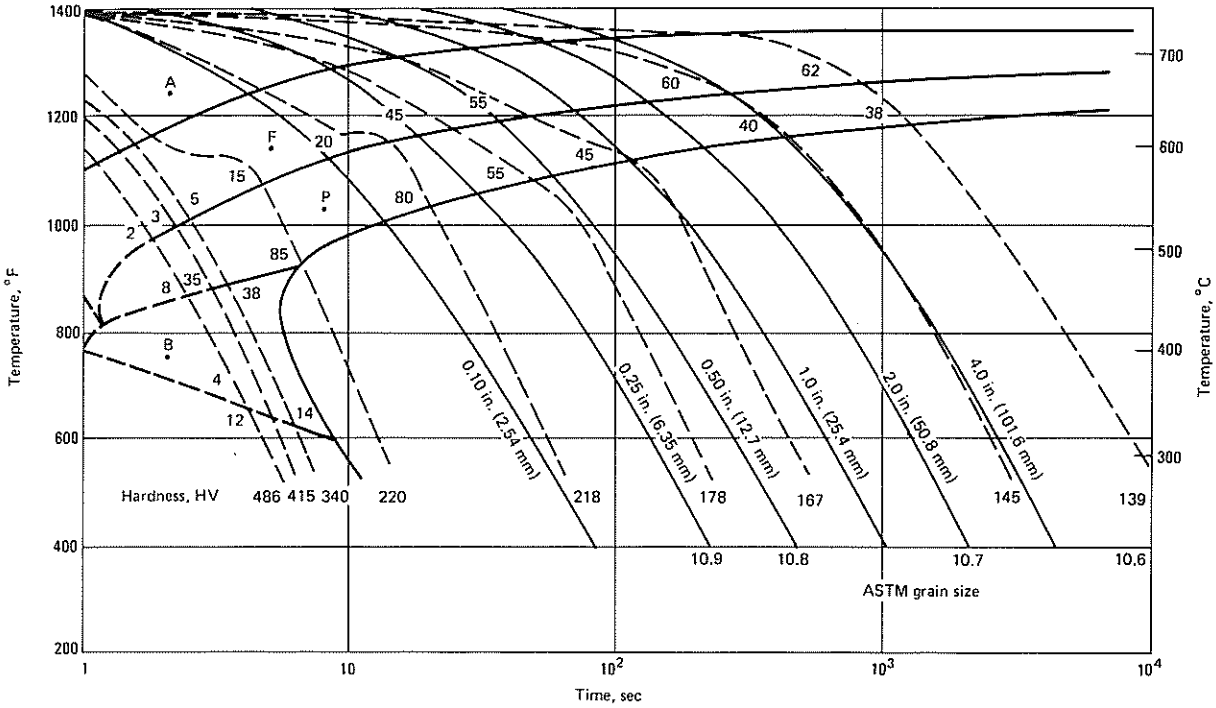
Distance from quenched surface		Hardness, HRC		Distance from quenched surface		Hardness, HRC	
1/16 in.	mm	max	min	1/16 in.	mm	max	min
1	1.58	58	51	6	9.48	28	21
1.5	2.37	56	42	6.5	10.27	27	20
2	3.16	55	34	7	11.06	27	...
2.5	3.95	53	29	7.5	11.85	26	...
3	4.74	49	26	8	12.64	26	...
3.5	5.58	43	24	9	14.22	25	...
4	6.32	37	23	10	15.80	25	...
4.5	7.11	33	22	12	18.96	24	...
5	7.90	30	22	14	22.12	23	...
5.5	8.69	29	21	16	25.28	21	...



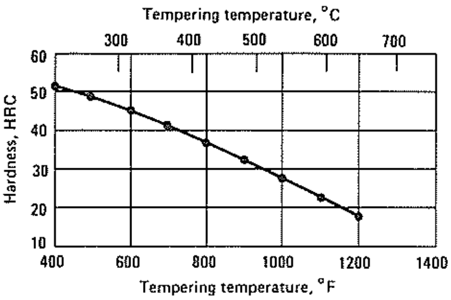
1038: Cooling Curve. 0.38 C, 0.70 Mn, 0.015 P, 0.030 S 0.25 Si, 0.063 Al, 0.003 N. Austenitized 1095 °C (2005 °F). Grain size, ASTM 5. Solid cooling curves are for bars of indicated diameters. M_f is 225 °C (435 °F); M_s is 400 °C (750 °F);Ac_1 is 710 °C (1310 °F); Ac_3 is 760 °C (1400 °F)



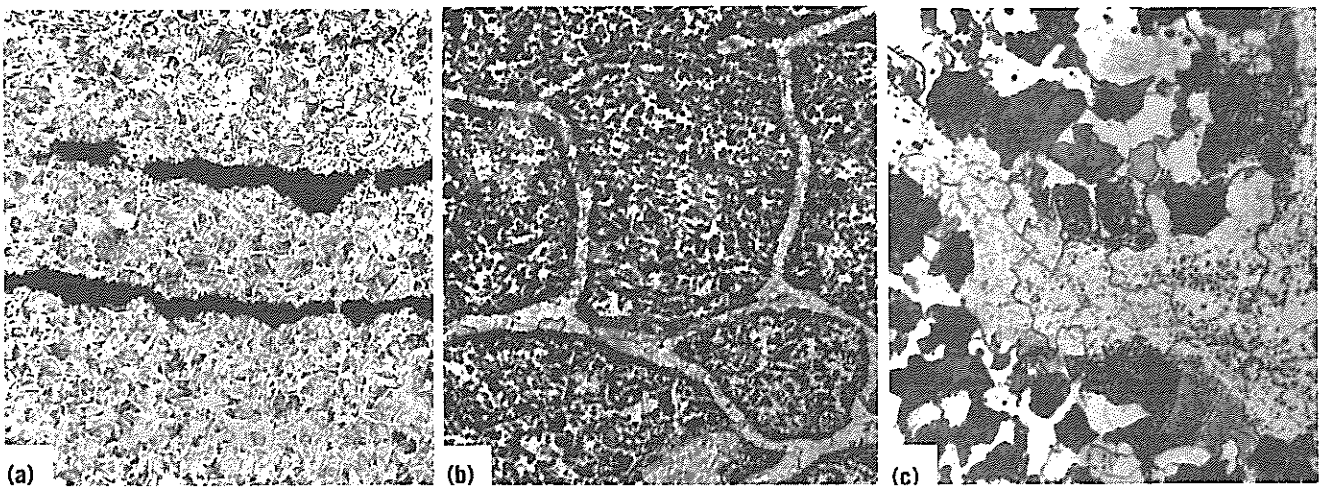
1038: Cooling Curve. Austenitized at 870 °C (1600 °F). Grain size, ASTM 8. Solid cooling curves are for bars of indicated diameters. Italic numbers are hardness, HV. Bold face numbers, ASTM grain size



1038: Hardness vs Tempering Temperature. Quenched specimen, 3.175 to 6.35 mm (0.125 to 0.25 in.). Tempered 1 h



1038: Microstructures. (a) 2% nital, 50×. Longitudinal section, as forged. Secondary pipe from original bar stock (black areas). Pearlite (gray). Ferrite (white). (b) 2% nital, 100×. Transverse section, as forged. Severely overheated, showing first stage of burning. Ferrite (white) outlines prior coarse austenite grains. Matrix of ferrite (white) and pearlite (black). (c) 2% nital, 550×. Same as (b), at higher magnification. Massive ferrite outlines coarse austenite grains. Contains particles of oxide (black dots). Matrix of ferrite (white) and pearlite (black)

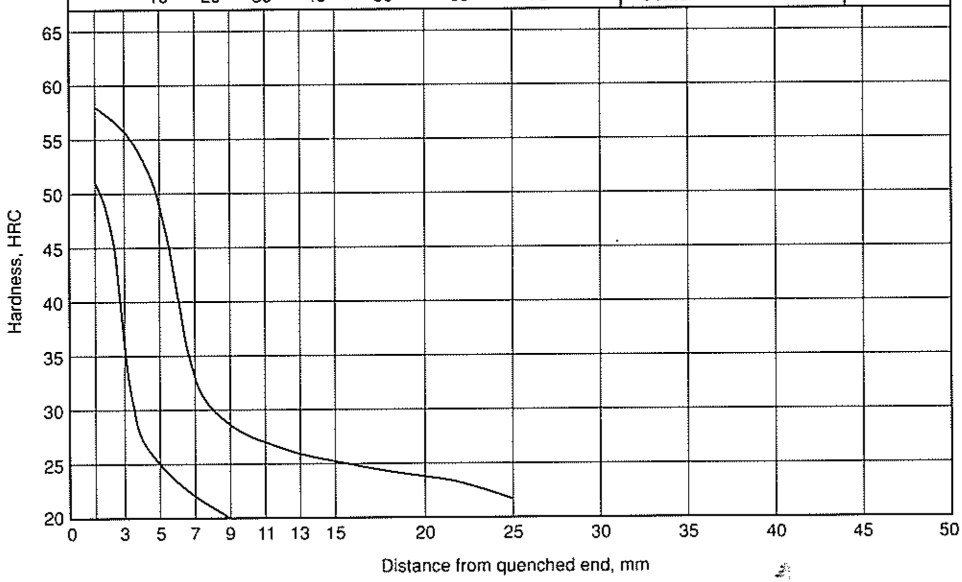


1038H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1550 °F)

Hardness Limits for Specification Purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	58	51
3	56	37
5	49	25
7	33	22
9	29	20
11	27	...
13	26	...
15	25	...
20	24	...
25	22	...
35	...	...

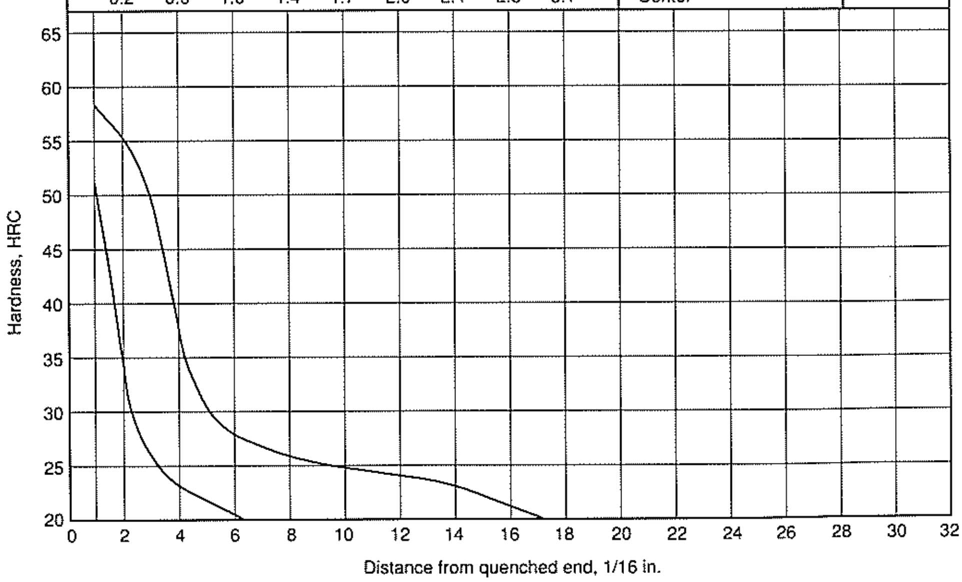
Approximate diameters of rounds with same as-quenched hardness (HRC), mm	Location in round	Quench
50 75	Surface	Mild water quench
20 30 60 90	3/4 radius from center	
20 30 40 50 60 80 100	Center	
20 40 60 80 100	Surface	Mild oil quench
15 30 45 60 75 90	3/4 radius from center	
10 20 30 40 50 60 75	Center	



Hardness Limits for Specification Purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	58	51
1.5	56	42
2	55	34
2.5	53	29
3	49	26
3.5	43	24
4	37	23
4.5	33	22
5	30	22
5.5	29	21
6	28	21
6.5	27	20
7	27	...
7.5	26	...
8	26	...
9	25	...
10	25	...
12	24	...
14	23	...
16	21	...

Diameters of rounds with same as-quenched hardness (HRC), in.	Location in round	Quench
3.8	Surface	Mild water quench
1.1 2.0 2.9 3.8 4.8 5.8 6.7	3/4 radius from center	
0.7 1.2 1.6 2.0 2.4 2.8 3.2 3.6 3.9	Center	
0.8 1.8 2.5 3.0 3.4 3.8	Surface	Mild oil quench
0.5 1.0 1.6 2.0 2.4 2.8 3.2 3.6 4.0	3/4 radius from center	
0.2 0.6 1.0 1.4 1.7 2.0 2.4 2.8 3.1	Center	



1039

:hemical Composition. AISI and UNS: 0.37 to 0.44 C, 0.70 to .00 Mn, 0.040 P max, 0.050 S max

:imilar Steels (U.S. and/or Foreign). UNS G10390; ASTM .510, A546, A576; SAE J403, J412, J414; (Ger.) DIN 1.1157; (Fr.) AF-OR 35 M 5; (U.K.) B.S. 120 M 36, 150 M 36, CDS 105/106

:haracteristics. Medium-carbon steel. Widely used for forgings that :ill be heat treated. Machinability is only fair. Since weldability is poor, ıe best preheating and postheating practice is required when welding is ıvolved. The slightly higher manganese content offers the possibility of ightly increased hardenability, compared with 1040

orging. Heat to 1245 °C (2275 °F). Do not forge below 900 °C (1650 °F)

lecommended Heat Treating Practice

lormalizing. Heat to 900 °C (1650 °F). Cool in air

.nnealing. Heat to 845 °C (1555 °F). Furnace cool to 650 °C (1200 °F), : a rate not to exceed 28 °C (50 °F) per hour

lardening. Heat to 845 °C (1555 °F). Carbonitriding is a suitable ırface treating process. Quench in water or brine. Rounds less than 6.35 ım (0.25 in.) diam may be oil quenched to full hardness

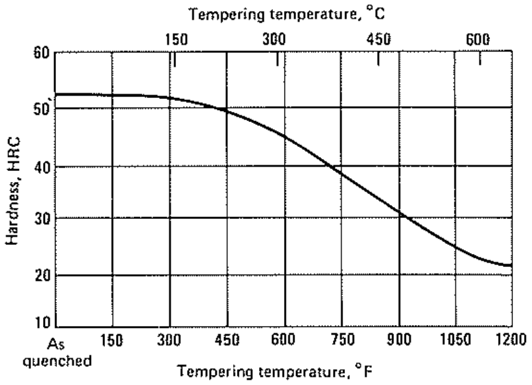
Tempering After Hardening. As-quenched hardness of approximately 52 HRC. Hardness can be reduced by tempering

Tempering After Normalizing. For large sections, normalize by conventional practice. Results in a structure of fine pearlite. A tempering treatment up to about 540 °C (1000 °F) is then applied. Mechanical properties not equal to those achieved by quenching and tempering. Resulting strength is far higher than that of annealed structure. Normalizing and tempering often applied to heavy forgings

Recommended Processing Sequence

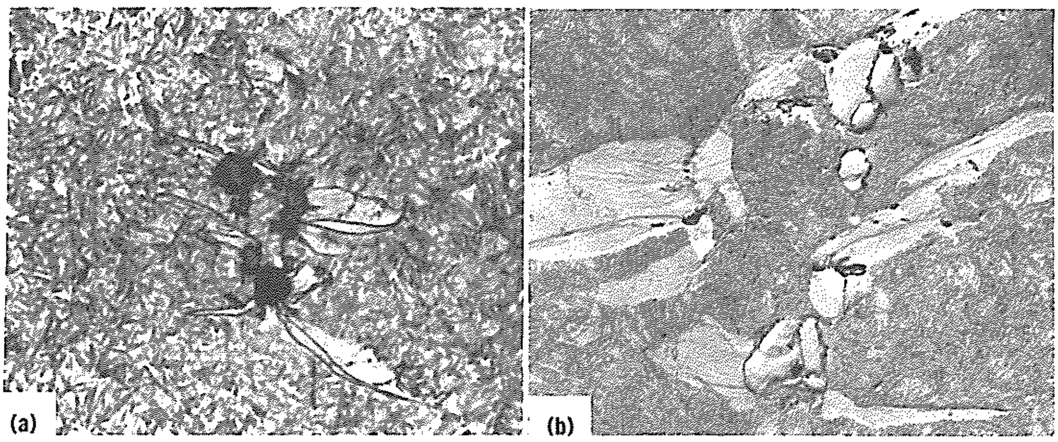
Forgings

- Forge
- Normalize
- Anneal (if necessary) or temper (optional)
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine



1039: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

1039: Microstructures. (a) 1% nital, 750×. Gas carburized roller for use in contact fatigue tests. Inclusions and "butterfly" alterations at center, about 0.127 mm (0.005 in.) from contact surface. Alterations believed to be work-hardened ferrite, caused by breakdown of martensite. (b) 2% picral, 1950×. Same as (a), but enlarged in electron micrograph of two-stage, carbon-chromium-shadowed replica. Lighter etching than (a). "Butterfly" alterations, formed at inclusions are believed to be oriented in direction of principal stress



1040

Chemical Composition. AISI and UNS: 0.37 to 0.44 C, 0.60 to 0.90 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). ASTM A510, A519, A546, A576, A682; MIL SPEC MIL-S-11310 (CS1040); SAE J403, J412, J414; (Ger.) DIN 1.1186; (Jap.) JIS S 40 C; (U.K.) B.S. 080 A 40, 2 S. 93

Characteristics. Medium-carbon steel. Widely used for forgings that will be heat treated. Machinability is only fair. Since weldability is poor, the best preheating and postheating practice is required when welding is involved

Forging. Heat to 1245 °C (2275 °F). Do not forge below 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F). Cool in air

Annealing. Heat to 845 °C (1555 °F). Furnace cool to 650 °C (1200 °F), at a rate not to exceed 28 °C (50 °F) per h

Hardening. Heat to 845 °C (1555 °F). Flame hardening, carbonitriding, and liquid carburizing are suitable surface hardening processes. Quench in water or brine. Rounds less than 6.35 mm (1/4 in.) diam may be oil quenched for full hardness

Tempering After Hardening. As-quenched hardness of approximately 52 HRC. Hardness can be reduced by tempering

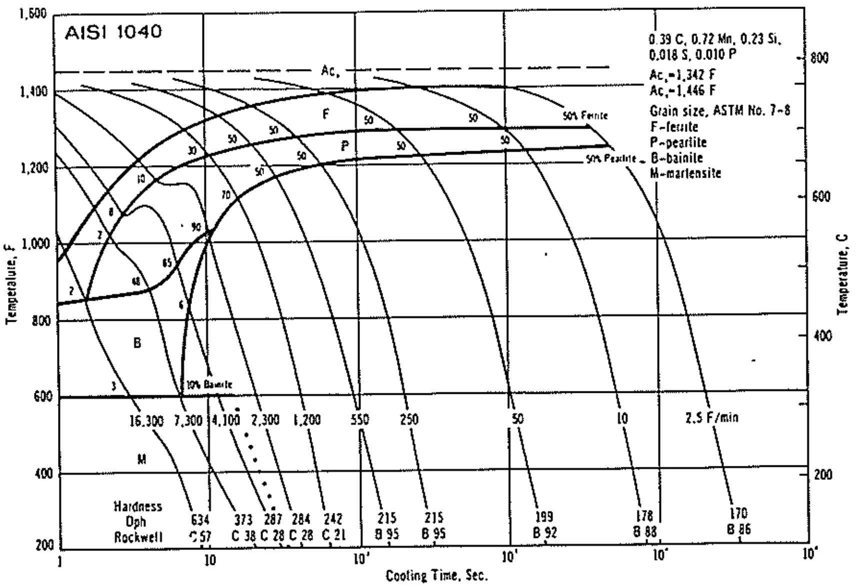
Tempering After Normalizing. For large sections, normalize by conventional practice. This results in a structure of fine pearlite. A tempering treatment up to about 540 °C (1000 °F) is then applied. Mechanical properties not equal to those achieved by quenching and tempering. Resulting strength is far higher than that of annealed structure. Normalizing and tempering often applied to heavy forgings

Recommended Processing Sequence

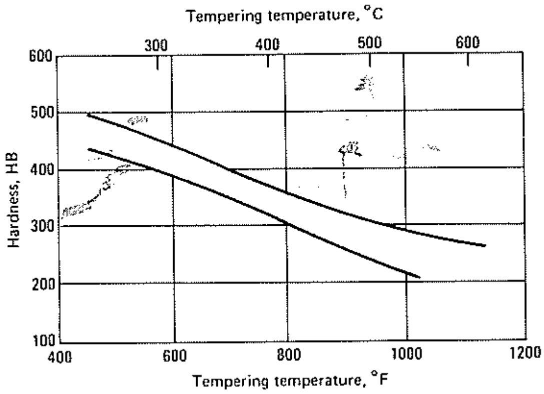
Forgings

- Forge
- Normalize
- Anneal (if necessary) or temper (optional)
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

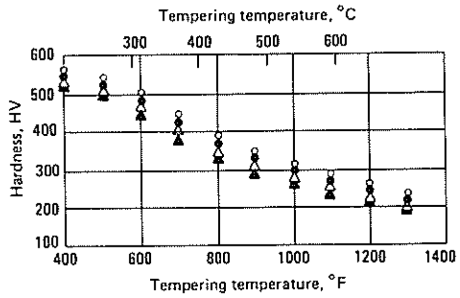
1040: CCT Diagram. Composition: 0.39% C - 0.72% Mn - 0.23% Si - 0.010% P - 0.018% S. Grain size: 7-8



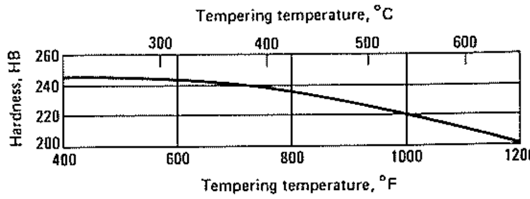
1040: Hardness vs Tempering Temperature. Specimen, 63.5 to 92.075 mm (2.50 to 3.62 in.) thick. Quenched.

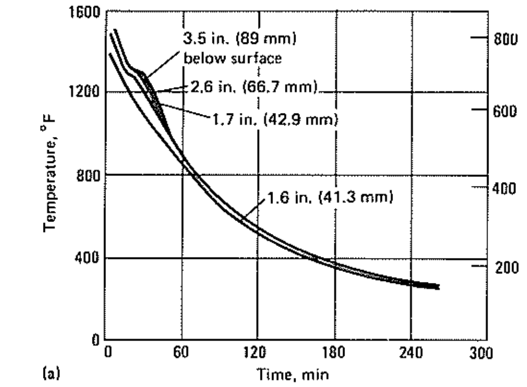


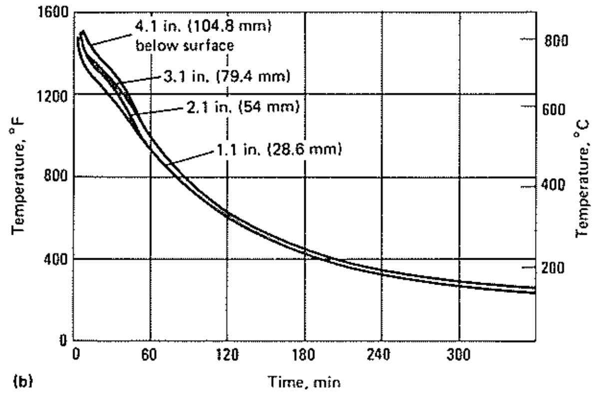
1040: Hardness vs Tempering Temperature. Specimen, 3.175 to 6.35 mm (0.125 to 0.25 in.) thick. Quenched. Legend: O: 10 min; ●: 1 h; Δ: 4 h; ▲: 24 h

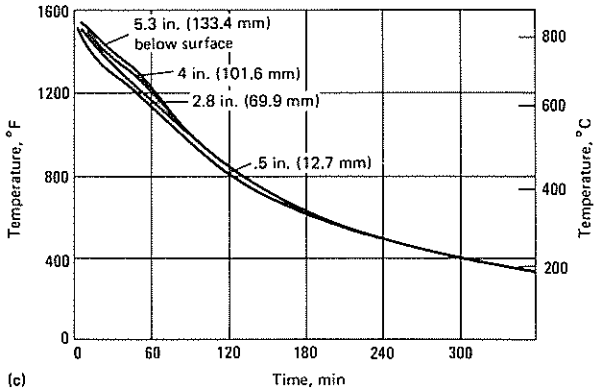


1040: Hardness vs Tempering Temperature. Normalized at 870 °C (1600 °F). Oil quenched from 845 °C (1555 °F). Tempered at 56 °C (100 °F) intervals, 13.716 mm (0.54 in.) rounds. Tested in 12.827 mm (0.505 in.) rounds. Source: Republic Steel

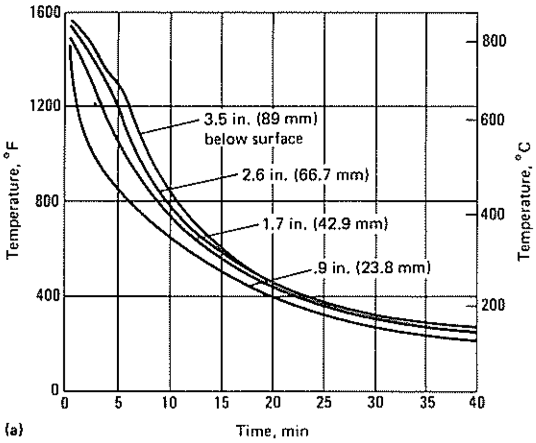


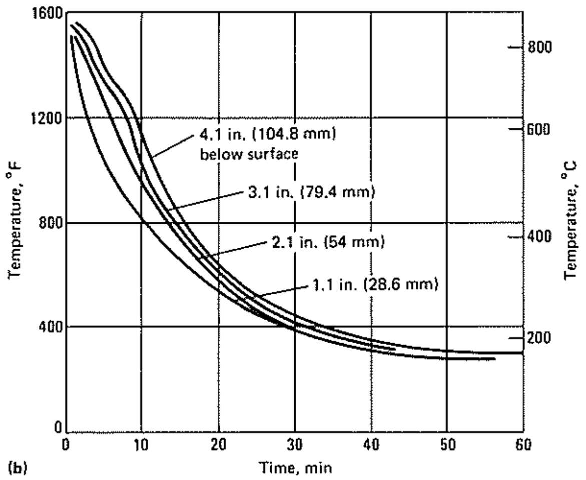


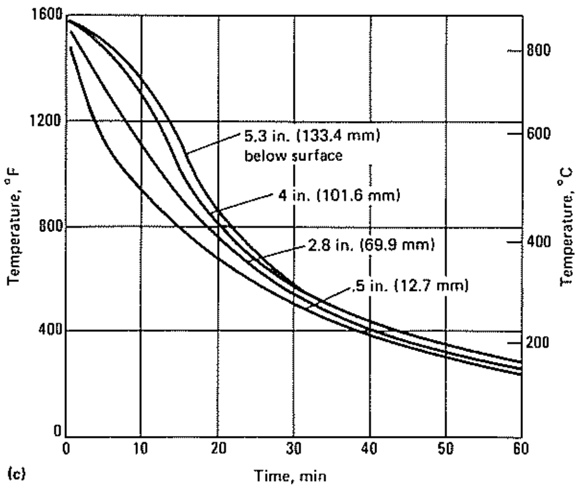




1040: Normalizing. (a) Specimen, 177.8 mm (7 in.) diam. Approximately 105 kg (230 lb). Still air at 22 °C (72 °F). (b) Specimen, 209.55 mm (8.25 in.) diam. Approximately 185 kg (410 lb). Air at 35 to 24 °C (94 to 74 °F). (c) Specimen, 266.7 mm (10.50 in.) diam. Approximately 335 kg (735 lb). Air at 22 °C (72 °F)

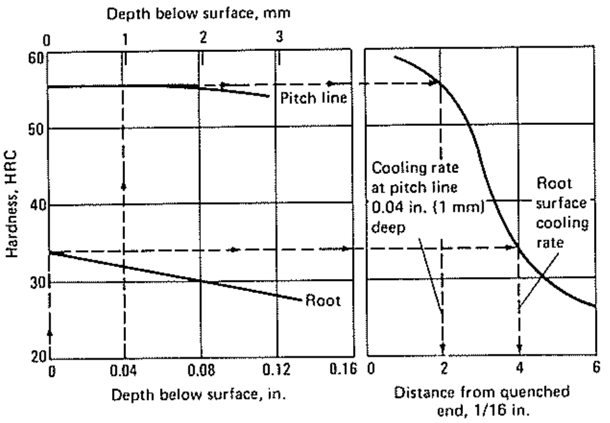




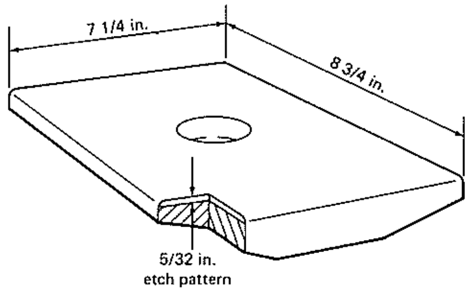


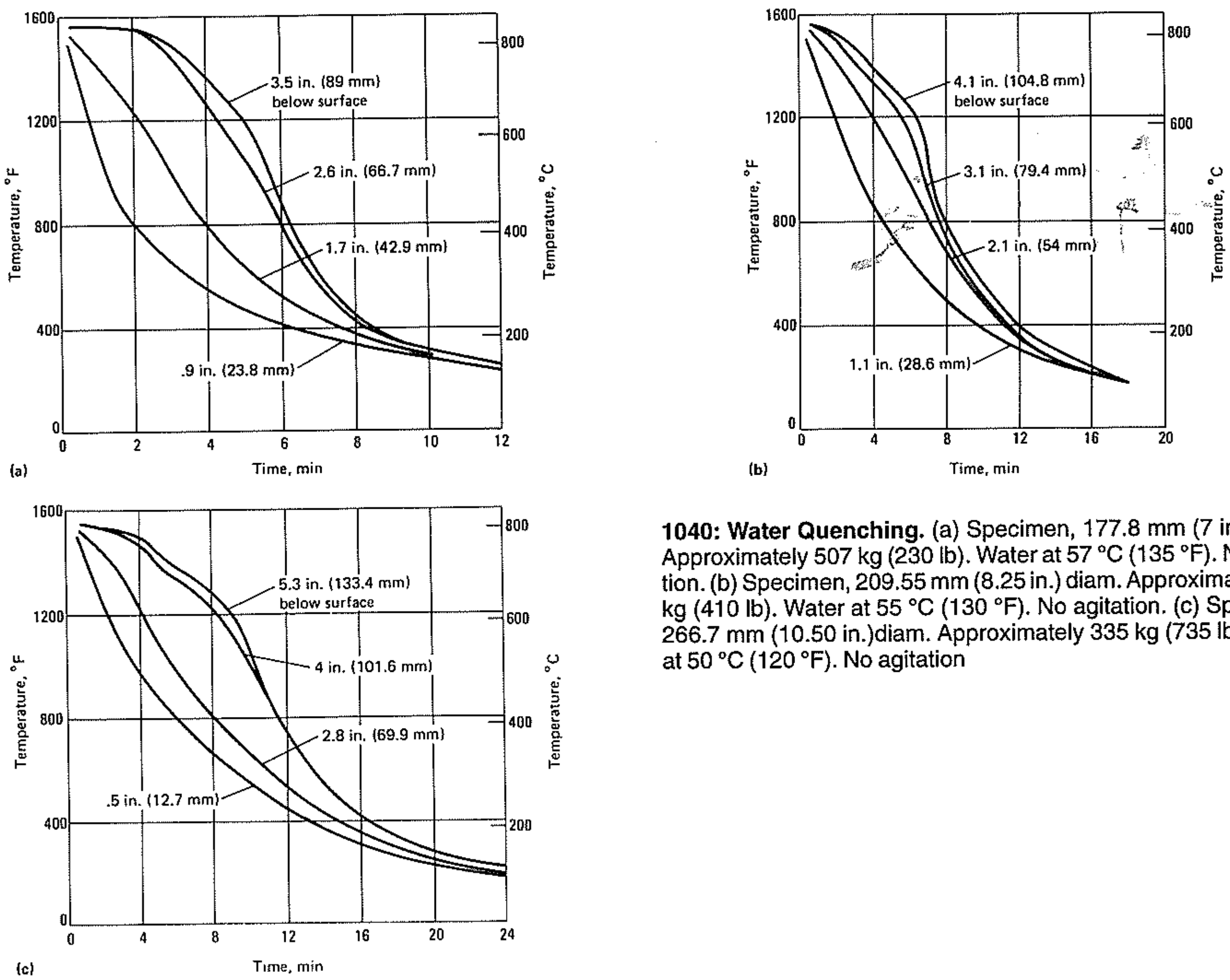
1040: Oil Quenching. (a) Specimen, 177.8 mm (7 in.) diam. Approximately 105 kg (230 lb). Oil at 31 °C (88 °F). (b) Specimen, 209.55 mm (8.25 in.) diam. Approximately 904 kg (185 lb). Oil at 50 °C (120 °F). (c) Specimen, 266.7 mm (10.50 in.) diam. Approximately 335 kg (735 lb). Oil at 30 °C (85 °F)

1040: Estimating Jominy Equivalent Hardenability. Method for estimating Jominy equivalent cooling rates (J_{eh}) in gears of specific size and configuration. Gears made from shallow hardening (1040) steel. Hardened in production. Hardness measured at various depths below surface at pitch line and root locations. Compared with hardnesses at various (J_{eh}) distances on end-quenched bar made from same 1040 bar and quenched from same austenitizing conditions



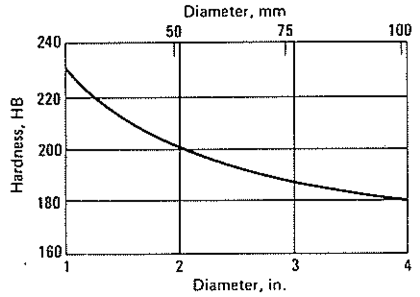
1040: Flame Hardening of Wear Blocks. Clean blocks of scale and rust, preferably by sand or shot blasting. Load blocks on conveyor. Flame head has two rows of number 54 drill size 1.397 mm (0.055 in.) flame holes. 24 of 49 holes are plugged. 152.4 mm (6 in.) between centers of end holes. Head also contains single row of water-quench holes. Head set at 15.875 mm (0.625 in.) total gap. Cone point clearance of flame, 4.763 mm (0.19 in.). Gas pressure: acetylene, 82.738 kPa (12 psi); oxygen, 151.686 kPa (22 psi). Conveyor speed, 148.08 mm (5.83 in.). Total flame hardening time, 1.5 min per pad. Hardness, 53 to 58 HRC. Total depth of hardening to core, 3.97 mm (0.16 in.)



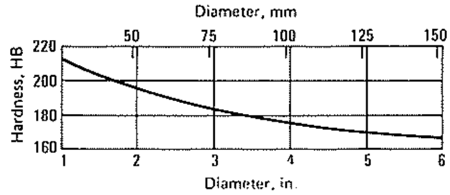


1040: Water Quenching. (a) Specimen, 177.8 mm (7 in.) diam. Approximately 507 kg (230 lb). Water at 57 °C (135 °F). No agitation. (b) Specimen, 209.55 mm (8.25 in.) diam. Approximately 185 kg (410 lb). Water at 55 °C (130 °F). No agitation. (c) Specimen, 266.7 mm (10.50 in.)diam. Approximately 335 kg (735 lb). Water at 50 °C (120 °F). No agitation

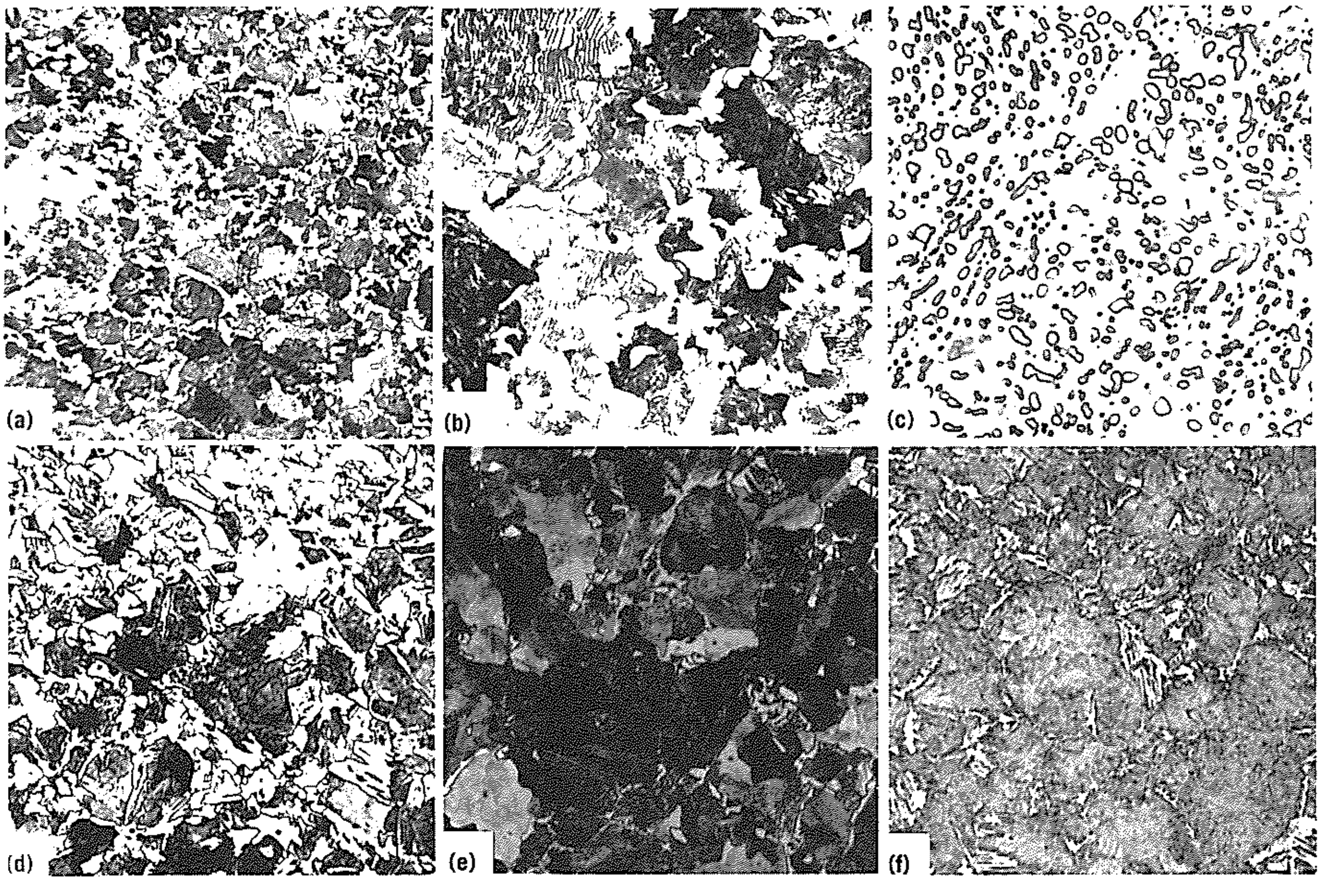
040: Hardness vs Tempering. Effect of mass: when normalized t 870 °C (1600 °F); oil quenched from 845 °C (1555 °F); temered at 540 °C (1000 °F). Tested in 12.827 mm (0.505 in.) ɔunds. Test from 38.1 mm (1.5 in.) diam bars and over, at half-raius position. Source: Republic Steel



1040: Hardness vs Tempering. Effect of mass: when normalized at 870 °C (1600 °F); oil quenched from 845 °C (1555 °F); tempered at 650 °C (1200 °F). Tested in 12.827 mm (0.505 in.) rounds. Test from 38.1 mm (1.5 in.) diam bars and over, at half-radius position. Source: Republic Steel

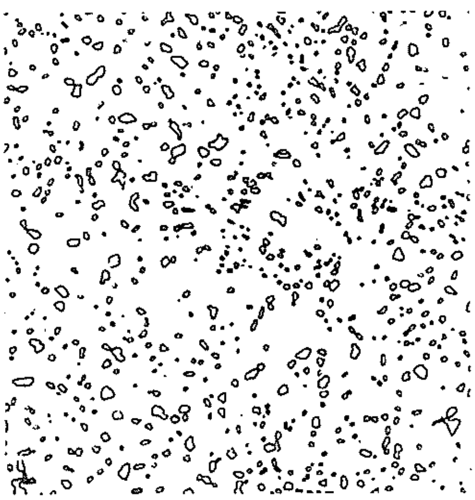


040: Microstructures. (a) Nital 200×. 25.4 mm (1 in.) diam bar. Austenitized at 915 °C (1680 °F), 30 min. Cooled slowly in furnace. Ferrite white areas) and pearlite (dark). (b) Nital, 500×. Same as (a), at higher magnification. Pearlite and ferrite grains more clearly resolved. Wide ifference in grain size in (a) and (b). (c) Picral, 1000×. Austenitized at 800 °C (1475 °F), 40 min. Held at 705 °C (1300 °F), 6 h, for isothermal ansformation. Structure is spheroidized carbide in ferrite matrix. (d) Nital, 500×. 25.4 mm (1 in.) diam bar. Austenitized at 915 °C (1680 °F). Quenched 30 min in salt bath at 420 °C (785 °F). Air cooled. Abnormal amount of ferrite (white) indicates partial decarburization at surface op). (e) Nital, 500×. Same as (d). Interior of bar. White areas are ferrite, outlining prior austenite grains. Black and gray are pearlite. (f) Nital, 00×. 25.4 mm (1 in.) diam bar. Austenitized at 915 °C (1680 °F). 30 min. Oil quenched. Tempered at 205 °C (400 °F). Tempered martensite gray); ferrite (white)

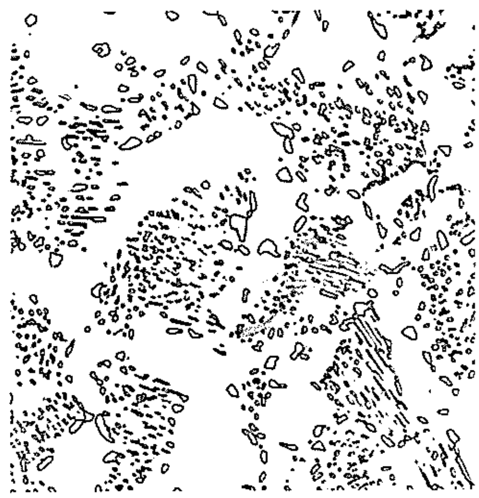


1040: Microstructure. A fully annealed 1040 steel showing a ferrite-pearlite microstructure. Etched in 4% picral plus 2% nital. 500×

1040: Microstructures. Effect of prior microstructure on spheroidizing a 1040 steel at 700 °C (1290 °F) for 21 h. (a) Starting from a martensitic microstructure (as-quenched). (b) Starting from a ferrite-pearlite microstructure (fully annealed). Etched in 4% picral plus 2% nital. 1000×



(a)



(b)

1042

Chemical Composition. AISI and UNS: 0.40 to 0.47 C, 0.60 to 0.90 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). ASTM A273, A510, A576; FED QQ-S-635 (C1042), SAE J403, J412, J414; (Ger.) DIN 1.1191; (Fr.) AFNOR XC 42, XC 42 TS, XC 45, XC 48; (Jap.) JIS S 45 C, S 48 C; (Swed.) SS_{14} 1672

Characteristics. Machinability is only fair. Weldability is poor. The best preheating and postheating practice is required when welding is involved. As-quenched hardness can be slightly higher than 1040

Forging. Heat to 1245 °C (2275 °F). Do not forge below 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F). Cool in air

Annealing. Heat to 845 °C (1555 °F). Furnace cool to 650 °C (1200 °F), at a rate not to exceed 28 °C (50 °F) per h

Hardening. Heat to 845 °C (1555 °F). Flame hardening, induction hardening, boriding, and carbonitriding are suitable surface hardening processes. Quench in water or brine. Rounds less than 6.35 mm (0.25 in.) diam may be oil quenched for full hardness

Tempering After Hardening. As-quenched hardness can be reduced as desired by tempering

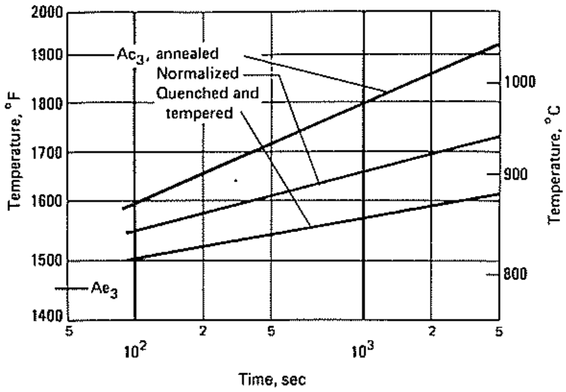
Tempering After Normalizing. For large sections, normalize by conventional practice. This results in a structure of fine pearlite. A tempering treatment up to about 540 °C (1000 °F) is applied. Mechanical properties not equal to those achieved by quenching and tempering. Resulting ɪngth is far higher than that of annealed structure. Normalizing and ɪpering often applied to heavy forgings

ɛcommended Processing Sequence

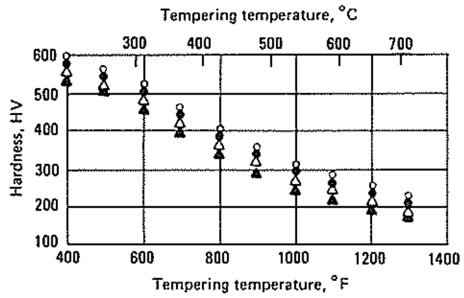
ɪrgings

- Forge
- Normalize
- Anneal (if necessary) or temper (optional)
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

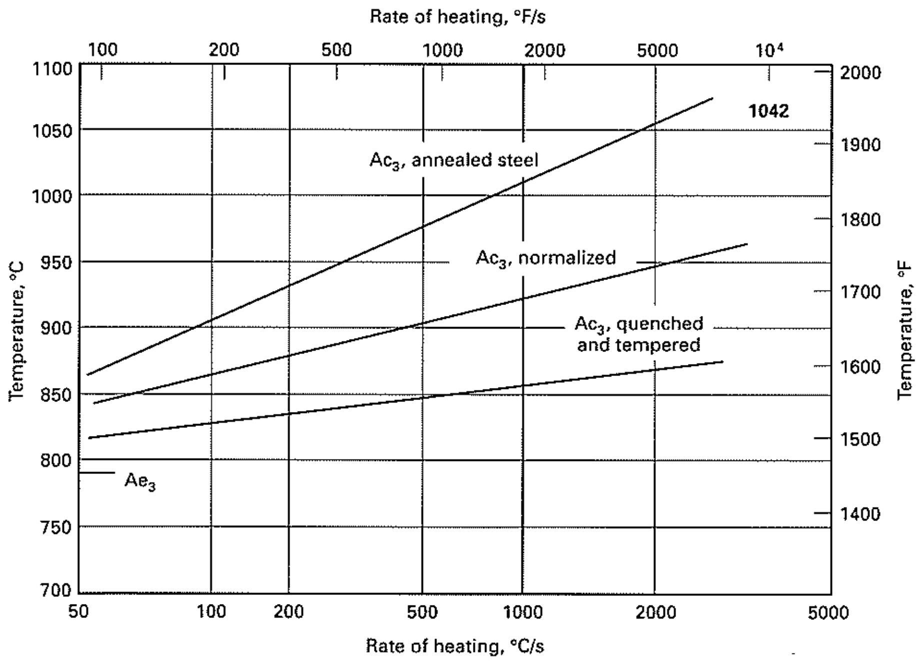
042: Change in Ac_3 Temperature



1042: Hardness vs Tempering Temperature. Tempered at 205 to 705 °C (400 to 1300 °F), 10 min to 24 h. Quenched specimen, 3.175 to 6.35 mm (0.125 to 0.25 in.). Legend: O: 10 min; ●: 1 h; Δ: 4 h; ▲: 24 h



042: Induction Process. Effect of prior structure and rate of heating on Ac_3 transformation temperature of 1042 steel



043

ɪemical Composition. AISI and UNS: 0.40 to 0.47 C, 0.70 to 0 Mn, 0.040 P max, 0.050 S max

milar Steels (U.S. and/or Foreign). UNS G10430; ASTM 10, A576; SAE J403, J412, J414; (Ger.) DIN 1.0503; (Fr.) AFNOR CC . (Ital.) UNI C 45; (Swed.) SS_{14} 1650; (U.K.) B.S. 060 A 47, 080 H 46,) M 40, 080 M 46

Characteristics. Machinability is only fair. Weldability is poor. The best preheating and postheating practice is required when welding is involved. Added manganese provides increased hardenability, compared with 1042

Forging. Heat to 1245 °C (2275 °F). Do not forge below 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F). Cool in air

Annealing. Heat to 845 °C (1555 °F). Furnace cool to 650 °C (1200 °F), at a rate not to exceed 28 °C (50 °F) per h

Hardening. Heat to 845 °C (1555 °F). Flame hardening, boriding, and carbonitriding are suitable surface hardening processes. Quench in water, brine, or aqueous polymers. Rounds less than 6.35 mm (0.25 in.) diam may be oil quenched for full hardness

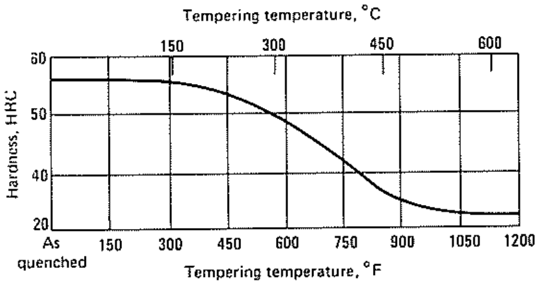
Tempering After Hardening. As-quenched hardness can be reduced by tempering

Tempering After Normalizing. For large sections, normalize by conventional practice. This results in a structure of fine pearlite. A tempering treatment up to about 540 °C (1000 °F) is applied. Mechanical properties not equal to those achieved by quenching and tempering. Resulting strength is far higher than that of annealed structure. Normalizing and tempering often applied to heavy forgings

Recommended Processing Sequence

Forgings

- Forge
- Normalize
- Anneal (if necessary) or temper (optional)
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine



1043: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

1044

Chemical Composition. **AISI and UNS:** 0.43 to 0.50 C, 0.30 to 0.60 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). UNS G10440; ASTM A510, A575, A576; SAE J403, J412, J414

Characteristics. Low-manganese version of widely used medium-carbon 1045. Often selected in preference to 1045 for surface hardening by flame or induction, because lower manganese decreases hardenability and susceptibility to quench cracking. Excellent forgeability. Fair machinability. Responds readily to heat treatment. As-quenched hardness of at least 55 HRC. Slightly higher, when carbon is near high side of the allowable range. Used extensively for parts that will be furnace heated or heated by induction prior to quenching

Forging. Heat to 1245 °C (2275 °F). Do not forge below 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F). Cool in air

Annealing. Heat to 845 °C (1555 °F). Furnace cool to 650 °C (1200 °F), at a rate not to exceed 28 °C (50 °F) per h

Hardening. Austenitize at 845 °C (1555 °F). Flame hardening, induction hardening, and carbonitriding are suitable surface hardening processes. Quench in water or brine. Rounds less than 6.35 mm (0.25 in.) diam may be oil quenched for full hardness

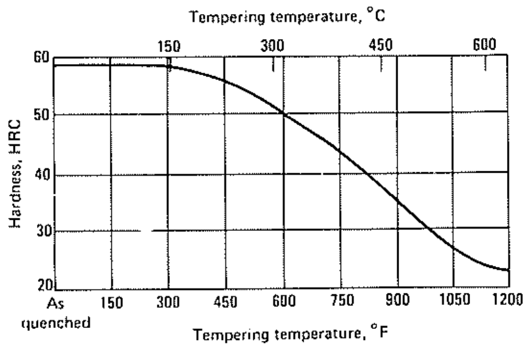
Tempering After Hardening. Hardness of at least 55 HRC if properly austenitized and quenched. Hardness can be adjusted by tempering

Tempering After Normalizing. Often normalized and tempered, as for 1040. For large sections, normalize by conventional practice. This results in a structure of fine pearlite. A tempering treatment up to about 540 °C (1000 °F) is then applied. Mechanical properties not equal to those achieved by quenching and tempering. Resulting strength is far higher than that of annealed structure. Normalizing and tempering often applied to heavy forgings

Recommended Processing Sequence

- Forge or machine (bars)
- Normalize (if forged. Not required for parts machined from hot rolled or cold drawn bars)
- Anneal (if necessary. Bar stock usually received in condition for best machining)
- Rough machine (forgings)
- Austenitize (parts from bars or forgings)
- Quench
- Temper
- Finish machine

1044: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure



045, 1045H

emical Composition. **1045. AISI and UNS:** 0.43 to 0.50 C, 0.60).90 Mn, 0.040 P max, 0.050 S max. **1045H. UNS H10450 and E/AISI 1045H:** 0.42 to 0.51 C, 0.50 to 1.00 Mn, 0.15 to 0.35 Si

nilar Steels (U.S. and/or Foreign). **1045.** UNS G10450; ΓM A510, A519, A576, A682; FED QQ-S-635 (C1045), QQ-S-700 045); SAE J403, J412, J414; (Ger.) DIN 1.1191; (Fr.) AFNOR XC 42, 42 TS, XC 45, XC 48; (Jap.) JIS S 45 C, S 48 C; (Swed.) SS_{14} 1672. **5H.** UNS H10450; SAE J1268; (Ger.) DIN 1.1191; (Fr.) AFNOR XC XC 42 TS, XC 45, XC 48; (Jap.) JIS S 45 C, S 48 C; (Swed.) SS_{14} 1672

aracteristics. Most often specified medium-carbon steel. Also ilable as special quality grades of proprietary steel compositions. Avail- ; in a variety of product forms, mainly as stock for forging. Excellent ;eability. Fair machinability. Responds readily to heat treatment. Avail- ; as an H grade. As-quenched hardness of at least 55 HRC. Slightly her, when carbon is near high side of the allowable range. Used exten- ly for parts to be furnace heated or heated by induction prior to nching

rging. Heat to 1245 °C (2275 °F). Do not forge below 870 °C (1600 °F)

ecommended Heat Treating Practice

rmalizing. Heat to 900 °C (1650 °F). Cool in air

nealing. Heat to 845 °C (1555 °F). Furnace cool to 650 °C (1200 °F), rate not to exceed 28 °C (50 °F) per h

rdening. Austenitize at 845 °C (1555 °F). Flame hardening, induc- ı hardening, liquid nitriding, carbonitriding, martempering, and electron m hardening are suitable surface hardening processes. Quench in water ɔrine. Rounds under 6.35 mm (0.25 in.) diam may be oil quenched for hardness. Other quenchants include aqueous polymers

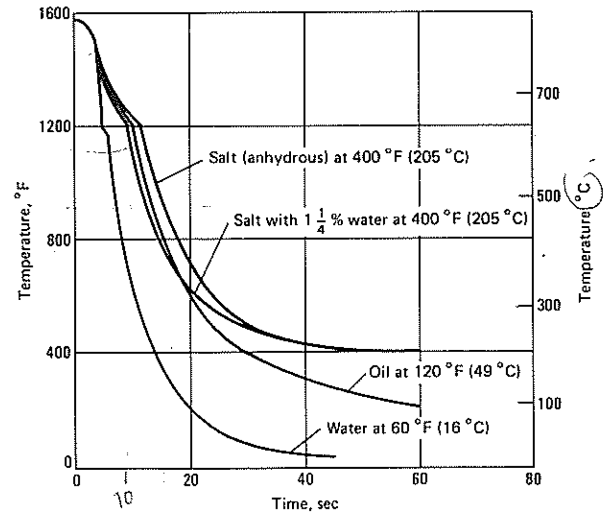
mpering After Hardening. Hardness of at least 55 HRC, if prop- austenitized and quenched. Hardness can be adjusted by tempering. en quenching in water, parts may be tempered at a range of tempera- s to get specific ranges in tensile strength: 565 °C (1050 °F) for 620 to) MPa (90 to 125 ksi); 480 °C (895 °F) for 860 to 1035 MPa (125 to 150); 370 °C (700 °F) for 1035 to 1175 MPa (150 to 170 ksi). When nching in oil or polymer, parts may be tempered at: 540 °C (1000 °F) for 620 to 860 MPa (90 to 125 ksi); 425 °C (795 °F) for 860 to 1035 MPa (125 to 150 ksi)

Tempering After Normalizing. Normalize and temper as for 1040. For large sections, normalize by conventional practice. This results in a structure of fine pearlite. A tempering treatment up to about 540 °C (1000 °F) is then applied. Mechanical properties not equal to those achieved by quenching and tempering. Resulting strength is far higher than that of annealed structure. Normalizing and tempering often applied to heavy forgings

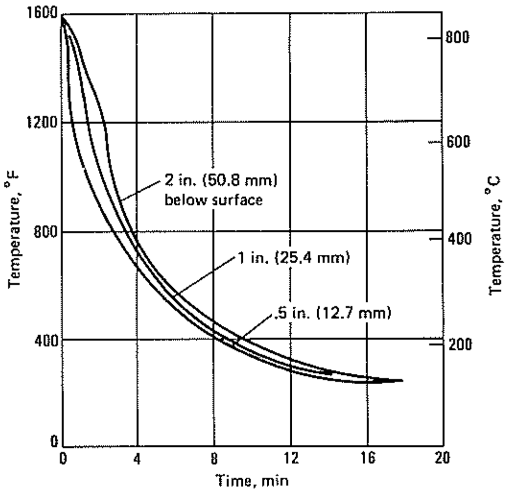
Recommended Processing Sequence

- Forge or machine (bars)
- Normalize (if forged. Not required for parts machined from hot rolled or cold drawn bars)
- Anneal (if necessary. Bar stock usually received in condition for best machining)
- Rough machine (forgings)
- Austenitize (parts from bars or forgings)
- Quench
- Temper
- Finish machine

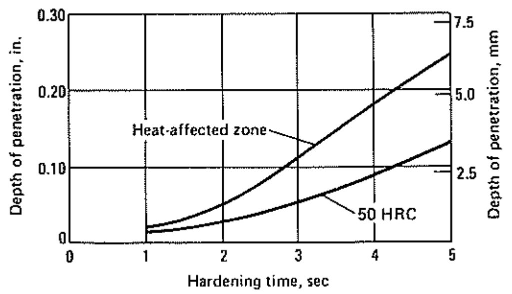
045: Cooling Rates in Quenching. Effect of quenching medi- ms on cooling rates. Cylinders, 25.4 mm (1 in.) diam by 101.6 ım (4 in.). Quenched in salt, water, and oil. Thermocouples at enters of specimens



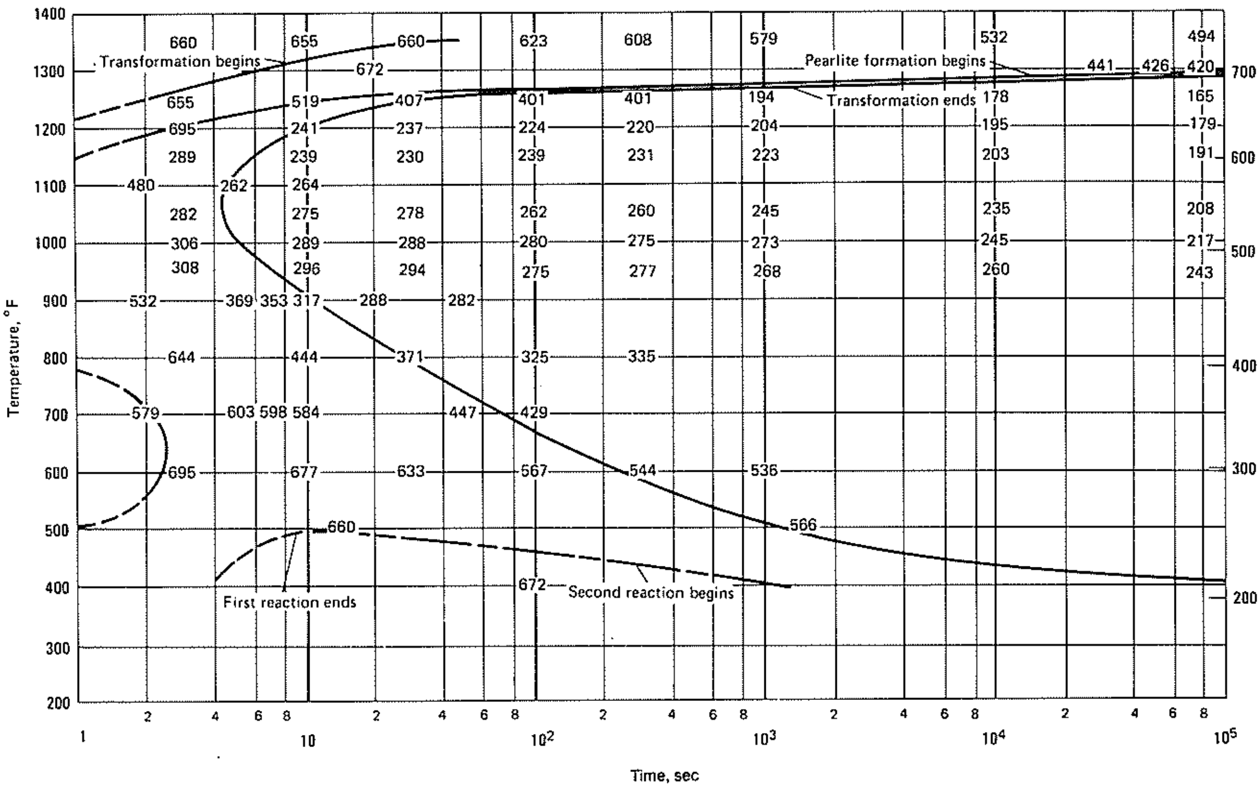
1045: Mass and Section Size vs Cooling Rate in Oil. Speci- men: 101.6 mm (4 in.) diam; approx. 20 kg (43 lb). Oil quenched at 35 °C (94 °F)



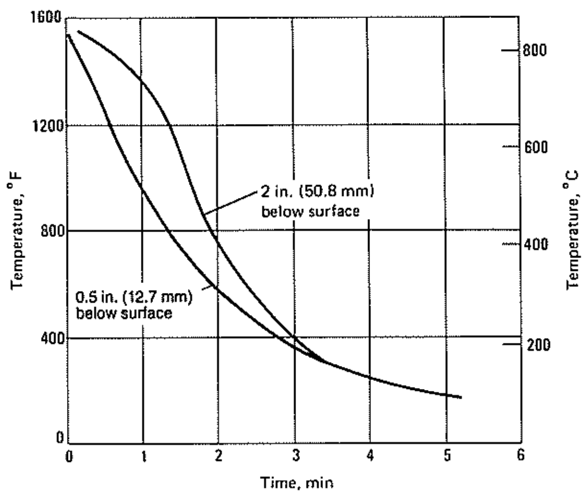
1045: Induction Hardening. Effect of heating time on depth of hardening. Tendency toward cracking of machined and ground specimens. Specimens, 25.4 mm (1 in.) diam, with a 50 kw, 450 000 cycle generator. Water quenched. Hardness, 61 to 63 HRC



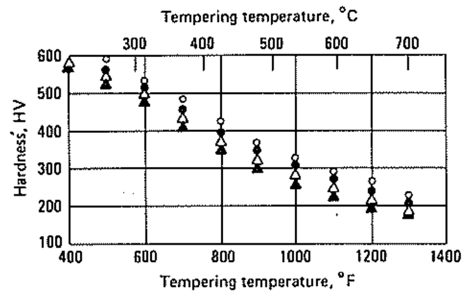
1045: Isothermal Transformation Diagram. Composition: 0.45 C, 0.67 Mn, 0.26 Si, 0.06 Ni, 0.009 Mn, 0.009 P, 0.012 S



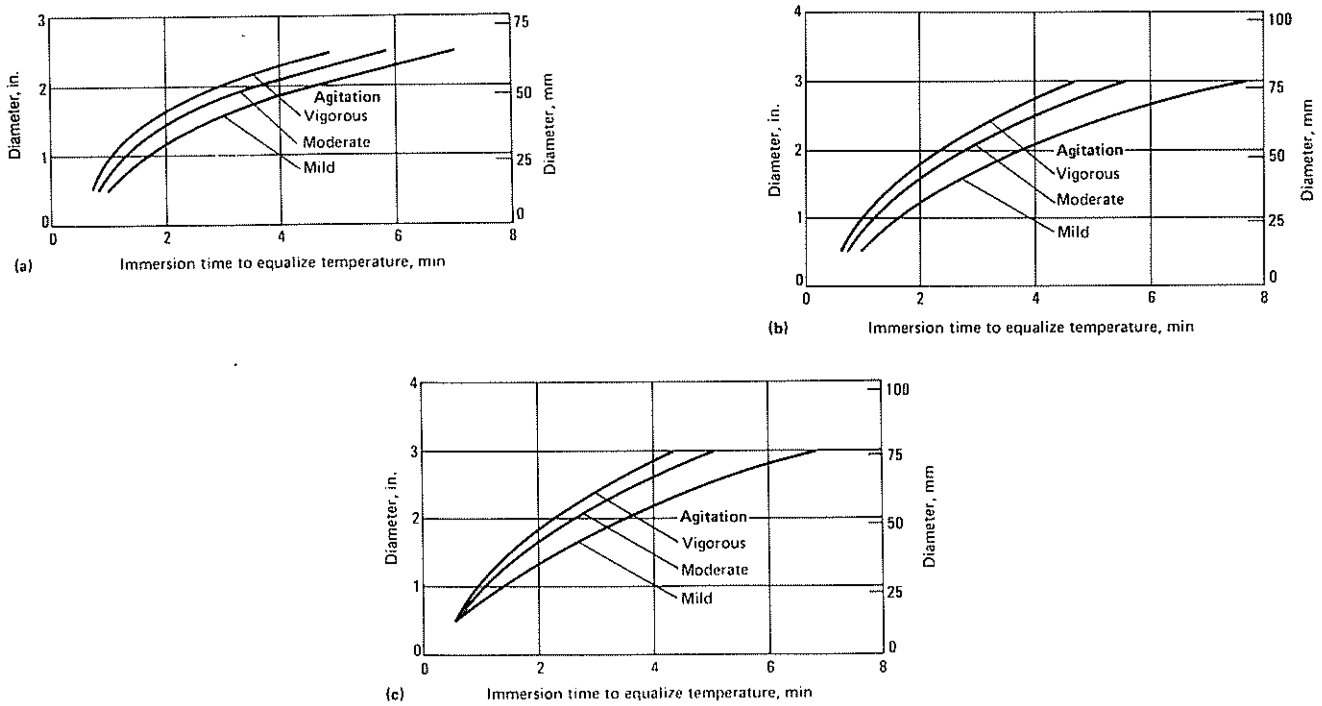
1045: Mass and Section Size vs Cooling Rate in Water. Specimen: 101.6 mm (4 in.) diam; approximately 20 kg (43 lb). Water quenching at 46 °C (115 °F). No agitation



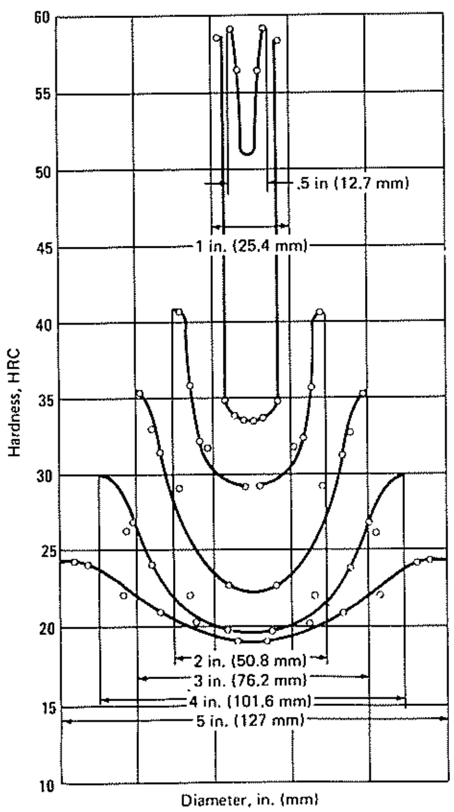
1045: Hardness vs Tempering Temperature/Specimen, 3.175 to 6.35 mm (0.125 to 0:25 in.) thick. Quenched. Legend: O: 10 min; ●: 1 h; Δ: 4 h; ▲: 24 h



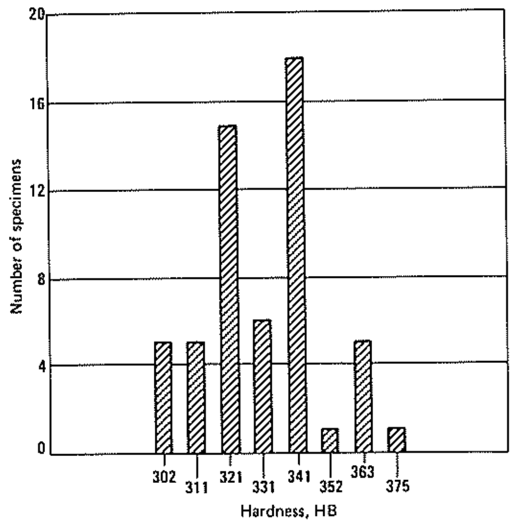
045: Cooling Rates in Martempering. Effects of section size and agitation of quench bath on time required for centers of steel bars to each martempering temperature. Quenching bath is a neutral chloride bath at 845 °C (1550 °F), into anhydrous nitrate - nitrate martem-ering salt at: (a) ; 205 °C (400 °F); (b) 260 °C (500 °F); (c) 315 °C (600 °F). Length of each bar, 3× diam



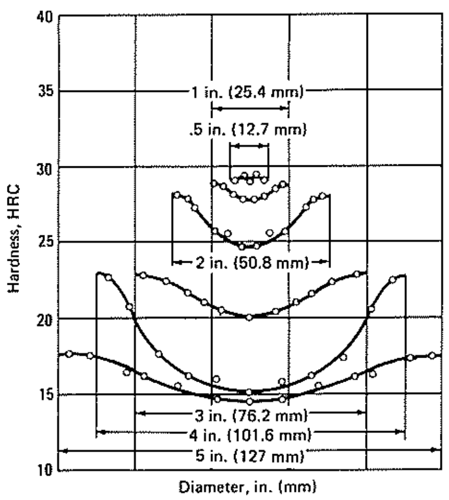
045: Hardness Distribution in Water-Quenched Bars



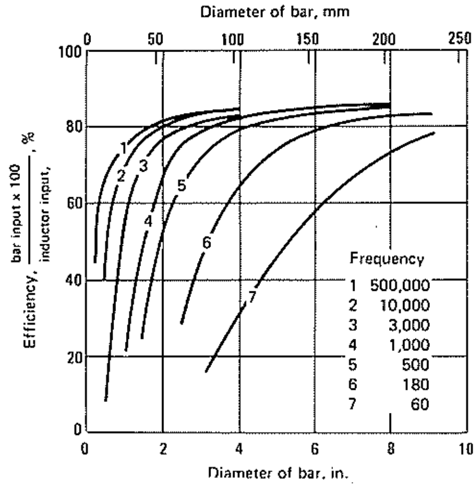
1045: Variations in Hardness After Production Tempering. Plate sections, 19.05 to 22.23 mm (0.75 to 0.875 in.) thick. Water quenched to hardness range of 534 to 653 HB. Tempered at 475 °C (890 °F) for 1 h in continuous roller hearth furnaces. Data represent two-month production period



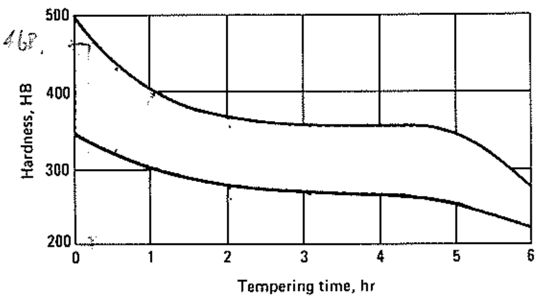
1045: Hardness Distribution in Oil-Quenched Bars



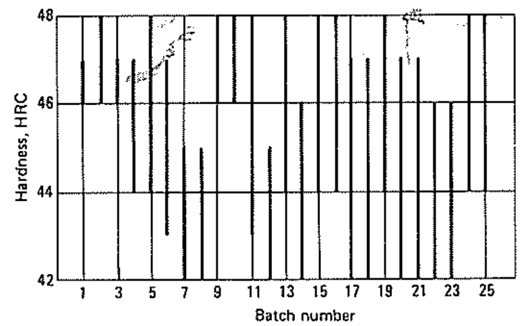
1045: Induction Hardening. Efficiency of energy transfer at several frequencies. Bars of various sizes heated to 1095 °C (2005 °F). Inside diam of inductors, 28.575 mm (1.125 in.) larger than outside diam of bars



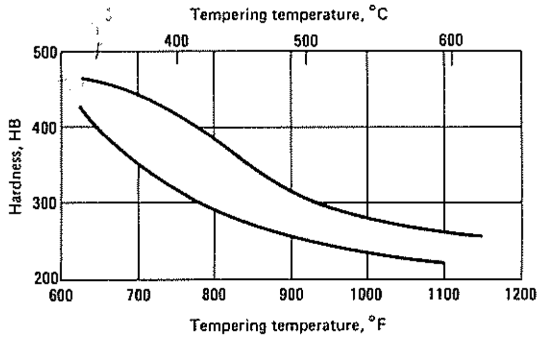
1045: Hardness vs Tempering Temperature. Effect of time at tempering temperature on Brinell hardness of four handgun frame forgings, 101.6 mm (4 in.) by 152.4 mm (6 in.) by 19.05 mm (¾ in.). Heated at 845 °C (1555 °F) in pusher conveyor furnace. Oil quenched. Tempered at 545 °C (1000 °F) in muffle furnace. Both furnaces gas fired, without temperature control. Hardness measured after removal of 0.635 mm (0.025 in.) of material by grinding. 20 heats



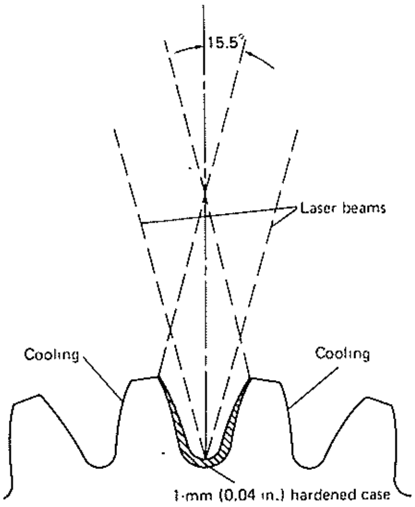
1045: Variations in Hardness After Production Tempering. Forged woodworking cutting tools. Section of cutting lip hardened locally by gas burners that heated steel to 815 °C (1500 °F). Oil quenched and tempered at 305 to 325 °C (585 to 615 °F), 10 min, in electrically heated, recirculating-air furnace to desired hardness, 42 to 48 HRC. Data recorded for 6-month period and represent forgings from 12 mill heats



1045: Hardness vs Tempering Temperature. Specimen, 38.1 to 63.5 mm (1.5 to 2.5 in.) thick. Quenched

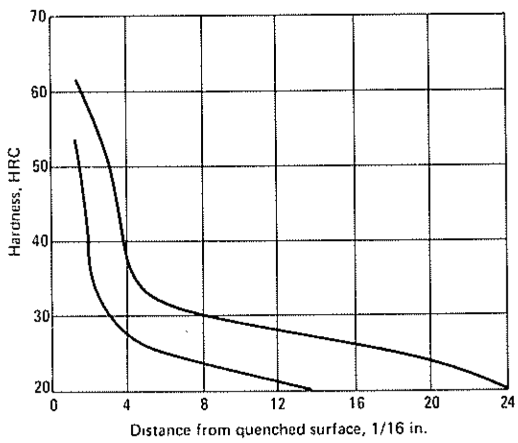


1045: Laser Hardening of Steel Gear



)45H: End-Quench Hardenability

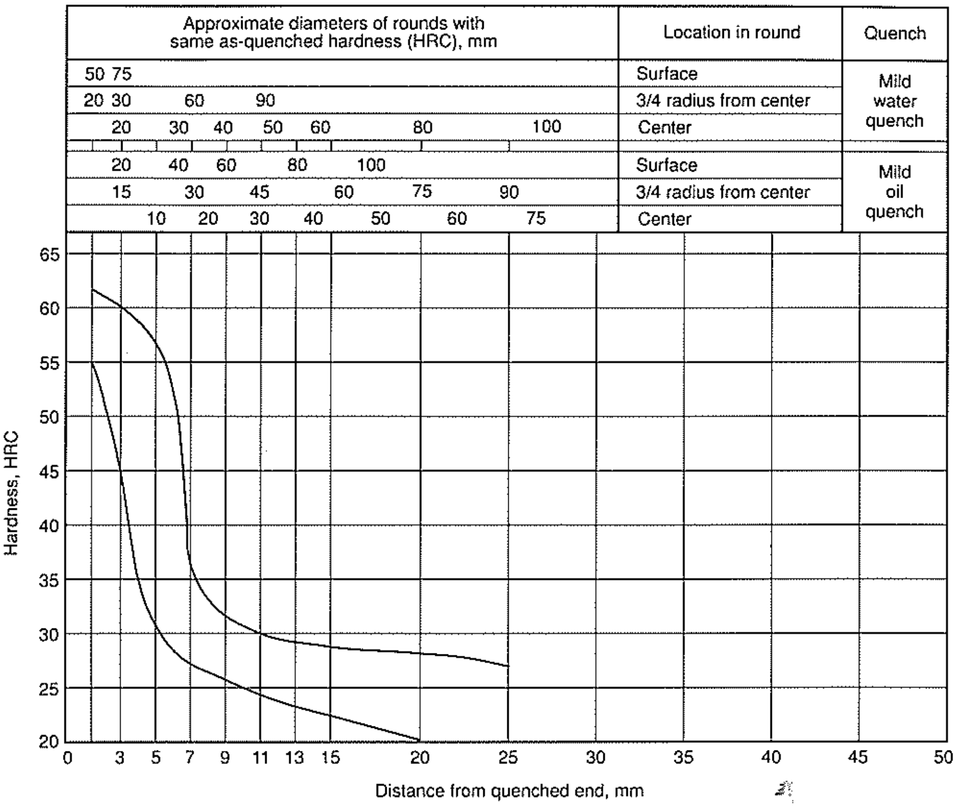
istance from quenched surface		Hardness, HRC		Distance from quenched surface		Hardness, HRC	
6 in.	mm	max	min	⅟16 in.	mm	max	min
l	1.58	62	55	7	11.06	31	25
l.5	2.37	61	52	7.5	11.85	30	24
?	3.16	59	42	8	12.64	30	24
?.5	3.95	56	34	9	14.22	29	23
ı	4.74	52	31	10	15.80	29	22
3.5	5.53	46	29	12	18.96	28	21
ł	6.32	38	28	14	22.12	27	20
4.5	7.11	34	27	16	25.28	26	...
5	7.90	33	26	18	28.44	25	...
5.5	8.69	32	26	20	31.60	23	...
5	9.48	32	25	22	34.76	22	...
5.5	10.27	31	25	24	37.92	21	...



1045H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1550 °F)

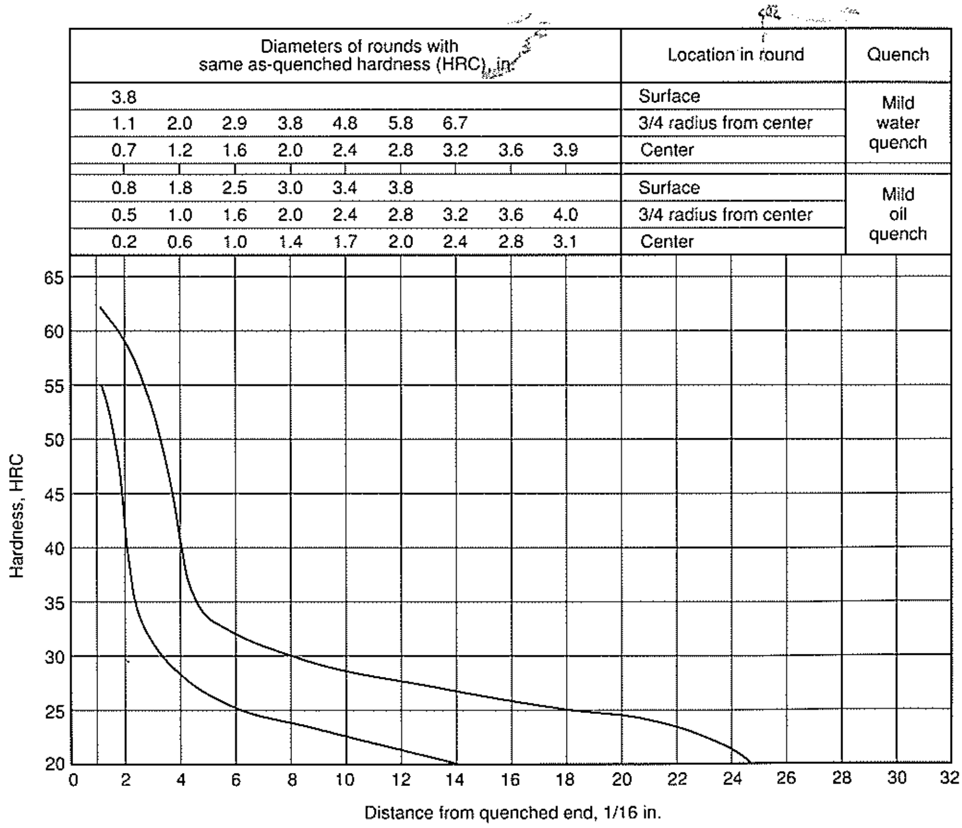
Hardness Limits for Specification Purposes

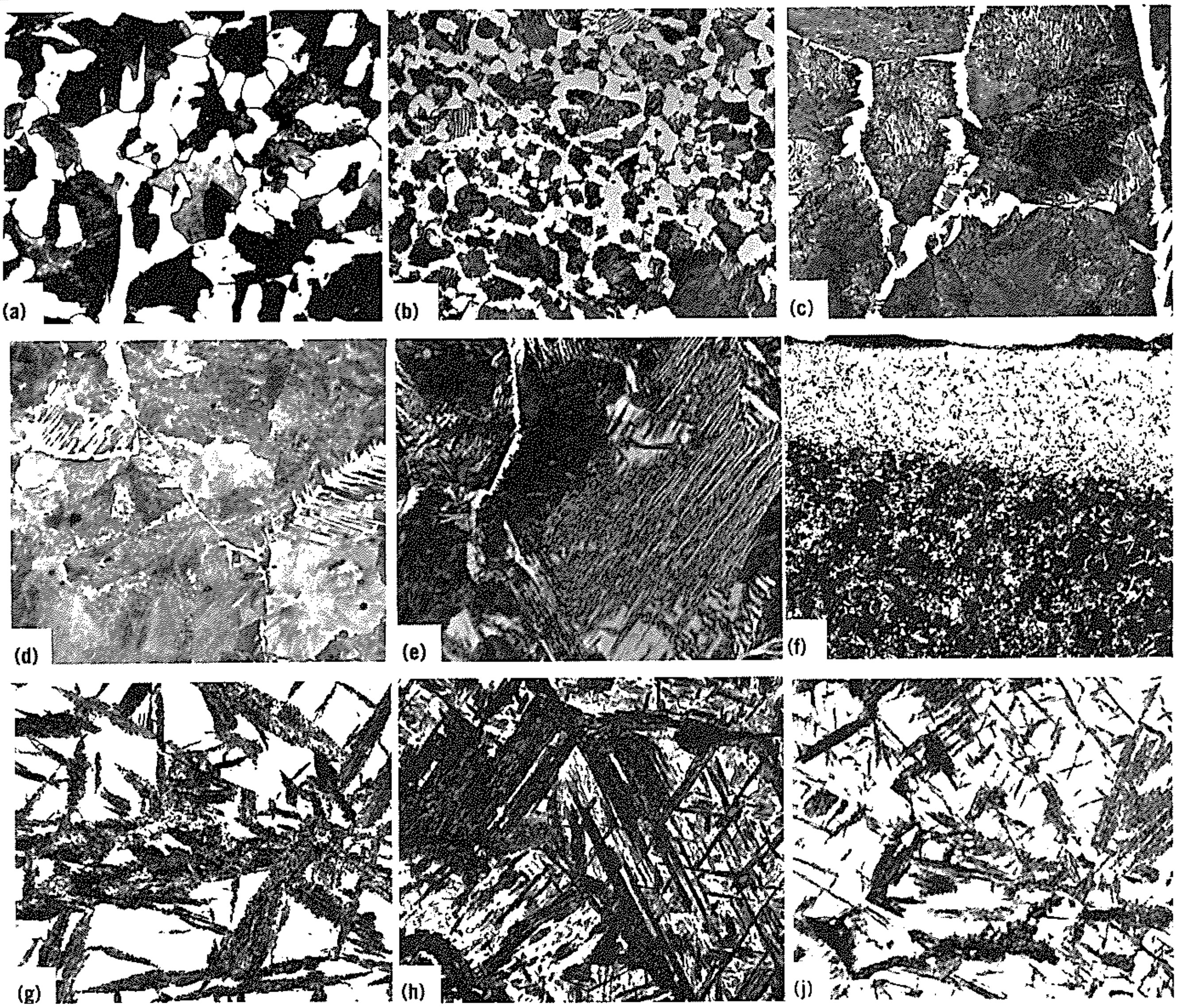
J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	62	55
3	60	45
5	53	31
7	36	27
9	32	25
11	31	24
13	30	23
15	29	22
20	28	20
25	27	...
30	...	...

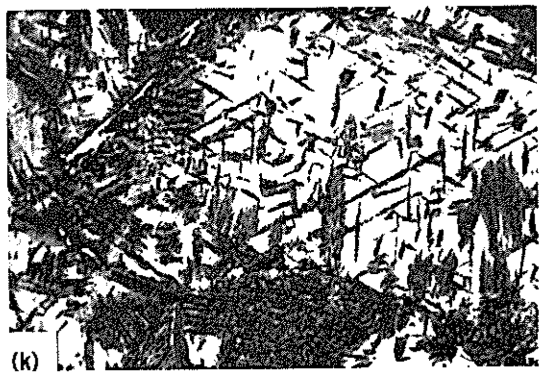


Hardness Limits for Specification Purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	62	55
1.5	61	52
2	59	42
2.5	56	34
3	52	31
3.5	46	29
4	38	28
4.5	34	27
5	33	26
5.5	32	26
6	32	25
6.5	31	25
7	31	25
7.5	30	24
8	30	24
9	29	23
10	29	22
12	28	21
14	27	20
16	26	...
18	25	...
20	23	...
22	22	...
24	21	...







045 : Microstructures. (a) 2% nital, 500×. 25.4 mm (1 in.) bar stock. Normal-:ed by austenitizing at 845 °C (1555 °F). Air cooled. Tempered at 480 °C (895 ⁼), 2 h. Fine lamellar pearlite (dark) and ferrite (white). (b) Picral, 500×. Sheet, .175 mm (1/8 in.) thick. Normalized by austenitizing at 1095 °C (2005 °F). ;ooled in air. Structure is pearlite (dark gray) and ferrite (light). **(c)** Picral, 500×. ;ame as (b), except bar specimen used. Grain size much larger. Pearlite (gray) /ith network of grain-boundary ferrite (white) and a few side plates of ferrite. (d) 'icral, 330×. Forging air cooled from forging temperature of 1205 °C (2200 °F). 'he structure consists of envelopes of proeutectoid ferrite at prior austenite rain boundaries, with emerging spines of ferrite, in matrix of pearlite. (e) 4% pi-ral, 500×. 50.8 mm (2 in.) bar stock, austenitized at 845 °C (1555 °F), 2 h. Oil uenched, 15 sec. Air cooled, 5 min. Quenched to room temperature. Ferrite at rior austenite grain boundaries. Acicular structure probably upper bainite. 'earlite matrix (dark). (f) 2% nital, 100×. Forging austenitized at 900 °C (1650 F), 3 h. Air cooled. Tempered at 205 °C (400 °F) for 2 h. At top is layer of chromium plate. Below, layer of martensite, due to overheating :uring abrasive cutoff. Remainder, ferrite and pearlite. (g) Picral, 500×. Austenitized at 1205 °C (2200 °F), 10 min. Held at 340 °C (640 °F) or 10 min, for partial isothermal transformation. Cooled in air to room temperature. Lower bainite (dark) in matrix of martensite (white). (h) :% nital, 500×. 50.8 mm (2 in.) bar stock. Austenitized 2 h at 845 °C (1555 °F). Oil quenched, 15 sec. Air cooled, 3 min. Water quenched to oom temperature. Specimen from 3.175 mm (1/8 in.) below surface. Dark stripes at prior austenite grain boundaries are probably upper ıainite. Matrix is martensite. (j) 4% picral, 500×. 50.8 mm (2 in.) bar stock. Austenitized 2 1/2 h at 845 °C (1555 °F). Water quenched, 4 sec. ır cooled, 3 min. Water quenched to room temperature. Specimen from 3.175 mm (1/8 in.) below surface. Dark, acicular structure probably ɔwer bainite. Light matrix of martensite. (k) 4% picral, 500×. Same as (j), except somewhat different structure. Gray aggregate probably ıpper bainite. Fine, acicular dispersion probably lower bainite. Martensite matrix

1046

Chemical Composition. **AISI and UNS:** 0.43 to 0.50 C, 0.70 to 1.00 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). UNS G10460; ASTM A510, A576; SAE J403, J412, J414

Characteristics. Higher manganese version of 1045 provides for slightly higher hardenability. As-quenched hardness of at least 55 HRC. Slightly higher when carbon is near high side of the allowable range. Used extensively for parts to be furnace heated or heated by induction prior to quenching. Excellent forgeability. Fair machinability

Forging. Heat to 1245 °C (2275 °F). Do not forge below 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F). Cool in air

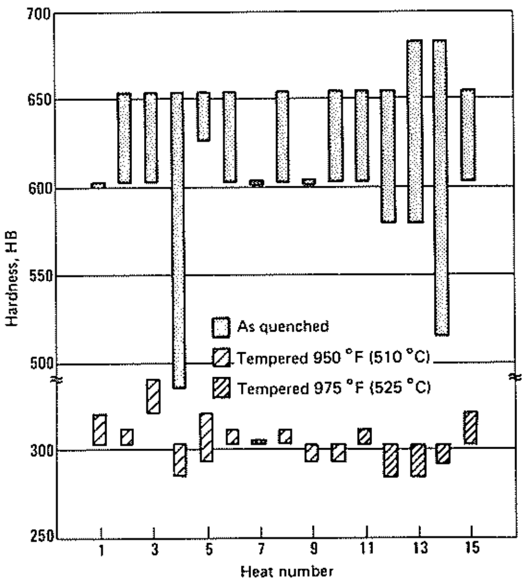
Annealing. Heat to 845 °C (1555 °F). Furnace cool to 650 °C (1200 °F), at a rate not to exceed 28 °C (50 °F) per h

Hardening. Austenitize at 845 °C (1555 °F). Flame hardening, induction hardening, and carbonitriding are suitable surface hardening processes. Quench in water or brine. Rounds under 6.35 mm (0.25 in.) diam may be oil quenched for full hardness

Tempering After Hardening. Hardness of at least 55 HRC if properly austenitized and quenched. Hardness can be adjusted by tempering

Tempering After Normalizing. Normalize and temper as for 1040. For large sections, normalize by conventional practice. This results in a structure of fine pearlite. A tempering treatment up to about 540 °C (1000 °F) is then applied. Mechanical properties not equal to those achieved by quenching and tempering. Resulting strength is far higher than that of annealed structure. Normalizing and tempering often applied to heavy forgings

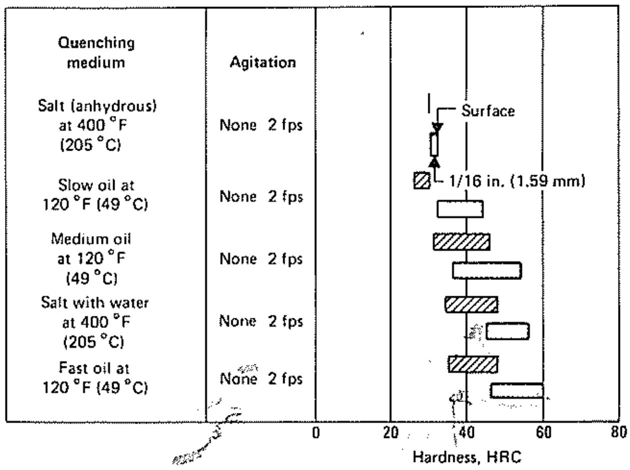
1046: Variations in Hardness After Tempering. Forged specimen heated to 830 °C (1525 °F). Quenched in caustic. Tempered 1 h to range of hardness, 285 to 321 HB. Forgings heated in continuous belt-type furnace and individually dump quenched in agitated caustic. Forgings, 44 to 53 kg (95 to 115 lb) each. Maximum section was 38.1 mm (1.50 in.)



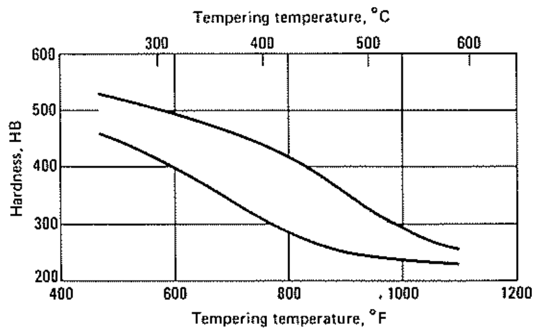
Recommended Processing Sequence

- Forge or machine (bars)
- Normalize (if forged. Not required for parts machined from hot rolled or cold drawn bars)
- Anneal (if necessary. Bar stock usually received in condition for best machining)
- Rough machine (forgings)
- Austenitize (parts from bars or forgings)
- Quench
- Temper
- Finish machine

1046: Quenching. Specimen, 22.225 mm (0.875 in.) diam by 76.2 mm (3 in.). Quenched from 815 °C (1500 °F)



1046: Hardness vs Tempering Temperature. Specimen, 57.15 to 63.5 mm (2.25 to 2.50 in.) thick. Quenched



049

emical Composition. **AISI and UNS:** 0.46 to 0.53 C, 0.60 to) Mn, 0.040 P max, 0.050 S max

nilar Steels (U.S. and/or Foreign). UNS G10490; ASTM 10, A576; SAE J403, J412, J414; (Ger.) DIN 1.1201; (Fr.) AFNOR XC TS; (Jap.) JIS S 50 C; (Swed.) SS_{14} 1660

aracteristics. As-quenched hardness of at least 57 HRC, even with bon on the low side of the allowable range. As-quenched hardness will ally approach 60 HRC, when the carbon is near the maximum, 0.53. :ellent forgeability. Fairly good machinability. Weldability is poor

rging. Heat to 1230 °C (2250 °F). Do not forge below 845 °C (1555 °F)

:commended Heat Treating Practice

rmalizing. Heat to 900 °C (1650 °F). Cool in air

nealing. Heat to 830 °C (1525 °F). Furnace cool to 650 °C (1200 °F), rate not to exceed 28 °C (50 °F) per h

Hardening. Heat to 830 °C (1525 °F). Flame hardening and carbonitriding are suitable surface hardening processes. Quench in water or brine. Rounds less than 6.35 mm (0.25 in.) diam may be fully hardened by oil quenching. Normalize and temper as for 1040

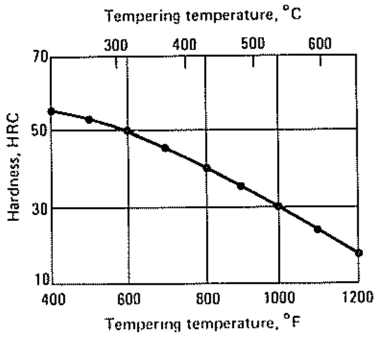
Tempering. As-quenched hardness of 57 to 60 HRC can be adjusted downward by proper tempering temperature

Recommended Processing Sequence

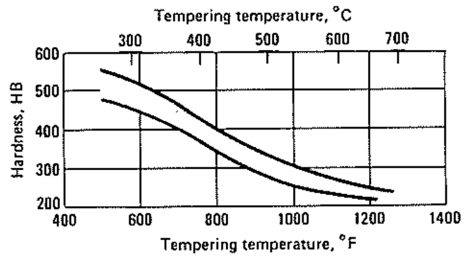
Forgings

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

049: Hardness vs Tempering Temperature. Specimen, 3.175) 6.35 mm (0.125 to 0.25 in.) thick. Quenched. Tempered 1 h



1049: Hardness vs Tempering Temperature. Specimen, 34.925 to 79.375 mm (1.375 to 3.125 in.) thick. Quenched



050

iemical Composition. **AISI and UNS:** 0.48 to 0.55 C, 0.60 to)0 Mn, 0.040 P max, 0.050 S max

milar Steels (U.S. and/or Foreign). UNS G10500; AMS 85; ASTM A510, A519, A576, A682; FED QQ-S-635 (C1050), QQ-S-0 (C1050); MIL SPEC MIL-S-16974; SAE J403, J412, J414; (Ger.) DIN 1210; (Jap.) JIS S 53 C, S 55 C

haracteristics. Carbon content as high as 0.55. Borderline between nedium carbon and a high-carbon grade. Used extensively for producing iall to medium size forgings. Often selected for parts to be induction rdened. Fully quenched hardness of at least 58 to 60 HRC, especially ien carbon is on the high side of the range. Excellent forgeability. Fairly od machinability. Weldability is poor. Not available as an H grade

orging. Heat to 1230 °C (2250 °F). Do not forge below 845 °C (1555 °F)

ecommended Heat Treating Practice

ormalizing. Heat to 900 °C (1650 °F). Cool in air

nnealing. Heat to 830 °C (1525 °F). Furnace cool to 650 °C (1200 °F), a rate not to exceed 28 °C (50 °F) per h

Hardening. Austenitize at 830 °C (1525 °F). Flame hardening, induction hardening, carbonitriding, austempering, and laser hardening are suitable surface hardening processes. Quench in water or brine. Rounds less than 6.35 mm (0.25 in.) diam may be fully hardened by oil quenching. Normalize and temper as for 1040

Tempering. As-quenched hardness of 58 to 60 HRC can be reduced by the proper tempering temperature

Recommended Processing Sequence

Forgings

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

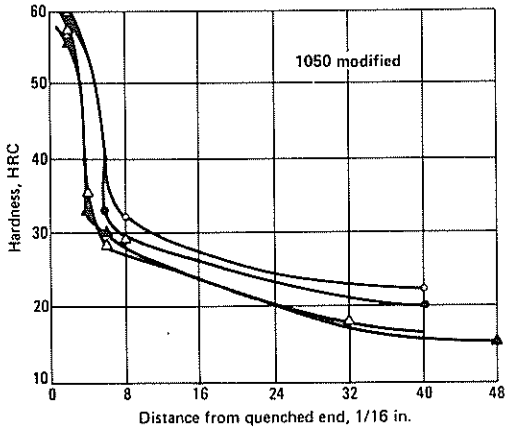
1050: As-Quenched Hardness (Oil)

Grade: 0.48 to 0.55 C, 0.60 to 0.90 Mn, 0.090 P max, 0.050 S max; grain size 5 to 7

Size round		Hardness, HRC		
in.	mm	Surface	½ radius	Center
½	12.7	57	37	34
1	25.4	33	30	26
2	50.8	27	25	21
4	101.6	98	95	91

Source: Bethlehem Steel

1050: Effect of Carbon and Manganese on End-Quench Hardenability. Modified 1050. O: 0.51 C, 1.29 Mn, 0.06 residual Cr; ●: 0.52 C, 1.27 Mn, 0.06 residual Cr; Δ:0.48 C, 1.07 Mn, 0.06 residual Cr; ▲:0.51 C, 1.04 Mn, 0.08 residual Cr



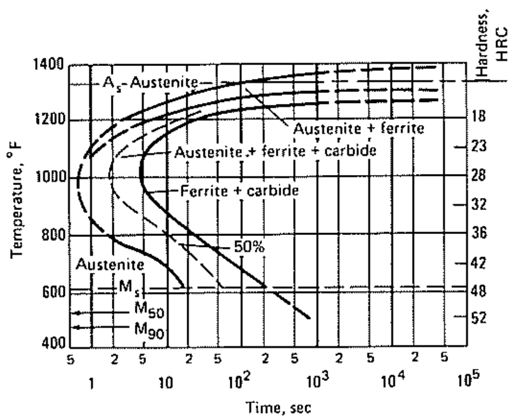
1050: As-Quenched Hardness (Water)

Grade: 0.48 to 0.55 C, 0.60 to 0.90 Mn, 0.040 P max, 0.050 S max; grain size 5 to 7

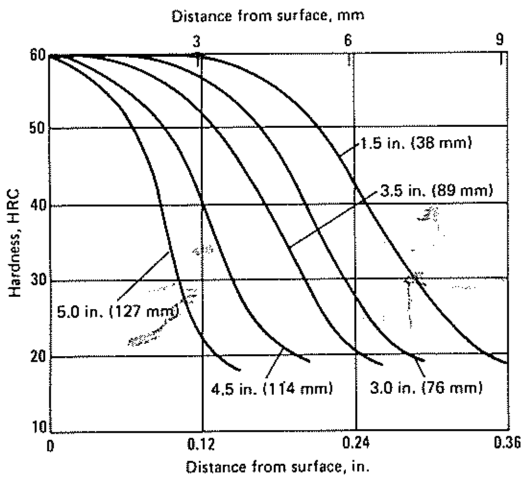
Size round		Hardness, HRC		
in.	mm	Surface	½ radius	Center
½	12.7	64	59	57
1	25.4	60	35	33
2	50.8	50	32	26
4	101.6	33	27	20

Source: Bethlehem Steel

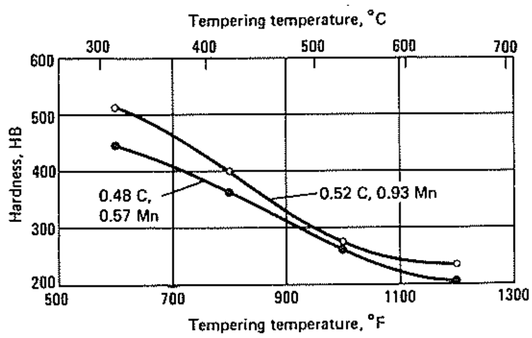
1050: Isothermal Transformation Diagram. Composition: 0.50 C, 0.91 Mn. Austenitized at 910 °C (1670 °F). Grain size, 7 to 8. Martensite temperatures estimated



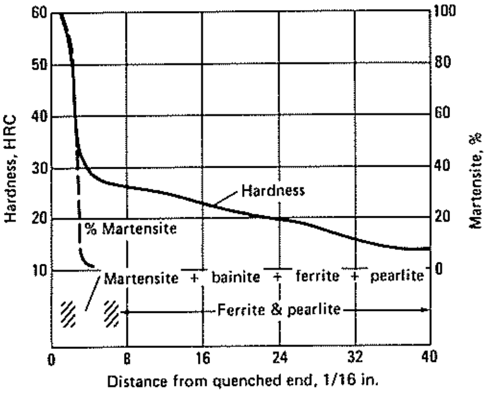
1050: Flame Hardening



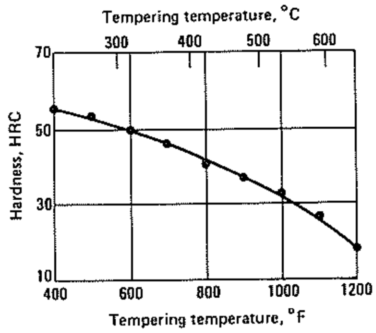
1050: Hardness vs Tempering Temperature and Chemical Composition



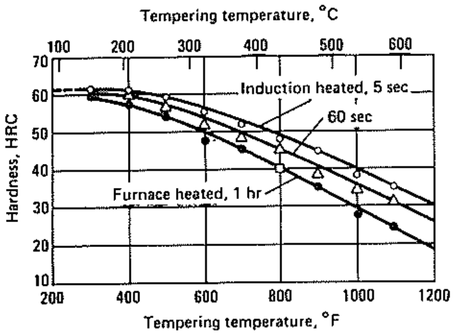
50: End-Quench Hardenability. Composition: 0.46 C, 0.99 n. Austenitized at 845 °C (1555 °F). Grain size, 7



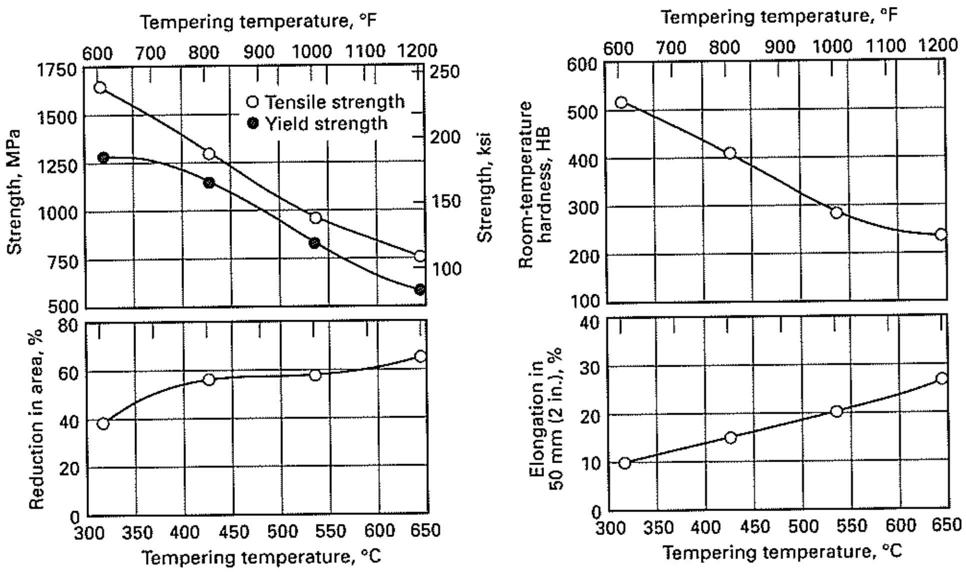
1050: Hardness vs Tempering Temperature. Specimen, 3.175 to 6.35 mm (0.125 to 0.25 in.) thick. Quenched. Tempered 1 h



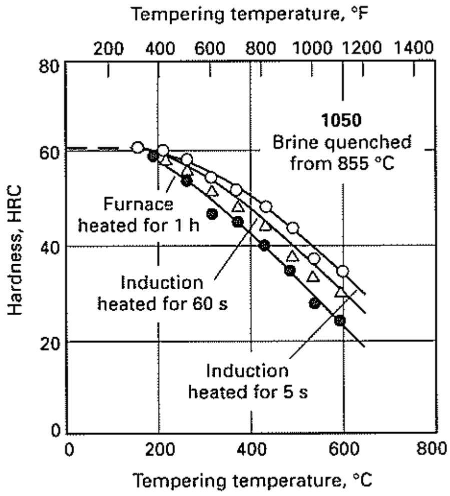
1050: Furnace vs Induction Hardening. Brine quenched from 855 °C (1570 °F)



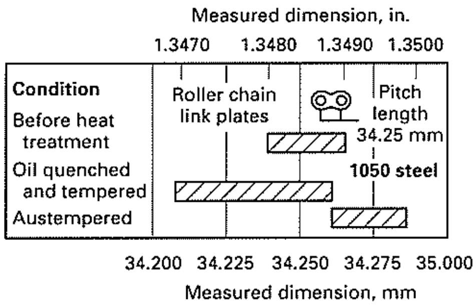
050: Tempering. Effect of tempering temperature on room-temperature mechanical properties of 1050 steel. Properties summarized are r one heat of 1050 steel that was forged to 38 mm (1.50 in.) in diameter, then water quenched and tempered at various temperatures. omposition of heat: 0.52% C, 0.93% Mn



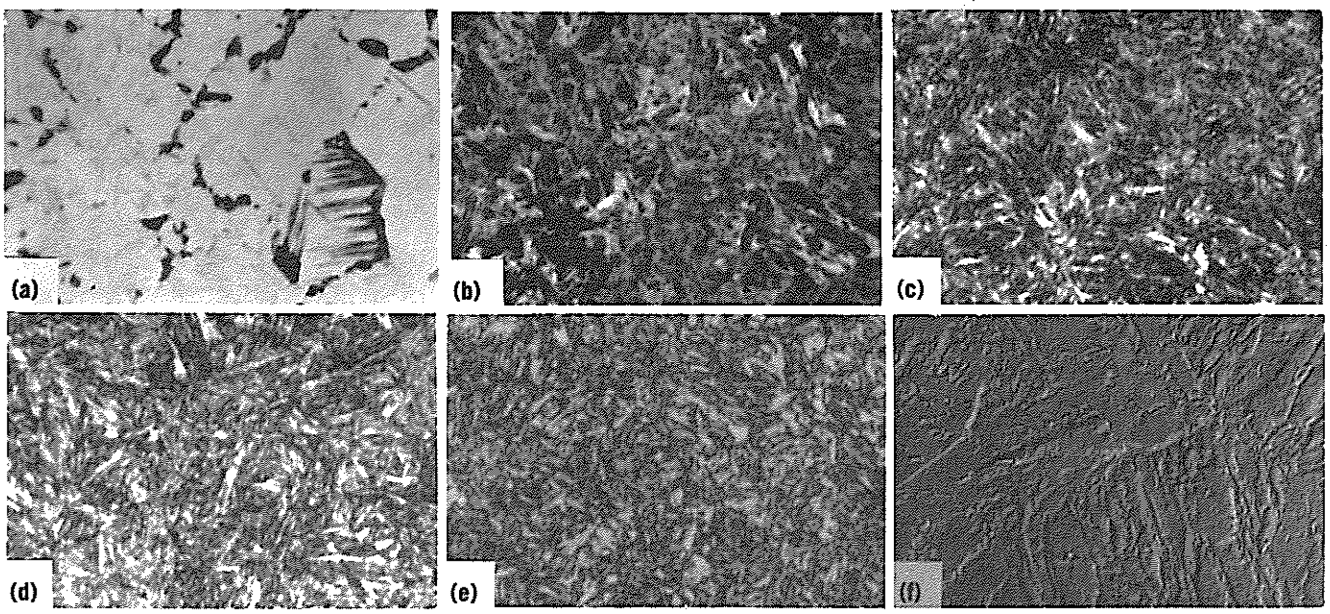
1050: Induction Heating. Variations of room-temperature hardness with tempering temperature for furnace and induction heating



1050: Austempering. Variation in pitch length of 2 mm (0.080 in.) thick link plates after austempering and after oil quenching and tempering. All link plates were austenitized at 855 °C (1570 °F) for 11 min; austempered link plates were held in salt at 340 °C (650 °F) for approximately 1 h, a time dictated by convenience in processing but not required to attain complete transformation



1050: Microstructures. (a) Nital, 825X. Austenitized at 870 °C (1600 °F), 1/2 h. Oil quenched. Slow quenching permitted formation of some grain-boundary ferrite and bainite (feathery areas). Matrix is martensite (white). (b) Austenitized at 870 °C (1600 °F); 1 h. Water quenched. Tempered at 260 °C (500 °F), 1 h. Structure is fine-tempered martensite. No free ferrite visible, indicating quench was effective. (c) Nital, 825×. Same as (b) except tempered at 370 °C (700 °F), 1 h. Tempered martensite. (d) Nital, 825×. Same as (b), except tempered at 480 °C (895 °F), 1 h. Tempered martensite. Ferrite and carbide barely resolved. (e) Nital, 825×. Same as (b), except tempered at 595 °C (1105 °F). Tempered martensite. Ferrite and carbide better resolved. (f) Nital, 913×. Same as (d). Replica electron micrograph. Typical of a thoroughly quenched structure



1053

Chemical Composition. **AISI and UNS:** 0.48 to 0.55 C, 0.70 to 1.00 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). UNS G10530; ASTM A510, A576; SAE J403, J412, J414

ıaracteristics. Similar to 1050, except a higher manganese content .ich slightly increases hardenability. In some application, higher har- ıability is useful. In induction hardening, higher hardenability may ıse quench cracking. Excellent forgeability. Fairly good machinability. :ldability is poor

ırging. Heat to 1230 °C (2250 °F). Do not forge below 845 °C (1555 °F)

ecommended Heat Treating Practice

ırmalizing. Heat to 900 °C (1650 °F). Cool in air

ınealing. Heat to 830 °C (1525 °F). Furnace cool to 650 °C (1200 °F), a rate not to exceed 28 °C (50 °F) per hour

ardening. Heat to 830 °C (1525 °F). Carbonitriding and induction rdening are suitable processes. Quench in water or brine. Rounds less ın 6.35 mm (0.25 in.) diam may be oil quenched for full hardness. ırmalize and temper, as for 1040

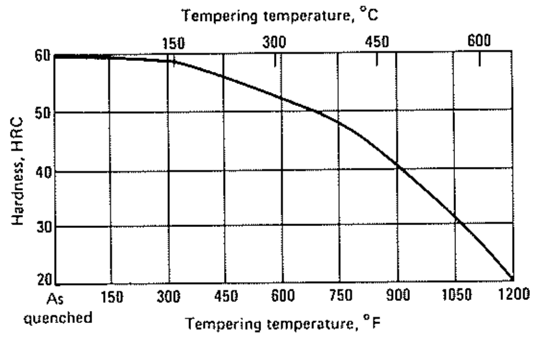
ımpering. As-quenched hardness of 58 to 60 HRC can be reduced by ɔper tempering temperature

ecommended Processing Sequence

ırgings

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

1053: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure



055

hemical Composition. AISI and UNS: 0.50 to 0.60 C, 0.60 to ɔ0 Mn, 0.040 P max, 0.050 S max

imilar Steels (U.S. and/or Foreign). UNS G10550; ASTM 510, A576, A682; FED QQ-S-700 (C1055); SAE J403, J412, J414; (Ger.) IN 1.1209

haracteristics. Generally considered a high-carbon steel. When ırbon approaches 0.60 a near saturated martensite is formed after austeni- :ing and severe quenching. As-quenched hardness of 60 to 64 HRC is ɔtained, depending on carbon content. A shallow hardening or low-hard- ıability steel. Good forgeability. Poor machinability. Not recommended r welding

orging. Heat to 1205 °C (2200 °F). Do not forge below 815 °C (1500 °F)

ecommended Heat Treating Practice

ormalizing. Heat to 900 °C (1650 °F). Cool in air

nnealing. Heat to 830 °C (1525 °F). Furnace cool to 650 °C (1200 °F), a rate not to exceed 28 °C (50 °F) per h

lardening. Heat to 830 °C (1525 °F). Flame hardening and carbonitrid- ıg are suitable surface hardening processes. Quench in water or brine. ounds less than 6.35 mm (1/4 in.) diam may be oil quenched for full ardness. Normalize and temper as for 1040

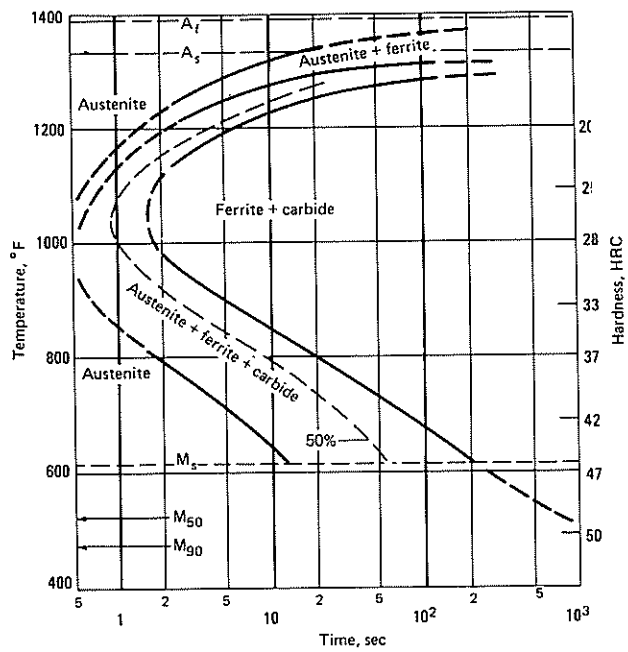
empering. As-quenched hardness of 60 to 64 HRC can be reduced by roper tempering temperature

ecommended Processing Sequence

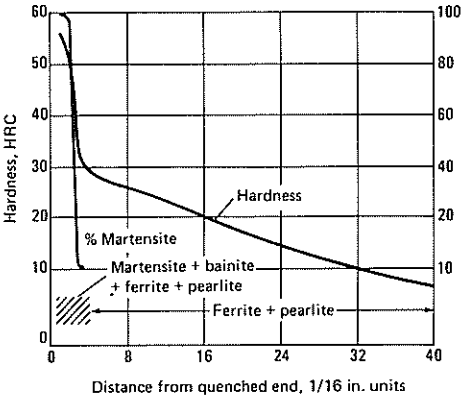
orgings

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

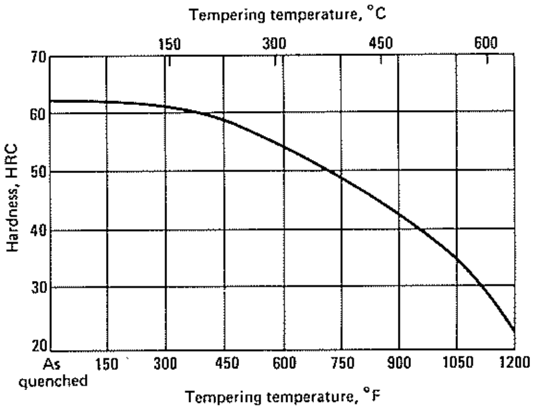
1055: Isothermal Transformation Diagram. Composition: 0.54 C, 0.46 Mn. Austenitized at 910 °C (1670 °F). Grain size, 7 to 8. Martensite temperatures estimated



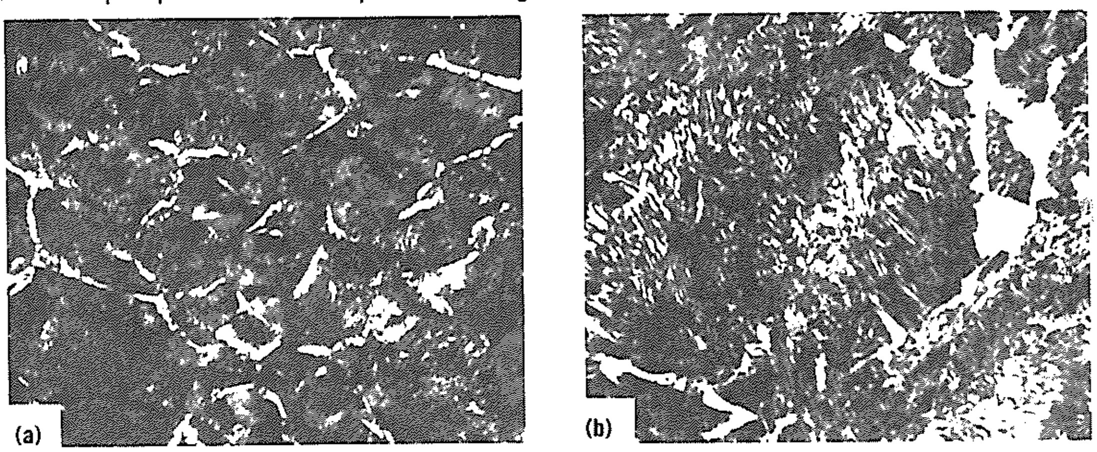
1055: End-Quench Hardenability. Composition: 0.47 C, 0.57 Mn. Austenitized at 845 °C (1555 °F). Grain size, 6 to 7



1055: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure



1055: Microstructures. (a) Picral, 1000×. 6.35 mm (0.25 in.) diam rod, patented by austenitizing 2 1/3 min at 930 °C (1705 °F). Quenched 35 sec in lead bath at 550 °C (1020 °F). Air cooled. Unresolved pearlite (dark). Ferrite (white), at prior austenite grain boundaries. (b) Picral, 1000×. 3.353 mm (0.132 in.) diam wire. Air patented by austenitizing 1 1/2 min at 1032 °C (1890 °F). Air cooled in strand form. Line lamellar pearlite with discontinuous precipitation of ferrite at prior austenite grain boundaries



1059

Chemical Composition. AISI and UNS: 0.55 to 0.65 C, 0.50 to 0.80 Mn, 0.040 P max, 0.050 S max (standard steel grade for wire rod and wire only)

Recommended Heat Treating Practice

Hardening. Flame hardening and carbonitriding are suitable surface hardening processes

1060

Chemical Composition. AISI and UNS: 0.55 to 0.65 C, 0.60 to 0.90 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). UNS G10600; AMS 7240; ASTM A510, A576, A682; MIL SPEC MIL-S-16974; SAE J403, J412, J414; (Ger.) DIN 1.0601; (Fr.) AFNOR CC 55; (Ital.) UNI C 60; (U.K.) B.S. 060 A 62

Characteristics. Versatile high-carbon grade. Product forms include various thicknesses of flat stock for fabricating parts to be spring tempered. Good forgeability. Not recommended for welding. As-quenched hardness of near 65 HRC. This is near maximum Rockwell hardness. When properly quenched, consists of a carbon-rich martensite structure with essentially no free carbide

ɪrging. Heat to 1205 °C (2200 °F). Do not forge below 815 °C (1500 °F)

ɜcommended Heat Treating Practice

ɪrmalizing. Heat to 885 °C (1625 °F). Cool in air

ınealing. Heat to 830 °C (1525 °F). Furnace cool to 650 °C (1200 °F), ı rate not to exceed 28 °C (50 °F) per h

ırdening. Heat to 815 °C (1500 °F). Flame hardening, carbonitriding, ıstempering, and martempering are suitable surface hardening processes. ɛench in water or brine. Rounds under 6.35 mm (0.25 in.) diam may be quenched for full hardness

ımpering. As-quenched hardness from 62 to 65 HRC. This maximum ɪdness can be reduced by proper tempering temperature

ıstempering. Thin sections (typically springs) are austempered. Re-ts in a bainitic structure and hardness of approximately 46 to 52 HRC. ıstenitize at 815 °C (1500 °F). Quench in molten salt bath at 315 °C (600). Hold at temperature for at least 1 h. Air cool. No tempering required

ɜcommended Processing Sequence

ɪrgings

Forge
Normalize
Anneal
Rough machine
Austenitize
Quench
Temper
Finish machine

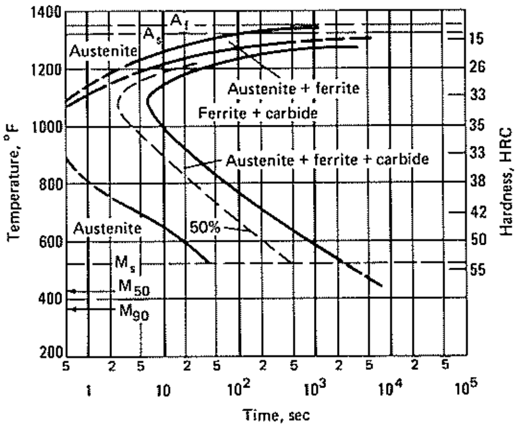
ı60: As-Quenched Hardness (Oil)

ɪade: 0.55 to 0.65 C, 0.60 to 0.90 Mn, 0.040 P max, 0.050 S max; ɜin size 5 to 7 (90%); 1 to 3 (10%)

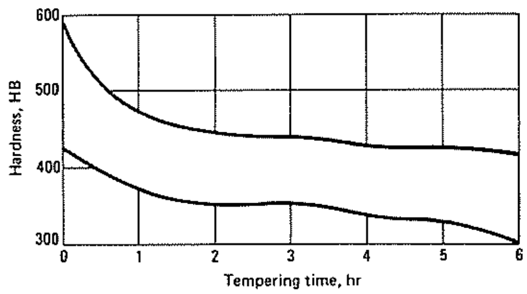
Size round	Hardness, HRC		
mm	Surface	½ radius	Center
12.7	59	37	35
25.4	34	32	30
50.8	30.5	27.5	25
101.6	29	26	24

ɪrce: Bethlehem Steel

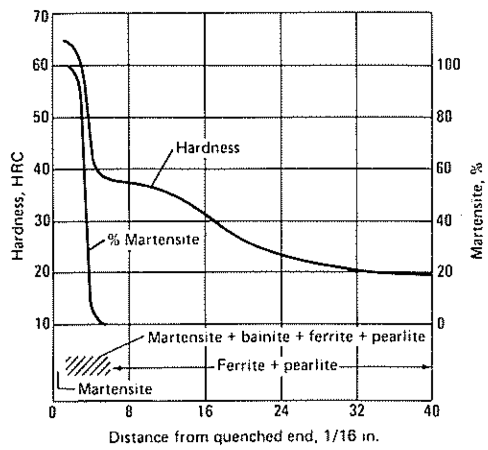
1060: Isothermal Transformation Diagram. Composition: 0.63 C, 0.87 Mn. Austenitized at 815 °C (1500 °F). Grain size, 5 to 6. Martensite temperatures estimated



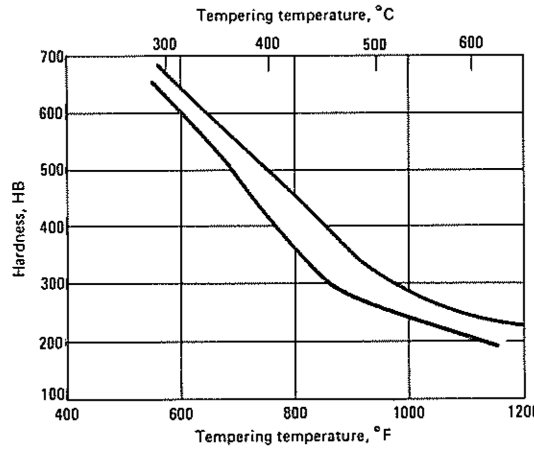
1060: Hardness vs Tempering Time. Machine tool component forging, 114.3 mm (4.5 in.) long. Rectangular cross section, 15.875 by 22.225 mm (0.625 by 0.875 in.). Heated at 815 °C (1500 °F) in pusher conveyor furnace. Oil quenched. Tempered at 480 °C (895 °F) in muffle furnace. Both furnaces gas fired. No atmosphere control. Hardness measured on polished flash line. 20 heats



1060: End-Quench Hardenability. Composition: 0.63 C, 0.87 Mn. Austenitized at 815 °C (1500 °F). Grain size, 5 to 6



1060: Hardness vs Tempering Temperature. 4.673 to 104.775 mm (0.19 to 4.125 in.) thick. Quenched

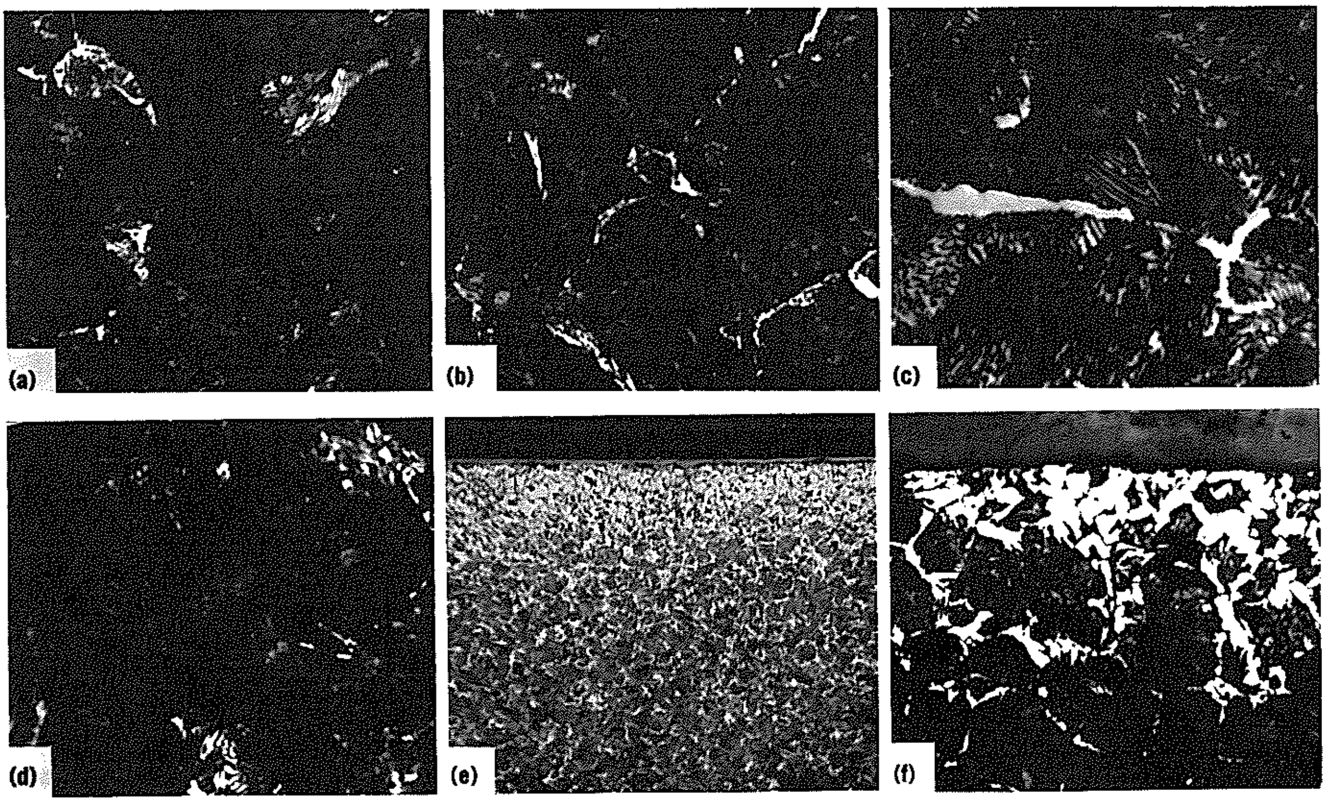


Equipment Requirements for Austenitizing, Austempering, and Corrosion Protection of Parts Made of 1035 and 1060 Steels

Equipment comprises a manually operated monorail heat-treating line

Production requirements			
Part	Fabricated disk	Rectangular tube	Rectangular plate
Steel	1035	1060	1060
Section thickness, mm (in.)	12.5 (0.492)	1.4 (0.055)	0.8 (0.032)
Weight of part, kg (lb)	1.1 (2.5)	0.2 (0.425)	0.01 (0.024)
Load weight (gross), kg (lb)	163 (360)	35.7 (78.75)	7.3 (16)
Number of pieces per h	432	720	3900
Preheating, °C (°F); min	705 (1300); 10	705 (1300); 5	705 (1300); 5
Austenitizing, °C (°F); min	845-870 (1550-1600); 10	830 (1525); 10	830 (1525); 10
Austempering, °C (°F); min	425 (800); 10	345 (650); 6	330 (630); 6
Equipment requirements			
Preheating furnace	Immersed-electrode salt bath, 0.45 by 0.6 by 1.6 m (18 by 24 by 62 in.)		
Amount of chloride salt, kg (lb)	590 (1300)		
Austenitizing furnace	Immersed-electrode salt bath, 0.45 by 0.6 by 1.6 m (18 by 24 by 62 in.)		
Amount of chloride salt, kg (lb)	590 (1300)		
Austempering furnace	Gas-fired salt bath, 0.6 by 1.2 by 1.8 m (24 by 48 by 72 in.)		
Amount of nitrate-nitrite salt, kg (lb)	2270 (5000)		
Heat input, kJ (Btu) per h	740,000 (700,000)		
Agitation	Two 150 mm (6 in.) impellers		
Two washing and rinsing tanks	Gas-fired, hot water; each 0.5 by 0.9 by 1.2 m (20 by 36 by 48 in.)		
Capacity, each tank	570 L (150 gal)		
Heat input, each tank, kJ (Btu) per h	316,000 (300,000)		
Tank for corrosion protection, m (in.)	0.5 by 0.9 by 1.2 m (20 by 36 by 48 in.)		

1060: Microstructures. (a) Picral, 1000×. 6.35 mm (0.25 in.) diam rod. Cooled from hot rolling in single strand by high-velocity air blast. Mostly unresolved pearlite. Some distinctly lamellar pearlite. Few scattered white areas are ferrite, partly outlining prior austenite grains. (b) Picral, 1000×. 6.747 mm (0.266 in.) diam rod, patented by austenitizing at 945 °C (1730 °F), 2.50 min. Quenched in lead bath at 530 °C (990 °F), 55 sec. Air cooled. Pearlite (dark areas) and ferrite (white) at prior austenite grain boundaries. (c) Picral, 1000×. 7.137 mm (0.281 in.) diam wire. Air patented by austenitizing at 1055 °C (1930 °F), 3 min. Air cooled in strand form. Partly resolved pearlite (dark). Ferrite (white) at prior austenitizing grain boundaries. (d) Picral, 1000×. 2.515 mm (0.099 in.) diam wire. Air patented by austenitizing at 1015 °C (1860 °F), 1 min. Air cooled in strand form. Fine pearlite (dark), mostly unresolved. Some ferrite at prior austenite grain boundaries. (e) Picral, 100×. Decarburized. Heated to 1205 °C (2200 °F), 1 h before rolling to size. Thin layer of scale at surface (top of micrograph). Decarburized white layer near top. Unresolved pearlite, ferrite. (f) Picral, 500×. Decarburized. Heated to 870 to 925 °C (1600 to 1695 °F), 12 min. Air cooled. Scale at top of micrograph. Partly decarburized layer, below scale. Pearlite (dark). Some grain-boundary ferrite



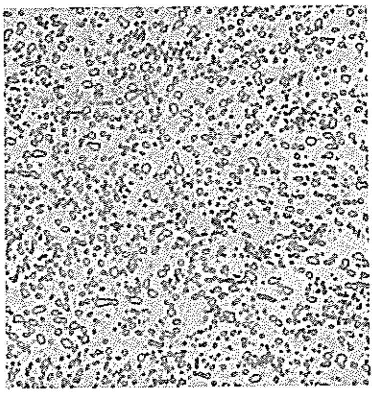
1064

Chemical Composition. **AISI and UNS:** 0.60 to 0.70 C, 0.50 to 0.80 Mn, 0.040 P max, 0.050 S max

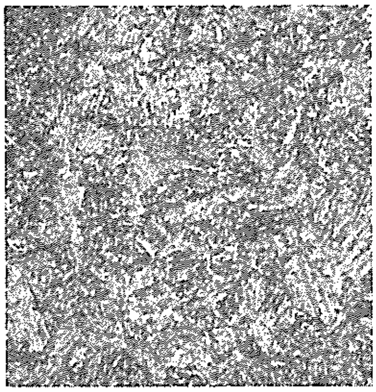
Recommended Heat Treating Practice

Hardening. Flame hardening and carbonitriding are suitable surface hardening processes

1064: Microstructure. 1064 cold-rolled steel strip, heated to 745 °C (1370 °F), furnace cooled to 650 °C (1200 °F), and air cooled to room temperature. Structure is fine spheroidal cementite in a matrix of ferrite. This structure is preferred for subsequent heat treatment. Picral. 500×



1064: Microstructure. 1064 cold-rolled steel strip, austenitized at 815 °C (1500 °F), quenched to 315 °C (600 °F) and held to complete isothermal transformation, air cooled, and tempered at 370 °C (700 °F). The structure is a mixture of bainite and tempered martensite. Picral. 500×

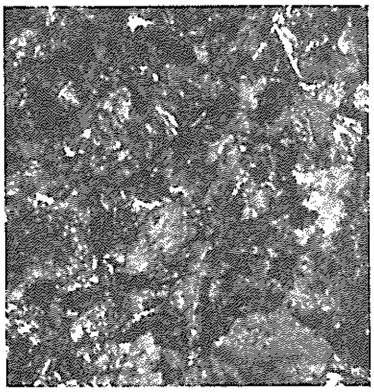


1065

Chemical Composition. **AISI and UNS:** 0.60 to 0.70 C, 0.60 to 0.90 Mn, 0.040 P max, 0.050 S max

Recommended Heat Treating Practice

Hardening. Flame hardening, carbonitriding, austempering, and martempering are suitable processes



1065: Microstructure. 1065 steel wire, 3.4 mm (0.14 in.) in diameter, patented by austenitizing 1.5 min at 930 °C (1705 °F), quenching 30 s in a lead bath at 545 °C (1015 °F), and air cooling. The structure is mostly unresolved pearlite with some grain-boundary ferrite. Picral. 500×

1069

Chemical Composition. AISI and UNS: 0.65 to 0.75 C, 0.40 to 0.70 Mn, 0.040 P max, 0.050 S max

Recommended Heat Treating Practice

Hardening. Flame hardening and carbonitriding are suitable surface hardening processes

1070

Chemical Composition. AISI and UNS: 0.65 to 0.75 C, 0.60 to 0.90 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). UNS G10700; AMS 5115; ASTM A510, A576, A682; MIL SPEC MIL-S-11713 (2); SAE J403, J412, J414; (Ger.) DIN 1.1231; (Fr.) AFNOR XC 68; (Swed.) SS_{14} 1770, 1778

Characteristics. Low hardenability. Widely used in hardened and tempered (notably, spring tempered) condition. Good forgeability and shallow hardening. Used extensively for making hand tools, such as hammers and woodcutting saws. Fully hardened microstructure is carbon-rich martensite with some small undissolved carbides. Carbides not present in 1060, due to lower carbon content. Although same hardness as 1060 (65 HRC), existence of some free carbide gives 1070 greater resistance to abrasive wear. Not recommended for welding

Forging. Heat to 1190 °C (2175 °F). Do not forge below 815 °C (1500 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 885 °C (1625 °F). Cool in air

Annealing. Heat to 830 °C (1525 °F). Furnace cool to 650 °C (1200 °F), at a rate not to exceed 28 °C (50 °F) per h

Hardening. Heat to 815 °C (1500 °F). Flame hardening, induction hardening, carbonitriding, laser hardening, electron beam hardening, austempering, and martempering are suitable surface hardening processes. Quench in water or brine. Rounds under 6.35 mm (0.25 in.) diam may be oil quenched for full hardness

Tempering. As-quenched hardness approximately 65 HRC. Hardness can be reduced by proper tempering

Austempering. Thin sections (typically, springs) are austempered. Results in a bainitic structure and hardness of approximately 46 to 52 HRC. Austenitize at 815 °C (1500 °F). Quench in molten salt bath at 315 °C (600 °F). Hold at temperature for at least 1 h. Air cool. No tempering required

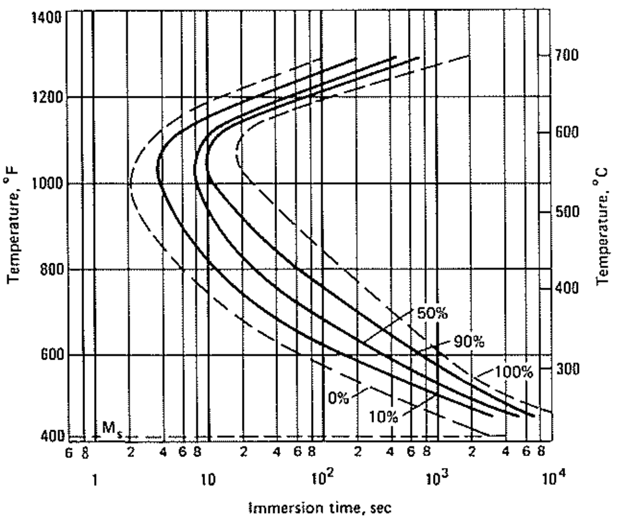
Martempering. Austenitize at 845 °C (1555 °F). Martemper in oil at 175 °C (345 °F)

Recommended Processing Sequence

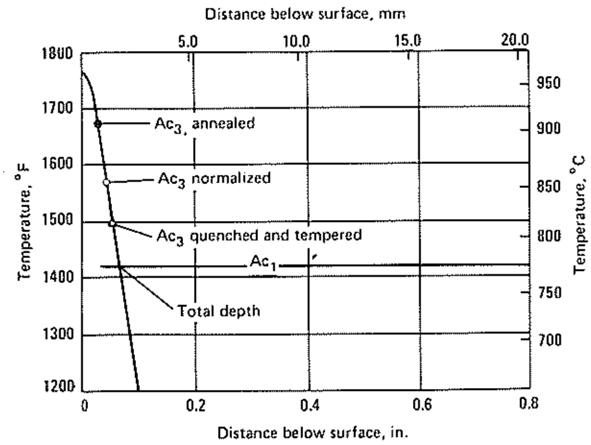
Forgings

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

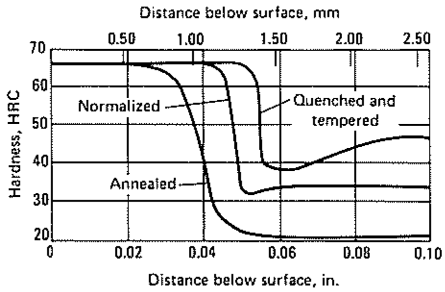
1070: Isothermal Transformation Diagram. Composition: 0.75 C, 0.70 Mn, 0.017 P, 0.016 S, 0.33 Si, 0.20 Ni, 0.17 Cr. Austenitized at 800 °C (1470 °F). Grain size, 5 to 6. Time held in constant temperature bath from start of quench



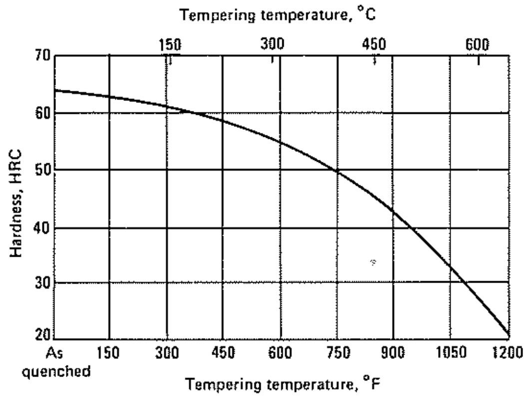
1070: Temperature vs Depth of Case



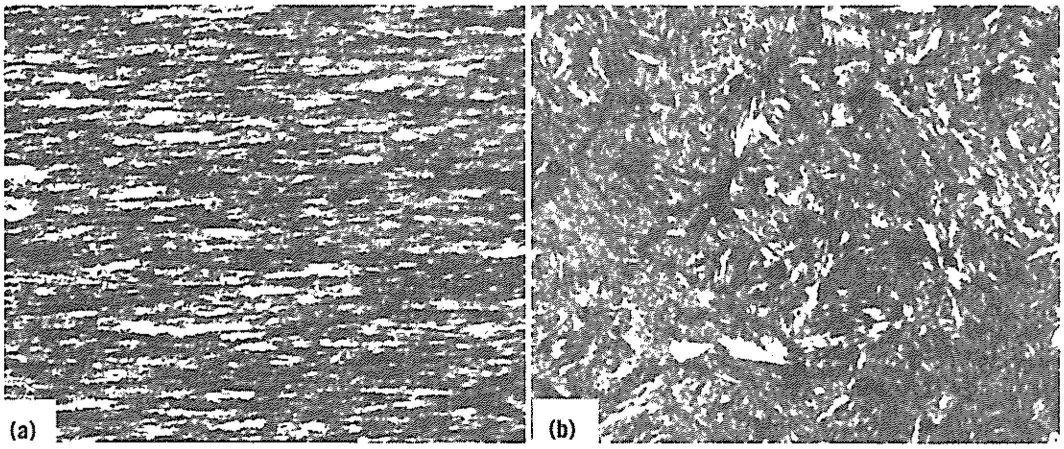
1070: Hardness vs Depth of Case



1070: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure



1070: Microstructures. (**a**) 2% nital, 100×. Hard drawn steel valve-spring wire, Longitudinal section. Tensile strength, 1689 MPa (245 ksi, obtained by 80% reduction. Deformed pearlite. Prior structure, fine lamellar pearlite. (**b**) 2% nital, 1000×. Valve-spring wire. Quenched and tempered. Austenitized at 870 °C (1600 °F). Oil quenched. Tempered at 455 °C (850 °F). Mainly tempered martensite. Some free ferrite (white)



1075

Chemical Composition. AISI and UNS: 0.70 to 0.80 C, 0.40 to 0.70 Mn, 0.040 P max, 0.050 S max

Recommended Heat Treating Practice

Hardening. Flame hardening, carbonitriding, and austempering are suitable processes

1078

Chemical Composition. AISI and UNS: 0.72 to 0.85 C, 0.30 to 0.60 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). UNS G10780; ASTM A510, A576; SAE J403, J412, J414; (Ger.) DIN 1.1248; (Fr.) AFNOR XC 75; (Swed.) SS_{14} 1774

Characteristics. High carbon allows more free carbide particles in quenched microstructure. Because lower manganese decreases hardenability, 1078 is often induction hardened. As-quenched hardness of 64 to 66 HRC, if properly austenitized and quenched. Forgeability is good. Never recommended for welding

Forging. Heat to 1175 °C (2150 °F). Do not forge below 815 °C (1550 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

Annealing. Heat to 815 °C (1500 °F). Furnace cool to 650 °C (1200 °F), at a rate not to exceed 28 °C (50 °F) per h

Hardening. Heat to 815 °C (1500 °F). Carbonitriding, laser surface hardening, and induction hardening are suitable processes. Quench in water or brine. Rounds under 6.35 mm (0.25 in.) diam may be oil quenched for full hardness

Tempering. As-quenched hardness of approximately 65 HRC. Hardness can be reduced by proper tempering temperature

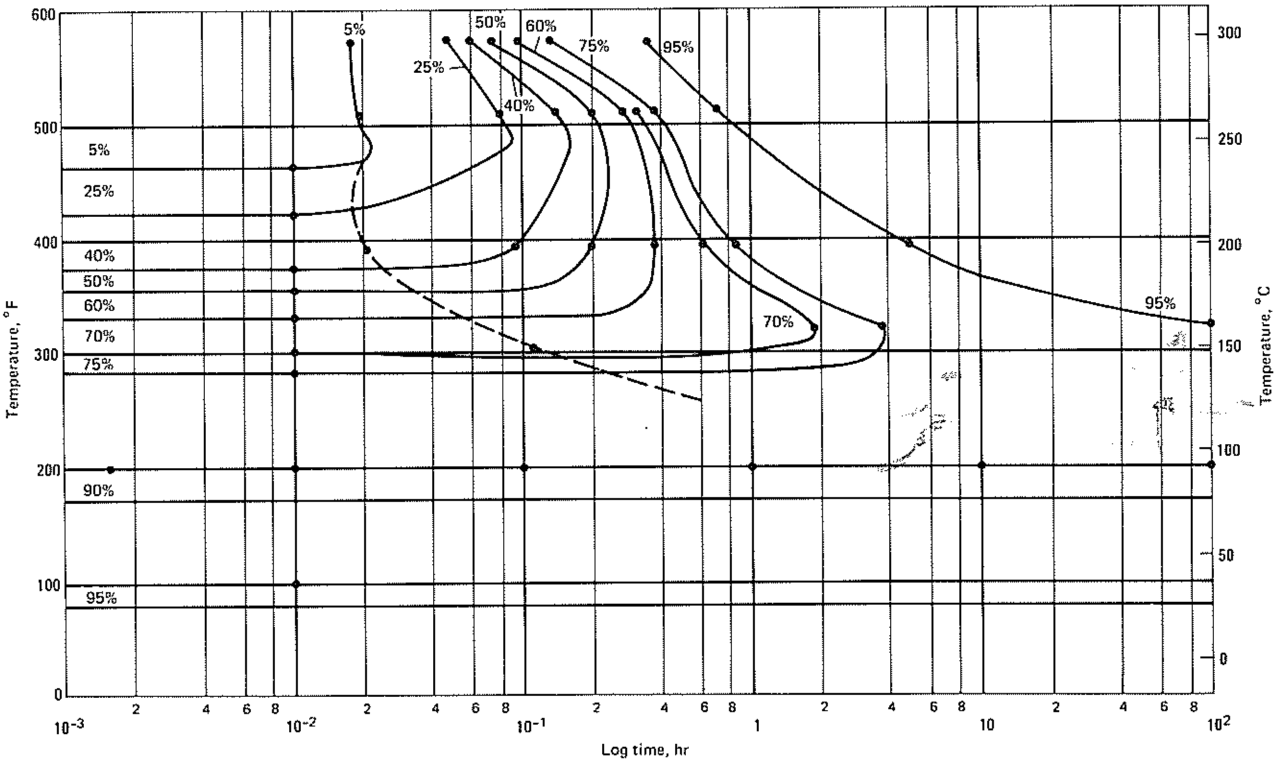
Austempering. Because of low hardenability, thin sections only are austempered, as for 1060. Thin sections (typically springs) are austempered. Results in a bainitic structure and hardness of approximately 46 to 52 HRC. Austenitize at 815 °C (1500 °F). Quench in molten salt bath at 315 °C (600 °F). Hold at temperature for at least 1 h. Air cool. No tempering required

Recommended Processing Sequence

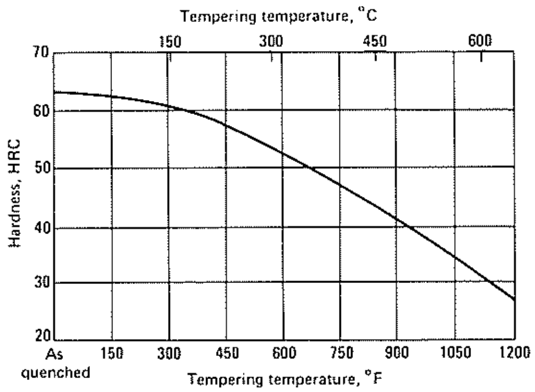
Forgings

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

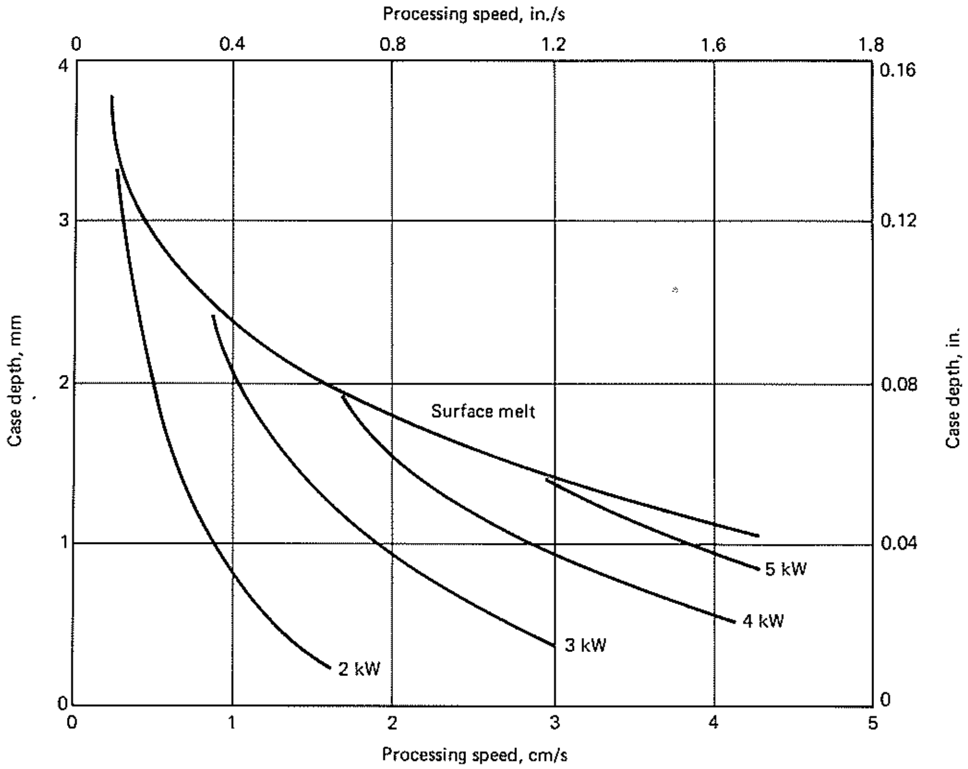
1078: Isothermal Transformation Diagram. Composition: 0.75 C, 0.50 Mn, 0.007 P, 0.020 S, 0.27 Si. Horizontal lines: formation of martensite on cooling. Curved lines: formation of bainite on isothermal holding. Dotted lines: beginning of isothermal transformation of holding below M_s

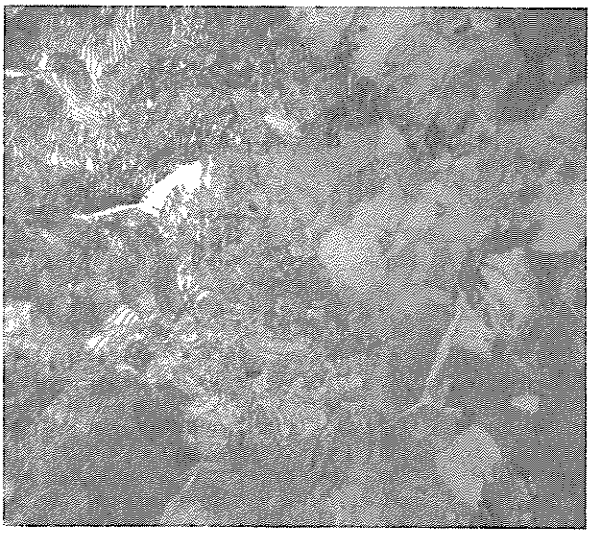


1078: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure



1078: Laser Surface Hardening. Laser surface transformation hardening of SAE 1078 using optical integrator with 1.27 × 1.27 cm (0.5 × 0.5 in.) laser spot





1078: Microstructure. Picral, 550×. Hot rolled bar. Air cooled from rolling temperature. Predominantly pearlite. Large amount of partly resolved lamellar pearlite. Some grain-boundary ferrite

1080

Chemical Composition. **AISI and UNS:** 0.75 to 0.88 C, 0.60 to 0.90 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). UNS G10800; AMS 110; ASTM A510, A576, A682; FED QQ-S-635 (C1080); MIL SPEC MIL-S-16974; SAE J403, J412, J414

Characteristics. Higher manganese content of 1080 can provide greater hardenability than 1078, particularly if manganese is near the high side of the range, 0.90. As-quenched hardness near 65 HRC. As carbon content increases, there is a gradual increase in amount of free carbide. This enhances abrasion resistance and decreases ductility. Forgeability is good. Weldability is poor

Forging. Heat to 1175 °C (2150 °F). Do not forge below 815 °C (1500 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

Annealing. Heat to 815 °C (1500 °F). Furnace cool to 650 °C (1200 °F), at a rate not to exceed 28 °C (50 °F) per h

Hardening. Heat to 815 °C (1500 °F). Induction hardening, carbonitriding, and austempering are suitable processes. Quench in water or brine. Rounds under 6.35 mm (0.25 in.) diam may be oil quenched for full hardness

Tempering. As-quenched hardness of approximately 65 HRC. Hardness can be reduced by proper tempering

Austempering. Because of low hardenability, thin sections are austempered, as for 1060. Thin sections (typically springs) are austempered. Results in a bainitic structure and hardness of approximately 46 to 52 HRC. Austenitize at 815 °C (1500 °F). Quench in molten salt bath at 315 °C (600 °F). Hold at temperature for at least 1 h. Air cool. No tempering required

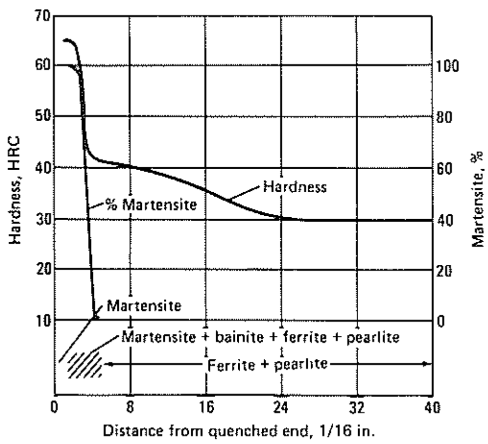
1080: As-Quenched Hardness (Oil)

Grade: 0.75 to 0.88 C, 0.60 to 0.90 Mn, 0.040 P max, 0.050 S max; grain size 80%, 5 to 7; 20%, 1 to 4

Size round		Hardness, HRC		
in.	mm	Surface	½ radius	Center
½	12.7	60	43	40
1	25.4	45	42	39
2	50.8	43	40	37
4	101.6	39	37	32

Source: Bethlehem Steel

1080: End-Quench Hardenability. 12.7 mm (0.5 in.) diam bar. Composition: 0.79 C, 0.76 Mn. Austenitized at 900 °C (1650 °F). Grain size, 6

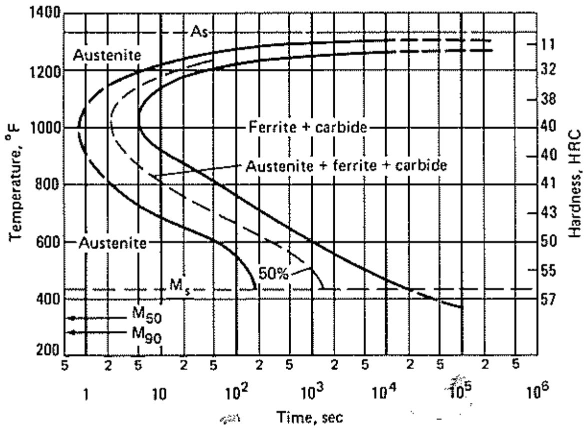


Recommended Processing Sequence

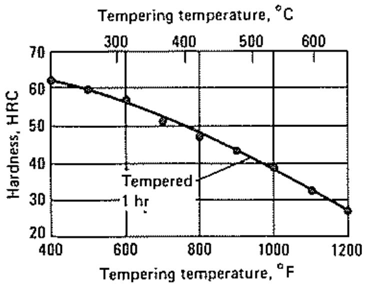
Forgings

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

1080: Isothermal Transformation Diagram. Composition: 0.79 C, 0.76 Mn. Austenitized at 900 °C (1650 °F). Grain size, 6. Martensite temperatures estimated



1080: Hardness vs Tempering Temperature. Specimen, 3.175 to 6.36 mm (0.125 to 0.25 in.) thick. Quenched. Tempered 1 h

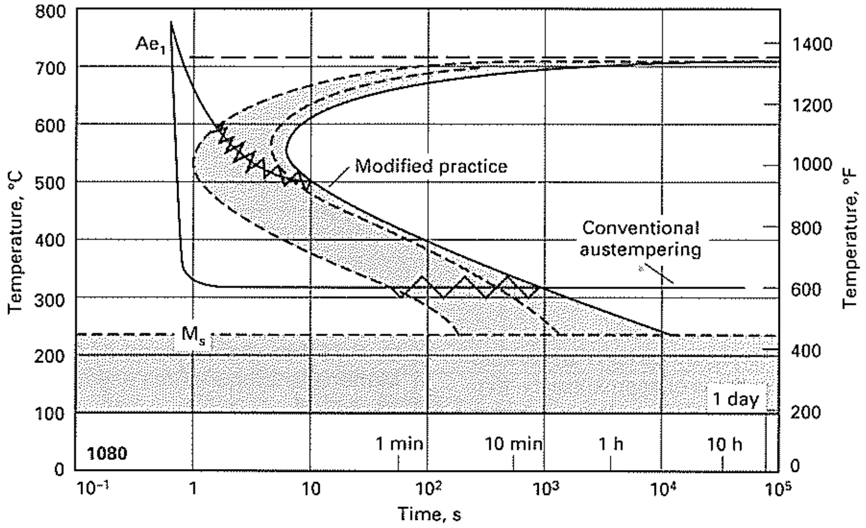


1080: Equipment Requirements for Austempering

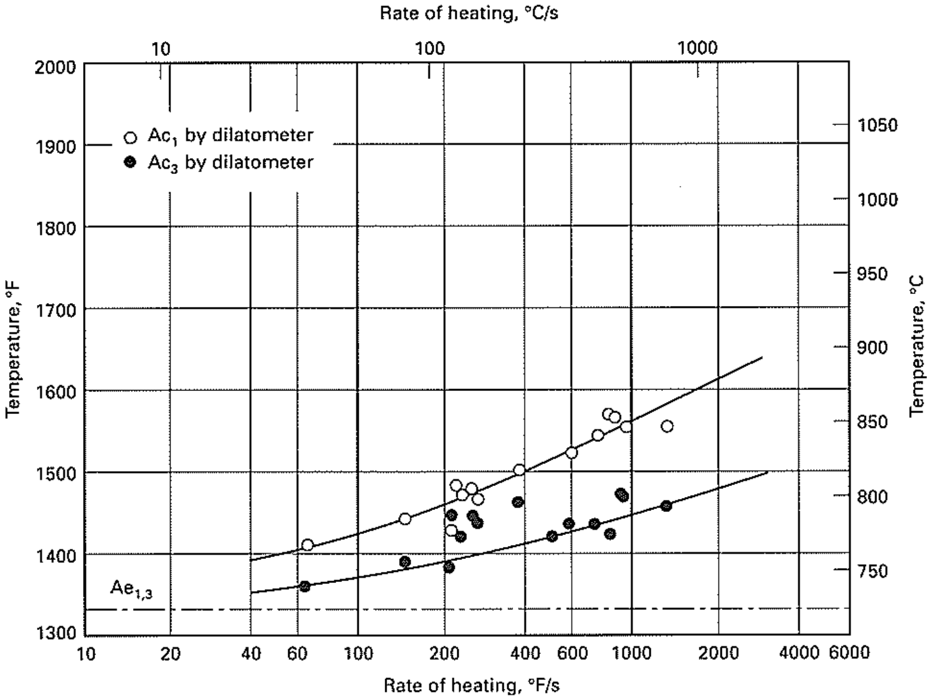
Parts austenitized at 925 °C (1695 °F)

Production requirements	
Weight of each piece, kg (lb)	1.1 to 1.8 (2.4 to 3.9)
Production per hour	1500 pieces
Equipment requirements	
Austempering furnace	Submerged fuel-fired salt pot
Size of furnace, m^3 (ft^3)	6.6 (233)
Nitrate-nitrite salt, kg (lb)	11 340 (25 000)
Temperature, °C (°F)	345-360 (650-675)
Agitation	Pump, directed at delivery chute
Cooling	Forced air through burner tube

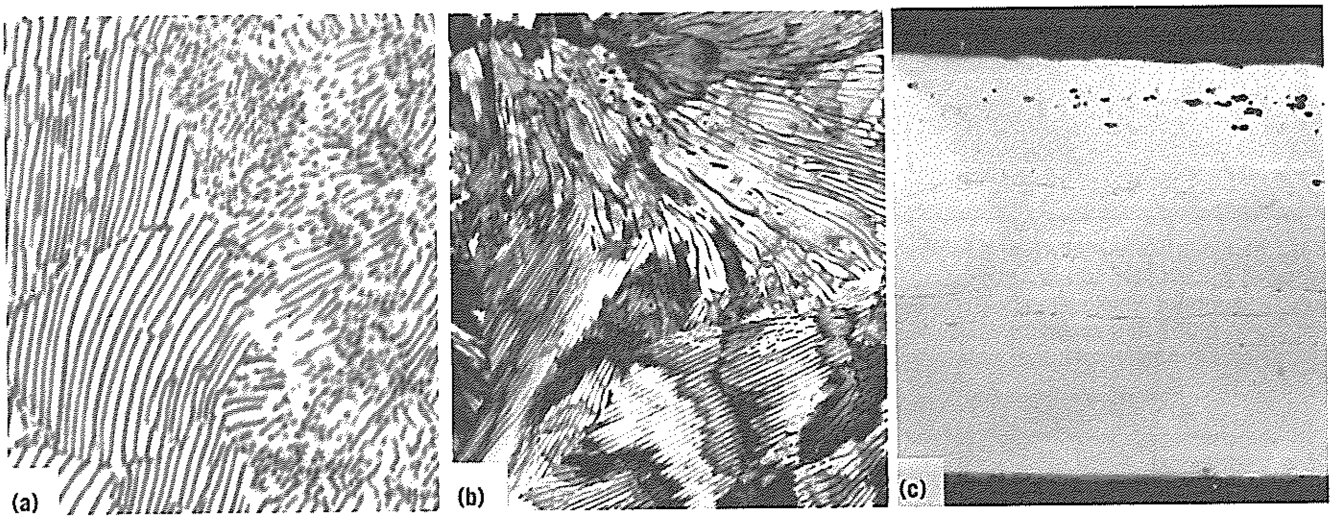
1080: TTT Diagram. Time-temperature transformation diagram for 1080 steel, showing difference between conventional and modified austempering. When applied to wire, the modification shown is known as patenting



1080: Induction Heating. Effect of heating rate on Ac_1 and Ac_3 temperatures for annealed 1080 steel



1080: Microstructures. (a) Picral, 2000×. Hot rolled bar, austenitized at 1050 °C (1920 °F), 1/2 h. Furnace cooled to room temperature at 28 °C (50 °F) per h. Mostly pearlite. Some spheroidal cementite particles. (b) Thin-foil specimen, 2000×. Same as (a), except cooling rate increased to 56 °C (100 °F) per h. Thin-foil transmission electron micrograph. Fine lamellar pearlite. (c) As polished. Not etched. 250×. Inclusions in flat spring. 0.008 mm (0.2032 in.) thick. Longitudinal section. Thickness shown as height in micrograph. Black spots are iron aluminide. Thin gray stringers near center are sulfide



1084

Chemical Composition. AISI and UNS: 0.80 to 0.93 C, 0.60 to 0.90 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). UNS G10840; ASTM A510, A576; FED QQ-S-700 (C1084); SAE J403, J412, J414; (Ger.) DIN 1.0647

Characteristics. Composition nearly identical to that of 1080. As-quenched hardness near 65 HRC. As carbon content increases, there is a gradual increase in amount of free carbides. This enhances abrasion resistance and decreases ductility. Forgeability is good. Weldability is very poor

Forging. Heat to 1175 °C (2150 °F). Do not forge below 815 °C (1500 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

Annealing. Heat to 815 °C (1500 °F). Furnace cool to 650 °C (1200 °F), at a rate not to exceed 28 °C (50 °F) per h

Hardening. Heat to 815 °C (1500 °F). Carbonitriding and austempering are suitable surface hardening processes. Quench in water or brine. Rounds under 6.35 mm (0.25 in.) diam may be oil quenched for full hardness

Tempering. As-quenched hardness of approximately 65 HRC. Hardness can be reduced by proper tempering

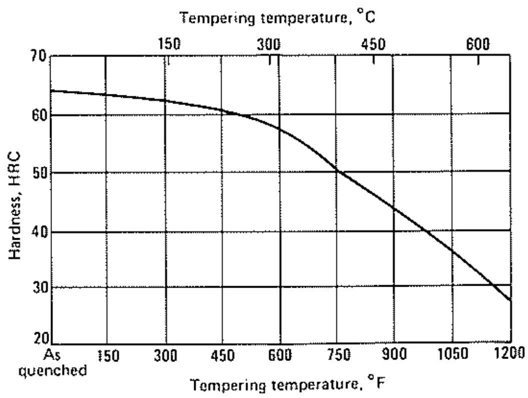
Austempering. Very thin sections, because of relatively low hardenability can be austempered, using the technique for 1060. Thin sections (typically springs) are austempered. Results in a bainitic structure and hardness of approximately 46 to 52 HRC. Austenitize at 815 °C (1500 °F). Quench in molten salt bath at 315 °C (600 °F). Hold at temperature for at least 1 h. Air cool. No tempering required

Recommended Processing Sequence

Forgings

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

1084: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure



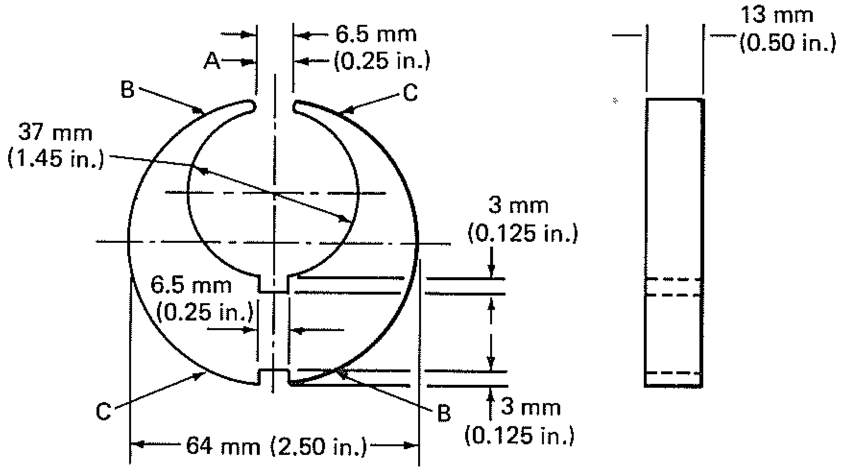
1085

Chemical Composition. AISI and UNS: 0.80 to 0.93 C, 0.70 to 1.00 Mn, 0.040 P max, 0.050 S max

Recommended Heat Treating Practice

Hardening. Carbonitriding is a suitable surface hardening process

1085: Effects of Quenching on Hardness and Dimensions. Hardness values and changes in dimensions of a 1085 plain carbon steel test specimen after quenching in water, fast oil, and conventional oil



Quenching medium	Hardness, HRC Maximum	Minimum	Variation
Water	67.0	63.0	4.0
Fast oil	66.0	63.0	3.0
Conventional oil	65.5	43.0	22.5

	Dimensional change: Gap A		Diameter B		Diameter C	
	mm	in.	mm	in.	mm	in.
Water	0.3404	0.0134	0.2591	0.0102	0.2946	0.0116
Fast oil	0.0533	0.0021	0.0813	0.0032	0.0610	0.0024
Conventional oil	0.0559	0.0022	0.0965	0.0038	0.0965	0.0038

1086

Chemical Composition. AISI and UNS: 0.80 to 0.93 C, 0.30 to .50 Mn, 0.040 P max, 0.050 S max; (standard steel grade for wire rod and wire only)

Recommended Heat Treating Practice

Hardening. Carbonitriding and austempering are suitable processes

1090

Chemical Composition. AISI and UNS: 0.85 to 0.98 C, 0.60 to .90 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). UNS G10200; AMS 112; ASTM A510, A576; SAE J403, J412, J414; (Ger.) DIN 1.1273

Characteristics. Commonly referred to as a commercial grade of carbon tool steel. Essentially same composition as W1 tool steel, but not made by tool steel practice and not expected to meet quality level of W1 tool steel. Easily forged. Blanking (cold) from strip or thin plate is common method of fabrication. Available in a variety of product forms. As hard as 66 HRC, fully quenched. Microstructure of carbon-rich martensite and considerable amount of free carbide, assuming normal austenitizing temperature used

Forging. Heat to 1150 °C (2100 °F). Do not forge below 815 °C (1500 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 855 °C (1570 °F). Cool in air

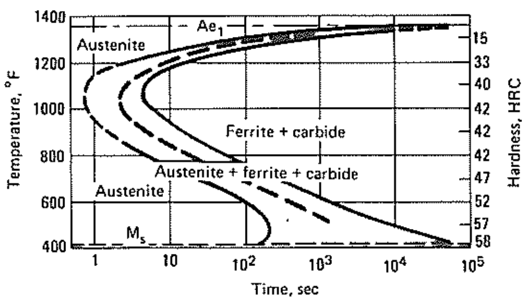
Annealing. As is generally true for all high carbon steels, bar stock supplied by mills in spheroidized condition. Annealed with structure of fine spheroidal carbides in ferrite matrix. When parts are machined from bars in this condition, no normalizing or annealing required. Forgings should always be normalized. Anneal by heating to 800 °C (1475 °F). Furnace cool to 650 °C (1200 °F), at a rate not to exceed 28 °C (50 °F) per h. From 800 °C (1475 °F) to ambient temperature, cooling rate is not critical. This relatively simple annealing process will provide predominantly spheroidized structure, desired for subsequent heat treating or machining

Hardening. Heat to 800 °C (1475 °F). Carbonitriding and austempering are suitable processes. Quench in water or brine. Rounds under 6.35 mm (0.25 in.) diam may be oil quenched for full hardness

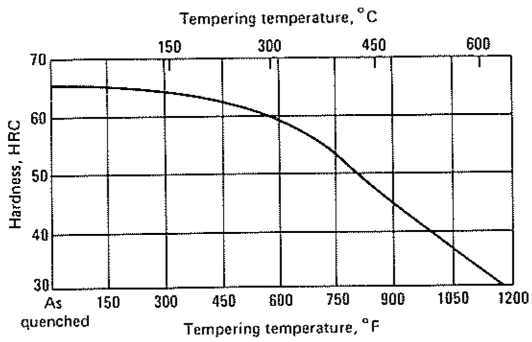
Tempering. As-quenched hardness of as high as 66 HRC. Hardness can be reduced by proper tempering

Austempering. Responds well to austempering (bainitic hardening). Austenitize at 800 °C (1475 °F). Quench in agitated molten salt bath at 315 °C (600 °F). Hold for 2 h. Cool in air

1090: TTT Curves. Transformation characteristics of a hypereutectoid steel after martempering. Austenitized at 885 °C (1625 °F). Grain size, 4 to 5



1090: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

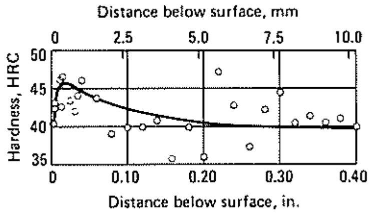


Recommended Processing Sequence

Forgings

- Forge
- Normalize
- Anneal
- Rough machine
- Semifinish machine
- Austenitize
- Quench
- Temper

1090: Hardness vs Section Thickness. Specimen, 20.828 mm (0.820 in.) diam. Austenitized at 885 °C (1625 °F). Quenched in salt at 370 °C (700 °F), 7 min. Rockwell hardness C, converted from microhardness readings taken with 100 g (4 oz) load. Low values of surface hardness result from decarburization

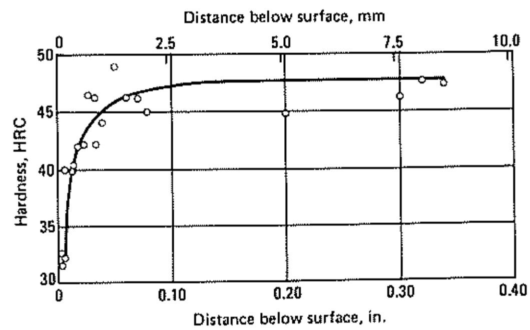


1090: Properties of Austempered and Oil-Quenched Sway Bars

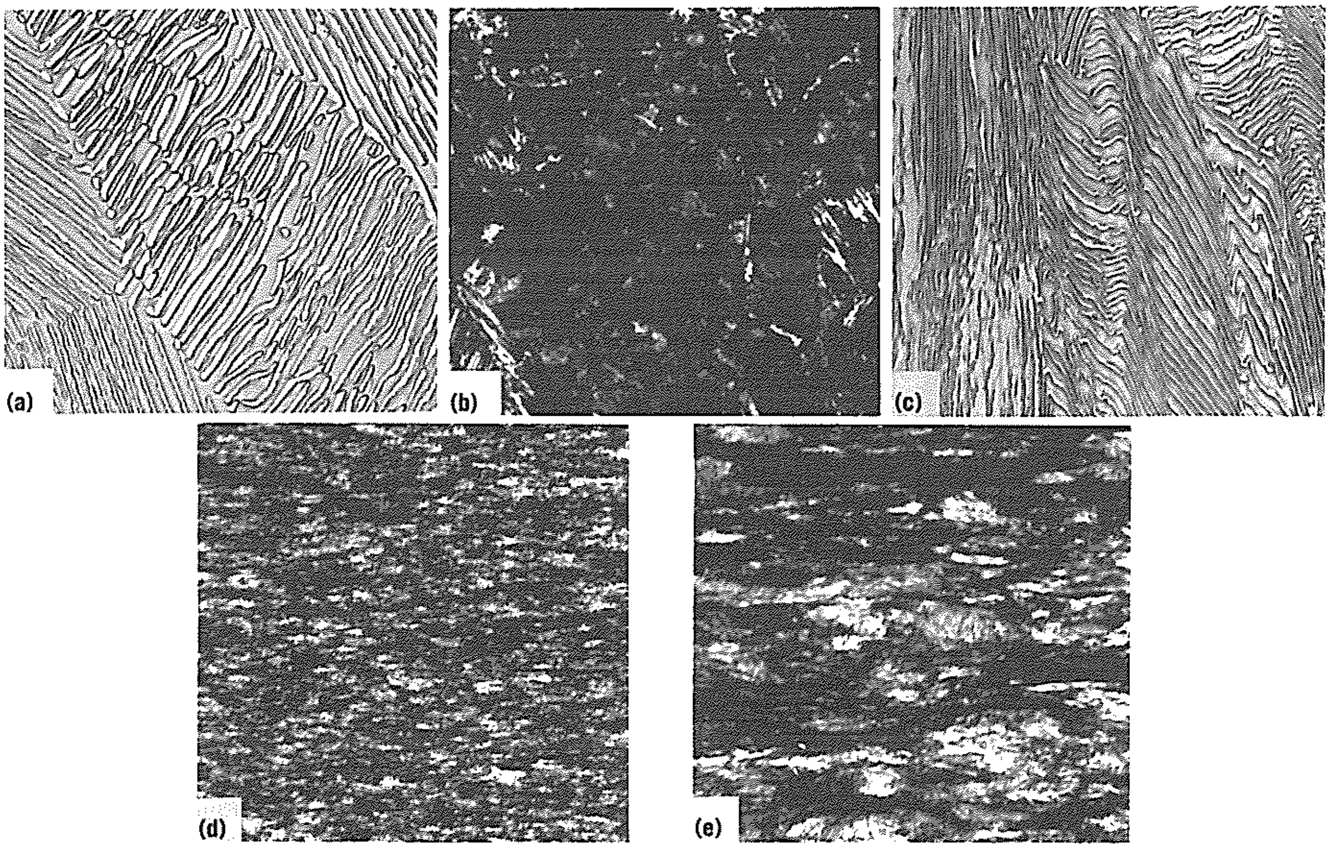
Property(a)	Austempered at 400 °C (750 °F)(b)	Quenched and tempered(c)
Tensile strength, MPa (ksi)	1415 (205)	1380 (200)
Yield strength, MPa (ksi)	1020 (148)	895 (130)
Elongation, %	11.5	6.0
Reduction of area, %	30	10.2
Hardness, HB	415	388
Fatigue cycles(d)	105,000(e)	58,600(f)

(a) Average values. (b) Six tests. (c) Two tests. (d) Fatigue specimens 21 mm (0.812 in.) in diameter. (e) Seven tests; range, 69 050 to 137 000. (f) Eight tests; range, 43,120 to 95,220

1090: Hardness vs Section Thickness. Specimen, 17.272 mm (0.680 in.) diam. Austenitized at 885 °C (1625 °F). Quenched in salt at 370 °C (700 °F), 7 min. Hardness, HRC, converted from microhardness readings taken with 100 g (4 oz) load. Low values of surface hardness result from decarburization



1090: Microstructures. (a) Picral, 2000×. Hot rolled bar, 25.4 mm (1 in.). As cooled from finish-rolling temperature of 870 to 900 °C (1600 to 1650 °F). Replica electron micrograph. Entirely lamellar pearlite. (b) Picral, 1000×. 8.712 mm (0.343 in.) diam rod. Patented by austenitizing at 955 °C (1750 °F), 4 1/2 min. Quenched in lead bath at 505 °C (940 °F), 70 sec. Air cooled. Mostly unresolved pearlite with bainite. (c) Picral, 8000×. Strip, cold reduced 80% after hot rolling. Rolling direction vertical in this replica electron micrograph. Deformed lamellar pearlite. (d) 2% nital, 100×. Modified steel music wire. 0.38 Mn. Cold drawn to 1813 MPa (263 ksi) tensile strength by 75% reduction. Deformed pearlite. Prior structure, fine pearlite. (e) 2% nital, 500×. Same as (d), but higher magnification. Drawing direction is horizontal. Prior structure produced by lead patenting



1095

Chemical Composition. AISI and UNS: 0.90 to 1.03 C, 0.30 to 0.50 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). UNS G10200; AMS 5121, 5122, 5132, 7304; ASTM A510, A576, A682; FED QQ-S-700 (C1095); MIL SPEC MIL-S-16788 (CS1095); SAE J403, J412, J414; (Ger.) DIN 1.1274; (Jap.) JIS SUP 4; (Swed.) SS_{14} 1870; (U.K.) B.S. 060 A 96, EN 44 B

Characteristics. Easily forged. Blanking (cold) from strip or thin plate also a common method of fabrication. Available in a variety of product forms. As hard as 66 HRC, fully quenched. Microstructure of carbon-rich martensite and considerable amount of free carbide, assuming normal austenitizing temperature is used. Carbon range slightly higher and manganese content lower than for 1090. This results in the possibility of more undissolved carbide in the microstructure and slightly lower hardenability

Forging. Heat to 1150 °C (2100 °F). Do not forge below 815 °C (1500 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 855 °C (1570 °F). Cool in air

In aerospace practice, parts are normalized at 900 °C (1550 °F)

Annealing. As is generally true for all high-carbon steels, bar stock supplied by mills in spheroidized condition. Annealed with structure of fine spheroidal carbides in ferrite matrix. When parts are machined from bars in this condition, no normalizing or annealing required. Forgings should always be normalized. Anneal by heating to 800 °C (1475 °F). Soak thoroughly. Furnace cool to 650 °C (1200 °F), at a rate not to exceed 28 °C (50 °F) per h. From 650 °C (1200 °F) to ambient temperature, cooling rate is not critical. This relatively simple annealing process will provide predominantly spheroidized structure, desired for subsequent heat treating or machining.

In aerospace practice, parts are annealed at 815 °C (1500 °F) and allowed to cool to below 540 °C (1000 °F)

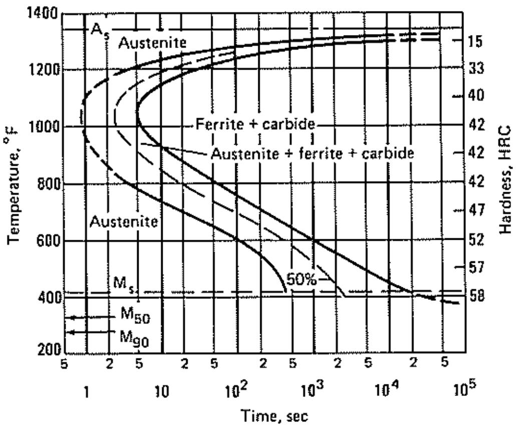
Hardening. Heat to 800 °C (1475 °F). Carbonitriding and austempering are suitable processes. Quench in water, brine, or aqueous polymers. Oil quench rounds under 1.588 mm (0.19 in.) for full hardening. Responds well to austempering (same procedure as for 1090).

In aerospace practice, parts are austenitized at 800 °C (1475 °F), and quenched in oil or polymers

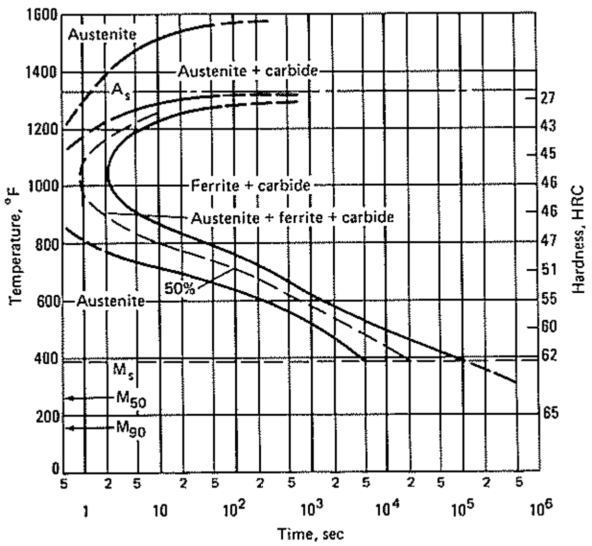
Tempering. As-quenched hardness as high as 66 HRC. Hardness can be reduced by proper tempering. When quenching with oils or polymers, parts may be tempered at a number of different temperatures to get specific ranges of tensile strengths as follows: 675 °C (1245 °F) for 620 to 860 MPa (90 to 125 ksi); 620 °C (1150 °F) for 860 to 1035 MPa (125 to 150 ksi); 540 °C (1000 °F) for 1035 to 1170 MPa (150 to 170 ksi); 480 °C (895 °F) for 1170 to 1240 MPa (170 to 185 ksi); 425 °C (795 °F) for 1240 to 1380 MPa (185 to 200 ksi); 370 °C (700 °F) for 1380 to 1520 MPa (200 to 220 ksi)

Austempering. Responds well to austempering (bainitic hardening). Austenitize at 800 °C (1475 °F). Quench in agitated molten salt bath at 315 °C (600 °F). Hold for 2 h. Cool in air

1095: Isothermal Transformation Diagram. Composition: 0.89 C, 0.29 Mn. Austenitized at 885 °C (1625 °F). Grain size, 4 to 5



1095: Isothermal Transformation Diagram. Modified. Composition: 1.13 C, 0.30 Mn. Austenitized at 910 °C (1670 °F). Grain size, 7 to 8. Martensite temperatures estimated

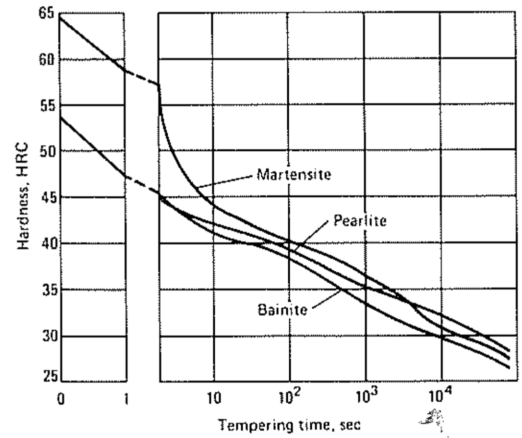


Recommended Processing Sequence

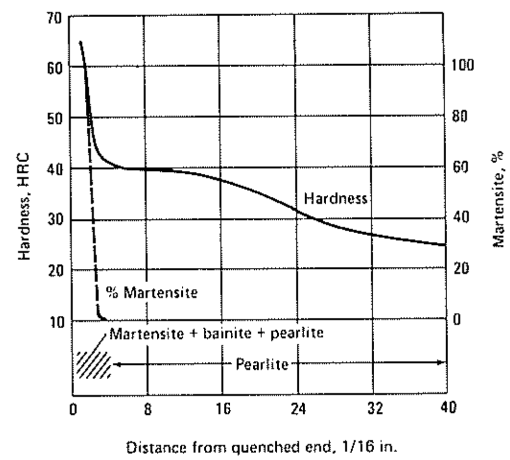
Forgings

- Forge
- Normalize
- Anneal
- Rough machine
- Semifinish machine
- Austenitize
- Quench
- Temper

1095: Effect of Prior Microstructure on Hardness After Tempering. Steel tempered at 565 °C (1050 °F)



1095: End-Quench Hardenability. Composition: 0.89 C, 0.34 Mn. Austenitized at 885 °C (1625 °F). Grain size, 5



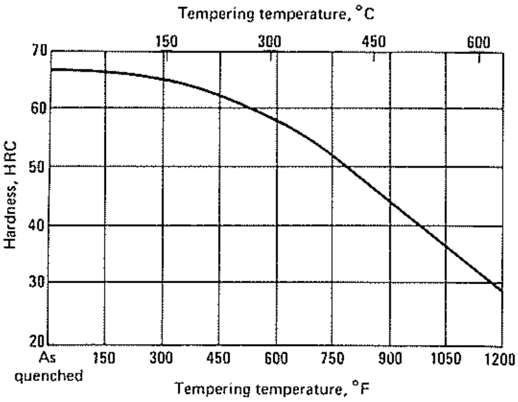
095: As-Quenched Hardness (Water)

ırade: 0.90 to 1.03 C, 0.30 to 0.40 Mn, 0.040 P max, 0.050 S max; rain size 50%, 5 to 7; 50%, 1 to 4

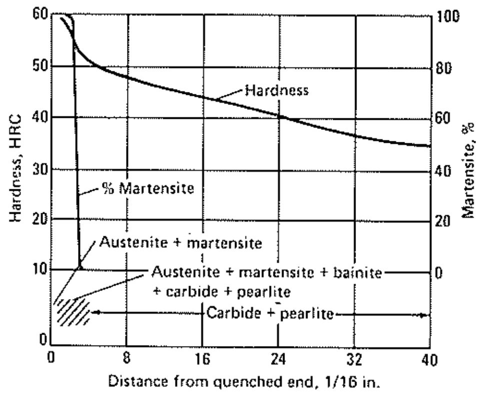
Size round		Hardness, HRC		
.	mm	Surface	½ radius	Center
!	12.7	65	55	48
	25.4	64	46	44
	50.8	63	43	40
	101.6	63	38	30

ɔurce: Republic Steel

1095: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure



1095: End-Quench Hardenability. Modified. Composition: 1.17 ͻ, 0.28 Mn. Austenitized at 925 °C (1695 °F). Grain size, 7 to 8

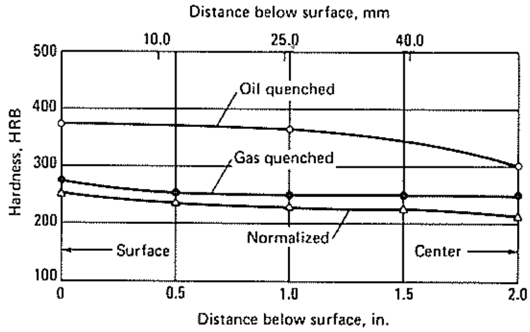


)95: Mechanical Properties of 1095 Steel Heat 'eated by Two Methods

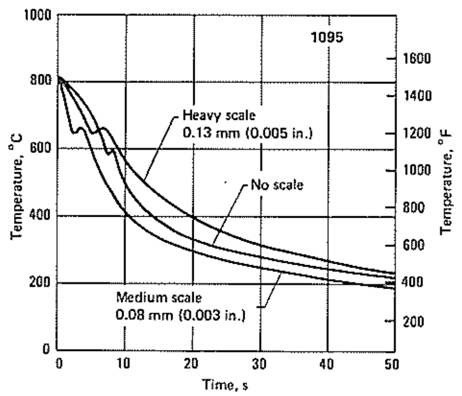
eci- ɪn mber	Heat treatment	Hardness, HRC	Impact energy J	Impact energy ft · lbf	Elonga- tion(a), %
	Water quench and temper	53.0	16	12	0
	Water quench and temper	52.5	19	14	0
	Martemper and temper	53.0	38	28	0
	Martemper and temper	52.8	33	24	0

In 25 mm or 1 in.

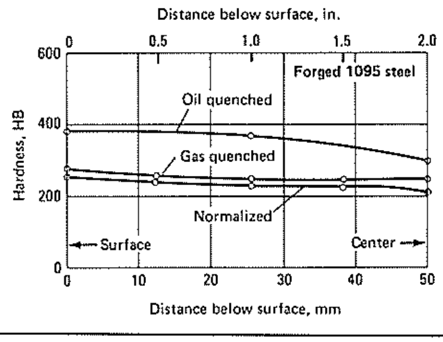
1095: As-Quenched Hardness. Forged steel disks, 101.6 mm (4 in.) thick, after oil quenching, gas quenching (forced air), and normalizing (cooling in still air)



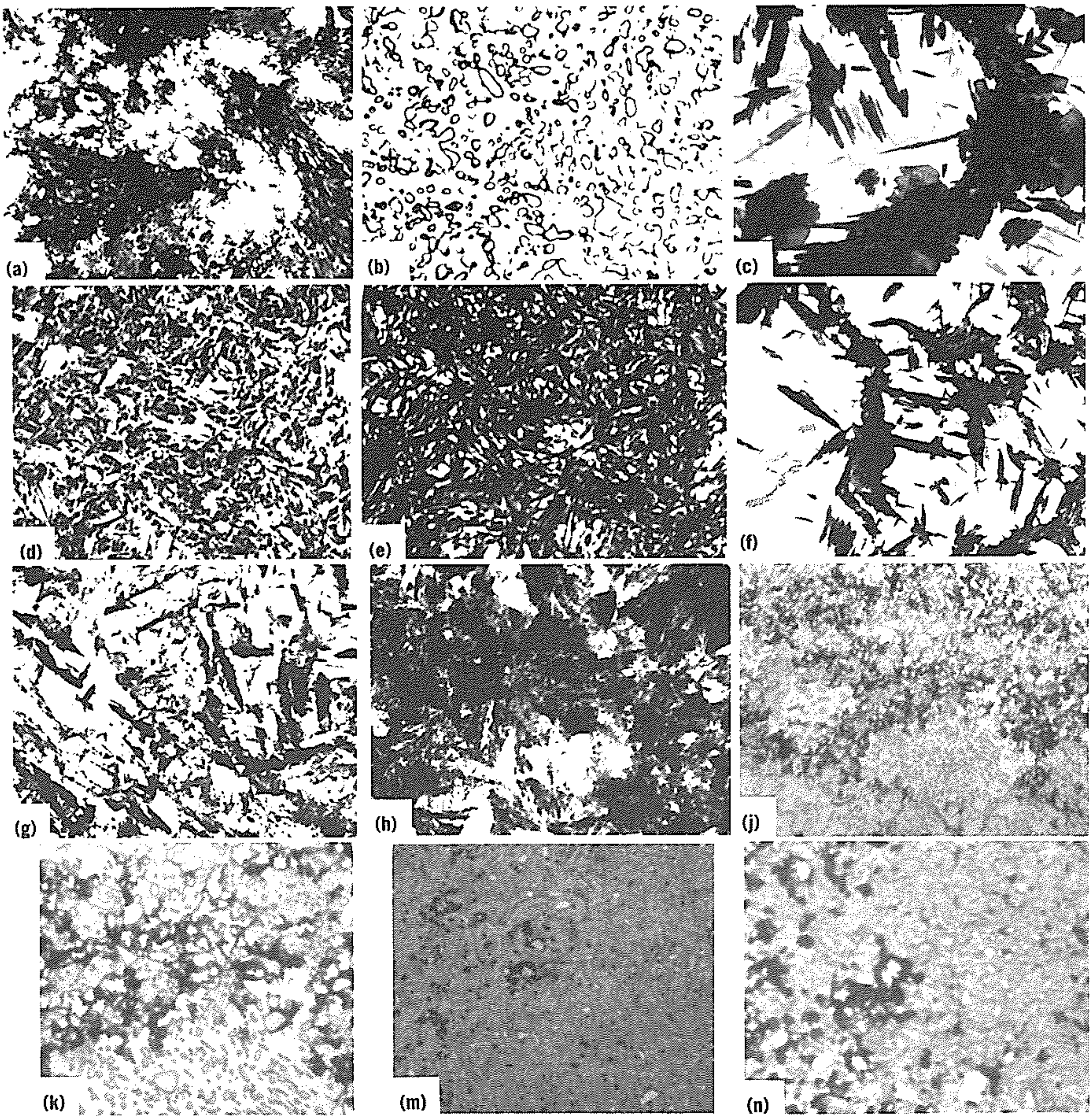
1095: Cooling Curves. Center cooling curves showing the effect of scale on the cooling curves of 1095 steels quenched without agitation in fast oil at 51 °C (125 °F). Specimens were 13 mm (0.50 in.) diam by 64 mm (2.50 in.) long



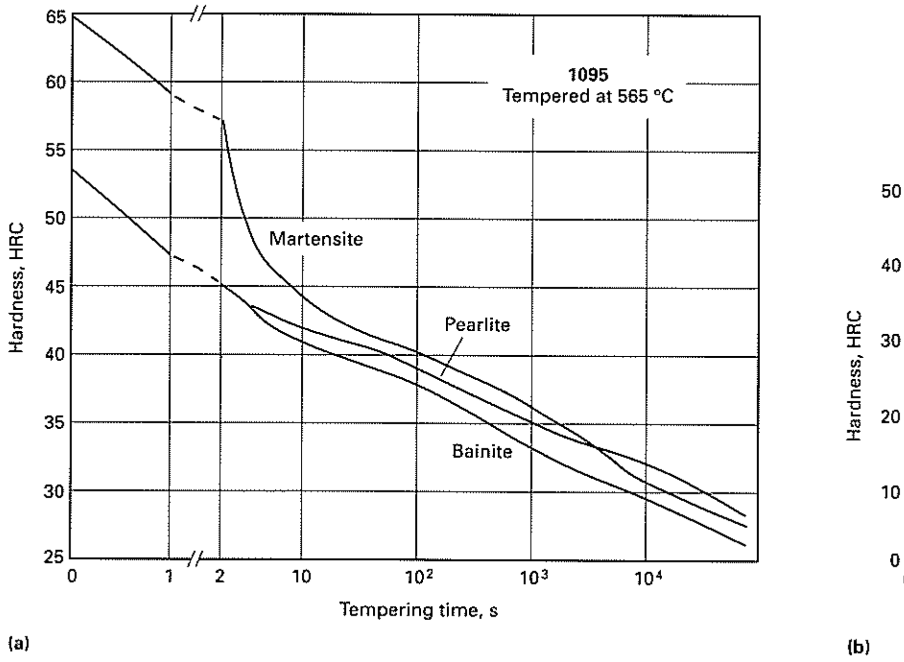
1095: Quenching. Differences in Brinell hardness of forged 1095 steel disks, 100 mm (4 in.) thick, after oil quenching, gas quenching (forced air), and cooling in still air (normalizing)



1095: Microstructures. (a) Picral, 1000×. Bar, normalized by austenitizing at 870 °C (1600 °F). Cooled in air. Partly unresolved pearlite (black); partly lamellar pearlite. (b) Nital, 1000×. Hot rolled bar, 31.75 mm (1.25 in.) diam. Spheroidized by holding at 675 °C (1245 °F), 15 h. Air cooled. Spheroidal cementite particles in ferrite matrix. (c) 2% nital, 500×. Wire, austenitized at 940 °C (1725 °F). Oil quenched. Mixture of fine pearlite and lower bainite (dark areas). Untempered martensite (light areas). Structure resulted from slack quenching. (d) Picral, 1000×. Austenitized at 870 °C (1600 °F); austenitized at 815 °C (1500 °F). Water quenched. Fine, untempered martensite, caused by more severe quench. Some spheroidal cementite. (e) Picral, 1000×. Same as (d), except tempered at 150 °C (300 °F) after quench. Tempered martensite, darker than (d). Some spheroidal cementite particles. (f) 2% nital, 550×. Wire. Austenitized at 885 °C (1625 °F), 1/2 h. Quenched to 625 °C (330 °F). Held 5 min. Oil quenched. Lower bainite (dark). Untempered martensite (light). (g) 2% nital, 550×. Same as (f), except held for 20 min in 329 °C (625 °F) quench. Air cooled. Lower bainite (dark). Untempered martensite (light). (h) 2% nital, 550×. Same as (f), except held 1 h in 445 °C (850 °F). Air cooled (austempered). Mainly upper bainite. (j) Nital, 500×. Die steel induction hardened to 2.54 mm (0.10 in.). Shown are transition-zone constituents from some fine martensite (top) to prior structure of spheroidal cementite in ferrite matrix (bottom). (k) Nital, 500×. Same as (j), except area shown is nearer surface of steel. Fine martensite (gray) and fine unresolved pearlite (black). Small white particles are spheroids of cementite from prior structure. (n) Nital, 1000×. Same as (m), except higher magnification



1095: Tempering. Effect of prior microstructure on room-temperature hardness after tempering. (a) 1095 steel tempered at 565 °C (1050 °F) for various periods of time. (b) Room-temperature hardness before and after tempering, as well as amount of martensite present before tempering in 4320 steel end-quenched hardenability specimens tempered 2h



Resulfurized Carbon Steels (1100 Series)

1108

Chemical Composition. AISI and UNS: 0.08 to 0.13 C, 0.50 to 0.80 Mn, 0.040 P max, 0.08 to 0.13 S

Recommended Heat Treating Practice

Hardening. Flame hardening and carbonitriding are suitable surface hardening processes

1110

Chemical Composition. AISI and UNS: 0.08 to 0.13 C, 0.30 to 0.60 Mn, 0.040 P max, 0.08 to 0.13 S

Similar Steels (U.S. and/or Foreign). UNS G11100; ASTM A107; FED QQ-S-637 (C1110); SAE J403, J412; (Ger.) DIN 1.0702; (Jap.) JIS SUM 11, SUM 12

Characteristics. Available principally in bar form. Costs more than low-carbon steels of the 1000 series, because it has been resulfurized to improve machinability. Sulfur addition impairs some mechanical properties, mainly impact and ductility in the transverse direction. Also, adversely affects forgeability, cold formability, and weldability. Use of this steel should be confined principally to applications where machining is the main fabricating operation

Recommended Heat Treating Practice

Hardening. Large portion of parts are used as machined. Can be surface hardened by carbonitriding, salt bath nitriding, or flame hardening

Normalizing and Annealing. Generally furnished in the hot rolled or hot rolled and cold drawn condition for best machinability. Rarely normalized or annealed

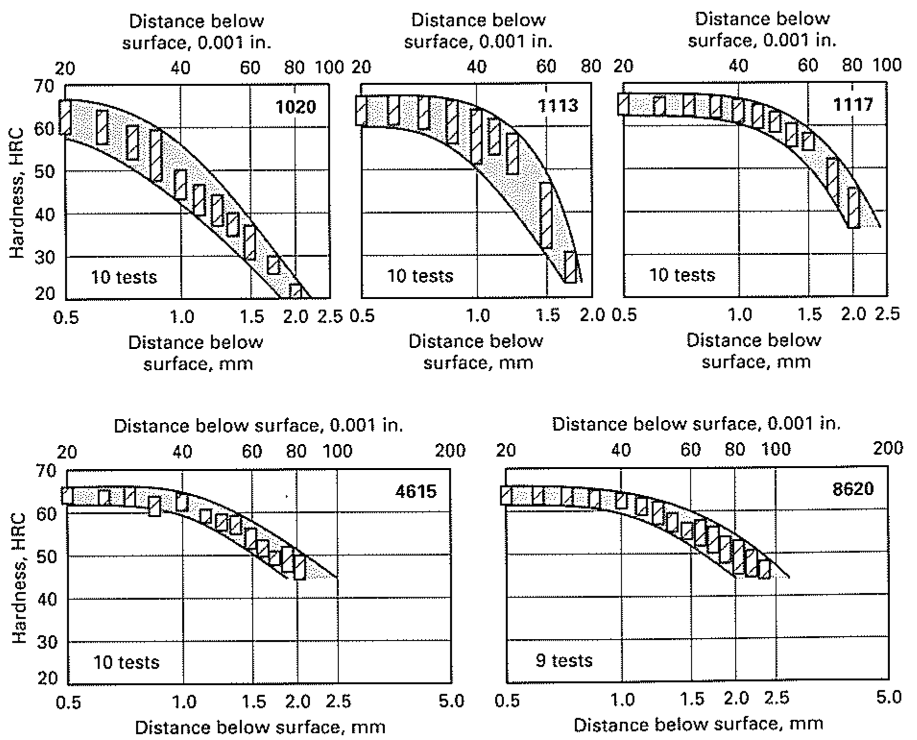
1113

Chemical Composition. AISI and UNS: 0.13 C max, 0.70 to 1.00 Mn, 0.07 to 0.12 P, 0.24 to 0.33 S

Recommended Heat Treating Practice

Hardening. Liquid carburizing is a suitable surface hardening process

1113: Case Hardening Gradients. Case-hardness gradients of 1113 steel showing scatter from normal variations in noncyanide liquid carburizing



117

hemical Composition. AISI and UNS: 0.14 to 0.20 C, 1.00 to 30 Mn, 0.040 P max, 0.08 to 0.13 S

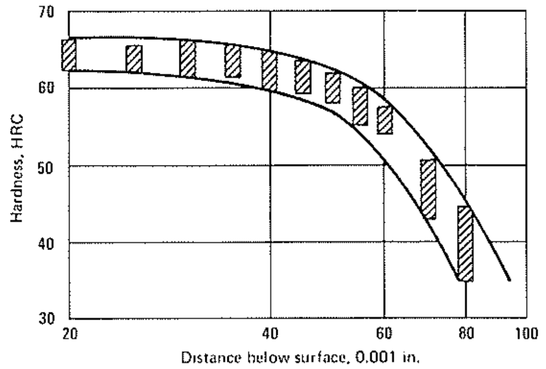
imilar Steels (U.S. and/or Foreign). UNS G11170; ASTM 107, A108; FED QQ-S-637 (C1117); MIL SPEC MIL-S-18411; SAE 03, J412, J414

haracteristics. More costly than the 1020 or 1021 grades, because it s been resulfurized for improved machinability. This impairs certain echanical properties, forgeability, and cold formability. Manganese cont is substantially higher than that of 1020 and 1021. Hardenability is not gnificantly higher, because a portion of the manganese combines with the higher sulfur to form manganese sulfide stringers. These promote chip breakage and excellent machinability. Available only in bar stock for machining directly into parts, most often in automatic machines

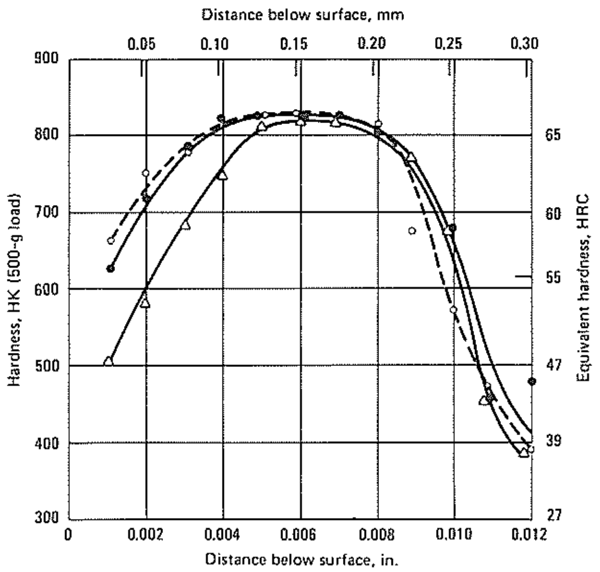
Recommended Heat Treating Practice

Case Hardening. Almost always used as machined or case hardened. (See process for 1020). Flame hardening, carbonitriding, liquid carburizing, gas carburizing, austempering, and martempering are suitable processes

Normalizing and Annealing. Rarely required by fabricator. Typical normalizing temperature is 900 °C (1650 °F)

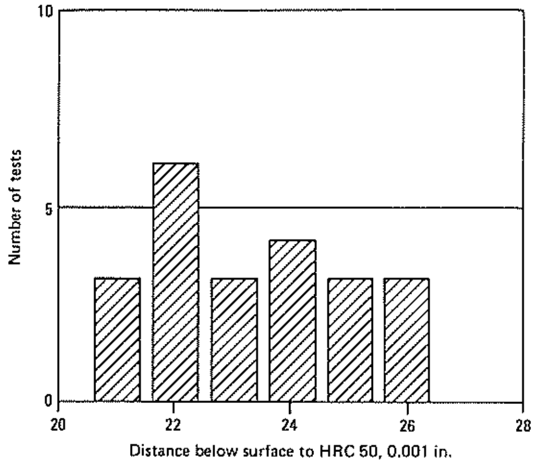


1117: Gas Carburizing. Effect of normal variations in gas carburizing on hardness gradients. 10 tests

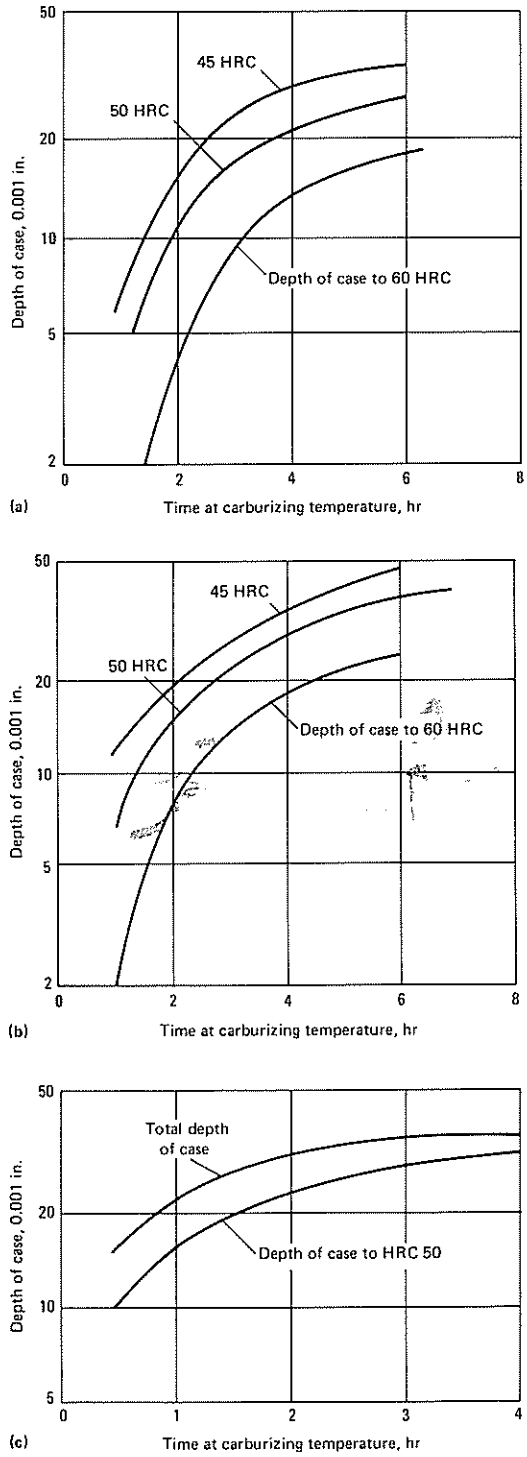


1117: Gas Carbonitriding. Carbonitrided at 815 °C (1500 °F), 1 1/2 h. Oil quenched. Required minimum hardness of 630 Knoop (500 g load) at 0.001 in. below surface was met by reducing percentage and flow rate of ammonia or by adding a diffusion period after carbonitriding, as indicated. Atmosphere consisted of: endothermic carrier gas, dew point of -1 °C (+30 °F), at 4.245 m^3 (150 ft^3) per h; natural gas at 0.170 m^3 (6 ft^3) per h; and ammonia in amounts indicated. O : 3% NH_3 at 5 ft^3/h. ●: 11% NH_3 at 20 ft^3/h and diffused last 15 min. Δ: 11% NH_3 at 20 ft^3/h

1117: Liquid Carburizing. Comparative case depth and case hardness. Specimen, 15.875 mm (0.625 in.) diam. Carburized at 900 °C (1650 °F), 2 h. Brine quenched. 22 tests



1117: Gas Carburizing. Effect of time and temperature on case depth. (a) Bars, 177.8 mm (7 in.) long. Carburized at 900 °C (1650 °F). Water quenched. (b) Bars, 177.8 mm (7 in.) long. Carburized at 925 °C (1695 °F). Water quenched. (c) 12.7 mm (0.5 in.) round bars. Carburized at 900 °C (1650 °F). Quenched in 10% brine



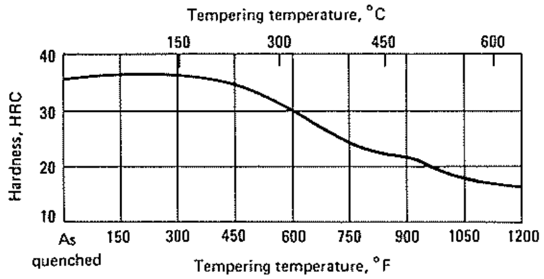
1117: As-Quenched Hardness (Water)

Effect of mass on as-quenched hardness of steel bars, quenched in water; contents: 0.19 C, 1.10 Mn, 0.015 P, 0.084 S, 0.11 Si; grain size: 2 to 4

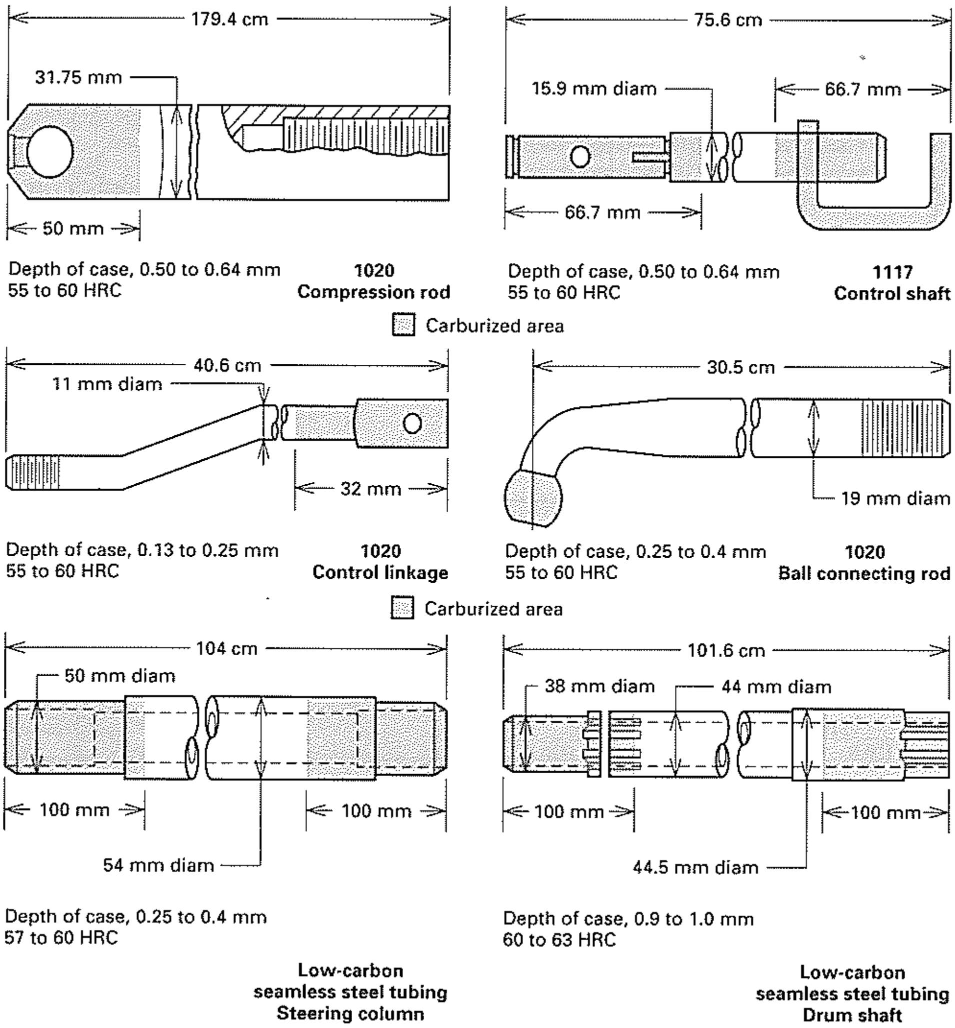
Size round		Surface,	½ radius		Center	
in.	mm	HRC	HRB	HRC	HRB	HRC
½	12.7	42	...	35.4	...	29.5
1	25.4	37	96	...	93	...
2	50.8	33	90	...	86	...
4	101.6	32	83	...	81	...

Source: Bethlehem Steel

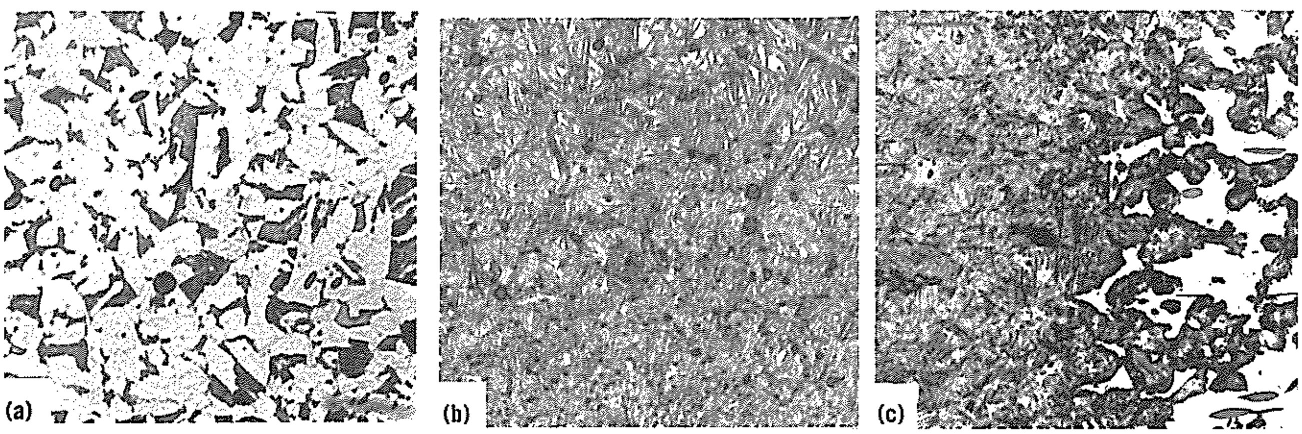
1117: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure



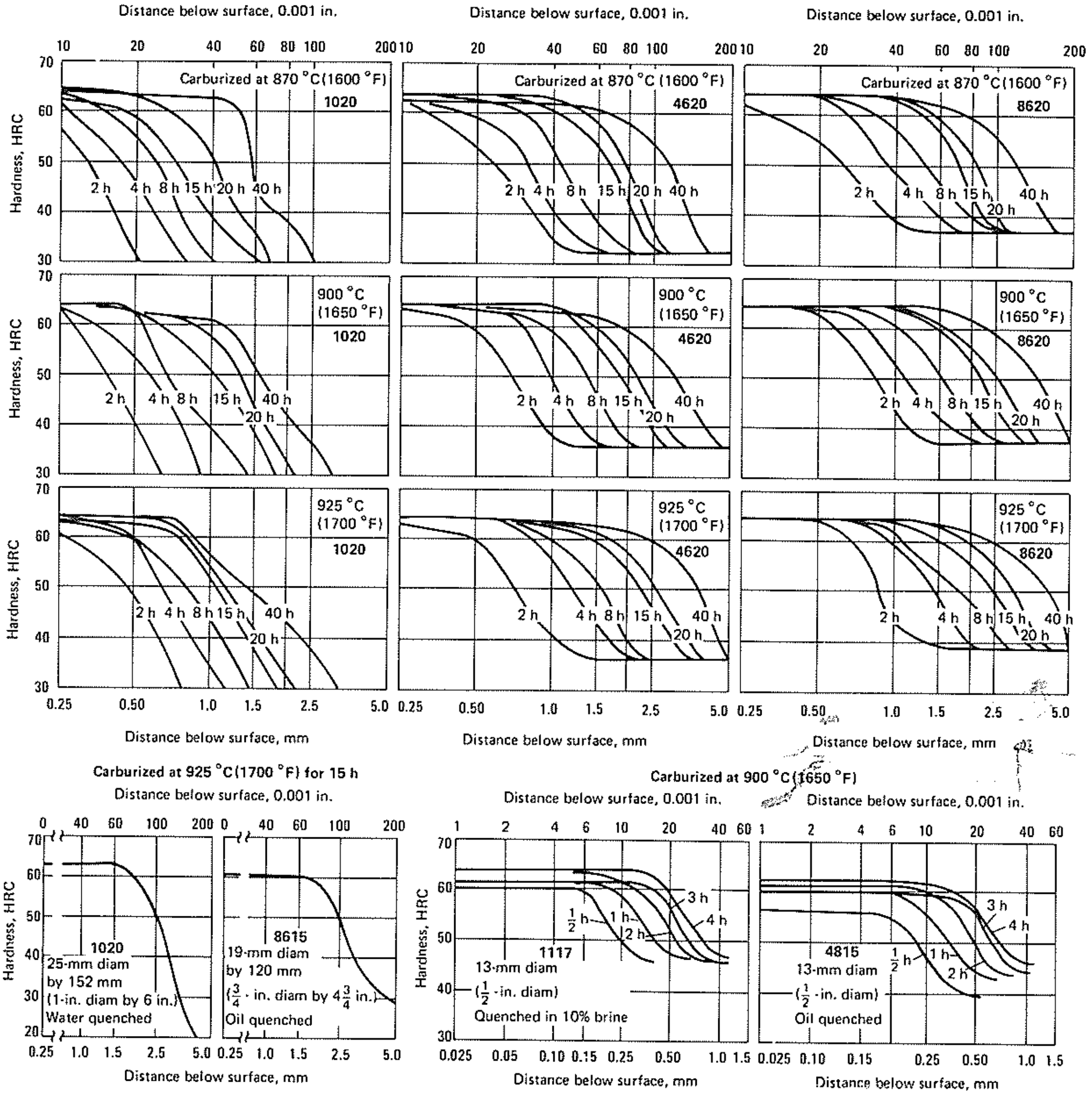
1117: Selective Carburizing. Typical part selectively carburized by partial immersion. Only the portion that is to be carburized is immersed in the bath. Area to be carburized is shaded



1117: Microstructures. (a) Picral, 200×. Steel bar normalized by austenitizing at 900 °C (1650 °F), 2 h. Cooled in still air. Blocky ferrite (light). Traces of Widmanstätten ferrite. Fine pearlite (dark). Round particles of manganese sulfide. (b) 3% nital, 200×. Carbonitrided 4 h at 845 °C (1555 °F) in 3% ammonia, 6% propane, and remainder, endothermic gas. Oil quenched. Tempered 1 1/2 h at 150 °C (300 °F). Retained austenite (white) and globules of manganese sulfide (dark) in matrix of tempered martensite. (c) Nital, 200×. Carbonitrided and oil quenched. Surface layer of decarburized ferrite, superimposed on a normal case structure of martensite (left side of micrograph). Core material (right) shows patches of ferrite (white)



1117: Case Hardness Gradients. Case hardness gradients for two carbon steels and four low alloy steels, showing effects of carburizing temperature and time. Specimens measuring 19 by 51 mm (0.75 by 2 in.) diam were carburized, air cooled, reheated in neutral salt at 845 °C (1555 °F), and quenched in nitrate/nitrite salt at 180 °C (355 °F)



1118

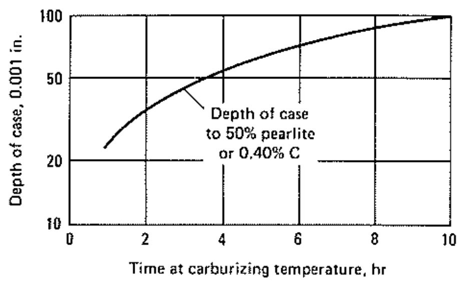
Chemical Composition. AISI and UNS: 0.14 to 0.20 C, 1.30 to 1.60 Mn, 0.040 P max, 0.08 to 0.13 S

Similar Steels (U.S. and/or Foreign). UNS G11180; ASTM A107, A108; FED QQ-S-637 (C1118); SAE J403, J412, J414

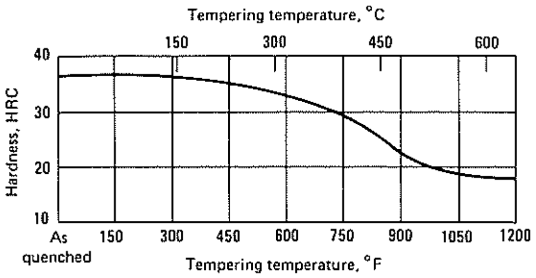
Characteristics. More costly than the 1020 or 1021 grades, because it has been resulfurized for improved machinability. This impairs certain mechanical properties, forgeability, and cold formability. While a portion of the manganese (relatively high) combines with sulfur, there is still a sufficient amount left over to result in higher hardenability compared with 1020 or 1021

Recommended Heat Treating Practice

Case Hardening. Almost always used as machined or case hardened, as described for 1020. Greater hardenability, compared with 1020, allows the section thickness of carburized 1118 to be extended at least to 12.7 mm (0.5 in.). Fully hardened by oil quenching. Flame hardening, carbonitriding, liquid carburizing, and martempering are suitable processes



1118: Liquid Carburizing. Carburized at 955 °C (1750 °F). Slowly cooled



1118: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

118: As-Quenched Hardness (Water)

fect of mass on as-quenched hardness of steel bars, quenched in ater; contents: 0.20 C, 1.34 Mn, 0.017 P, 0.08 S, 0.09 Si; grain size:)%, 3 to 5; 10%, 2

Size round		Surface,	½ radius		Center	
in.	mm	HRC	HRC	HRB	HRC	HRB
½	12.7	43	36	...	33	...
1	25.4	36	...	99	...	96.5
2	50.8	34	...	91	...	87.0
4	101.6	32	...	84	...	82.0

urce: Bethlehem Steel

137

hemical Composition. **AISI and UNS:** 0.32 to 0.39 C, 1.35 to 55 Mn, 0.040 P max, 0.08 to 0.13 S

imilar Steels (U.S. and/or Foreign). UNS G10200; AMS 5024 ASTM A107, A109, A311; FED QQ-S-637 (C1137); SAE J403, J412, 14

haracteristics. Essentially a high-manganese version of 1037, which s been resulfurized for improved machinability. Higher manganese con-1t provides higher hardenability, although not as much as indicated by the inganese content (1.35 to 1.65). Some of this manganese combines with creased sulfur to form manganese sulfide stringers. Available only as hot lled or hot rolled and cold drawn bars, for producing parts by machining ocesses. Too high in carbon for good weldability. Sulfur content can use hot shortness. Should not be used when welding is involved

ecommended Heat Treating Practice

ormalizing. Not usually required. If necessary, heat to 900 °C (1650). Cool in air.

In aerospace practice, parts are normalized at 900 °C (1650 °F)

Annealing. Heat to 885 °C (1625 °F). Furnace cool to 650 °C (1200 °F) at a rate not to exceed 28 °C (50 °F) per h to 650 °C (1200 °F).

In aerospace practice, parts are normalized at 785 °C (1450 °F) and allowed to cool below 540 °C (1000 °F)

Hardening. Heat to 845 °C (1555 °F). Flame hardening and carbonitriding are suitable surface hardening processes. Quench in water, brine, or aqueous polymers.

In aerospace practice, parts are austenitized at 845 °C (1555 °F) and quenched in oil, water, or polymer. For full hardness, oil quench sections not exceeding 9.525 mm (0.375 in.) thick

Tempering. As-quenched hardness of approximately 45 HRC. Hardness can be reduced by tempering. In quenching with oils or polymers, parts may be tempered at several different temperatures to get specific ranges of tensile strengths: 480 °C (895 °F) for 620 to 860 MPa (90 to 125 ksi); 329 °C (625 °F) for 860 to 1035 MPa (125 to 150 ksi). In quenching with water, more options are available, as follows: 540 °C (1000 °F) for 620 to 860 MPa (90 to 125 ksi); 480 °C (895 °F) for 860 to 1035 MPa (125 to 150 ksi); 425 °C (795 °F) for 1035 to 1170 MPa (150 to 170 ksi); 370 °C (700 °F) for 1175 to 1240 MPa (160 to 180 ksi); 315 °C (600 °F) for 1240 to 1380 MPa (180 to 200 ksi)

Strengthening by Cold Drawing and Stress Relieving. Grade 1137 bars and other medium-carbon resulfurized steels are frequently strengthened to desirable levels without quench hardening. Increase the draft during cold drawing by 10 to 35% above normal. Stress relieve by heating at approximately 315 °C (600 °F). Produces yield strengths of up to 690 MPa (100 ksi) or higher in bars up to about 19.05 mm (0.75 in.) diam. Machinability is very good

Recommended Processing Sequence

- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

1137 As-Quenched Hardness (Water)

Effect of mass on as-quenched hardness of steel bars, quenched in water; contents: 0.37 C, 1.40 Mn, 0.015 P, 0.08 S, 0.17 Si; grain size: 1 to 4

Size round		Hardness, HRC		
in.	mm	Surface	½ radius	Center
½	12.7	57	53	50
1	25.4	56	50	45
2	50.8	52	35	24
4	101.6	48	23	20

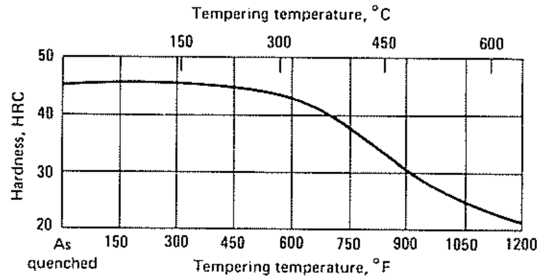
Source: Bethlehem Steel

1137 As-Quenched Hardness (Oil)

Effect of mass on as-quenched hardness of steel bars, quenched in oil; contents: 0.37 C, 1.40 Mn, 0.015 P, 0.08 S, 0.17 Si; grain size: 1 to 4

Size round		Hardness, HRC		
in.	mm	Surface	½ radius	Center
½	12.7	48	43	42
1	25.4	34	28	23
2	50.8	28	22	18
4	101.6	21	18	16

Source: Bethlehem Steel



1137: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

1139

Chemical Composition. **AISI and UNS:** 0.35 to 0.43 C, 1.35 to 1.65 Mn, 0.040 P max, 0.13 to 0.20 S

Similar Steels (U.S. and/or Foreign). UNS G11390; FED QQ-S-637 (C1139); SAE J403

Characteristics. Characteristics nearly parallel with 1137. Carbon and sulfur contents slightly higher. These differences result in slightly higher as-quenched hardness (as high as 47 HRC), slightly lower hardenability (because of higher sulfur content), and even better machinability than 1137. Never recommended for welding or forging

Recommended Heat Treating Practice

Normalizing. Not usually required. If necessary, heat to 900 °C (1650 °F). Cool in air

Annealing. Heat to 885 °C (1625 °F). Furnace cool to 650 °C (1200 °F), at a rate not to exceed 28 °C (50 °F) per h

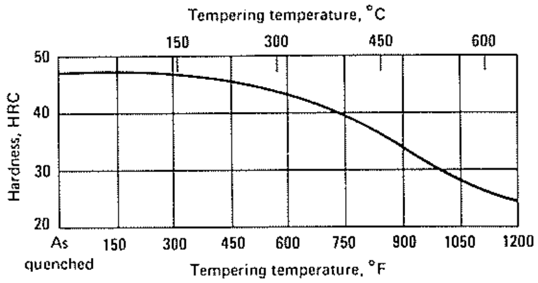
Hardening. Heat to 845 °C (1555 °F). Flame hardening and carbonitriding are suitable surface hardening processes. Quench in water or brine. For full hardness, oil quench sections not exceeding 9.525 mm (0.375 in.) thick

Tempering. As-quenched hardness of approximately 47 HRC. Hardness can be reduced by tempering

Strengthening by Cold Drawing and Stress Relieving. Grade 1139 bars and other medium-carbon resulfurized steels are frequently strengthened to desirable levels without quench hardening. Increase the draft during cold drawing by 10 to 35% above normal. Stress relieve by heating at approximately 315 °C (600 °F). Produces yield strengths of up to 690 MPa (100 ksi) or higher in bars up to about 19.05 mm (0.75 in.) diam. Machinability is very good

Recommended Processing Sequence

- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine



1139: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

140

ıemical Composition. AISI and UNS: 0.37 to 0.44 C, 0.70 to ı0 Mn, 0.040 P max, 0.08 to 0.13 S

milar Steels (U.S. and/or Foreign). UNS G11400; FED QQ-ɜ37 (C1140); SAE J403, J412, J414; (Ger.) DIN 1.0726; (Fr.) AFNOR MF 4; (Swed.) SS_{14} 1957

ıaracteristics. Slightly higher carbon range, compared with 1139, of practical significance. Hardenability is lower because of lower mangaɜe content. Otherwise, same characteristics as 1137 and 1139, including ponse to abnormal drafts in cold drawing and a subsequent stress relief. ıt used where forging or welding is involved. Machinability is excellent

ɜcommended Heat Treating Practice

ırmalizing. Not usually required. If necessary, heat to 900 °C (1650 ı. Cool in air

ınealing. Heat to 885 °C (1625 °F). Furnace cool to 650 °C (1200 °F), ı rate not to exceed 28 °C (50 °F) per h

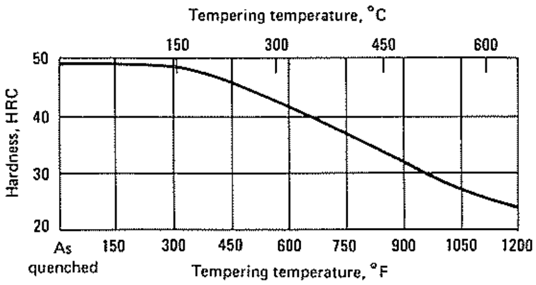
Hardening. Heat to 845 °C (1555 °F). Flame hardening and carbonitriding are suitable surface hardening processes. Quench in water or brine. For full hardness, oil quench sections not exceeding 9.525 mm (0.375 in.) thick

Tempering. As-quenched hardness of approximately 50 HRC. Hardness can be reduced by tempering

Strengthening by Cold Drawing and Stress Relieving. Grade 1140 bars and other medium-carbon resulfurized steels are frequently strengthened to desirable levels without quench hardening. Increase the draft during cold drawing by 10 to 35% above normal. Stress relieve by heating at approximately 315 °C (600 °F). Produces yield strengths of up to 690 MPa (100 ksi) or higher in bars up to about 19.05 mm (0.75 in.) diam. Machinability is very good

Recommended Processing Sequence

- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine



1140: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

141

ıemical Composition. AISI and UNS: 0.37 to 0.45 C, 1.35 to ɜ5 Mn, 0.040 P max, 0.08 to 0.13 S

milar Steels (U.S. and/or Foreign). UNS G11410; ASTM .07, A108, A311; FED QQ-S-637; SAE J403, J412, J414

Characteristics. Most widely used medium-carbon resulfurized steel. As-quenched full hardness of approximately 52 HRC, when carbon is near high side of the range. Slightly lower hardness for middle or lower end of the range. High manganese content imparts higher hardenability compared with 1140, but almost the same as 1139. Available in pretreated condition.

Subjected to abnormally heavy drafts followed by stress relieving. (See grade 1137.) Never recommended for forging or welding

Recommended Heat Treating Practice

Normalizing. Not usually required. If necessary, heat to 885 °C (1625 °F). Cool in air

Annealing. Usually purchased by fabricator in condition for machining. If required, may be annealed by heating to 845 °C (1555 °F). Furnace cool to 650 °C (1200 °F) at a rate not to exceed 28 °C (50 °F) per h

Hardening. Austenitize at 830 °C (1525 °F). Flame hardening, carbonitriding, and martempering are suitable processes. Quench in water or brine. For full hardness, oil quench sections under 9.525 mm (0.375 in.) thick

Tempering. Depending upon precise carbon content, as-quenched hardness is usually 48 to 52 HRC. Hardness can be reduced by tempering

Recommended Processing Sequence

- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

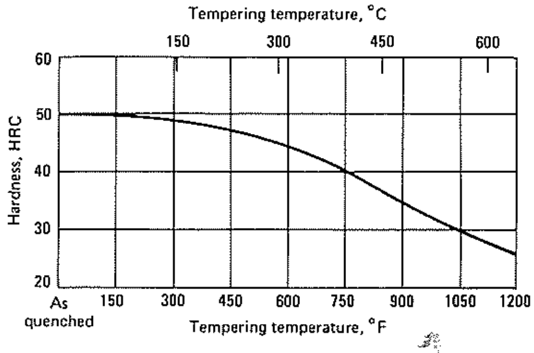
1141 As-Quenched Hardness (Oil)

Effect of mass on as-quenched hardness of steel bars, quenched in oil; contents: 0.39 C, 1.58 Mn, 0.02 P, 0.08 S, 0.19 Si; grain size: 90%, 2 to 4; 10%, 5

Size round		Hardness, HRC		
in.	mm	Surface	½ radius	Center
½	12.7	52	49	46
1	25.4	48	43	38
2	50.8	36	28	22
4	101.6	27	22	18

Source: Bethlehem Steel

1141: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure



1144

Chemical Composition. **AISI and UNS:** 0.40 to 0.48 C, 1.35 to 1.65 Mn, 0.040 P max, 0.24 to 0.33 S

Similar Steels (U.S. and/or Foreign). UNS G11440; ASTM A108, A311; FED QQ-S-637 (C1144); SAE J403, J412, J414

Characteristics. Special-purpose grade. Very high sulfur content, equal to free-machining 1213, permits extremely fast machining with heavy cuts. Machined finishes unusually good. High sulfur content reduces transverse impact and ductility. Can be drawn by heavy drafts at elevated temperature, 370 °C (700 °F), which results in relatively high strength and high hardness, up to 35 HRC. Machinability is excellent. Widely used for producing machined parts put in service without heat treatment. Can be purchased in cold drawn condition and heat treated. Depending upon precise carbon content, as-quenched and fully hardened 1144 should be approximately 52 to 55 HRC. Never used where forging or welding is involved

Recommended Heat Treating Practice

Normalizing. Seldom required. If necessary, heat to 885 °C (1625 °F). Cool in air

Annealing. Seldom necessary. May be annealed by heating to 845 °C (1555 °F). Furnace cool to 650 °C (1200 °F), at a rate not to exceed 28 °C (50 °F) per h

Hardening. Austenitize at 830 °C (1525 °F). Flame hardening and carbonitriding are suitable surface hardening processes. Quench in water or brine. For full hardness, oil quench sections less than 9.525 mm (0.755 in.) thick

Tempering. Depending upon precise carbon content, as-quenched hardness of usually 52 to 55 HRC. Hardness can be reduced by tempering

Recommended Processing Sequence

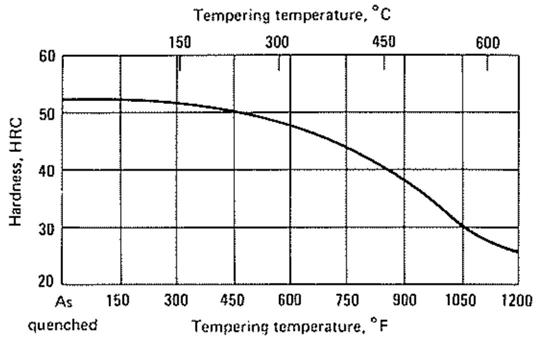
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

1144: As-Quenched Hardness (Oil)

Effect of mass on as-quenched hardness of steel bars, quenched in oil; contents: 0.46 C, 1.37 Mn, 0.019 P, 0.24 S, 0.05 Si; grain size: 75%, 1 to 4; 25%, 5 to 6

Size round		Hardness, HRC				
in.	mm	Surface	½ radius		Center	
½	12.7	39	32	...	28	...
1	25.4	36	29	...	24	...
2	50.8	30	27	...	22	...
4	101.6	27	...	98	...	97

Source: Bethlehem Steel



1144: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

146

ıemical Composition. **AISI and UNS:** 0.42 to 0.49 C, 0.70 to)0 Mn, 0.040 P max, 0.08 to 0.13 S

milar Steels (U.S. and/or Foreign). UNS G11460; FED QQ-537 (C1146); SAE J403, J412, J414; (Ger.) DIN 1.0727; (Fr.) AFNOR MF 4; (Swed.) SS_{14} 1973

ıaracteristics. An 1140 with higher carbon. Excellent machinability d relatively low hardenability. Amenable to strengthening by heavy ıfts and stress relieving. Higher carbon, lower manganese, and lower rdenability make it popular for induction hardening. Never use when ·ging or welding is involved. Can be quenched and tempered. As-enched hardness of 55 HRC or slightly higher, depending on carbon ntent

ecommended Heat Treating Practice

ɔrmalizing. Seldom required. If necessary, heat to 885 °C (1625 °F). ıol in air

Annealing. Seldom required by the fabricator. If necessary, heat to 845 °C (1555 °F). Furnace cool to 650 °C (1200 °F) at a rate not to exceed 28 °C (50 °F) per h

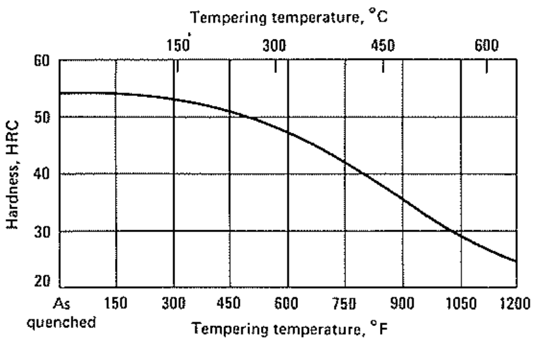
Hardening. Austenitize at 830 °C (1525 °F). Flame hardening, carbonitriding, austempering, and martempering are suitable processes. Quench in water or brine. For full hardness, oil quench sections less than 9.525 mm (0.375 in.) thick

Tempering. Depending upon precise carbon content, as-quenched hardness is usually 55 HRC. Hardness can be reduced by tempering, under recommended practice

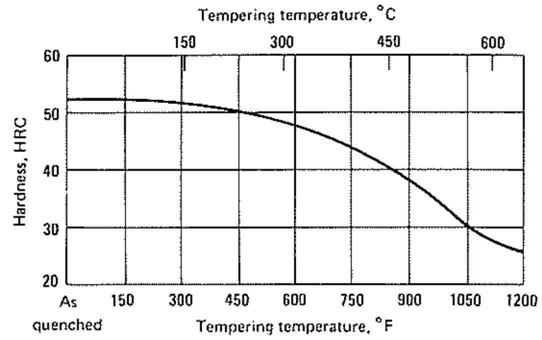
Martempering. Austenitize at 815 °C (1500 °F). Martemper in oil at 175 °C (345 °F)

Recommended Processing Sequence

- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine



1146: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure



1144: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

146

ıemical Composition. **AISI and UNS:** 0.42 to 0.49 C, 0.70 to)0 Mn, 0.040 P max, 0.08 to 0.13 S

milar Steels (U.S. and/or Foreign). UNS G11460; FED QQ-537 (C1146); SAE J403, J412, J414; (Ger.) DIN 1.0727; (Fr.) AFNOR MF 4; (Swed.) SS_{14} 1973

ıaracteristics. An 1140 with higher carbon. Excellent machinability d relatively low hardenability. Amenable to strengthening by heavy ıfts and stress relieving. Higher carbon, lower manganese, and lower rdenability make it popular for induction hardening. Never use when ·ging or welding is involved. Can be quenched and tempered. As-enched hardness of 55 HRC or slightly higher, depending on carbon ntent

ecommended Heat Treating Practice

ɔrmalizing. Seldom required. If necessary, heat to 885 °C (1625 °F). ıol in air

Annealing. Seldom required by the fabricator. If necessary, heat to 845 °C (1555 °F). Furnace cool to 650 °C (1200 °F) at a rate not to exceed 28 °C (50 °F) per h

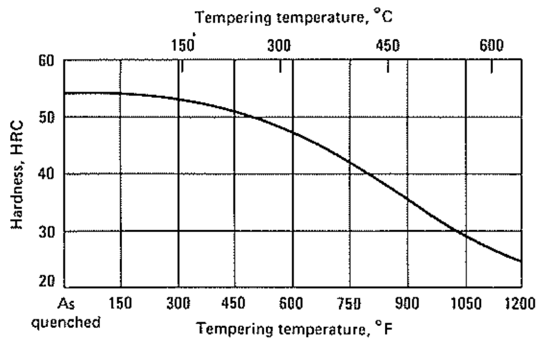
Hardening. Austenitize at 830 °C (1525 °F). Flame hardening, carbonitriding, austempering, and martempering are suitable processes. Quench in water or brine. For full hardness, oil quench sections less than 9.525 mm (0.375 in.) thick

Tempering. Depending upon precise carbon content, as-quenched hardness is usually 55 HRC. Hardness can be reduced by tempering, under recommended practice

Martempering. Austenitize at 815 °C (1500 °F). Martemper in oil at 175 °C (345 °F)

Recommended Processing Sequence

- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine



1146: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

1151

Chemical Composition. AISI and UNS: 0.48 to 0.55 C, 0.70 to 1.00 Mn, 0.040 P max, 0.08 to 0.13 S

Similar Steels (U.S. and/or Foreign). UNS G11510; ASTM A107, A108, A311; FED QQ-S-637 (C1151); MIL SPEC MIL-S-20137A; SAE J403, J412, J414

Characteristics. Resulfurized version of 1050. Carbon ranges the same. Although the 1151 manganese content is slightly higher, some of this manganese combines with the high sulfur, so that the hardenability is almost the same as 1050. As-quenched hardnesses of 1050 and 1151 are essentially the same, 55 HRC or slightly higher. 1151 also used for induction hardening. 1050 used for parts to be forged. 1151 used for parts to be machined from bars

Recommended Heat Treating Practice

Normalizing. Seldom used. If necessary, heat to 900 °C (1600 °F). Cool in air

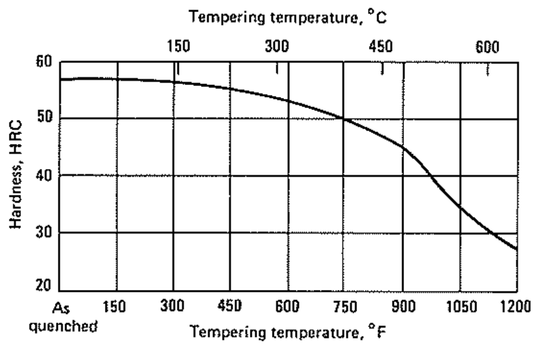
Annealing. Heat to 870 °C (1600 °F). Furnace cool to 650 °C (1200 °F) at a rate not to exceed 28 °C (50 °F) per h

Hardening. Austenitize at 830 °C (1525 °F). Flame hardening, induction, and carbonitriding are suitable surface hardening processes. Quench in water or brine. Oil quench sections under 6.35 mm (0.25 in.) thick

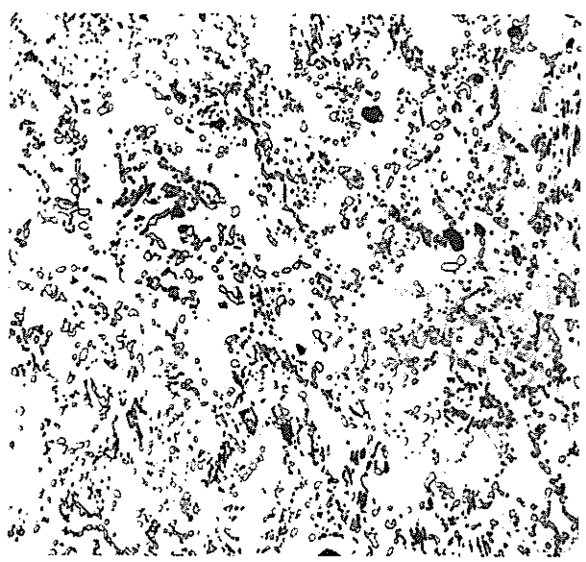
Tempering After Hardening. Hardness of at least 55 HRC, if properly austenitized and quenched. Hardness can be adjusted by tempering

Recommended Processing Sequence

- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine



1151: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure



1151: Microstructure. 2% nital, 500×. Manganese sulfide stringers (black) in steel bar. Remainder is dispersion of spheroidized carbide in ferrite matrix. Micrograph is cross section, taken perpendicular to rolling direction

Rephosphorized and Resulfurized Carbon Steels (1200 Series)

Compositions for 12XX steels in this section are applicable for semi-ished products for forging, hot rolled, and cold-finished bars, wire rods, d seamless tubing. The compositions that follow are the same as those in : 1982 edition with one exception: at that time the sanctioning bodies were UNS and AISI. Now they are UNS and SAE/AISI. Also note: it is not common practice to produce 12XX steels to specified limits for silicon because of its adverse effect on machinability.

211

ıemical Composition. **UNS G12110 and AISI/SAE 1211:** 0.13 C ıx, 0.60 to 0.90 Mn, 0.07 to 0.12 P, 0.10 to 0.15 S

milar Steels (U.S. and/or Foreign). UNS G12110; ASTM .07, A107 (B1111), A108, A108 (B1111); FED QQ-S-637 (C1211); SAE)3

ıaracteristics. Machinery steel that has been resulfurized and re-osphorized has better machinability than that of grade 1110. Furnished hot rolled or hot rolled and cold drawn condition. The latter condition is the better for machinability. Intended for fabrication by machining. Never recommended for forging, cold forming, or welding

Recommended Heat Treating Practice

Normalizing and Annealing. Seldom required

Light Case Hardening. May be desired. See carbonitriding and salt bath nitriding process described for 1008

212

hemical Composition. **UNS and SAE/AISI:** 0.13 C max, 0.70 to)0 Mn, 0.07 to 0.12 P, 0.16 to 0.23 S

imilar Steels (U.S. and/or Foreign). UNS G12120; AMS 5010 ASTM A107, A107 (B1212), A108, A108 (B1212); FED QQ-S-637 1212); SAE J403; (Ger.) DIN 1.0711; (Ital.) UNI 10 S 20; (Jap.) JIS SUM

haracteristics. Similar to 1211, except sulfur and manganese con-ıts are higher. Machinability better than that of 1211. Adverse effects of sulfur and phosphorus on mechanical and fabrication properties are slightly greater

Recommended Heat Treating Practice

Normalizing and Annealing. Seldom required

Light Case Hardening. May be desired. See carbonitriding and salt bath nitriding process described for 1008

213

hemical Composition. **UNS and SAE/AISI:** 0.13 C max, 0.70 to)0 Mn, 0.07 to 0.12 P, 0.24 to 0.33 S

imilar Steels (U.S. and/or Foreign). UNS G12130; ASME 107, A107 (B1113), A108, A108 (B1113); FED QQ-S-637 (C1913); SAE 03; (Ger.) DIN 1.0715; (Ital.) UNI 9 SMn 23; (Jap.) JIS SUM 22; (U.K.) S. 220 M 07

haracteristics. Nearly identical to those of 1212. Greater content of lfur further enhances machinability at the sacrifice of mechanical and brication properties

Recommended Heat Treating Practice

Normalizing and Annealing. Seldom required

Light Case Hardening. May be desired. See carbonitriding and salt bath nitriding process described for 1008

12L14

Chemical Composition. **UNS and SAE/AISI:** 0.15 C max, 0.85 to 1.15 Mn, 0.04 to 0.09 P, 0.26 to 0.35 S, 0.15 to 0.35 Pb

Similar Steels (U.S. and/or Foreign). UNS G12144; ASTM A107, A108; SAE J403, J412, J414; (Ger.) DIN 1.0718; (Ital.) UNI 9 SMnPb 23; (Jap.) JIS SUM 22 L, SUM 24 L; (Swed.) SS_{14} 1914

Characteristics. Contains a lead addition of 0.15 to 0.35%, indicated by L in designation. Represents the ultimate in free-machining characteristics, but an even further sacrifice of mechanical and fabricating properties, such as forgeability, cold formability, and weldability. Addition of lead further enhances machinability in terms of high speeds with heavy cuts and provides excellent finishes on machined surfaces. Sometimes saves an extra machining operation

Recommended Heat Treating Practice

Normalizing and Annealing. Seldom required

Light Case Hardening. May be desired. See carbonitriding and salt bath nitriding process described for 1008

1215

Chemical Composition. **UNS and SAE/AISI:** 0.09 C max, 0.75 to 1.05 Mn, 0.04 to 0.09 P, 0.26 to 0.35 S

Similar Steels (U.S. and/or Foreign). UNS G12150; FED QQ-S-637; SAE J412

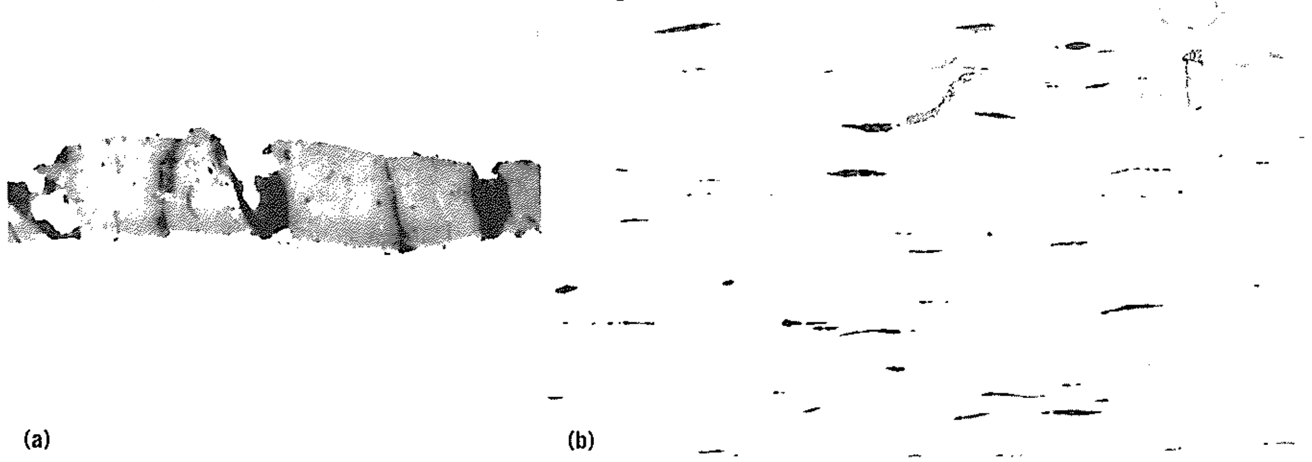
Characteristics. Compared with 1213, with minor adjustments in carbon, manganese, phosphorus, and sulfur contents. No major effects on mechanical or fabricating properties. Represents another free-machining steel. Commonly used for parts completed in automatic multispindle machine tools

Recommended Heat Treating Practice

Normalizing and Annealing. Seldom required

Light Case Hardening. May be desired. See carbonitriding and salt bath nitriding process described for 1008

1215: Microstructures. (a) As polished (not etched), 1000×. Cold drawn steel tube. Longitudinal view. Segmented sulfide inclusion. (b) As polished (not etched), 1000×. Cold drawn steel tube, at lower magnification. Sulfide inclusions shown



(a) (b)

High Manganese Carbon Steels (1500 Series)

513

hemical Composition. **AISI** and **UNS:** 0.10 to 0.16 C, 1.10 to 40 Mn, 0.040 P max, 0.050 S max

imilar Steels (U.S. and/or Foreign). UNS G15130; SAE J403, 12

haracteristics. Essentially the high-manganese version of 1012. ›wever, the higher manganese content provides slightly greater strength the normalized or annealed condition and somewhat better core proper-s when case hardened. Excellent forgeability and weldability. Reason-ly good cold formability, only slightly less than 1012. Machinability is ry poor when compared with the 1100 and 1200 grades. Generally ailable in various product forms, including flat stock, bars, and forging ›ck

Forging. Heat to approximately 1290 °C (2355 °F). Finish forging before temperature drops below 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 885 °C (1625 °F). Cool in still air

Annealing. For clean surfaces, heat to approximately 885 °C (1625 °F) in lean exothermic atmosphere. Cool in cooler section of continuous furnace

Case Hardening. Carbonitride at 760 to 870 °C (1400 to 1600 °F) in an enriched endothermic carrier gas, plus about 10% anhydrous ammonia. Case depths from 0.076 to 0.26 mm (0.003 to 0.01 in.). Oil quench directly from carbonitriding temperature. Provides maximum surface hardness. Salt baths can produce similar results

5B21H, 15B21RH

hemical Composition. **15B21H. UNS H15211 and SAE/AISI:** 17 to 0.24 C, 0.70 to 1.20 Mn, 0.15 to 0.35 Si, (0.0005 to 0.003 B can be pected). **SAE 15B21RH:** 0.17 to 0.22 C, 0.80 to 1.10 Mn, 0.15 to 0.35 (0.0005 to 0.003 B can be expected)

imilar Steels (U.S. and/or Foreign). **15B21H.** UNS H15211; \E J1268, J1868; (Ger.) DIN 1.5523; ASTM 914

haracteristics. Nonfree machining steel. Can be cold formed to me degree. Readily weldable. When carbon is on the high side and with higher manganese and addition of boron, a combination can exist where me preheating prior to welding is necessary to avoid weld cracking. ›mbination of higher manganese and boron provides substantial increase hardenability, compared with 1020

›rging. Excellent forgeability. Heat to 1260 °C (2300 °F). Do not forge low 925 °C (1695 °F)

ecommended Heat Treating Practice

ormalizing. Heat to 925 °C (1695 °F). Air cool

Annealing. Heat to 870 °C (1600 °F). Cool slowly, preferably in the furnace

Hardening. Can be case hardened by any one of several processes, from light case hardening by carbonitriding and salt bath nitriding described for grade 1008 to deeper case carburizing in gas, solid, or liquid media. Because of higher hardenability, oil quench thicker sections for full hardness. Carburize and quench as for 1020

Tempering. Optional. Temper at 150 °C (300 °F) for 1 h or higher if some sacrifice of hardness can be tolerated

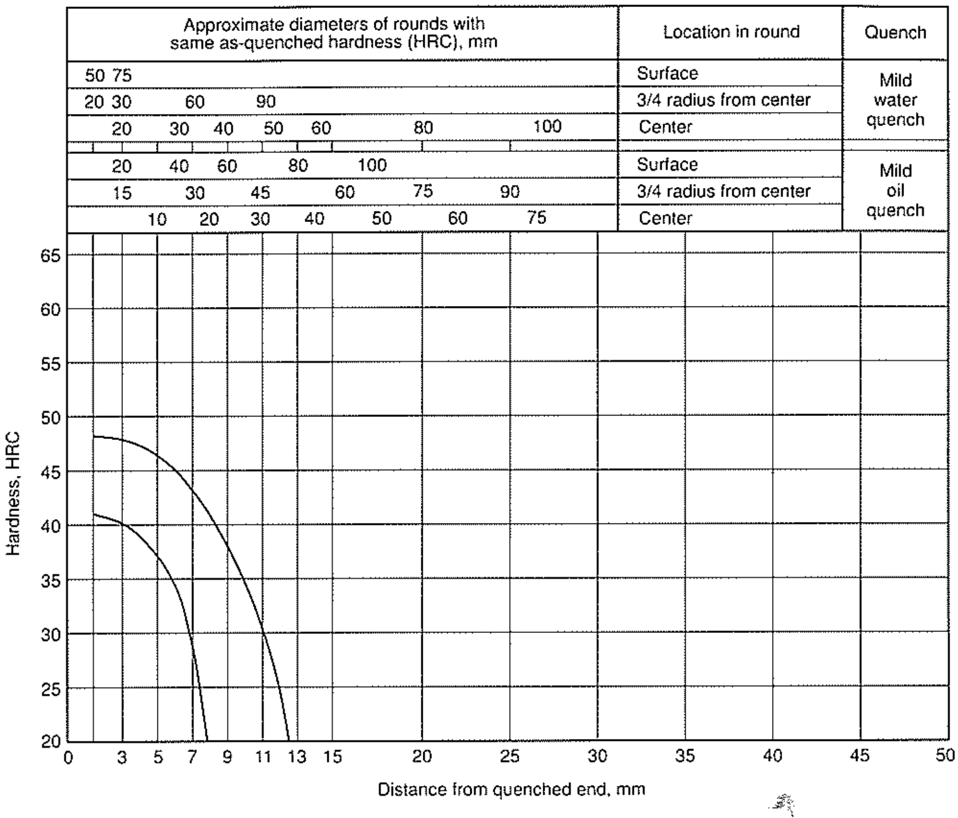
Recommended Processing Sequence

- Forge
- Normalize
- Rough machine
- Semifinish machine and grind
- Carburize
- Diffusion cycle
- Quench
- Temper
- Finish grind

15B21H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 925 °C (1700 °F)

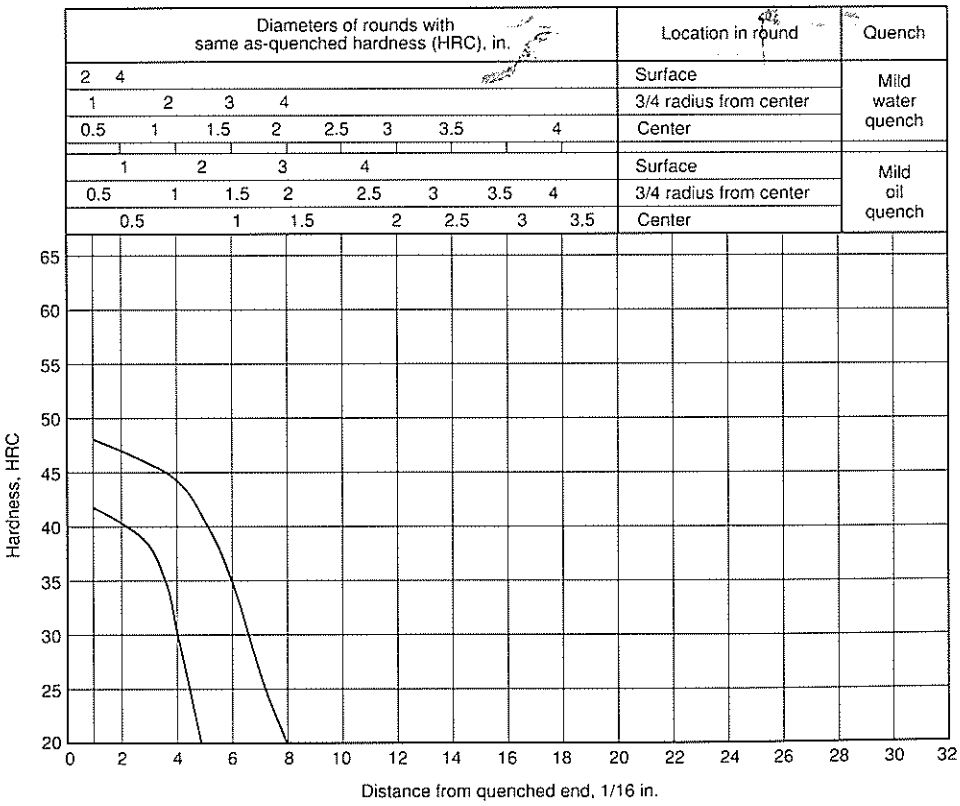
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	48	41
3	48	40
5	46	36
7	43	27
9	38	...
11	30	...
13	...	...



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	48	41
1.5	48	41
2	47	40
2.5	47	39
3	46	38
3.5	45	36
4	44	30
4.5	42	23
5	40	20
5.5	38	...
6	35	...
6.5	32	...
7	27	...
7.5	22	...
8	20	...
9	...	...



1151

Chemical Composition. AISI and UNS: 0.48 to 0.55 C, 0.70 to 1.00 Mn, 0.040 P max, 0.08 to 0.13 S

Similar Steels (U.S. and/or Foreign). UNS G11510; ASTM A107, A108, A311; FED QQ-S-637 (C1151); MIL SPEC MIL-S-20137A; SAE J403, J412, J414

Characteristics. Resulfurized version of 1050. Carbon ranges the same. Although the 1151 manganese content is slightly higher, some of this manganese combines with the high sulfur, so that the hardenability is almost the same as 1050. As-quenched hardnesses of 1050 and 1151 are essentially the same, 55 HRC or slightly higher. 1151 also used for induction hardening. 1050 used for parts to be forged. 1151 used for parts to be machined from bars

Recommended Heat Treating Practice

Normalizing. Seldom used. If necessary, heat to 900 °C (1600 °F). Cool in air

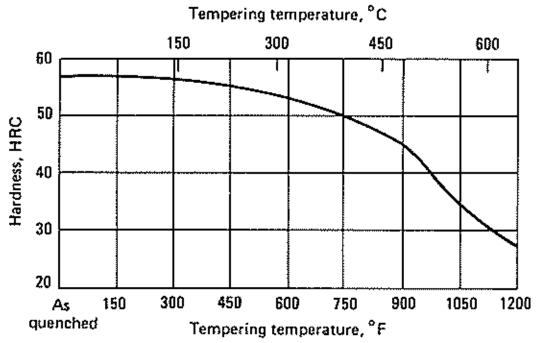
Annealing. Heat to 870 °C (1600 °F). Furnace cool to 650 °C (1200 °F) at a rate not to exceed 28 °C (50 °F) per h

Hardening. Austenitize at 830 °C (1525 °F). Flame hardening, induction, and carbonitriding are suitable surface hardening processes. Quench in water or brine. Oil quench sections under 6.35 mm (0.25 in.) thick

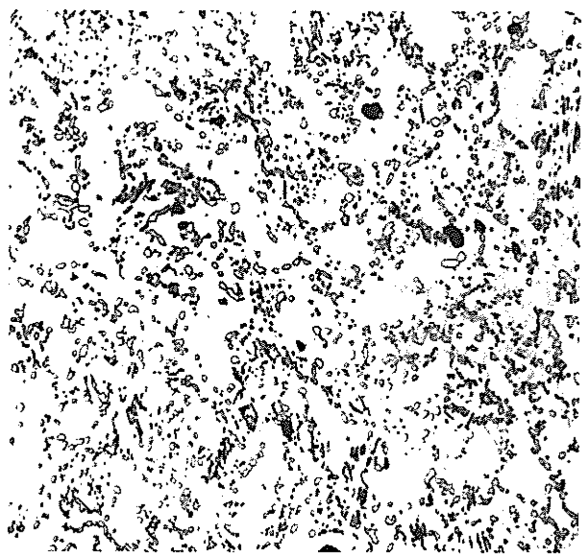
Tempering After Hardening. Hardness of at least 55 HRC, if properly austenitized and quenched. Hardness can be adjusted by tempering

Recommended Processing Sequence

- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine



1151: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure



1151: Microstructure. 2% nital, 500×. Manganese sulfide stringers (black) in steel bar. Remainder is dispersion of spheroidized carbide in ferrite matrix. Micrograph is cross section, taken perpendicular to rolling direction

Rephosphorized and Resulfurized Carbon Steels (1200 Series)

Compositions for 12XX steels in this section are applicable for semi-ished products for forging, hot rolled, and cold-finished bars, wire rods, d seamless tubing. The compositions that follow are the same as those in ; 1982 edition with one exception: at that time the sanctioning bodies were UNS and AISI. Now they are UNS and SAE/AISI. Also note: it is not common practice to produce 12XX steels to specified limits for silicon because of its adverse effect on machinability.

211

ıemical Composition. **UNS G12110 and AISI/SAE 1211:** 0.13 C ıx, 0.60 to 0.90 Mn, 0.07 to 0.12 P, 0.10 to 0.15 S

milar Steels (U.S. and/or Foreign). UNS G12110; ASTM .07, A107 (B1111), A108, A108 (B1111); FED QQ-S-637 (C1211); SAE)3

ıaracteristics. Machinery steel that has been resulfurized and re-osphorized has better machinability than that of grade 1110. Furnished hot rolled or hot rolled and cold drawn condition. The latter condition is the better for machinability. Intended for fabrication by machining. Never recommended for forging, cold forming, or welding

Recommended Heat Treating Practice

Normalizing and Annealing. Seldom required

Light Case Hardening. May be desired. See carbonitriding and salt bath nitriding process described for 1008

212

hemical Composition. **UNS and SAE/AISI:** 0.13 C max, 0.70 to)0 Mn, 0.07 to 0.12 P, 0.16 to 0.23 S

imilar Steels (U.S. and/or Foreign). UNS G12120; AMS 5010 ASTM A107, A107 (B1212), A108, A108 (B1212); FED QQ-S-637 1212); SAE J403; (Ger.) DIN 1.0711; (Ital.) UNI 10 S 20; (Jap.) JIS SUM

haracteristics. Similar to 1211, except sulfur and manganese con-ıts are higher. Machinability better than that of 1211. Adverse effects of sulfur and phosphorus on mechanical and fabrication properties are slightly greater

Recommended Heat Treating Practice

Normalizing and Annealing. Seldom required

Light Case Hardening. May be desired. See carbonitriding and salt bath nitriding process described for 1008

213

hemical Composition. **UNS and SAE/AISI:** 0.13 C max, 0.70 to)0 Mn, 0.07 to 0.12 P, 0.24 to 0.33 S

imilar Steels (U.S. and/or Foreign). UNS G12130; ASME 107, A107 (B1113), A108, A108 (B1113); FED QQ-S-637 (C1913); SAE 03; (Ger.) DIN 1.0715; (Ital.) UNI 9 SMn 23; (Jap.) JIS SUM 22; (U.K.) S. 220 M 07

haracteristics. Nearly identical to those of 1212. Greater content of lfur further enhances machinability at the sacrifice of mechanical and brication properties

Recommended Heat Treating Practice

Normalizing and Annealing. Seldom required

Light Case Hardening. May be desired. See carbonitriding and salt bath nitriding process described for 1008

12L14

Chemical Composition. **UNS and SAE/AISI:** 0.15 C max, 0.85 to 1.15 Mn, 0.04 to 0.09 P, 0.26 to 0.35 S, 0.15 to 0.35 Pb

Similar Steels (U.S. and/or Foreign). UNS G12144; ASTM A107, A108; SAE J403, J412, J414; (Ger.) DIN 1.0718; (Ital.) UNI 9 SMnPb 23; (Jap.) JIS SUM 22 L, SUM 24 L; (Swed.) SS_{14} 1914

Characteristics. Contains a lead addition of 0.15 to 0.35%, indicated by L in designation. Represents the ultimate in free-machining characteristics, but an even further sacrifice of mechanical and fabricating properties, such as forgeability, cold formability, and weldability. Addition of lead further enhances machinability in terms of high speeds with heavy cuts and provides excellent finishes on machined surfaces. Sometimes saves an extra machining operation

Recommended Heat Treating Practice

Normalizing and Annealing. Seldom required

Light Case Hardening. May be desired. See carbonitriding and salt bath nitriding process described for 1008

1215

Chemical Composition. **UNS and SAE/AISI:** 0.09 C max, 0.75 to 1.05 Mn, 0.04 to 0.09 P, 0.26 to 0.35 S

Similar Steels (U.S. and/or Foreign). UNS G12150; FED QQ-S-637; SAE J412

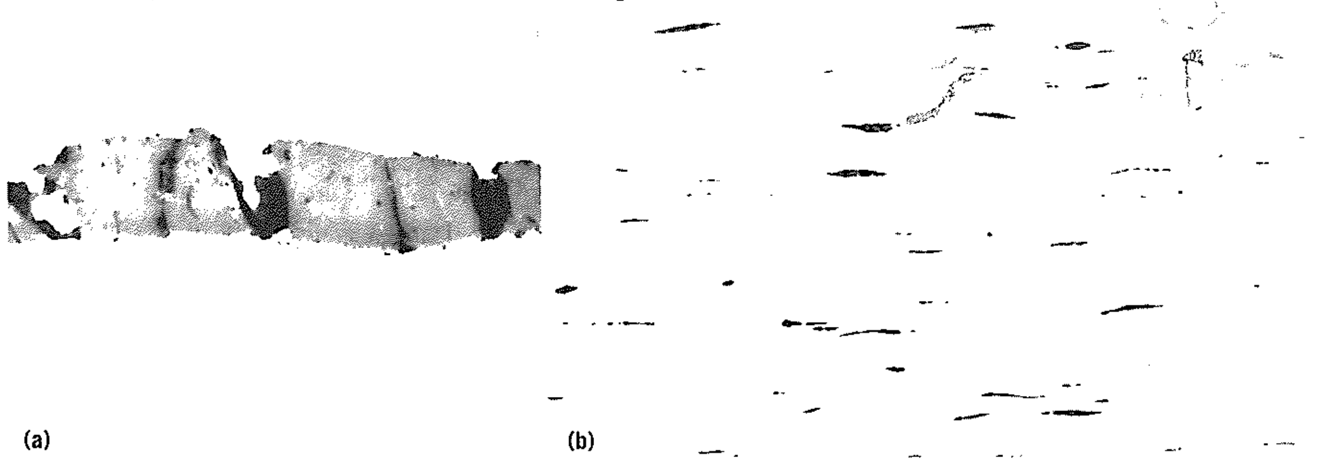
Characteristics. Compared with 1213, with minor adjustments in carbon, manganese, phosphorus, and sulfur contents. No major effects on mechanical or fabricating properties. Represents another free-machining steel. Commonly used for parts completed in automatic multispindle machine tools

Recommended Heat Treating Practice

Normalizing and Annealing. Seldom required

Light Case Hardening. May be desired. See carbonitriding and salt bath nitriding process described for 1008

1215: Microstructures. (a) As polished (not etched), 1000×. Cold drawn steel tube. Longitudinal view. Segmented sulfide inclusion. (b) As polished (not etched), 1000×. Cold drawn steel tube, at lower magnification. Sulfide inclusions shown



(a) (b)

High Manganese Carbon Steels (1500 Series)

513

hemical Composition. AISI and UNS: 0.10 to 0.16 C, 1.10 to 40 Mn, 0.040 P max, 0.050 S max

imilar Steels (U.S. and/or Foreign). UNS G15130; SAE J403, 12

haracteristics. Essentially the high-manganese version of 1012. owever, the higher manganese content provides slightly greater strength the normalized or annealed condition and somewhat better core propers when case hardened. Excellent forgeability and weldability. Reasonly good cold formability, only slightly less than 1012. Machinability is ry poor when compared with the 1100 and 1200 grades. Generally ailable in various product forms, including flat stock, bars, and forging ock

Forging. Heat to approximately 1290 °C (2355 °F). Finish forging before temperature drops below 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 885 °C (1625 °F). Cool in still air

Annealing. For clean surfaces, heat to approximately 885 °C (1625 °F) in lean exothermic atmosphere. Cool in cooler section of continuous furnace

Case Hardening. Carbonitride at 760 to 870 °C (1400 to 1600 °F) in an enriched endothermic carrier gas, plus about 10% anhydrous ammonia. Case depths from 0.076 to 0.26 mm (0.003 to 0.01 in.). Oil quench directly from carbonitriding temperature. Provides maximum surface hardness. Salt baths can produce similar results

5B21H, 15B21RH

hemical Composition. **15B21H. UNS H15211 and SAE/AISI:** 17 to 0.24 C, 0.70 to 1.20 Mn, 0.15 to 0.35 Si, (0.0005 to 0.003 B can be pected). **SAE 15B21RH:** 0.17 to 0.22 C, 0.80 to 1.10 Mn, 0.15 to 0.35 (0.0005 to 0.003 B can be expected)

imilar Steels (U.S. and/or Foreign). **15B21H.** UNS H15211; AE J1268, J1868; (Ger.) DIN 1.5523; ASTM 914

haracteristics. Nonfree machining steel. Can be cold formed to me degree. Readily weldable. When carbon is on the high side and with e higher manganese and addition of boron, a combination can exist where me preheating prior to welding is necessary to avoid weld cracking. ombination of higher manganese and boron provides substantial increase hardenability, compared with 1020

orging. Excellent forgeability. Heat to 1260 °C (2300 °F). Do not forge low 925 °C (1695 °F)

ecommended Heat Treating Practice

ormalizing. Heat to 925 °C (1695 °F). Air cool

Annealing. Heat to 870 °C (1600 °F). Cool slowly, preferably in the furnace

Hardening. Can be case hardened by any one of several processes, from light case hardening by carbonitriding and salt bath nitriding described for grade 1008 to deeper case carburizing in gas, solid, or liquid media. Because of higher hardenability, oil quench thicker sections for full hardness. Carburize and quench as for 1020

Tempering. Optional. Temper at 150 °C (300 °F) for 1 h or higher if some sacrifice of hardness can be tolerated

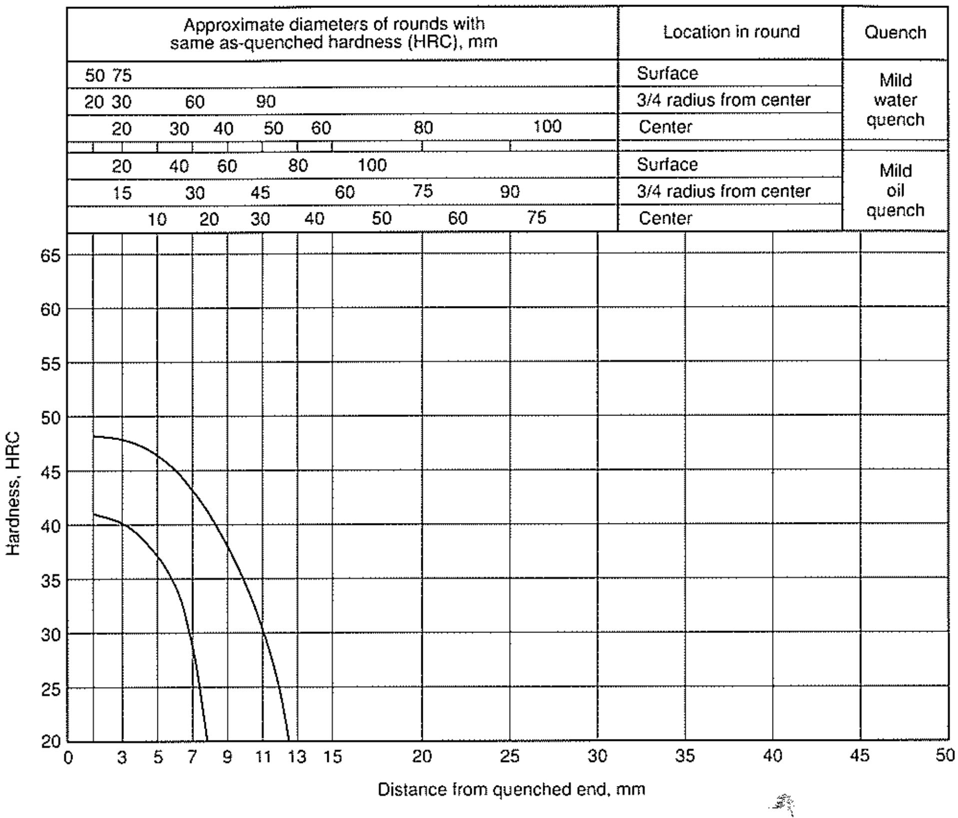
Recommended Processing Sequence

- Forge
- Normalize
- Rough machine
- Semifinish machine and grind
- Carburize
- Diffusion cycle
- Quench
- Temper
- Finish grind

15B21H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 925 °C (1700 °F)

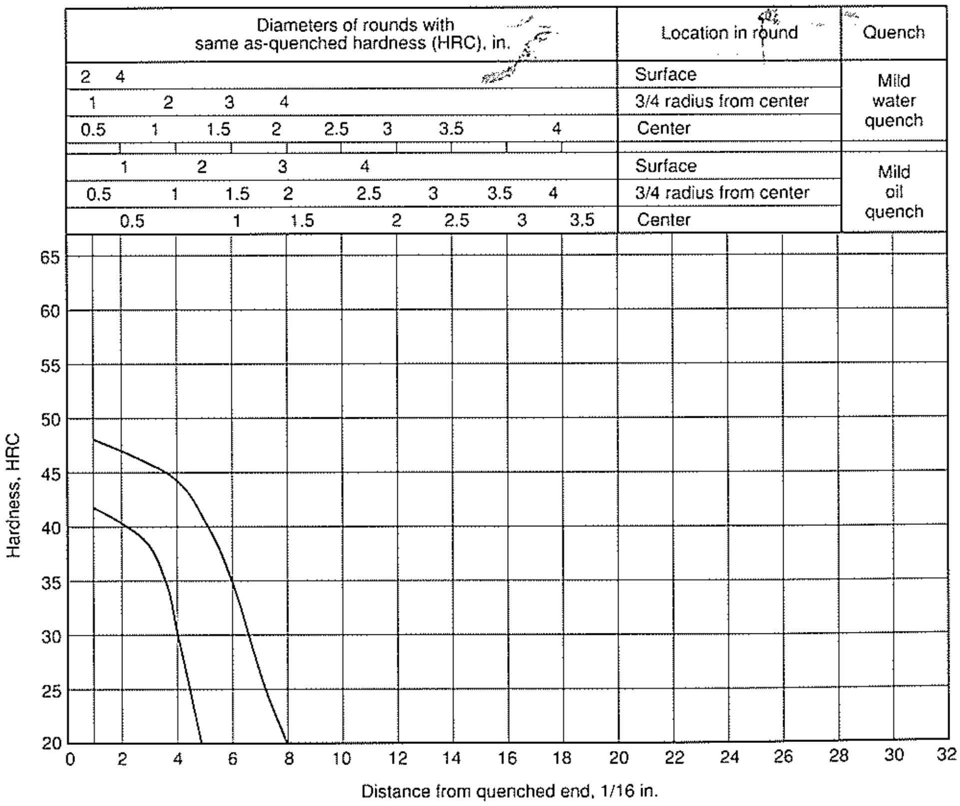
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	48	41
3	48	40
5	46	36
7	43	27
9	38	...
11	30	...
13	...	...



Hardness limits for specification purposes

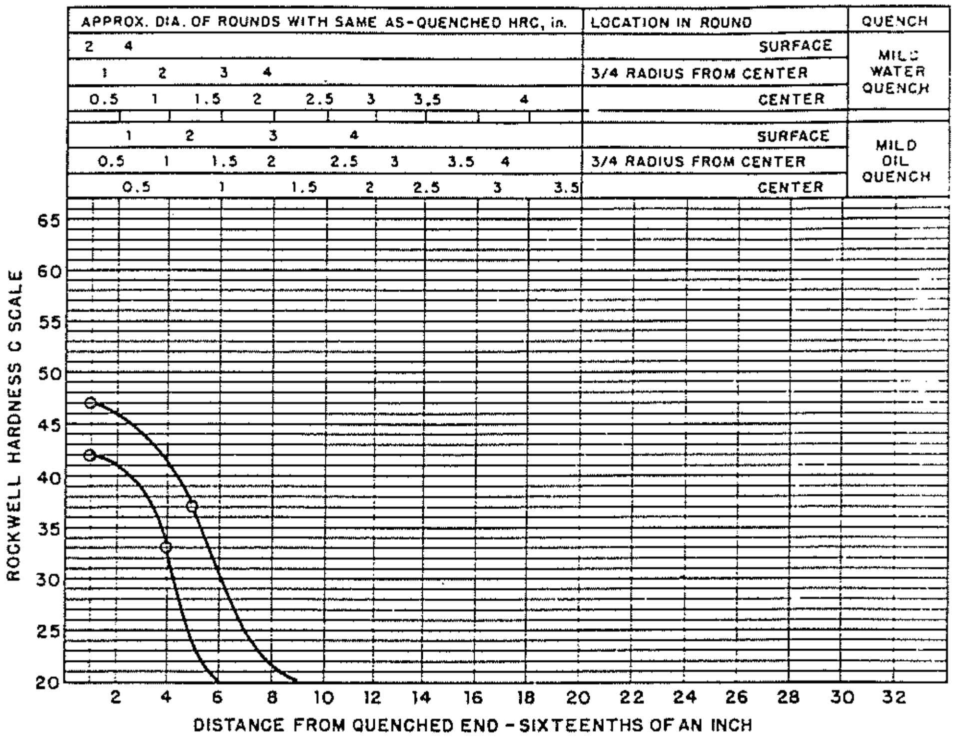
J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	48	41
1.5	48	41
2	47	40
2.5	47	39
3	46	38
3.5	45	36
4	44	30
4.5	42	23
5	40	20
5.5	38	...
6	35	...
6.5	32	...
7	27	...
7.5	22	...
8	20	...
9	...	...



15B21RH: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize for forged or rolled specimens only: 925 °C (1700 °F). Austenitize: 925 °C (1700 °F)

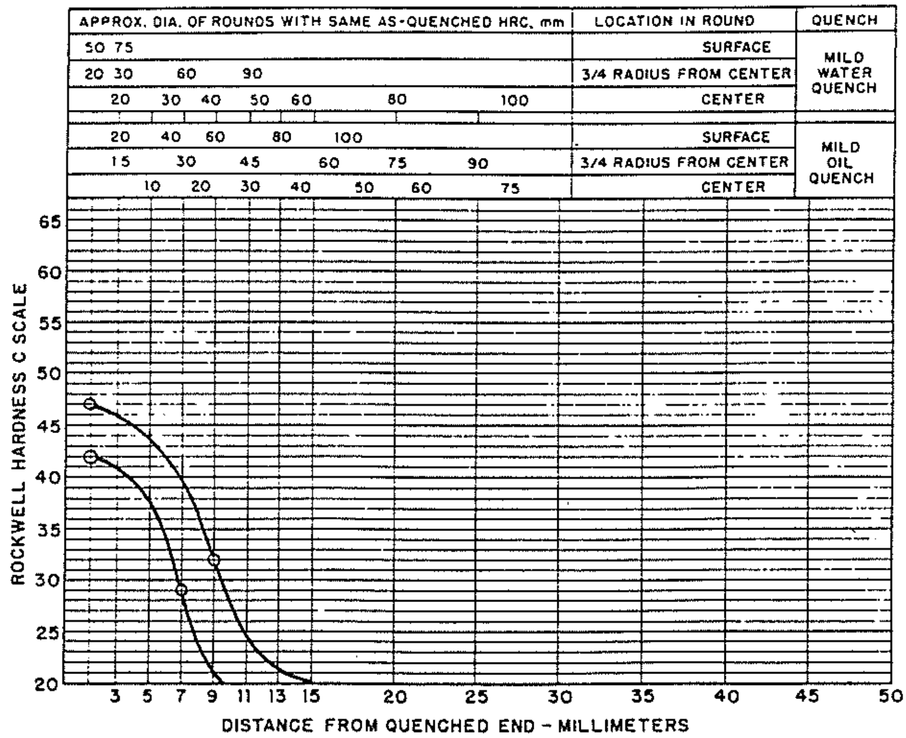
Hardness limits for specification ɔurposes

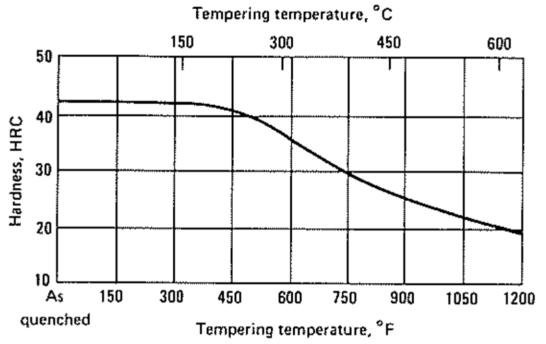
J distance, nm	Hardness, HRC Maximum	Minimum
l	47	42
:	46	41
}	44	39
l	42	33
;	37	24
;	30	20
/	24	...
}	22	...
)	20	...
.0	...	...
.1	...	...
.2	...	...
.3	...	...
.4	...	...
.5	...	...
6	...	...
.8	...	...
:0	...	...
:2	...	...
:4	...	...
:6	...	...
:8	...	...
;0	...	...
;2	...	...



Hardness limits for specification ɔurposes

' distance, millimeters	HRC Maximum	Minimum
.5	47	42
'	46	41
:	44	38
'	40	29
'	32	21
1	24	...
3	22	...
5	20	...
.0	...	...
5	...	...
0	...	...
5	...	...
0	...	...
5	...	...
0	...	...

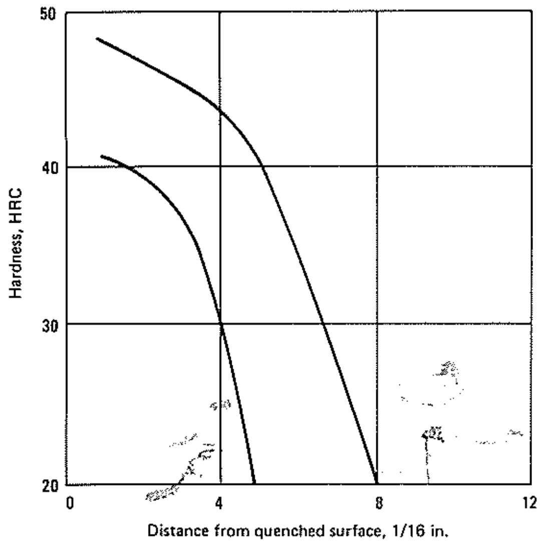




15B21H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

15B21H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max
1	1.58	48	41	6	9.48	35
1.5	2.37	48	41	6.5	10.27	32
2	3.16	47	40	7	11.06	27
2.5	3.95	47	39	7.5	11.85	22
3	4.74	46	38	8	12.64	20
3.5	5.53	45	36	9	14.22	...
4	6.32	44	30	10	15.80	...
4.5	7.11	42	23	12	18.96	...
5	7.90	40	20	14	22.12	...



1522, 1522H

Chemical Composition. 1522. AISI and UNS: 0.18 to 0.24 C, 1.10 to 1.40 Mn, 0.040 P max, 0.050 S max. **1522H. UNS H15220 and SAE/AISI 1522H:** 0.17 to 0.25 C, 1.00 to 1.50 Mn, 0.15 to 0.35 Si

Similar Steels (U.S. and/or Foreign). 1522. UNS G15220; SAE J403, J412. **1522H.** UNS H15220; SAE J1268; (Ger.) DIN 1.1133; (Ital.) UNI G 22 Mn 3; (Jap.) JIS SMnC 21

Characteristics. Represents the principal carburizing grade of the 1500 series. Characteristics similar to 15B21H. Nominal manganese content is higher which increases hardenability to a considerable extent. However, contains no boron. As a result, hardenability bands are not greatly different for steels 15B21H and 1522H. Weldability and forgeability are good

Forging. Heat to 1260 °C (2300 °F). Do not forge below 925 °C (1695 °F). For 1522H, drop forge from 900 to 1250 °C (1650 to 2280 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Air cool

Annealing. Heat to 870 °C (1600 °F). Cool slowly, preferably in the furnace

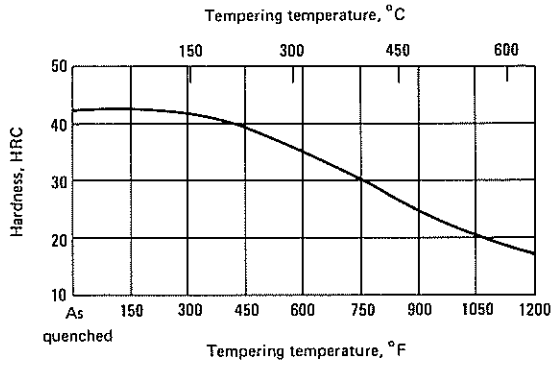
Hardening. Can be case hardened by any one of several processes, from light case hardening by carbonitriding and salt bath nitriding described for grade 1008 to deeper case carburizing in gas, solid, or liquid media. See carburizing process described for grade 1020. For 1522H, use carburizing temperature of 900 to 1250 °C (1650 to 2280 °F). Use oil for cooling medium. Because of higher hardenability, thicker sections can be oil quenched for full hardness

Tempering. Optional. Temper at 150 °C (300 °F) for 1 h or higher if some sacrifice of hardness can be tolerated

Recommended Processing Sequence

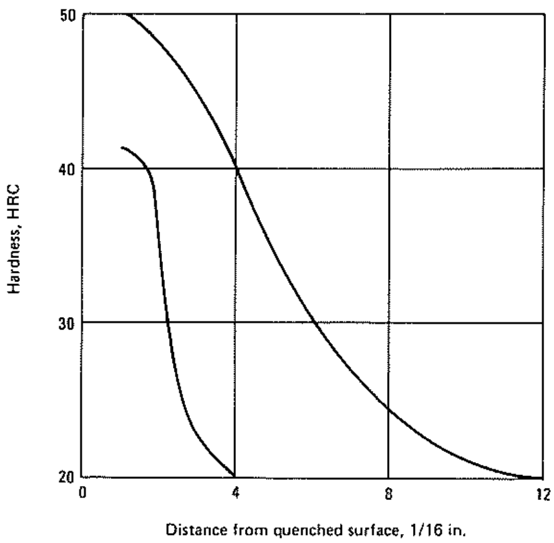
- Forge
- Normalize
- Rough machine
- Semifinish machine and grind
- Carburize
- Diffusion cycle
- Quench
- Temper
- Finish grind

1522, 1522H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure



1522H: End-Quench Hardenability

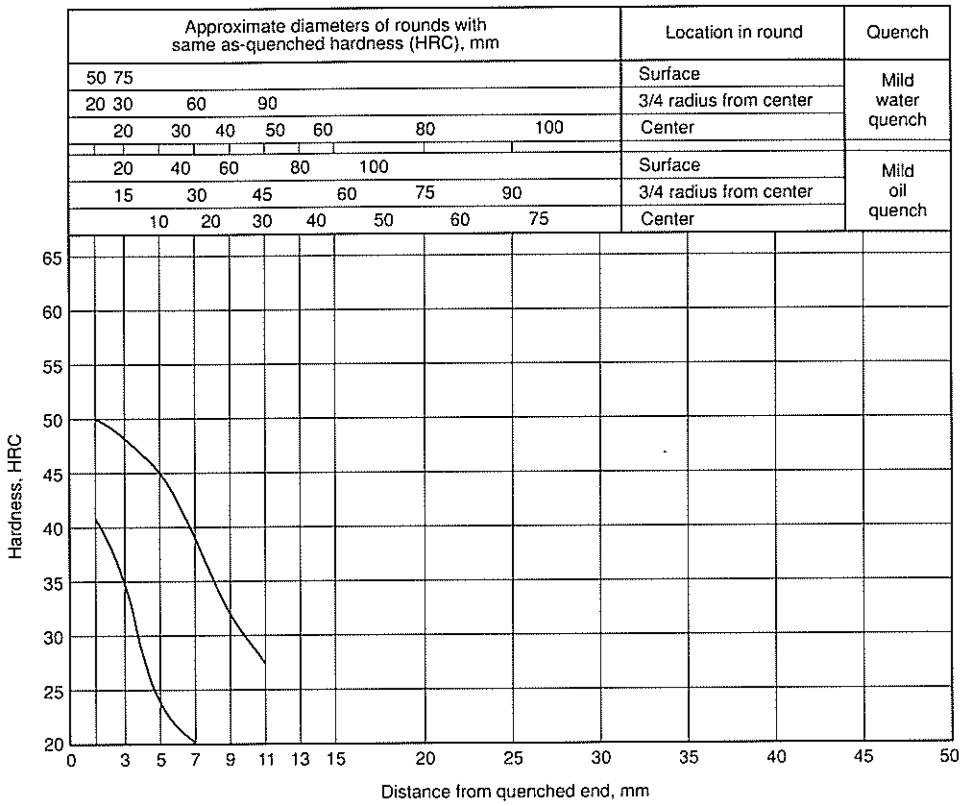
Distance from quenched surface		Hardness, HRC		Distance from quenched surface		Hardness, HRC
¹⁄₁₆ in.	mm	max	min	¹⁄₁₆ in.	mm	max
1	1.58	50	41	6	9.48	30
1.5	2.37	48	41	6.5	10.27	28
2	3.16	47	32	7	11.06	27
2.5	3.95	46	27	7.5	11.58	...
3	4.74	45	22	8	12.64	25
3.5	5.53	42	21	9	14.22	23
4	6.32	39	20	10	15.80	22
4.5	7.11	37	...	12	18.96	20
5	7.90	34	...	14	22.12	...
5.5	8.69	32	...	16	25.28	...



1522H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 925 °C (1700 °F)

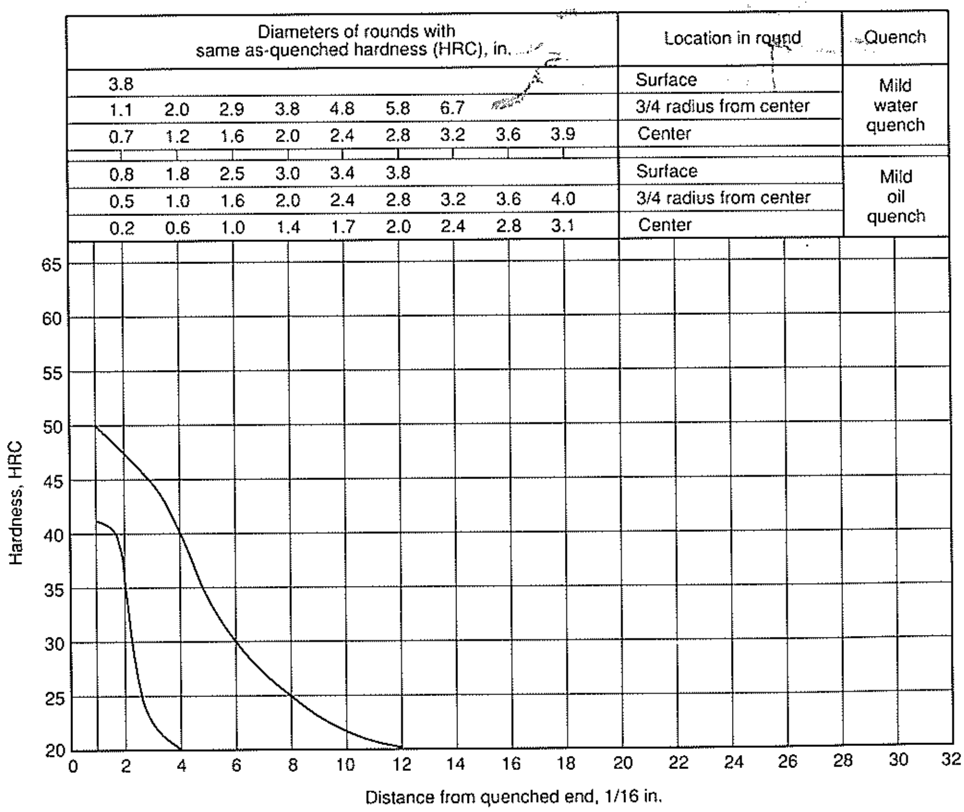
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	50	41
3	48	35
5	45	23
7	39	20
9	32	...
11	27	...
13	...	...

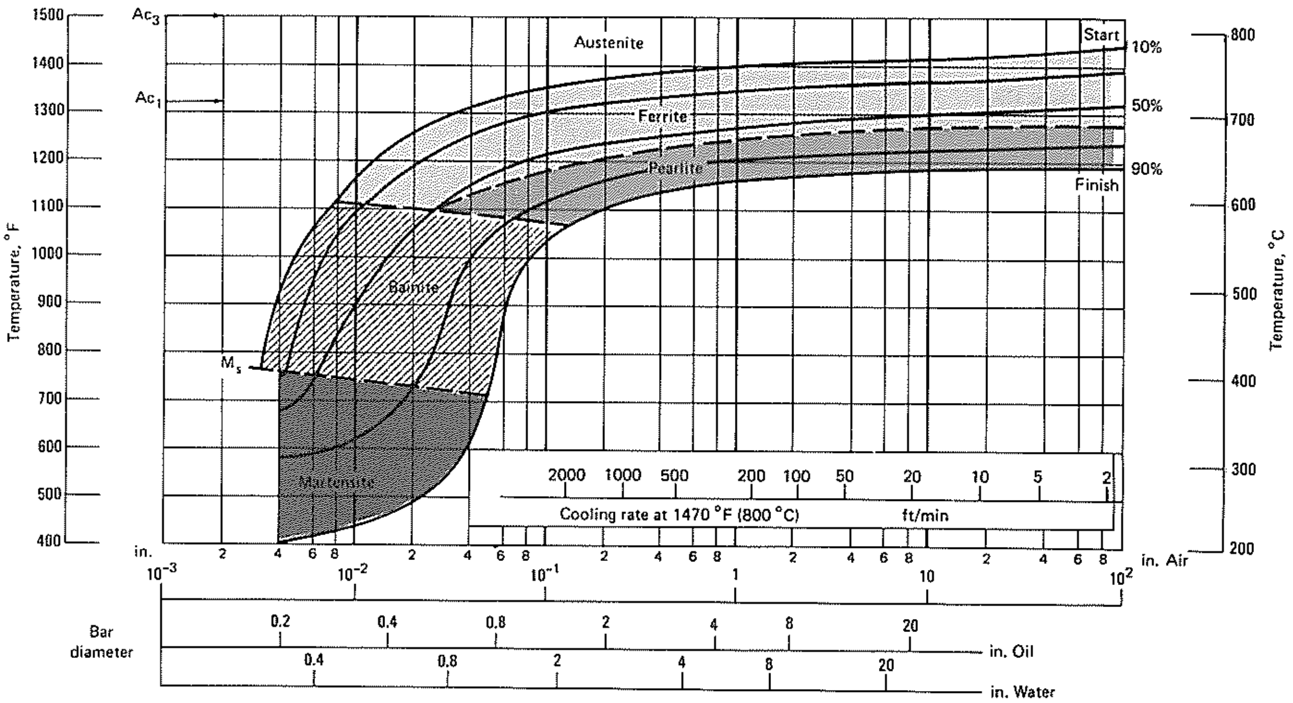


Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	50	41
1.5	48	41
2	47	32
2.5	46	27
3	45	22
3.5	42	21
4	39	20
4.5	37	...
5	34	...
5.5	32	...
6	30	...
6.5	28	...
7	27	...
7.5	...	...
8	25	...
9	23	...
10	22	...
12	20	...
14	...	...



1522: Continuous Cooling Transformation Diagram. A British steel with a chemical composition roughly equivalent to 1522: 0.19 C, 1.20 Mn, 0.020 P, 0.020 S, 0.20 Si. Hot rolled and austenitized at 870 °C (1600 °F)



1524, 1524H

Chemical Composition. **1524. AISI and UNS:** 0.19 to 0.25 C, 1.35 to 1.65 Mn, 0.040 P max, 0.050 S max. **1524H. UNS H15240 and SAE/AISI 1524H:** 0.18 to 0.26 C, 1.25 to 1.75 Mn, 0.15 to 0.35 Si; 1524 was formerly designated as 10XX grade

Similar Steels (U.S. and/or Foreign). **1524:** UNS G15240; ASTM A510, A513 (1024), A519, A545; SAE J403, J412, J414; (W. Ger.) DIN 1.1160. **1524H.** UNS H15240; SAE J1268; (Ger.) DIN 1.1160

Characteristics. Essentially a higher manganese version of 1023. Has higher hardenability. Grade 1524H is now available with a guaranteed hardenability band. Considered a borderline grade because it can be case hardened by carburizing or carbonitriding. Popular for this purpose because of relatively high core hardness. This permits use of thinner cases, which conserve thermal energy and decrease processing cost. 1524H also used in the hardened and tempered condition where moderate strength is needed. As-quenched hardness of 43 HRC or slightly higher can be expected. Even though the carbon content is only 0.26 max, welding must be done with care, because the high manganese may raise the carbon equivalent to a dangerous degree unless preheating and postheating practices are used. Forgeability is excellent. Grade 1524H may be obtained in various product forms

Forging. Heat to 1245 °C (2275 °F). Do not forge below 900 °C (1650 °F). For 1524H, drop forge between 900 to 1250 °C (1650 to 2280 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Cool in air

Annealing. Heat to 900 °C (1650 °F). Furnace cool to 675 °C (1245 °F) at a rate not to exceed 28 °C (50 °F) per h

Direct Hardening. Austenitize at 885 °C (1625 °F). Quench in oil or brine. Quenchant depends on section thickness

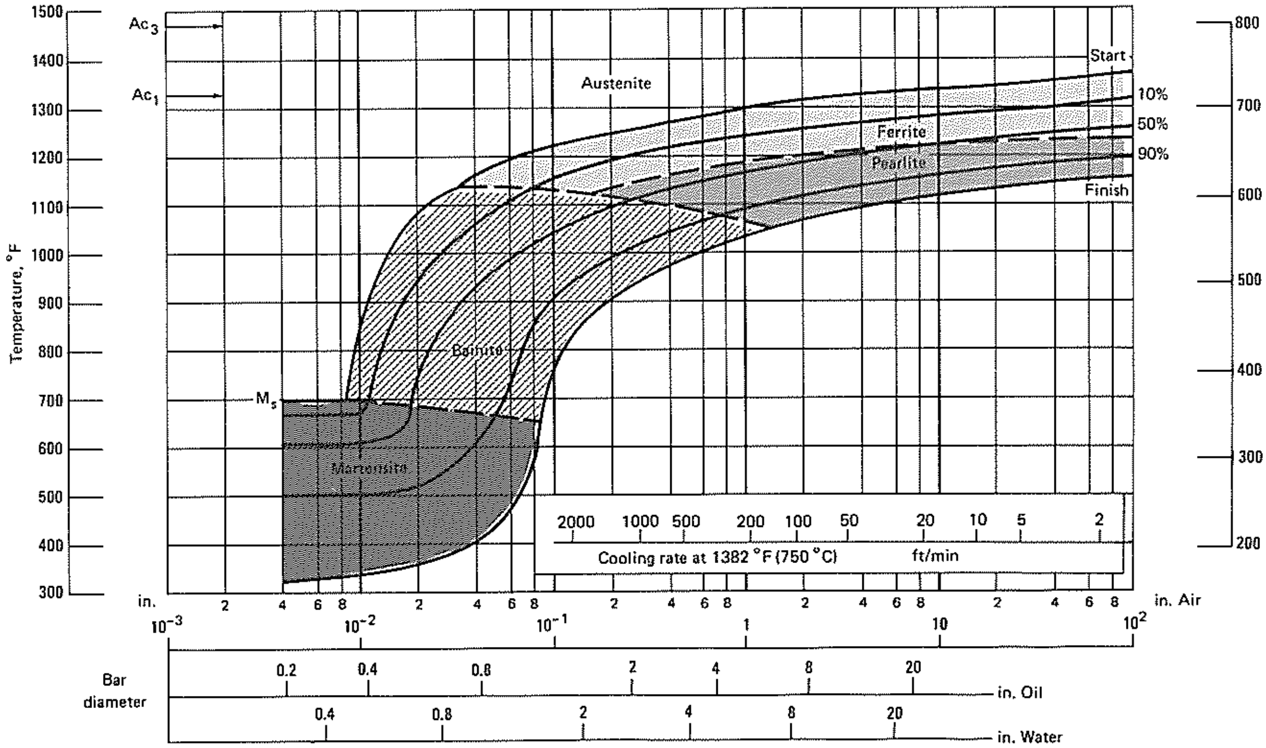
Tempering. As-quenched hardness of 43 HRC or higher can be reduced by tempering, as required

Case Hardening. Can be case hardened by any one of several processes, from light case hardening by carbonitriding and salt bath nitriding described for grade 1008 to deeper case carburizing in gas, solid, or liquid media. Plasma (ion) carburizing is an alternative process. (See carburizing process described for grade 1020). For 1524H, use carburizing temperature of 900 to 925 °C (1650 to 1695 °F). Use oil for cooling medium

Recommended Processing Sequence

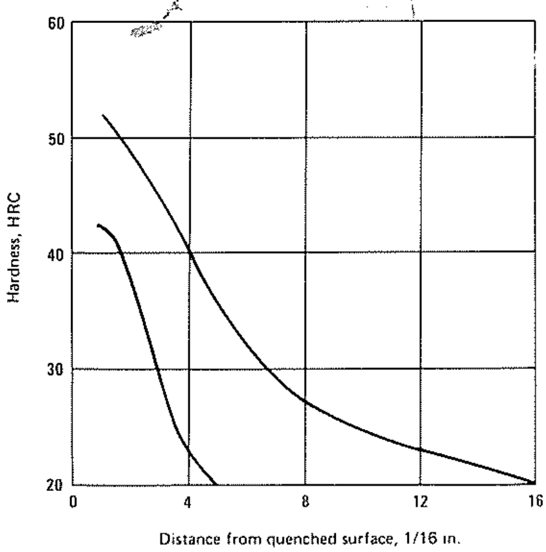
- Normalize
- Anneal
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

1524: Continuous Cooling Transformation Diagram. A British steel with a chemical composition roughly equivalent to 1524: 0.19 C, 1.50 Mn, 0.020 P, 0.020 S, 0.20 Si. Hot rolled and austenitized at 870 °C (1600 °F)



1524H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max
1	1.58	51	42	6	9.48	32
1.5	2.37	49	42	6.5	10.27	30
2	3.16	48	38	7	11.06	29
2.5	3.95	47	34	7.5	11.58	28
3	4.74	45	29	8	12.64	27
3.5	5.53	43	25	9	14.22	26
4	6.32	39	22	10	15.80	25
4.5	7.11	38	20	12	18.96	23
5	7.90	35	...	14	22.12	22
5.5	8.69	34	...	16	25.28	20



1526, 1526H

:hemical Composition. **1526. AISI and UNS:** 0.22 to 0.29 C, 1.10 o 1.40 Mn, 0.040 P max, 0.050 S max. **1526H. UNS H15260, SAE/AISI 526H:** 0.21 to 0.30 C, 1.00 to 1.50 Mn, 0.15 to 0.35 Si

;imilar Steels (U.S. and/or Foreign). **1526:** UNS G15260; ASTM A510; SAE J403, J412; (Ger.) DIN 1.1161; **1526H.** UNS H15260; ;AE J1268

:haracteristics. Considered a borderline grade because it can be case ıardened by carburizing or carbonitriding. Popular for this purpose because of relatively high core hardness. This permits use of thinner cases, which :onserve thermal energy and decrease processing cost. 1526H also used in he hardened and tempered condition where moderate strength is needed. As-quenched hardness of 43 HRC or slightly higher can be expected. Even hough the carbon content is only 0.26 max, welding must be done with :are, because the higher manganese may raise the carbon equivalent to a langerous degree, unless preheating and postheating practices are used. ·orgeability is excellent. Grade 1526H may be obtained in various product orms

·orging. Heat to 1245 °C (2275 °F). Do not forge below 900 °C (1650 F). For 1526H, drop forge between 1205 to 850 °C (2200 to 1560 °F)

?ecommended Heat Treating Practice

\ormalizing. Heat to 925 °C (1695 °F). Air cool

Annealing. Heat to 900 °C (1650 °F). Furnace cool to 675 °C (1245 °F) at a rate not to exceed 28 °C (50 °F) per h

Direct Hardening. Austenitize at 885 °C (1625 °F). Quench in water, brine or oil. Quenchant will depend on section thickness and required hardness

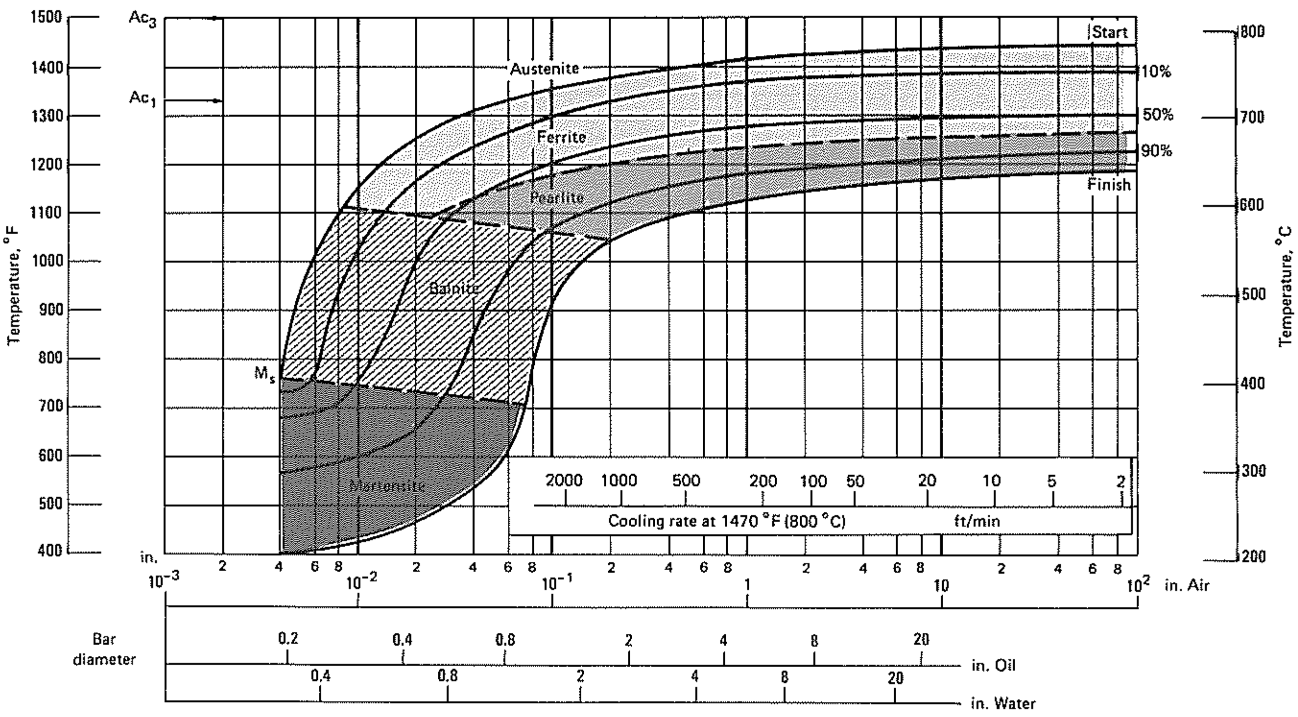
Tempering. As-quenched hardness of 43 HRC or higher can be reduced by tempering, as required

Case Hardening. Can be case hardened by any one of several processes, from light case hardening by carbonitriding and salt bath nitriding described for grade 1008 to deeper case carburizing in gas, solid, or liquid media. See carburizing process described for grade 1020. For 1526H, use carburizing temperature of 900 to 925 °C (1650 to 1695 °F). Use oil for cooling medium

Recommended Processing Sequence

- Normalize
- Anneal
- Rough machine
- Austenitize (or case harden)
- Quench
- Temper
- Finish grind

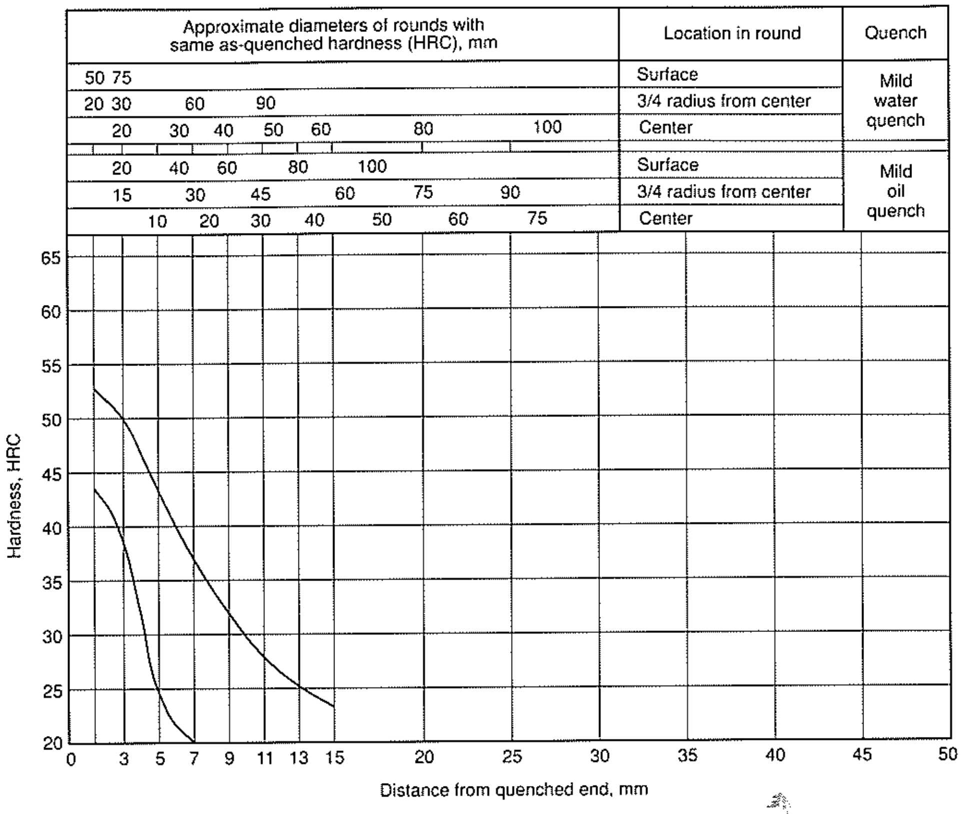
1526: Continuous Cooling Transformation Diagram. A British steel with a chemical composition roughly equivalent to 1526: 0.28 C, 1.20 Mn, 0.020 P, 0.020 S, 0.20 Si. Hot rolled and austenitized at 870 °C (1600 °F)



1526H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 900 °C (1650 °F). Austenitize: 870 °C (1600 °F)

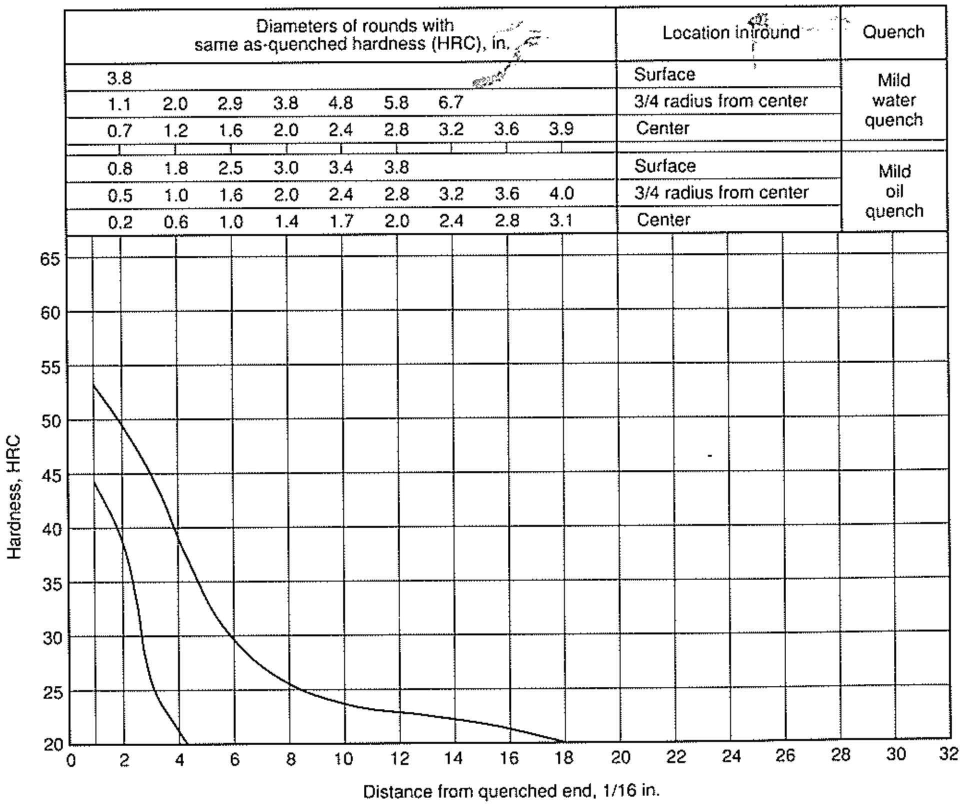
Hardness limits for specification purposes

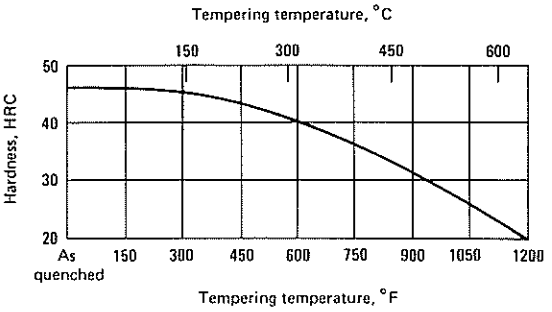
J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	53	44
3	50	39
5	44	24
7	37	20
9	32	...
11	28	...
13	25	...
15	24	...
20	...	...



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	53	44
1.5	50	42
2	49	38
2.5	47	33
3	46	26
3.5	42	25
4	39	21
4.5	37	20
5	33	...
5.5	31	...
6	30	...
6.5	28	...
7	27	...
7.5	26	...
8	26	...
9	24	...
10	24	...
12	23	...
14	22	...
16	21	...
18	20	...

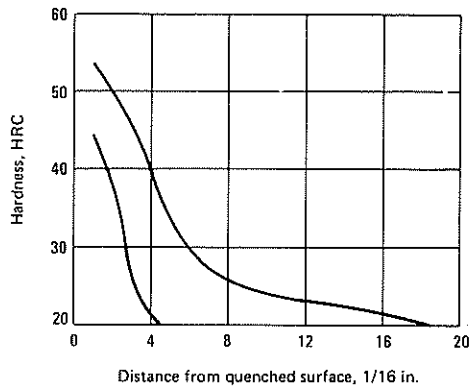




1526, 1526H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

1526H: End-Quench Hardenability

Distance from quenched surface		Hardness, HRC		Distance from quenched surface		Hardness, HRC
1/16 in.	mm	max	min	1/16 in.	mm	max
1	1.58	53	44	6.5	10.27	28
1.5	2.37	50	42	7	11.06	27
2	3.16	49	38	7.5	11.85	26
2.5	3.95	47	33	8	12.64	26
3	4.74	46	26	9	14.22	24
3.5	5.58	42	25	10	15.80	24
4	6.32	39	21	12	18.96	23
4.5	7.11	37	20	14	22.12	22
5	7.90	33	...	16	25.28	21
5.5	8.69	31	...	18	28.44	20
6	9.48	30	...			



1527

Chemical Composition. **AISI and UNS:** 0.22 to 0.29 C, 1.20 to .50 Mn, 0.040 P max, 0.050 S max. **UNS G15270 and AISI/SAE 1527:** standard composition range for manganese is 1.20 to 1.55 Mn; was fornerly designated as 10XX grade

Similar Steels (U.S. and/or Foreign). UNS G15270; ASTM A510, A513 (1027); SAE J403, J412; (Ger.) DIN 1.1161

Characteristics. Considered a borderline grade because it can be case hardened by carburizing or carbonitriding. Popular for this purpose because of relatively high core hardness. This permits use of thinner cases, which conserve thermal energy and decrease processing cost. 1527 also used in the hardened and tempered condition where moderate strength is needed. As-quenched hardness of 43 HRC or slightly higher can be expected. Even though the carbon content is only 0.29 max, welding must be done with care, because the higher manganese may raise the carbon equivalent to a dangerous degree, unless preheating and postheating practices are used. Forgeability is excellent. Grade 1527 may be obtained in various product forms

Forging. Heat to 1245 °C (2275 °F). Do not forge below about 900 °C (1650 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Cool in air

Annealing. Heat to 900 °C (1650 °F). Furnace cool to 675 °C (1245 °F) at a rate not to exceed 28 °C (50 °F) per h

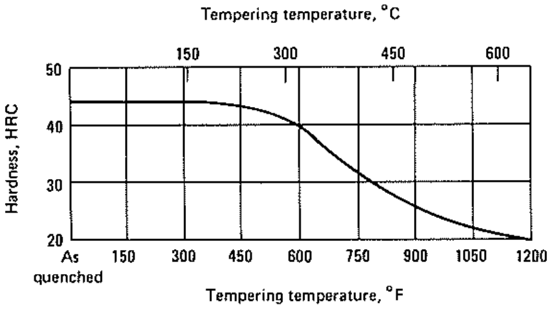
Hardening. Can be case hardened by any one of several processes, from light case hardening by carbonitriding and salt bath nitriding described for grade 1008 to deeper case carburizing in gas, solid, or liquid media. (See carburizing process described for grade 1020). For 1522H, use carburizing temperature of 900 to 925 °C (1650 to 1695 °F). Use oil for cooling medium

Direct Hardening. Austenitize at 885 °C (1625 °F). Quench in oil, water or brine. Quenchant will depend on section thickness and required hardness

Tempering. As-quenched hardness of 43 HRC or higher can be reduced by tempering as required (see curve)

Recommended Processing Sequence

- Normalize
- Anneal
- Rough machine
- Austenitize (or case harden)
- Quench
- Temper
- Finish machine



1527: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

15B28H

Chemical Composition. 15B28H. UNS H15281 and SAE B28H: 0.25 to 0.34 C, 1.00 to 1.50 Mn, 0.15 to 0.35 Si, (0.0005 to 0.003 B can be expected)

Similar Steels (U.S. and/or Foreign). SAE J1268; ASTM A304

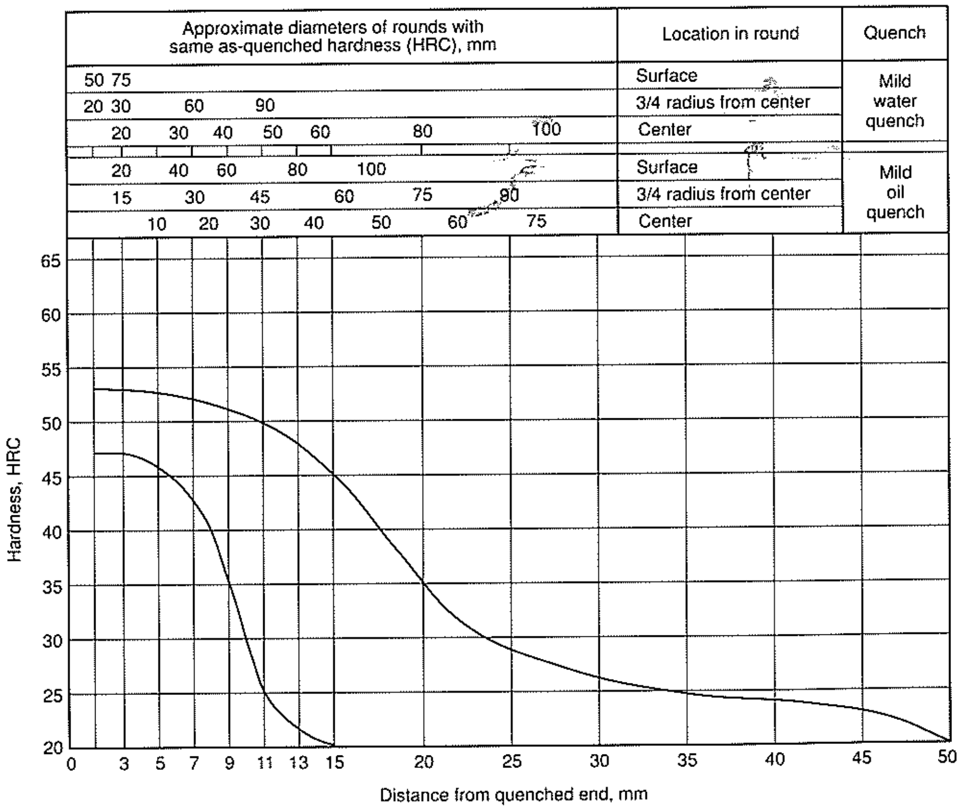
Recommended Heat Treating Practice

Hardening. Carbonitriding is a suitable surface hardening process

15B28H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 900 °C (1650 °F). Austenitize: 870 °C (1600 °F)

Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	53	47
3	53	47
5	53	46
7	52	43
9	51	35
11	50	24
13	48	21
15	45	20
20	35	...
25	29	...
30	26	...
35	25	...
40	24	...
45	23	...
50	20	...

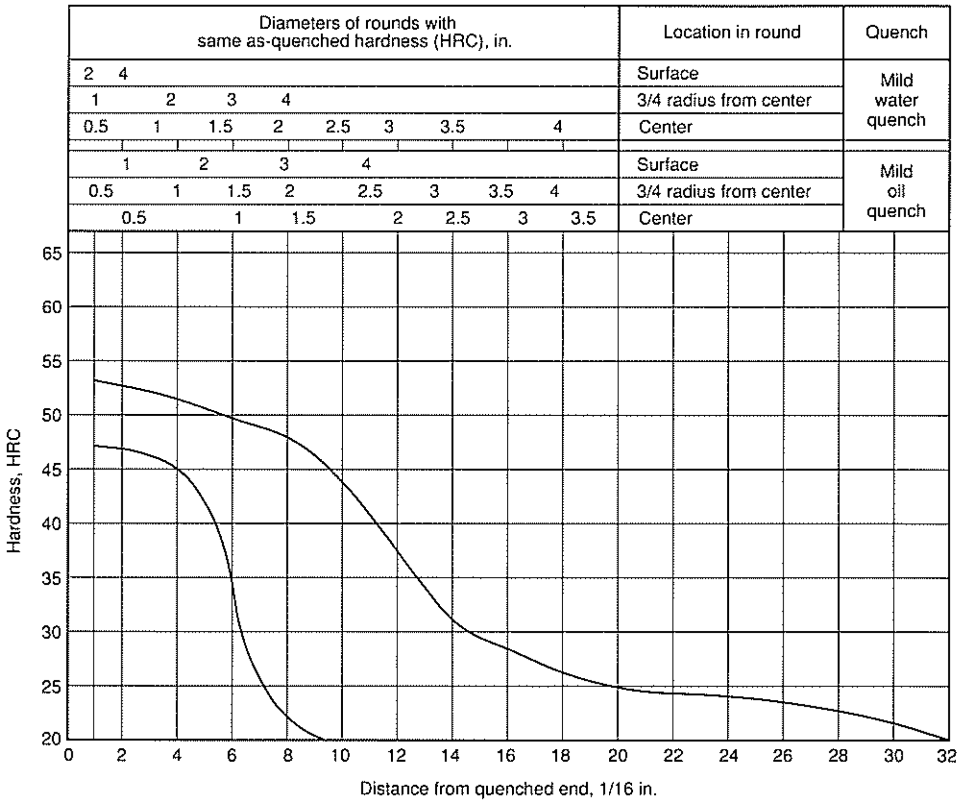


(continued)

15B28H: Hardenability Curves (continued). Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 900 °C (1650 °F). Austenitize: 870 °C (1600 °F)

Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	53	47
2	53	47
3	52	46
4	51	45
5	51	42
6	50	32
7	49	25
8	48	21
9	46	20
10	43	...
11	40	...
12	37	...
13	34	...
14	31	...
15	30	...
16	29	...
18	27	...
20	25	...
22	25	...
24	24	...
26	23	...
28	22	...
30	21	...
32	20	...



15B30H

Chemical Composition. **UNS H15301 and SAE 15B30H:** 0.27 to 0.35 C, 0.70 to 1.20 Mn, 0.15 to 0.35 Si (0.0005 to 0.003 B can be expected)

Similar Steels (U.S. and/or Foreign). SAE J1268; ASTM A304

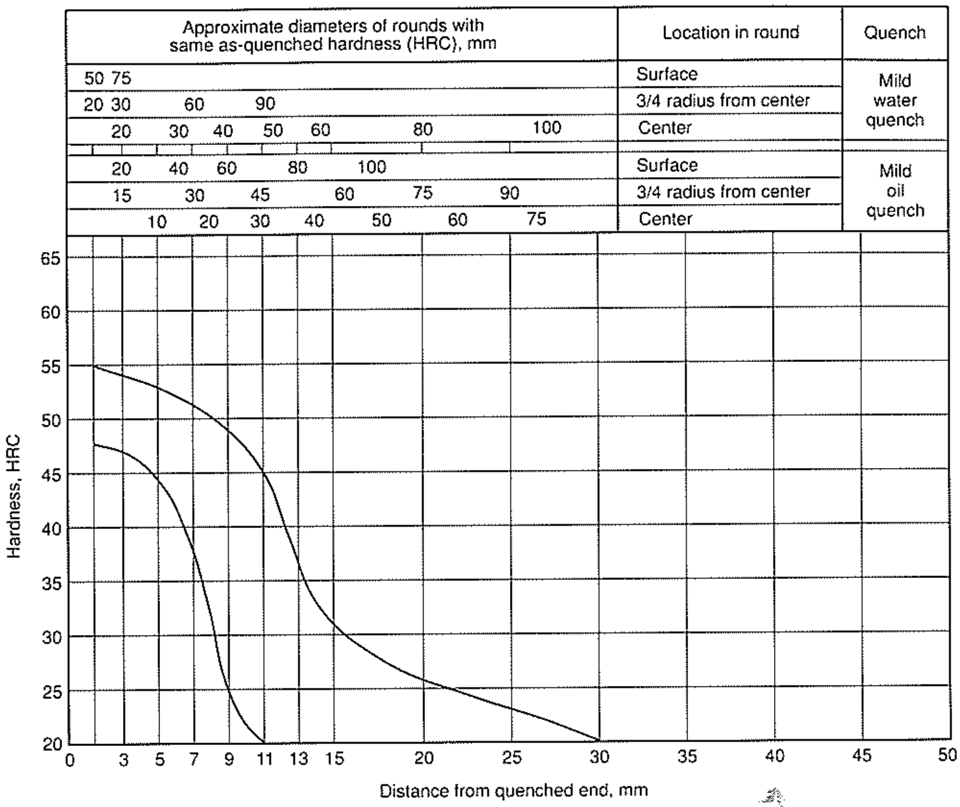
Recommended Heat Treating Practice

Hardening. Carbonitriding is a suitable surface hardening process

15B30H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 900 °C (1650 °F). Austenitize: 870 °C (1600 °F)

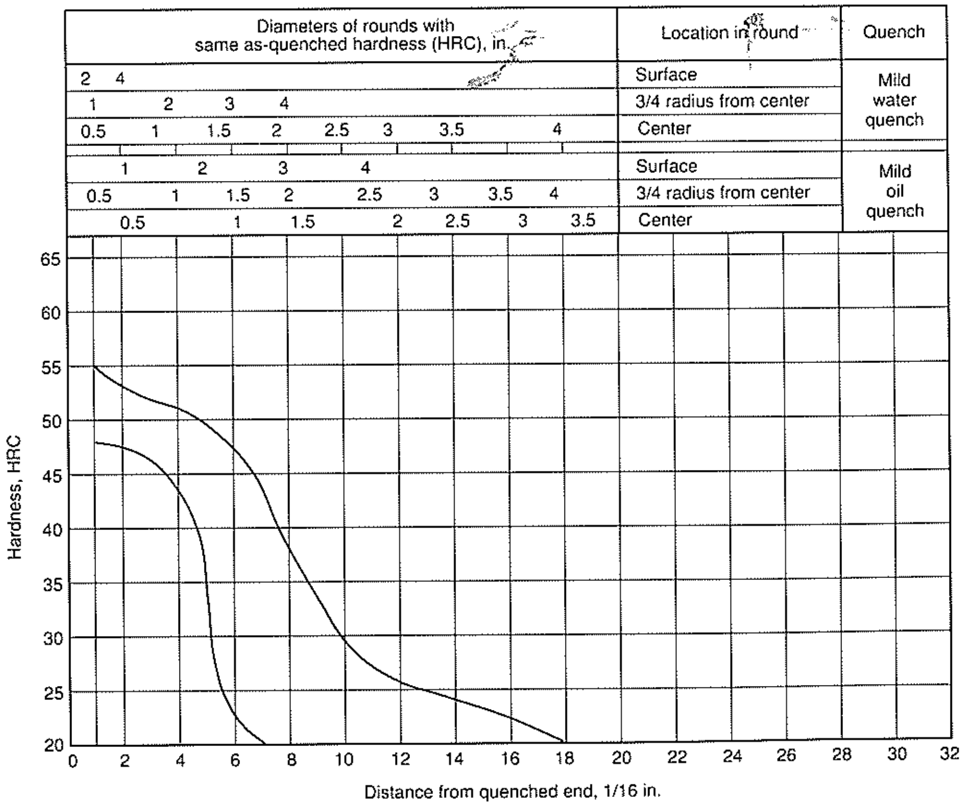
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	55	48
3	54	47
5	53	45
7	52	38
9	49	25
11	45	20
13	38	...
15	31	...
20	26	...
25	23	...
30	20	...
35	...	...



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	55	48
2	53	47
3	52	46
4	51	44
5	50	32
6	48	22
7	43	20
8	38	...
9	33	...
10	29	...
11	27	...
12	26	...
13	25	...
14	24	...
15	23	...
16	22	...
18	20	...
20	...	...



15B35H, 15B35RH

:hemical Composition. **UNS H15351 and SAE/AISI 15B35H:** .31 to 0.39 C, 0.70 to 1.20 Mn, 0.15 to 0.35 Si, (0.0005 to 0.003 B can be xpected). **SAE 15B35RH:** 0.33 to 0.38 C, 0.80 to 1.10 Mn, 0.15 to 0.35 ;i (0.0005 to 0.003 B can be expected)

;imilar Steels (U.S. and/or Foreign). **15B35H.** UNS H15351; ;AE J1268, J1868; ASTM A914. **15B35RH.** UNS H15351; SAE J1268, 1868; ASTM A914

:haracteristics. Excellent forgeability. Special quality grades for cold eading, cold forging, and cold extrusion. Can be welded. Because of arbon content, preheating and postheating are required and interpass emperature must be controlled. Machinability only fair. Wide range of iechanical properties can be attained by quenching and tempering. Similar) 1035. Higher manganese content and boron addition increase harenability

:orging. Heat to 1245 °C (2275 °F). Do not forge below 870 °C (1600 F)

ecommended Heat Treating Practice

lormalizing. Heat to 915 °C (1680 °F). Cool in air

Annealing. Heat to 870 °C (1600 °F). Furnace cool to 650 °C (1200 °F) at a rate not to exceed 28 °C (50 °F) per h

Hardening. Austenitize at 855 °C (1575 °F). Carbonitriding is a suitable surface hardening process. Depending on section thickness, this steel is usually oil quenched

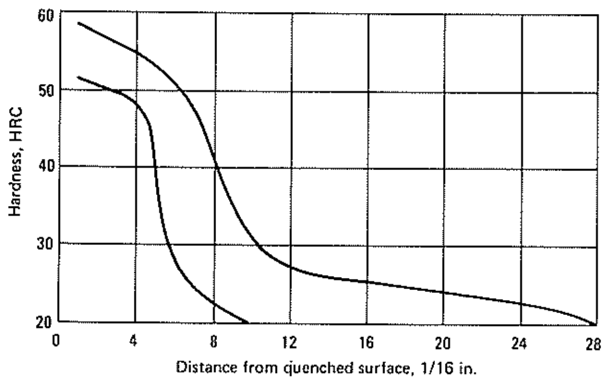
Tempering. Hardness of approximately 45 HRC can be reduced by tempering

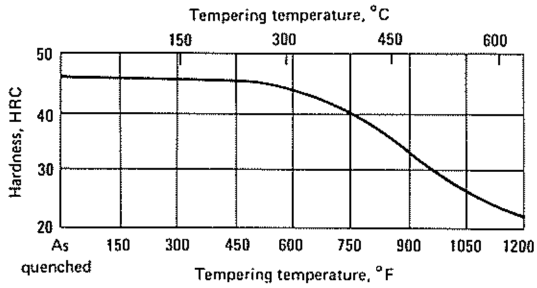
Recommended Processing Sequence

- Forge
- Normalize
- Anneal (if necessary for machining)
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

15B35H: End-Quench Hardenability

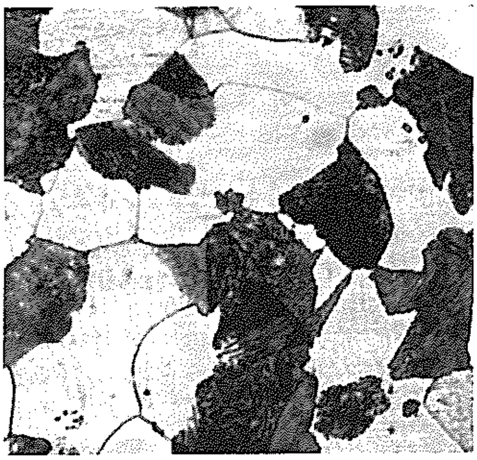
Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max
1	1.58	58	51	13	20.54	...
2	3.16	56	50	14	22.12	26
3	4.74	55	49	15	23.70	...
4	6.32	54	48	16	25.28	25
5	7.90	53	39	18	28.44	...
6	9.48	51	28	20	31.60	24
7	11.06	47	24	22	34.76	...
8	12.64	41	22	24	37.92	22
9	14.22	...	...	26	41.08	...
10	15.80	30	20	28	44.24	20
11	17.38	...	...	30	47.40	...
12	18.96	27	...	32	50.56	...





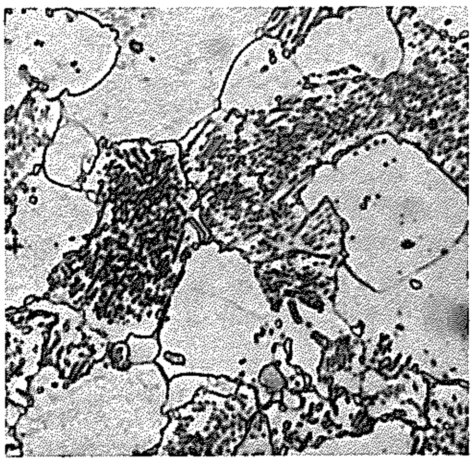
15B35H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

15B35H: Microstructures. Microstructures of 15B35 steel. (a) In the as-received hot-rolled condition, microstructure is blocky pearlite. Hardness is 87 to 88 HRB. (b) In the partially spheroidized condition following annealing in a continuous furnace. Hardness is 81 to 82 HRB. (c) In the nearly fully spheroidized condition following annealing in a bell furnace. Hardness is 77 to 78 HRB



(a)

(b)

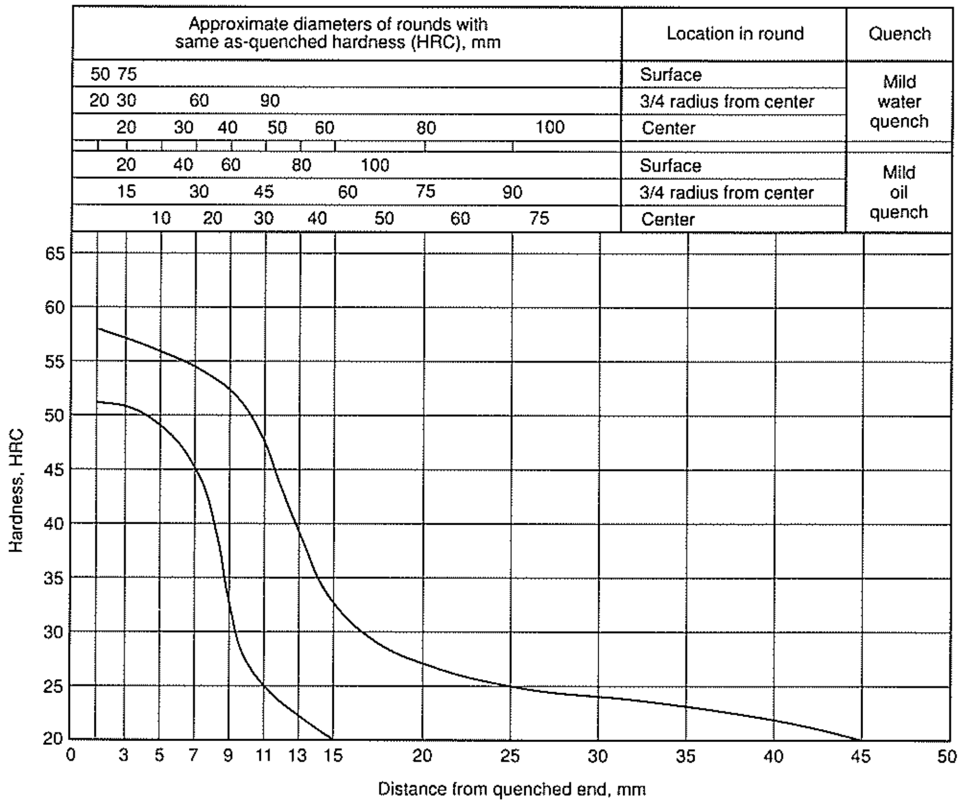


(c)

15B35H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1550 °F)

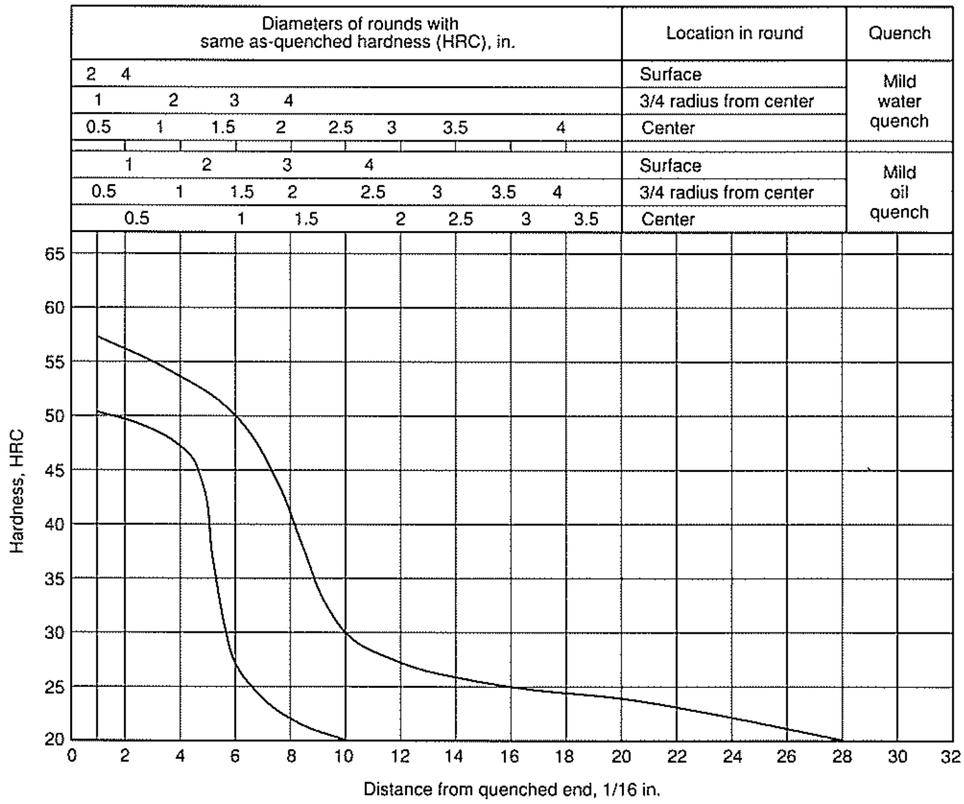
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	58	51
3	57	50
5	56	49
7	54	45
9	52	32
11	47	24
13	39	21
15	32	20
20	27	...
25	25	...
30	24	...
35	23	...
40	22	...
45	20	...
50	...	...



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	58	51
2	56	50
3	55	48
4	54	48
5	53	39
6	51	28
7	47	24
8	41	22
9	...	...
10	30	20
11	...	...
12	27	...
13	...	...
14	26	...
15	...	...
16	25	...
18	...	...
20	24	...
22	...	...
24	22	...
26	...	...
28	20	...
30	...	...



1536

Chemical Composition. **UNS G15360, SAE/AISI:** 0.30 to 0.37 C, 1.20 to 1.50 Mn, 0.040 P max, 0.050 S max; was formerly designated 10XX grade

Recommended Heat Treating Practice

Hardening. Carbonitriding is a suitable surface hardening process

15B37H

Chemical Composition. **UNS15371 and SAE/AISI 15B37H:** 0.30 to 0.39 C, 1.00 to 1.50 Mn, 0.15 to 0.35 Si (0.0005 to 0.003 B can be expected)

Similar Steels (U.S. and/or Foreign). UNS H15371; SAE J1268

Characteristics. Same characteristics, except greater hardenability than 15B35H because of higher manganese content. Maximum hardness about the same. 15B37H is an oil hardening grade because hardenability equals that of some alloy grades. Excellent forgeability. Fair machinability

Forging. Heat to 1245 °C (2275 °F). Do not forge below 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 915 °C (1680 °F). Cool in air

Annealing. Heat to 870 °C (1600 °F). Furnace cool to 650 °C (1200 °F) at a rate not to exceed 28 °C (50 °F) per h

Hardening. Austenitize at 855 °C (1575 °F). Carbonitriding is a suitable surface hardening process. Quench in oil

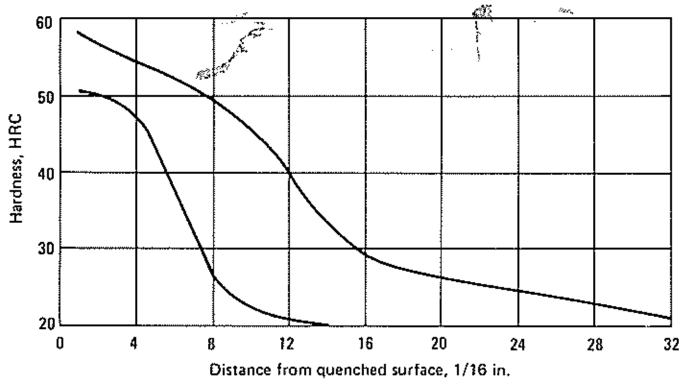
Tempering. As-quenched hardness of approximately 45 HRC can be reduced by tempering

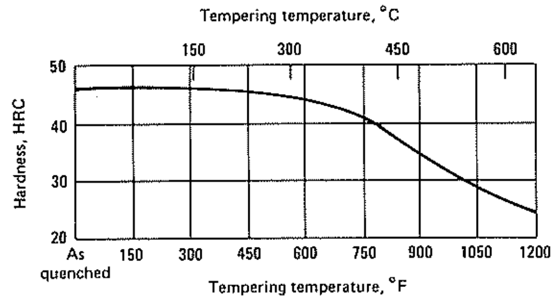
Recommended Processing Sequence

- Forge
- Normalize
- Anneal (if necessary for machining)
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

15B37H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min
1	1.58	58	50	13	20.54	...	...
2	3.16	56	50	14	22.12	33	20
3	4.74	55	49	15	23.70	...	...
4	6.32	54	48	16	25.28	29	...
5	7.90	53	43	18	28.44	...	...
6	9.48	52	37	20	31.60	27	...
7	11.06	51	33	22	34.76	...	...
8	12.64	50	26	24	37.92	25	...
9	14.22	...	...	26	41.08	...	...
10	15.80	45	22	28	44.26	23	...
11	17.38	...	...	30	47.40	...	...
12	18.96	40	21	32	50.56	21	...





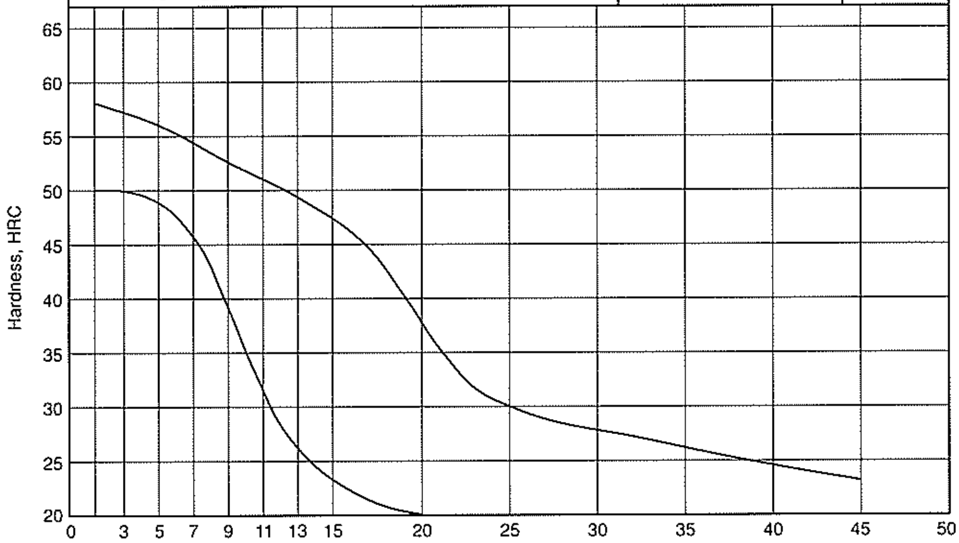
15B37H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

15B37H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1550 °F)

ɪardness limits for specification ɪurposes

distance, ɪm	Hardness, HRC Maximum	Minimum
.5	58	50
	57	50
	56	49
	54	46
	53	39
1	51	31
3	50	26
5	47	23
0	38	20
5	30	...
0	28	...
5	26	...
0	25	...
5	23	...
0	...	...

Approximate diameters of rounds with same as-quenched hardness (HRC), mm	Location in round	Quench
50 75	Surface	Mild water quench
20 30 60 90	3/4 radius from center	
20 30 40 50 60 80 100	Center	
20 40 60 80 100	Surface	Mild oil quench
15 30 45 60 75 90	3/4 radius from center	
10 20 30 40 50 60 75	Center	

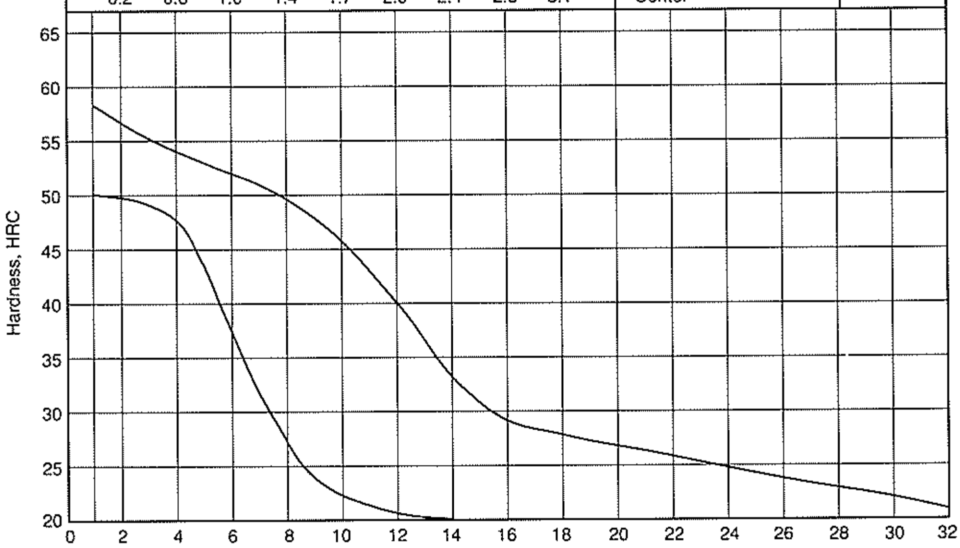


Distance from quenched end, mm

ɪardness limits for specification ɪurposes

distance, 1/16 in.	Hardness, HRC Maximum	Minimum
	58	50
	56	50
	55	49
	54	48
	53	43
	52	37
	51	33
	50	26
	...	...
0	45	22
1	...	...
2	40	21
3	...	...
4	33	20
5	...	...
6	29	...
8	...	...
0	27	...
2	...	...
4	25	...
6	...	...
8	23	...
0	...	...
2	21	...

Diameters of rounds with same as-quenched hardness (HRC), in.	Location in round	Quench
3.8	Surface	Mild water quench
1.1 2.0 2.9 3.8 4.8 5.8 6.7	3/4 radius from center	
0.7 1.2 1.6 2.0 2.4 2.8 3.2 3.6 3.9	Center	
0.8 1.8 2.5 3.0 3.4 3.8	Surface	Mild oil quench
0.5 1.0 1.6 2.0 2.4 2.8 3.2 3.6 4.0	3/4 radius from center	
0.2 0.6 1.0 1.4 1.7 2.0 2.4 2.8 3.1	Center	



Distance from quenched end, 1/16 in.

1541, 1541H

Chemical Composition. **1541. AISI and UNS:** 0.36 to 0.44 C, 1.35 to 1.65 Mn, 0.040 P max, 0.050 S max. **1541H. UNS 15410 and SAE/AISI 1541H:** 0.35 to 0.45 C, 1.25 to 1.75 Mn, 0.15 to 0.35 Si; 1541 was formerly designated as 10XX grade; Composition range and limits for UNS G15410 and AISI/SAE 1541: 0.36 to 0.45 C, 1.30 to 1.65 Mn

Similar Steels (U.S. and/or Foreign). **1541.** UNS G15410; ASTM A510, A519, A545, A546; SAE J403, J412, J414; (Ger.) DIN 1.1161; (Fr.) AFNOR 40 M 5; (Jap.) JIS SMn 2 H, SMn 2, SCMn 3; (Swed.) SS_{14} 2120. **1541H.** UNS H15410; SAE J1268; (Ger.) DIN 1.167; (Fr.) AFNOR 40 M 5; (Jap.) JIS SMn 2 H, SMn 2, SCMn 3; (Swed.) SS_{14} 2120

Characteristics. Essentially a 1040 with a higher manganese content. This greatly increases its hardenability. As-quenched hardness about 52 HRC or slightly greater, when fully hardened. However, 1541H is relatively deep hardening, so that oil quenching can be used for considerably heavier sections when compared with 1040. Grade 1541H is available in various product forms. Forgeability is good. Machinability is fair. Can be welded, using practice recommended for other high-hardenability steels

Forging. Heat to 1245 °C (2275 °F). Do not forge below 870 °C (1600 °F). For 1541H, drop forge from 1205 to 850 °C (2200 to 1560 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F). Cool in air

Annealing. Heat to 830 °C (1525 °F). Furnace cool to 650 °C (1200 °F) at a rate not to exceed 28 °C (50 °F) per h

Hardening. Heat to 845 °C (1555 °F). Carbonitriding is a suitable surface hardening process. Except for very heavy sections, oil quench from austenitizing temperature, as with alloy steels. Water of brine quenching may cause quench cracking. Full precautions should be taken when parts made from 1541H are induction hardened. Overly severe quenching may also result in quench cracking

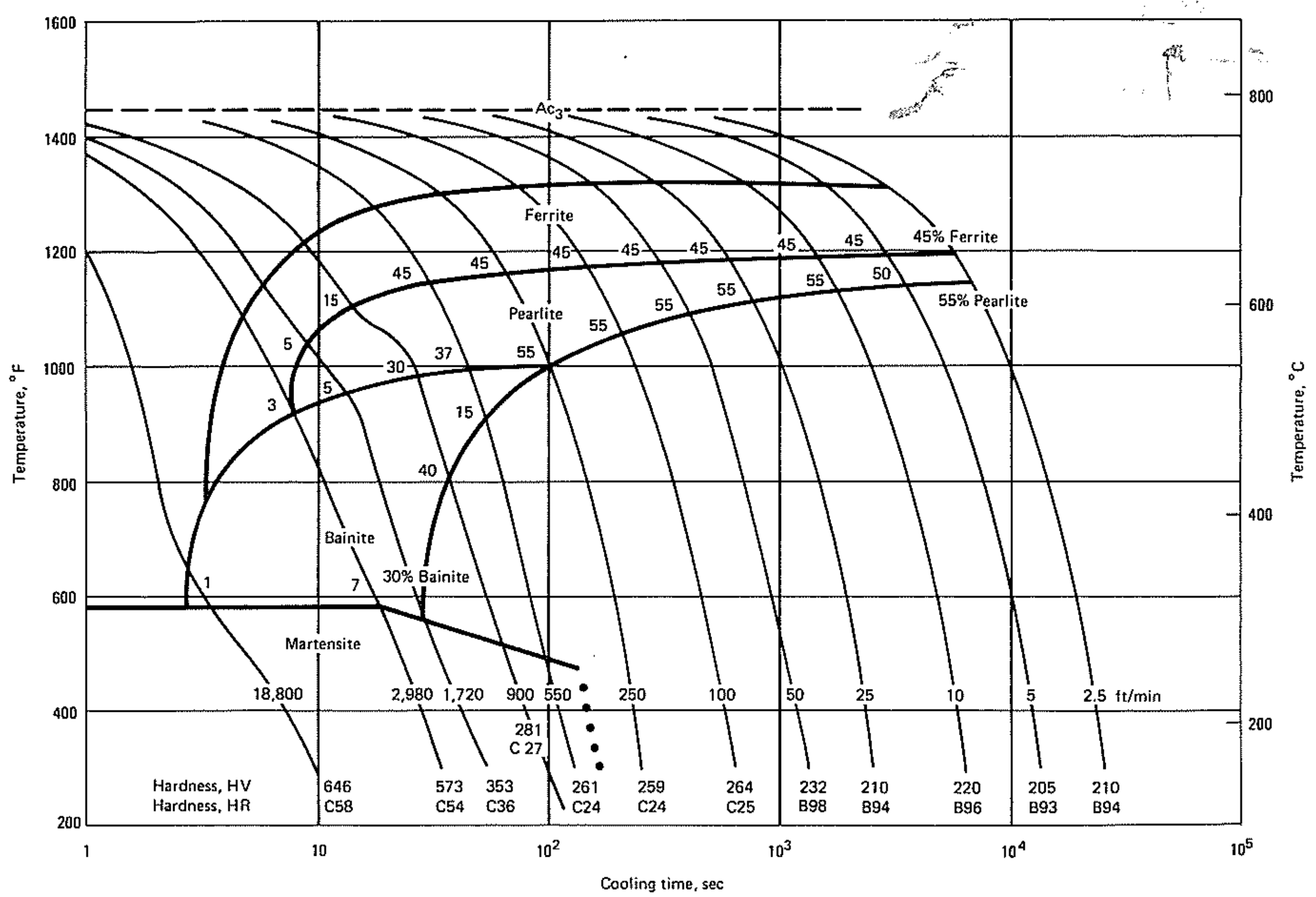
Tempering After Hardening. As-quenched hardness of approximately 52 HRC can be reduced by tempering

Tempering After Normalizing. Normalize large sections by conventional practice, which results in a structure of fine pearlite. Temper to about 540 °C (1000 °F). Mechanical properties not equal to those achieved by quenching and tempering. Resulting strength is far higher than annealed structure. Normalize and temper heavy forgings

Recommended Processing Sequence

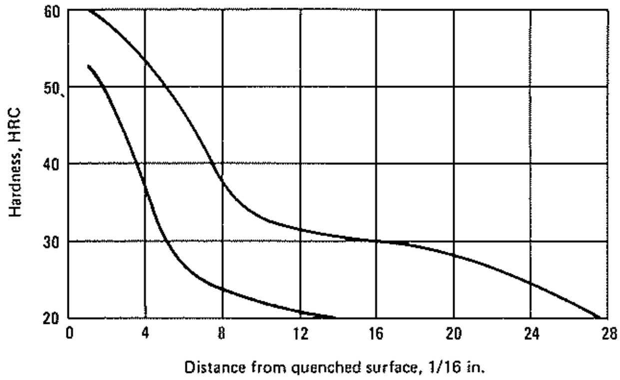
- Forge
- Normalize
- Anneal (if necessary) or temper (optional)
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

1541: Continuous Cooling Transformation Diagram. Composition: 0.39 C, 1.56 Mn, 0.010 P, 0.024 S, 0.21 Si. Grain size, 8. Ac_1 at 715 °C (1320 °F). Ac_3 at 790 °C (1455 °F)

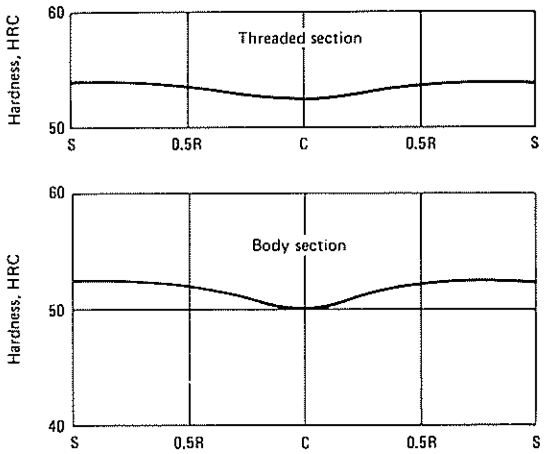


1541H: End-Quench Hardenability

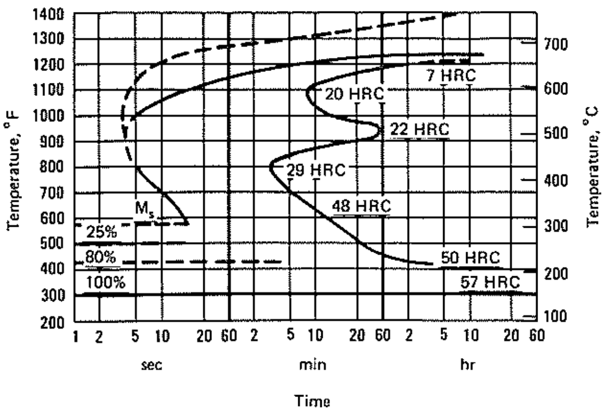
Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min
1	1.58	60	53	7	11.06	44	25
1.5	2.37	59	52	7.5	11.85	41	24
2	3.16	59	50	8	12.64	39	23
2.5	3.95	58	47	9	14.22	35	23
3	4.74	57	44	10	15.80	33	22
3.5	5.58	56	41	12	18.96	32	21
4	6.32	55	38	14	22.12	31	20
4.5	7.11	53	35	16	25.28	30	...
5	7.90	52	32	18	28.44	30	...
5.5	8.69	50	29	20	31.60	29	...
6	9.48	48	27	22	34.76	28	...
6.5	10.27	46	26	24	37.92	26	...



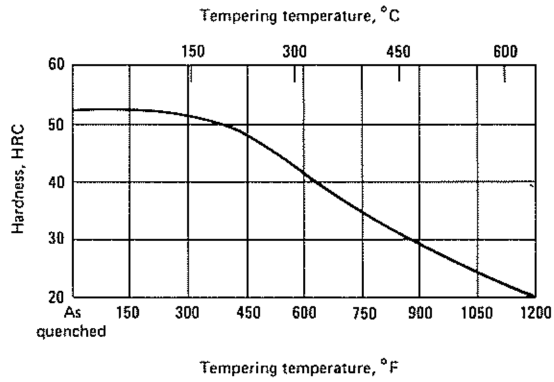
1541: Hardenability of Oil-Quenched Bolts. Curves represent average as-quenched hardnesses of 15 bolts 19 mm (0.75 in.) diam from one heat. C is center of bolt; 0.5R is mid-radius; S is surface



1541: Isothermal Transformation Diagram. Composition: 0.43 C, 1.57 Mn, 0.011 P, 0.029 S, 0.23 Si, 0.20 Ni, 0.12 Cr, 0.07 Mo. Austenitized at 900 °C (1650 °F)



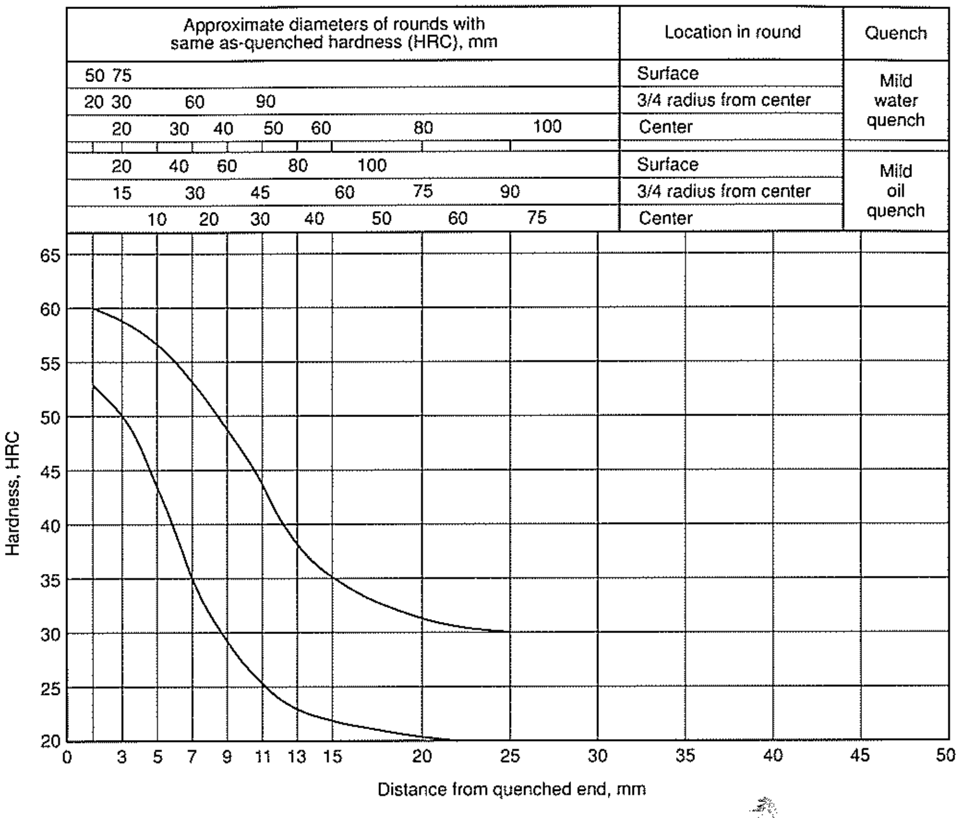
1541, 1541H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure



1541H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1550 °F)

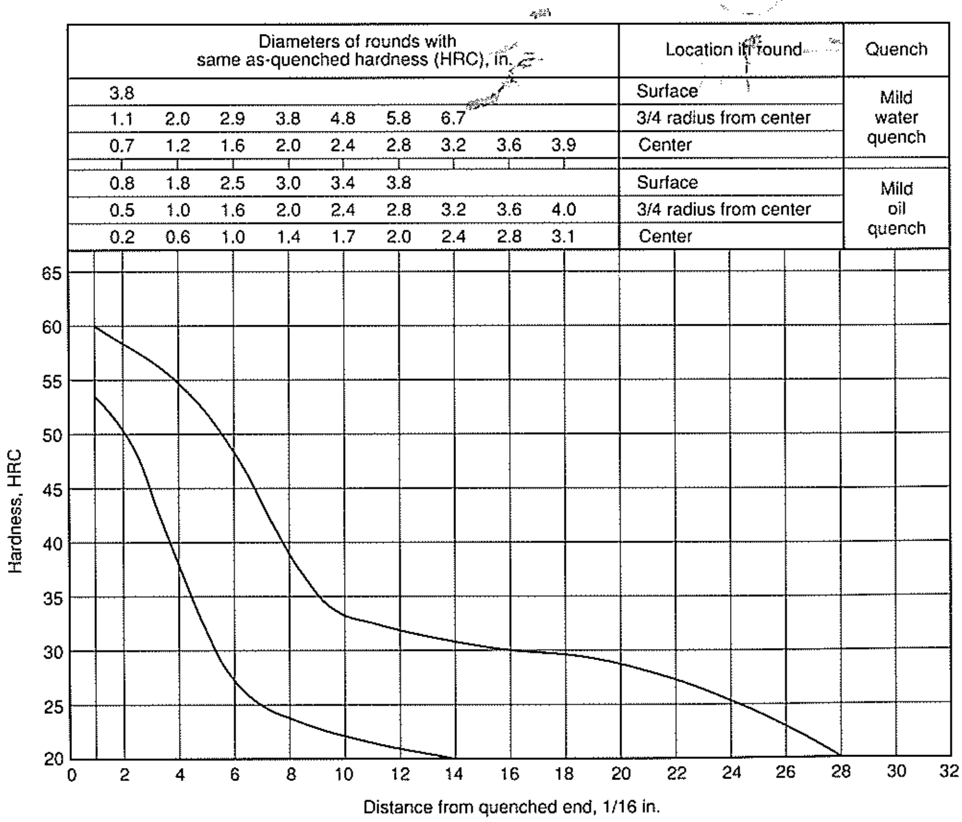
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	60	53
3	59	50
5	57	43
7	53	36
9	49	29
11	44	25
13	38	23
15	35	22
20	32	20
25	30	...
30	...	...

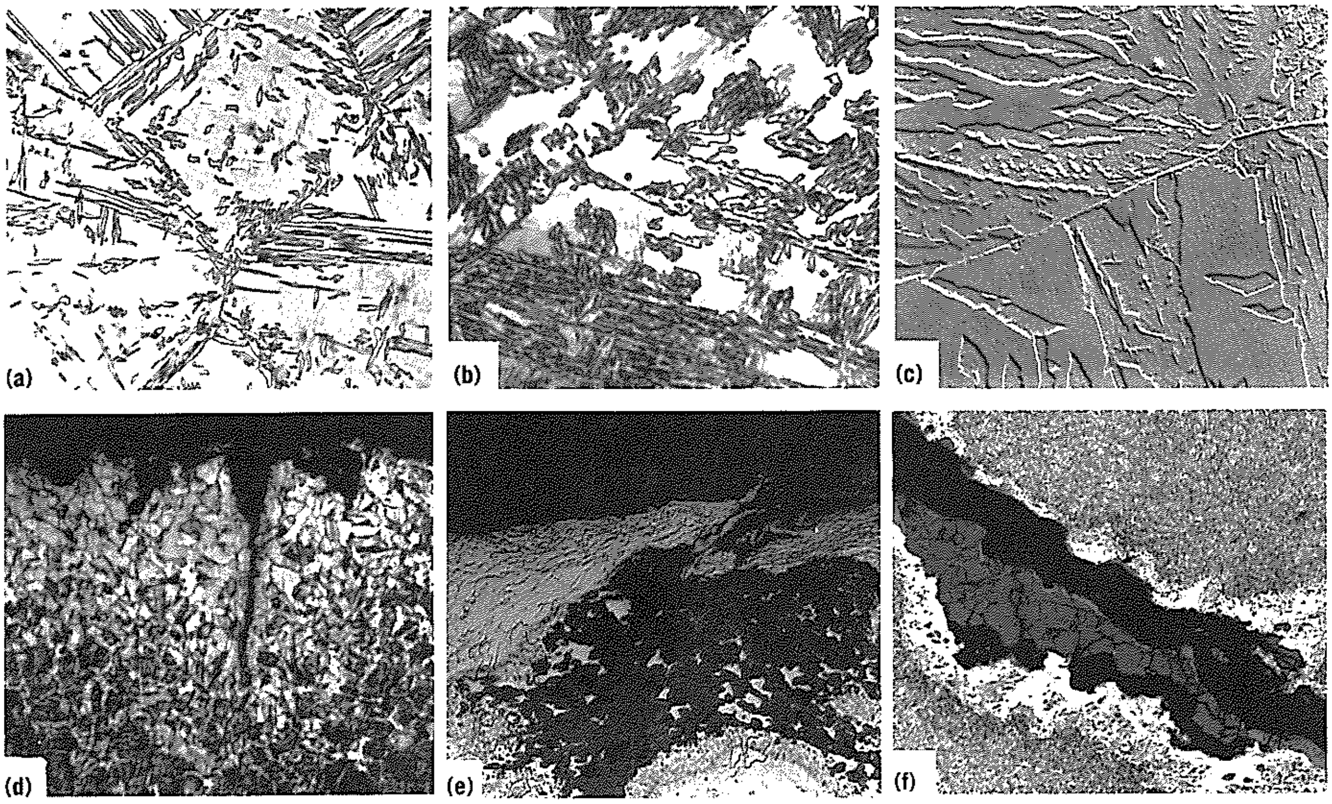


Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	60	53
1.5	59	52
2	59	50
2.5	58	47
3	57	44
3.5	56	41
4	55	38
4.5	53	35
5	52	32
5.5	50	29
6	48	27
6.5	46	26
7	44	25
7.5	41	24
8	39	23
9	35	23
10	33	22
12	32	21
14	31	20
16	30	...
18	30	...
20	29	...
22	28	...
24	26	...



l541: Microstructures. (a) Nital, 330×. Forged at 1205 °C (2200 °F). Cooled in air blast. Widmanstätten platelets of ferrite at prior austenite jrain boundaries and within grains. Martensite matrix. (b) Nital, 550×. Forged at 1205 °C (2200 °F), but cooled in milder air blast. Slower :ooling rate resulted in upper bainite formation (dark areas). Martensite matrix. (c) Nital, 2850×. Forging and cooling same as (b). Replica :lectron micrograph. Etched areas are upper bainite, consisting of carbide particles in ferrite. Smooth, featureless areas are martensite. (d) ?% nital, 110×. Hot rolled steel bar, 23.82 mm (0.94 in.) in diam. Transverse section. Top surface shows 0.254 mm (0.010 in.) deep seam ınd partial decarburization (white areas). Ferrite core (white) outlining prior austenite grains in pearlite matrix (dark). (e) 1% nital, 100×. ⁼orging lap of steel austenitized at 870 °C (1600 °F) for 2 h. Water quenched. Tempered at 650 °C (1200 °F) for 2 h. Iron oxide (dark); ferrite light); tempered martensite. Core is ferrite and tempered martensite. (f) 1% nital, 100×. Elongated forging flap in steel that was austenitized. Vater quenched. Tempered to hardness, 25 to 30 HRC. Iron oxide (dark). White area surrounding flap is caused by decarburization. Renainder is tempered martensite



5B41H

hemical Composition. UNS H15411 and SAE/AISI: 0.35 to 0.45 1.25 to 1.75 Mn, 0.15 to 0.35 Si (0.0005 to 0.003 B can be expected)

imilar Steels (U.S. and/or Foreign). UNS H15411; SAE 268; (Ger.) DIN 1.5527

haracteristics. A boron treated 1541H. Significant increase in harnability caused by boron addition. Forgeability is good. Machinability is :r. Weldability is poor

orging. Heat to 1245 °C (2275 °F). Do not forge below 870 °C (1600 °F)

ecommended Heat Treating Practice

ormalizing. Heat to 900 °C (1650 °F). Cool in air

nnealing. Heat to 830 °C (1525 °F). Furnace cool to 650 °C (1200 °F) a rate not to exceed 28 °C (50 °F) per h

Hardening. Heat to 845 °C (1555 °F).Carbonitriding is a suitable surface hardening process. Should be regarded as an alloy steel in quenching from austenitizing temperature. Usually quenched in oil, except for very heavy sections. Water or brine quenching likely to result in quench cracking. Full precautions should be taken when parts are induction hardened. Overly severe quenching can also cause quench cracking

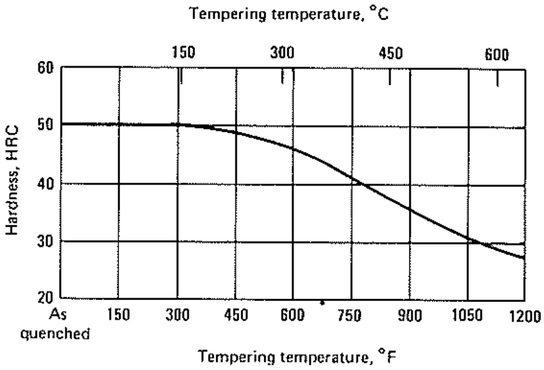
Tempering After Hardening. Hardness of approximately 52 HRC can be reduced by tempering

Tempering After Normalizing. For large sections, normalize by conventional practice. Results in structure of fine pearlite. Temper up to about 540 °C (1000 °F). Mechanical properties not equal to those achieved by quenching and tempering. Resulting strength far higher than that of annealed structure. Normalize and temper heavy forgings

Recommended Processing Sequence

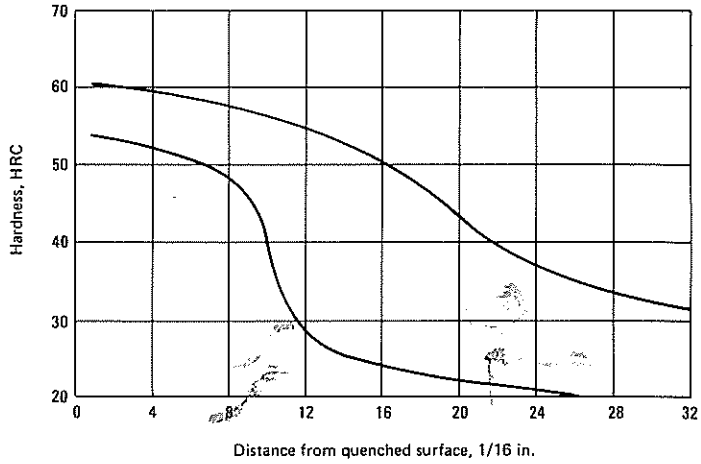
- Forge
- Normalize
- Anneal (if necessary) or temper (optional)
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

15B41H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure



15B41H: End-Quench Hardenability

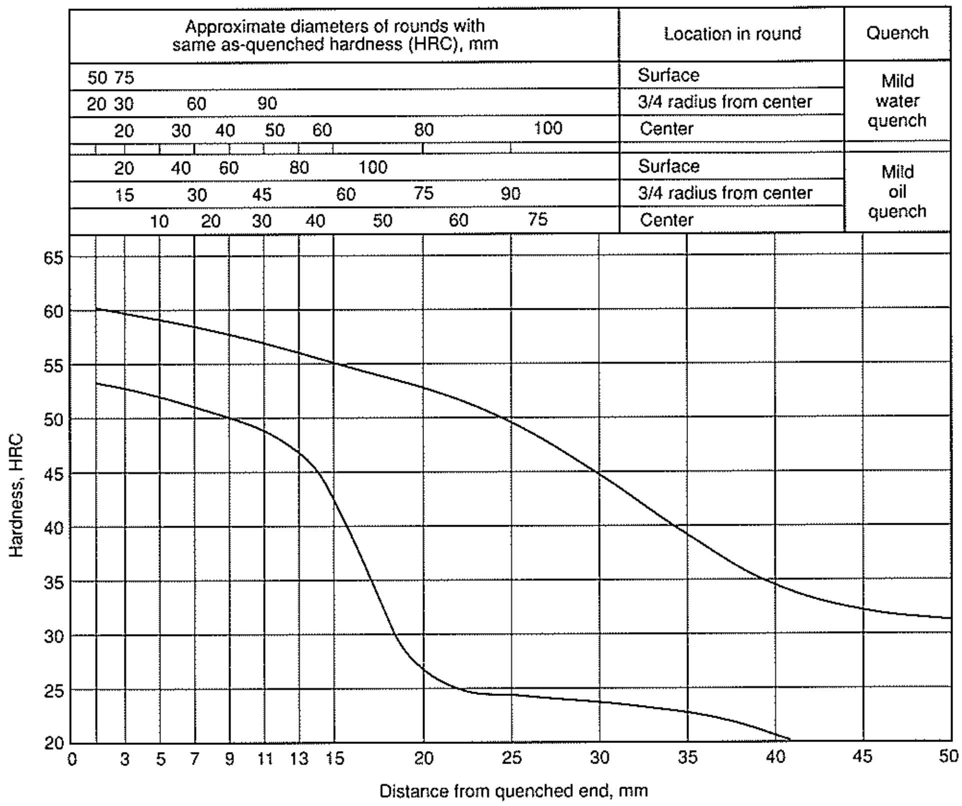
Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min
1	1.58	60	53	13	20.54	52	26
2	3.16	59	52	14	22.12	51	25
3	4.74	59	52	15	23.70	50	25
4	6.32	58	51	16	25.28	49	24
5	7.90	58	51	18	28.44	46	23
6	9.48	57	50	20	31.60	42	22
7	11.06	57	49	22	34.76	39	21
8	12.64	56	48	24	37.92	36	21
9	14.22	55	44	26	41.08	34	20
10	15.80	55	37	28	44.24	33	...
11	17.38	54	32	30	47.40	31	...
12	18.96	53	28	32	50.56	31	...



5B41H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 C (1600 °F). Austenitize: 845 °C (1550 °F)

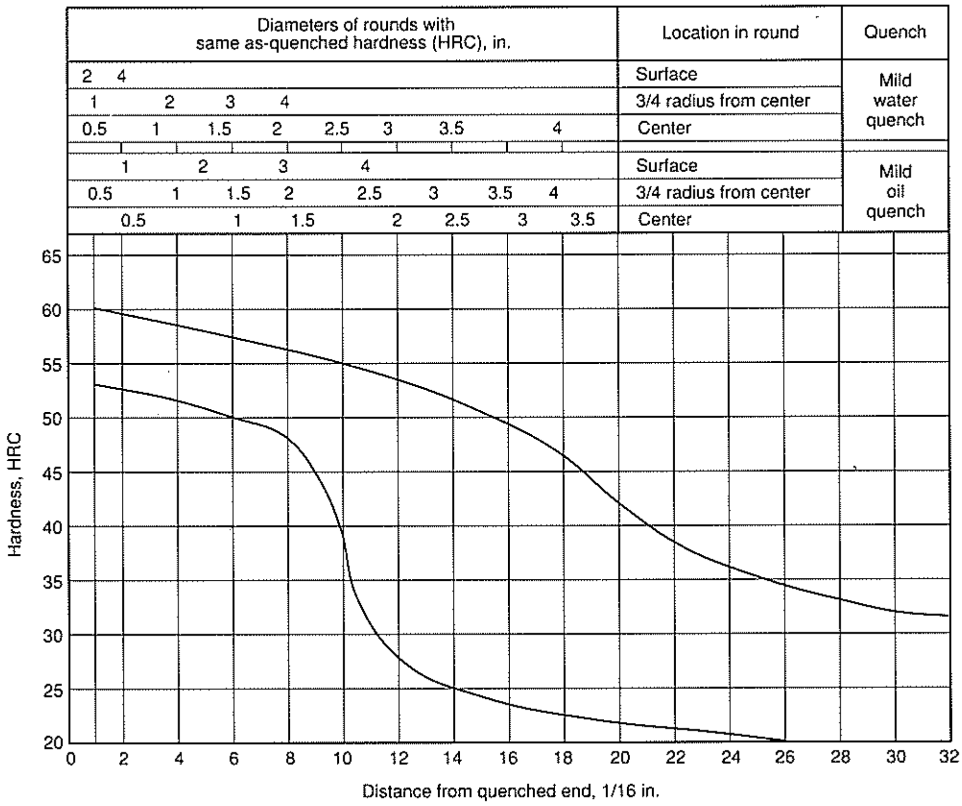
ardness limits for specification urposes

distance, m	Hardness, HRC Maximum	Minimum
5	60	53
	60	52
	59	52
	58	51
	58	50
	57	49
[illegible]	56	47
[illegible]	55	41
[illegible]	53	26
[illegible]	50	24
[illegible]	45	23
[illegible]	39	21
[illegible]	35	20
[illegible]	32	...
[illegible]	31	...

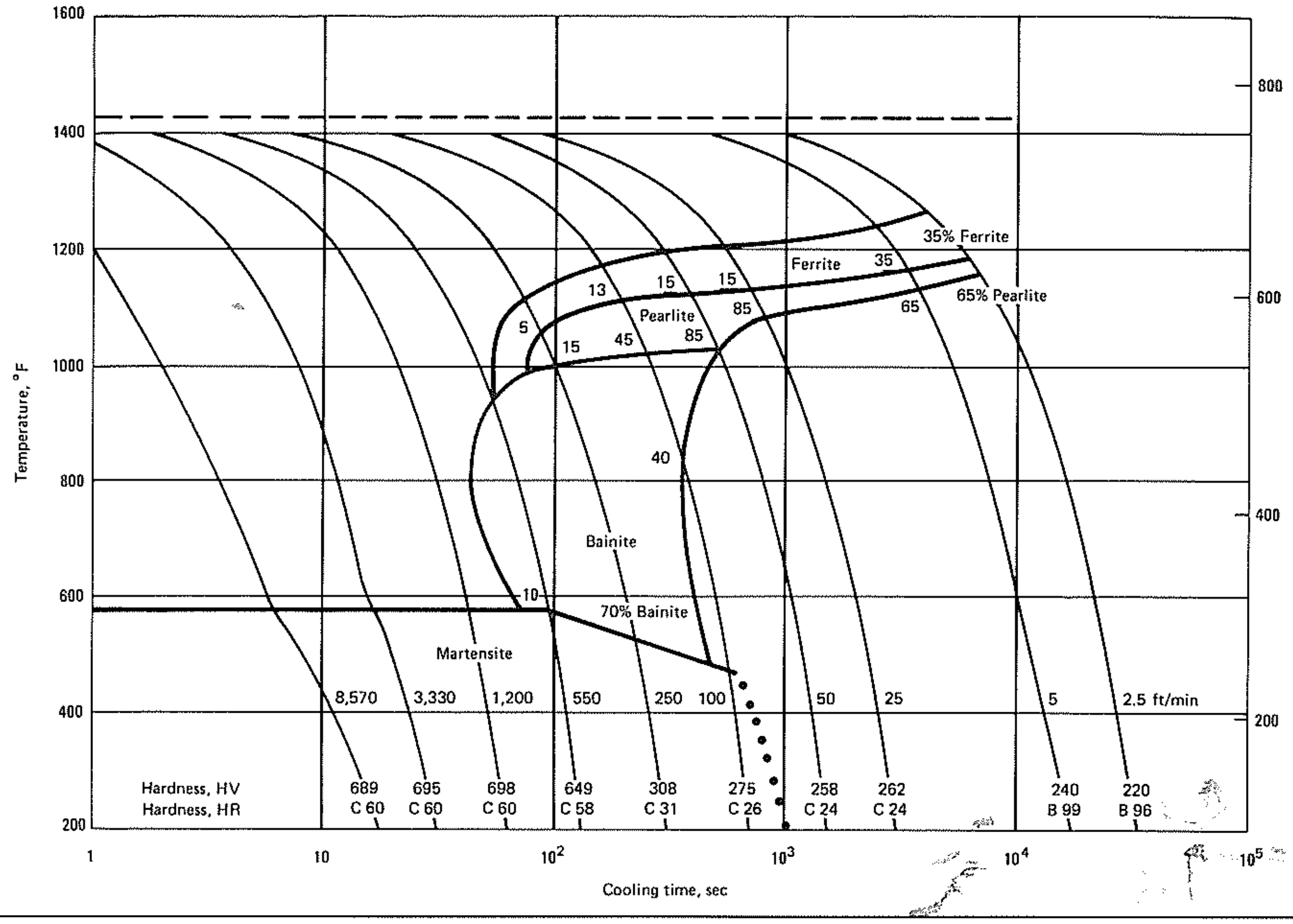


ardness limits for specification urposes

distance, 6 in.	Hardness, HRC Maximum	Minimum
	60	53
	59	52
	59	52
	58	51
	58	51
	57	50
	57	49
	56	48
	55	44
[illegible]	55	37
	54	32
[illegible]	53	28
[illegible]	52	26
[illegible]	51	25
[illegible]	50	25
[illegible]	49	24
[illegible]	46	23
[illegible]	42	22
[illegible]	39	21
[illegible]	36	21
[illegible]	34	20
[illegible]	33	...
[illegible]	31	...
[illegible]	31	...



15B41H: Continuous Cooling Transformation Diagram. Composition: 0.42 C, 1.61 Mn, 0.006 P, 0.019 S, 0.29 Si, 0.004 B. Grain size, ASTM 7 to 8. Ac_1 at 725 °C (1335 °F). Ac_3 at 780 °C (1435 °F)



1548

Chemical Composition. **AISI and UNS:** 0.45 to 0.56 C, 0.85 to 1.15 Mn, 0.040 P max, 0.050 S max. **UNS G15480 and AISI/SAE 1548:** Standard composition ranges and limits: 0.42 to 0.43 C, 1.05 to 1.40 Mn; was formerly designated as 10XX grade

Similar Steels (U.S. and/or Foreign). UNS G15480; ASTM A510; SAE J403, J412, J414; (Ger.) DIN 1.1226

Characteristics. High-manganese version of 1045. Slight difference in composition provides for higher hardenability. As-quenched hardness of at least 55 HRC or slightly higher, when carbon is near the high side of the allowable range. Used extensively for parts to be furnace heated or heated by induction prior to quenching. Excellent forgeability. Fair machinability

Forging. Heat to 1245 °C (2275 °F). Do not forge below 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F). Cool in air

Annealing. Heat to 845 °C (1555 °F). Furnace cool to 650 °C (1200 °F) at a rate not to exceed 28 °C (50 °F) per h

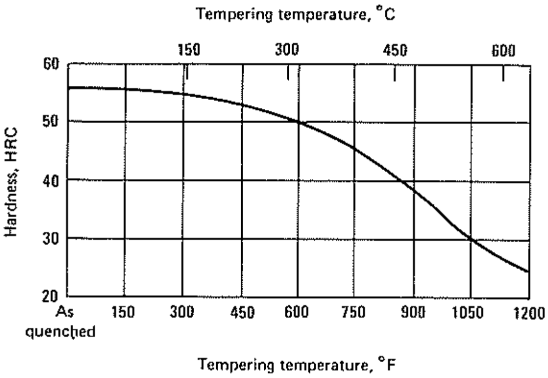
Hardening. Austenitize at 845 °C (1555 °F). Carbonitriding is a suitable surface hardening process. Because of high hardenability, a less severe quench may be desired for a given section thickness

Tempering After Hardening. Hardness of at least 55 HRC, if properly austenitized and quenched. Hardness can be adjusted by tempering

Tempering After Normalizing. For large sections, normalize by conventional practice. This results in a structure of fine pearlite. A tempering treatment up to approximately 540 °C (1000 °F) is then applied. Mechanical properties not equal to those achieved by quenching and tempering. Resulting strength is far higher than that of annealed structure. Normalizing and tempering often applied to heavy forgings

Recommended Processing Sequence

- Forge or machine (from bars)
- Normalize (if forged. Not required for parts machined from hot rolled or cold drawn bars)
- Anneal (if necessary. Bar stock usually received in condition for best machining)
- Rough machine (forgings)
- Austenitize (parts from bars or forgings)
- Quench
- Temper
- Finish machine



1548: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

5B48H

hemical Composition. UNS H15481 and SAE/AISI 15B48H: 43 to 0.53 C, 1.00 to 1.50 Mn, 0.15 to 0.35 Si (0.0005 to 0.003 B can be pected)

imilar Steels (U.S. and/or Foreign). UNS H15481; SAE J1268

haracteristics. Composition similar to 1548 with boron added. naracteristics, other than hardenability, are the same. Forgeability is cellent. Machinability is fair

orging. Heat to 1245 °C (2275 °F). Do not forge below 870 °C (1600 °F)

ecommended Heat Treating Practice

ormalizing. Heat to 900 °C (1650 °F). Cool in air

nnealing. Heat to 845 °C (1555 °F). Furnace cool to 650 °C (1200 °F) a rate not to exceed 28 °C (50 °F) per h

ardening. Austenitize at 845 °C (1555 °F). Carbonitriding is a suitable rface hardening process. Quench in oil except for thicker sections. If duction hardened, use extreme care when water quenching

Tempering After Hardening. As-quenched hardness of 55 HRC can be reduced by tempering

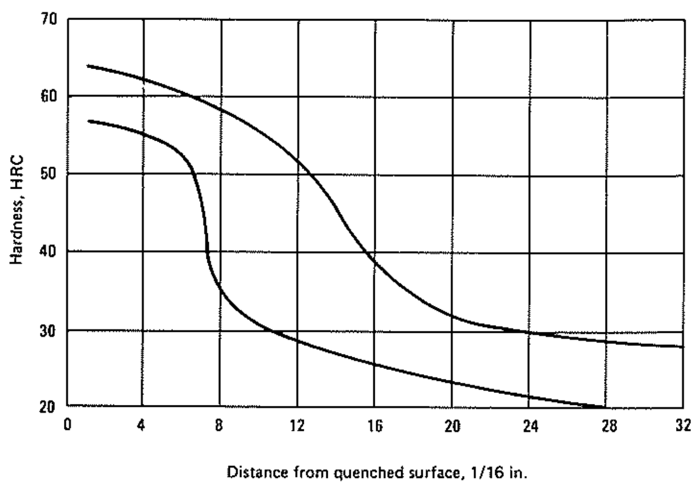
Tempering After Normalizing. For large sections, normalize by conventional practice. This results in a structure of fine pearlite. A tempering treatment up to approximately 540 °C (1000 °F) is then applied. Mechanical properties not equal to those achieved by quenching and tempering. Resulting strength is far higher than that of annealed structure. Normalizing and tempering often applied to heavy forgings

Recommended Processing Sequence

- Forge or machine (from bars)
- Normalize (if forged. Not required for parts machined from hot rolled or cold drawn bars)
- Anneal (if necessary. Bar stock is usually received in condition for best machining)
- Rough machine (forgings)
- Austenitize
- Quench
- Temper
- Finish machine

15B48H: End-Quench Hardenability

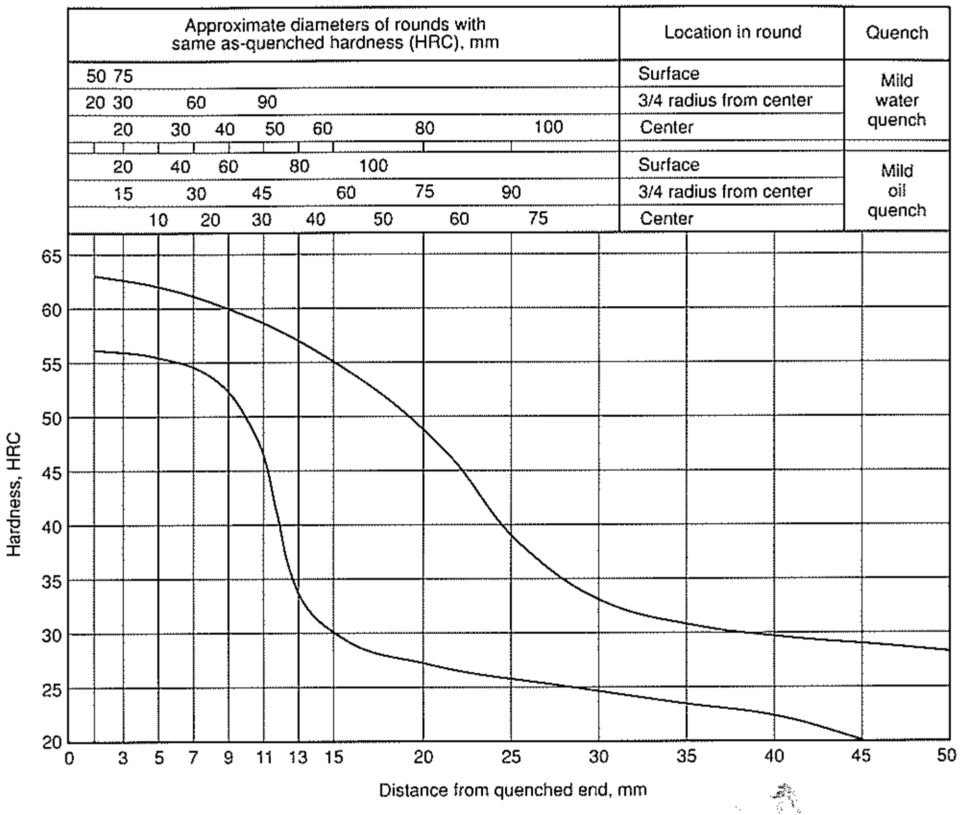
Distance from quenched surface		Hardness, HRC		Distance from quenched surface		Hardness, HRC	
1/16 in.	mm	max	min	1/16 in.	mm	max	min
1	1.58	63	56	13	20.54	48	27
2	3.16	62	56	14	22.12	45	27
3	4.74	62	55	15	23.70	41	26
4	6.32	61	54	16	25.28	38	26
5	7.90	60	53	18	28.44	34	25
6	9.48	59	52	20	31.60	32	24
7	11.06	58	42	22	34.76	31	23
8	12.64	57	34	24	37.92	30	22
9	14.22	56	31	26	41.08	29	21
10	15.80	55	30	28	44.24	29	20
11	17.38	53	29	30	47.40	28	...
12	18.96	51	28	32	50.56	28	...



15B48H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1550 °F)

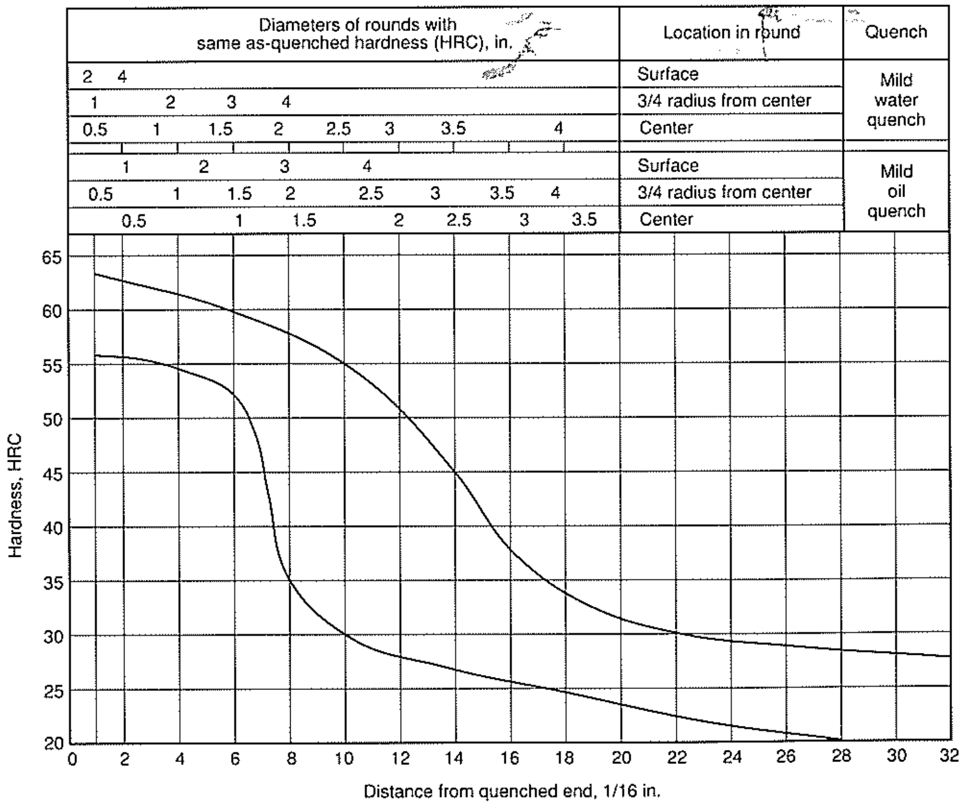
Hardness limits for specification purposes

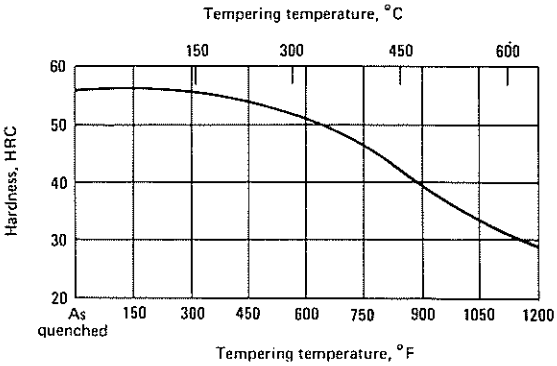
J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	63	56
3	63	55
5	62	55
7	61	54
9	60	53
11	59	45
13	57	33
15	56	30
20	49	27
25	39	25
30	33	24
35	31	23
40	30	22
45	29	...
50	28	...



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	63	56
2	62	56
3	62	55
4	61	54
5	60	53
6	59	52
7	58	42
8	57	34
9	56	31
10	55	30
11	53	29
12	51	28
13	48	27
14	45	27
15	41	26
16	38	26
18	34	25
20	32	24
22	31	23
24	30	22
26	29	21
28	29	20
30	28	...
32	28	...





15B48H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

551

ıemical Composition. **AISI and UNS:** 0.45 to 0.56 C, 0.85 to [5 Mn, 0.040 P max, 0.050 S max

milar Steels (U.S. and/or Foreign). UNS G15510; ASTM ;10; SAE J403, J412, J414

ıaracteristics. Carbon content as high as 0.56. Borderline grade tween medium carbon and high carbon. Available in various product ·ms. Used extensively for producing small to medium size forgings. ten selected for parts to be induction hardened. Excellent forgeability. irly good machinability. Weldability is poor. Similar to 1050. Higher ınganese content increases hardenability

›rging. Heat to 1230 °C (2250 °F). Do not forge below 845 °C (1555)

ecommended Heat Treating Practice

ɔrmalizing. Heat to 900 °C (1650 °F). Cool in air

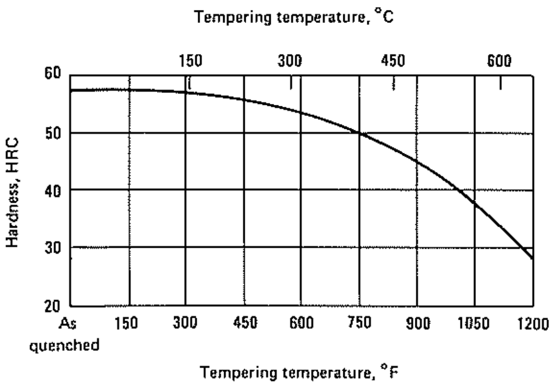
ınealing. Heat to 830 °C (1525 °F). Furnace cool to 650 °C (1200 °F) a rate not to exceed 28 °C (50 °F) per h

Hardening. Heat to 830 °C (1525 °F). Carbonitriding and induction hardening are suitable surface hardening processes. Quench in water or brine. For full hardening, oil quench rounds less than 6.4 mm (¼ in.) thick. High hardenability must be considered in quenching. Normalize and temper as for 1541, if desired

Tempering. As-quenched hardness of 58 to 60 HRC can be reduced by tempering

Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine



1551: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

1552

Chemical Composition. **AISI and UNS:** 0.47 to 0.55 C, 1.20 to 1.50 Mn, 0.040 P max, 0.050 S max. **UNS G15520 and AISI/SAE 1552:** Composition limits and ranges: 0.46 to 0.55 C, 1.20 to 1.55 Mn; was formerly designated as 10XX grade

Similar Steels (U.S. and/or Foreign). UNS G15520; ASTM A510; SAE J403, J412, J414; (Ger.) DIN 1.1226

Characteristics. Carbon content as high as 0.55. Borderline grade between medium carbon and high carbon. Available in various product forms. Used extensively for producing small to medium size forgings. Often selected for parts to be induction hardened. Excellent forgeability. Fairly good machinability. Weldability is poor. Similar to 1050. Higher manganese content increases hardenability

Forging. Heat to 1230 °C (2250 °F). Do not forge below 845 °C (1555 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F). Cool in air

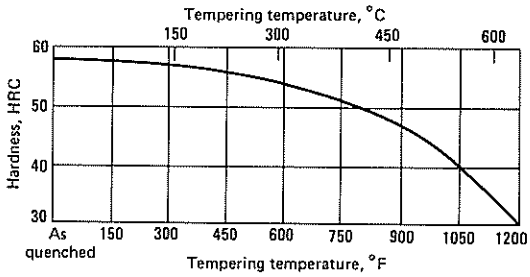
Annealing. Heat to 830 °C (1525 °F). Furnace cool to 650 °C (1200 °F) at a rate not to exceed 28 °C (50 °F) per h

Hardening. Heat to 830 °C (1525 °F). Carbonitriding and induction hardening are suitable surface hardening processes. Because of higher hardenability, oil quench heavier sections for full hardness. When induction hardening, use the least severe quench that will produce full hardness. This minimizes the possibility of quench cracking

Tempering. As-quenched hardness of 58 to 60 HRC can be reduced by tempering

Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine



1552: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

1561

Chemical Composition. **AISI and UNS:** 0.55 to 0.65 C, 0.75 to 1.05 Mn, 0.040 P max, 0.050 S max

Similar Steels (U.S. and/or Foreign). UNS G15610; ASTM A510; SAE J403, J412

Characteristics. Versatile high-carbon grade. Available in a variety of product forms, including various thicknesses of flat stock used for fabricating parts to be spring tempered. Good forgeability. Not recommended for welding. As-quenched hardness of near 65 HRC can be expected. When properly quenched, consists of a carbon-rich martensite structure with essentially no free carbide. Similar to 1060, with slightly higher hardenability and manganese content

Forging. Heat to 1205 °C (2200 °F). Do not forge below 815 °C (1500 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 885 °C (1625 °F). Cool in air

Annealing. Heat to 830 °C (1525 °F). Furnace cool to 650 °C (1200 °F) at a rate not to exceed 28 °C (50 °F) per h

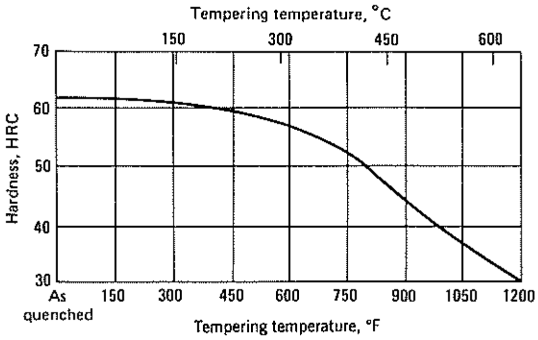
Hardening. Heat to 815 °C (1500 °F). Carbonitriding is a suitable surface hardening process. Hardenability must be considered in quenching. Oil quench sections thicker than for 1060

Tempering. Maximum hardness near 65 HRC can be reduced by tempering

Austempering. Thin sections (typically springs) usually austempered. Results in bainitic structure. Hardness of approximately 46 to 52 HRC. Austenitize at 815 °C (1500 °F). Quench in molten salt bath at 315 °C (600 °F). Hold at temperature for 1 h. Air cool. No tempering required

Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine



1561: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

5B62H

ıemical Composition. UNS H15621 and SAE/AISI 15B62H: ¡4 to 0.67 C, 1.00 to 1.50 Mn, 0.40 to 0.60 Si (0.0005 to 0.003 B can be ɔected)

milar Steels (U.S. and/or Foreign). UNS H15621; SAE J1268

ıaracteristics. Similar to 1060. Good forgeability. Poor weldability. ıximum as-quenched hardness of 65 HRC. Higher manganese content, ron addition, and higher silicon content all contribute to its relatively ;h hardenability. Extensively used in the spring temper hardness range, ıerally 45 to 52 HRC, for springs having relatively thick sections

ɔrging. Heat to 1205 °C (2200 °F). Do not forge below 815 °C (1500 °F)

ecommended Heat Treating Practice

ɔrmalizing. Heat to 885 °C (1625 °F). Cool in air

ınealing. Heat to 830 °C (1525 °F). Furnace cool to 650 °C (1200 °F) a rate not to exceed 28 °C (50 °F) per h

ardening. Austenitize at 815 °C (1500 °F). Carbonitriding is a suitable rface hardening process. Quench in oil

Austempering. Thin sections (typically springs) commonly austempered, resulting in bainitic structure and hardness of approximately 45 to 52 HRC. Austenitize at 815 °C (1500 °F). Quench in molten salt bath at 315 °C (600 °F). Hold at this temperature for 1 h. Air cool. No tempering required

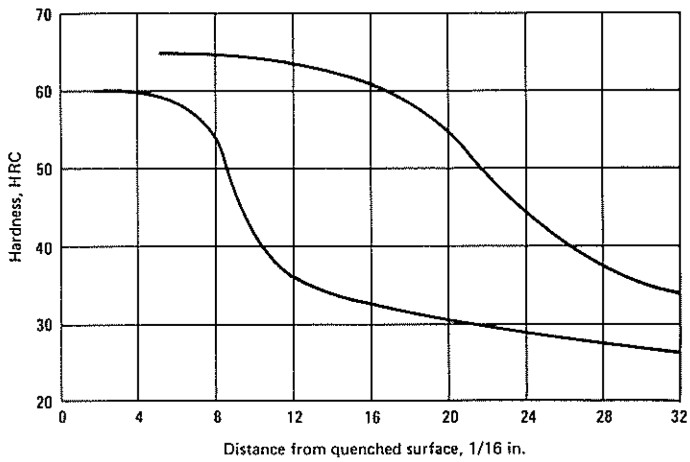
Tempering. As-quenched hardness from 62 to 65 HRC. This maximum hardness can be reduced by tempering

Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

15B62H: End-Quench Hardenability

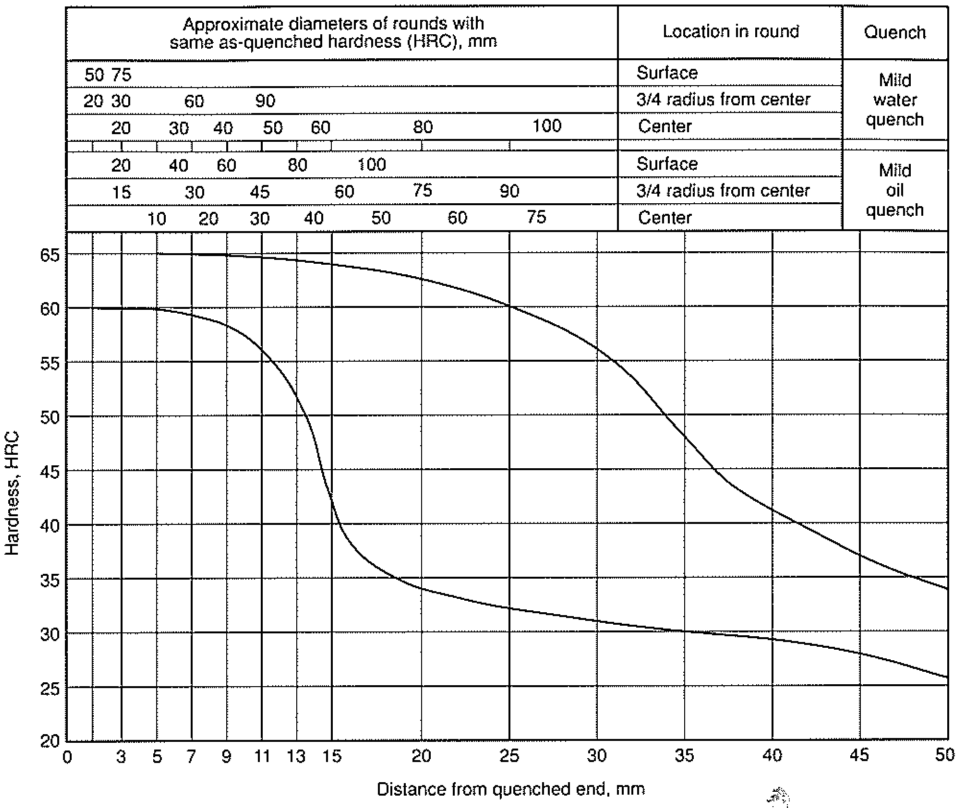
Distance from quenched surface		Hardness, HRC		Distance from quenched surface		Hardness, HRC	
1/16 in.	mm	max	min	1/16 in.	mm	max	min
1	1.58	...	60	13	20.54	62	35
2	3.16	...	60	14	22.12	62	34
3	4.74	...	60	15	23.70	61	33
4	6.32	...	60	16	25.28	60	33
5	7.90	65	59	18	28.44	58	32
6	9.48	65	58	20	31.60	54	31
7	11.06	64	57	22	34.76	48	30
8	12.64	64	52	24	37.92	43	30
9	14.22	64	43	26	41.08	40	29
10	15.80	63	39	28	44.24	37	28
11	17.38	63	37	30	47.40	35	27
12	18.96	63	35	32	50.56	34	26



15B62H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1550 °F)

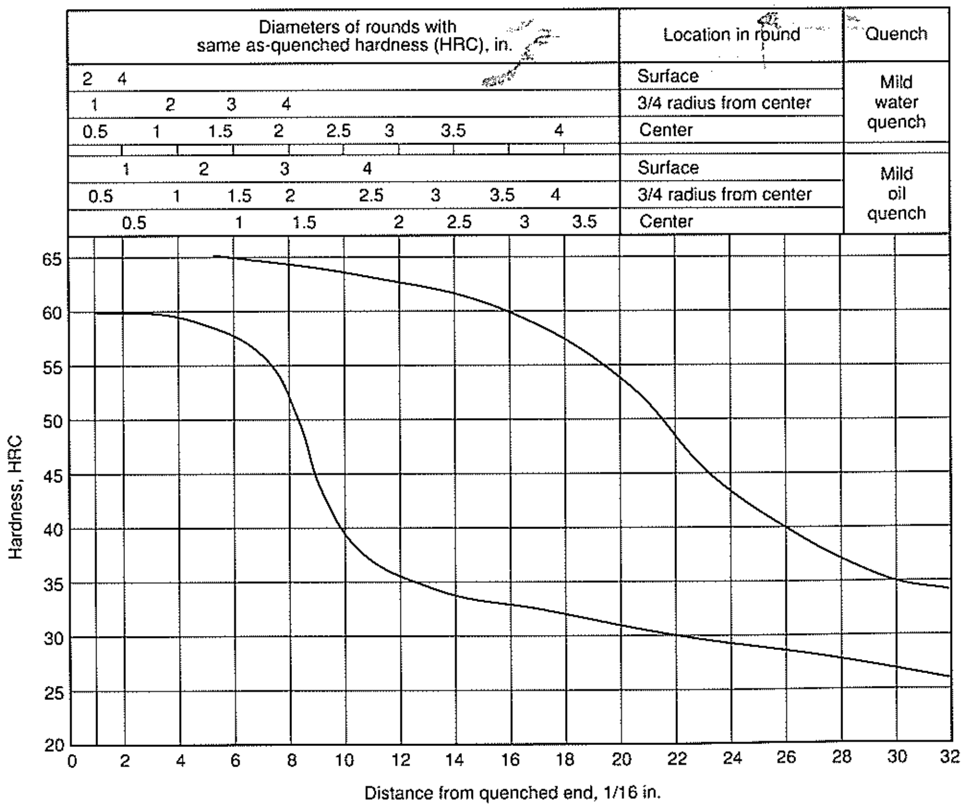
Hardness limits for specification purposes

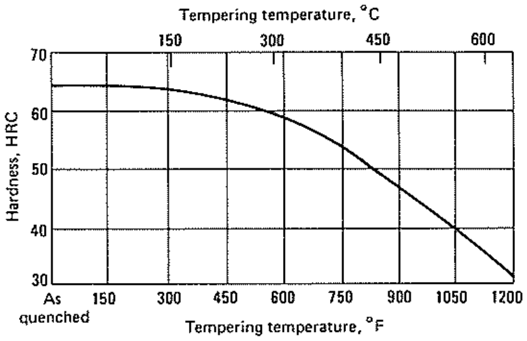
J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	...	60
3	...	60
5	65	60
7	65	59
9	65	58
11	65	56
13	64	50
15	64	42
20	63	34
25	60	32
30	56	31
35	48	30
40	42	29
45	37	27
50	34	26



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	...	60
2	...	60
3	...	60
4	...	60
5	65	59
6	65	58
7	64	57
8	64	52
9	64	43
10	63	39
11	63	37
12	63	35
13	62	35
14	62	34
15	61	33
16	60	33
18	58	32
20	54	31
22	48	30
24	43	30
26	40	29
28	37	28
30	35	27
32	34	26





15B62H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

566

ıemical Composition. AISI and UNS: 0.60 to 0.71 C, 0.85 to l5 Mn, 0.040 P max, 0.050 S max

milar Steels (U.S. and/or Foreign). UNS G15660; ASTM ;10; SAE J403, J412; (Ger.) DIN 1.1260

haracteristics. High-manganese version of 1070. Widely used in the rdened and tempered (notably spring tempered) condition. Good forge-ility and shallow hardening. Extensively used for making hand tools such hammers and woodcutting saws. Not recommended for welding

ırging. Heat to 1190 °C (2175 °F). Do not forge below 815 °C (1500 °F)

ecommended Heat Treating Practice

ormalizing. Heat to 885 °C (1625 °F). Cool in air

nnealing. Heat to 830 °C (1525 °F). Furnace cool to 650 °C (1200 °F) a rate not to exceed 28 °C (50 °F) per h

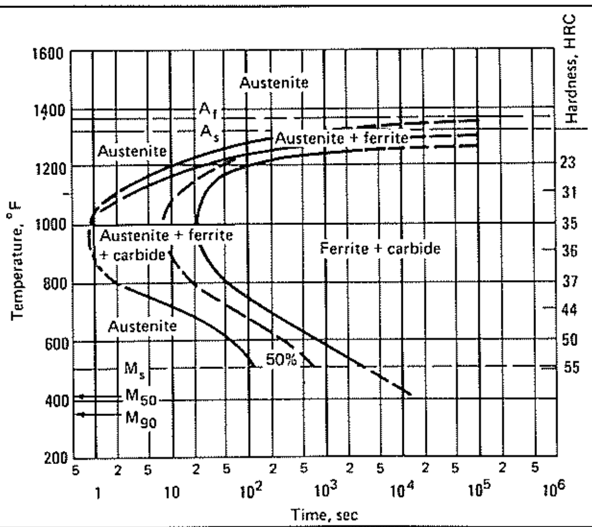
ardening. Heat to 815 °C (1500 °F). Carbonitriding is a suitable rface hardening process. Lessen severity of quench to avoid cracking mpared with quenching of 1070

Austempering. Thin sections (typically springs) are commonly austempered, resulting in bainitic structure and a hardness range of approximately 46 to 52 HRC. Austenitize at 815 °C (1500 °F). Quench in molten salt bath at 315 °C (600 °F). Hold at temperature for 1 h. Air cool. No tempering required

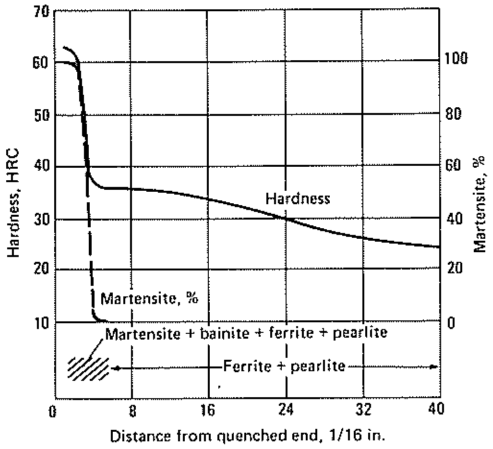
Tempering. Maximum hardness near 65 HRC can be reduced by tempering

Recommended Processing Sequence

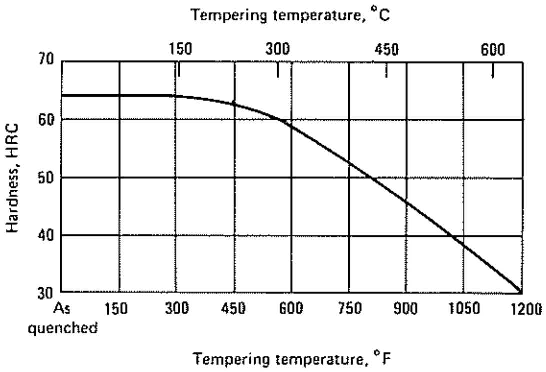
- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine



1566: Isothermal Transformation Diagram. Contains 0.64 C and 1.13 Mn. Grain size 7. Austenitized at 910 °C (1670 °F). Martensite temperatures estimated



1566: End-Quench Hardenability. Contains 0.68 C and 1.00 Mn. Grain size, 6 to 7. Austenitized at 845 °C (1555 °F)



1566: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

Alloy Steels (1300 through 9700 Series)

The alloy steels discussed in this section, as well as their subsequent heat treatment, are those listed in the latest issue of the AISI Steel Products Manual on alloy steel bars. They include both the standard alloy steels and the standard H and RH steels, which have modified hardenability limits. They also have slightly different carbon ranges, generally broader than the standard alloy steels. These steels are similar to standard grades in other respects, including their general characteristics and recommended heat treating practice.

There are fourteen separate families of alloy steels that are considered standard. In numerical sequence, these steels begin with the 1300 manganese steels and conclude with 9260 manganese-silicon steels.

Boron-modified alloy steels generally contain 0.0005 to 0.003% boron. There are five families of boron-modified alloy steels beginning with 50B00 chromium steels and concluding with the 94B00 nickel-chromium-molybdenum steels. Because of the very small amounts of boron used, boron is not considered as an alloy. These steels, which are denoted by the use of the letter "B" between the second and third digits of their designations, are instead commonly referred to as boron-treated steels. Boron is used for the purpose of increasing hardenability. When the end-quench data for any specific boron steel are compared with its counterpart not containing boron, the effect of boron becomes evident. The use of boron steels has provided an economic advantage because it offers high hardenability in low-alloy steels, significantly lower in cost than the higher alloy grades that would be necessary to provide the hardenability required without the boron.

1330, 1330H

Chemical Composition. **1330. AISI and UNS:** 0.28 to 0.33 C, 1.60 to 1.90 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si. **UNS H13300 and SAE/AISI 1330H:** 0.27 to 0.33 C, 1.45 to 2.05 Mn, 0.15 to 0.35 Si.

Similar Steels (U.S. and/or Foreign). **1330.** UNS G13300; ASTM A304, A322, A331, A519; MIL SPEC MIL-S-16974; SAE J404, J412, J770; (Ger.) DIN 1.1165; (Jap.) JIS SMn 1 H, SCMn 2. **1330H.** UNS H13300; ASTM A304; SAE J1268; (Ger.) DIN 1.1165; (Jap.) JIS SMn 1 H, SCMn 2

Characteristics. A medium-carbon steel of the manganese alloy steel series. While the manganese content of 1330H can overlap with the manganese content of the high-manganese carbon steels, the nominal manganese content is considerably higher for 1330H, giving the steel higher hardenability. Thus, with a carbon content in the middle of the range, as-quenched hardness can be expected to approach 50 HCR. This steel is usually oil quenched, although large sections may have to be water quenched to develop maximum hardness. Water quenching of 1330H is hazardous because high-manganese steels are susceptible to quench cracking. This applies especially to induction or flame hardening. When these processes are used, the quenching phase of the process must be extremely well controlled. 1330H can be welded only when closely controlled preheating and postheating practices are followed. Forgeability is very good, but machinability is only fair

Forging. Heat to 1230 °C (2245 °F). Do not forge after temperature drops below approximately 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F). Cool in air

Annealing. For a predominately pearlitic structure, heat to 855 °C (1570 °F), and cool to 620 °C (1150 °F) at a rate not to exceed 11 °C (20 °F) per h; or cool fairly rapidly to 620 °C (1150 °F) and hold for 4 ½ h after which cooling rate is not critical. To obtain a structure predominately composed of ferrite and spheroidized carbide, heat to 750 °C (1380 °F), cool fairly rapidly to 730 °C (1350 °F). Then cool to 640 °C (1185 °F) at a rate not to exceed 6 °C (10 °F) per h and hold for 10 h, after which cooling rate is no longer critical

Hardening. Austenitize at 860 °C (1580 °F), and quench in oil. Use water or brine for heavy sections. Carbonitriding, austempering, and martempering are suitable processes.

Tempering. Temper to desired hardness

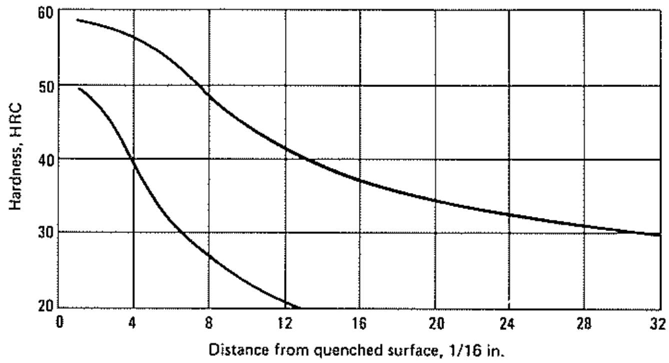
Recommended Processing Sequence (if forged, see 1335 and 1335H)

- Rough machine
- Stress relieve
- Finish machine
- Preheat
- Austenitize
- Quench
- Temper
- Final grind to size

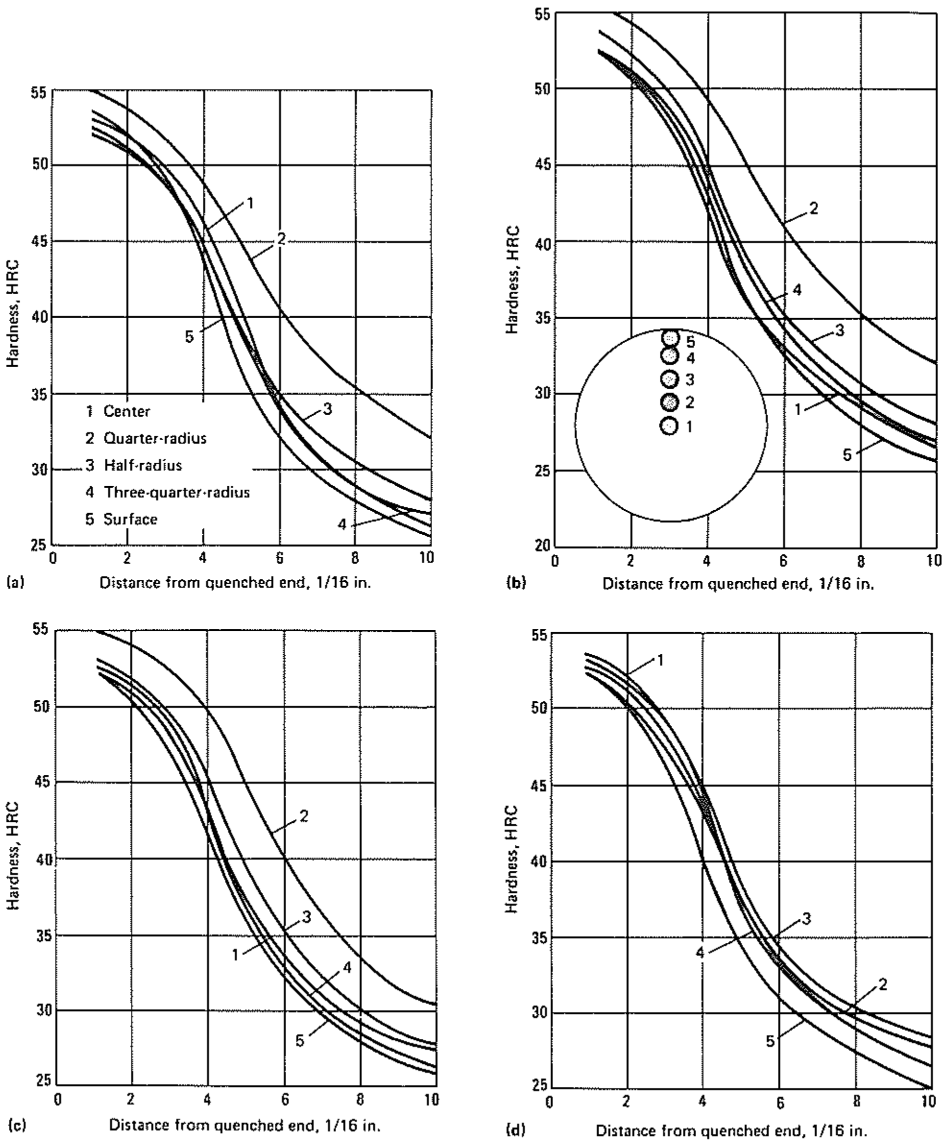
1330H: End-Quench Hardenability

Distance from quenched surface		Hardness, HRC		Distance from quenched surface		Hardness, HRC	
1/16 in.	mm	max	min	1/16 in.	mm	max	min
1	1.58	56	49	13	20.54	38	20
2	3.16	56	47	14	22.12	37	...
3	4.74	55	44	15	23.70	36	...
4	6.32	53	40	16	25.28	35	...
5	7.90	52	35	18	28.44	34	...
6	9.48	50	31	20	31.60	33	...
7	11.06	48	28	22	34.76	32	...
8	12.64	45	26	24	37.92	31	...
9	14.22	43	25	26	41.08	31	...
10	15.80	42	23	28	44.24	31	...
11	17.38	40	22	30	47.40	30	...
12	18.96	39	21	32	50.56	30	...

Source: *Metals Handbook*, 9th ed., Vol 1, American Society for Metals, 1978



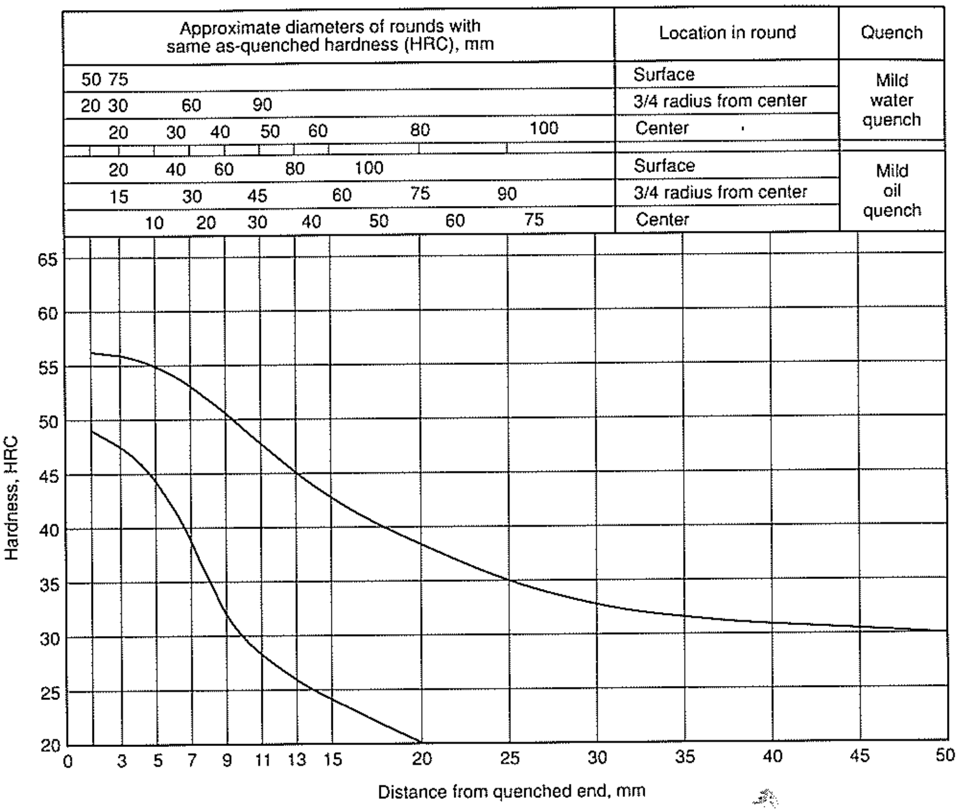
1330: Effect of Hot Working and Location of Test Bars on End-Quench Hardenability. (a) 305 mm (12 in.) diam. (b) 254 mm (10 in.) diam. (c) 203 mm (8 in.) diam. (d) 152 mm (6 in.) diam.



1330H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 900 °C (1650 °F). Austenitize: 870 °C (1600 °F)

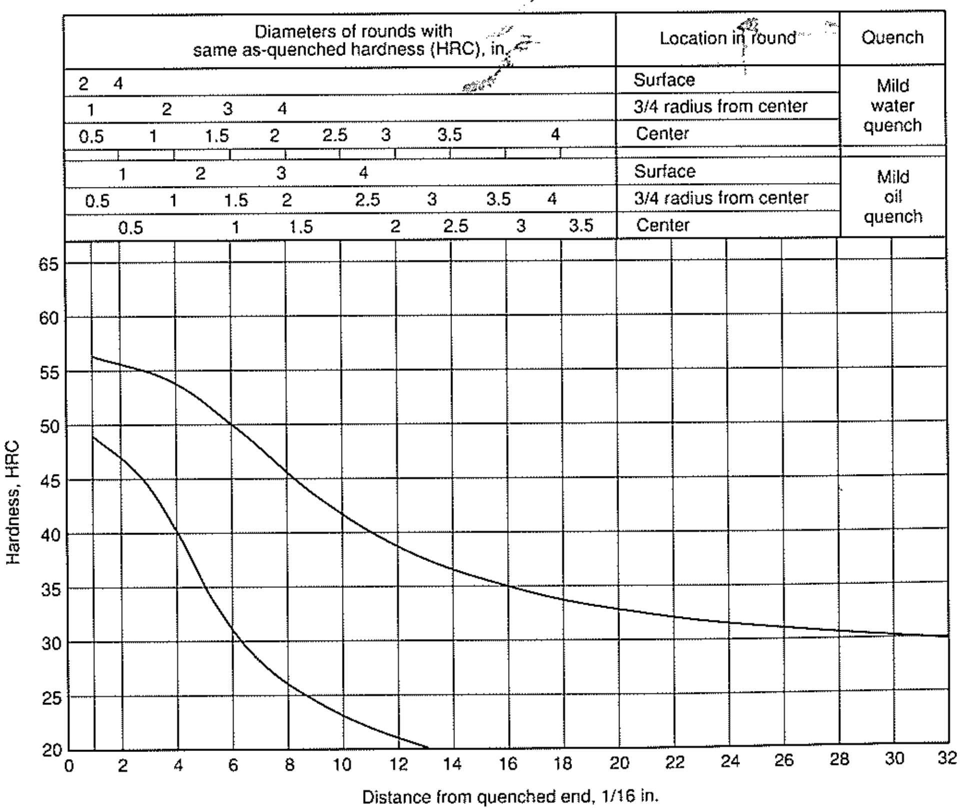
Hardness Limits for Specification Purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	56	49
3	56	47
5	55	44
7	53	38
9	51	32
11	48	28
13	45	25
15	43	24
20	39	20
25	35	...
30	33	...
35	32	...
40	31	...
45	31	...
50	30	...

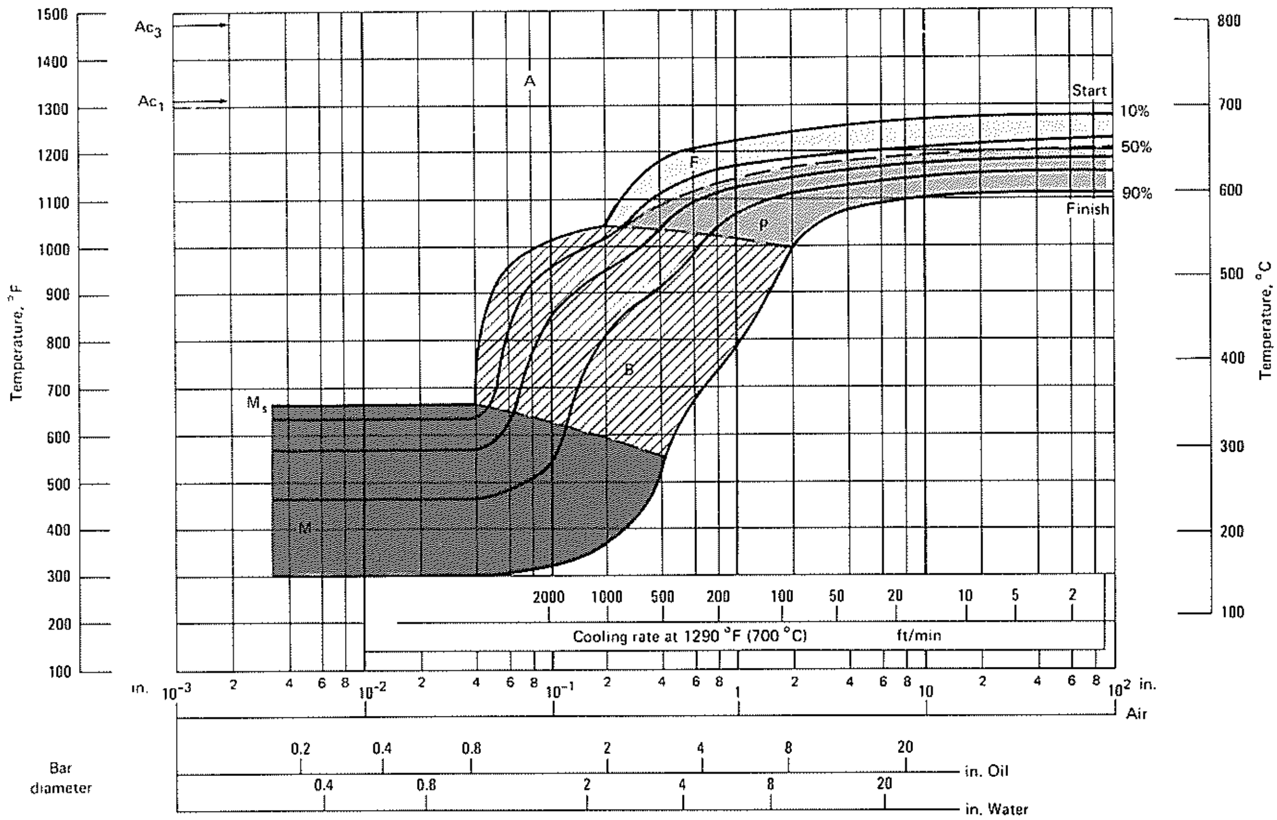


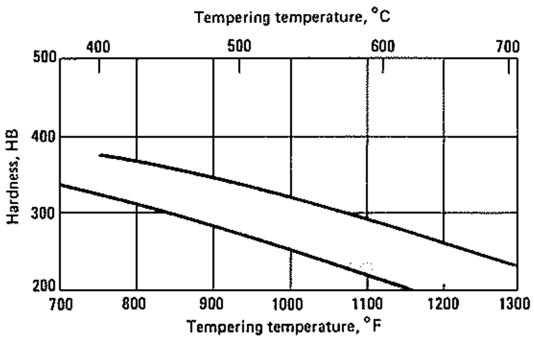
Hardness Limits for Specification Purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	56	49
2	56	47
3	55	44
4	53	40
5	52	35
6	50	31
7	48	28
8	45	26
9	43	25
10	42	23
11	40	22
12	39	21
13	38	20
14	37	...
15	36	...
16	35	...
18	34	...
20	33	...
22	32	...
24	31	...
26	31	...
28	31	...
30	30	...
32	30	...



1330: Continuous Cooling Transformation Diagram. Composition: 0.30 C, 1.80 Mn, 0.020 P, 0.020 S, 0.15 Si. Austenitized at 860 °C (1580 °F). Previous treatment, rolled





1330: Hardness vs Tempering Temperature. Austenitized at 870 °C (1600 °F) and quenched in oil. Limiting section size: 11.11 mm (7/16 in.)

1335, 1335H

Chemical Composition. **1335. AISI and UNS:** 0.33 to 0.38 C, 1.60 to 1.90 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si. **UNS H13350 and SAE/AISI 1335H:** 0.32 to 0.38 C, 1.45 to 2.05 Mn, 0.15 to 0.35 Si

Similar Steels (U.S. and/or Foreign). **1335.** UNS G13350; ASTM A322, A331, A519, A547; MIL SPEC MIL-S-16974; SAE J404, J412, J770; (Ger.) DIN 1.1167; (Fr.) AFNOR 40 M 5; (Jap.) JIS SMn 2 H, SMn 2, SCMn 3; (Swed.) SS_{14} 2120. **1335H.** UNS H13350; ASTM A304; SAE J407; (Ger.) DIN 1.1167; (Fr.) AFNOR 40 M 5; (Jap.) JIS SMn 2 H, SMn 2, SCMn 3; (Swed.) SS_{14} 2120;

Characteristics. The general characteristics are nearly the same as those given for 1330H. Expected as-quenched hardness for 1335H is slightly higher than that for 1330H, approximately 52 HRC. Hardenability patterns are also similar. This steel is usually oil quenched, although large sections may have to be water quenched to develop maximum hardness.

Water quenching high-manganese steels is hazardous because of their susceptibility to quench cracking. This applies especially to induction or flame hardening. When these processes are used, the quenching phase of the process must be extremely well controlled. 1335H can be welded, but only when closely controlled preheating and postheating practices are followed. Forgeability is very good, but machinability is only fair

Forging. Heat to 1230 °C (2245 °F). Do not forge after temperature drops below approximately 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F). Cool in air

Annealing. For a predominately pearlitic structure, heat to 855 °C (1570 °F), and cool to 620 °C (1150 °F) at a rate not to exceed 11 °C (20 °F) per h; or cool fairly rapidly to 620 °C (1150 °F), and hold for 4 ½ h, after which cooling rate is not critical. To obtain a structure predominately composed of ferrite and spheroidized carbide, heat to 750 °C (1385 °F), cool fairly rapidly to 730 °C (1350 °F). Then cool to 640 °C (1185 °F) at a rate not to exceed 6 °C (10 °F) per h and hold for 10 h, after which cooling rate is no longer critical

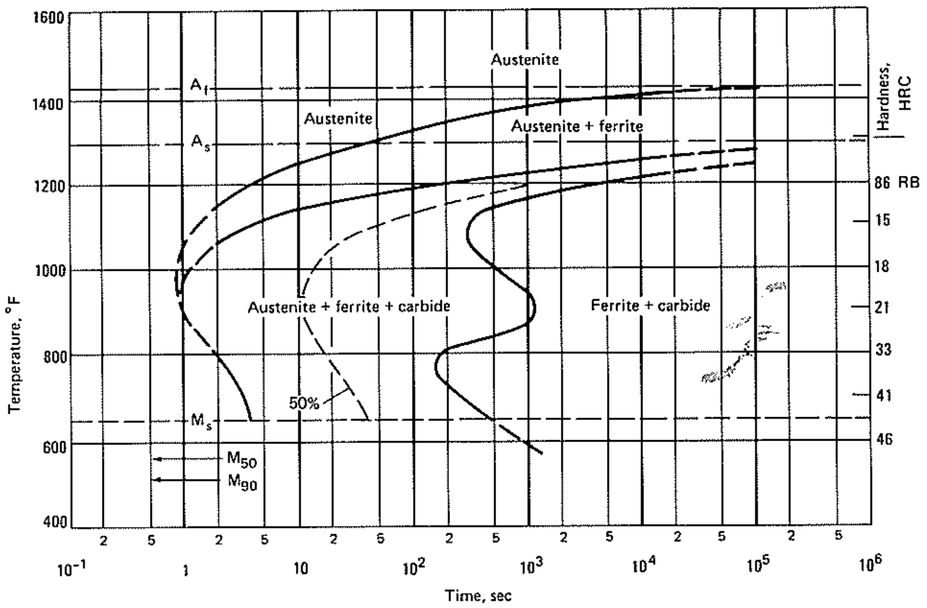
Hardening. Austenitize at 855 °C (1570 °F), and quench in oil. Use water or brine for heavy sections. Carbonitriding and martempering are suitable surface hardening processes

Tempering. Temper to desired hardness

Recommended Processing Sequence

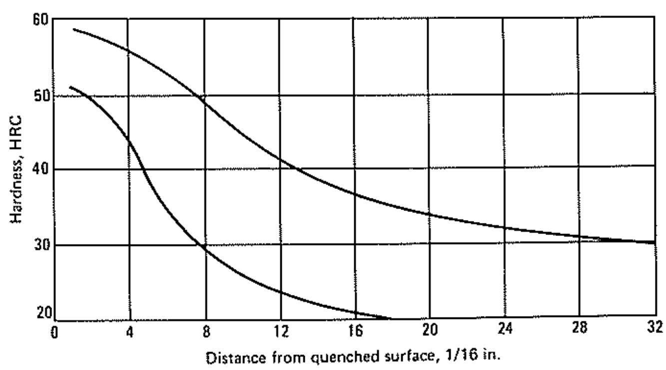
- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

1335: Isothermal Transformation Diagram. Composition: 0.35 C, 1.85 Mn. Austenitized at 845 °C (1555 °F). Grain size: 70% No. 7, 30% No. 2



1335: End-Quench Hardenability

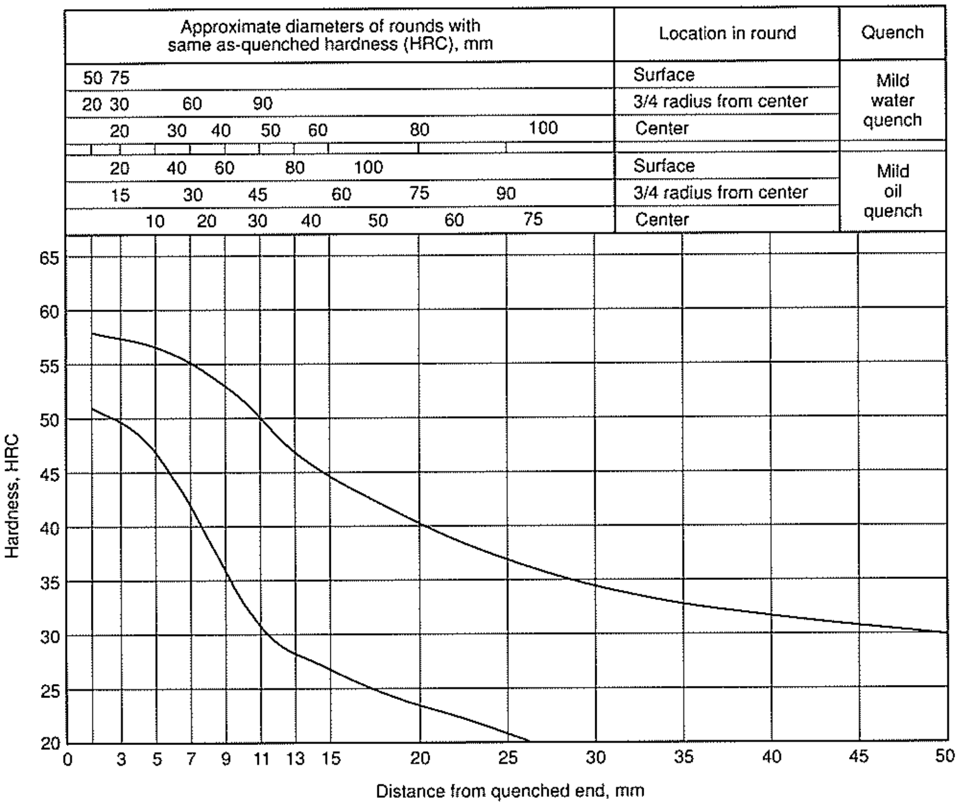
Distance from quenched surface, ¹⁄₁₆ in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, ¹⁄₁₆ in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min
1	1.58	58	51	13	20.54	40	23
2	3.16	57	49	14	22.12	39	22
3	4.74	56	47	15	23.70	38	22
4	6.32	55	44	16	25.28	37	21
5	7.90	54	38	18	28.44	35	20
6	9.48	52	34	20	31.60	34	...
7	11.06	50	31	22	34.76	33	...
8	12.64	48	29	24	37.92	32	...
9	14.22	46	27	26	41.08	31	...
10	15.80	44	26	28	44.24	31	...
11	17.38	42	25	30	47.40	30	...
12	18.96	41	24	32	50.56	30	...



1335H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1550 °F)

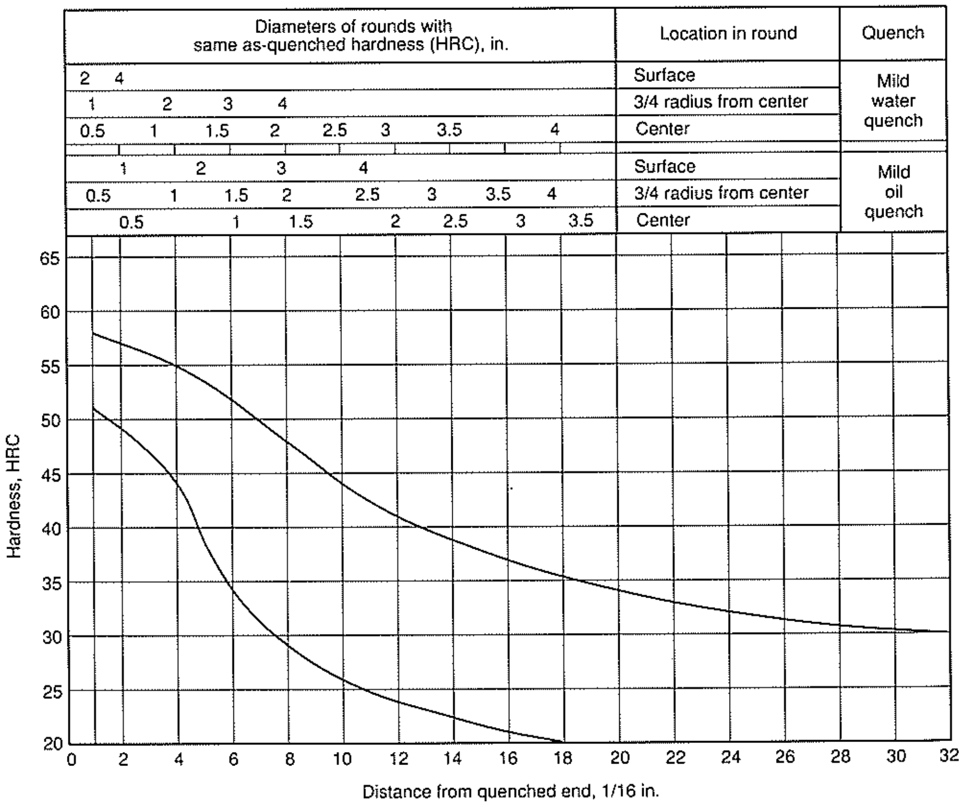
Hardness Limits for Specification Purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	58	51
3	58	49
5	57	46
7	55	42
9	53	36
11	50	31
13	47	28
15	45	27
20	41	23
25	37	21
30	35	...
35	33	...
40	32	...
45	31	...
50	30	...

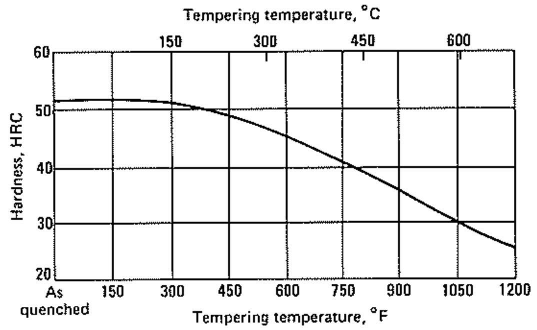


Hardness Limits for Specification Purposes

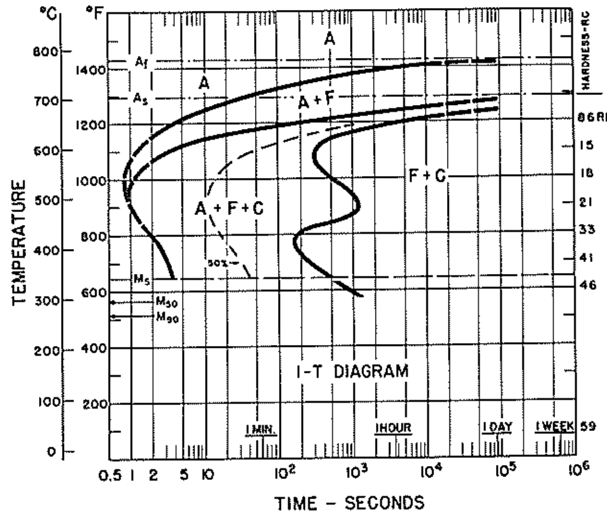
J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	58	51
2	57	49
3	56	47
4	55	44
5	54	38
6	52	34
7	50	31
8	48	29
9	46	27
10	44	26
11	42	25
12	41	24
13	40	23
14	39	22
15	38	22
16	37	21
18	35	20
20	34	...
22	33	...
24	32	...
26	31	...
28	31	...
30	30	...
32	30	...



1335, 1335H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure



1335: ITT Curve. Composition: Fe, 0.35 C, 1.85 Mn. Grain size: 70% No. 7, 30% No. 2. Austenitized at 843 °C (1550 °F)



1340, 1340H

Chemical Composition. **1340. AISI and UNS:** 0.38 to 0.43 C, 1.60 to 1.90 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si. **UNS H13400 and SAE/AISI 1340H:** 0.37 to 0.44 C, 1.45 to 2.05 Mn, 0.15 to 0.35 Si

Similar Steels (U.S. and/or Foreign). **1340.** UNS G13400; ASTM A322, A331, A519, A547; MIL SPEC MIL-S-16974; SAE J404, J412, J770. **1340H.** UNS H13400; ASTM A304; SAE J407; (Ger.) DIN 1.5069

Characteristics. Comparable to those outlined for 1330H and 1335H. As carbon content is increased, a higher as-quenched hardness can be expected (about 54 HRC for 1340H, depending on precise carbon content). The hardenability pattern is also quite similar to those shown for grades 1330H and 1335H. As is true for all of the 1300 grades, hardenability band is relatively wide, caused primarily by the broad range in manganese content

Forging. Heat to 1230 °C (2245 °F). Do not forge after temperature drops below 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

Annealing. For a predominately pearlitic structure, heat to 830 °C (1525 °F), and cool from 730 °C (1350 °F) to 610 °C (1130 °F) at a rate not to exceed 11 °C (20 °F) per h; or cool rapidly from 730 °C (1350 °F) to 620 °C (1150 °F), and hold for 4.5 h. For a predominately ferritic and spheroidized structure, heat to 750 °C (1380 °F), and cool from 730 °C (1350 °F) to 610 °C (1130 °F) at a rate not to exceed 6 °C (10 °F) per h; or cool fairly rapidly from 750 °C (1380 °F) to 640 °C (1185 °F), and hold for 8 h

Hardening. Austenitize at 830 °C (1525 °F), and quench in oil. Use water or brine for heavy sections. Electron beam, carbonitriding, and austempering are suitable processes

Tempering. Temper immediately after quenching to desired hardness

Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

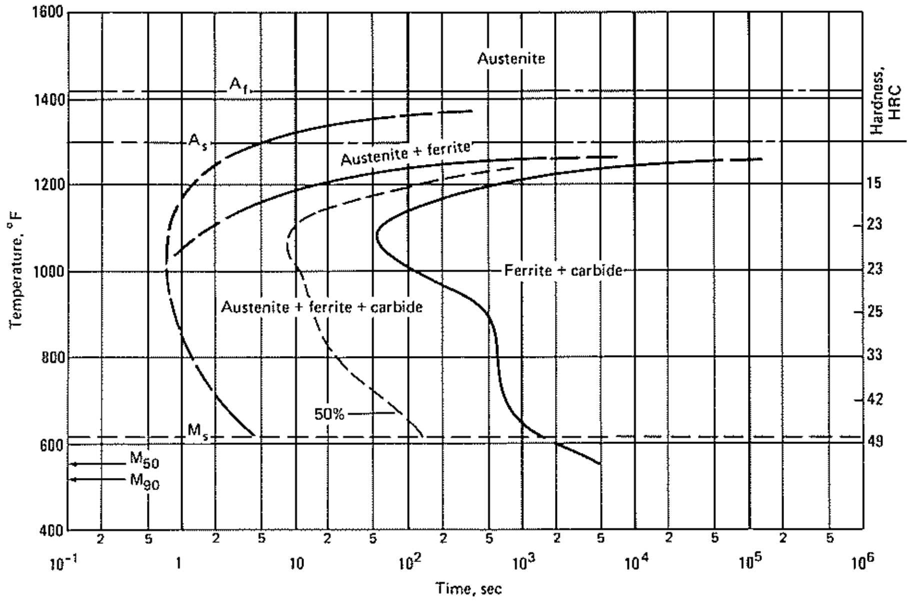
1340: As-Quenched Hardness

Specimens quenched in oil from 830 °C (1525 °F)

Size round		Hardness, HRC		
in.	mm	Surface	½ radius	Center
½	13	58	57	57
1	25	57	56	50
2	51	39	34	32
4	102	32	30	26

Source: Bethlehem Steel

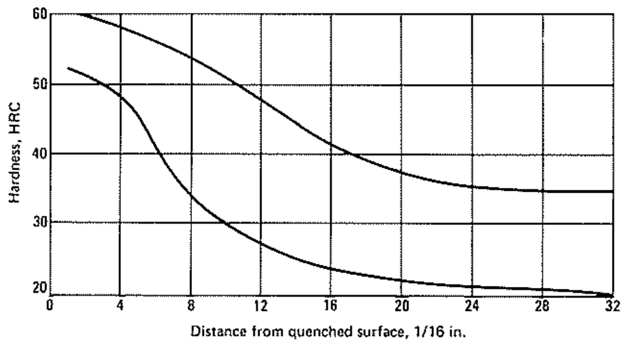
1340: Isothermal Transformation Diagram. Composition: 0.43 C, 1.58 Mn. Austenitized at 885 °C (1625 °F). Grain size: 8 to 9



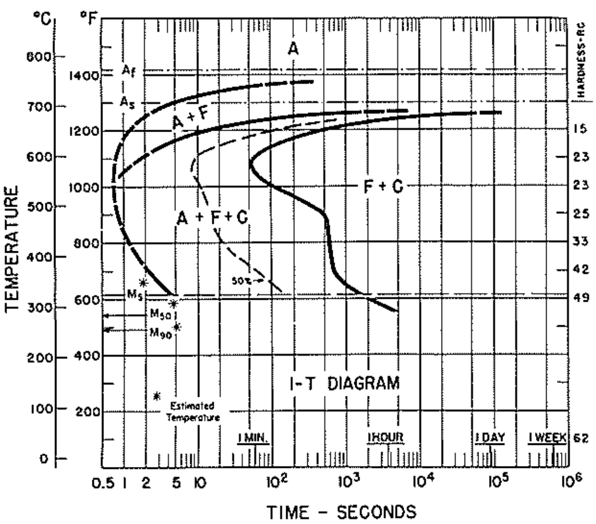
1340H: End-Quench Hardenability

Distance from quenched surface		Hardness, HRC		Distance from quenched surface		Hardness, HRC	
1/16 in.	mm	max	min	1/16 in.	mm	max	min
1	1.58	60	53	13	20.54	46	26
2	3.16	60	52	14	22.12	44	25
3	4.74	59	51	15	23.70	42	25
4	6.32	58	49	16	25.28	41	24
5	7.90	57	46	18	28.44	39	23
6	9.48	56	40	20	31.60	38	23
7	11.06	55	35	22	34.76	37	22
8	12.64	54	33	24	37.92	36	22
9	14.22	52	31	26	41.08	35	21
10	15.80	51	29	28	44.24	35	21
11	17.38	50	28	30	47.40	34	20
12	18.96	48	27	32	50.56	34	20

Source: *Metals Handbook*, 9th ed., Vol 1, American Society for Metals, 1978



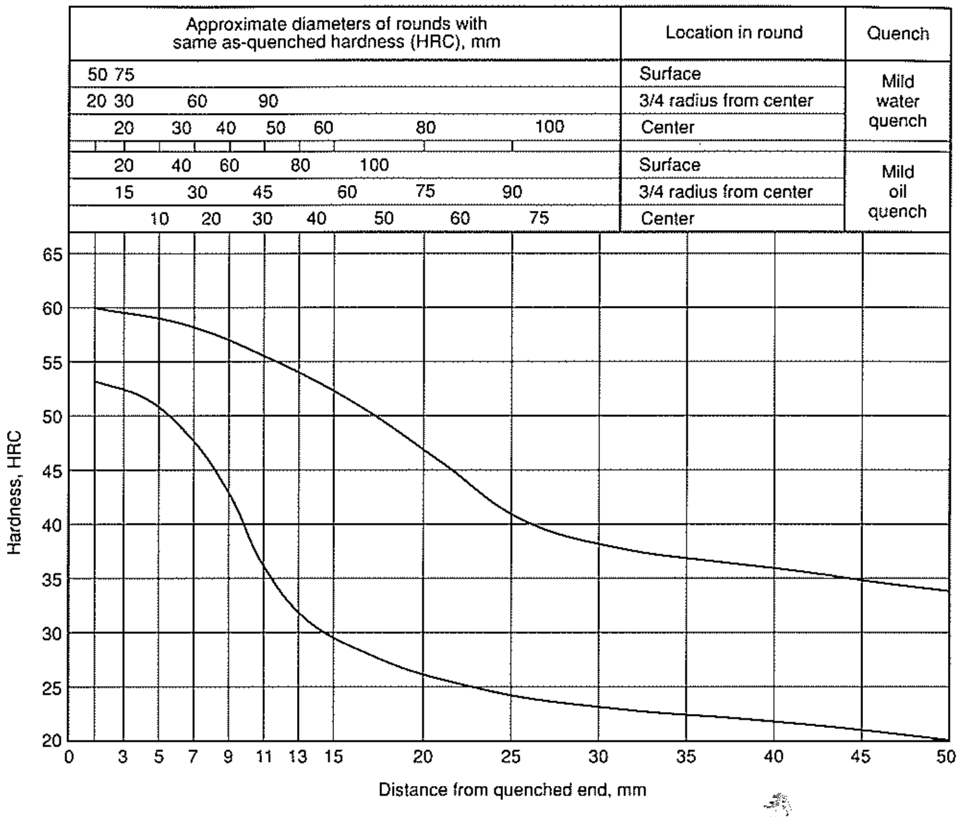
1340: ITT Diagram. Composition: Fe, 0.43 C, 1.58 Mn. Grain size: 8-9. Austenitized at 885 °C (1625 °F)



1340H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

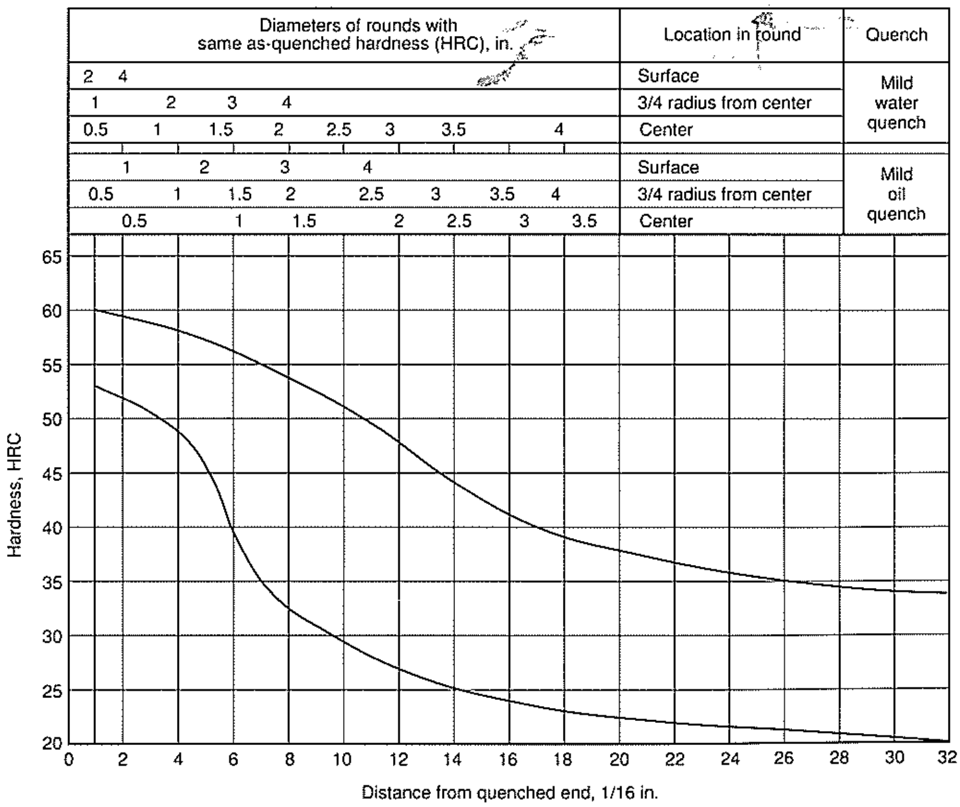
Hardness Limits for Specification Purposes

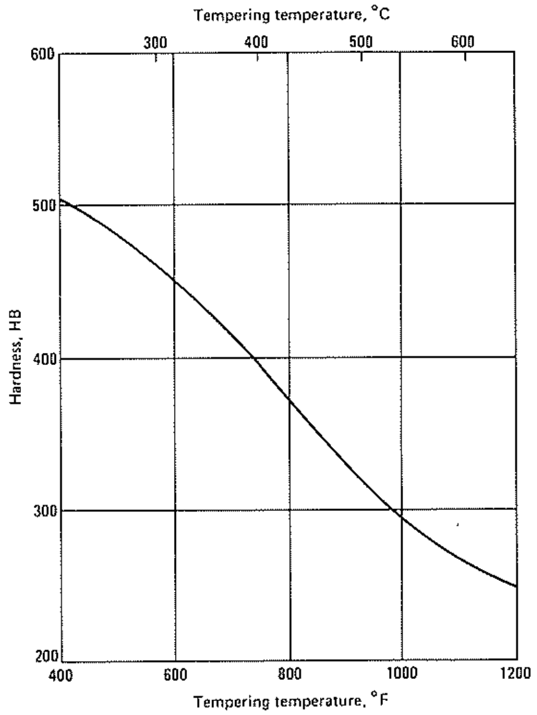
J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	60	53
3	60	52
5	59	50
7	58	48
9	57	42
11	56	36
13	54	32
15	52	30
20	47	26
25	41	24
30	39	23
35	37	22
40	36	21
45	35	20
50	34	20



Hardness Limits for Specification Purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	60	53
2	60	52
3	59	51
4	58	49
5	57	46
6	56	40
7	55	35
8	54	33
9	52	31
10	51	29
11	50	28
12	48	27
13	46	26
14	44	25
15	42	25
16	41	24
18	39	23
20	38	23
22	37	22
24	36	22
26	36	21
28	35	21
30	34	20
32	34	20





1340: Hardness vs Tempering Temperature. Normalized at 870 °C (1600 °F). Quenched from 845 °C (1555 °F) in oil and tempered at 56 °C (100 °F) intervals in 13.716 mm (0.540 in.) rounds. Tested in 12.827 mm (0.505 in.) rounds. (Source: Republic Steel)

1345,1345H

Chemical Composition. **1345. AISI and UNS:** 0.43 to 0.48 C, 1.60 to 1.90 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si. **UNS H13450 and SAE/AISI 1345H:** 0.42 to 0.49 C, 1.45 to 2.05 Mn, 0.15 to 0.35 Si

Similar Steels (U.S. and/or Foreign). **1345.** UNS G13450; ASTM A322, A331, A519; SAE J404, J412, J770; (Ger.) DIN 1.0912; (U.K.) B.S. 2 S 516, 2 S 517. **1345H.** UNS H13450; ASTM A304; SAE J407; (Ger.) DIN 1.0912; (U.K.) B.S. 2 S 516, 2 S 517

Characteristics. The general characteristics of 1345H closely parallel those given for other medium-carbon 1300 series steels (see details for 1330H). There are exceptions. As-quenched hardness is higher. Fully hardened 1345H should provide a minimum hardness of approximately 56 HRC, slightly higher if the carbon content is at the high end of the allowable range. Weldability is further decreased. Susceptibility to quench cracking is intensified as the carbon content is increased. The hardenability pattern for 1345H is very similar to that of 1340H, but adjusted upward because of the higher carbon content of 1345H

Forging. Heat to 1230 °C (2245 °F). Do not forge after temperature drops below 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

Annealing. For a predominately pearlitic structure, heat to 830 °C (1525 °F), and cool from 730 °C (1350 °F) to 610 °C (1130 °F) at a rate not to exceed 11 °C (20 °F) per h; or cool rapidly from 730 °C (1350 °F) to 620 °C (1150 °F), and hold for 4.5 h. For a predominately ferritic and spheroidized structure, heat to 750 °C (1380 °F), and cool from 730 °C (1350 °F) to 610 °C (1130 °F) at a rate not to exceed 6 °C (10 °F) per h; or cool fairly rapidly from 750 °C (1380 °F) to 640 °C (1185 °F), and hold for 8 h

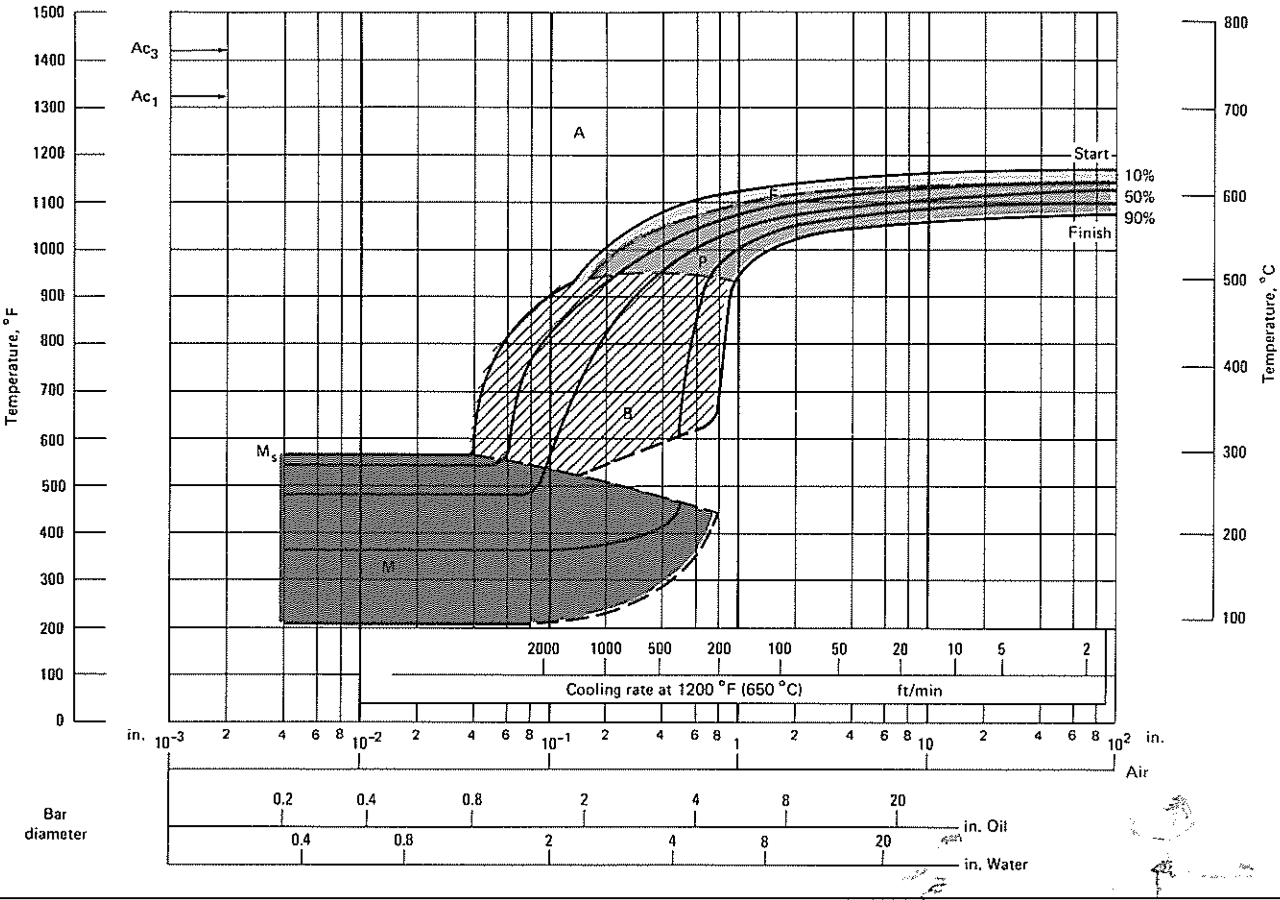
Hardening. Austenitize at 830 °C (1525 °F), and quench in oil. Use water or brine for heavy sections. Flame hardening and carbonitriding are suitable processes

Tempering. Temper immediately after quenching to desired hardness

Recommended Processing Sequence

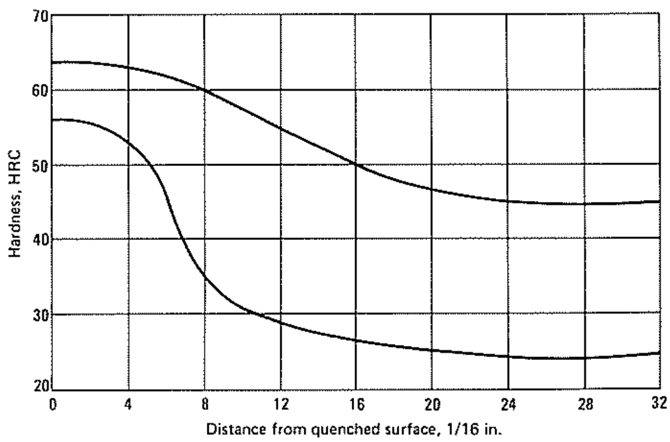
- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

1345: Continuous Cooling Transformation Diagram. Composition: 0.46 C, 1.80 Mn, 0.020 P, 0.015 S, 0.25 Si. Austenitized at 850 °C (1560 °F)



1345H: End-Quench Hardenability

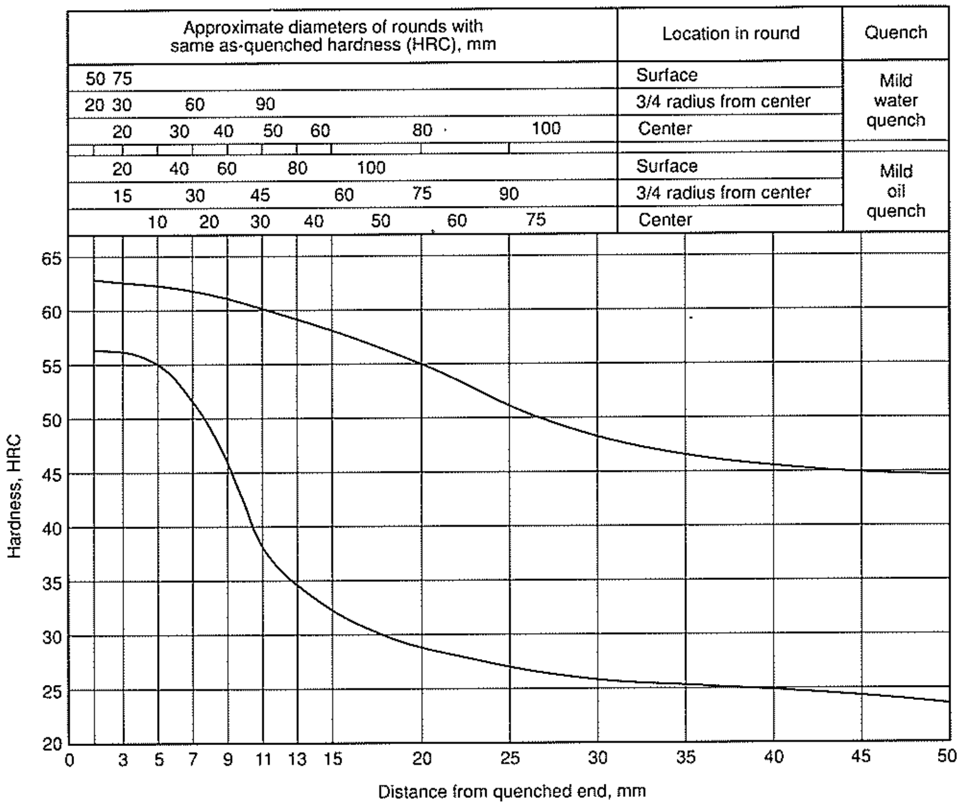
Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min
1	1.58	63	56	13	20.54	54	29
2	3.16	63	56	14	22.12	53	29
3	4.74	62	55	15	23.70	52	28
4	6.32	61	54	16	25.28	51	28
5	7.90	61	51	18	28.44	49	27
6	9.48	60	44	20	31.60	47	27
7	11.06	60	38	22	34.76	45	26
8	12.64	59	35	24	37.92	44	26
9	14.22	58	33	26	41.08	47	25
10	15.80	57	32	28	44.24	46	25
11	17.38	56	31	30	47.40	45	24
12	18.96	55	30	32	50.56	45	24



1345H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

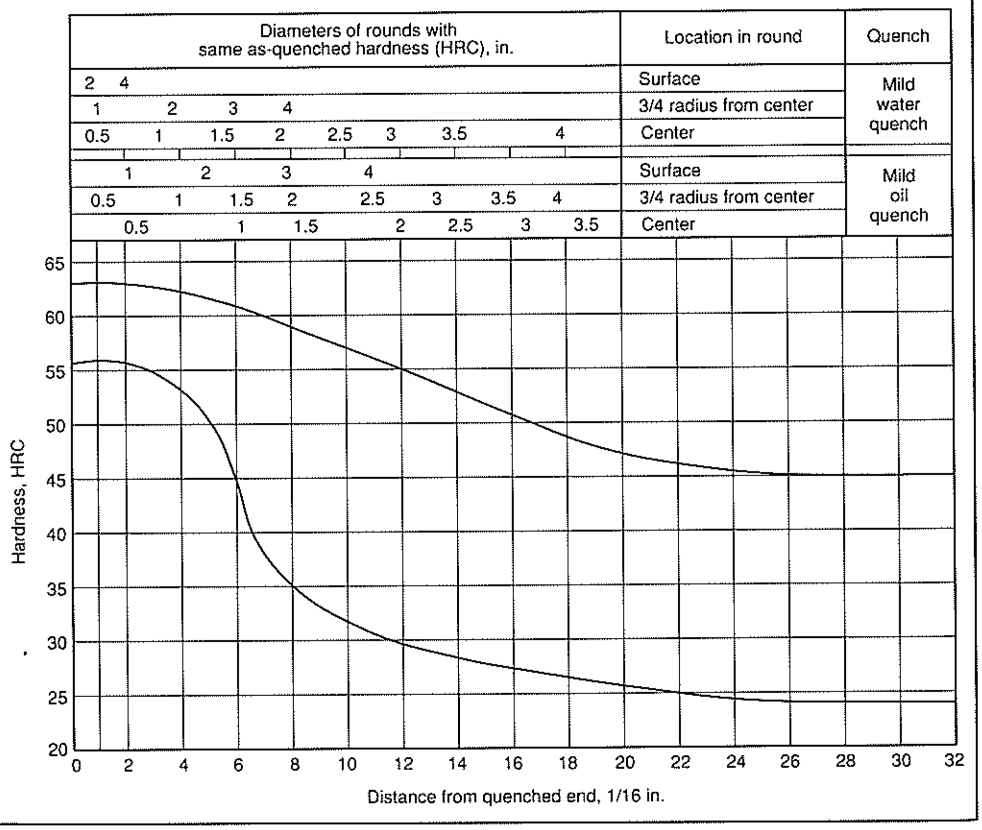
Hardness Limits for Specification Purposes

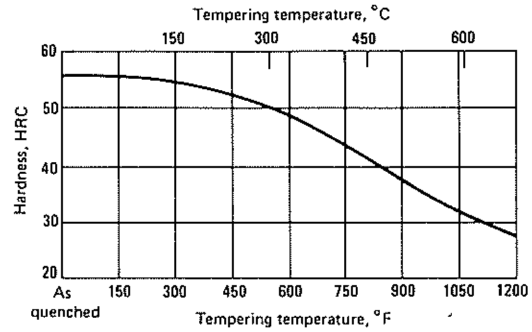
J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	63	56
3	63	56
5	63	54
7	62	52
9	61	46
11	60	38
13	59	35
15	58	31
20	55	29
25	51	27
30	48	26
35	47	25
40	46	24
45	45	24
50	45	24



Hardness Limits for Specification Purposes

J distance, $\frac{1}{16}$ in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	63	56
2	63	56
3	62	55
4	61	54
5	61	51
6	60	44
7	60	38
8	59	35
9	58	33
10	57	32
11	56	31
12	55	30
13	54	29
14	53	29
15	52	28
16	51	28
18	49	27
20	48	27
22	47	26
24	46	26
26	45	25
28	45	25
30	45	24
32	45	24





1345, 1345H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

3310RH

Chemical Composition. 1330RH. AISI and UNS: 0.08 to 0.13 C, 0.40 to 0.60 Mn, 0.15 to 0.35 Si, 3.25 to 3.75 Ni, 1.40 to 1.75 Cr

Similar Steels (U.S. and/or Foreign). SAE 3310RH. Has been added to SAE J1868 and ASTM A914. There is no existing standard H-grade

Characteristics. Applications include carburized bearing and gears

Recommended Heat Treating Practice

Hardening. Suitable processes include gas carburizing, liquid nitriding, gas nitriding, carbonitriding, and flame hardening

3310RH: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 845 °C (1555 °F)

Hardness Limits for Specification Purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	42	37
2	42	37
3	42	37
4	41	36
5	41	36
6	41	35
7	40	34
8	40	33
9	39	32
10	39	32
11	39	31
12	39	31
13	38	30
14	38	30
15	37	29
16	37	29
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24	35	27
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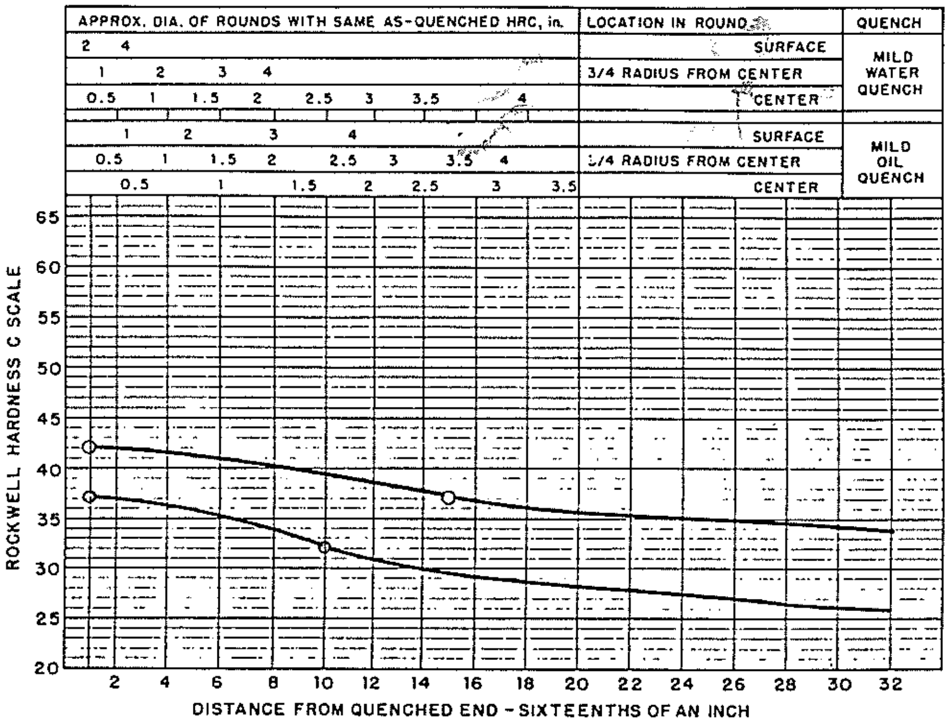
28	34	26
30	34	26
32	34	26

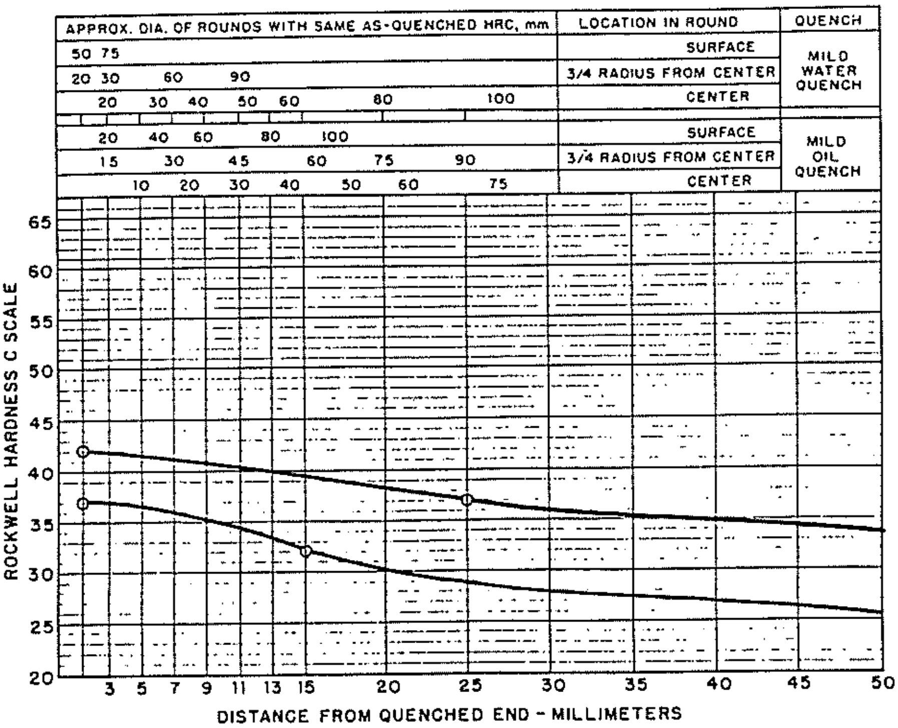


(continued)

3310RH: Hardenability Curves (continued) Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 845 °C (1555 °F)

Hardness Limits for Specification Purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	42	37
3	42	37
5	42	37
7	41	36
9	41	35
11	40	34
13	40	33
15	39	32
20	38	30
25	37	29
30	36	28
35	35	27
40	35	27
45	34	26
50	34	26



4023

Chemical Composition. AISI and UNS: 0.20 to 0.25 C, 0.70 to 0.90 Mn, 0.15 to 0.30 Si, 0.035 P max, 0.040 S max, 0.20 to 0.30 Mo

Similar Steels (U.S. and/or Foreign). UNS G40230; ASTM A322, A331, A519, A534; SAE J404, J412, J770

Characteristics. One of the two straight molybdenum steels, used almost exclusively for making parts that will be case hardened by carburizing or carbonitriding. When fully quenched, surface hardness is in the range of 40 to 45 HRC. While its hardenability is higher than that of a plain carbon steel of like carbon content, 4023 is not considered a high-hardenability grade. This steel does not have an H counterpart. Grade 4023 is readily forgeable and weldable. Before welding, the carbon equivalent should be checked to determine the need for preheating and postheating

Forging. Heat to 1245 °C (2275 °F) maximum. Do not forge after the temperature of the forging stock drops below approximately 900 °C (1650 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Cool in air

Annealing. Annealing is not usually required for this grade. Structures that are well suited to machining are generally obtained by normalizing or by isothermal annealing after rolling or forging. Isothermal annealing may be accomplished by heating to 700 °C (1290 °F) and holding for 8 h

Case Hardening. See recommended carburizing, carbonitriding, and tempering procedures described for 4118H

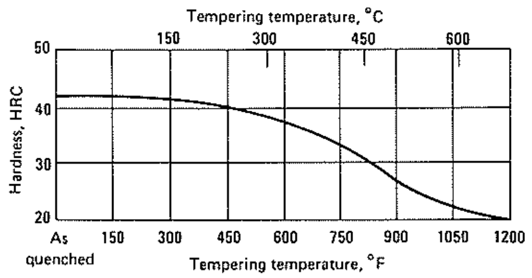
Recommended Processing Sequence

- Forge
- Normalize
- Anneal (optional)
- Rough and semifinish machine
- Austenitize
- Case harden
- Temper
- Finish machine (carburized parts only)

4023: Approximate Core Hardness of Heat Treated Specimens

Reheat temperature °F	Reheat temperature °C	Hardness, HB 1-in. (25.4-mm) rounds	Hardness, HB 0.540-in. (13.7-mm) rounds
1425	775	223	285
1425	775	229	293
1575	855	248	321
1700(a)	925	255	331

(a) Pseudocarburized for 8 h and quenched. Source: Republic Steel



4023: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

4023: Approximate Critical Points

Transformation point	Temperature °F	Temperature °C
Ac_1	1350	750
Ac_3	1540	840
Ar_3	1440	780
Ar_1	1250	670

Source: Republic Steel

4024

Chemical Composition. **AISI and UNS:** 0.20 to 0.25 C, 0.70 to 0.90 Mn, 0.15 to 0.30 Si, 0.035 P max, 0.035 to 0.050 S, 0.20 to 0.30 Mo

Similar Steels (U.S. and/or Foreign). UNS G40240; ASTM A322, A331, A519; SAE J404, J412, J770

Characteristics. One of the two straight molybdenum steels, used almost exclusively for making parts that will be case hardened by carburizing or carbonitriding. When fully quenched, surface hardness is in the range of 40 to 45 HRC. While its hardenability is higher than that of a plain carbon steel of like carbon content, 4024 is not considered a high-hardenability grade. This steel does not have an H counterpart. Grade 4024 is readily forgeable and weldable. Before welding, the carbon equivalent should be checked to determine the need for preheating and postheating. With the exception of a slightly higher allowable sulfur content, grades 4023 and 4024 are identical. This difference in sulfur content provides a slight improvement in machinability, but is not sufficient to significantly impair forgeability or weldability

Forging. Heat to 1245 °C (2275 °F) maximum. Do not forge after temperature of the forging stock drops below approximately 900 °C (1650 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Cool in air

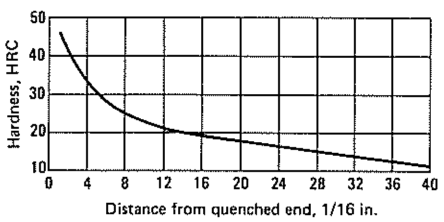
Annealing. Annealing is not usually required for this grade. Structures that are well suited to machining are generally obtained by normalizing or by isothermal annealing after rolling or forging. Isothermal annealing may be accomplished by heating to 700 °C (1290 °F) and holding for 8 h

Case Hardening. See recommended carburizing, carbonitriding, and tempering procedures described for 4118H. Martempering is also a suitable process

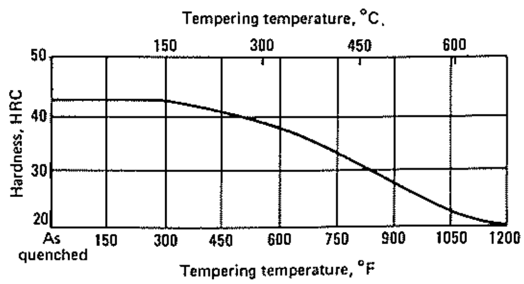
Recommended Processing Sequence

- Forge
- Normalize
- Rough and semifinish machine
- Case harden
- Temper
- Finish machine (carburized parts only)

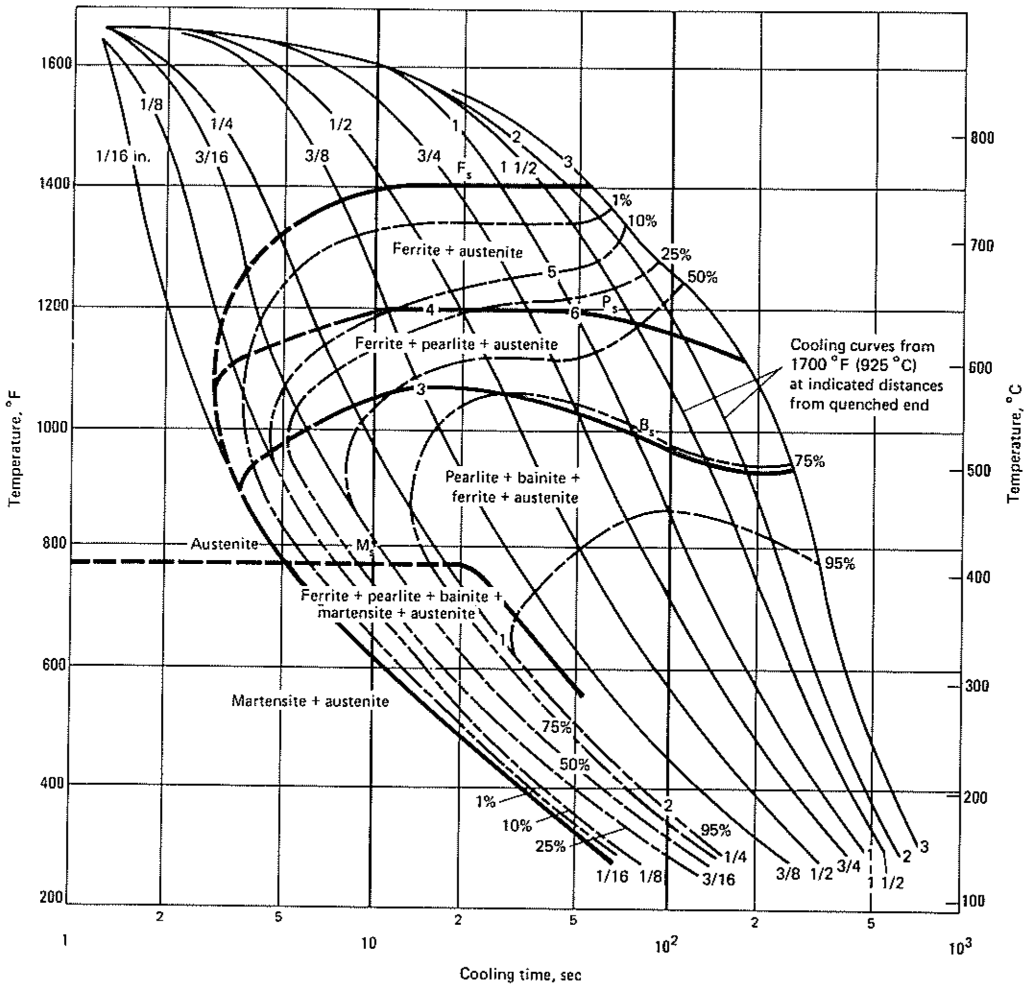
4024: End-Quench Hardenability. Composition: 0.24 C, 0.88 Mn, 0.33 Si, 0.23 Mo. Quenched from 925 °C (1695 °F)



4024: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure



4024: Cooling Transformation Diagram. Composition: 0.24 C, 0.88 Mn, 0.33 Si, 0.23 Mo. Austenitized at 925 °C (1695 °F). Grain size: 8. Ac_3, 825 °C (1520 °F); Ac_1, 750 °C (1380 °F). A: austenite, F: ferrite, P: pearlite, B: bainite, M: martensite



4027, 4027H, 4027RH

Chemical Composition. **4027. AISI and UNS:** 0.25 to 0.30 C, 0.70 to 0.90 Mn, 0.15 to 0.30 Si, 0.035 P max, 0.040 S max, 0.20 to 0.30 Mo. **UNS H40270 and SAE/AISI 4027H:** 0.24 to 0.30 C, 0.60 to 1.00 Mn, 0.15 to 0.35 Si, 0.20 to 0.30 Mo. **SAE 4027RH:** 0.25 to 0.30 C, 0.70 to 0.90 Mn, 0.15 to 0.35 Si, 0.20 to 0.30 Mo

Similar Steels (U.S. and/or Foreign). **4027.** UNS G40270; ASTM A322, A331, A519; SAE J404, J412, J770. **4027H.** UNS H40270; ASTM A304, A914; SAE J1268, J1868

Characteristics. Often considered borderline between a carburizing grade and a direct-hardening grade. Commonly used for either case-hardening or direct-hardening applications. The hardenability of 4027H is somewhat higher than a carbon steel of equivalent carbon content, although not as high as a 1300 grade having the same carbon content. As-quenched hardness (no carburizing) is generally 45 to 48 HRC. Has excellent forgeability, but only fair machinability. Can be welded using alloy steel practice. Preheating and postheating are required because of the relatively high carbon equivalent

Forging. Heat to 1245 °C (2275 °F). Do not forge after temperature of forging stock drops below approximately 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F). Cool in air

Annealing. For a predominately pearlitic structure, heat to 855 °C (1570 °F), and cool rapidly to 750 °C (1380 °F), then to 640 °C (1185 °F) at a rate not to exceed 11 °C (20 °F) per h; or heat to 870 °C (1600 °F), cool rapidly to 660 °C (1220 °F), and hold for 5 h. For a predominately spheroidized structure, heat to 775 °C (1425 °F), cool from 745 °C (1370 °F) to 640 °C (1185 °F) at a rate not to exceed 6 °C (10 °F) per h; or heat to 775 °C (1425 °F), cool rapidly to 660 °C (1220 °F) and hold for 8 h

Direct Hardening. Heat to 855 °C (1570 °F), and quench in oil. As-quenched hardness, 42 to 48 HRC. Gas carburizing is a suitable process

Tempering. Reheat to obtain desired hardness

Case Hardening. See recommended carburizing, carbonitriding, and tempering procedures described for 4118H

Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize or case harden
- Quench
- Temper
- Finish machine

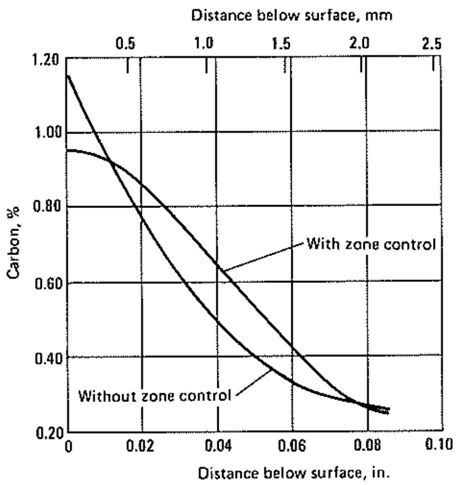
4027: As-Quenched Hardness

Specimens quenched in water

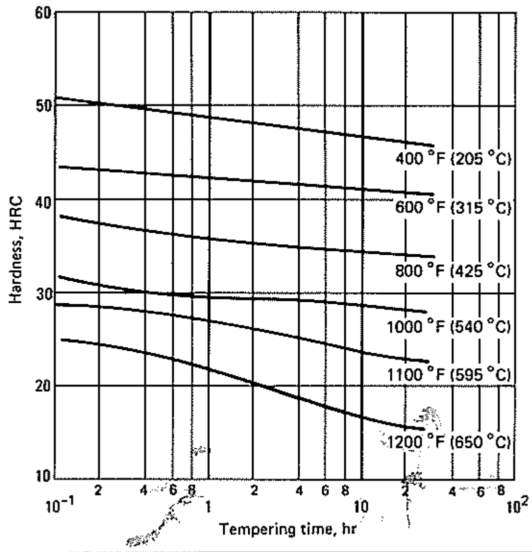
Size round		Hardness, HRC		
in.	mm	Surface	½ radius	Center
0.565	14.351	50 HRC	50 HRC	50 HRC
1.000	25.400	50 HRC	47 HRC	44 HRC
2.000	50.800	47 HRC	27 HRC	27 HRC
4.000	101.600	83 HRB	77 HRB	75 HRB

Source: Bethlehem Steel

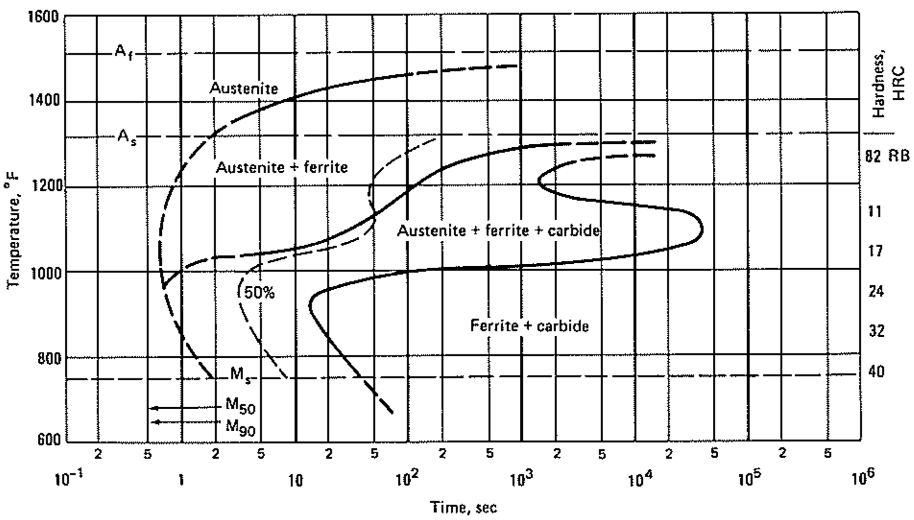
4027: Gas Carburizing. Carburized at 925 °C (1695 °F) and finished at 845 °C (1555 °F)



4027: Hardness vs Tempering Temperature. Tempered at indicated temperatures showing effect of time at temperature



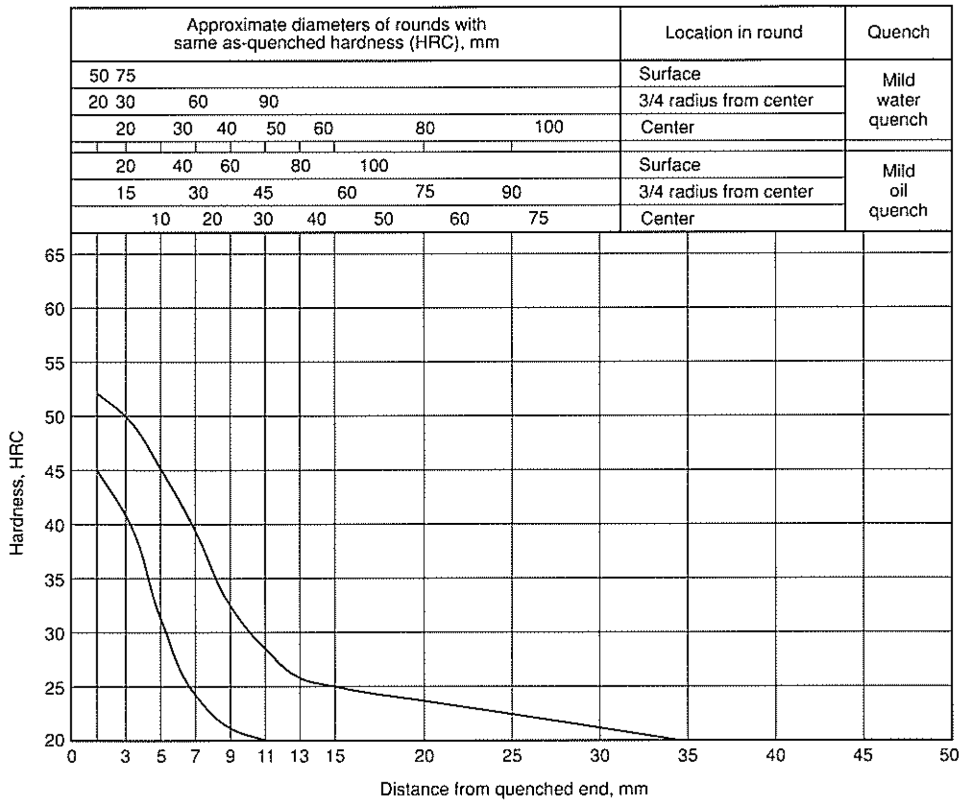
4027: Isothermal Transformation Diagram. Composition: 0.26 C, 0.87 Mn, 0.26 Mo. Austenitized at 855 °C (1570 °F). Grain size: 7



4027H, 4028H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 900 °C (1650 °F). Austenitize: 870 °C (1600 °F)

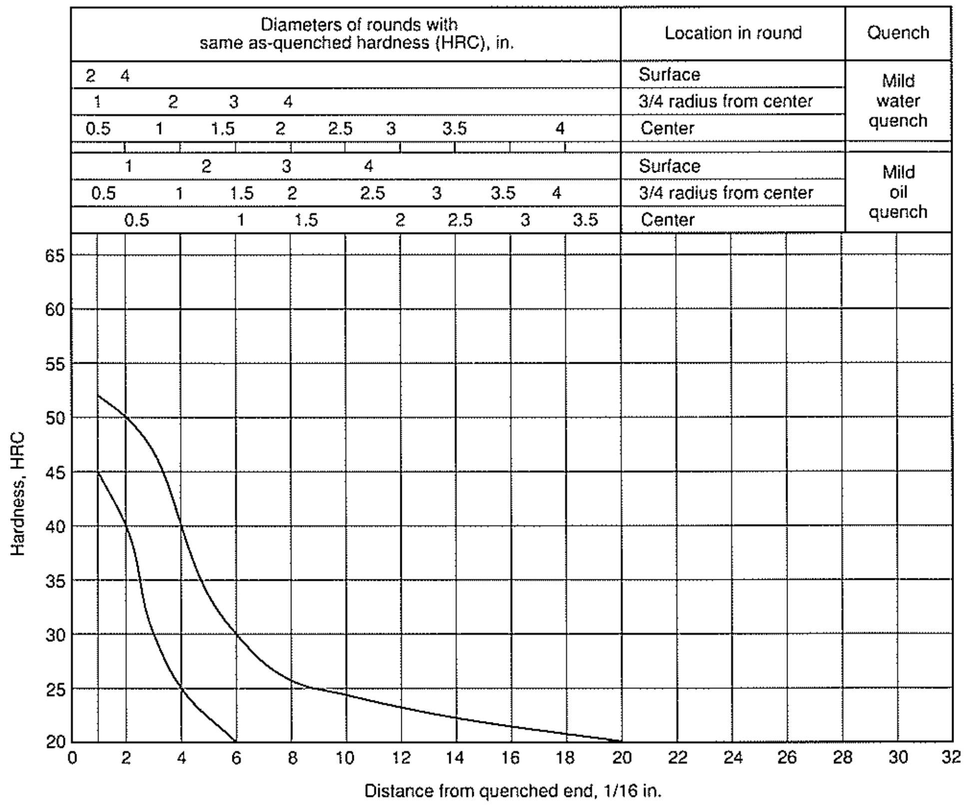
Hardness Limits for Specification Purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	52	45
3	51	41
5	45	32
7	40	23
9	32	20
11	29	...
13	26	...
15	25	...
20	23	...
25	22	...
30	21	...
35	...	...



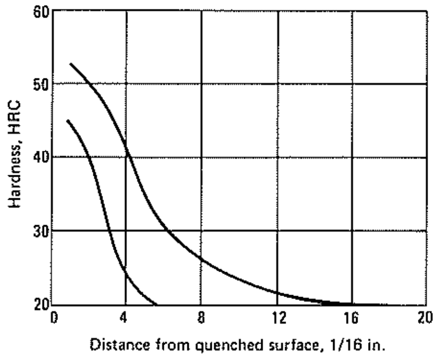
Hardness Limits for Specification Purposes

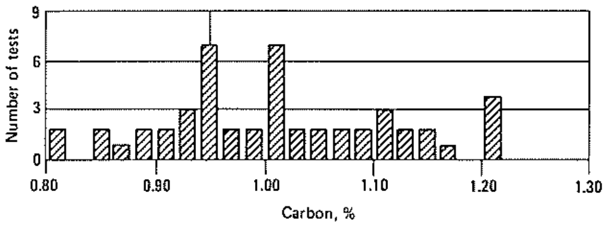
J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	52	45
2	50	40
3	46	31
4	40	25
5	34	22
6	30	20
7	28	...
8	26	...
9	25	...
10	25	...
11	24	...
12	23	...
13	23	...
14	22	...
15	22	...
16	21	...
18	21	...
20	20	...
22	...	...



4027H: End-Quench Hardenability

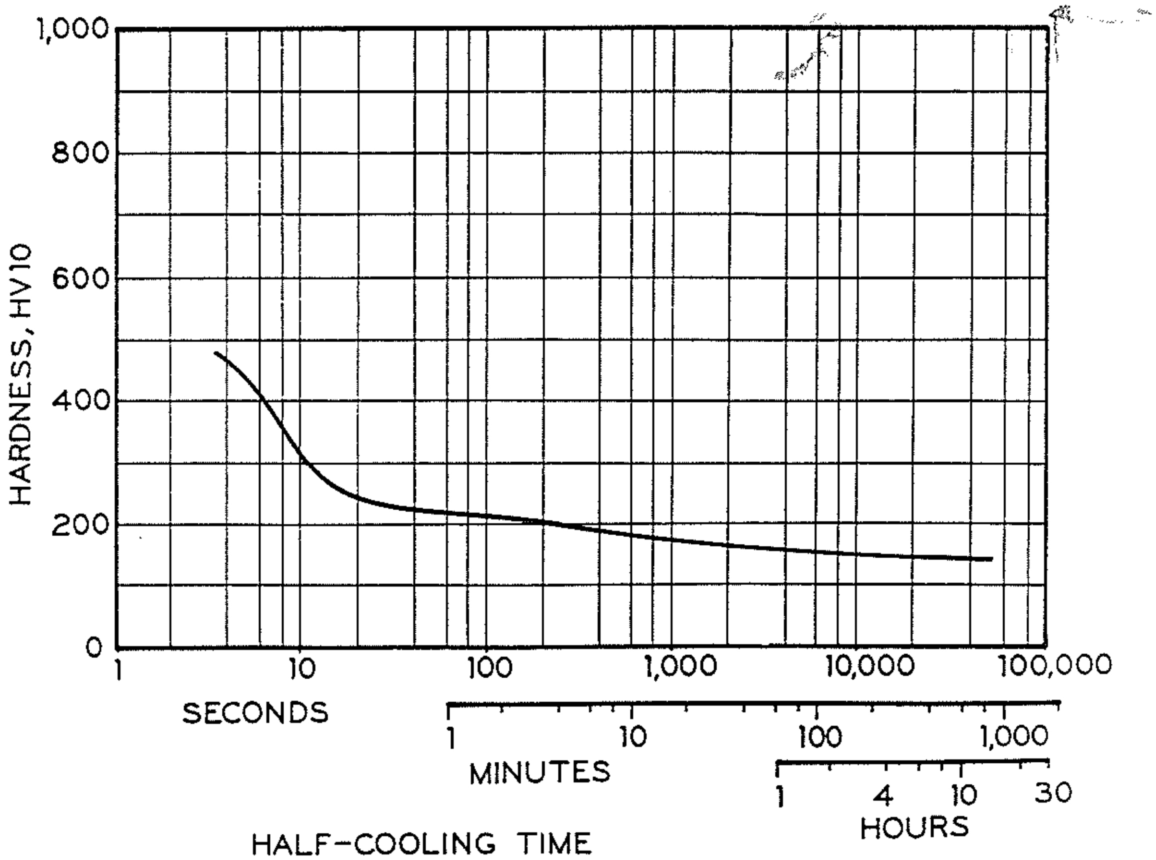
Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max
1	1.58	52	45	13	20.54	23
2	3.16	50	40	14	22.12	22
3	4.74	46	31	15	23.70	22
4	6.32	40	25	16	25.28	21
5	7.90	34	22	18	28.44	21
6	9.48	30	20	20	31.60	20
7	11.06	28	...	22	34.76	...
8	12.64	26	...	24	37.92	...
9	14.22	25	...	26	41.08	...
10	15.80	25	...	28	44.24	...
11	17.38	24	...	30	47.40	...
12	18.96	23	...	32	50.56	...





4027: Gas Carburizing. Results of 50 tests that represent variation in carbon concentration for continuous carburizing. Results were obtained over a 3 to 4 year period of operation using an automatic dew point controller

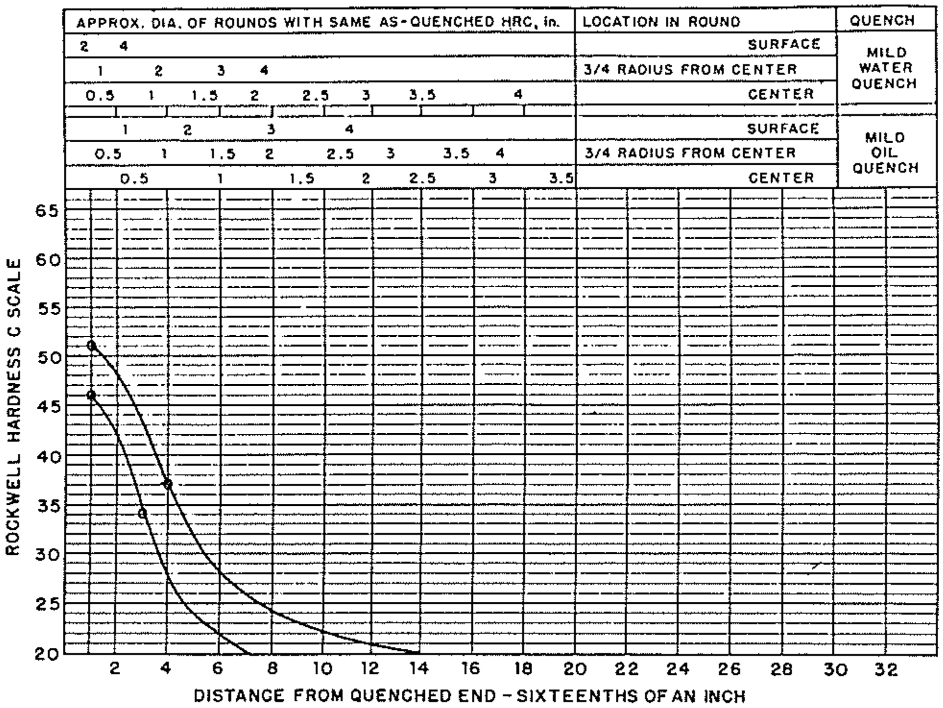
4027: Cooling Curve. Half cooling time. Source: Datasheet I-91, Climax Molybdenum Company



4027RH: Hardenability Curves. Heat-treating recommedned by SAE. Normalized (for forged or rolled specimens only: 900 °C (1650 °F). Austenitize: 870 °C (1600 °F)

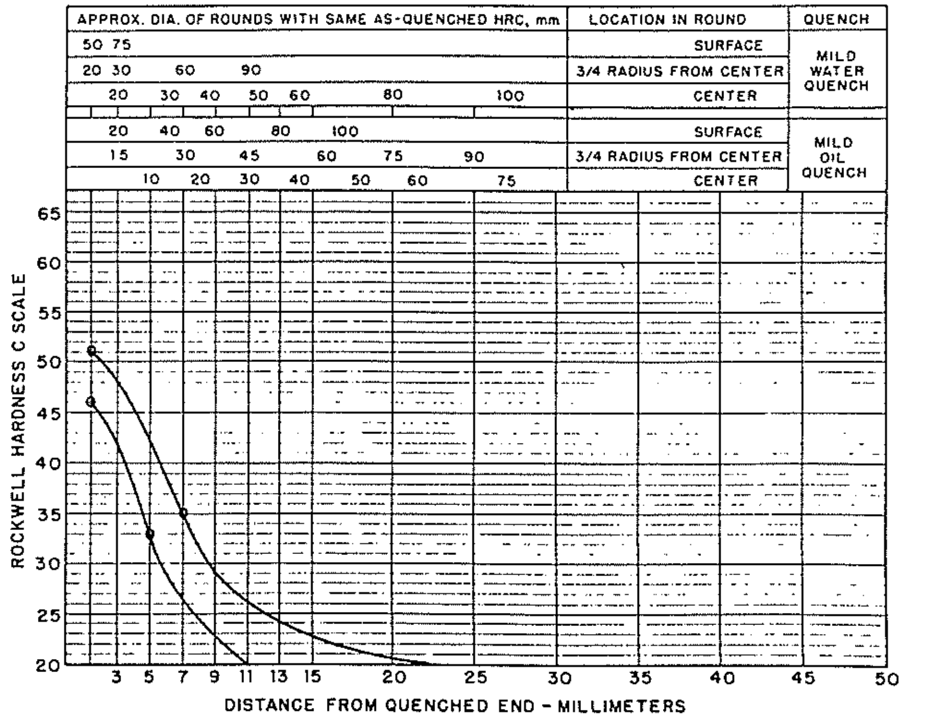
Hardness Limits for Specification Purposes

J distance, $\frac{1}{16}$ in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	51	46
2	48	42
3	43	34
4	37	28
5	32	24
6	28	22
7	26	20
8	24	...
9	23	...
10	22	...
11	22	...
12	21	...
13	21	...
14	20	...
15	...	...
16	...	...
18	...	...
20	...	...
22	...	...
24	...	...
26	...	...
28	...	...
30	...	...
32	...	...

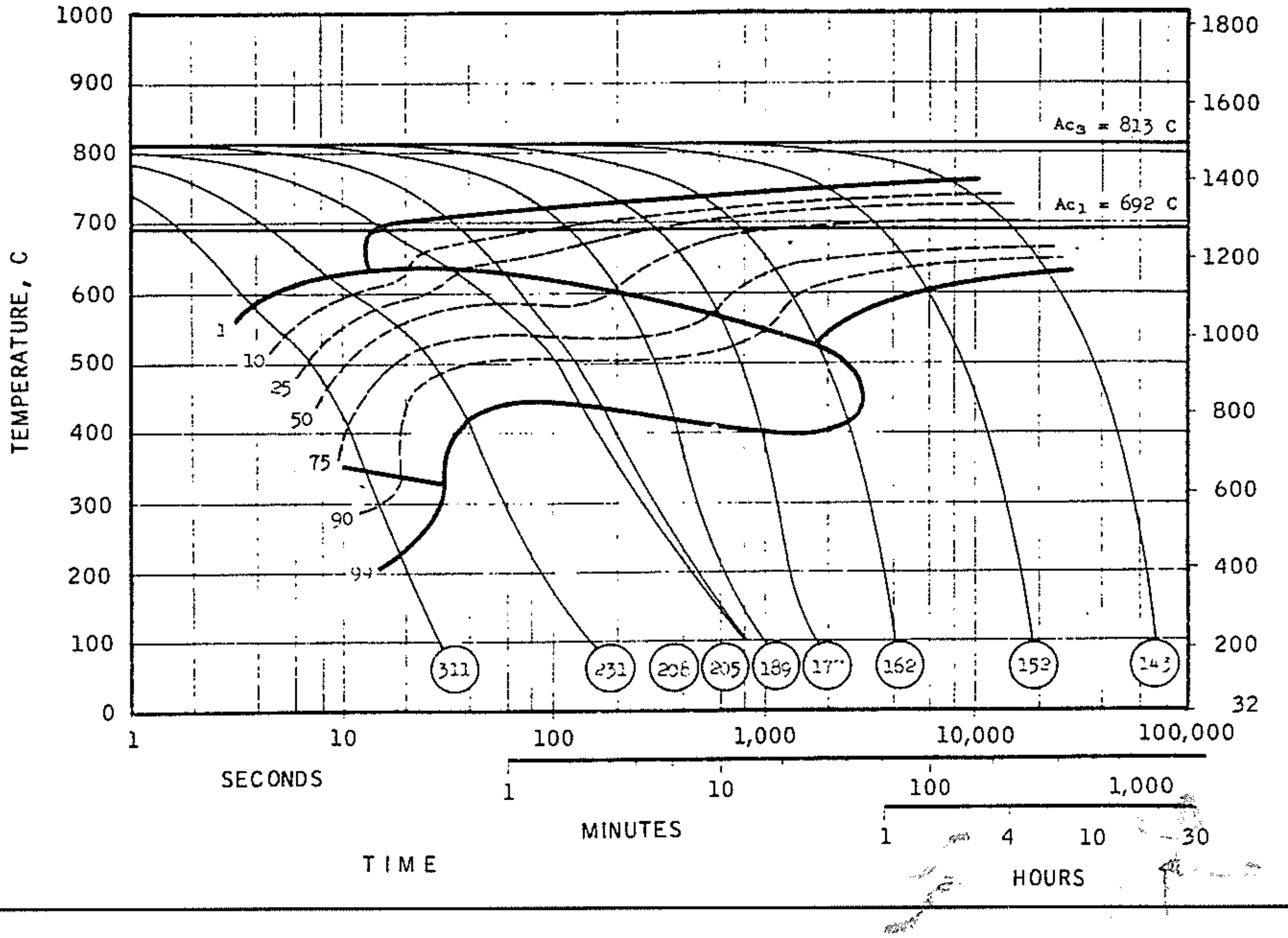


Hardness Limits for Specification Purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	51	46
3	48	42
5	42	33
7	35	26
9	29	23
11	26	20
13	24	...
15	23	...
20	21	...
25	...	...
30	...	...
35	...	...
40	...	...
45	...	...
50	...	...



4027: CCT Diagram. Constructional alloy steel. Chemical composition: 0.28 C, 0.25 Si, 0.86 Mn, 0.020 P, 0.028 S, 0.062 Cr, 0.026 Ni, 0.23 Mo, 0.11 Cu. A commercial heat; bar stock austenitized at 870 °C (1600 °F) 20 min



4028, 4028H

Chemical Composition. 4028. AISI and UNS: 0.25 to 0.30 C, 0.70 to 0.90 Mn, 0.15 to 0.30 Si, 0.035 P max, 0.035 to 0.050 S, 0.20 to 0.30 Mo. **UNS H40280 and SAE/AISI 4028H:** 0.24 to 0.30 C, 0.60 to 1.00 Mn, 0.035 to 0.050 S, 0.15 to 0.35 Si, 0.20 to 0.30 Mo

Similar Steels (U.S. and/or Foreign). 4028. UNS G40280; ASTM A322, A331, A519; SAE J404, J412, J770. **4028H.** UNS H40280; ASTM A304; SAE J407

Forging. Heat to 1245 °C (2275 °F). Do not forge after temperature of forging stock drops below approximately 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F). Cool in air

Annealing. For a predominately pearlitic structure, heat to 855 °C (1570 °F), cool rapidly to 750 °C (1380 °F), then to 870 °C (1600 °F) at a rate not to exceed 11 °C (20 °F) per h; or heat to 870 °C (1600 °F), cool rapidly to 660 °C (1220 °F), and hold for 5 h. For a predominately spheroidized structure, heat to 775 °C (1425 °F), cool from 745 °C (1370 °F) to 640 °C (1185 °F) at a rate not to exceed 6 °C (10 °F) per h; or heat to 775 °C (1425 °F), cool rapidly to 660 °C (1220 °F), and hold for 8 h

Direct Hardening. Heat to 855 °C (1570 °F) and quench in oil. As-quenched hardness, approximately 42 to 48 HRC. Martempering is a suitable process

Tempering. Reheat to obtain the desired hardness

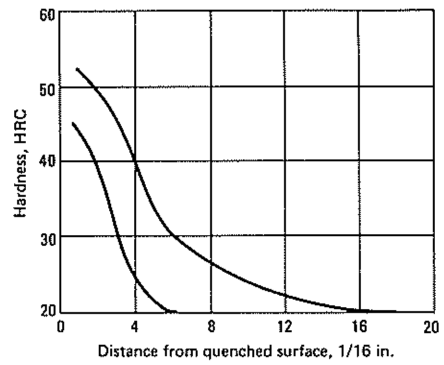
Case Hardening. See recommended carburizing, carbonitriding, and tempering procedures described for 4118H

Recommended Processing Sequence

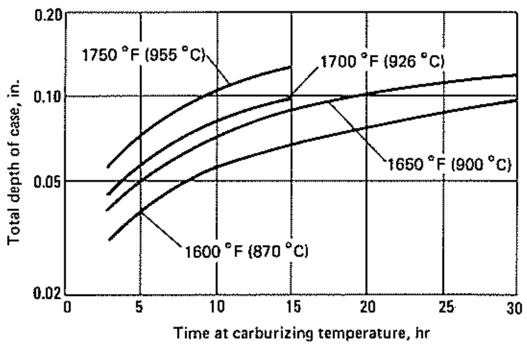
- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize or case harden
- Quench
- Temper
- Finish machine

4028H: End-Quench Hardenability

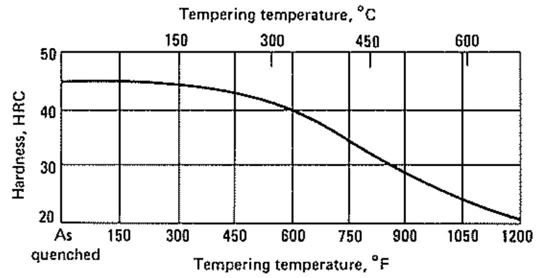
Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max
1	1.58	52	45	13	20.54	23
2	3.16	50	40	14	22.12	22
3	4.74	46	31	15	23.70	22
4	6.32	40	25	16	25.28	21
5	7.90	34	22	18	28.44	21
6	9.48	30	20	20	31.60	20
7	11.06	28	...	22	34.76	...
8	12.64	26	...	24	37.92	...
9	14.22	25	...	26	41.08	...
10	15.80	25	...	28	44.24	...
11	17.38	24	...	30	47.40	...
12	18.96	23	...	32	50.56	...



4028: Liquid Carburizing. $1\frac{11}{32}$ in. outside diameter by $6\frac{3}{4}$ in. Oil quenched. Carburized at the temperatures indicated



4028, 4028H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure



4032, 4032H

hemical Composition. **4032. AISI:** 0.30 to 0.35 C, 0.70 to 0.90 n, 0.20 to 0.35 Si, 0.035 P max, 0.040 S max, 0.20 to 0.30 Mo. **UNS:** 0.30 0.35 C, 0.70 to 0.90 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.20 0.30 Mo. **UNS H40320 and SAE/AISI 4032H: Nominal.** 0.29 to 0.35 , 0.60 to 1.00 Mn, 0.15 to 0.35 Si, 0.20 to 0.30 Mo

imilar Steels (U.S. and/or Foreign). **4032.** UNS G40320; STM A322; FED QQ-S-00629 (FS4032); SAE J404, J412, J770. **4032H.** NS H40320; ASTM A304; SAE J1268

haracteristics. With a carbon content that slightly overlaps 4027H ıd with an otherwise identical composition, the general characteristics of)32H and 4027H are the same. The hardenability pattern for 4032H sembles that of 4027H, although the curves for 4032H are moved slightly ›ward compared with those for 4027H because of a higher nominal ırbon content. Fully hardened 4032H will provide a surface hardness of ›proximately 48 HRC or slightly higher.

Grade 4032H is less weldable and has a slightly lower machinability an 4027H because of a higher nominal carbon content. Direct hardening ther than case hardening is used for 4032H, although for special applications carbonitriding has been applied to 4032H. Forgeability of this grade is excellent

Forging. Heat to 1245 °C (2275 °F). Do not forge after temperature of forging stock drops below approximately 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F). Cool in air

Annealing. For a predominately pearlitic structure, heat to 855 °C (1570 °F), cool rapidly to 750 °C (1380 °F), then to 640 °C (1185 °F) at a rate not to exceed 11 °C (20 °F) per h; or heat to 870 °C (1600 °F), cool rapidly to 660 °C (1220 °F), and hold for 5 h. For a predominately spheroidized structure, heat to 775 °C (1425 °F), cool from 745 °C (1370 °F) to 640 °C (1185 °F) at a rate not to exceed 6 °C (10 °F) per h; or heat to 775 °C (1425 °F), cool rapidly to 660 °C (1220 °F), and hold for 8 h

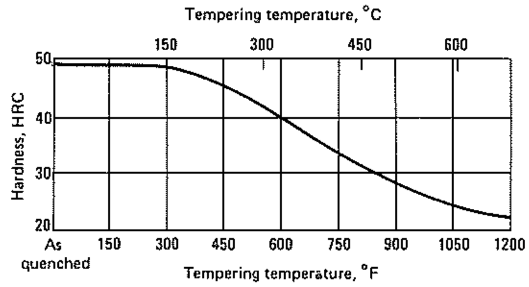
Hardening. Heat to 855 °C (1570 °F), and quench in oil. Carbonitriding is a suitable process

Tempering. Reheat to obtain the desired hardness

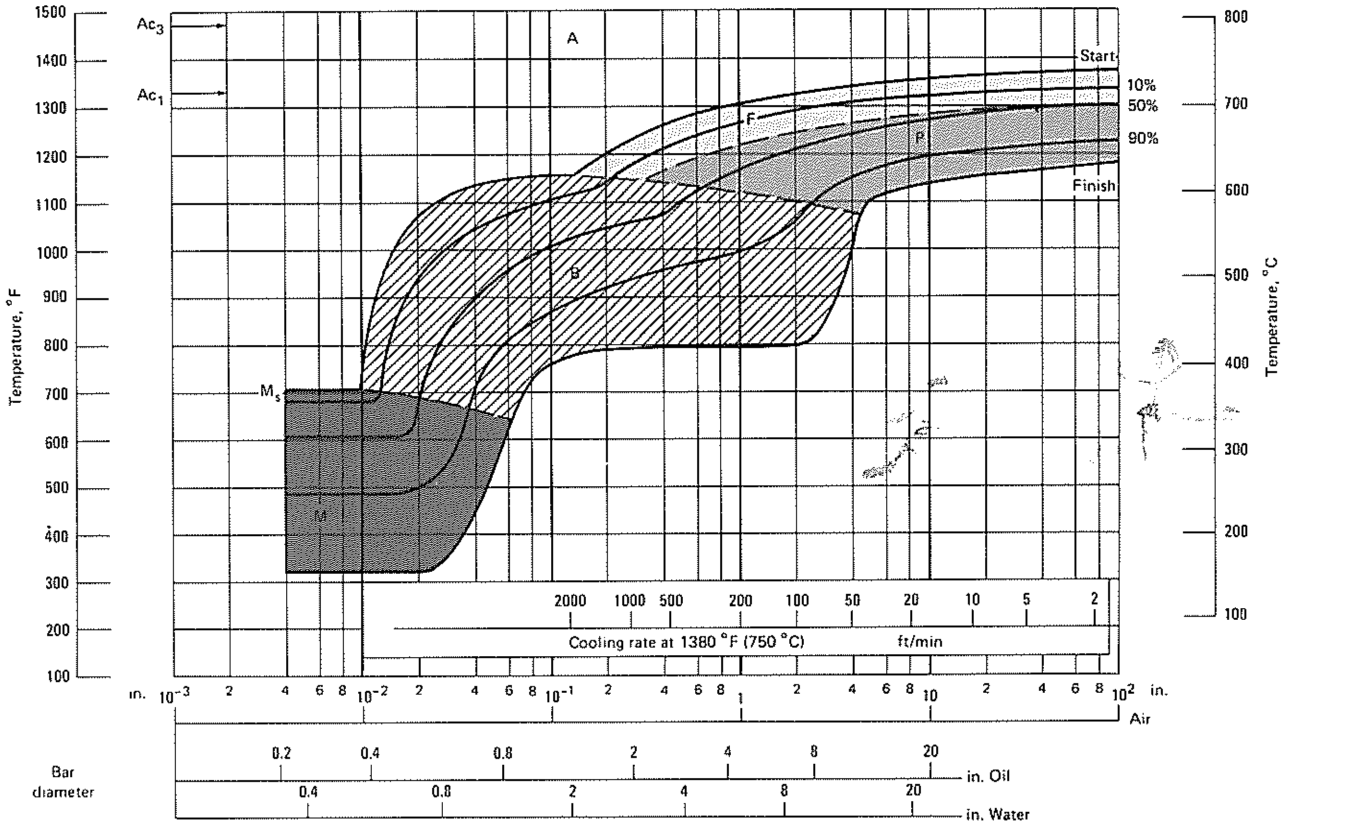
Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

4032, 4032H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure



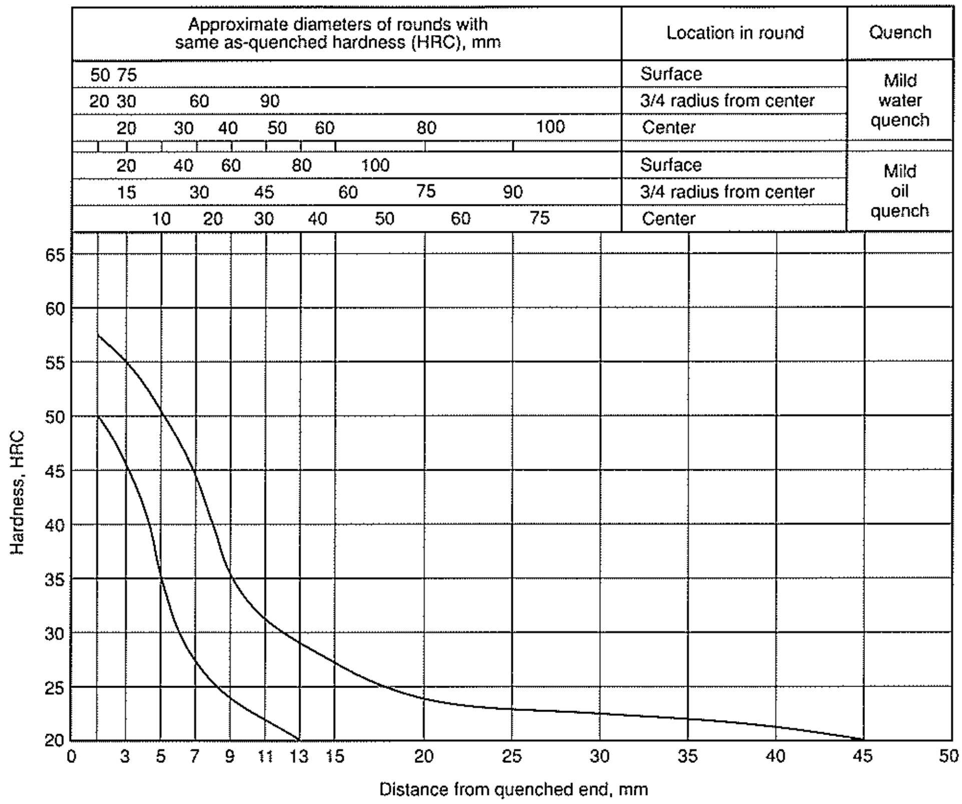
4032: Continuous Cooling Transformation Diagram. Composition: 0.32 C, 0.80 Mn, 0.025 P, 0.020 S, 0.30 Si, 0.26 Mo. Austenitized at 830 °C (1525 °F)



4032H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 900 °C (1650 °F). Austenitize: 870 °C (1600 °F)

Hardness Limits for Specification Purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	57	50
3	55	46
5	51	34
7	44	27
9	36	24
11	32	22
13	29	20
15	27	...
20	24	...
25	23	...
30	23	...
35	22	...
40	21	...
45	20	...
50	...	...



Hardness Limits for Specification Purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	57	50
2	54	45
3	51	36
4	46	29
5	39	25
6	34	23
7	31	22
8	29	21
9	28	20
10	26	...
11	26	...
12	25	...
13	24	...
14	24	...
15	23	...
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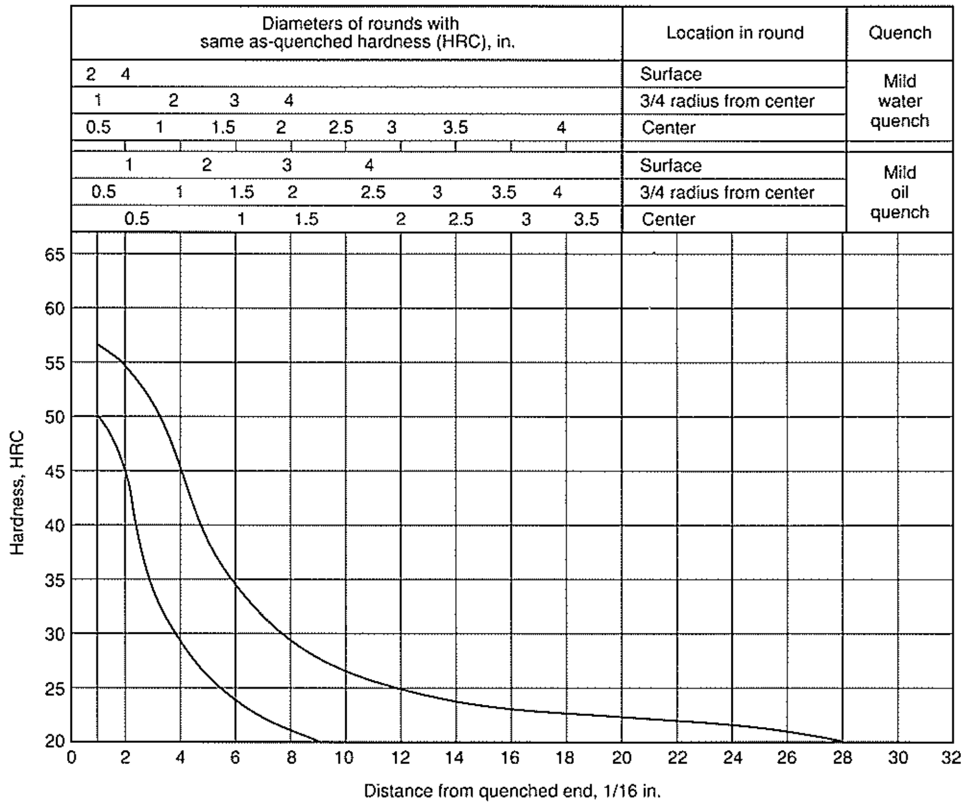
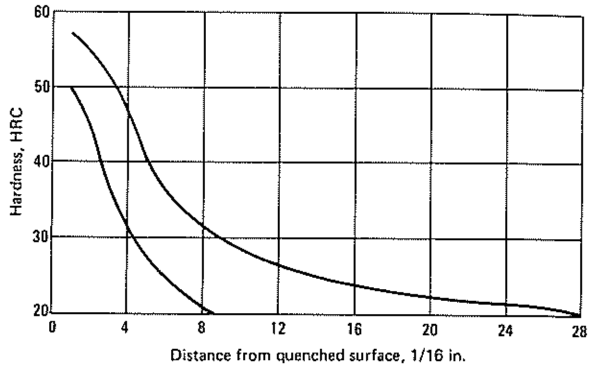
18	23	...
20	22	...
22	22	...
24	21	...
26	21	...
28	20	...
30	...	...



4032H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max
1	1.58	57	50	13	20.54	24
2	3.16	54	45	14	22.12	24
3	4.74	51	36	15	23.70	23
4	6.32	46	29	16	25.28	23
5	7.90	39	25	18	28.44	23
6	9.48	34	23	20	31.60	22
7	11.06	31	22	22	34.76	22
8	12.64	29	21	24	37.92	21
9	14.22	28	20	26	41.08	21
10	15.80	26	...	28	44.24	20
11	17.38	26	...	30	47.40	...
12	18.96	25	...	32	50.56	...



4037, 4037H

Chemical Composition. **4037. AISI and UNS:** 0.35 to 0.40 C, 0.70 to 0.90 Mn, 0.15 to 0.30 Si, 0.035 P max, 0.040 S max, 0.20 to 0.30 Mo. **UNS H40370 and SAE/AISI 4037H:** 0.34 to 0.41 C, 0.60 to 1.00 Mn, 0.15 to 0.35 Si, 0.20 to 0.30 Mo

Similar Steels (U.S. and/or Foreign). **4037.** UNS G40370; ASTM A322, A331, A519, A547; SAE J404, J412, J770. **4037H.** UNS H40370; ASTM A304; SAE J1268

Characteristics. A medium-carbon, low-alloy steel that can be hardened to approximately 50 HRC or slightly higher, provided it is properly quenched, and the carbon is on the high side of the allowable range. The hardenability pattern is similar to that of other carbon-molybdenum steels (4027H and 4032H) except that the curves move upward because of the higher carbon content. Has excellent forgeability, but weldability (principally in terms of susceptibility to weld cracking) decreases as carbon content increases

Forging. Heat to 1230 °C (2245 °F). Do not forge after temperature of forging stock drops below approximately 855 °C (1570 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air.

In aerospace practice, parts are normalized at 900 °C (1650 °F)

Annealing. For a predominately pearlitic structure, heat to 845 °C (1555 °F), cool rapidly to 745 °C (1370 °F), then to 630 °C (1170 °F) at a rate not to exceed 11 °C (20 °F) per h; or heat to 845 °C (1555 °F), cool rapidly to 660 °C (1220 °F), and hold for 5 h. For a predominately spheroidized structure, heat to 760 °C (1400 °F), cool from 745 °C (1370 °F) to 630 °C (1170 °F) at a rate not to exceed 6 °C (10 °F) per h; or heat to 760 °C (1400 °F), cool rapidly to 660 °C (1220 °F), and hold for 8 h.

In aerospace practice, parts are annealed at 845 °C (1555 °F). Parts are cooled to below 400 °C (750 °F) at a rate not to exceed 110 °C (200 °F) per h

Hardening. Heat to 845 °C (1555 °F), and quench in oil. Carbonitriding is a hardening process. In aerospace practice, parts are austenitized at 845 °C (1555 °F), and quenched in oil or water

Tempering. Reheat to the temperature required to provide the desired hardness. See table

Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

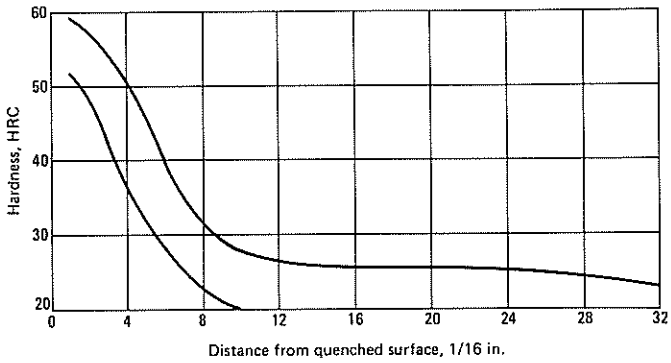
4037: Suggested Tempering Temperatures (Aerospace practice)

Tensile Strength Ranges				
620 to 860 MPa (90 to 125 ksi)	860 to 1035 MPa (125 to 150 ksi)	1035 to 1175 MPa (150 to 170 ksi)	1175 to 1240 MPa (160 to 180 ksi)	1380 to 1520 MPa (180 to 200 ksi)
595 °C(a) (1100 °F)	540 °C (1000 °F)	495 °C (925 °F)	440 °C (825 °F)	370 °C (700 °F)
650 °C(b) (1200 °F)	595 °C (1100 °F)	540 °C (1000 °F)	470 °C (875 °F)	385 °C (725 °F)

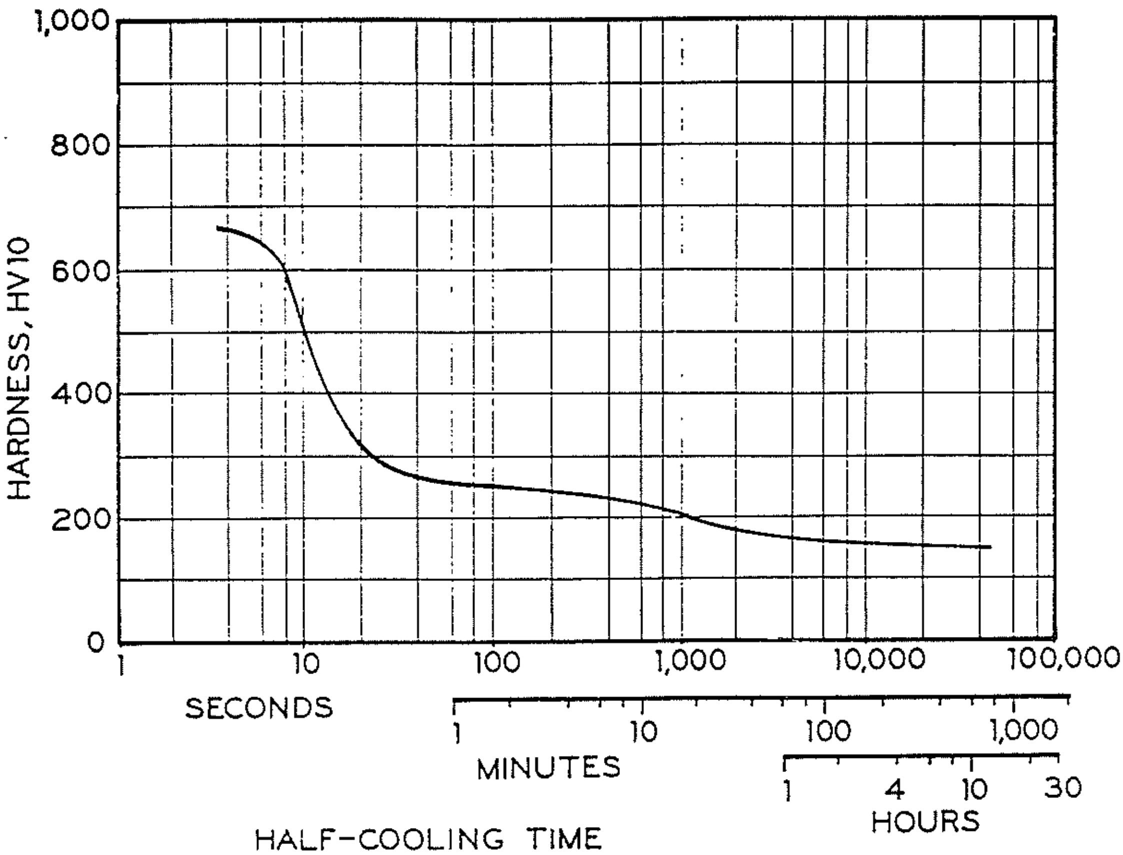
(a) Quench in oil or polymer. (b) Quench in water. Source: AMS 2759/1

4037H: End-Quench Hardenability

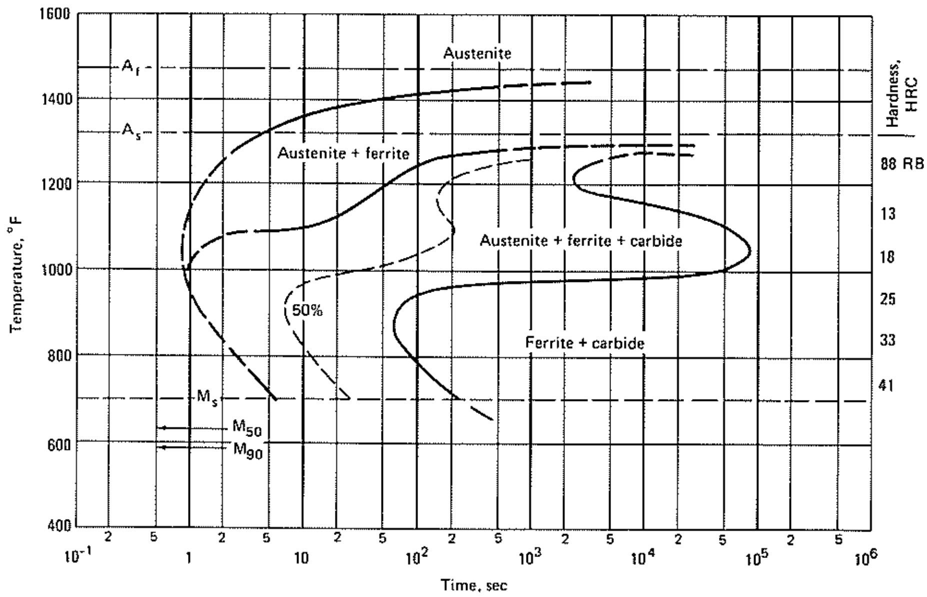
Distance from quenched surface, 1⁄16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1⁄16 in.	Distance from quenched surface, mm	Hardness, HRC max
1	1.58	59	52	13	20.54	26
2	3.16	57	49	14	22.12	26
3	4.74	54	42	15	23.70	26
4	6.32	51	35	16	25.28	25
5	7.90	45	30	18	28.44	25
6	9.48	38	26	20	31.60	25
7	11.06	34	23	22	34.76	25
8	12.64	32	22	24	37.92	24
9	14.22	30	21	26	41.08	24
10	15.80	29	20	28	44.24	24
11	17.38	28	...	30	47.40	23
12	18.96	27	...	32	50.56	23



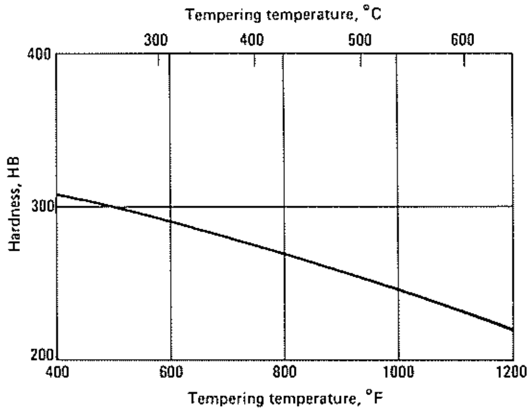
4037: Cooling Curve. Source: Datasheet I-216. Climax Molybdenum Company



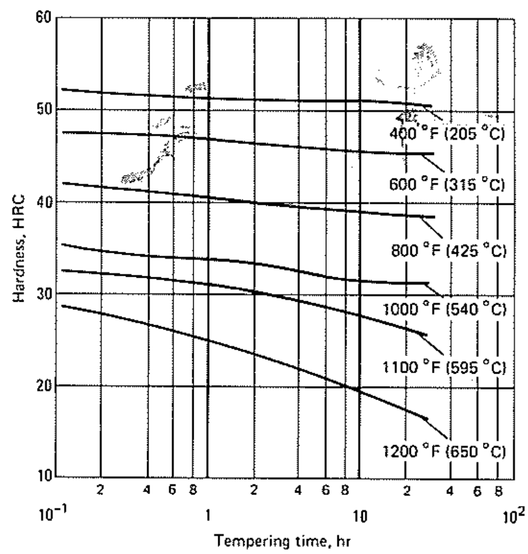
4037: Isothermal Transformation Diagram. Composition: 0.35 C, 0.80 Mn, 0.25 Mo. Austenitized at 855 °C (1570 °F). Grain size: 7



4037: Hardness vs Tempering Temperature. Normalized at 870 °C (1600 °F). Quenched from 845 °C (1555 °F) and tempered in 56 °C (100 °F) intervals in 13.716 mm (0.540 in.) rounds. Tested in 12.827 mm (0.505 in.)



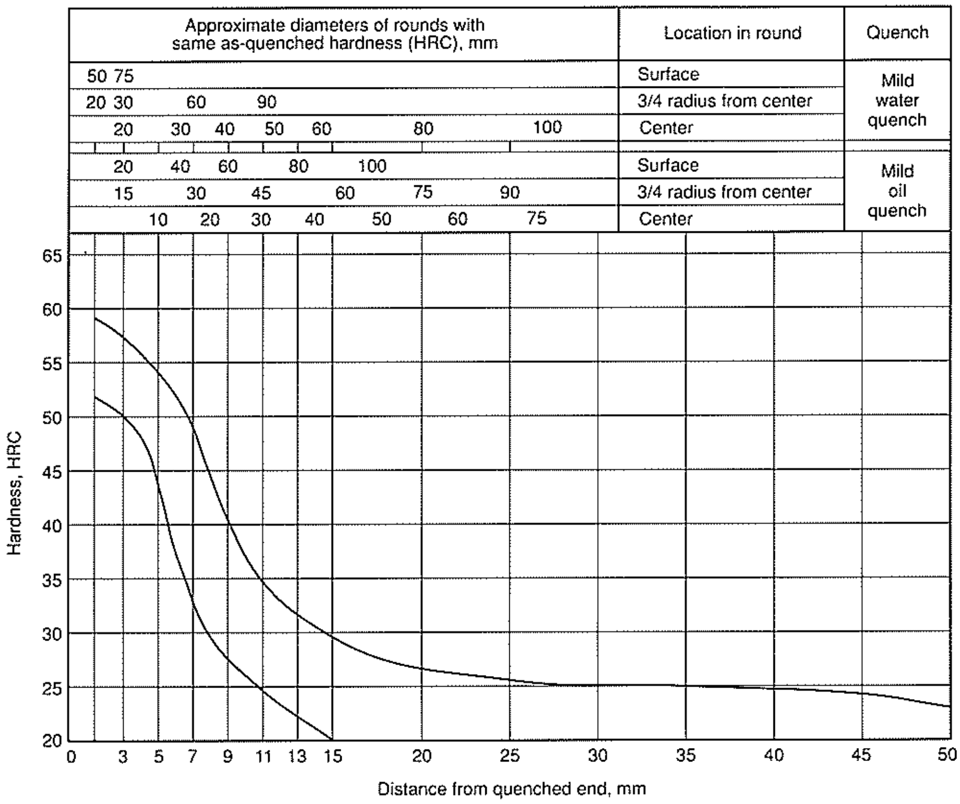
4037: Hardness vs Tempering Time and Tempering Temperature. Tempered at temperatures indicated



4037H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

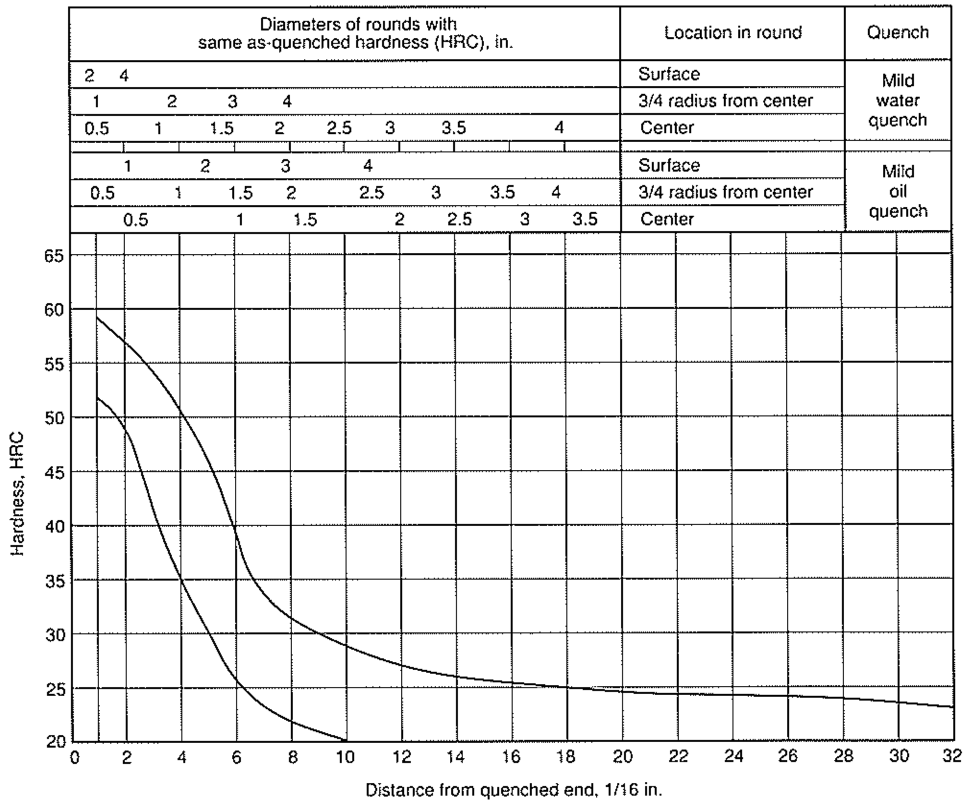
Hardness Limits for Specification Purposes

distance, mm	Hardness, HRC Maximum	Minimum
.5	59	52
;	57	50
;	54	42
'	49	32
)	41	27
.1	35	24
.3	32	21
.5	30	20
:0	27	...
:5	26	...
;0	25	...
;5	25	...
:0	25	...
;5	24	...
;0	23	...

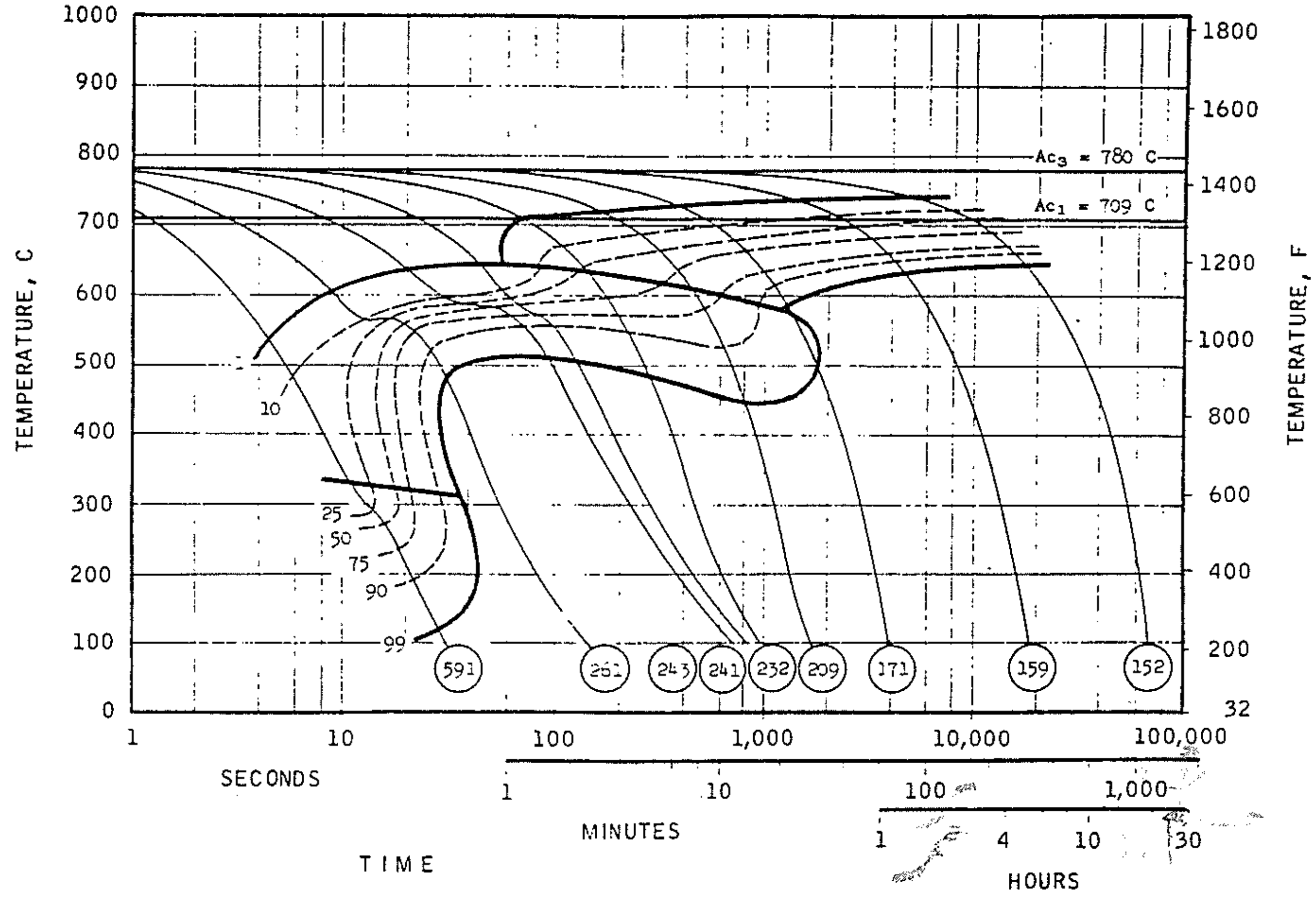


Hardness Limits for Specification Purposes

distance, 1/16 in.	Hardness, HRC Maximum	Minimum
.	59	52
!	57	49
	54	42
	51	35
;	45	30
;	38	26
'	34	23
;	32	22
)	30	21
10	29	20
11	28	...
12	27	...
13	26	...
14	26	...
15	26	...
16	25	...
18	25	...
20	25	...
22	25	...
24	24	...
26	24	...
28	24	...
30	23	...
32	23	...



4037: CCT Diagram. Constructional alloy steel composition: 0.41 C, 0.74 Mn, 0.008 P, 0.032 S, 0.28 Si, 0.014 Ni, 0.034 Cr, 0.21 Mo, 0.065 Cu. A commercial heat; bar stock steel was austenitized for 20 min at 845 °C (1555 °F). Source: Datasheet I-216. Climax Molybdenum Company



4042, 4042H

Chemical Composition. **4042. AISI:** 0.40 to 0.45 C, 0.70 to 0.90 Mn, 0.20 to 0.35 Si, 0.040 P max, 0.040 S max, 0.20 to 0.30 Mo. **UNS:** 0.40 to 0.45 C, 0.70 to 0.90 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.20 to 0.30 Mo. **UNS H40420 and SAE/AISI 4042H:** 0.39 to 0.46 C, 0.60 to 1.00 Mn, 0.15 to 0.35 Si, 0.20 to 0.30 Mo

Similar Steels (U.S. and/or Foreign). **4042.** UNS G40420; ASTM A322, A331, A519; SAE J404, J412, J770. **4042H.** UNS H40420; ASTM A304; SAE J1268

Characteristics. Has characteristics that closely parallel those of the other medium-carbon, molybdenum-alloy steels (see 4027H and 4037H). As the carbon content increases, the as-quenched hardness increases. Depending to some extent upon the precise carbon content, fully hardened 4042H has a surface hardness of approximately 55 HRC. Forgeability of this grade is excellent, but welding is difficult because of the difficulty in producing crack-free welds

Forging. Heat to 1230 °C (2245 °F). Do not forge after temperature of forging stock drops below approximately 855 °C (1570 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

Annealing. For a predominately pearlitic structure, heat to 845 °C (1555 °F), cool rapidly to 745 °C (1370 °F), then to 630 °C (1170 °F) at a rate not to exceed 11 °C (20 °F) per h; or heat to 845 °C (1555 °F), cool rapidly to 660 °C (1220 °F), and hold for 5 h. For a predominately spheroidized structure, heat to 760 °C (1400 °F), cool from 745 °C (1370 °F) to 630 °C (1170 °F) at a rate not to exceed 6 °C (10 °F) per h; or heat to 760 °C (1400 °F), cool rapidly to 660 °C (1220 °F), and hold for 8 h

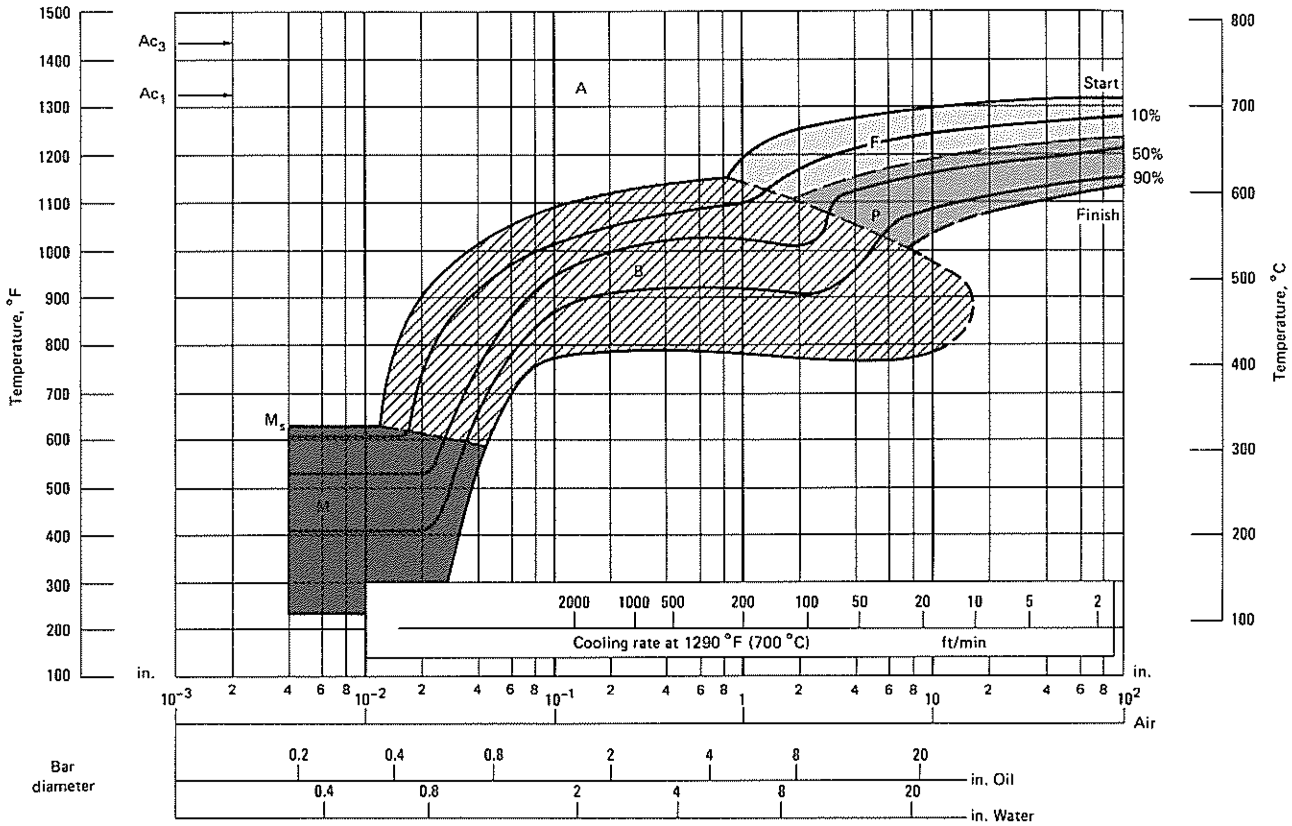
Hardening. Heat to 845 °C (1555 °F), and quench in oil. Carbonitriding is a suitable process

Tempering. Reheat to the temperature required to provide the desired hardness

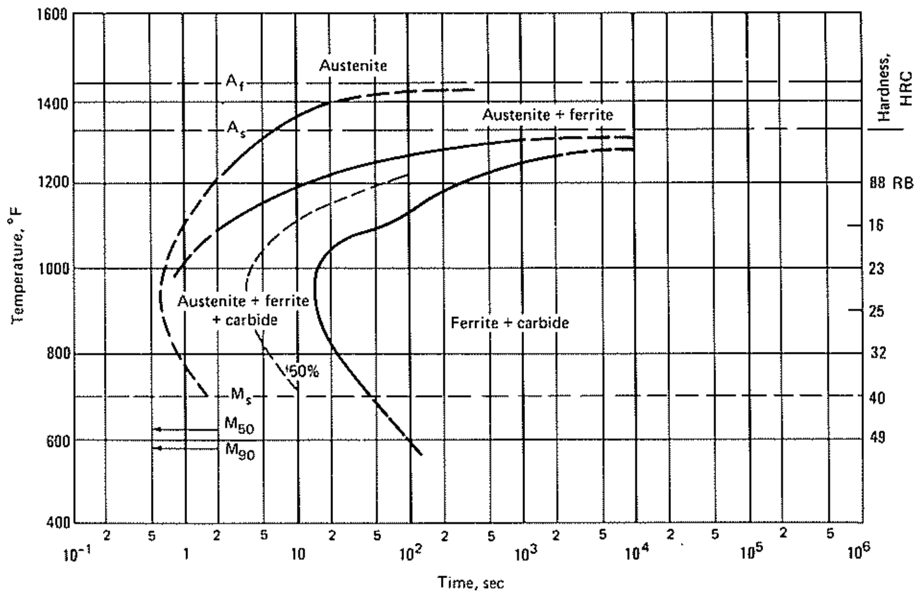
Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine

4042: Continuous Cooling Transformation Diagram. Composition: 0.40 C, 0.80 Mn, 0.025 P, 0.020 S, 0.30 Si, 0.26 Mo. Austenitized at 810 °C (1490 °F)

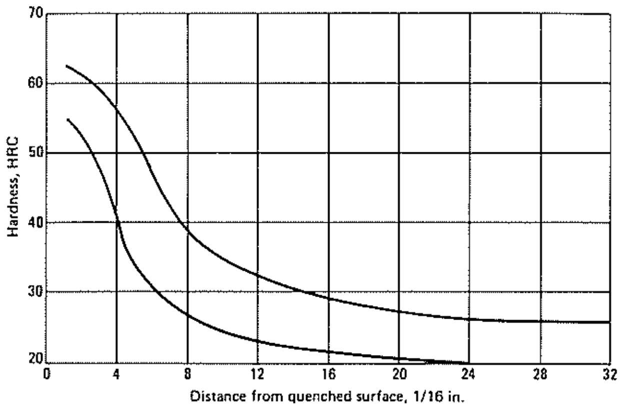


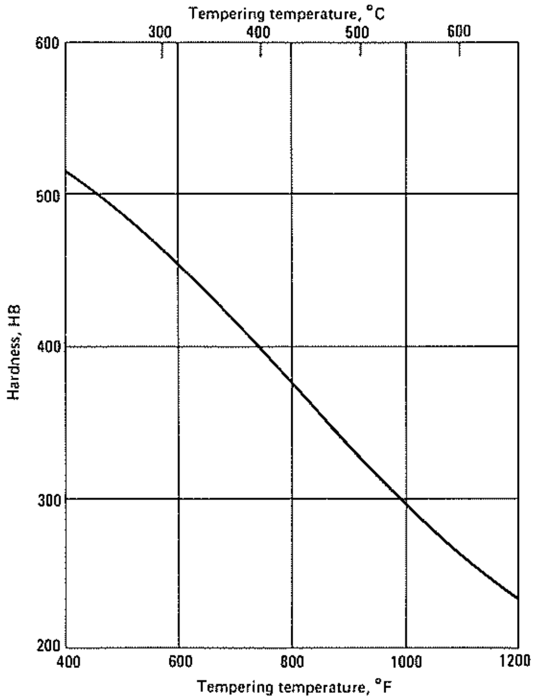
4042: Isothermal Transformation Diagram. Composition: 0.42 C, 0.20 Mn, 0.21 Mo. Austenitized at 870 °C (1600 °F). Grain size: 5 to 6



4042H: End-Quench Hardenability

Distance from quenched surface, $\frac{1}{16}$ in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, $\frac{1}{16}$ in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min
1	1.58	62	55	13	20.54	30	23
2	3.16	60	52	14	22.12	30	23
3	4.74	58	48	15	23.70	29	22
4	6.32	55	40	16	25.28	29	22
5	7.90	50	33	18	28.44	28	22
6	9.48	45	29	20	31.60	28	21
7	11.06	39	27	22	34.76	28	20
8	12.64	36	26	24	37.92	27	20
9	14.22	34	25	26	41.08	27	...
10	15.80	33	24	28	44.24	27	...
11	17.38	32	24	30	47.40	26	...
12	18.96	31	23	32	50.56	26	...



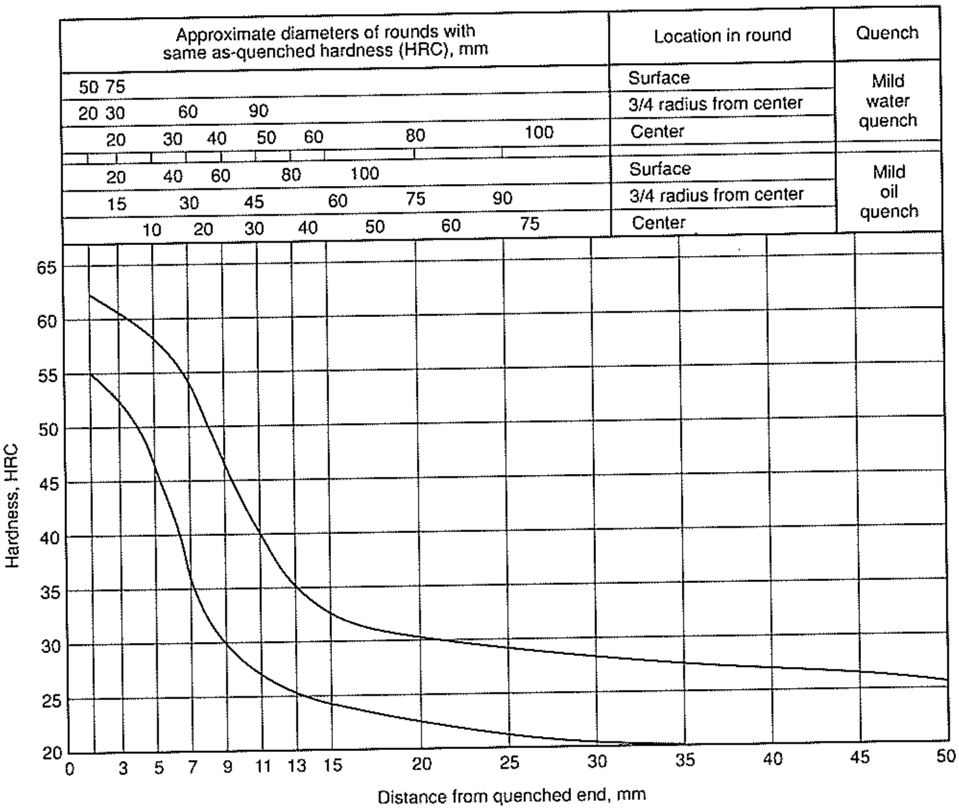


4042: Hardness vs Tempering Temperature. Normalized at 870 °C (1600 °F). Quenched from 845 °C (1555 °F) in oil and tempered in 56 °C (100 °F) intervals in 13.716 mm (0.540 in.) rounds. Tested in 12.827 mm (0.505 in.) rounds. Source: Republic Steel

4042H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

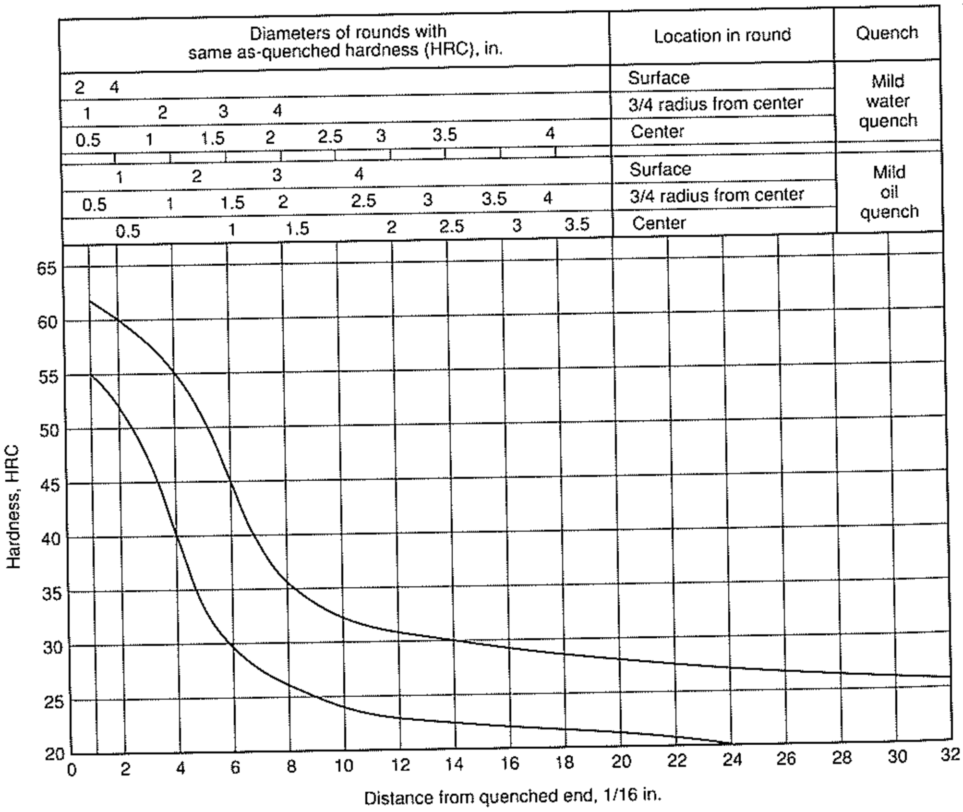
Hardness Limits for Specification Purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	62	55
3	61	53
5	58	47
7	54	36
9	48	30
11	40	27
13	36	25
15	33	24
20	31	23
25	29	22
30	28	21
35	28	20
40	27	...
45	27	...
50	26	...



Hardness Limits for Specification Purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	62	55
2	60	52
3	58	48
4	55	40
5	50	33
6	45	29
7	39	27
8	36	26
9	34	25
10	33	24
11	32	24
12	31	23
13	30	23
14	30	23
15	29	22
16	29	22
18	28	22
20	28	21
22	28	20
24	27	20
26	27	...
28	27	...
30	26	...
32	26	...



4047, 4047H

Chemical Composition. **4047. AISI and UNS:** 0.45 to 0.50 C, 0.70 to 0.90 Mn, 0.15 to 0.30 Si, 0.035 P max, 0.040 S max, 0.20 to 0.30 Mo. **UNS H40470 and SAE/AISI 4047H:** 0.44 to 0.51 C, 0.60 to 1.00 Mn, 0.15 to 0.35 Si, 0.20 to 0.30 Mo

Similar Steels (U.S. and/or Foreign). **4047.** UNS G40470; ASTM A322, A331, A519; SAE J404, J412, J770. **4047H.** UNS H40470; ASTM A304; SAE J1268

Characteristics. 4047H, which may have a carbon content of up to 0.51, borders on what may be considered high-carbon steel and is sometimes used in applications that require spring grades. The hardenability of 4047H exhibits a pattern very similar to the lower or medium-carbon grades of the 40XX series, although both the minimum and maximum curves are shifted further upward on the hardenability chart because of the higher carbon content of 4047H. As-quenched hardness of fully hardened 4047H should be near 55 HRC or slightly higher, depending upon the precise carbon content. Readily forged, but not recommended for welding. In addition to direct hardening and tempering, 4047H is well adapted to heat treating by the austempering process

Forging. Heat to 1220 °C (2225 °F). Do not forge after temperature of forging stock drops below approximately 845 °C (1555 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

Annealing. For a predominately pearlitic structure, heat to 830 °C (1525 °F), cool fairly rapidly to 730 °C (1350 °F), then to 630 °C (1170 °F) at a rate not to exceed 11 °C (20 °F) per h; or cool fairly rapidly from 830 °C (1525 °F) to 660 °C (1220 °F), and hold for 5 h. For a predominately spheroidized structure, heat to 760 °C (1400 °F), cool fairly rapidly to 730 °C (1350 °F), then to 630 °C (1170 °F), at a rate not to exceed 6 °C (10 °F) per h; or heat to 760 °C (1400 °F), cool fairly rapidly to 650 °C (1200 °F), and hold for 9 h

Hardening. Austenitize at 830 °C (1525 °F), and quench in oil. Austempering and carbonitriding are suitable processes

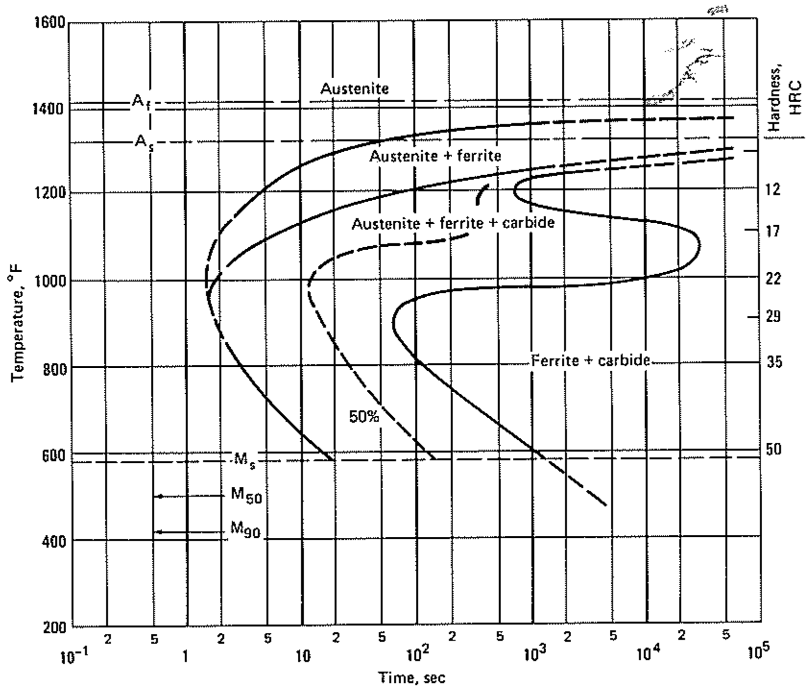
Tempering. Reheat to the temperature required to provide the desired hardness

Austempering. Austenitize at 845 °C (1555 °F), quench in agitated molten salt at 345 °C (655 °F), hold for 2 h and cool in air. Resulting hardness should be 45 to 50 HRC. No tempering is required

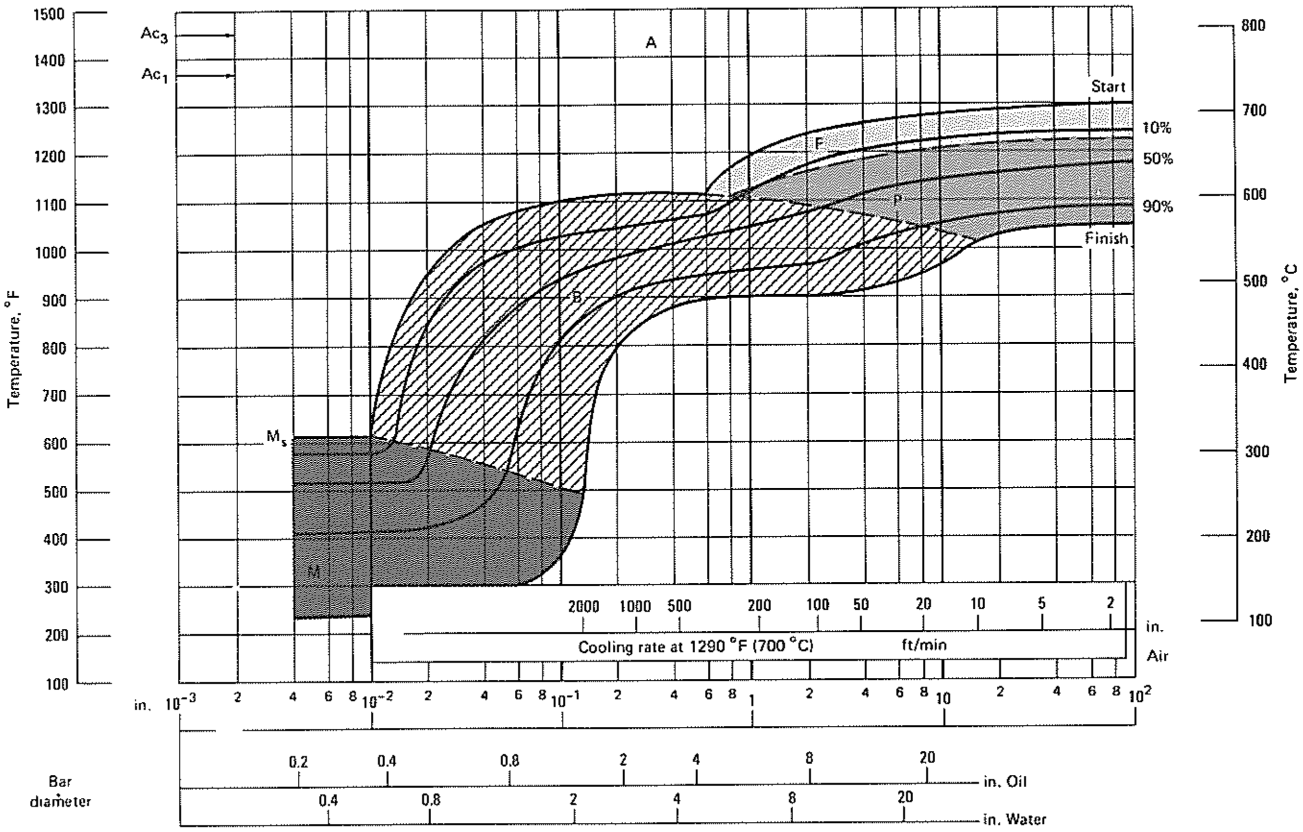
Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize (or austemper)
- Quench (or austemper)
- Temper (or austemper)
- Finish machine

4047: Isothermal Transformation Diagram. Composition: 0.48 C, 0.94 Mn, 0.25 Mo. Austenitized at 815 °C (1500 °F). Grain size: 6 to 7

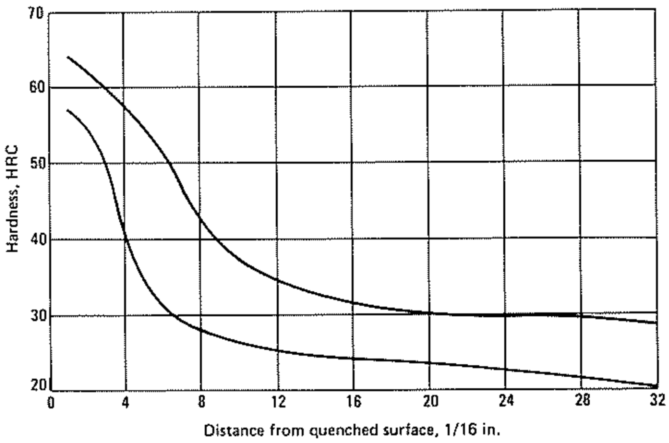


4047: Continuous Cooling Transformation Diagram. Composition: 0.48 C, 0.80 Mn, 0.025 P, 0.020 S, 0.25 Si, 0.26 Mo. Austenitized at 810 °C (1490 °F)

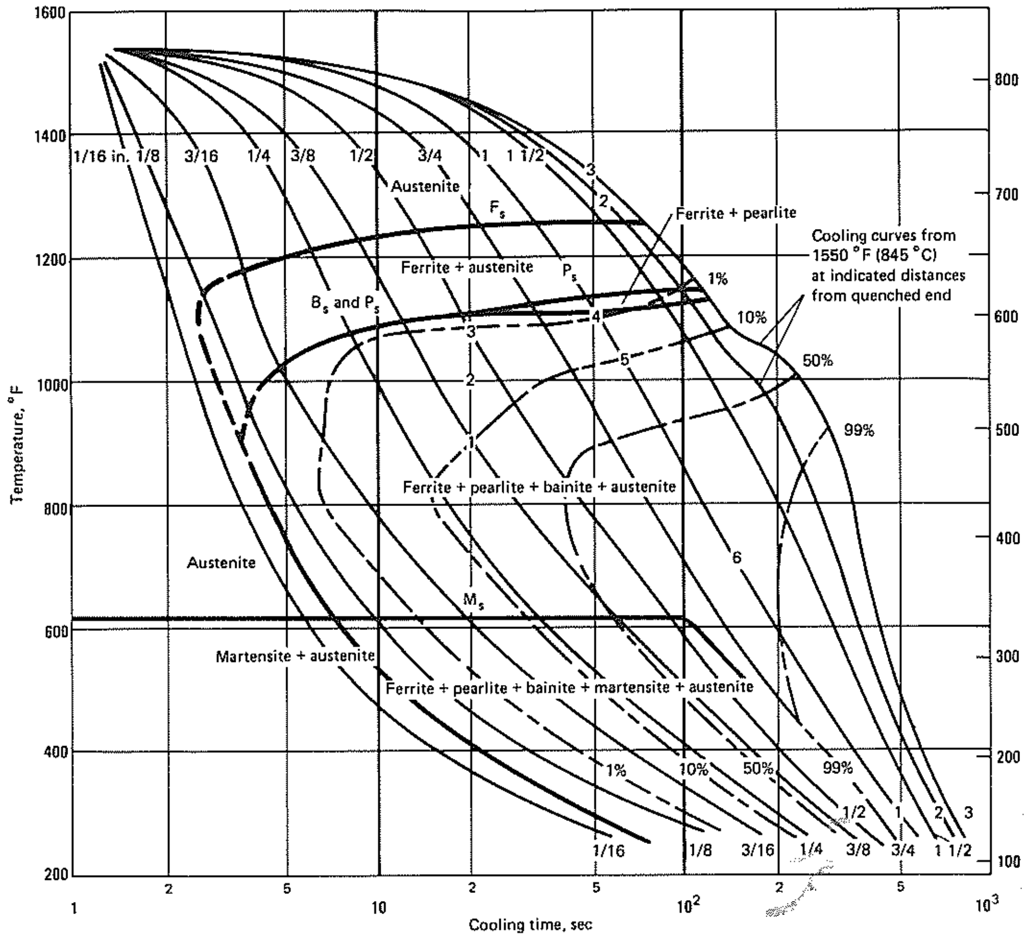


4047H: End-Quench Hardenability

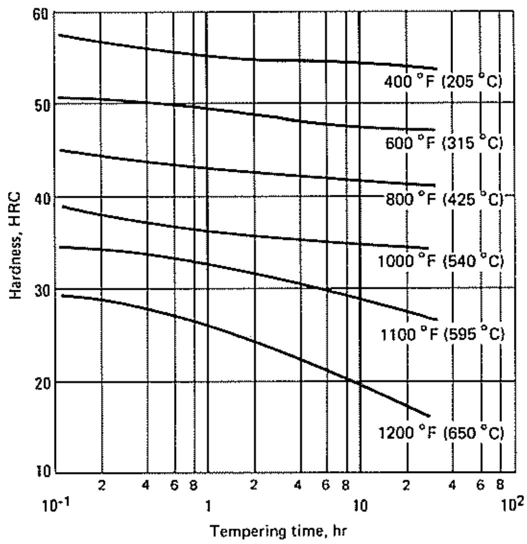
Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max	Hardness, HRC min
1	1.58	64	57	13	20.54	34	25
2	3.16	62	55	14	22.12	33	25
3	4.74	60	50	15	23.70	33	25
4	6.32	58	42	16	25.28	32	25
5	7.90	55	35	18	28.44	31	24
6	9.48	52	32	20	31.60	30	24
7	11.06	47	30	22	34.76	30	23
8	12.64	43	28	24	37.92	30	23
9	14.22	40	28	26	41.08	30	22
10	15.80	38	27	28	44.24	29	22
11	17.38	37	26	30	47.40	29	21
12	18.96	35	26	32	50.56	29	21

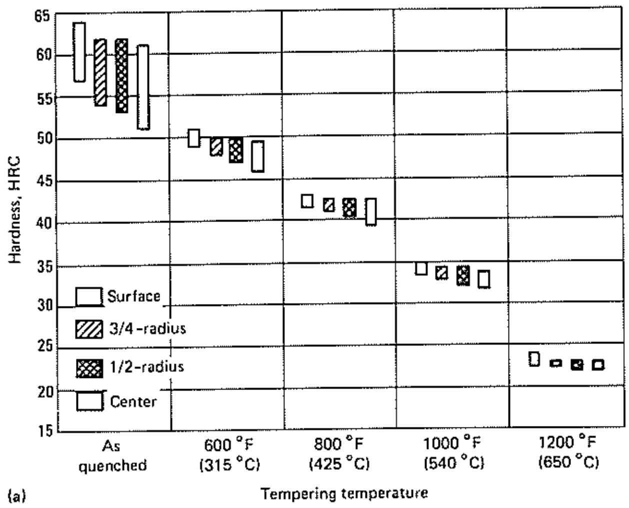


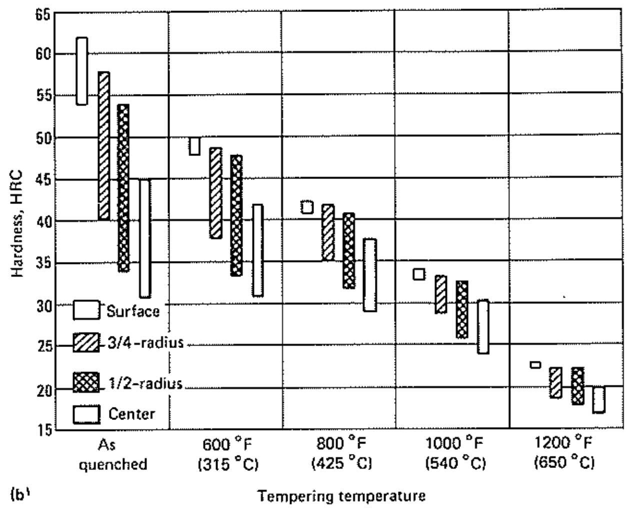
4047: Cooling Transformation Diagram. Composition: 0.51 C, 0.81 Mn, 0.25 Si, 0.26 Mo. Austenitized at 845 °C (1555 °F). Grain size: 8. Ac_3, 790 °C (1455 °F); Ac_1, 745 °C (1370 °F). A: austenite, G: ferrite, P: pearlite, B: bainite, M: martensite. Source: Bethlehem Steel

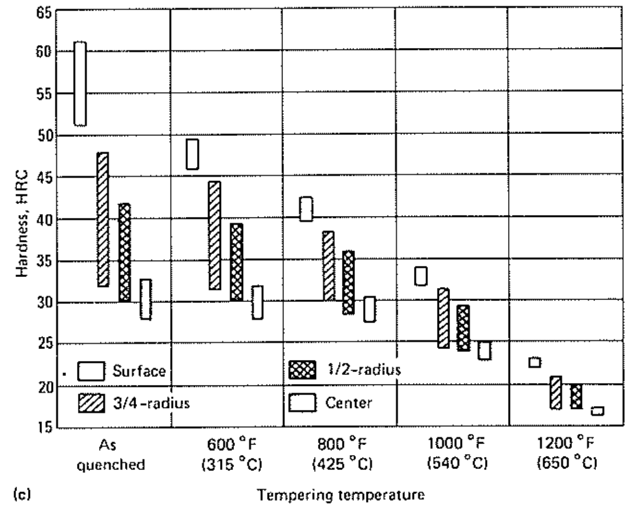


4047: Hardness vs Tempering Time and Tempering Temperature. Tempering temperatures indicated



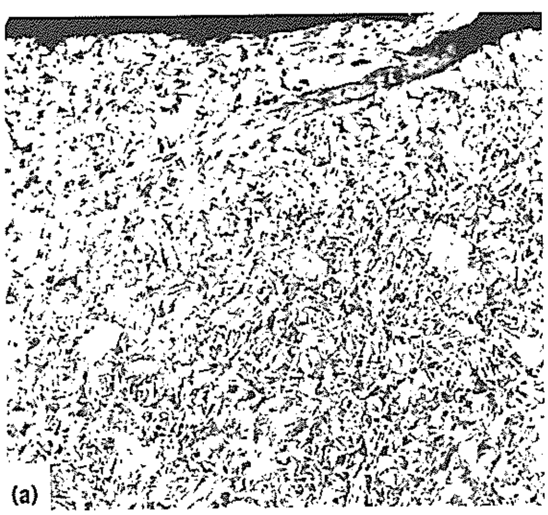


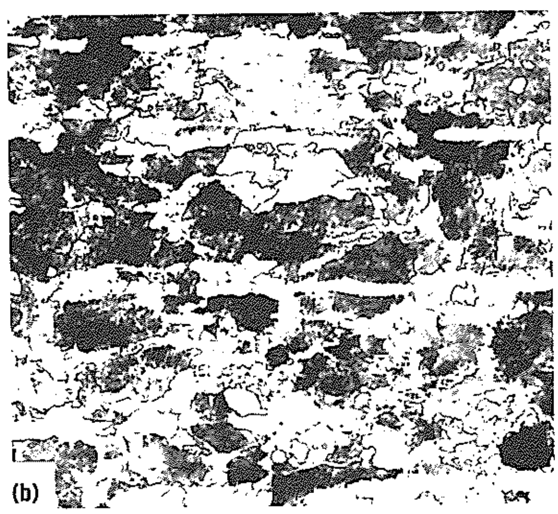




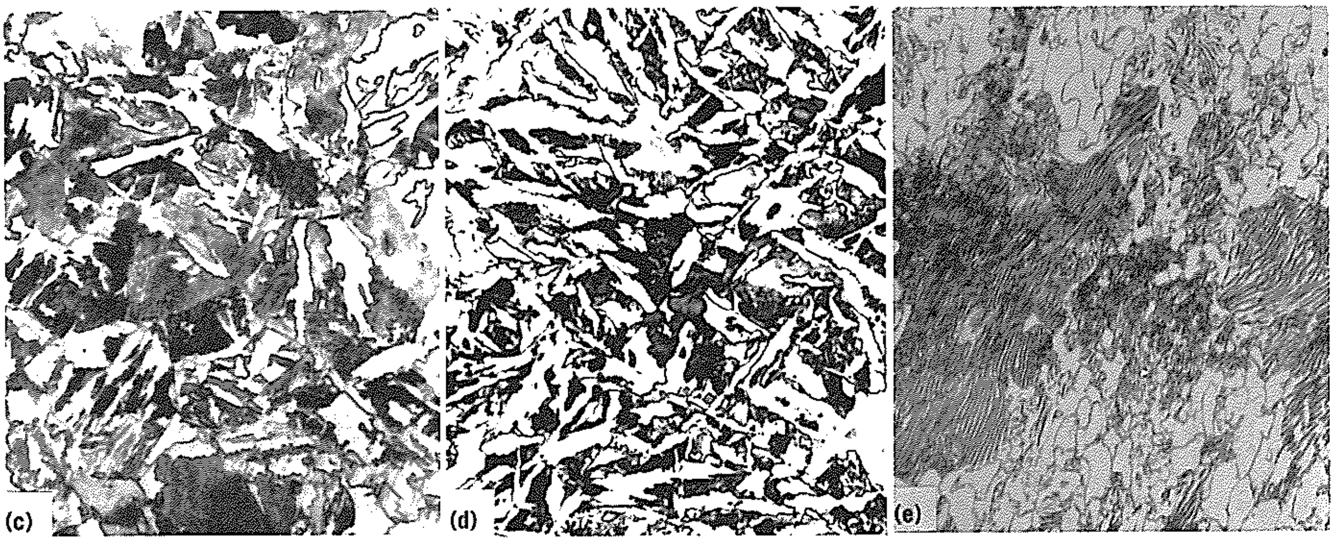
4047: Variations in Depth of Hardening. Tempered 1 h at indicated temperatures. (a) 12.7 mm (½ in.) diam cylinders; (b) 25.4 mm (1 in.) diam cylinders; (c) 38.1 mm (1½ in.) diam cylinders

4047: Microstructures. (a) 2% nital, 110×. Hot rolled steel bar. 28.6 mm (1⅛ in.) diam with a mill defect (a sliver of metal) at the surface, folded over oxide (dark gray). Primarily ferrite, resulting from decarburization, with patches of fine pearlite (dark). (b) 2% nital, 550×. Cold drawn steel bar, 23 mm (29/32 in.), mill annealed; longitudinal section. Somewhat segregated ferrite (white) and fine pearlite (dark) caused difficulty in machining (drilling) *(continued)*

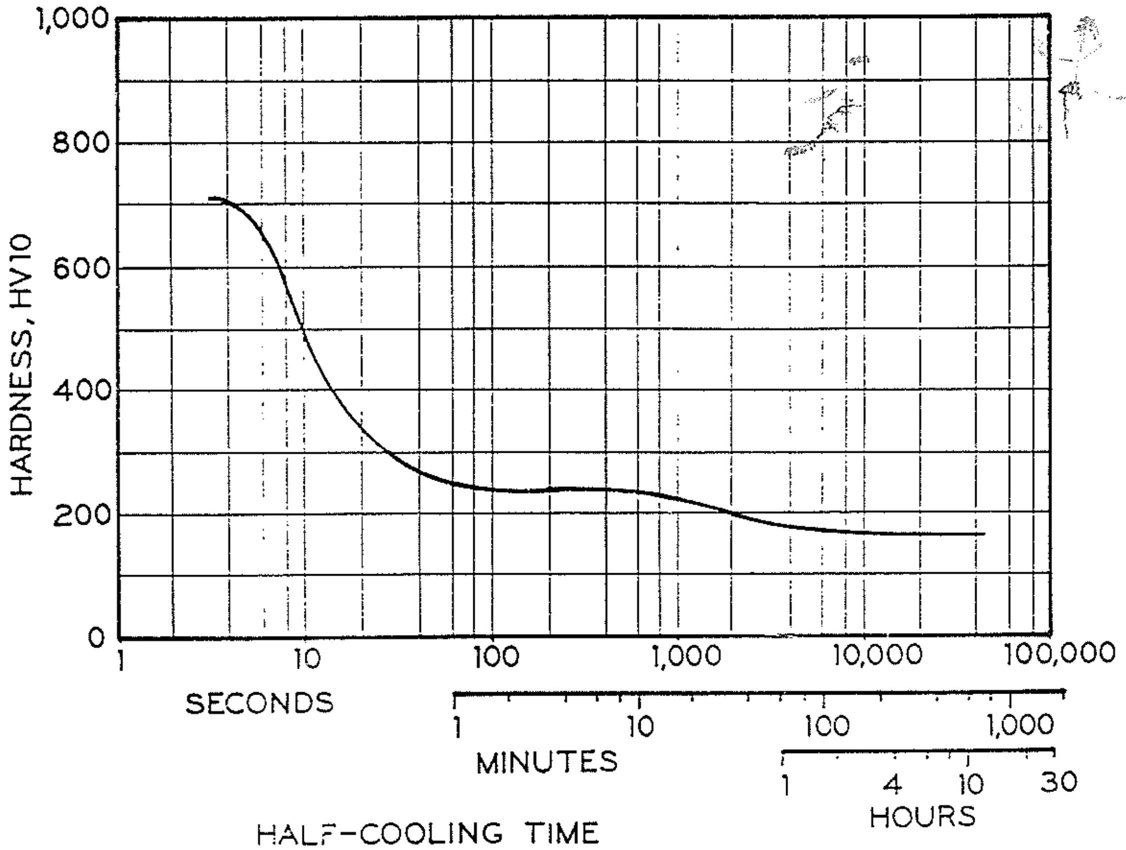




4047: Microstructures (continued). (c) 2% nital, 550×. Hot rolled steel 26.2 mm (1 1⁄32 in.) diam; longitudinal section taken at midradius. Acicular ferrite and upper bainite, resulting from rapid cooling from rolling temperature. Large dark areas are pearlite. (d) 2% nital, 550×. Steel forging, 12.7 mm (½ in.) thickness, air cooled from forging temperature of 1205 °C (2200 °F); longitudinal section. Plates of ferrite (white) and fine pearlite (dark). (e) 2% nital, 500×. Steel forging. Longitudinal section, 15.9 mm (5/8 in.). Austenitized at 830 °C (1525 °F), cooled to 665 °C (1230 °F) and held 6 h, furnace cooled to 540 °C (1000 °F), air cooled. Ferrite (white) and lamellar pearlite (dark)



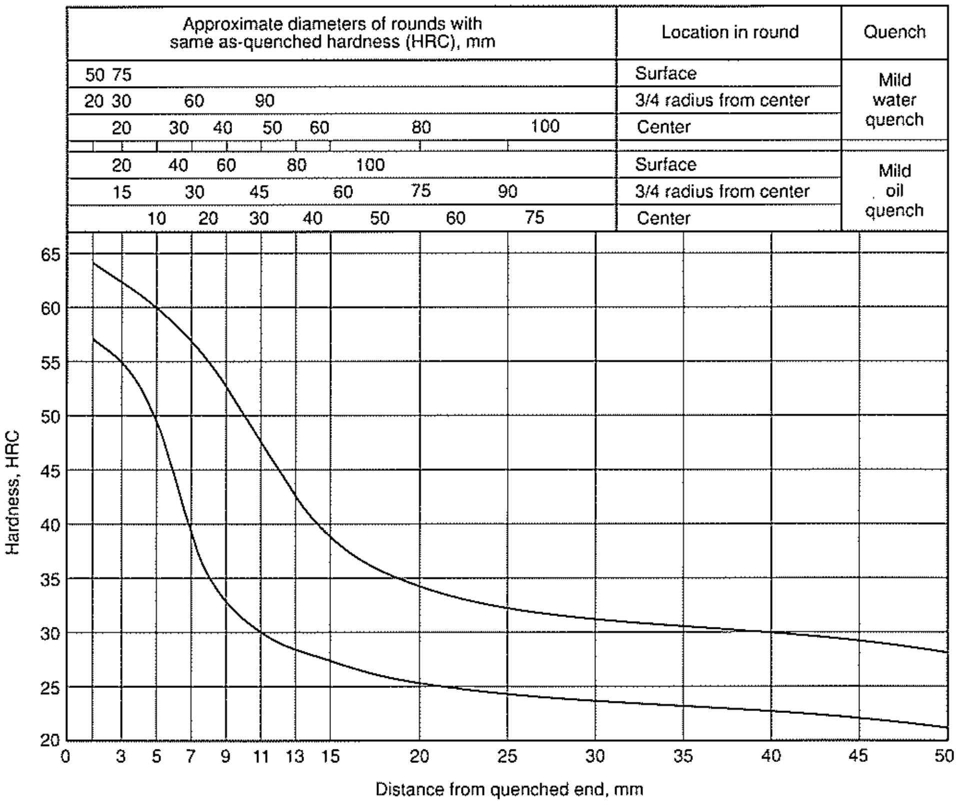
4047: Cooling Curve. Half cooling time. Source: Datasheet I-219, Climax Molybdenum Company



4047H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

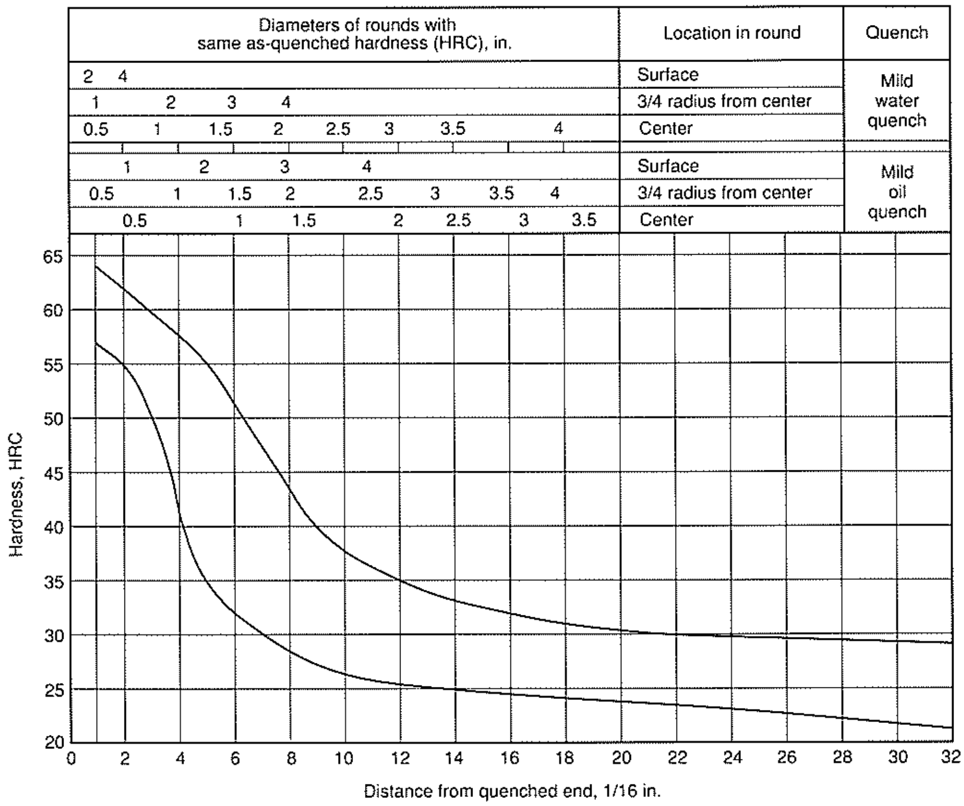
Hardness Limits for Specification Purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	64	57
3	63	55
5	60	49
7	57	39
9	53	33
11	48	30
13	43	28
15	39	27
20	34	25
25	33	24
30	31	24
35	30	23
40	30	23
45	29	22
50	29	21

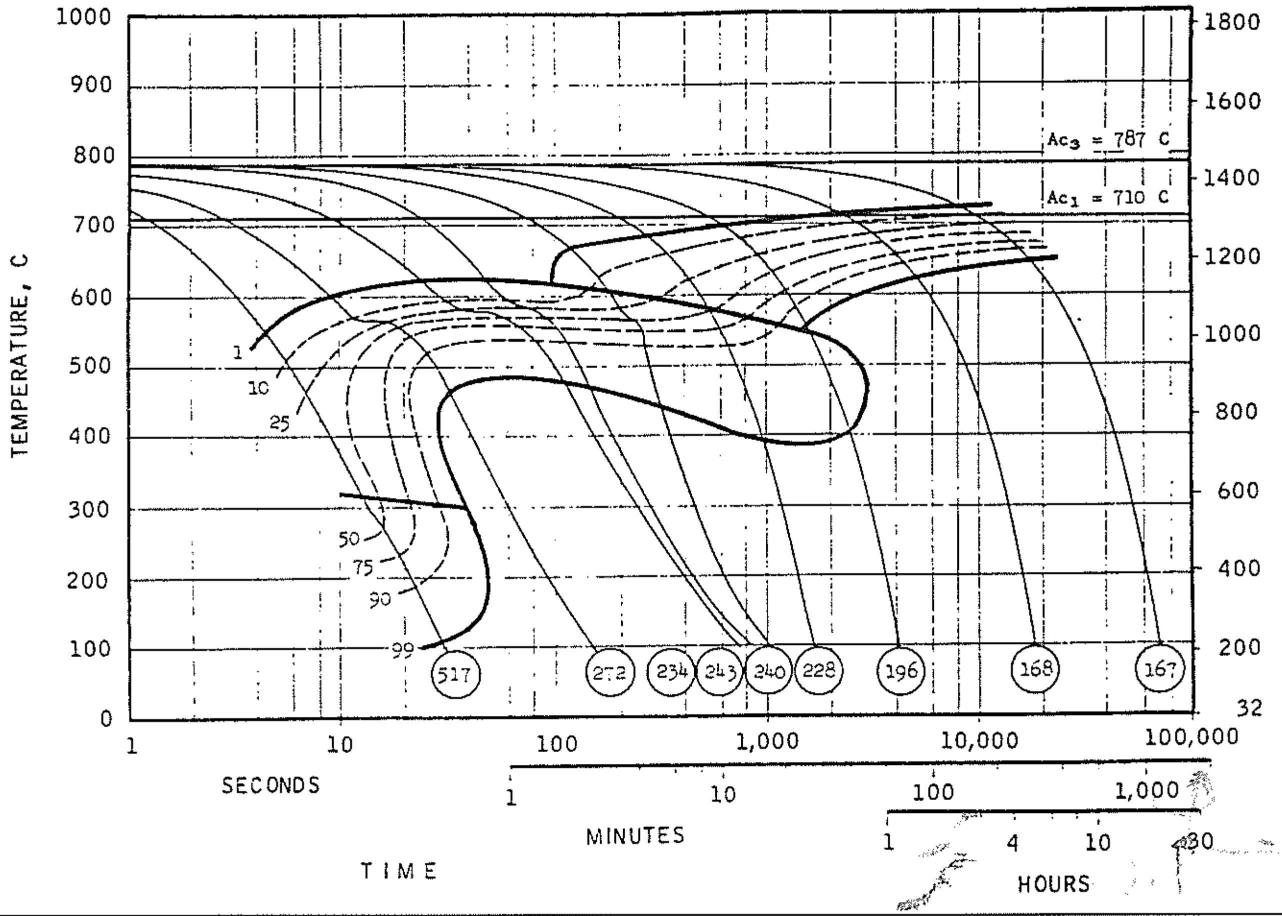


Hardness Limits for Specification Purposes

J distance, $\frac{1}{16}$ in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	64	57
2	62	55
3	60	50
4	58	42
5	55	35
6	52	32
7	47	30
8	43	28
9	40	28
10	38	27
11	37	26
12	35	26
13	34	25
14	33	25
15	33	25
16	32	25
18	31	24
20	30	24
22	30	23
24	30	23
26	30	22
28	29	22
30	29	21
32	29	21



4047: CCT Diagram. Constructional alloy steel. Chemical composition: 0.48 C, 0.23 Si, 0.78 Mn, 0.005 P, 0.020 S, 0.06 Cr, 0.012 Ni, 0.25 Mo, 0.015 Cu. Bar stock from commercial heat was used in study. Steel was austenitized at 845 °C (1555 °F) 20 min. Source: Datasheet I-219, Climax Molybdenum Company



4118, 4118H, 4118RH

Chemical Composition. **4118. AISI and UNS:** 0.18 to 0.23 C, 0.70 to 0.90 Mn, 0.15 to 0.30 Si, 0.035 P max, 0.040 S max, 0.40 to 0.60 Cr, 0.08 to 0.15 Mo. **UNS H41180 and SAE/AISI 4118H:** 0.17 to 0.23 C, 0.60 to 1.00 Mn, 0.15 to 0.35 Si, 0.30 to 0.70 Cr, 0.08 to 0.15 Mo. **SAE 4118RH:** 0.18 to 0.23 C, 0.70 to 0.90 Mn, 0.15 to 0.35 Si, 0.40 to 0.60 Cr, 0.08 to 0.15 Mo

Similar Steels (U.S. and/or Foreign). **4118.** UNS G41180; ASTM A322, A331, A505, A519; SAE J404, J412, J770. **4118H.** UNS H41180; ASTM A304; SAE J1268, J1868; ASTM A914

Characteristics. Low-alloy steel which is used extensively for case hardening applications, conventional carburizing as well as carbonitriding. As can be observed in the hardenability data for 4118H, the hardenability differs little from that of a comparable 4000 series steel. The chromium addition in 4118H little more than offsets the decrease in molybdenum content. Depending somewhat upon the precise carbon content of 4118H, the as-quenched surface hardness will be approximately 38 HRC or slightly higher. Forgeability is excellent, but machinability is only fair. 4118H can be readily welded, although before any welding is attempted the carbon equivalent should be determined, and recommended welding practices observed

Forging. Heat to 1245 °C (2275 °F) maximum. Do not forge after temperature of forging stock drops below approximately 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Cool in air

Annealing. Not usually required for this grade. Structures that are well suited to machining are generally obtained by normalizing or by isothermal annealing after rolling or forging. Isothermal annealing may be accomplished by heating to 700 °C (1290 °F) and holding for 8 h

Direct Hardening. While applications for 4118H seldom require direct hardening, it can be accomplished by austenitizing at 900 °C (1650 °F) and quenching in oil. Ion nitriding, gas nitriding, carbonitriding, and gas or liquid salt bath carburizing are suitable processes

Carburizing. 4118H responds readily to any gas or liquid salt bath carburizing processes. The most widely used gas carburizing procedure is described below:

- Heat to 925 °C (1695 °F) in a gaseous atmosphere with a carbon potential of approximately 0.90% for the required time. About 4 h at temperature is required to attain a case depth of 1.27 mm (0.050 in.)
- Decrease temperature to 845 °C (1555 °F), decrease carbon potential slightly, and hold for a 1 h diffusion cycle
- Quench in oil
- Temper at 150 to 175 °C (300 to 345 °F). Higher tempering temperatures may be used if some case hardness can be sacrificed

Other carburizing cycles may be used. One cycle consists of slow cooling from the carburizing temperature, then reheating to 845 °C (1555 °F) and oil quenching. However, this cycle is used less frequently because it wastes energy and takes too much time. Double treatments which were extensively used at one time are all but obsolete.

Depth of carburized cases depends upon time and temperature. The rate of carburization can be increased exponentially by increasing the carburizing temperature from 925 °C (1695 °F) to 1040 °C (1905 °F) or even higher. However, the economics must be considered. As a rule, the rate of deterioration of conventional carburizing furnaces becomes intolerable as temperatures exceed 925 °C (1695 °F). Using a vacuum furnace has proved to be the most practical answer to carburizing at temperatures as high as 1095 °C (2005 °F).

Carbonitriding. 4118H is widely used in applications involving small hardware items where only a thin, file hard case is required. In carbonitriding, the parts are heated in a carburizing atmosphere with an addition of approximately 10 vol % anhydrous ammonia. Carbonitriding temperatures are most often within the range of 790 to 845 °C (1455 to 1555 °F)

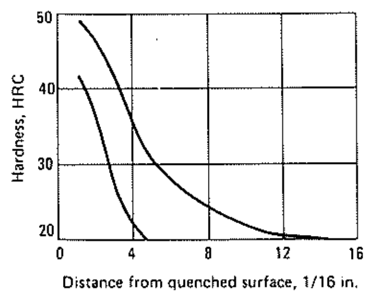
A common carbonitriding cycle for low-carbon alloy steels, such as 4118H, is to carbonitride at 815 °C (1500 °F) for 45 min and quench in oil. This results in a file hard case approximately 0.127 mm (0.005 in.) in depth. Somewhat deeper cases may be obtained by increasing the temperature, the time, or both. However, this process is designed especially for developing thin cases on small parts which will not be subjected to such finishing operations as grinding.

Tempering of carbonitrided parts is recommended (150 to 260 °C, or 300 to 500 °F), because it decreases the tendency for brittleness, although the vast majority of carbonitrided parts are placed in service without tempering

Recommended Processing Sequence

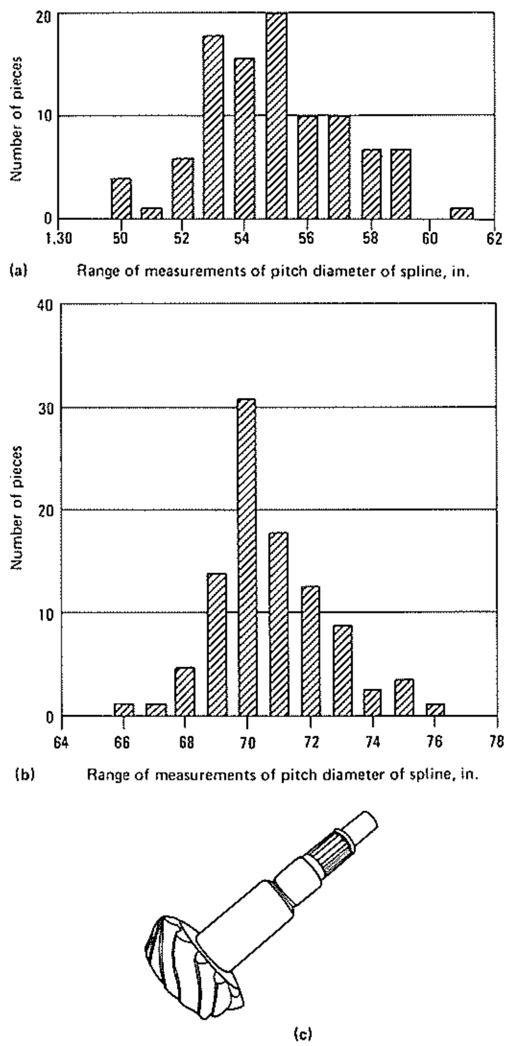
- Forge
- Normalize
- Anneal (optional)
- Rough and semifinish machine
- Case harden or direct harden
- Temper
- Finish machine (carburized parts only)

4118H: End-Quench Hardenability

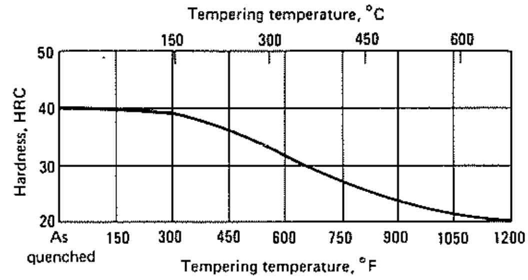


Distance from quenched surface		Hardness, HRC		Distance from quenched surface		Hardness, HRC
1/16 in.	mm	max	min	1/16 in.	mm	max
1	1.58	48	41	13	20.54	21
2	3.16	46	36	14	22.12	20
3	4.74	41	27	15	23.70	...
4	6.32	35	23	16	25.28	...
5	7.90	31	20	18	28.44	...
6	9.48	28	...	20	31.60	...
7	11.06	27	...	22	34.76	...
8	12.64	26	...	24	37.92	...
9	14.22	24	...	26	41.08	...
10	15.80	23	...	28	44.24	...
11	17.38	22	...	30	47.40	...
12	18.96	21	...	32	50.56	...

4118: Diametral Dimensions of a Pinion Before and After Carburizing and Hardening. Carburized at 885 °C (1625 °F), oil quenched from 830 °C (1525 °F), tempered at 185 °C (365 °F). Depth of case, 1.016 to 1.270 mm (0.040 to 0.050 in.). 60 HRC minimum. (a) Before treatment. (b) After treatment. (c) Differential drive pinion gear



4118, 4118H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure



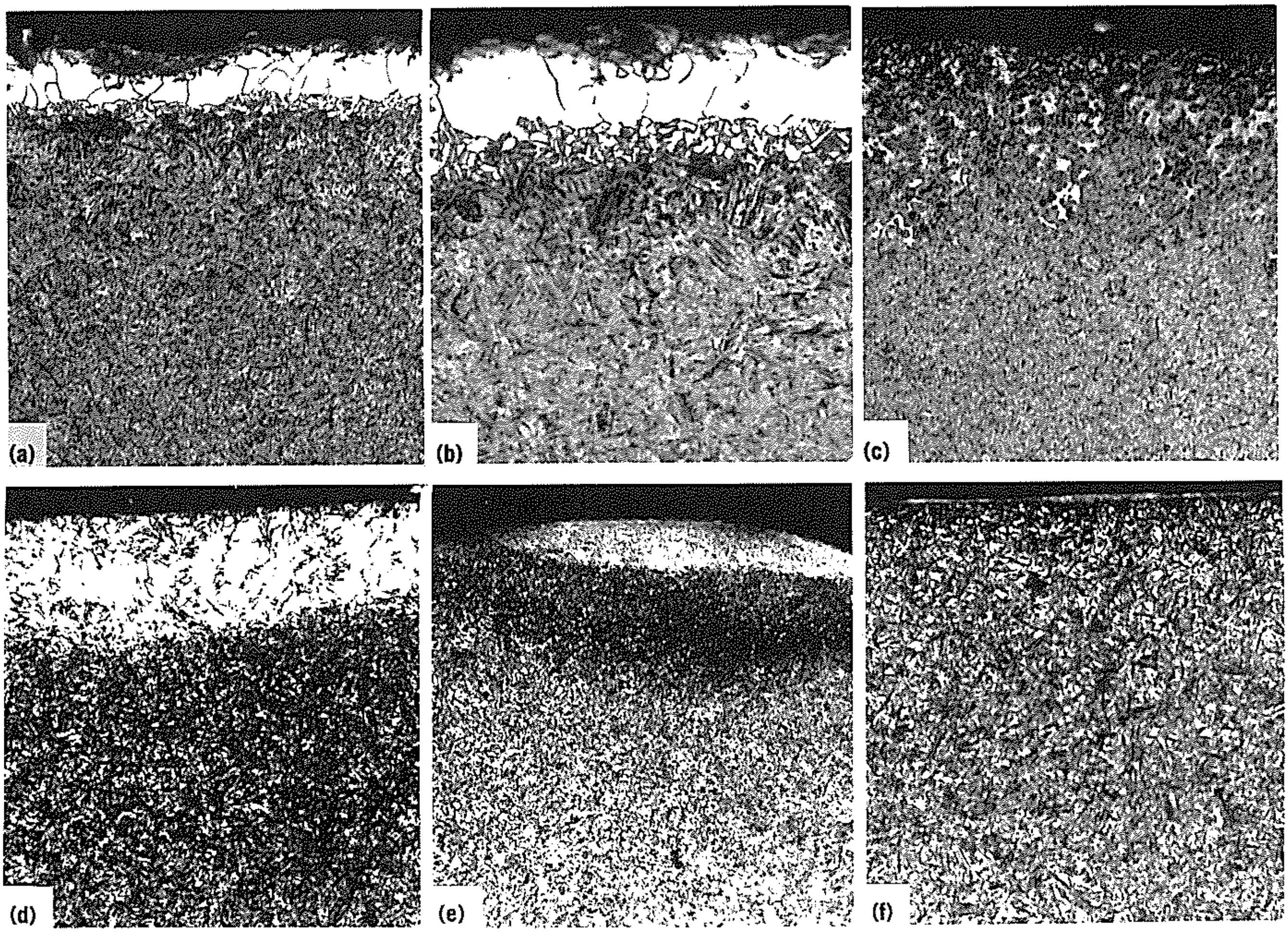
4118H: As-Quenched Hardness

Specimens were quenched in oil

Size round		Hardness		
in.	mm	Surface	½ radius	Center
0.565	14.3	33 HRC	33 HRC	33 HRC
1	25	22 HRC	20 HRC	20 HRC
2	51	88 HRB	88 HRB	87 HRB
4	102	87 HRB	87 HRB	85 HRB

Source: Bethlehem Steel

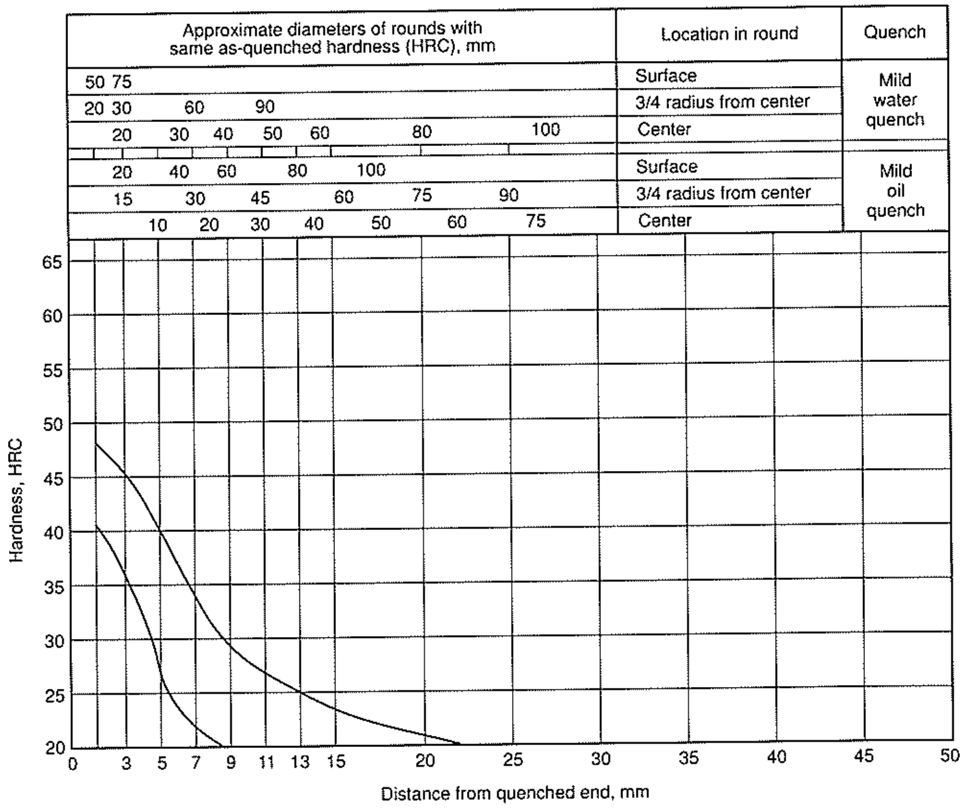
4118H: Microstructures. (a) 4% nital, 250×. Steel bar, gas carburized for 8 h at 925 °C (1695 °F), quenched in oil, heated to 845 °C (1555 °F) and held for 15 min, quenched in oil, tempered for 1 h at 170 °C (340 °F). Completely decarburized surface layer (white). Structure identified in (b). (b) 4% nital, 500×. Same as (a), but a higher magnification. Shows surface oxidation (dark at top), decarburized surface layer (ferrite), transition zone consisting of ferrite plus low-carbon martensite, and matrix of tempered martensite and retained austenite. (c) 4% nital, 100×. Carburized, hardened, and tempered same as (a), but shows only partial decarburization near surface because specimen previously contained precipitated intergranular carbide particles. Case matrix same as (b). (d) 4% nital, 250×. Steel tubing, gas carburized 5 h at 925 °C (1695 °F) and oil quenched, then hardened and tempered same as (a). Specimen shows the effect of localized overheating (burning) of the carburized surface during grinding. See (e) and (f). (e) 4% nital, 100×. Same as (d), but with less severe grinding burn. As in (d), the light-etching surface layer is untempered martensite and retained austenite (not distinguishable here), and adjacent dark-etching zone is self-tempered martensite. See (f). (f) 4% nital, 500×. Same as (d) and (e), except grinding burn is extremely slight. White surface layer (untempered martensite) is barely perceptible, and the underlying layer of self-tempered martensite is shallow. As in (d) and (e), matrix is tempered martensite



4118H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 925 °C (1700 °F)

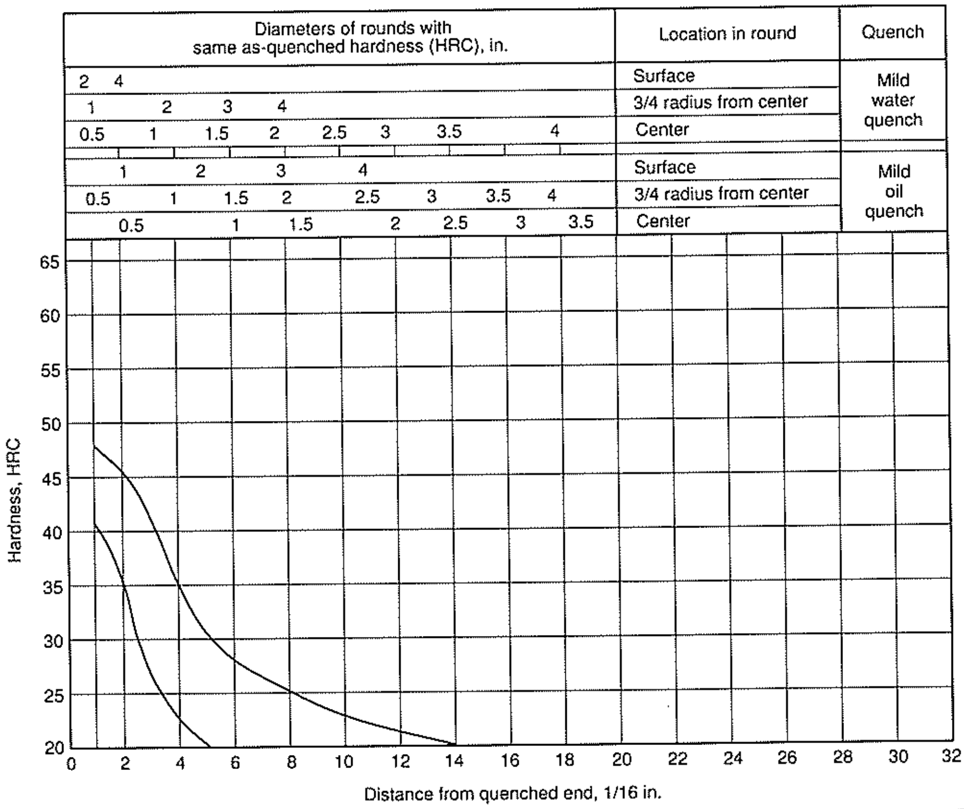
Hardness Limits for Specification Purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	48	41
3	46	37
5	40	27
7	34	22
9	29	...
11	27	...
13	25	...
15	24	...
20	21	...
25	...	...



Hardness Limits for Specification Purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	48	41
2	46	36
3	41	27
4	35	23
5	31	20
6	28	...
7	27	...
8	25	...
9	24	...
10	23	...
11	22	...
12	21	...
13	21	...
14	20	...
15	...	...



4118: Carburizing, Single Heat Results

Specimens contained 0.21 C, 0.80 Mn, 0.008 P, 0.007 S, 0.27 Si, 0.16 Ni, 0.52 Cr, 0.08 Mo; grain size was 6 to 8; critical points included Ac_1, 750 °C (1380 °F); Ac_3, 825 °C (1520 °F); Ar_3, 775 °C (1430 °F); Ar_1, 680 °C (1260 °F); 14.4-mm (0.565-in.) rounds were treated; 12.8-mm (0.505-in.) rounds were tested

	Case properties					Core properties					
						Yield strength 0.2% offset		Elongation in 2 in.			
	Hardness,	Depth		Tensile strength					Reduction	Hardness,
Recommended practice	HRC	in.	mm	ksi	MPa	ksi	MPa	(50 mm), %	of area, %	HB
For maximum case hardness										
Direct quench from pot(a)	61	0.063	1.600	177.5	1223.8	131.0	903.2	9.0	42.3	352
Single quench and temper(b)	62	0.047	1.194	143.0	985.6	93.5	644.7	17.5	41.3	293
Double quench and temper(c)	62	0.047	1.194	126.0	868.7	63.5	437.8	21.0	42.4	241
For maximum core toughness										
Direct quench from pot(d)	57	0.063	1.600	177.0	1220.4	130.0	896.3	13.0	48.0	341
Single quench and temper(e)	56	0.047	1.194	138.0	961.5	89.5	617.1	17.5	41.9	277
Double quench and temper(f)	56	0.047	1.194	120.0	827.4	63.0	434.4	22.0	48.9	229

(a) Carburized at 1700 °F (925 °C) for 8 h, quenched in agitated oil, tempered at 300 °F (150 °C). (b) Carburized at 1700 °F (925 °C) for 8 h, pot cooled, reheated to 1525 °F (830 °C), quenched in agitated oil, tempered at 300 °F (150 °C). Good case and core properties. (c) Carburized at 1700 °F (925 °C) for 8 h, pot cooled, reheated to 1525 °F (830 °C), quenched in agitated oil, tempered at 300 °F (150 °C). Maximum refinement of case and core. (d) Carburized at 1700 °F (925 °C) for 8 h, quenched in agitated oil, tempered at 450 °F (230 °C). (e) Carburized at 1700 °F (925 °C) for 8 h, pot cooled, reheated to 1525 °F (830 °C), quenched in agitated oil, tempered at 450 °F (230 °C). Good case and core properties. (f) Carburized at 1700 °F (925 °C) for 8 h, pot cooled, reheated to 1525 °F (830 °C), quenched in agitated oil, tempered at 450 °F (230 °C). Maximum refinement of case and core. Source: Bethlehem Steel

4120H, 4120RH

Chemical Composition. **4120H. AISI and UNS H41200:** 0.18 to 0.23 C, 0.90 to 1.20 Mn, 0.15 to 0.35 Si, 0.40 to 0.60 Cr, 0.13 to 0.20 Mo. **SAE 4120RH:** 0.18 to 0.23 C, 0.90 to 1.20 Mn, 0.15 to 0.35 Si, 0.40 to 0.60 Cr, 0.13 to 0.20 Mo

Similar Steels (U.S. and/or Foreign). Both steels were recently added to SAE J1268 and J1868 and to ASTM A914. There is no existing standard H-steel

Characteristics. The RH grade is made to narrower composition limits, but is carefully controlled to provide restricted hardenability. Both steels are equivalent to 8620H and 8620RH in hardenability, but have higher manganese content, no nickel, slightly higher chromium, and slightly less molybdenum. In application, these steels are alternatives for 8620

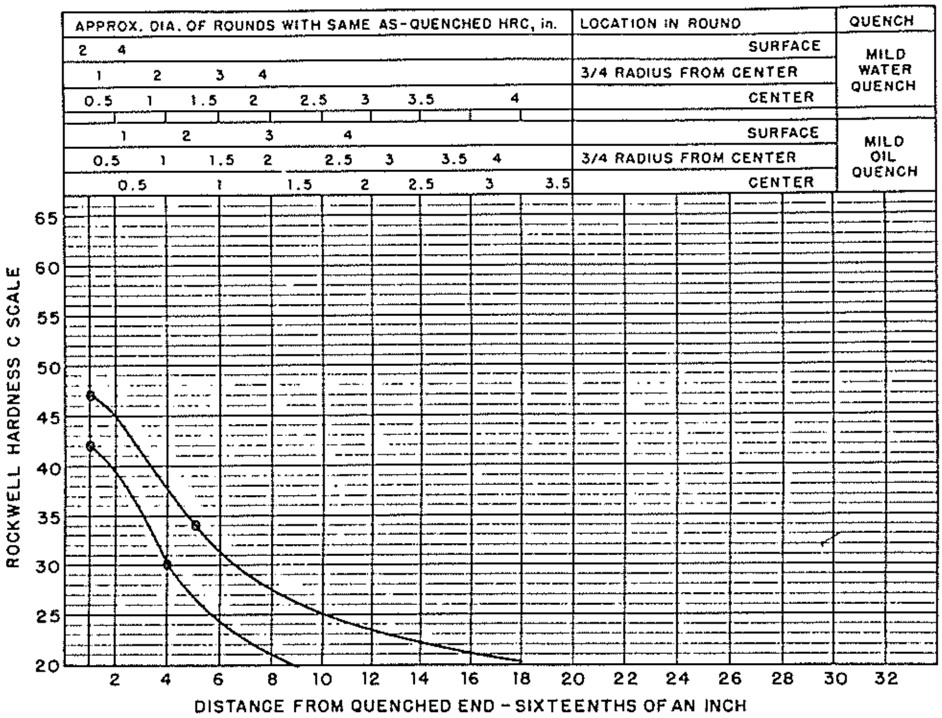
Recommended Heat Treating Practice

Hardening. Ion nitriding, gas nitriding, and carbonitriding are suitable processes

4120RH: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 925 °C (1700 °F)

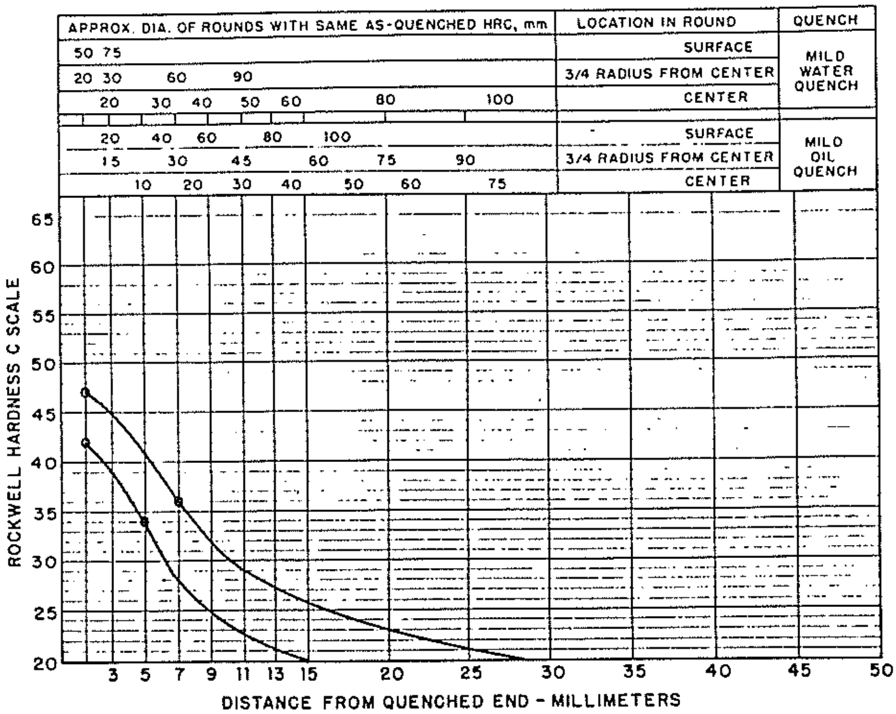
Hardness Limits for Specification Purposes

J distance, $\frac{1}{16}$ in.	Hardness, HRC Maximum	Minimum
1	47	42
2	45	39
3	41	35
4	38	30
5	34	26
6	31	24
7	29	22
8	28	21
9	26	20
10	25	...
11	24	...
12	23	...
13	23	...
14	22	...
15	22	...
16	21	...
18	20	...
20	...	...
22	...	...
24	...	...
26	...	...
28	...	...
30	...	...
32	...	...



Hardness Limits for Specification Purposes

J distance, mm	Hardness, HRC Maximum	Minimum
1.5	47	42
3	45	39
5	41	34
7	36	28
9	32	25
11	29	22
13	28	21
15	26	20
20	23	...
25	21	...
30	...	...
35	...	...
40	...	...
45	...	...
50	...	...



4130, 4130H

Chemical Composition. **4130. AISI and UNS:** 0.28 to 0.33 C, 0.40 to 0.60 Mn, 0.15 to 0.30 Si, 0.035 P max, 0.040 S max, 0.80 to 1.10 Cr, 0.15 to 0.25 Mo. **UNS H41300 and SAE/AISI 4130H:** 0.27 to 0.33 C, 0.30 to 0.70 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.75 to 1.20 Cr, 0.15 to 0.25 Mo

Similar Steels (U.S. and/or Foreign). **4130.** UNS G41300; AMS 6350, 6356, 6360, 6361, 6362, 6370, 6371, 6373; ASTM A322, A331, A505, A513, A519, A646; MIL SPEC MIL-S-16974; SAE J404, J412, J770; (Ger.) DIN 1.7218; (Fr.) AFNOR 25 CD 4(S); (Ital.) UNI 25 CrMo 4, 25 CrMo 4 KB; (Jap.) JIS SCM 2, SCCrM 1; (Swed.) SS_{14} 2225; (U.K.) B.S. CDS 110. **4130H.** UNS H41300; ASTM A304; SAE J407; (Ger.) DIN 1.7218; (Fr.) AFNOR 25 CD 4(S); (Ital.) UNI 25 CrMo 4, 25 CrMo 4 KB; (Jap.) JIS SCM 2, SCCrM 1; (Swed.) SS_{14} 2225; (U.K.) B.S. CDS 110

Characteristics. A medium-carbon alloy steel which can be oil quenched to attain a maximum as-quenched hardness of approximately 48 HRC. Its hardenability is significantly higher than that of the carbon-molybdenum (40XX) grades.

4130H is produced in a number of product forms including tubing. 4130H has been used extensively for structures such as airframes that are fabricated from tubing. 4130H is weldable, but because of its fairly high hardenability, preheating and postheating must be used

Forging. Heat to 1230 °C (2245 °F) maximum. Do not forge after temperature of forging stock drops below approximately 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F). Cool in air

Annealing. For a predominately pearlitic structure, heat to 855 °C (1570 °F), cool fairly rapidly to 760 °C (1400 °F), then to 665 °C (1230 °F) at a rate not to exceed 18 °C (35 °F) per h; or heat to 855 °C (1575 °F), cool rapidly to 675 °C (1245 °F), and hold for 4 h. For a predominately spheroidized structure, heat to 750 °C (1380 °F), cool from 750 °C (1380 °F) to 665 °C (1230 °F) at a rate not to exceed 6 °C (10 °F) per h; cool rapidly from 750 °C (1380 °F) to 675 °C (1245 °F), and hold for 8 h

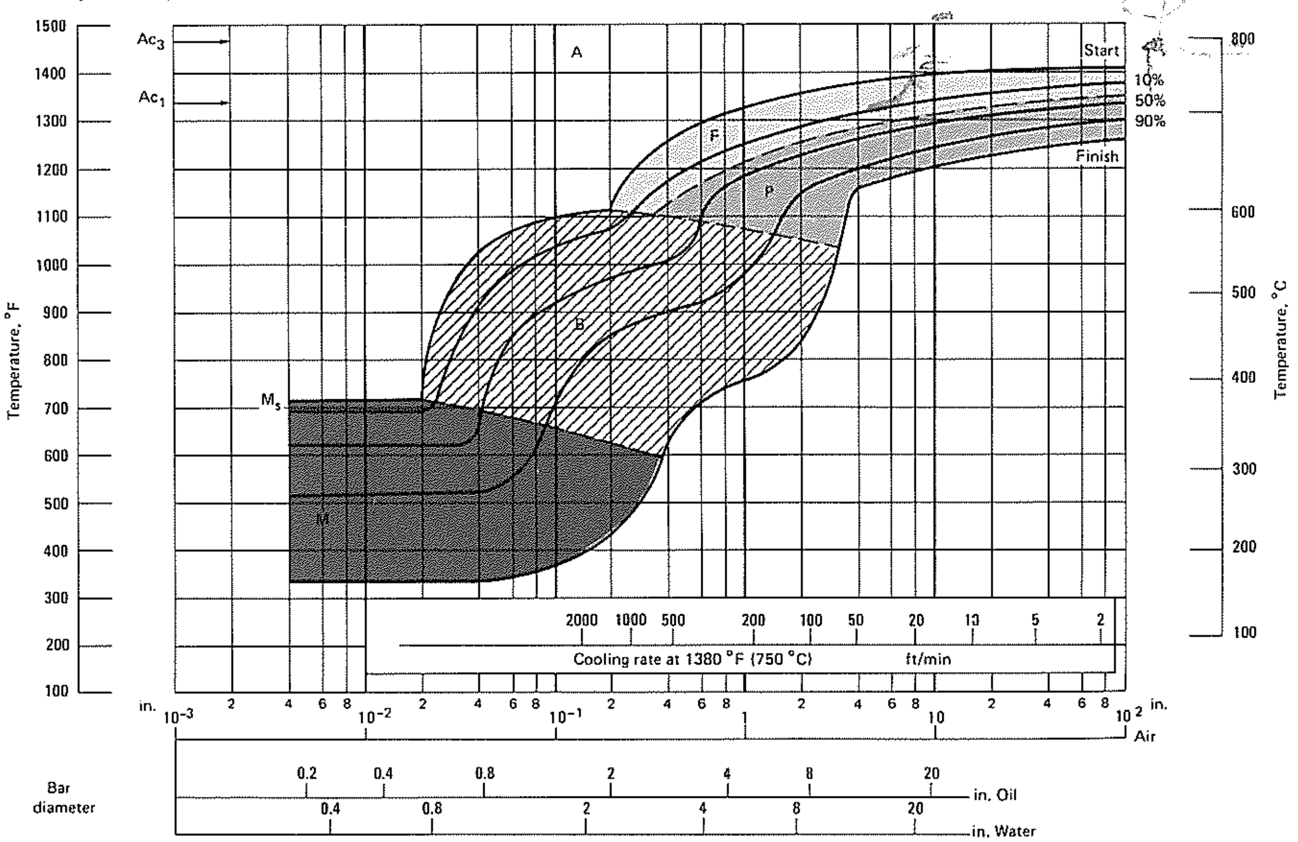
Hardening. Austenitize at 870 °C (1600 °F), and quench in oil

Tempering.
Reheat to the temperature which will result in the required hardness

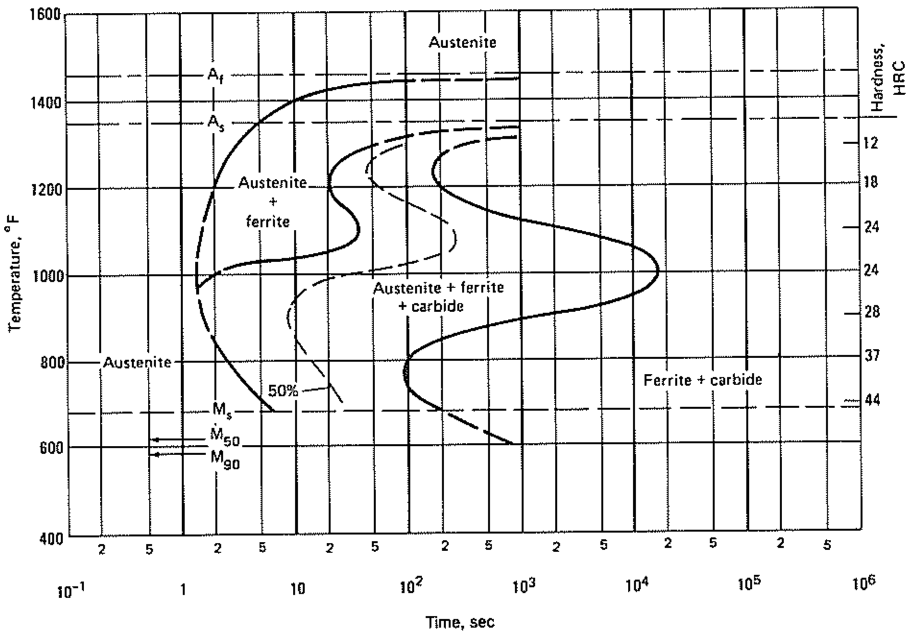
Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize and quench
- Temper
- Finish machine

4130: Continuous Cooling Transformation Diagram. Composition: 0.30 C, 0.50 Mn, 0.020 P, 0.020 S, 0.25 Si, 1.00 Cr, 0.20 Mo. Austenitized at 850 °C (1560 °F)

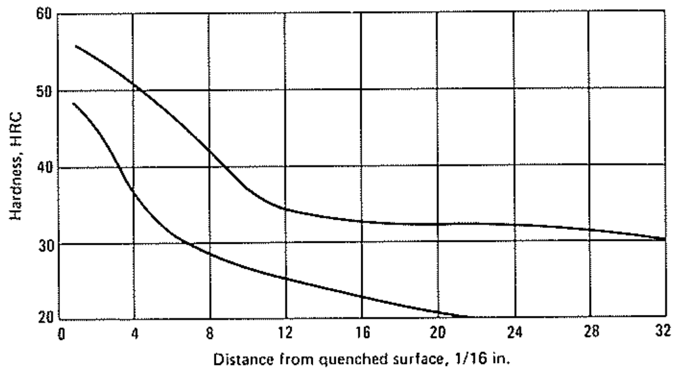


4130: Isothermal Transformation Diagram. Composition: 0.33 C, 0.53 Mn, 0.90 Cr, 0.18 Mo. Austenitized at 845 °C (1555 °F). Grain size: 9 to 10



4130H: End-Quench Hardenability

Distance from quenched surface, 1⁄16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1⁄16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min
1	1.58	56	49	13	20.54	34	24
2	3.16	55	46	14	22.12	34	24
3	4.74	53	42	15	23.70	33	23
4	6.32	51	38	16	25.28	33	23
5	7.90	49	34	18	28.44	32	22
6	9.48	47	31	20	31.60	32	21
7	11.06	44	29	22	34.76	32	20
8	12.64	42	27	24	37.92	31	...
9	14.22	40	26	26	41.08	31	...
10	15.80	38	26	28	44.24	30	...
11	17.38	36	25	30	47.40	30	...
12	18.96	35	25	32	50.56	29	...



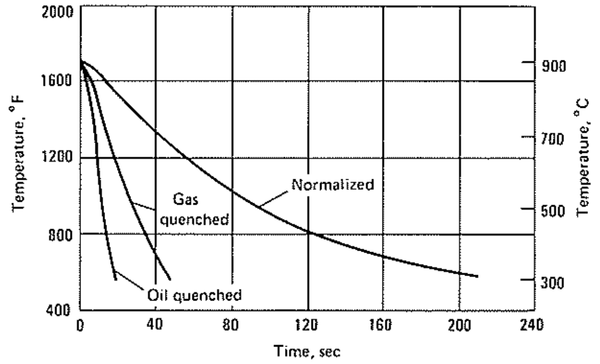
4130: As-Quenched Hardness

Specimens were quenched in water

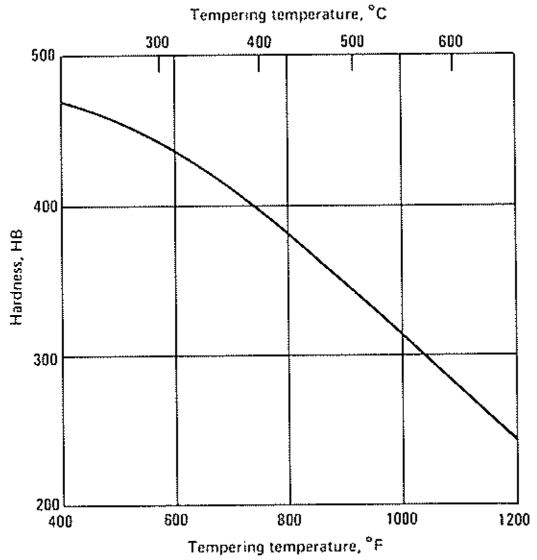
Size round		Hardness, HRC		
in.	mm	Surface	½ radius	Center
½	13	51	50	50
1	25	51	50	44
2	51	47	32	31
4	102	45.5	25	24.5

Source: Bethlehem Steel

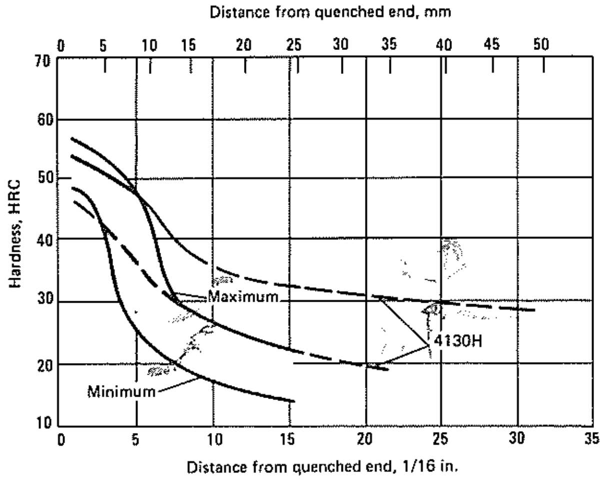
4130: Cooling Curves. Steel tubing. 31.75 mm (1.25 in.) outside diameter by 1.651 mm (0.065 in.) wall



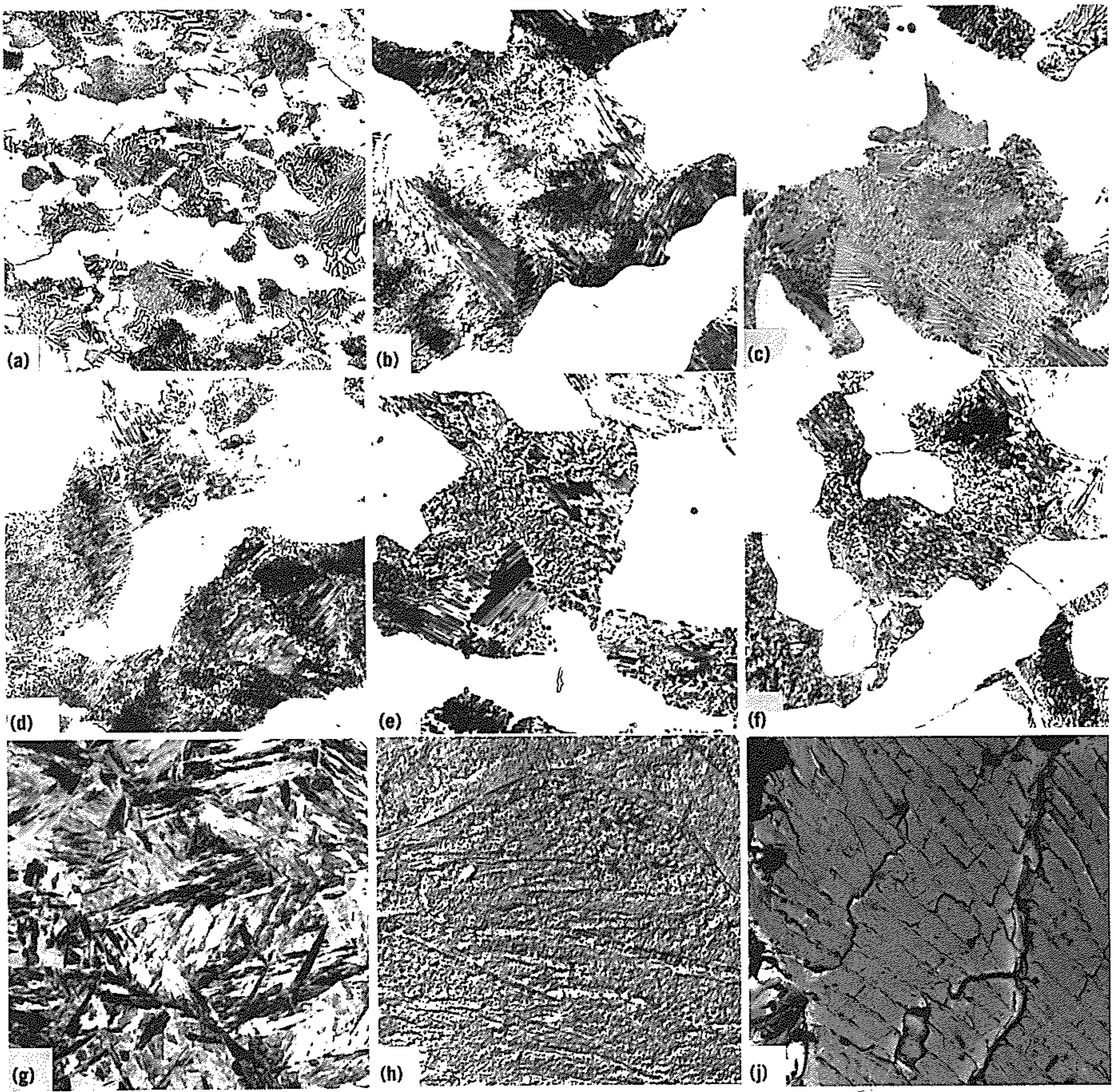
4130: Hardness vs Tempering Temperature. Normalized at 900 °C (1650 °F). Quenched from 870 °C (1600 °F) in water and tempered at 56 °C (100 °F) intervals in 13.7 mm (0.540 in.) rounds. Source: Republic Steel



4130H: End-Quench Hardenability. 48 heats of 14B35 containing 0.35 to 0.39 C, 0.65 to 1.10 Mn, 0.13 Ni max, 0.05 Cr max, 0.03 Mo max and boron treated; compared with 4130H



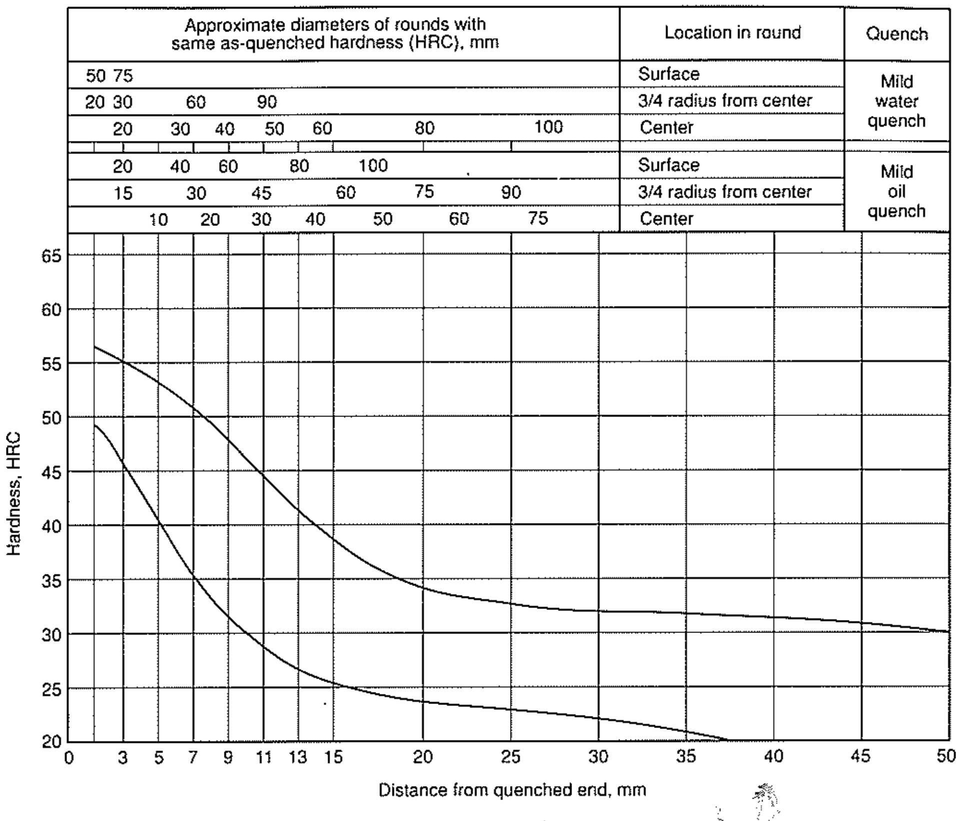
4130: Microstructures. (a) 2% nital, 500×. Normalized by austenitizing at 870 °C (1600 °F) and air cooling to room temperature. Ferrite (white areas) and lamellar pearlite (dark areas). Specimen shows slight banding. (b) 2% nital, 750×. Hot rolled steel bar, 25.4 mm (1 in.) diam, annealed by austenitizing at 845 °C (1555 °F) and cooling slowly in the furnace. Coarse lamellar pearlite (dark areas) in a matrix of ferrite (white). (c) 2% nital, 750×. Hot rolled steel bar 25.4 mm (1 in.) diam, austenitized at 845 °C (1555 °F) for 1 h, cooled to 675 °C (1245 °F) and held for 2 h, and air cooled. Partly spheroidized pearlite (dark) in a matrix of ferrite (white). (d) 2% nital, 750×. Same as (c), except the time at 675 °C (1245 °F) was increased to 4 h. Structure essentially the same as (c), except the degree of spheroidization of the pearlite is greater. (e) 2% nital, 750×. Same as (c) and (d), except the time at 675 °C (1245 °F) was increased to 8 h. Structure is similar to those shown in (c) and (d), except the degree of spheroidization of the pearlite has increased further. (f) 2% nital, 750×. Same as (c), (d), and (e), except that the time at 675 °C (1245 °F) was increased to 16 h. The degree of spheroidization is greater than in (e). (g) 2% nital, 750×. Hot rolled steel bar, 25.4 mm (1 in.) diam, austenitized at 870 °C (1600 °F) for 1 h and water quenched. Untempered martensite. (h) 5% picric acid, 2 ½% HNO_3, in ethanol; 11 000×. Same as (g), except an electron micrograph of a platinum-carbon-shadowed two-stage carbon replica. Untempered martensite. (j) Not polished, not etched; 8600×. Annealed. Replica electron fractograph. Note fatigue striations, resolved only at high magnification



4130H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 900 °C (1650 °F). Austenitize: 870 °C (1600 °F)

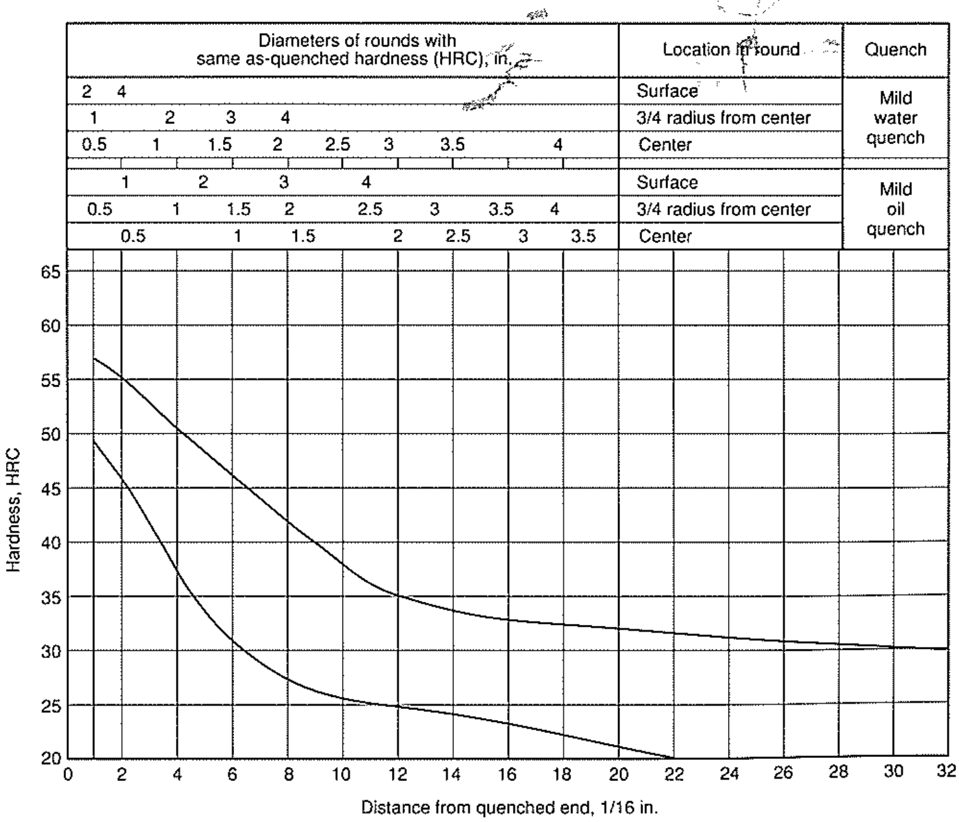
Hardness Limits for Specification Purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	56	49
3	55	46
5	53	40
7	51	36
9	48	32
11	44	28
13	41	26
15	39	25
20	34	24
25	33	23
30	33	22
35	32	20
40	31	...
45	31	...
50	30	...



Hardness Limits for Specification Purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	56	49
2	55	46
3	53	42
4	51	38
5	49	34
6	47	31
7	44	29
8	42	27
9	40	26
10	38	26
11	36	25
12	35	25
13	34	24
14	34	24
15	33	23
16	33	23
18	32	22
20	32	21
22	32	20
24	31	...
26	31	...
28	30	...
30	30	...
32	29	...



4135, 4135H

Chemical Composition. **4135. AISI:** 0.33 to 0.38 C, 0.70 to 0.90 Mn, 0.80 to 1.10 Cr, 0.035 P max, 0.040 S max, 0.15 to 0.25 Mo. **UNS:** 0.33 to 0.38 C, 0.70 to 0.90 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.80 to 1.10 Cr, 0.70 to 0.90 Mo. **UNS H41350 and SAE/AISI 4135H:** 0.32 to 0.38 C, 0.60 to 1.00 Mn, 0.15 to 0.35 Si, 0.75 to 1.20 Cr, 0.15 to 0.25 Mo

Similar Steels (U.S. and/or Foreign). **4135.** UNS G41350; AMS 6365 C, 6372 C; ASTM A274, A355, A519; MIL SPEC MIL-S-16974, MIL-S-18733; SAE J404, J412, J770; (Ger.) DIN 1.7220; (Fr.) AFNOR 35 CD 4, 35 CD 4 TS; (Ital.) UNI 35 CrMo 4, 35 CrMo 4 F, 34 CrMo 4 KB; (Jap.) JIS SCM 1, SCCrM 3; (Swed.) SS_{14} 2234; (U.K.) B.S. 708 A 37. **4135H.** UNS H41350; ASTM A304; SAE J1268; (Ger.) DIN 1.7220; (Fr.) AFNOR 35 CD 4, 35 CD 4 TS; (Ital.) UNI 35 CrMo 4, 35 CrMo 4 F, 34 CrMo 4 KB; (Jap.) JIS SCM 1, SCCrM 3; (Swed.) SS_{14} 2234; (U.K.) B.S. 708 A 37

Characteristics. 4135H has generally the same characteristics as 4130H, except the higher mean carbon content results in a slightly higher as-quenched hardness, about 50 to 52 HRC for 4135H. In addition, the higher mean manganese content of 4135H results in higher hardenability. Compare hardenability data for 4130H with 4135H. Also, as the hardenability increases, the suitability for welding decreases. Forgeability of 4135H is very good

Forging. Heat to 1230 °C (2245 °F) maximum. Do not forge after temperature of forging stock drops below approximately 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F). Cool in air.

In aerospace practice, normalize at 900 °C (1650 °F)

Annealing. For a predominately pearlitic structure, heat to 855 °C (1570 °F), cool fairly rapidly to 760 °C (1400 °F), then to 665 °C (1230 °F) at a rate not to exceed 19 °C (35 °F) per h; or heat to 855 °C (1570 °F), cool rapidly to 675 °C (1245 °F), and hold for 4 h. For a predominately spheroidized structure, heat to 750 °C (1380 °F), cool from 750 °C (1380 °F) to 665 °C (1230 °F) at a rate not to exceed 6 °C (10 °F) per h; or cool rapidly from 750 °C (1380 °F) to 675 °C (1245 °F), and hold for 8 h. Anneal at 845 °C (1555 °F); cool to below 540 °C (1000 °F) at a rate not to exceed 110 °C (200 °F) per h

Hardening. Austenitize at 870 °C (1600 °F), and quench in oil or polymer. Flame hardening, ion nitriding, gas nitriding, and carbonitriding are suitable processes.

In aerospace practice, austenitize at 855 °C (1570 °F). Quench in oil or polymer

Tempering. Reheat to the temperature which will result in the required hardness.

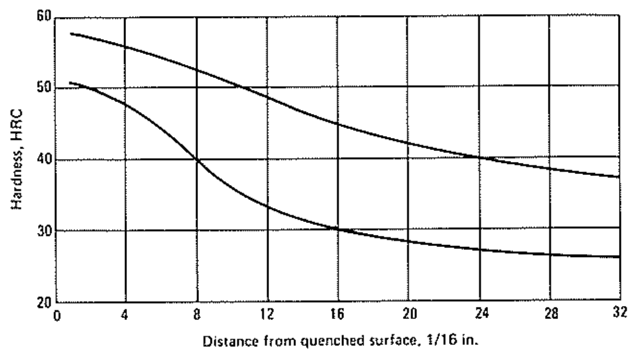
In aerospace practice, see table for suggested tempering temperatures per different tensile strengths. Quenchants include oil and polymers

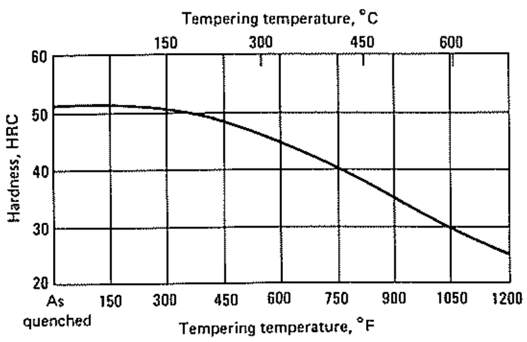
Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize and quench
- Temper
- Finish machine

4135H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max	min	Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max	min
1	1.58	58	51	13	20.54	48	32
2	3.16	58	50	14	22.12	47	31
3	4.74	57	49	15	23.70	46	30
4	6.32	56	48	16	25.28	45	30
5	7.90	56	47	18	28.44	44	29
6	9.48	55	45	20	31.60	42	28
7	11.06	54	42	22	34.76	41	27
8	12.64	53	40	24	37.92	40	27
9	14.22	52	38	26	41.08	39	27
10	15.80	51	36	28	44.24	38	26
11	17.38	50	34	30	47.40	38	26
12	18.96	31	33	32	50.56	37	26



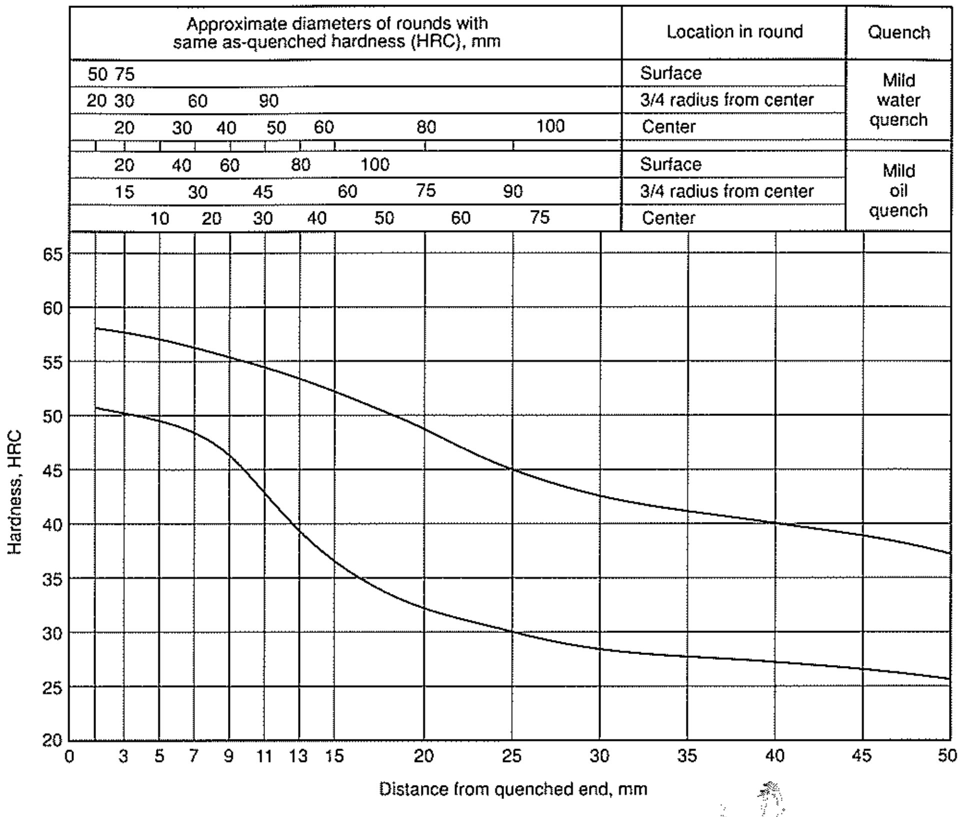


4135, 4135H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

4135H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

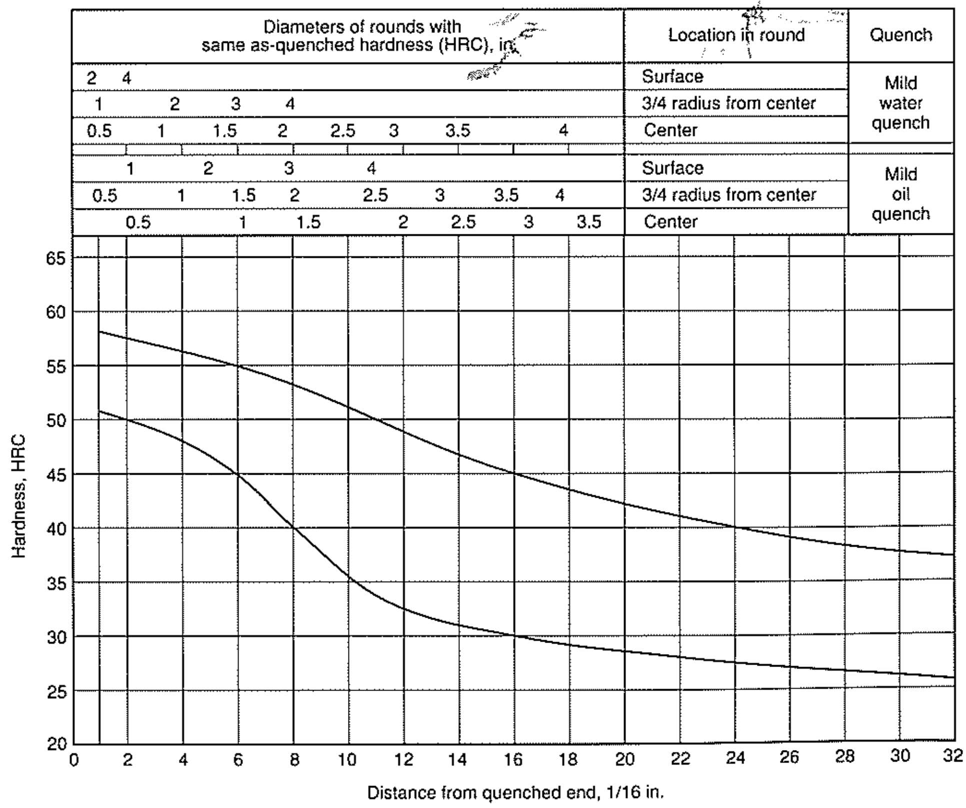
Hardness Limits for Specification Purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	58	51
3	58	50
5	57	49
7	56	48
9	56	46
11	55	42
13	53	39
15	52	37
20	49	32
25	45	30
30	43	28
35	41	27
40	40	27
45	39	26
50	37	26



Hardness Limits for Specification Purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	58	51
2	58	50
3	57	49
4	56	48
5	56	47
6	55	45
7	54	42
8	53	40
9	52	38
10	51	36
11	50	34
12	49	33
13	48	32
14	47	31
15	46	30
16	45	30
18	44	29
20	42	28
22	41	27
24	40	27
26	39	27
28	38	26
30	38	26
32	37	26



4135: Suggested Tempering Temperatures (Aerospace Practice)(a)

Tensile strength ranges				
620-860 MPa (90-125 ksi)	860-1035 MPa (125-150 ksi)	1035-1175 MPa (150-170 ksi)	1175-1240 MPa (160-180 ksi)	1240-1380 MPa (180-200 ksi)
675 °C (1550 °F)	605 °C (1250 °F)	550 °C (1125 °F)	480 °C (900 °F)	425 °C (800 °F)

(a) Quench in oil or polymer. Source: AMS 2759/1

4135: Suggested Tempering Temperatures Based on As-Quenched Hardness (Aerospace Practice)

Tensile strength range	As-Quenched Hardness RC 47-49	RC 50-52	RC 53-55
860 to 1035 MPa (125 to 150 ksi)	500 °C (1025 °F)	595 °C (1100 °F)	650 °C (1200 °F)
965 to 1035 MPa (140 to 160 ksi)	510 °C (950 °F)	550 °C (1025 °F)	595 °C (1100 °F)
1035 to 1175 MPa (150 to 170 ksi)	470 °C (875 °F)	510 °C (950 °F)	550 °C (1025 °F)
1175 to 1310 MPa (170 to 190 ksi)	425 °C (800 °F)	480 °C (900 °F)	525 °C (975 °F)
1240 to 1380 MPa (180 to 200 ksi)	400 °C (750 °F)	455 °C (850 °F)	495 °C (925 °F)

Source: AMS 2759/1

4137, 4137H

Chemical Composition. **4137. AISI and UNS:** 0.35 to 0.40 C, 0.70 to 0.90 Mn, 0.15 to 0.30 Si, 0.80 to 1.10 Cr, 0.035 P max, 0.040 S max, 0.15 to 0.25 Mo. **UNS H41370 and SAE/AISI 4137H:** 0.34 to 0.41 C, 0.60 to 1.00 Mn, 0.15 to 0.35 Si, 0.75 to 1.20 Cr, 0.15 to 0.25 Mo

Similar Steels (U.S. and/or Foreign). **4137.** UNS G41370; ASTM A322, A331, A505, A519, A547; SAE J404, J412, J770; (Ger.) DIN 1.7225; (Fr.) AFNOR 40 CD 4, 42 CD 4; (Ital.) UNI G 40 CrMo 4, 38 CrMo 4 KB, 40 CrMo 4; (Jap.) JIS SCM 4 H, SCM 4; (Swed.) SS_{14} 2244; (U.K.) B.S. 708 A 42, 708 M 40, 709 M 40. **4137H.** UNS H41370; ASTM A304; SAE J1268; (Ger.) DIN 1.7225; (Fr.) AFNOR 40 CD 4, 42 CD 4; (Ital.) UNI G 40 CrMo 4, 40 CrMo 4, 38 CrMo 4 KB; (Jap.) JIS SCM 4 H, SCM 4; (Swed.) SS_{14} 2244; (U.K.) B.S. 708 A 42, 708 A 40, 709 A 40

Characteristics. A typical medium-carbon, moderately high hardenability steel. Often referred to as a shaft steel, 4137H is frequently used for a variety of shaft applications in the quenched and tempered condition. Depending upon the precise carbon content, the as-quenched hardness of fully hardened 4137H is generally about 52 HRC or slightly higher, usually a little higher than 4135H, but not as high as for 4140H. The hardenability pattern is essentially the same for 4137H as shown for 4135H; the only difference is that the band is moved upward for 4137H because of the higher carbon content. Forgeability of 4137H is very good, but machinability is only fair and welding, although possible, is seldom recommended

Forging. Heat to 1230 °C (2245 °F). Do not forge after temperature of forging stock drops below approximately 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

Annealing. For a predominately pearlitic structure, heat to 845 °C (1555 °F), cool fairly rapidly to 755 °C (1390 °F), then cool from 755 °C (1390 °F) to 665 °C (1230 °F) at a rate not to exceed 14 °C (25 °F) per h; or heat to 845 °C (1555 °F), cool rapidly to 675 °C (1245 °F), and hold for 5 h. For a predominately spheroidized structure, heat to 750 °C (1380 °F), cool to 665 °C (1230 °F) at a rate not to exceed 6 °C (10 °F) per h; or heat to 750 °C (1380 °F), cool fairly rapidly to 675 °C (1245 °F), and hold for 9 h

Hardening. Austenitize at 855 °C (1570 °F), and quench in oil. Carbonitriding, salt bath and gas nitriding, and ion nitriding are suitable processes

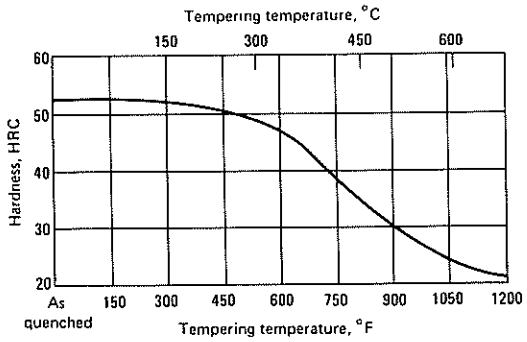
Tempering. Reheat after quenching to the temperature shown by the hardness-tempering temperature curve to obtain the required hardness for these specific steels

Nitriding. If nitriding is considered, the steel must be treated (hardened and tempered), and nitriding must be done on finished parts because any finishing operation will remove the most useful portion of the case. First, use a typical processing cycle consisting of: rough machining, austenitizing at 845 °C (1555 °F), oil quenching, tempering at 620 °C (1150 °F), and finish machining. Then, nitride in ammonia gas at 525 °C (975 °F) for 24 h, using an ammonia dissociation of 30%; or nitride at 525 °C (975 °F) for 5 h with an ammonia dissociation of 25%, then at 565 °C (1050 °F) for 20 h with an ammonia dissociation of 75 to 80%. Certain proprietary salt bath nitriding processes are also applicable for surface hardening

Recommended Processing Sequence

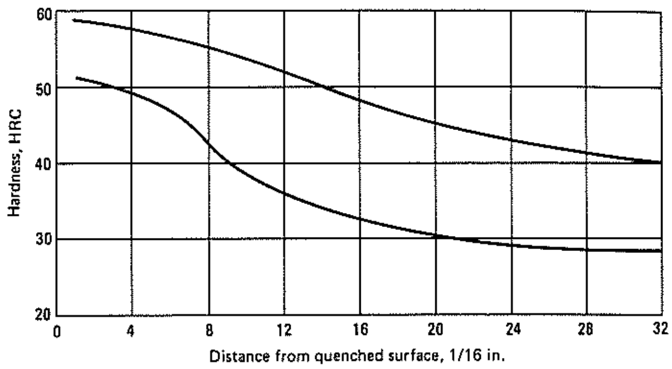
- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine
- Nitride (optional)

4137, 4137H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

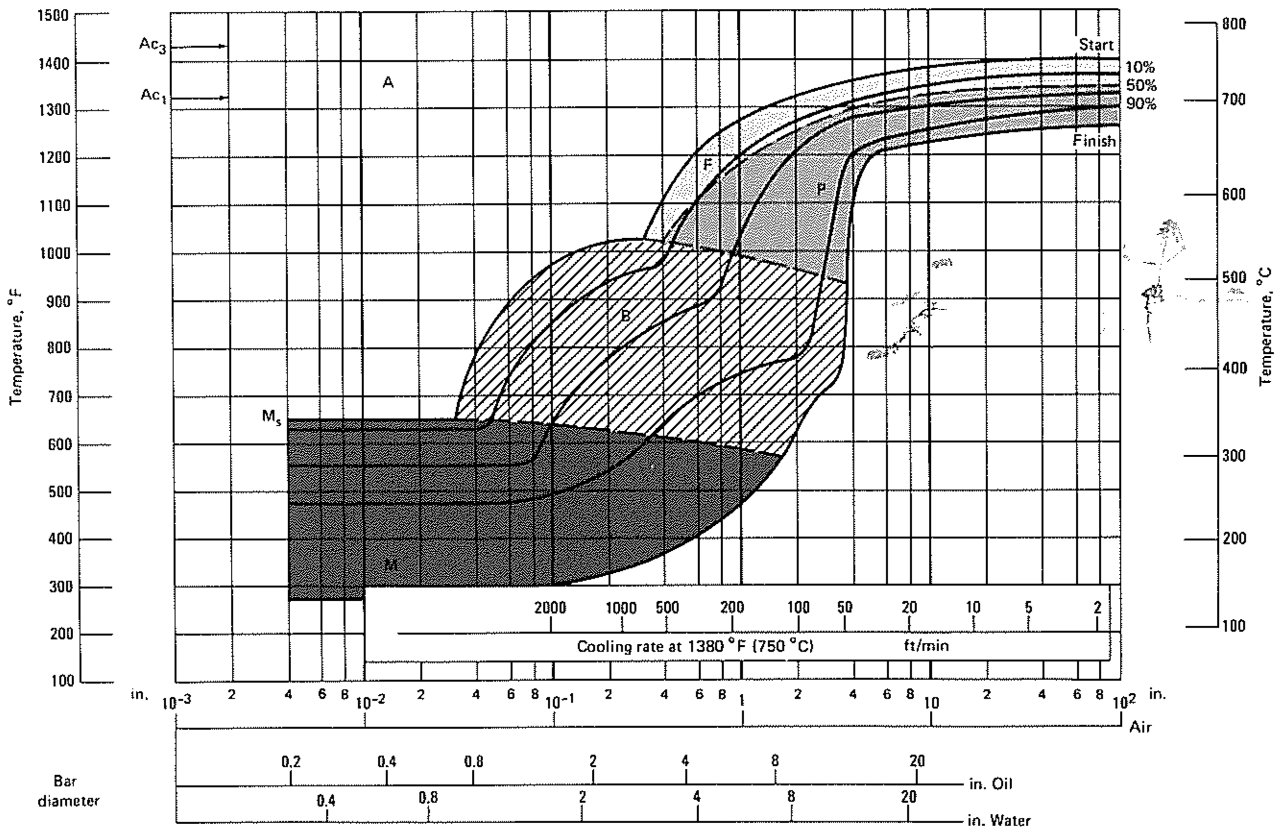


4137H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min
1	1.58	59	52	13	20.54	51	35
2	3.16	59	51	14	22.12	50	34
3	4.74	58	50	15	23.70	49	33
4	6.32	58	49	16	25.28	48	33
5	7.90	57	49	18	28.44	46	32
6	9.48	57	48	20	31.60	45	31
7	11.06	56	45	22	34.76	44	30
8	12.64	55	43	24	37.92	43	30
9	14.22	55	40	26	41.08	42	30
10	15.80	54	39	28	44.24	42	29
11	17.38	53	37	30	47.40	41	29
12	18.96	52	36	32	50.56	41	29



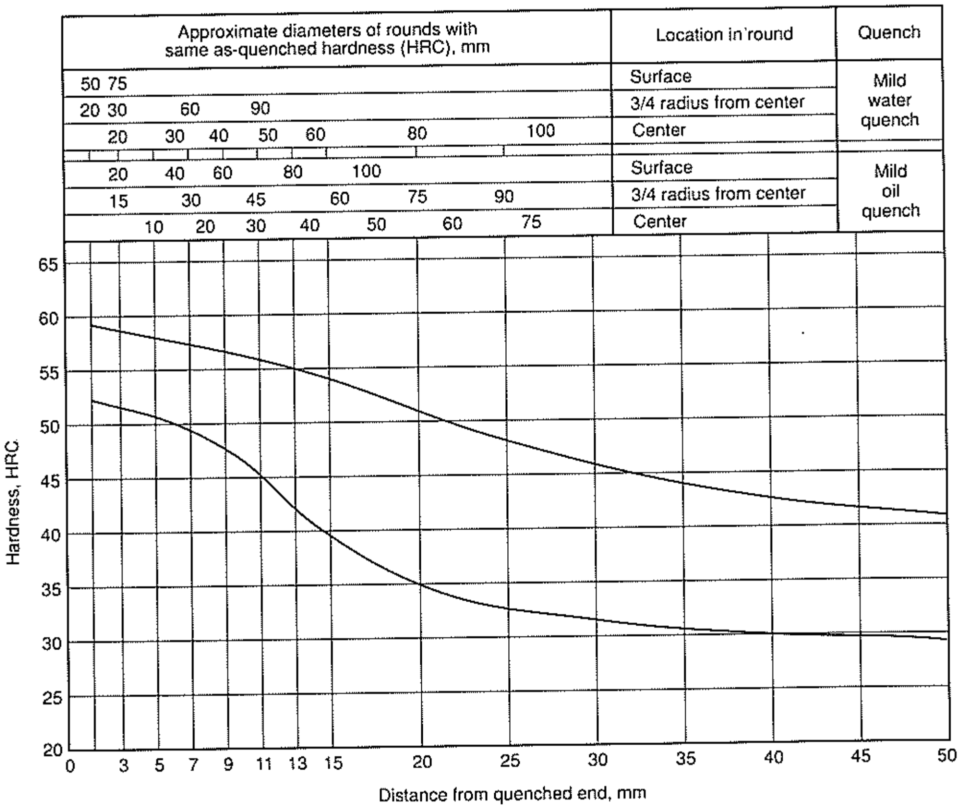
4137: Continuous Cooling Transformation Diagram. Composition: 0.36 C, 0.80 Mn, 0.020 P, 0.020 S, 0.25 Si, 1.00 Cr, 0.20 Mo. Austenitized at 860 °C (1580 °F)



4137H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

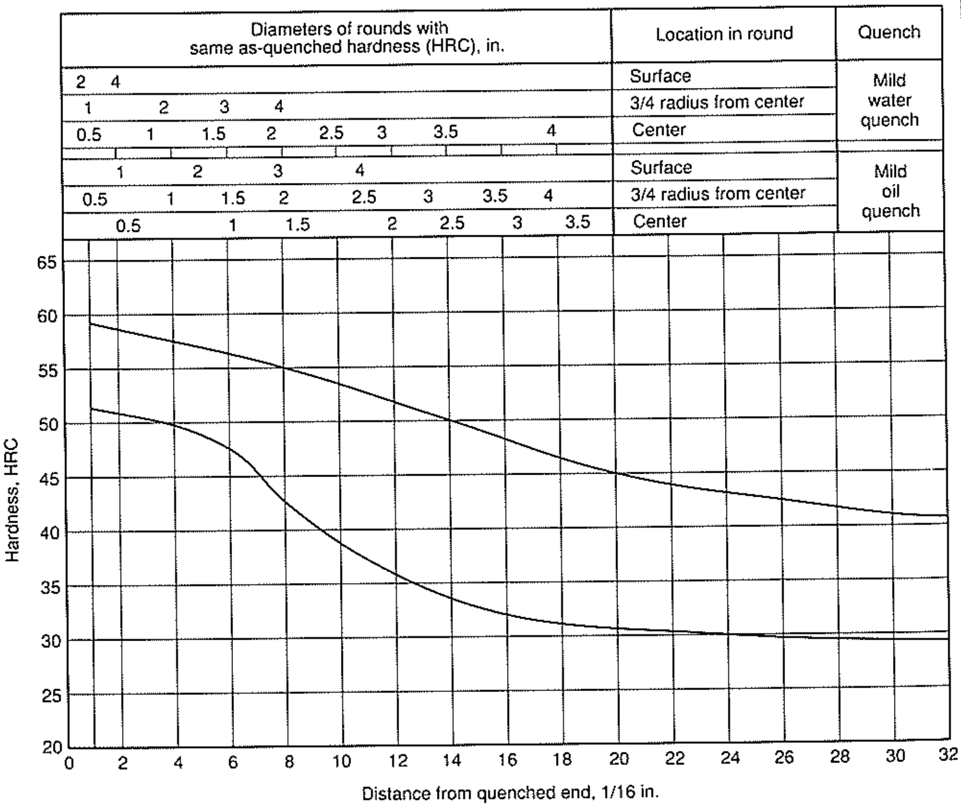
Hardness Limits for Specification Purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	59	52
3	59	51
5	58	50
7	58	49
9	57	48
11	56	45
13	55	42
15	55	39
20	52	35
25	48	33
30	46	31
35	44	30
40	43	29
45	42	29
50	41	29



Hardness Limits for Specification Purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	59	52
2	59	51
3	58	50
4	58	49
5	57	49
6	57	48
7	56	45
8	55	43
9	55	40
10	54	39
11	53	37
12	52	36
13	51	35
14	50	34
15	49	33
16	48	33
18	46	32
20	45	31
22	44	30
24	43	30
26	42	30
28	42	29
30	41	29
32	41	29



4140, 4140H

Chemical Composition. **4140. AISI and UNS:** 0.38 to 0.43 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.80 to 1.10 Cr, 0.15 to 0.25 Mo. **4140H. AISI and UNS:** 0.37 to 0.44 C, 0.65 to 1.10 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.75 to 1.20 Cr, 0.15 to 0.25 Mo

Similar Steels (U.S. and/or Foreign). **4140.** UNS G41400; AMS 6381, 6382, 6390, 6395; ASTM A322, A331, A505, A519, A547, A646; MIL SPEC MIL-S-16974; SAE J404, J412, J770; (Ger.) DIN 1.7225; (Fr.) AFNOR 40 CD 4, 42 CD 4; (Ital.) UNI 40 CrMo 4, G 40 CrMo 4, 38 CrMo 4 KB; (Jap.) JIS SCM 4 H, SCM 4; (Swed.) SS_{14} 2244; (U.K.) B.S. 708 A 42, 708 M 40, 709 M 40. **4140H.** UNS H41400; ASTM A304; SAE J407; (Ger.) DIN 1.7225; (Fr.) AFNOR 40 CD 4, 42 CD 4; (Ital.) UNI G 40 CrMo 4, 40 CrMo 4, 38 CrMo 4 KB; (Jap.) JIS SCM 4 H, SCM 4; (Swed.) SS_{14} 2244; (U.K.) B.S. 708 A 42, 708 M 40, 709 M 40

Characteristics. Among the most widely used medium-carbon alloy steels. Relatively inexpensive considering the relatively high hardenability 4140H offers. Fully hardened 4140H ranges from about 54 to 59 HRC, depending upon the exact carbon content. Forgeability is very good, but machinability is only fair and weldability is poor, because of susceptibility to weld cracking

Forging. Heat to 1230 °C (2250 °F). Do not forge after temperature of forging stock drops below approximately 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

Annealing. For a predominately pearlitic structure, heat to 845 °C (1555 °F), cool fairly rapidly to 755 °C (1390 °F), then cool from 755 °C (1390 °F) to 665 °C (1230 °F), at a rate not to exceed 14 °C (25 °F) per h; or heat to 845 °C (1555 °F), cool rapidly to 675 °C (1245 °F), and hold for 5 h. For a predominately spheroidized structure, heat to 750 °C (1380 °F), cool to 665 °C (1230 °F) at a rate not to exceed 6 °C (10 °F) per h; or heat to 750 °C (1380 °F), cool fairly rapidly to 675 °C (1245 °F), and hold for 9 h

Hardening. Austenitize at 855 °C (1570 °F), and quench in oil

Tempering. Reheat after quenching to obtain the required hardness

Nitriding. 4140H responds to the ammonia gas nitriding process, resulting in a thin, file hard case, the outer portion of which is composed of epsilon nitride. This constituent not only provides an abrasion-resistant surface, but also increases fatigue strength of components such as shafts by as much as 30%. However, if nitriding is considered, the steel must be pretreated (hardened and tempered), and nitriding must be done on finished parts because any finishing operation will remove the most useful portion of the case. A typical processing cycle that includes nitriding is:

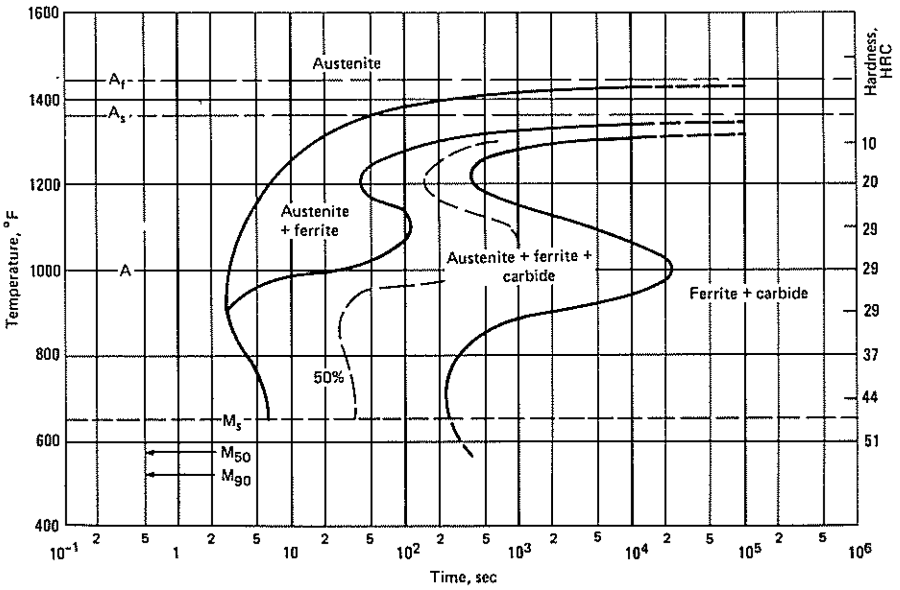
- Rough machine
- Austenitize at 845 °C (1555 °F)
- Oil quench
- Temper at 620 °C (1150 °F)
- Finish machine
- Nitride at 525 °C (975 °F) for 24 h, using an ammonia dissociation of 30%; or nitride at 525 °C (975 °F) for 5 h with an ammonia dissociation of 25%, then at 565 °C (1050 °F) for 20 h with an ammonia dissociation of 75 to 80%

Certain proprietary salt bath nitriding processes are also applicable for surface hardening of 4140H

Recommended Processing Sequence

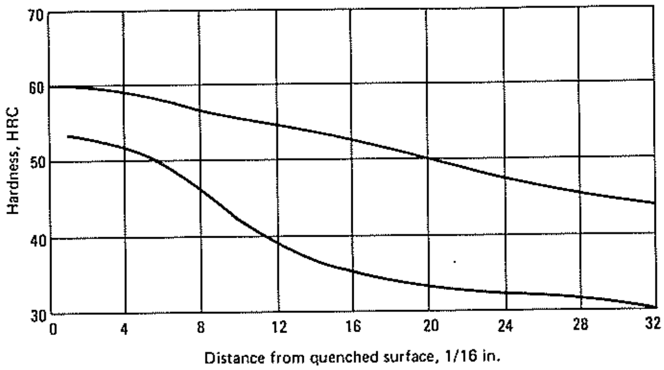
- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine
- Nitride (optional)

4140: Isothermal Transformation Diagram. Composition: 0.37 C, 0.77 Mn, 0.98 Cr, 0.21 Mo. Austenitized at 845 °C (1555 °F) Grain size: 7 to 8

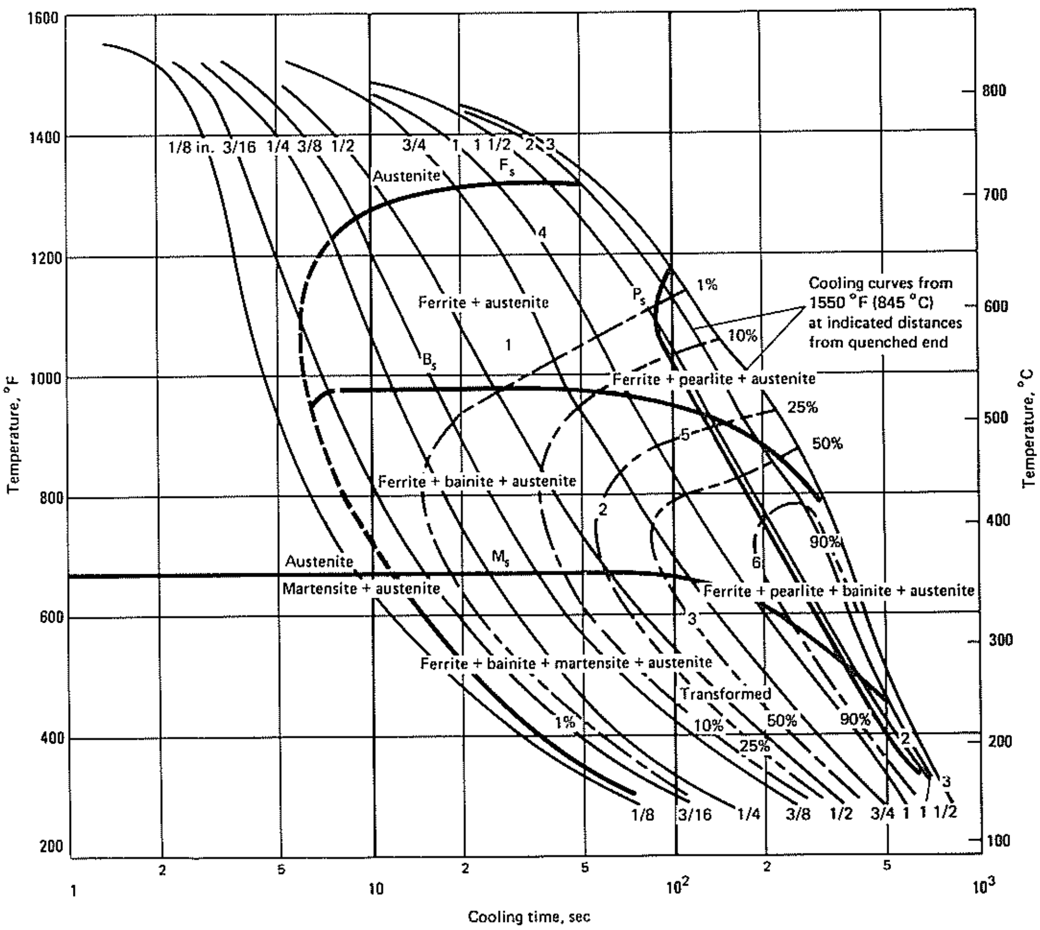


4140H: End-Quench Hardenability

Distance from quenched surface		Hardness, HRC		Distance from quenched surface		Hardness, HRC	
1/16 in.	mm	max	min	1/16 in.	mm	max	min
1	1.58	60	53	13	20.54	55	38
2	3.16	60	53	14	22.12	54	37
3	4.74	60	52	15	23.70	54	36
4	6.32	59	51	16	25.28	53	35
5	7.90	59	51	18	28.44	52	34
6	9.48	58	50	20	31.60	51	33
7	11.06	58	48	22	34.76	49	33
8	12.64	57	47	24	37.92	48	32
9	14.22	57	44	26	41.08	47	32
10	15.80	56	42	28	44.24	46	31
11	17.38	56	40	30	47.40	45	31
12	18.96	55	39	32	50.56	44	30



4140: Cooling Transformation Diagram. Composition: 0.44 C, 1.04 Mn, 0.29 Si, 1.13 Cr, 0.15 Mo. Austenitized at 845 °C (1555 °F). Grain size: 9. Ac_3, 795 °C (1460 °F); Ac_1, 750 °C (1380 °F). A: austenite, F: ferrite, P: pearlite, B: bainite, M: martensite. Source: Bethlehem Steel



4140: Effect of Microstructure on Tool Life

Feed was 0.010 in./rev (0.25 mm/rev) for all specimens; depth of cut was 0.100 in. (2.5 mm).

Steel condition	Hardness, HB	Microstructure constituent, %			Cutting speed	
		Pearlite	Ferrite	Tempered martensite	ft/min	mm/s
Normalized	192	90	10	...	300	1520
Annealed	180	65	35	...	360	1830
Quenched, tempered	300	...	...	100	300	1520

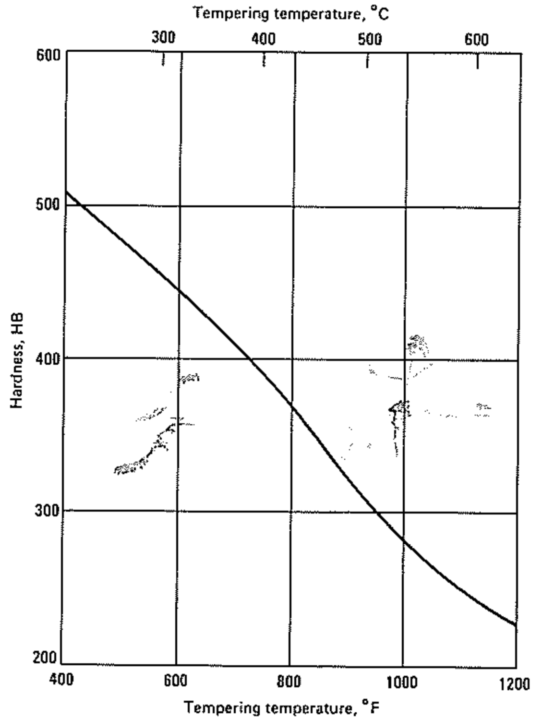
4140: As-Quenched Hardness

Specimens quenched in oil

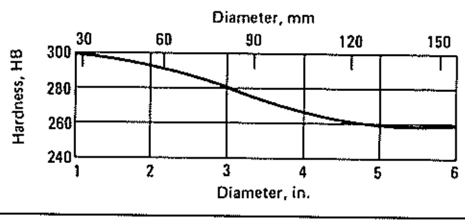
Size round		Hardness, HRC		
in.	mm	Surface	½ radius	Center
½	13	57	56	55
1	25	55	55	50
2	51	49	43	38
4	102	36	34.5	34

Source: Bethlehem Steel

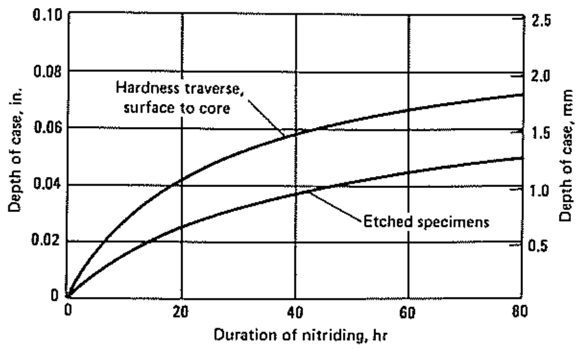
4140: Hardness vs Tempering Temperature. Normalized at 870 °C (1600 °F). Quenched from 845 °C (1555 °F) in oil and tempered in 56 °C (100 °F) intervals in 13.716 mm (0.540 in.) rounds. Tested in 12.827 mm (0.505 in.) rounds. Source: Republic Steel



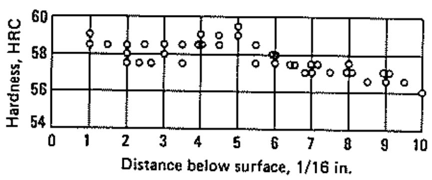
4140: Effect of Mass. Composition: 0.38 to 0.43 C, 0.75 to 1.00 Mn, 0.040 P max, 0.040 S max, 0.20 to 0.35 Si, 0.80 to 1.10 Cr, 0.15 to 0.25 Mo. Approximate critical points: Ac_1, 730 °C (1350 °F); Ac_3, 805 °C (1480 °F); Ar_3, 745 °C (1370 °F); Ar_1, 680 °C (1255 °F). Recommended thermal treatment: forge at 1205 °C (2200 °F) maximum, anneal at 815 to 870 °C (1500 to 1600 °F) for a maximum hardness of 197 HB, normalize at 845 to 900 °C (1555 to 1650 °F) for an approximate hardness of 311 HB; quench from 830 to 855 °C (1525 to 1570 °F) in oil. Test specimens were normalized at 870 °C (1600 °F) in over-sized rounds, quenched from 845 °C (1555 °F) in oil in sizes shown, tempered at 540 °C (1000 °F), tested on 12.827 mm (0.505 in.) rounds. Tests from 38.1 mm (1.5 in.) diam bars and over are taken at half radius position. Source: Republic Steel



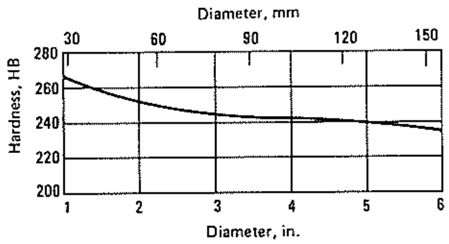
4140: Gas Nitriding. Oil quenched from 845 °C (1555 °F), tempered at 595 °C (1105 °F), and nitrided at 550 °C (1020 °F)



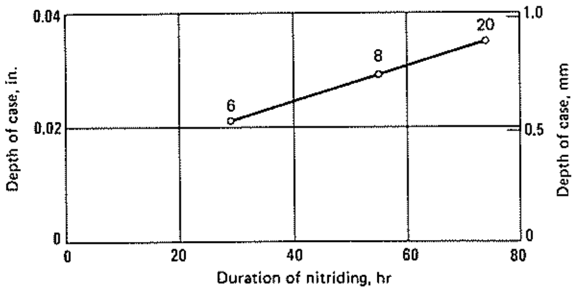
4140: Depth of Hardness. 31.75 mm (1.25 in.) diam bars, through hardened by induction



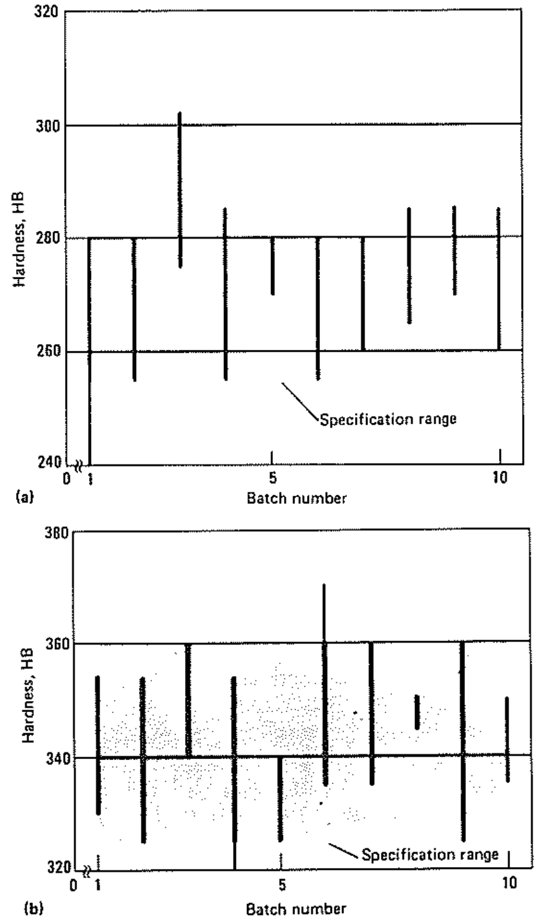
4140: Effect of Mass. Composition: 0.38 to 0.43 C, 0.75 to 1.00 Mn, 0.040 P max, 0.040 S max, 0.20 to 0.35 Si, 0.80 to 1.10 Cr, 0.15 to 0.25 Mo. Approximate critical points: Ac_1, 730 °C (1350 °F); Ac_3, 805 °C (1480 °F); Ar_3, 745 °C (1370 °F); Ar_1, 680 °C (1255 °F). Recommended thermal treatment: forge at 1205 °C (2200 °F) maximum, anneal at 815 to 870 °C (1500 to 1600 °F) for a maximum hardness of 197 HB, normalize at 845 to 900 °C (1555 to 1650 °F) for an approximate hardness of 311 HB; quench from 830 to 855 °C (1525 to 1570 °F) in oil. Test specimens were normalized at 870 °C (1600 °F) in over-sized rounds, quenched from 845 °C (1555 °F) in sizes shown, tempered at 650 °C (1200 °F), tested on 12.827 mm (0.505 in.) rounds. Tests from 38.1 mm (1.5 in.) diam bars and over are taken at half radius position. Source: Republic Steel



4140: Depth of Case vs Duration of Nitriding. Double stage nitrided at 525 °C (975 °F). Numbers indicate hours of nitriding at 15 to 25% dissociation. Remainder of cycle at 83 to 85% dissociation

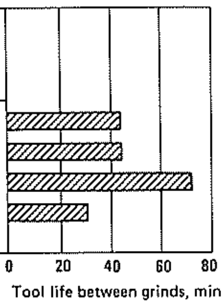


4140: Variations in Hardness after Production Tempering. (a) 76.2 mm (3 in.) diam valve bonnets. Steel from one mill heat. Parts heated at 870 °C (1600 °F), oil quenched, and tempered at 605 °C (1125 °F) to a hardness of 255 to 302 HB. (b) Valve segments, 12.7 to 25.4 mm (0.5 to 1 in.) section thickness. Steel from one mill heat. Parts heated at 870 °C (1600 °F), oil quenched, and tempered at 580 °C (1075 °F) to a hardness of 321 to 363 HB

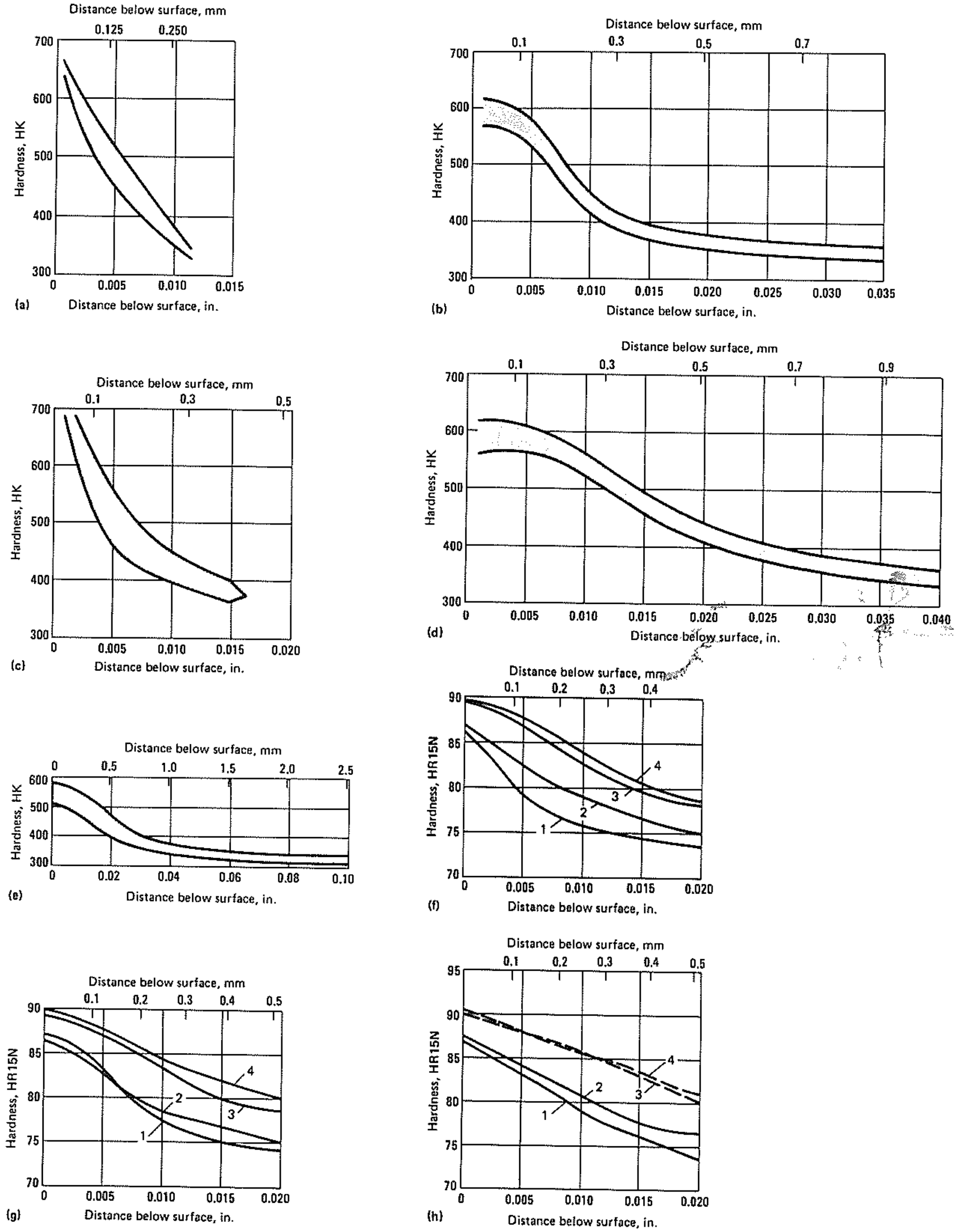


4140: Effect of Microstructure on Tool Life

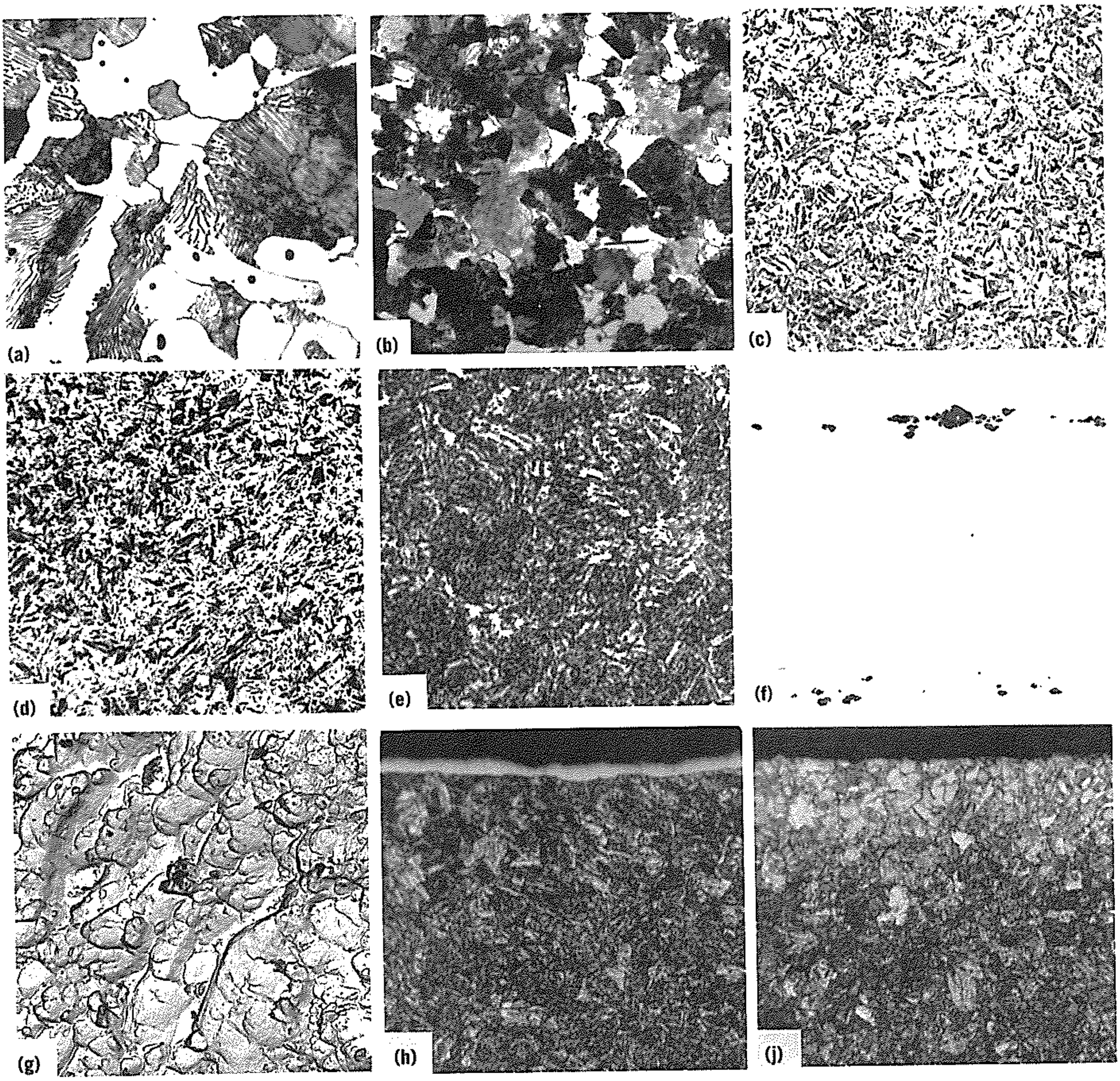
Steel condition	Cutting speed ft/min	Cutting speed m/s	Metal removed between grinds in.^{3}	Metal removed between grinds m^3
Normalized	300	1.5	165	2.3×10^{-3}
Annealed	360	1.8	190	3.1×10^{-3}
Annealed	300	1.5	260	4.3×10^{-3}
Quenched and tempered	300	1.5	115	1.9×10^{-3}



4140: Gas Nitriding. (a) 7 h, 2 suppliers, 20 to 30% dissociation; (b) 9 h, 2 heats, 25 to 30% dissociation; (c) 24 h, 2 suppliers, 20 to 30% dissociation; (d) 40 h, 5 heats, 25 to 30% dissociation; (e) 90 h, 9 heats, 25 to 35% dissociation; (f) 25 h, 20 to 30% dissociation; (g) 35 h, 20 to 30% dissociation; (h) 50 h, 20 to 30% dissociation. For (f), (g), (h), 1: 21 to 23 HRC; 2: 26 to 28 HRC; 3: 33 to 35 HRC; 4: 36 to 37 HRC core hardness



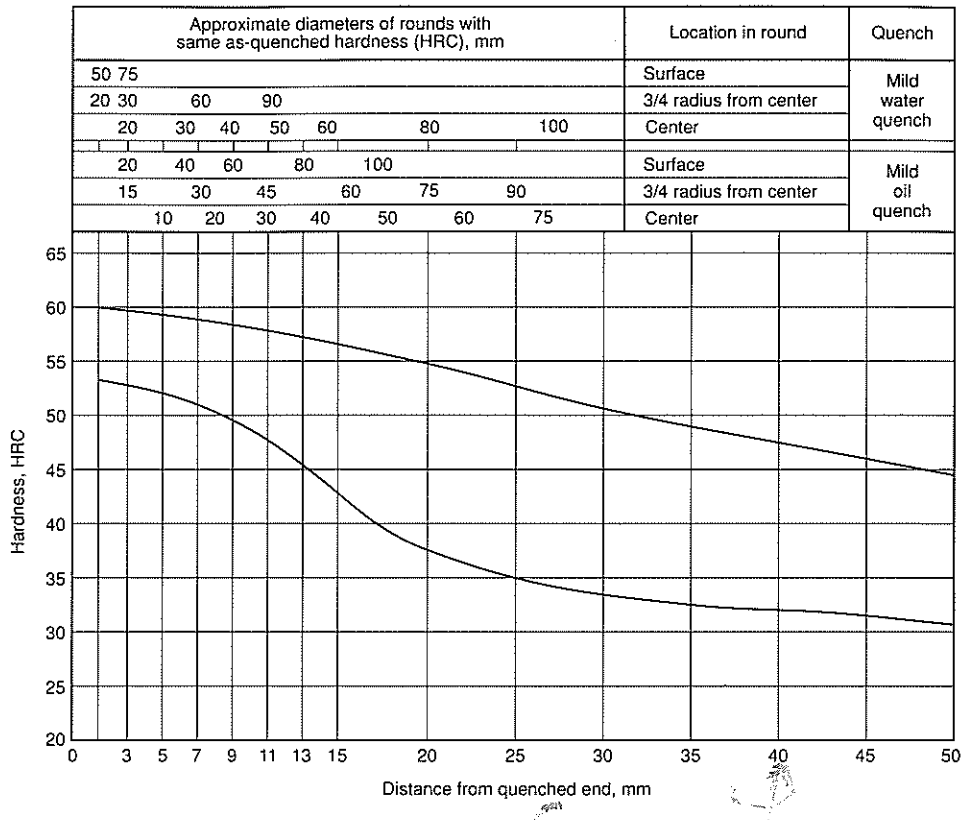
4140: Microstructures. (a) 2% nital, 825×. Resulfurized forging normalized by austenitizing at 900 °C (1650 °F) ½ h, air cooling; annealed by heating at 815 °C (1500 °F) 1 h, furnace cooling to 540 °C (1000 °F), air cooling. Blocky ferrite and fine-to-coarse lamellar pearlite. Black dots are sulfide. (b) Nital, 500×. 25.4 mm (1 in.) diam, austenitized at 845 °C (1555 °F) 1 h, cooled to 650 °C (1200 °F), and held 1 h for isothermal transformation, then air cooled to room temperature. White areas, ferrite; gray and black areas, pearlite with fine and coarse lamellar spacing. (c) 2% nital, 500×. Hot rolled steel round bar. 25.4 mm (1 in.) diam, austenitized at 845 °C (1555 °F) for 1 h and water quenched. Fine, homogeneous, untempered martensite. Tempering at 150 °C (300 °F) would result in a darker etching structure. (d) 2% nital, 500×. Same as (c), except the steel was quenched in oil rather than water, resulting in the presence of bainite (black constituent) along with the martensite (light). (e) 2% nital, 750×. Steel bar austenitized at 845 °C (1555 °F), oil quenched to 66 °C (150 °F), and tempered 2 h at 620 °C (1150 °F). Martensite-ferrite-carbide aggregate. (f) As polished (not etched), 200×. Oxide inclusions (stringers) in a steel bar, 25.4 mm (1 in.) diam. Stringers parallel to the direction of rolling on the as-polished surface of the bar. (g) Not polished, not etched, 8600×. Replica electron fractograph showing the dimpled structure typical of the overstress mode of failure. (h) 2% nital, 400×. Oil quenched from 845 °C (1555 °F), tempered for 2 h at 620 °C (1150 °F), surface activated in manganese phosphate, gas nitrided for 24 h at 525 °C (975 °F), 20 to 30% dissociation. 0.0050 to 0.0076 mm (0.0002 to 0.0003 in.) white surface layer Fe_2N, iron nitride, and tempered martensite. (j) 2% nital, 400×. Same steel and prenitriding conditions as (h), except double stage gas nitrided: 5 h at 525 °C (975 °F), 20 to 30% dissociation; 20 h at 565 °C (1050 °F), 75 to 80% dissociation. High second-stage dissociation caused absence of white layer. Diffused nitride layer and a matrix of tempered martensite



4140H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

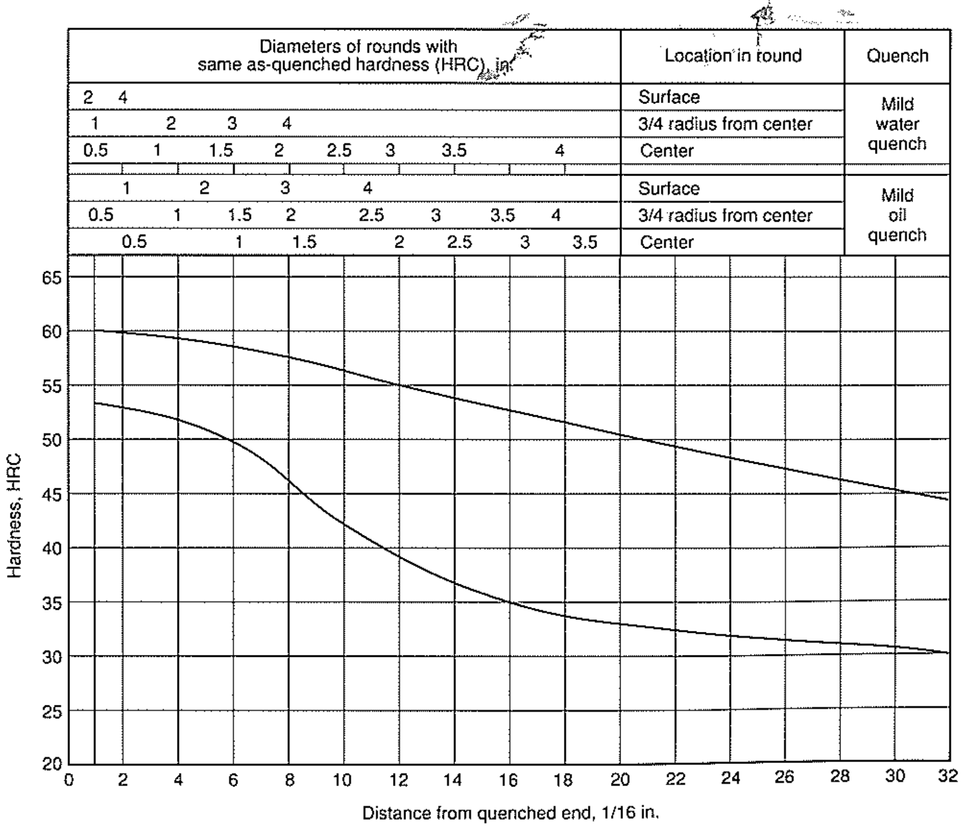
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	60	53
3	60	52
5	60	52
7	59	51
9	59	50
11	58	48
13	57	46
15	57	43
20	55	38
25	53	35
30	51	33
35	49	32
40	48	32
45	46	31
50	45	30



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	60	53
2	60	53
3	60	52
4	59	51
5	59	51
6	58	50
7	58	48
8	57	47
9	57	44
10	56	42
11	56	40
12	55	39
13	55	38
14	54	37
15	54	36
16	53	35
18	52	34
20	51	33
22	49	33
24	48	32
26	47	32
28	46	31
30	45	31
32	44	30



4142, 4142H

Chemical Composition. 4142. AISI and UNS: 0.40 to 0.45 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.80 to 1.10 Cr, 0.15 to 0.25 Mo. **UNS H41420 and SAE/AISI 4142H:** 0.39 to 0.46 C, 0.65 to 1.10 Mn, 0.15 to 0.35 Si, 0.75 to 1.20 Cr, 0.15 to 0.35 Mo

Similar Steels (U.S. and/or Foreign). 4142. UNS G41420; ASTM A322, A331, A505, A519, A 547; SAE J404, J412, J770. **4142H.** UNS H41420; ASTM A304; SAE J1268; (Ger.) DIN 1.7223; (Ital.) UNI 38 CrMo 4

Characteristics. A slightly higher carbon version of 4140H. Characteristics are essentially the same as those described for 4140H. Depending on the precise carbon content within the allowable range, as-quenched hardness of fully hardened 4142H should be at least 54 HRC and may be as high as 60 HRC. 4142H is also a high hardenability steel. Can be readily forged, but as carbon increases, the susceptibility to cracking in heat treating or welding also increases, while machinability decreases

Forging. Heat to 1230 °C (2250 °F). Do not forge after temperature of forging stock drops below approximately 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

Annealing. For a predominately pearlitic structure, heat to 845 °C (1555 °F), cool fairly rapidly to 755 °C (1390 °F), then cool from 755 °C (1390 °F) to 665 °C (1230 °F) at a rate not to exceed 14 °C (25 °F) per h; or heat to 845 °C (1555 °F), cool rapidly to 675 °C (1245 °F), and hold for 5 h. For a predominately spheroidized structure, heat to 750 °C (1380 °F), cool to 665 °C (1230 °F) at a rate not to exceed 6 °C (10 °F) per h; or heat to 750 °C (1380 °F), cool fairly rapidly to 675 °C (1245 °F), and hold for 9 h

Hardening. Austenitize at 855 °C (1570 °F), and quench in oil. Flame hardening, ion nitriding, gas nitriding, and carbonitriding are suitable processes

Tempering. Reheat after quenching to the temperature to obtain the required hardness

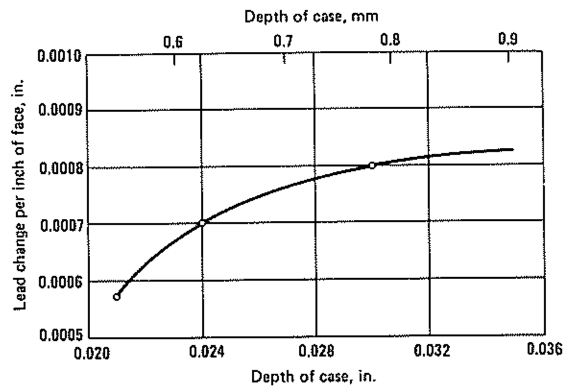
Nitriding. If nitriding is considered, the steel must be pretreated (hardened and tempered), and nitriding must be done on finished parts because any finishing operation will remove the most useful portion of the case. A typical processing cycle that includes nitriding is

- Rough machine
- Austenitize at 845 °C (1555 °F)
- Oil quench
- Temper at 620 °C (1150 °F)
- Finish machine
- Nitride at 525 °C (975 °F) for 24 h, using an ammonia dissociation of 30%; or nitride at 525 °C (975 °F) for 5 h with an ammonia dissociation of 25%, then at 565 °C (1050 °F) for 20 h with an ammonia dissociation of 75 to 80%

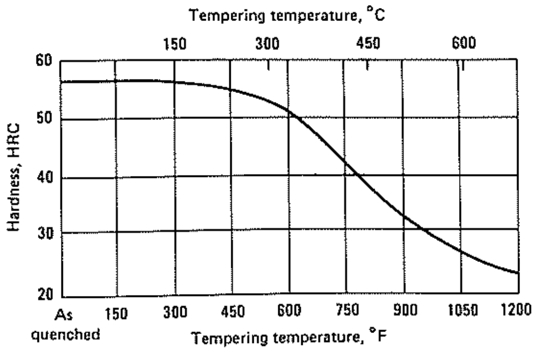
Certain proprietary salt bath nitriding processes are also applicable for surface hardening

Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine
- Nitride (optional)

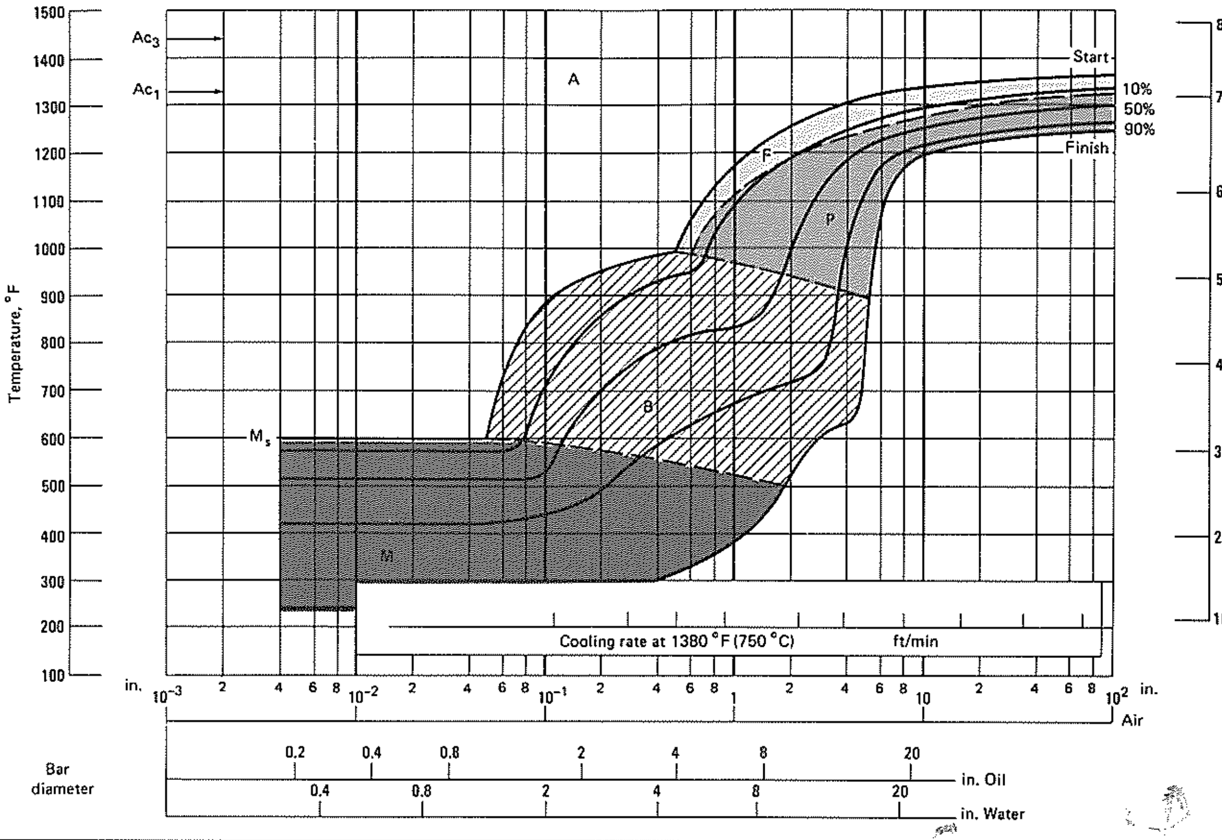


4142: Increase in Lead Change with Depth of Nitrided Case. 13-tooth five-pitch helical pinion gear, hardened and tempered at 565 °C (1050 °F)and nitrided in two stages at 525 °C (975 °F) using ammonia dissociation rates of 15 to 25% for the first stage and 83 to 85% for the second stage



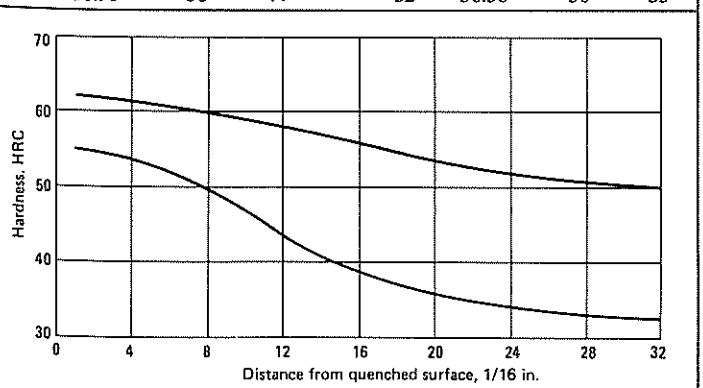
4142, 4142H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

4142H: Continuous Cooling Transformation Diagram. Composition: 0.42 C, 0.85 Mn, 0.020 P, 0.020 S, 0.25 Si, 1.15 Cr, 0.20 Mo. Austenitized at 860 °C (1580 °F)

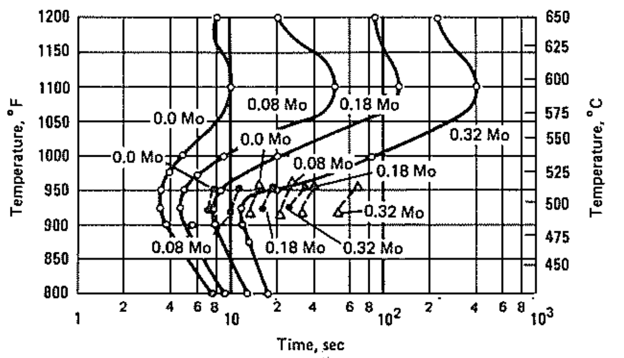


4142H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min
1	1.58	62	55	13	20.54	58	42
2	3.16	62	55	14	22.12	57	41
3	4.74	62	54	15	23.70	57	40
4	6.32	61	53	16	25.28	56	39
5	7.90	61	53	18	28.44	55	37
6	9.48	61	52	20	31.60	54	36
7	11.06	60	51	22	34.76	53	35
8	12.64	60	50	24	37.92	53	34
9	14.22	60	49	26	41.08	52	34
10	15.80	59	47	28	44.24	51	34
11	17.38	59	46	30	47.40	51	33
12	18.96	58	44	32	50.56	50	33



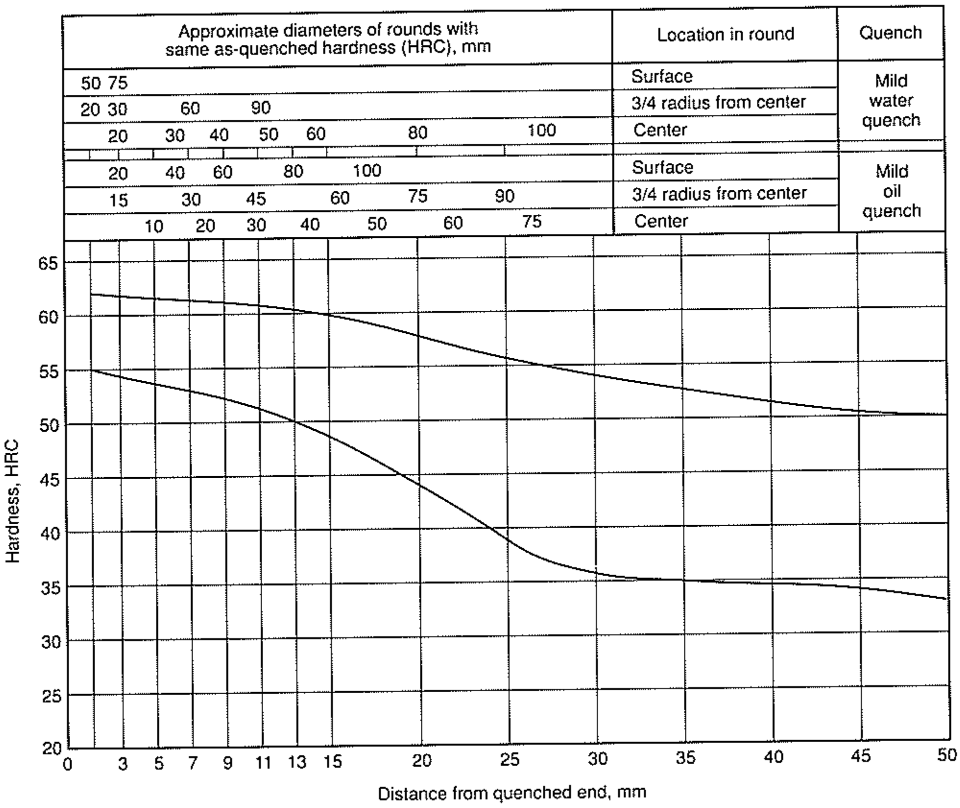
4142: Isothermal Transformation Diagram. Composition: 0.42 C, 0.69 Mn, 0.018 P, 0.028 S, 0.23 Si, 0.05 Ni, 0.94 Cr, 0.18 Mo, 0.025 Al. O: austenitized at 870 °C (1600 °F); ●: austenitized at 980 °C (1795 °F); Δ: austenitized at 1095 °C (2005 °F)



4142H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1550 °F)

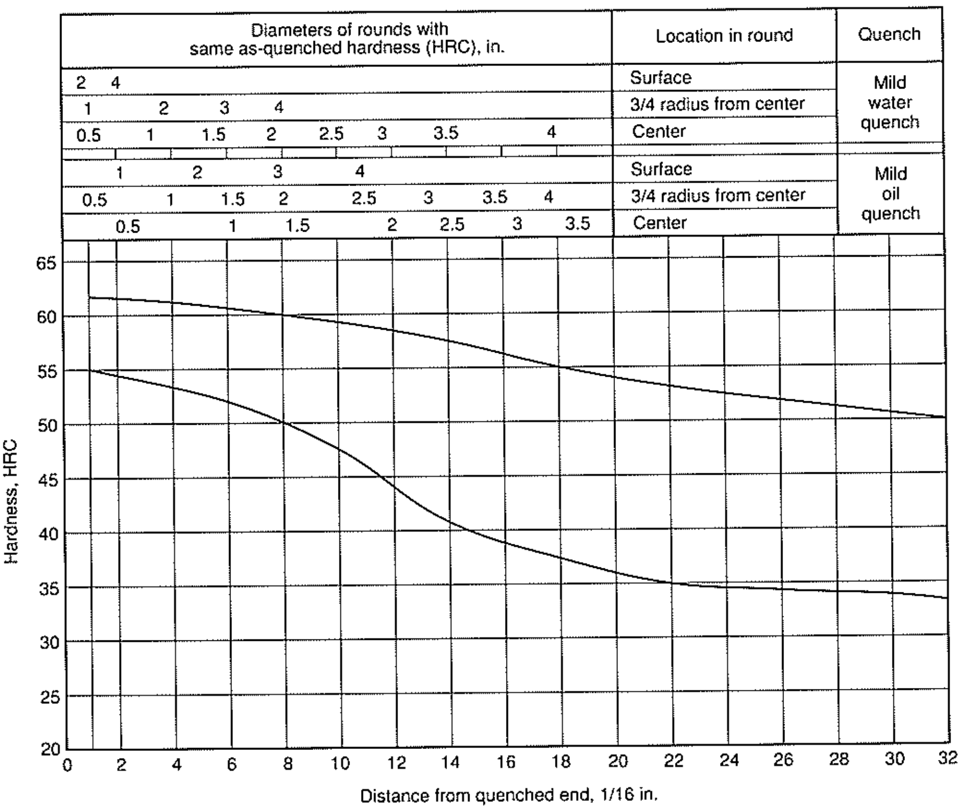
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Minimum
1.5	62	55
3	62	54
5	62	54
7	62	53
9	61	52
11	61	51
13	60	49
15	60	48
20	58	43
25	56	39
30	55	36
35	53	35
40	52	34
45	51	33
50	50	33



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Minimum
1	62	55
2	62	55
3	62	54
4	61	53
5	61	53
6	61	52
7	60	51
8	60	50
9	60	49
10	59	47
11	59	46
12	58	44
13	58	42
14	57	41
15	57	40
16	56	39
18	55	37
20	54	36
22	53	35
24	53	34
26	52	34
28	51	34
30	51	33
32	50	33



4145, 4145H, 4145RH

Chemical Composition. **4145. AISI and UNS:** 0.43 to 0.48 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.80 to 1.10 Cr, 0.15 to 0.25 Mo. **UNS H41450 and SAE/AISI 4145H:** 0.42 to 0.49 C, 0.65 to 1.10 Mn, 0.15 to 0.35 Si, 0.75 to 1.20 Cr, 0.15 to 0.25 Mo. **SAE 4145RH:** 0.43 to 0.48 C, 0.75 to 1.00 Mn, 0.80 to 1.10 Cr, 0.15 to 0.25 Mo

Similar Steels (U.S. and/or Foreign). **4145.** UNS G41450; ASTM A322, A331, A505, A519; MIL SPEC MIL-S-16974; SAE J404, J412, J770. **4145H.** UNS H41450; ASTM A304, A914; SAE J1268, J1868

Characteristics. 4145H, along with 4147H and 4150H, is commonly known as a high-strength steel. All are capable of being heat treated to high strengths. As-quenched 4145H will have hardness values ranging generally from approximately 55 to 62 HRC. In hardenability, 4145H ranks as one of the highest of the AISI alloy steels. Forgeability is good, but because of high carbon content and high hardenability, restricted cooling rate from the finish forging temperature is generally recommended. This can be accomplished by cooling in a furnace or by covering with an insulating material. Rapid cooling from the forging temperature can result in cracking, especially for forgings of complex configuration. Machinability is generally regarded as poor, although 4145H is machined by all of the conventional processes. Strongly susceptible to weld cracking, and the entire welding process must be closely controlled. Often welded using more sophisticated processes such as plasma arc and electron beam, partly because of the applications for which it is most often used

Forging. Heat to 1220 °C (2225 °F). Do not forge after temperature of forging stock drops below approximately 870 °C (1600 °F). Slow cooling is recommended

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

Annealing. For a predominately pearlitic structure, heat to 830 °C (1525 °F), cool fairly rapidly to 745 °C (1370 °F), then to 670 °C (1240 °F) at a rate not to exceed 8 °C (15 °F) per h; or heat to 830 °C (1525 °F), cool rapidly to 675 °C (1245 °F), and hold for 6 h. For a predominately ferritic and spheroidized carbide structure, heat to 750 °C (1380 °F), cool to 670 °C (1240 °F) at a rate not to exceed 6 °C (10 °F) per h; or cool fairly rapidly from 750 °C (1380 °F) to 660 °C (1220 °F), and hold for 10 h

Hardening. Heat to 845 °C (1555 °F), and quench in oil or polymer. Flame hardening, ion nitriding, gas nitriding, and carbonitriding are suitable processes

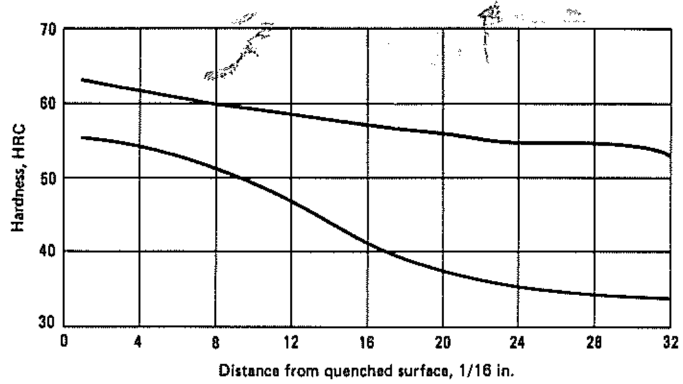
Tempering. After quenching, reheat immediately to the tempering temperature that will provide the required strength and/or hardness

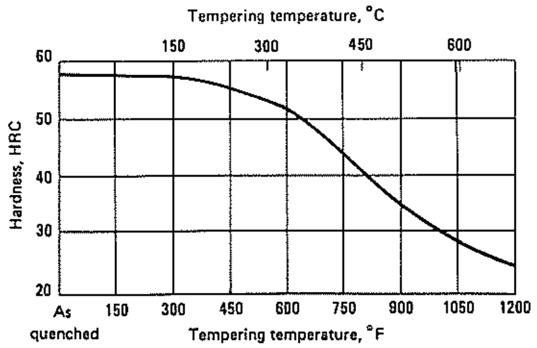
Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize and quench
- Temper
- Finish machine

4145H: End-Quench Hardenability

Distance from quenched surface 1/16 in.	mm	Hardness, HRC max	min	Distance from quenched surface 1/16 in.	mm	Hardness, HRC max	min
1	1.58	63	56	13	20.54	59	46
2	3.16	63	55	14	22.12	59	45
3	4.74	62	55	15	23.70	58	43
4	6.32	62	54	16	25.28	58	42
5	7.90	62	53	18	28.44	57	40
6	9.48	61	53	20	31.60	57	38
7	11.06	61	52	22	34.76	56	37
8	12.64	61	52	24	37.92	55	36
9	14.22	60	51	26	41.08	55	35
10	15.80	60	50	28	44.24	55	35
11	17.38	60	49	30	47.40	55	34
12	18.96	59	48	32	50.56	54	34



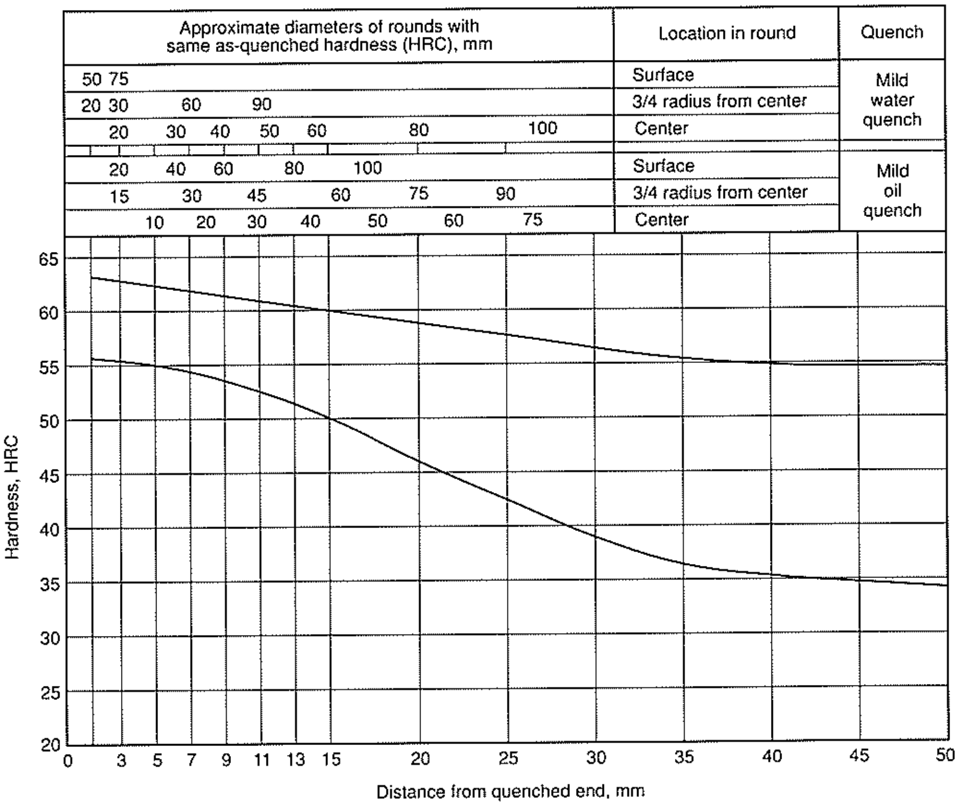


4145, 4145H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

4145H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

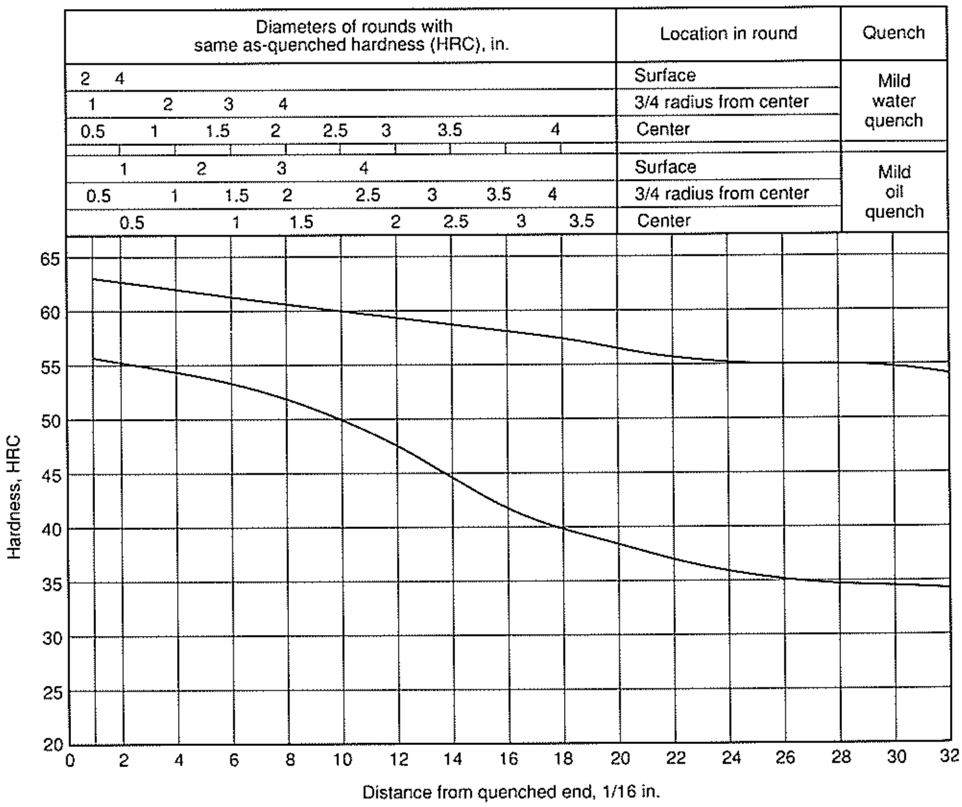
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	63	56
3	63	55
5	63	55
7	62	54
9	62	53
11	61	52
13	61	51
15	60	50
20	59	47
25	58	42
30	57	39
35	56	37
40	55	35
45	55	34
50	55	34



Hardness limits for specification purposes

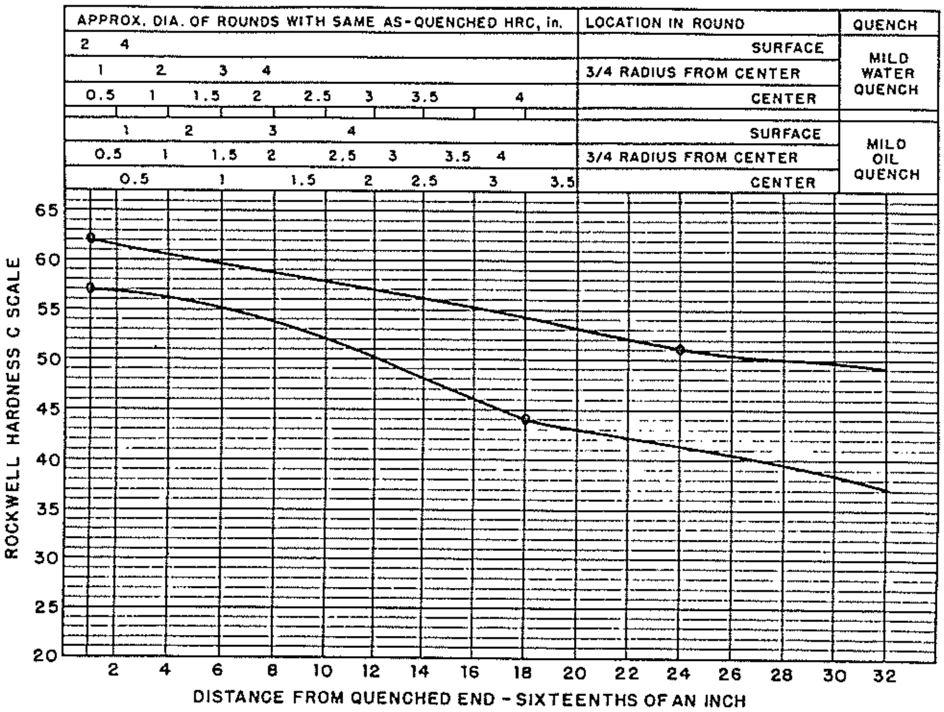
J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	63	56
2	63	55
3	62	55
4	62	54
5	62	53
6	61	53
7	61	52
8	61	52
9	60	51
10	60	50
11	60	49
12	59	48
13	59	46
14	59	45
15	58	43
16	58	42
18	57	40
20	57	38
22	56	37
24	55	36
26	55	35
28	55	35
30	55	34
32	54	34



4145RH: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

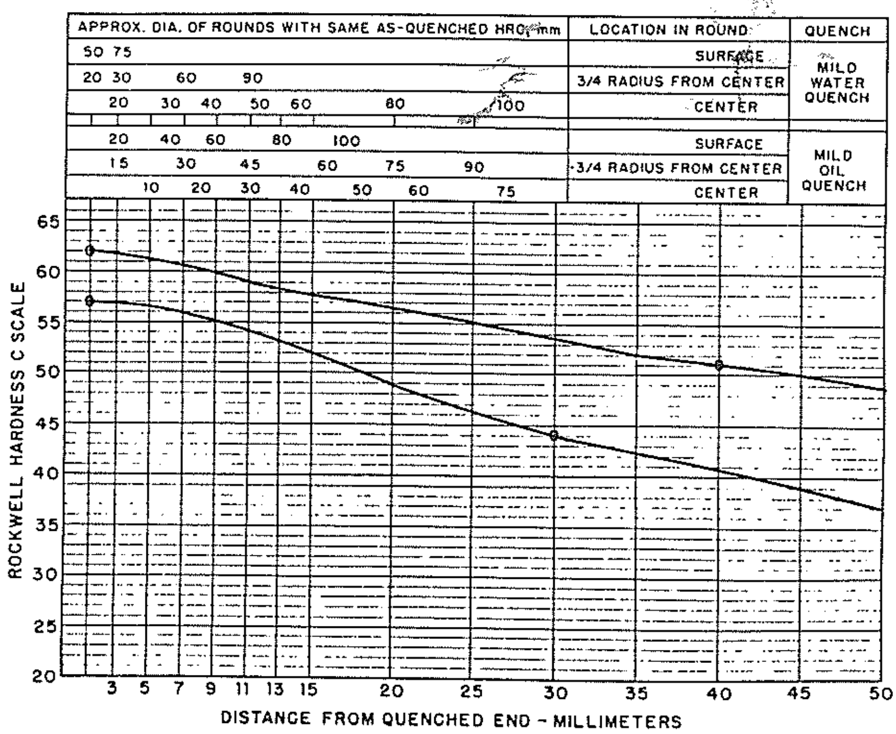
Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	62	57
2	62	57
3	61	56
4	61	56
5	60	55
6	60	55
7	59	54
8	59	53
9	58	52
10	58	52
11	58	51
12	57	50
13	57	49
14	56	48
15	56	47
16	55	46
18	54	44
20	53	43
22	52	42
24	51	40
26	51	40
28	50	39
30	50	38
32	49	37



Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	62	57
3	62	57
5	61	56
7	61	56
9	60	55
11	59	54
13	59	53
15	58	52
20	57	49
25	55	46
30	54	44
35	52	42
40	51	40
45	50	39
50	49	37



4147, 4147H

Chemical Composition. **4147. AISI and UNS:** 0.45 to 0.50 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.80 to 1.10 Cr, 0.15 to 0.25 Mo. **UNS H41470 and SAE/AISI 4147H:** 0.44 to 0.51 C, 0.65 to 1.10 Mn, 0.15 to 0.35 Si, 0.75 to 1.20 Cr, 0.15 to 0.25 Mo

Similar Steels (U.S. and/or Foreign). **4147.** UNS G41470; ASTM A322, A331, A505, A519; SAE J404, J412, J770; (Ger.) DIN 1.7228; (Jap.) JIS SCM 5 H, SCM 5. **4147H.** UNS H41470; ASTM A304; SAE J1268; (Ger.) DIN 1.7228; (Jap.) JIS SCM 5 H, SCM 5

Characteristics. The characteristics are much the same as those outlined for 4145H. Because of increased carbon content, the maximum as-quenched hardness is slightly higher, approximately 56 to 63 HRC, depending on the precise carbon content. Hardenability is high, and the band shows about the same pattern as that for 4145H, except for a shift slightly upward. Susceptibility to cracking because of rapid cooling after forging, welding, or heat treating is greater than that for 4145H because of the higher carbon content

Forging. Heat to 1220 °C (2225 °F). Do not forge after temperature of forging stock drops below approximately 870 °C (1600 °F). Slow cooling is recommended

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

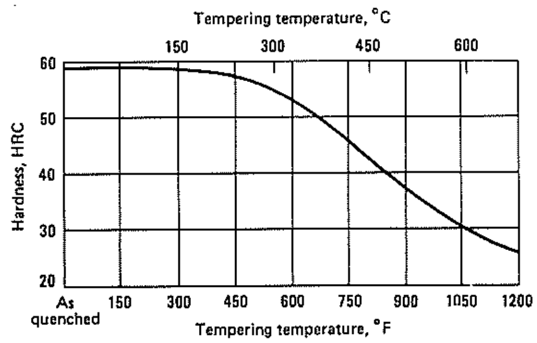
Annealing. For a predominately pearlitic structure, heat to 830 °C (1525 °F), cool fairly rapidly to 745 °C (1370 °F), then to 670 °C (1240 °F) at a rate not to exceed 8 °C (15 °F) per h; or heat to 830 °C (1525 °F), cool rapidly to 675 °C (1245 °F), and hold for 6 h. For a predominately ferritic and spheroidized carbide structure, heat to 750 °C (1380 °F), cool to 670 °C (1240 °F) at a rate not to exceed 6 °C (10 °F) per h; or cool fairly rapidly from 750 °C (1380 °F) to 660 °C (1220 °F), and hold for 10 h

Hardening. Heat to 845 °C (1555 °F), and quench in oil. Flame hardening, ion nitriding, gas nitriding, and carbonitriding are suitable processes

Tempering. After quenching, reheat immediately to the tempering temperature that will provide the required strength and/or hardness

Recommended Processing Sequence

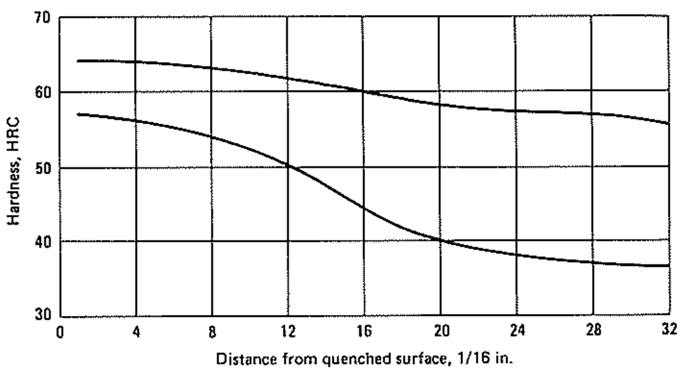
- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize and quench
- Temper
- Finish machine



4147, 4147H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

4147H: End-Quench Hardenability

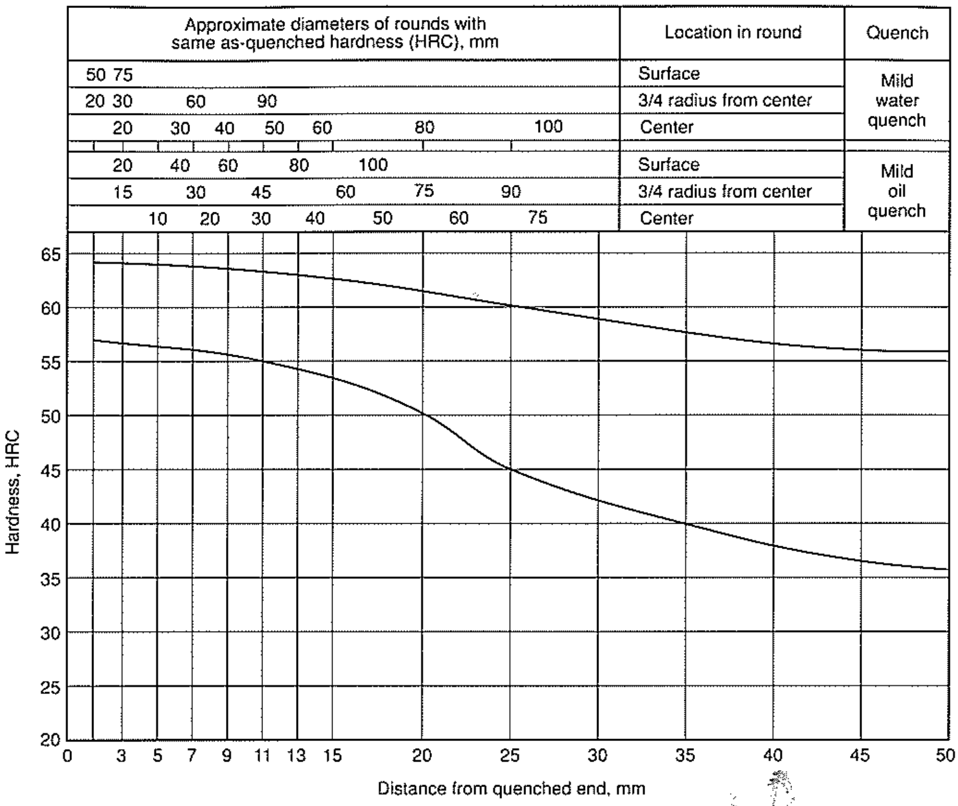
Distance from quenched surface		Hardness, HRC		Distance from quenched surface		Hardness, HRC	
1/16 in.	mm	max	min	1/16 in.	mm	max	min
1	1.58	64	57	13	20.54	61	49
2	3.16	64	57	14	22.12	61	48
3	4.74	64	56	15	23.70	60	46
4	6.32	64	56	16	25.28	60	45
5	7.90	63	55	18	28.44	59	42
6	9.48	63	55	20	31.60	59	40
7	11.06	63	55	22	34.76	58	39
8	12.64	63	54	24	37.92	57	38
9	14.22	63	54	26	41.08	57	37
10	15.80	62	53	28	44.24	57	37
11	17.38	62	52	30	47.40	56	37
12	18.96	62	51	32	50.56	56	36



4147H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

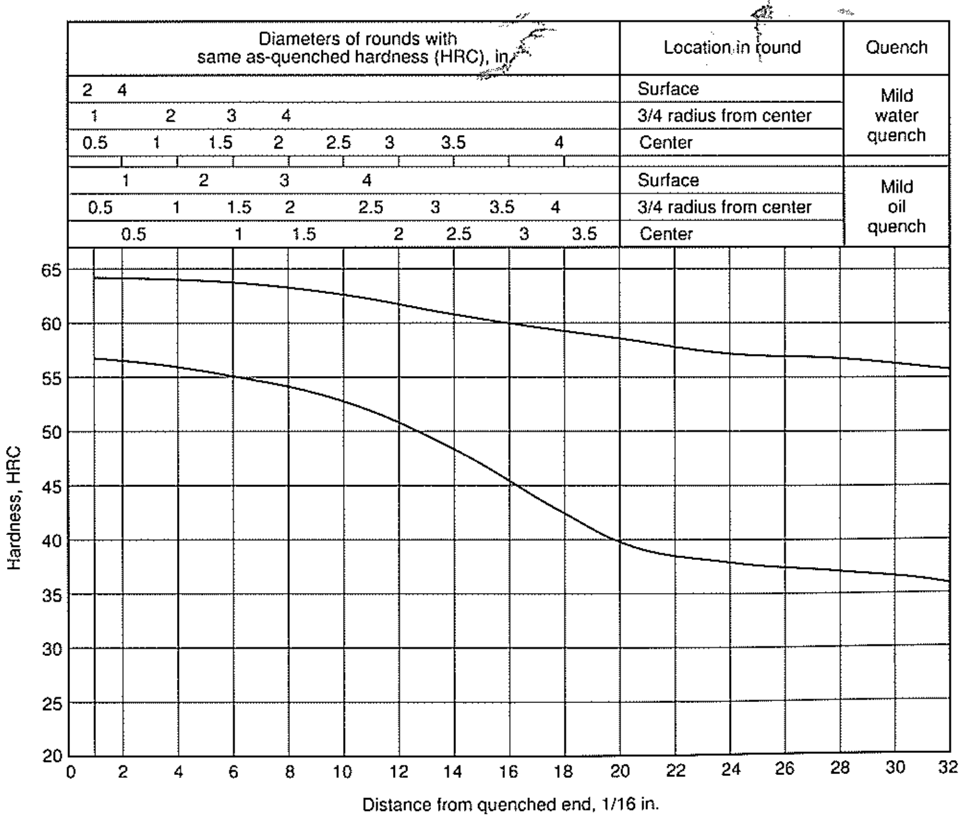
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	64	57
3	64	57
5	64	56
7	64	55
9	63	55
11	63	55
13	63	54
15	63	53
20	62	50
25	60	45
30	59	42
35	58	39
40	57	37
45	57	36
50	56	36

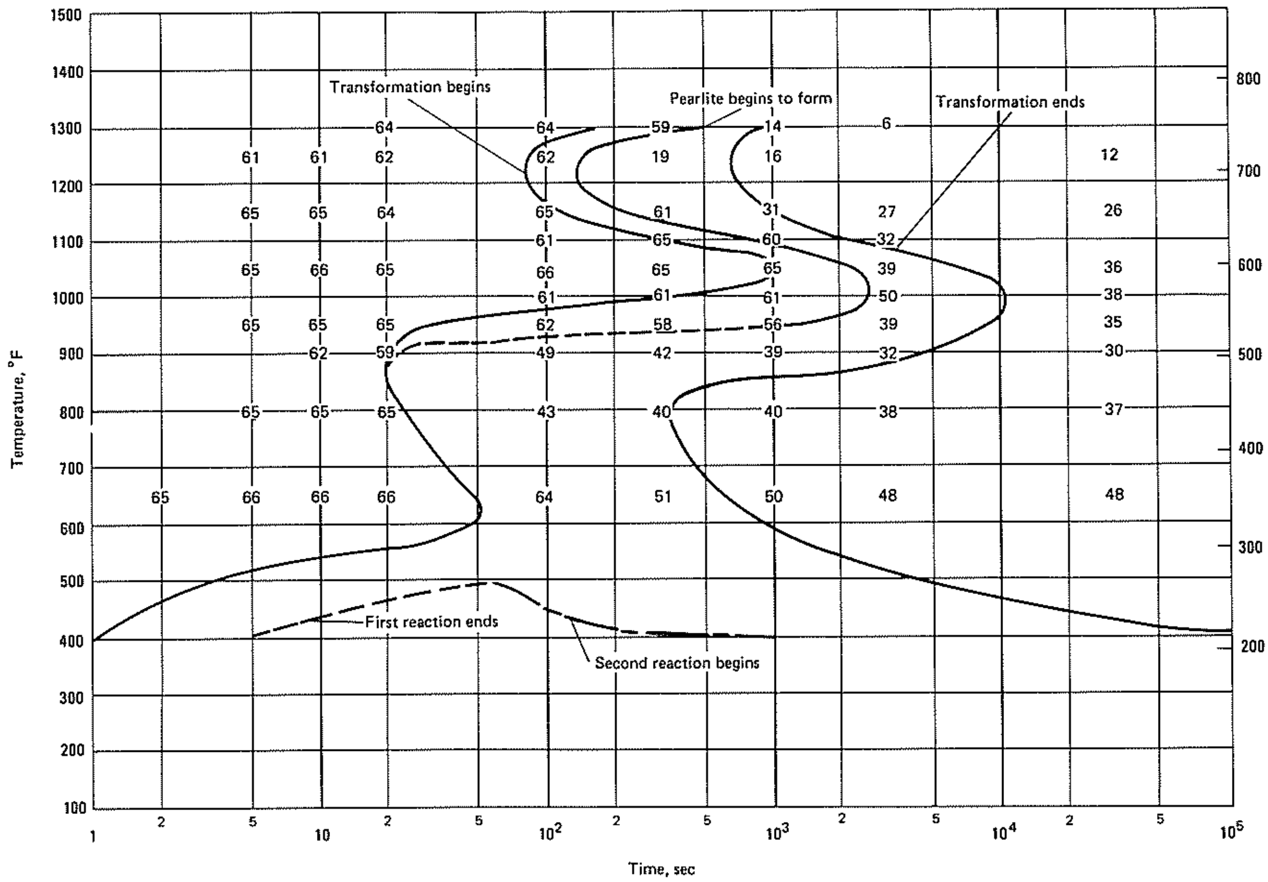


Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	64	57
2	64	57
3	64	56
4	64	56
5	63	55
6	63	55
7	63	55
8	63	54
9	63	54
10	62	53
11	62	52
12	62	51
13	61	49
14	61	48
15	60	46
16	60	45
18	59	42
20	59	40
22	58	39
24	57	38
26	57	37
28	57	37
30	56	37
32	56	36



4147: Isothermal Transformation Diagram. Composition: 0.46 C, 0.77 Mn, 0.016 P, 0.025 S, 0.28 Si, 0.15 Ni. 1.06 Cr, 0.22 Mo



4150, 4150H

Chemical Composition. 4150. AISI and UNS: 0.48 to 0.53 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.80 to 1.10 Cr, 0.15 to 0.25 Mo. **UNS H41500 and SAE/AISI 4150H:** 0.47 to 0.54 C, 0.65 to 1.10 Mn, 0.15 to 0.35 Si, 0.75 to 1.20 Cr, 0.15 to 0.25 Mo

Similar Steels (U.S. and/or Foreign). 4150. UNS G41500; ASTM A322, A331, A505, A519; MIL SPEC MIL-S-11595 (ORD4150); SAE J404, J412, J770; (Ger.) DIN 1.7228; (Jap.) JIS SCM 5 H, SCM 5. **4150H.** UNS H41500; ASTM A304; SAE J1268; (Ger.) DIN 1.7228; (Jap.) JIS SCM 5 H, SCM 5

Characteristics. High-hardenability steel, capable of being heat treated to high levels of strength. When the carbon content is on the higher side of the allowable range (0.54%), as-quenched hardness can approach 65 HRC. Characteristics are generally the same as those given for 4145H and 4147H. Minor differences because of higher carbon content include higher as-quenched hardness, an upward shift of the hardenability band, and an even greater tendency to cracking during heat processing

Forging. Heat to 1220 °C (2225 °F). Do not forge after temperature of forging stock drops below approximately 870 °C (1600 °F). Slow cooling is recommended

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air.

In aerospace practice, normalize at 870 °C (1600 °F)

Annealing. For a predominately pearlitic structure, heat to 830 °C (1525 °F), cool fairly rapidly to 745 °C (1370 °F), then to 670 °C (1240 °F) at a rate not to exceed 8 °C (15 °F) per h; or heat to 830 °C (1525 °F), cool rapidly to 675 °C (1245 °F), and hold for 6 h. For a predominately ferritic and spheroidized carbide structure, heat to 750 °C (1380 °F), cool to 670 °C (1240 °F) at a rate not to exceed 6 °C (10 °F) per h; or cool fairly rapidly from 750 °C (1380 °F) to 660 °C (1220 °F), and hold for 10 h.

In aerospace practice, anneal at 830 °C (1525 °F). Cool below 540 °C (1000 °F) at a rate not to exceed 110 °C (200 °F) per h

Hardening. Heat to 845 °C (1555 °F), and quench in oil or polymer. Flame hardening, boriding, ion nitriding, gas nitriding, carbonitriding, austempering and martempering are candidate processes. In aerospace practice, parts are austenitized at 830 °C (1525 °F), and are quenched with oil or polymer

Tempering. After quenching, reheat immediately to the tempering temperature that will provide the required strength and/or hardness. See table

Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize and quench
- Temper
- Finish machine

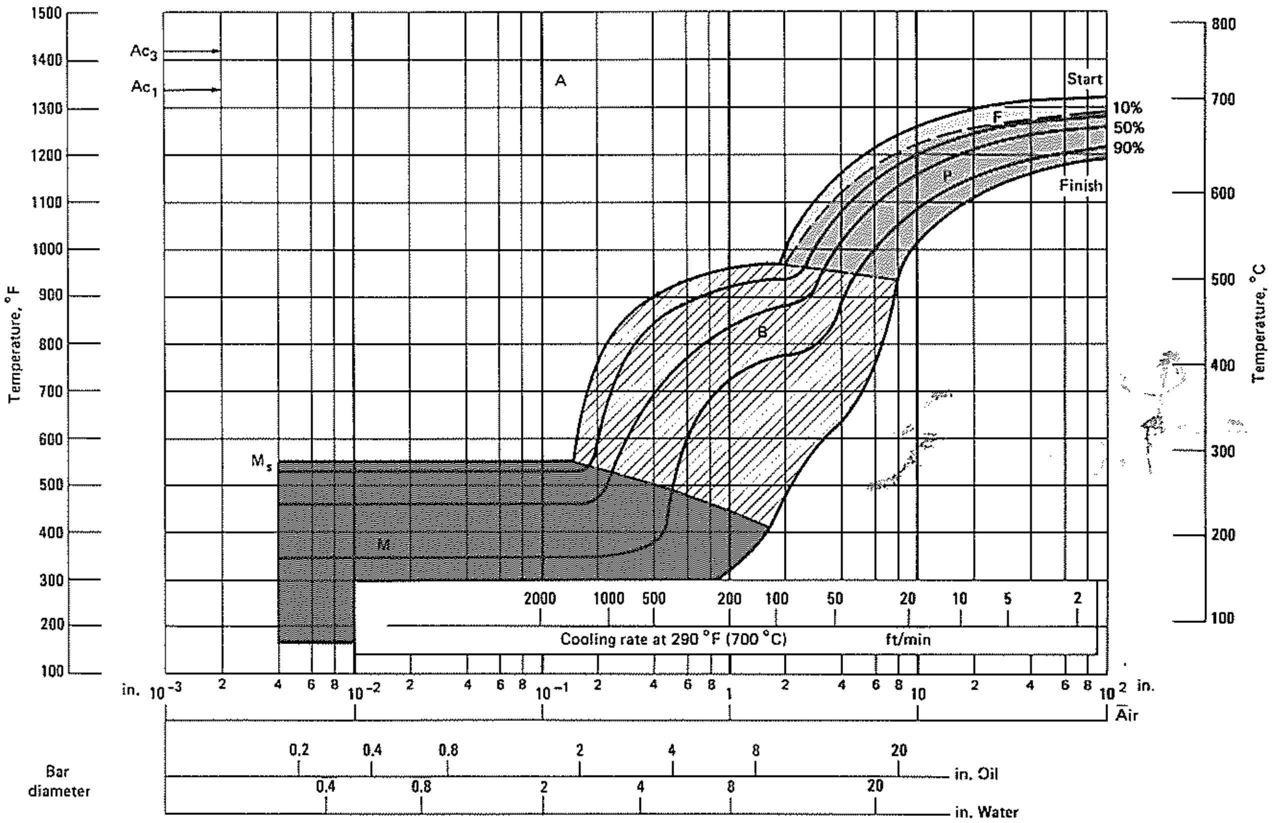
4150: As-Quenched Hardness

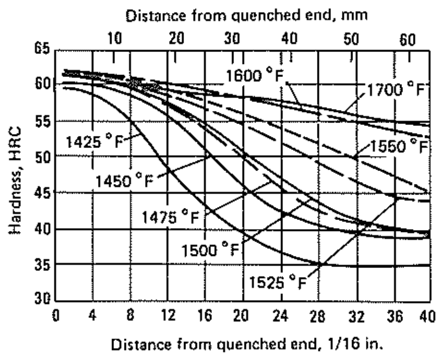
Specimens quenched in oil

Size round		Hardness, HRC		
in.	mm	Surface	½ radius	Center
½	13	64	64	63
1	25	62	62	62
2	51	58	57	56
4	102	47	43	42

Source: Bethlehem Steel

4150: Continuous Cooling Transformation Diagram. Composition: 0.50 C, 0.85 Mn, 0.020 P, 0.020 S, 0.25 Si, 1.00 Cr, 0.22 Mo. Austenitized at 850 °C (1560 °F)



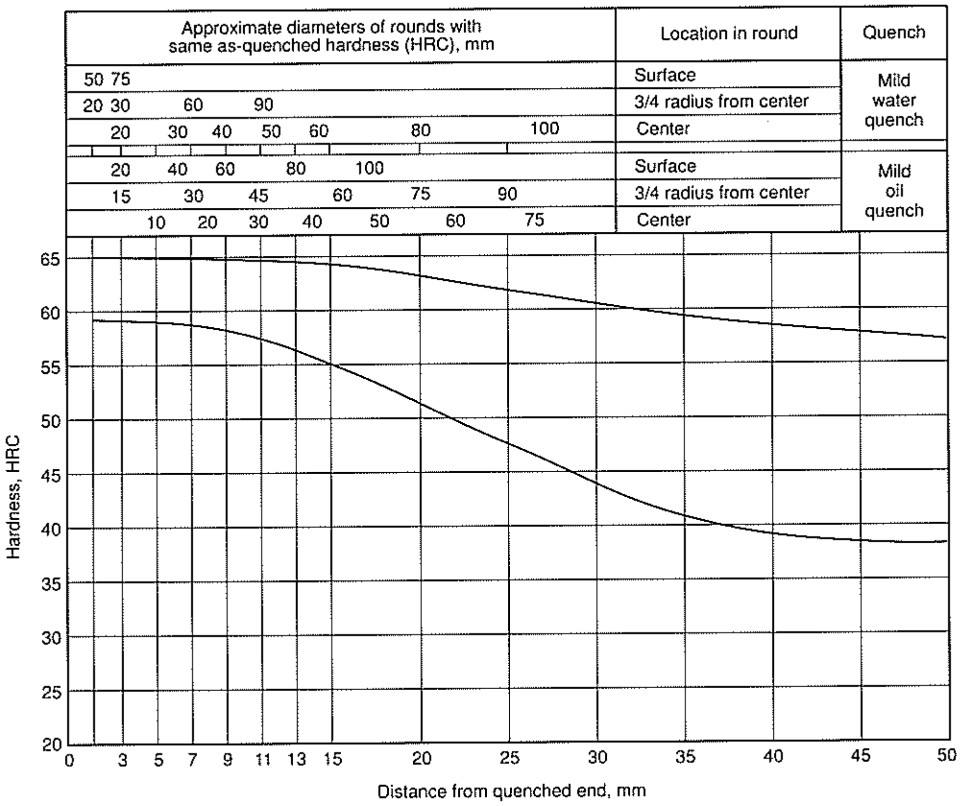


4150: End-Quench Hardenability. Use of successively higher austenitizing temperatures. Composition: 0.55 C, 0.84 Mn, 0.30 Si, 0.13 Ni, 0.92 Cr, 0.21 Mo

4150H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

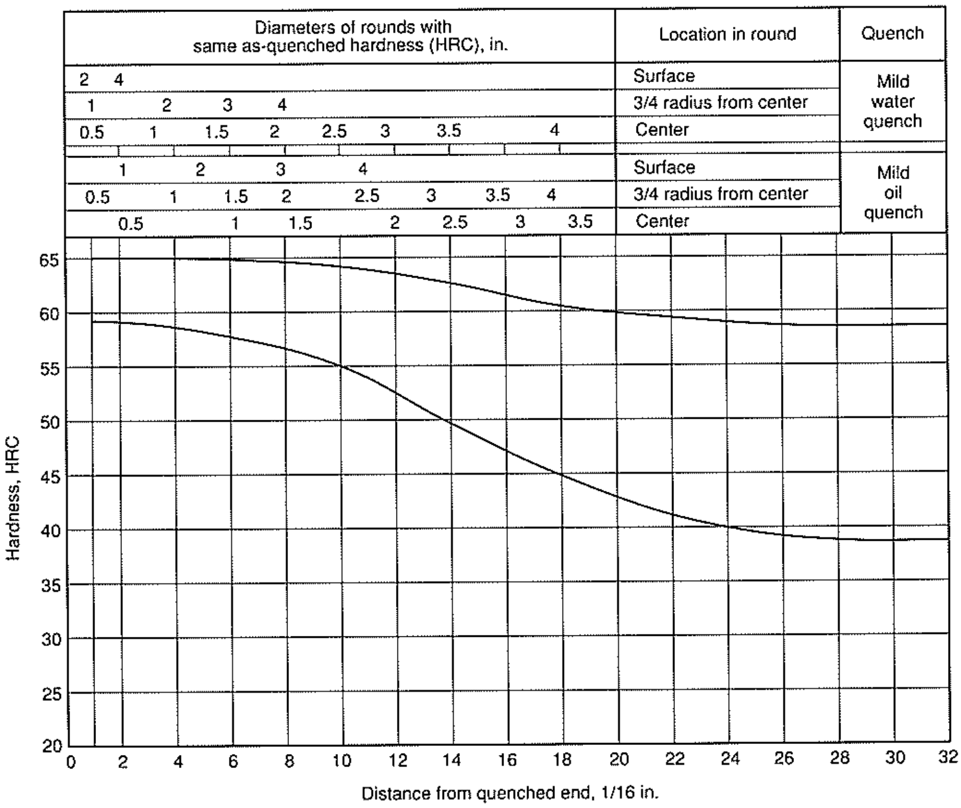
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	65	59
3	65	59
5	65	58
7	65	58
9	65	57
11	65	57
13	65	56
15	64	55
20	63	51
25	62	47
30	61	44
35	60	41
40	59	39
45	58	38
50	58	38



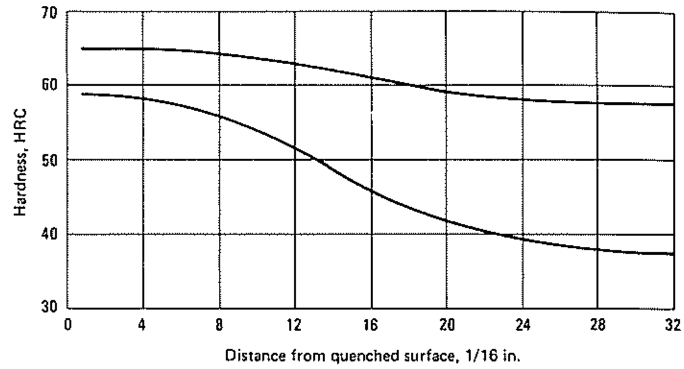
Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	65	59
2	65	59
3	65	59
4	65	58
5	65	58
6	65	57
7	65	57
8	64	56
9	64	56
10	64	55
11	64	54
12	63	53
13	63	51
14	62	50
15	62	48
16	62	47
18	61	45
20	60	43
22	59	41
24	59	40
26	58	39
28	58	38
30	58	38
32	58	38

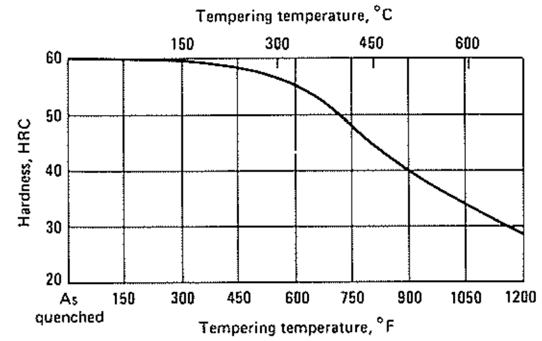


4150H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min
1	1.58	65	59	13	20.54	63	51
2	3.16	65	59	14	22.12	62	50
3	4.74	65	59	15	23.70	62	48
4	6.32	65	58	16	25.28	62	47
5	7.90	65	58	18	28.44	61	45
6	9.48	65	57	20	31.60	60	43
7	11.06	65	57	22	34.76	59	41
8	12.64	64	56	24	37.92	59	40
9	14.22	64	56	26	41.08	58	39
10	15.80	64	55	28	44.24	58	38
11	17.38	64	54	30	47.40	58	38
12	18.96	63	53	32	50.56	58	38



4150, 4150H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

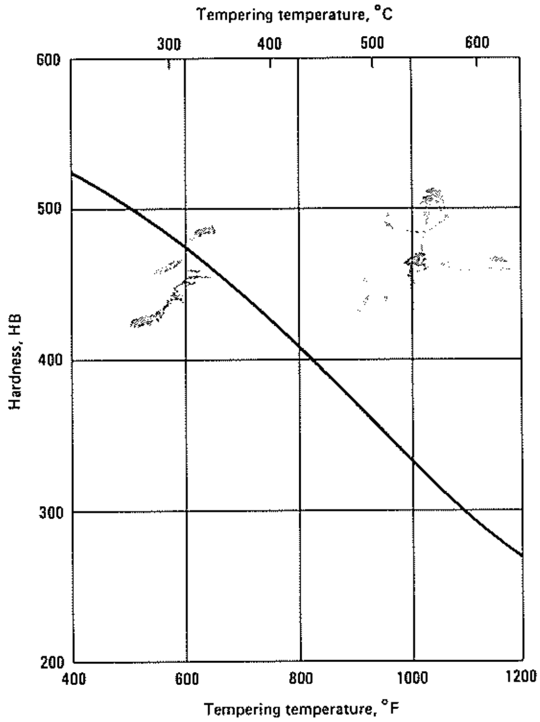


4150: Suggested Tempering Temperatures (Aerospace Practice)(a)

Tensile strength ranges 860-1035 MPa (125-150 ksi)	1035-1175 MPa (150-620 ksi)	1175-1240 MPa (160-180 ksi)	1240-1380 MPa (180-200 ksi)
650 °C (1200 °F)	595 °C (1100 °F)	525 °C (975 °F)	425 °C (800 °F)

(a) Quench with oil or polymer. Source: AMS 2759/1

4150: Hardness vs Tempering Temperature. Normalized at 870 °C (1600 °F), quenched from 845 °C (1555 °F), and tempered in 56 °C (100 °F) intervals in 13.716 mm (0.540 in.) rounds. Tested in 12.827 mm (0.505 in.) rounds. Source: Republic Steel



4161, 4161H, 4161RH

Chemical Composition. **4161. AISI and UNS:** 0.56 to 0.64 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.70 to 0.90 Cr, 0.25 to 0.35 Mo. **UNS H41610 and SAE/AISI 4161H:** 0.55 to 0.65 C, 0.65 to 1.10 Mn, 0.15 to 0.35 Si, 0.65 to 0.95 Cr, 0.25 to 0.35 Mo. **SAE 4161RH:** 0.56 to 0.64 C, 0.75 to 1.00 Mn, 0.15 to 0.35 Si, 0.70 to 0.90 Cr, 0.25 to 0.35 Mo

Similar Steels (U.S. and/or Foreign). **4161.** UNS G41610; ASTM A322, A331; SAE J404, J412, J770. **4161H.** UNS H41610; ASTM A304, A914; SAE J1268

Characteristics. A high-carbon steel, with a mean carbon content of 0.60%, has the highest carbon content of the 4100 steels. Chromium content is lower and the molybdenum content is higher than that of 4150H and other steels in the 4100 series. As a result, hardenability is higher. The band shows clearly that when all elements affecting hardenability are on the high side, the upper line of the band approaches that of an air-hardening steel, nearly a straight line. Depending on the precise carbon content, as-quenched hardness for 4161H ranges from 60 to 65 HRC. Often used for various tool, die, and spring applications. Well suited for heat treating by the austempering process. Must be treated carefully in all heat processing applications to avoid cracking

Forging. Heat to 1205 °C (2200 °F). Do not forge after temperature of forging stock drops below approximately 870 °C (1600 °F). Forgings should always be cooled slowly to avoid cracking

Recommended Heat Treating Practice

Normalizing. Heat to 855 °C (1570 °F). Cool in air

Annealing. For subsequent machining or operations involved in fabricating parts, a predominately spheroidized microstructure is usually preferred. This can be achieved by heating to 760 °C (1400 °F), cooling to 705 °C (1300 °F) at a rate not to exceed 6 °C (10 °F) per h; or by heating to 760 °C (1400 °F), cooling fairly rapidly to 660 °C (1220 °F), and holding for 10 h

Hardening. Heat to 830 °C (1525 °F), and quench in oil. Thin sections may be fully hardened by air cooling from 830 °C (1525 °F). Ion nitriding, gas nitriding, austempering, and carbonitriding are suitable processes. In austempering, quenching is in a molten salt bath

Tempering. Before parts reach room temperature, temper immediately. 38 to 50 °C (100 to 120 °F) is ideal. The tempering temperature depends upon the desired hardness or combination of properties

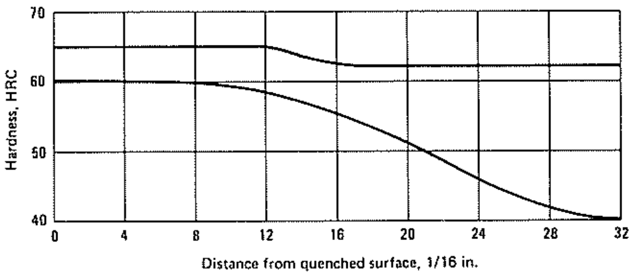
Austempering. Austenitize at 830 °C (1525 °F), quench into a well-agitated molten salt bath at 315 °C (600 °F), hold for 2 h, and cool in air. No tempering is required

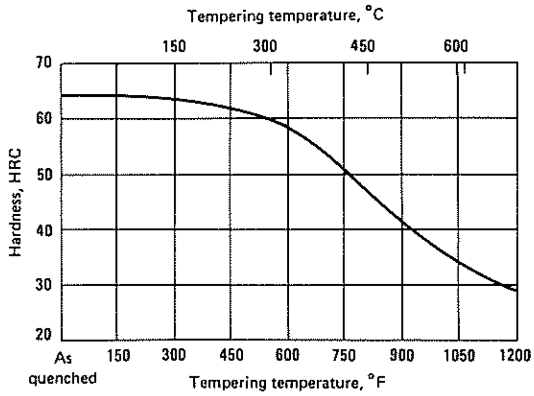
Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize and quench (or austemper)
- Temper (or austemper)
- Finish machine (or austemper)

4161H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min
1	1.58	65	60	13	20.54	64	58
2	3.16	65	60	14	22.12	64	58
3	4.74	65	60	15	23.70	64	57
4	6.32	65	60	16	25.28	64	56
5	7.90	65	60	18	28.44	64	55
6	9.48	65	60	20	31.60	63	53
7	11.06	65	60	22	34.76	63	50
8	12.64	65	60	24	37.92	63	48
9	14.22	65	59	26	41.08	63	45
10	15.80	65	59	28	44.24	63	43
11	17.38	65	59	30	47.40	63	42
12	18.96	64	59	32	50.56	63	41



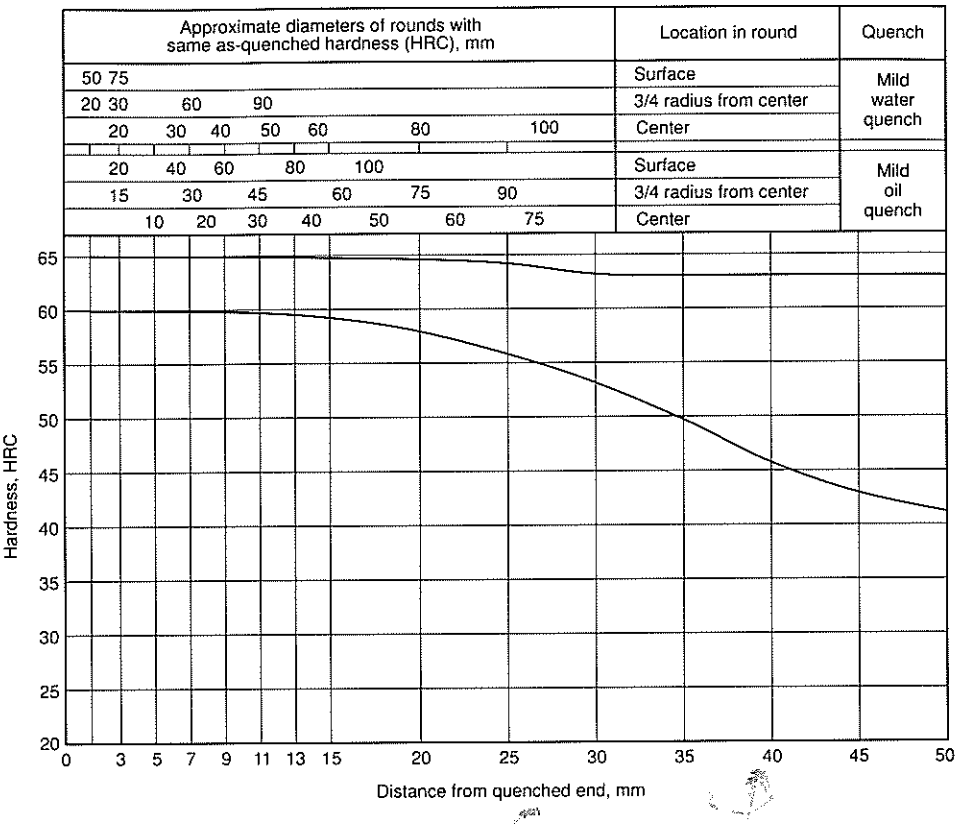


4161, 4161H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

4161H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

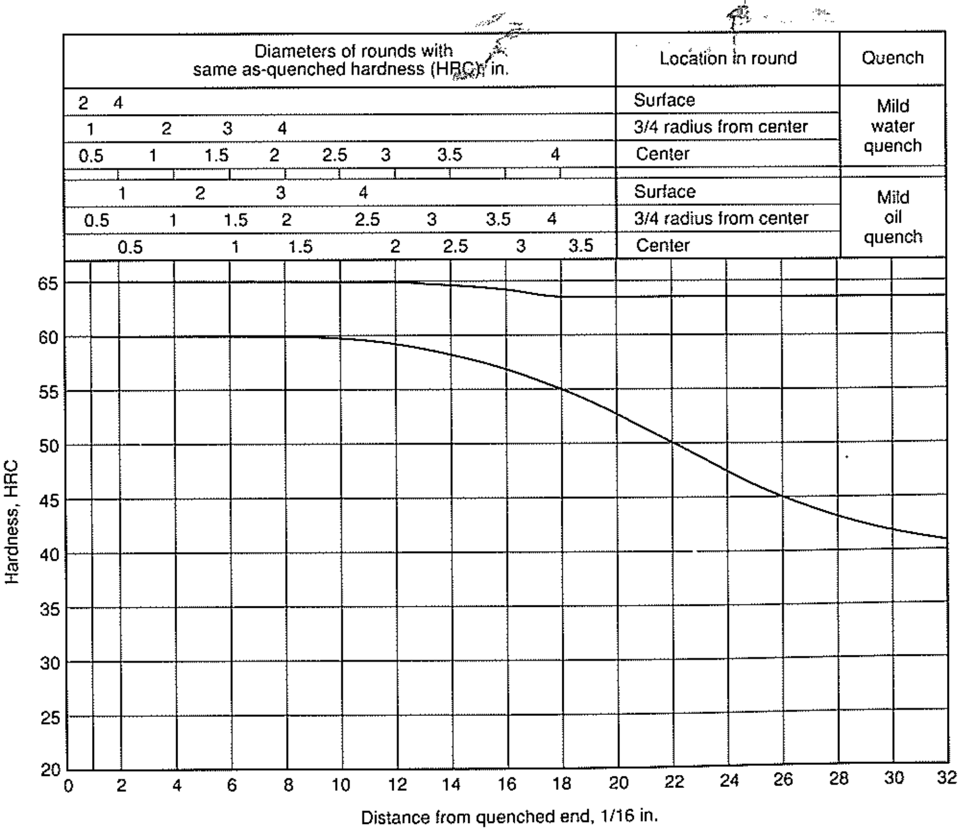
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	65	60
3	65	60
5	65	60
7	65	60
9	65	60
11	65	60
13	65	60
15	65	60
20	65	58
25	64	56
30	63	53
35	63	50
40	63	46
45	63	43
50	63	41



Hardness limits for specification purposes

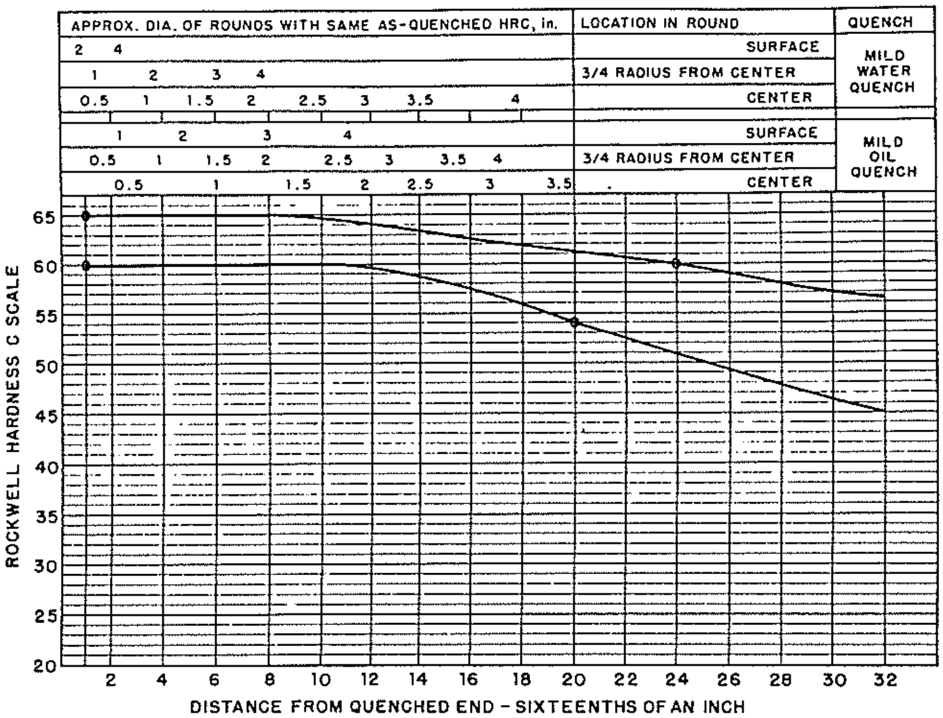
J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	65	60
2	65	60
3	65	60
4	65	60
5	65	60
6	65	60
7	65	60
8	65	60
9	65	59
10	65	59
11	65	59
12	64	59
13	64	58
14	64	58
15	64	57
16	64	56
18	64	55
20	63	53
22	63	50
24	63	48
26	63	45
28	63	43
30	63	42
32	63	41



4161RH: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

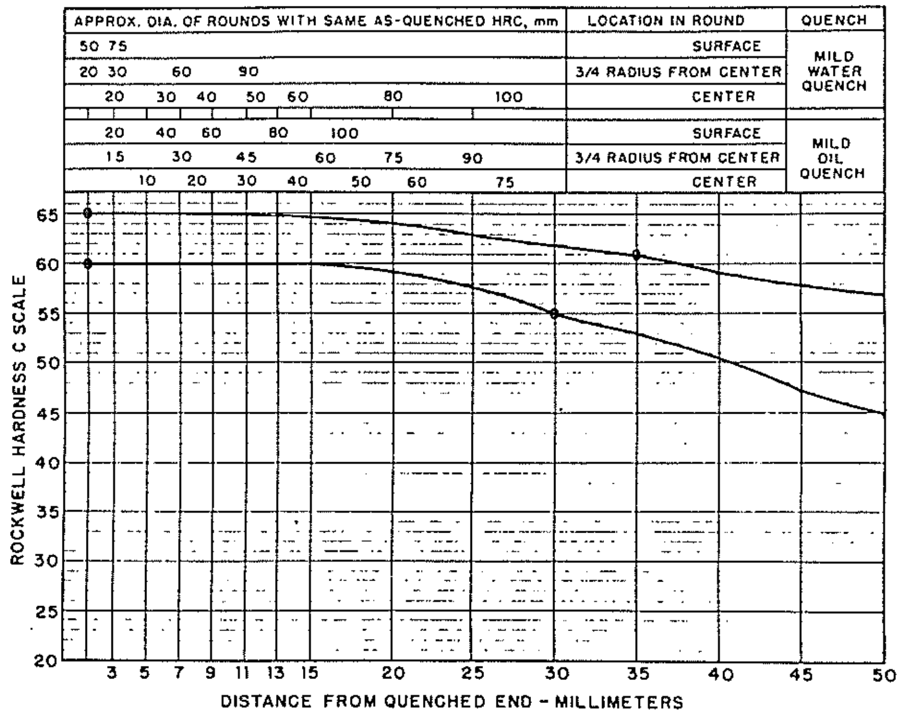
Hardness limits for specification purposes

J distance, $^1/_{16}$ in.	Hardness, HRC Maximum	Minimum
1	65	60
2	65	60
3	65	60
4	65	60
5	65	60
6	65	60
7	65	60
8	65	60
9	65	60
10	65	60
11	65	60
12	64	59
13	64	59
14	64	59
15	63	58
16	63	57
18	62	56
20	62	54
22	61	53
24	60	51
26	59	49
28	58	47
30	57	46
32	57	45



Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Minimum
1.5	65	60
3	65	60
5	65	60
7	65	60
9	65	60
11	65	60
13	65	60
15	65	60
20	64	59
25	63	57
30	62	55
35	61	53
40	59	50
45	58	47
50	57	45



4320, 4320H, 4320RH

Chemical Composition. **4320. AISI and UNS:** 0.17 to 0.22 C, 0.45 to 0.65 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 1.65 to 2.00 Ni, 0.40 to 0.60 Cr, 0.20 to 0.30 Mo. **UNS H43200 and SAE/AISI 4320H:** 0.17 to 0.23 C, 0.40 to 0.70 Mn, 0.15 to 0.35 Si, 1.55 to 2.00 Ni, 0.35 to 0.65 Cr, 0.20 to 0.30 Mo. **SAE 4320RH:** 0.17 to 0.22 C, 0.45 to 0.65 Mn, 0.15 to 0.35 Si, 1.65 to 2.00 Ni, 0.40 to 0.60 Cr, 0.20 to 0.30 Mo

Similar Steels (U.S. and/or Foreign). **4320.** UNS G43200; ASTM A322, A331, A505, A519, A535; SAE J404, J412, J770. **4320H.** UNS H43200; ASTM A304, A914; SAE J1268, J1868

Characteristics. Used almost exclusively for carburizing applications, notably heavy-duty, heavy-section gears, pinions, and related machinery components. Can be directly hardened to 40 HRC or higher through relatively thick sections because of high hardenability. Use of 4320H, however, is far less extensive when compared with most other alloy carburizing steels because it costs more, and because its properties (relating mainly to hardenability) are not required for a majority of applications. Forgeable and weldable, but has relatively poor machinability

Forging. Heat to 1245 °C (2275 °F) maximum. Do not forge after temperature of forging stock drops below approximately 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Cool in air

Annealing. Not usually annealed for a pearlitic structure because machinability is better when the predominate structure is spheroidal carbide. This is best obtained by heating after normalizing (following forging or rolling), to 775 °C (1425 °F), cooling rapidly to 650 °C (1200 °F), then holding for 8 h

Tempering. Tempering of carburized or carbonitrided parts made from 4320H is always recommended. Tempering temperature should be at least 150 °C (300 °F). Somewhat higher tempering temperatures may be used if some hardness can be traded off for increased toughness

Case Hardening. Carburizing procedures are the same as those given for 4118H. 4320H can be carbonitrided, although this process is infrequently applied. Parts made from 4320H are not, as a rule, well suited to the carbonitriding process. If used, see carbonitriding procedure described for grade 4118H. Gas carburizing, ion nitriding, austempering, and martempering are alternative processes

Recommended Processing Sequence

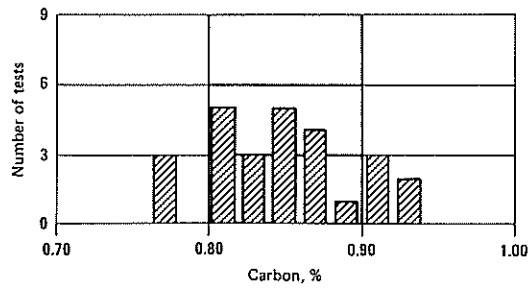
- Forge
- Normalize
- Anneal
- Rough and semifinish machine
- Carburize and harden
- Temper
- Finish machine (usually grinding, removing no more than 10% of the total case per side from critical areas)

4320: Carburizing, Single Heat Results

Specimens contained 0.20 C, 0.59 Mn, 0.021 P, 0.018 S, 0.25 Si, 1.77 Ni, 0.47 Cr, 0.23 Mo; grain size was 6 to 8; critical points included Ac_1, 1350 °F (730 °C); Ac_3, 1485 °F (805 °C); Ar_3, 1330 °F (720 °C); Ar_1, 840 °F (450 °C); 0.565-in. (14.4-mm) round treated, 0.505-in. (12.8-mm) round tested

Recommended practice	Case Hardness, HRC	Case Depth, in.	Case Depth, mm	Tensile strength, ksi	Tensile strength, MPa	Yield point, ksi	Yield point, MPa	Elongation in 2 in. (50 mm), %	Reduction of area, %	Hardness, HB
For maximum case hardness										
Direct quench from pot(a)	60.5	0.060	1.52	217	1496	159.5	1100	13.0	50.1	429
Single quench and temper(b)	62.5	0.075	1.91	218.25	1505	178	1227	13.5	48.2	429
Double quench and temper(c)	62	0.075	1.91	151.75	1046	97	669	19.5	49.4	302
For maximum core toughness										
Direct quench from pot(d)	58.5	0.060	1.52	215.5	1486	158.75	1095	12.5	49.4	415
Single quench and temper(e)	59	0.075	1.91	211.5	1458	173	1193	12.5	50.9	415
Double quench and temper(f)	59	0.075	1.91	145.75	1005	94.5	652	21.8	56.3	293

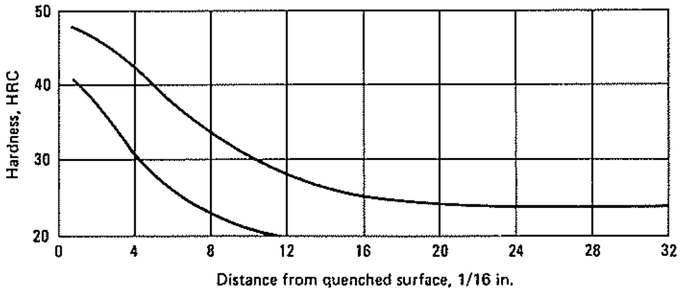
(a) Carburized at 1700 °F (925 °C) for 8 h, quenched in agitated oil, tempered at 300 °F (150 °C). (b) Carburized at 1700 °F (925 °C) for 8 h, pot cooled, reheated to 1500 °F (815 °C), quenched in agitated oil, tempered at 300 °F (150 °C). Good case and core properties. (c) Carburized at 1700 °F (925 °C) for 8 h, pot cooled, reheated to 1500 °F (815 °C), quenched in agitated oil, reheated to 1425 °F (775 °C), quenched in agitated oil, tempered at 300 °F (150 °C). Maximum refinement of case and core. (d) Carburized at 1700 °F (925 °C) for 8 h, quenched in agitated oil, tempered at 450 °F (230 °C). (e) Carburized at 1700 °F (925 °C) for 8 h, pot cooled, reheated to 1500 °F (815 °C), quenched in agitated oil, tempered at 450 °F (230 °C). Good case and core properties. (f) Carburized at 1700 °F (925 °C) for 8 h, pot cooled, reheated to 1500 °F (815 °C), quenched in agitated oil, reheated to 1425 °F (775 °C), quenched in agitated oil, tempered at 450 °F (230 °C). Maximum refinement of case and core. (Source: Bethlehem Steel)

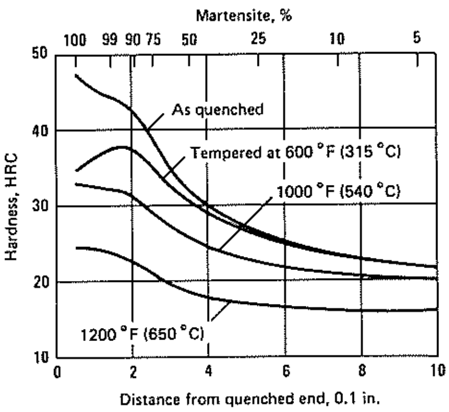


4320: Surface Carbon Content after Carburizing. 25.4 mm (1 in.) diam bar, 26 tests. Carburized at 925 °C (1695 °F)using a diffusion cycle, quenched from 815 °C (1500 °F) in oil at 60 °C (140 °F), tempered at 650 °C (1200 °F). Dew point, -1 °C (30 °F) at discharge end. Desired carbon concentration, 0.85 0.05%

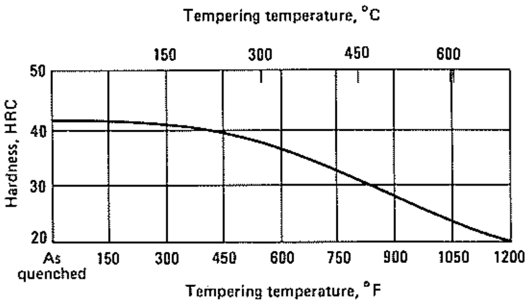
4320H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max
1	1.58	48	41	13	20.54	28
2	3.16	47	38	14	22.12	27
3	4.74	45	35	15	23.70	27
4	6.32	43	32	16	25.28	26
5	7.90	41	29	18	28.44	25
6	9.48	38	27	20	31.60	25
7	11.06	36	25	22	34.76	24
8	12.64	34	23	24	37.92	24
9	14.22	33	22	26	41.08	24
10	15.80	31	21	28	44.24	24
11	17.38	30	20	30	47.40	24
12	18.96	29	20	32	50.56	24





4320: Effect of Prior Microstructure on Hardness after Tempering. Specimens tempered 2 h



4320, 4320H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

4320: As-Quenched Hardness

Specimens were quenched in oil.

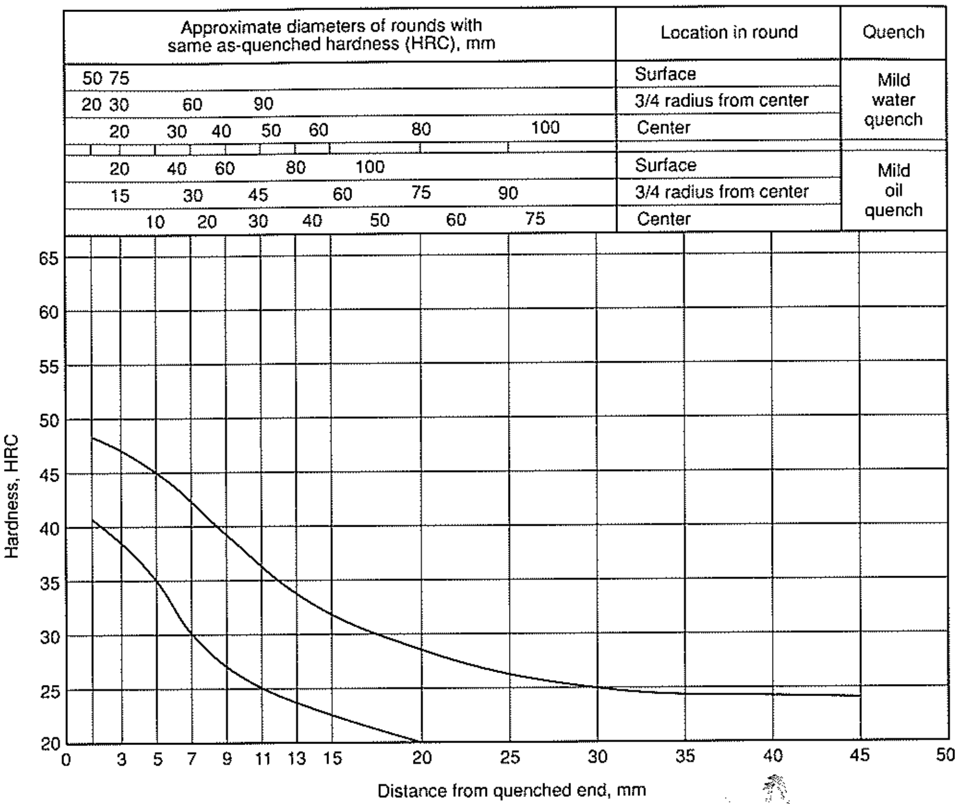
Size round, in.	Size round, mm	Hardness, HRC Surface	Hardness, HRC ½ radius	Hardness, HRC Center
½	13	44.5	44.5	44.5
1	25	39	37	36
2	51	35	30	27
4	102	25	24	24

Source: Bethlehem Steel

4320H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 925 °C (1700 °F)

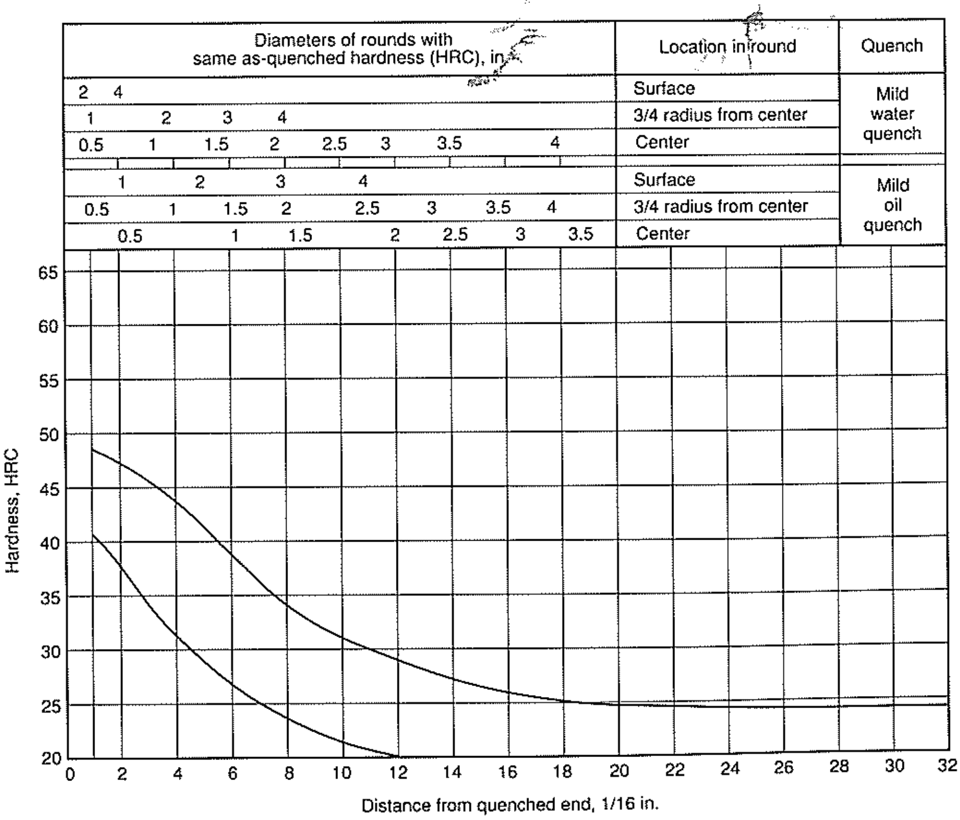
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	48	41
3	47	39
5	45	35
7	42	30
9	39	27
11	36	25
13	34	23
15	32	22
20	28	...
25	26	...
30	25	...
35	25	...
40	24	...
45	24	...
50	24	...

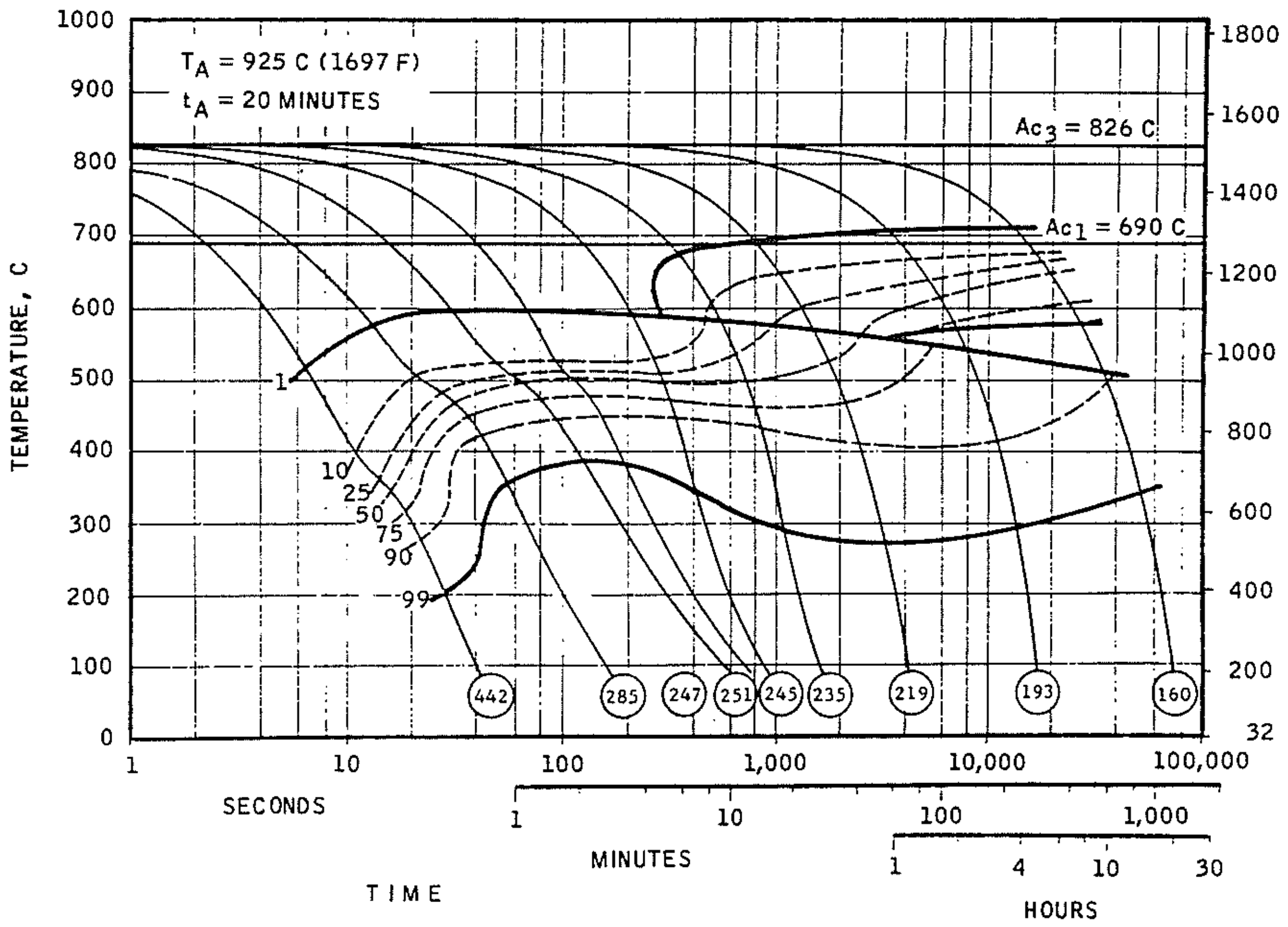


Hardness limits for specification purposes

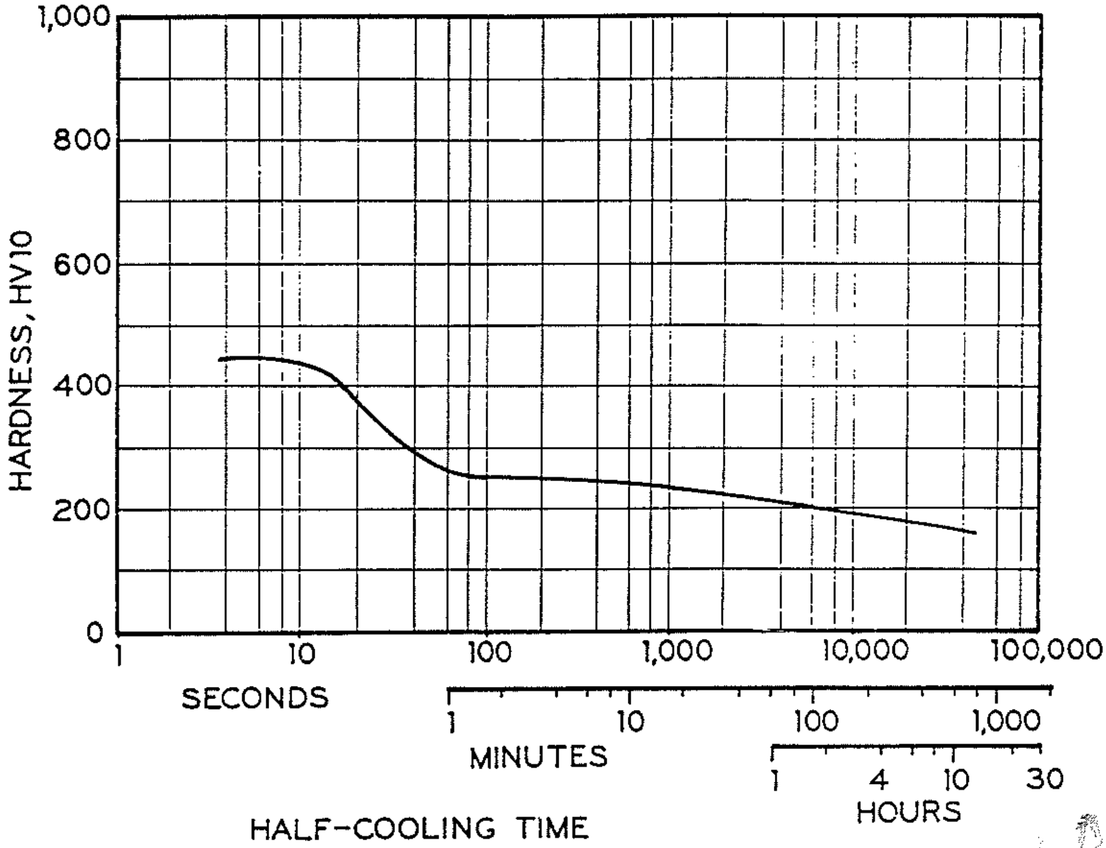
J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	48	41
2	47	38
3	45	35
4	43	32
5	41	29
6	38	27
7	36	25
8	34	23
9	33	22
10	31	21
11	30	20
12	29	20
13	28	...
14	27	...
15	27	...
16	26	...
18	25	...
20	25	...
22	24	...
26	24	...
28	24	...
30	24	...
32	24	...



4320: CCT Diagram. Carburizing composition: 0.20 C, 0.28 Si, 0.57 Mn, 0.0113P, 0.022 S, 0.50 Cr, 1.83 Ni, 0.26 Mo. A laboratory, induction air melted heat; ingot was forged to 12.7 mm (0.5 in.) square bar stock heated at 925 °C (1700 °F) for 1 h and air cooled. Steel was austenitized for 20 min at 925 °C (1700 °F). Source: Datasheet I-57. Climax Molybdenum Company



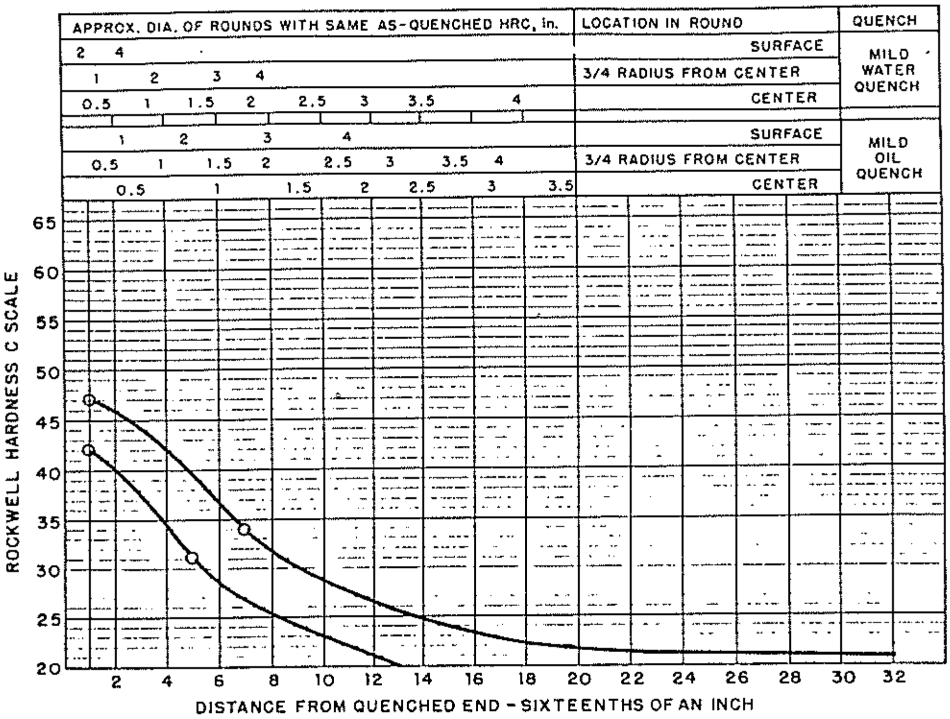
4320: Cooling Curve. Half cooling time. Source: Datasheet I-57. Climax Molybdenum Company



4320RH: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 925 °C (1700 °F)

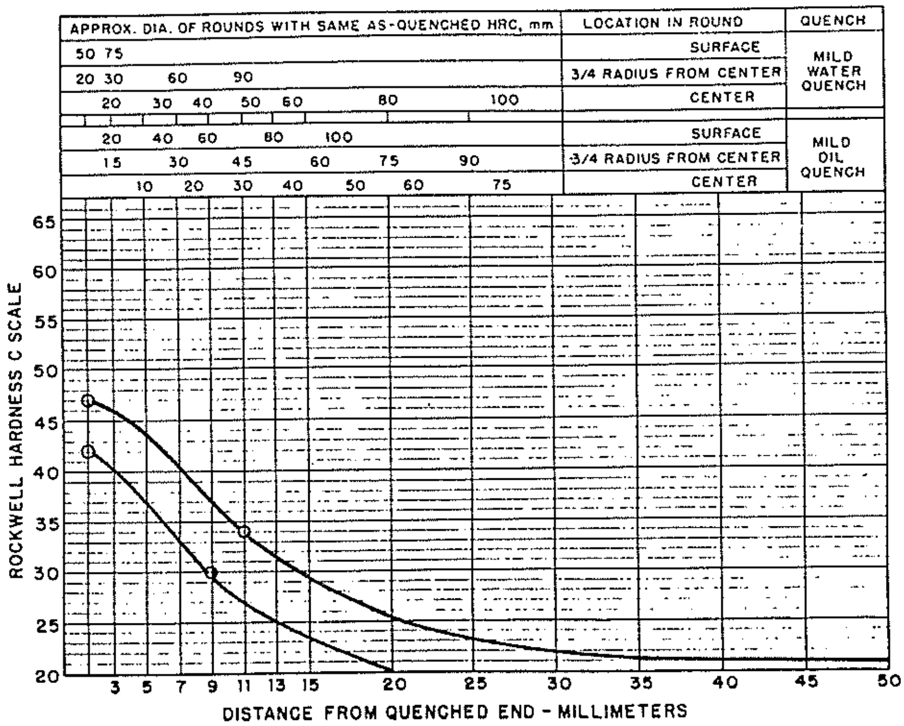
Hardness limits for specification purposes

distance, $\frac{1}{16}$ in.	Hardness, HRC Maximum	Minimum
	47	42
	46	40
	44	37
	41	34
	39	31
	36	29
	34	27
	32	25
	31	24
0	29	23
1	28	22
2	26	21
3	25	20
4	24	...
5	24	...
6	23	...
8	22	...
:0	22	...
:2	21	...
:4	21	...
:6	21	...
:8	21	...
;0	21	...
;2	21	...



Hardness limits for specification purposes

distance, mm	Hardness, HRC Maximum	Minimum
1.5	47	42
3	46	40
5	44	37
7	40	33
9	37	30
11	34	27
13	31	25
15	30	23
20	25	20
25	23	...
30	22	...
35	21	...
40	21	...
45	21	...
50	21	...



4330V

Chemical Composition: **AISI 4330V.** 0.30 C, 1.80 Ni, 0.80 Cr, 0.40 Mo, 0.07 V steel

Characteristics. An aerospace grade steel (AMS 2759/1)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F)

Annealing. Heat to 855 °C (1575 °F)

Austenitizing. Temperature is 870 °C (1600 °F), Hardening quenchants are oils or polymers

4335V

Chemical Composition. **AISI 4335V.** 0.35 C, 1.80 Ni, 0.72 Cr, 0.35 Mo, 0.2 V steel

Characteristics. An aerospace grade steel (AMS 2759/1)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F)

Annealing. Heat to 845 °C (1555 °F)

Austenitizing. Temperature is 870 °C (1600 °F), Hardening quenchants are oils or polymers

4340, 4340H

Chemical Composition. **4340. AISI and UNS:** 0.38 to 0.43 C, 0.60 to 0.80 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 1.65 to 2.00 Ni, 0.70 to 0.90 Cr, 0.20 to 0.30 Mo. **4340H. AISI and UNS:** 0.37 to 0.44 C, 0.60 to 0.95 Mn, 0.025 P max, 0.025 S max, 0.15 to 0.35 Si, 1.55 to 2.00 Ni, 0.65 to 0.95 Cr, 0.20 to 0.30 Mo

Similar Steels (U.S. and/or Foreign). **4340.** UNS G43400; AMS 5331, 6359, 6414, 6415; ASTM A322, A331, A505, A519, A547, A646; MIL SPEC MIL-S-16974; SAE J404, J412, J770; (Ger.) DIN 1.6565; (Jap.) JIS SNCM 8; (U.K.) B.S. 817 M 40,3111 Type 6, 2 S 119, 3 S 95. **4340H:** UNS H43400; ASTM A304; SAE J407; (Ger.) DIN 1.6565; (Jap.) JIS SNCM 8; (U.K.) B.S. 817 M 40,3111 Type 6, 2 S 119, 3 S 95

Characteristics. A high-hardenability steel, higher in hardenability than any other standard AISI grade. When the elements that contribute to hardenability are on the high side of their allowable ranges, the upper curve of the hardenability band is virtually a straight line, thus indicating that 4340H would be air-hardening in thin sections. Depending on the precise carbon content, as-quenched hardness ranges from 54 to 59 HRC. Because of high hardenability, 4340H is not considered suitable for welding by conventional means, although it can be welded by sophisticated processes such as electron beam welding. 4340H can be forged without difficulty, although its hot strength is considerably higher than that of carbon or lower alloy grades, requiring more powerful forging machines. Machinability is relatively poor

Forging. Heat to 1230 °C (2250 °F). Do not forge after temperature of forging stock drops below approximately 900 °C (1650 °F). Slow cooling from forging is recommended to prevent the possibility of cracking

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

Annealing. For a predominately pearlitic structure (not usually preferred for this grade), heat to 830 °C (1525 °F), cool rapidly to 705 °C (1300 °F), then to 565 °C (1050 °F) at a rate not to exceed 8 °C (15 °F) per h; or heat to 830 °C (1525 °F), cool rapidly to 650 °C (1200 °F), and hold for 8 h. For a predominately spheroidized structure, heat to 750 °C (1380 °F), cool rapidly to 705 °C (1300 °F) then cool to 565 °C (1050 °F) at a rate not to exceed 3 °C (5 °F) per h; or heat to 750 °C (1380 °F), cool rapidly to 650 °C (1200 °F), and hold for 12 h. A spheroidized structure is usually preferred for both machining and heat treating

Hardening. Austenitize at 845 °C (1555 °F), and quench in oil. Thin sections may be fully hardened by air cooling

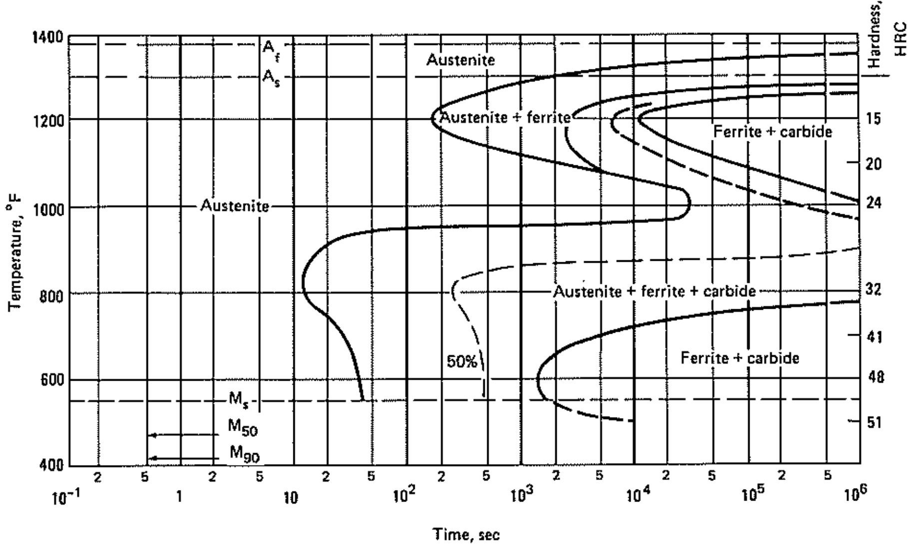
Tempering. In common with all high-hardenability steels, 4340H is susceptible to quench cracking. Before parts reach ambient temperature (38 to 50 °C, 100 to 120 °F), they should be placed in the tempering furnace. Tempering temperature depends upon the desired hardness or combination of mechanical properties

Nitriding. Can be nitrided to produce high surface hardness and for increased fatigue strength. See processing procedure given for 4140H

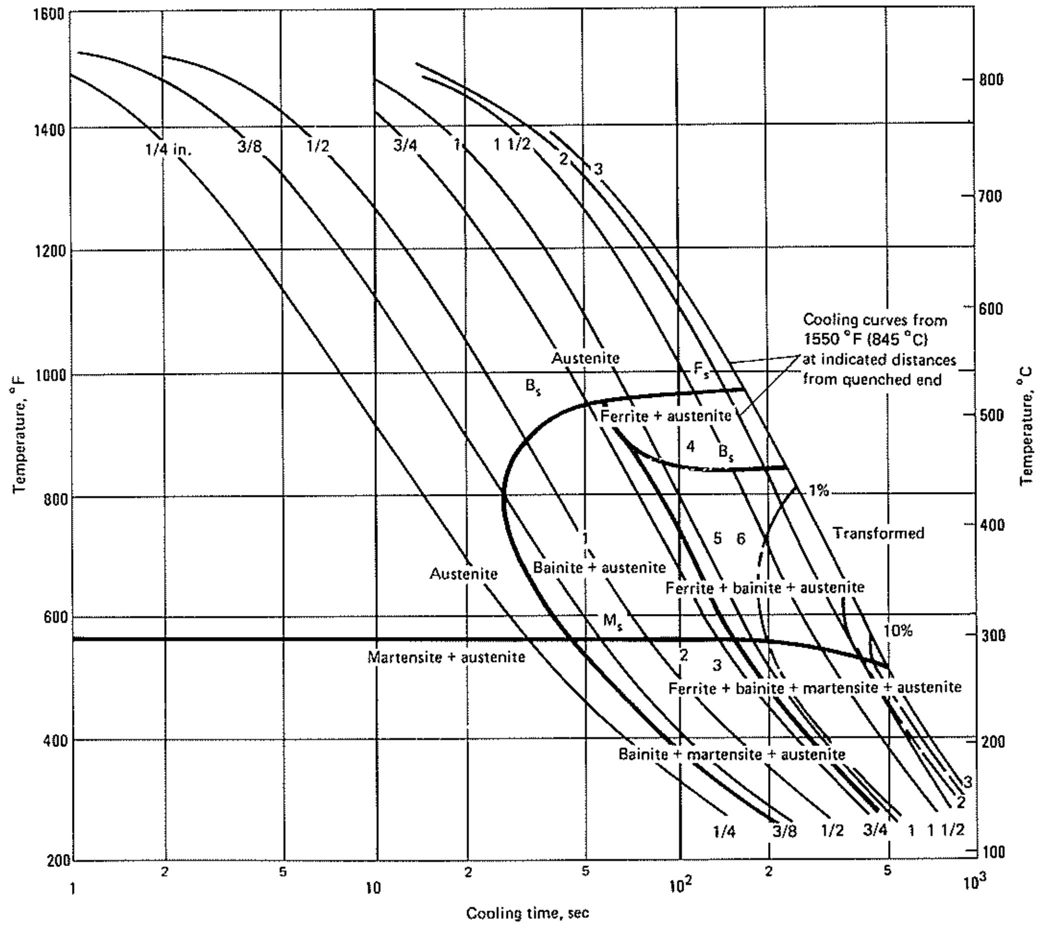
Recommended Processing Sequence

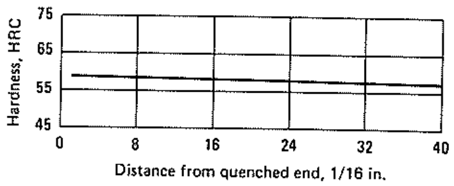
- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize, quench, and temper
- Finish machine
- Nitride (optional)

4340: Isothermal Transformation Diagram. Composition: 0.42 C, 0.78 Mn, 1.79 Ni, 0.80 Cr, 0.33 Mo. Austenitized at 845 °C (1555 °F). Grain size: 7 to 8



4340: Cooling Transformation Diagram. Composition: 0.41 C, 0.87 Mn, 0.28 Si, 1.83 Ni, 0.72 Cr, 0.20 Mo. Austenitized at 845 °C (1555 °F). Grain size: 7. Ac_3, 755 °C (1390 °F); Ac_1, 720 °C (1330 °F). A: austenite, F: ferrite, B: bainite, M: martensite. Source: Bethlehem Steel





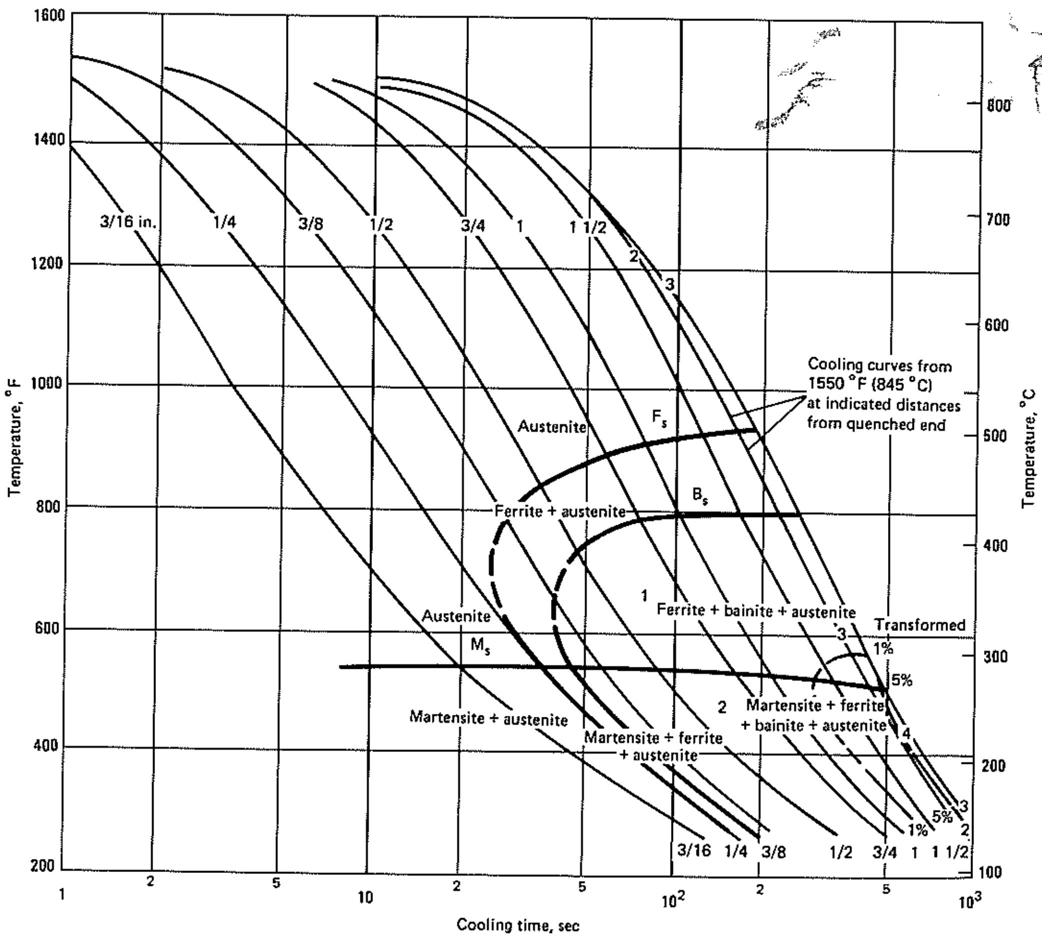
4340 + Si: End-Quench Hardenability. Composition: 0.42 C, 0.83 Mn, 1.5 Si, 1.85 Ni, 0.90 Cr, 0.41 Mo. Quenched from 845 °C (1555 °F). Source: Bethlehem Steel

4340: Tempered Hardness Versus Austenitizing Temperature and Section Size

Specimens were quenched in oil.

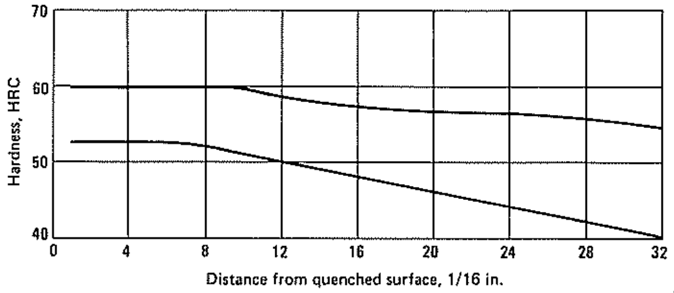
Austenitizing temperature °F (°C)	Section size in.	Section size mm	Hardness, HRC Tempered for 2 h at 400 °F (205 °C)	600 °F (315 °C)	800 °F (425 °C)	1000 °F (540 °C)	1200 °F (650 °C)
1500 (815)	½	12.7	53.5	50.0	44.5	39.0	29.5
	1¼	31.8	53.5	50.0	45.5	40.0	28.5
	2⅛	54	51.0	49.0	44.0	37.5	28.0
1550 (845)	½	12.7	53.5	49.5	44.0	39.0	29.0
	1¼	31.8	53.0	50.0	45.0	39.5	27.0
	2⅛	54	52.0	48.0	43.0	38.0	27.5
1600 (870)	½	12.7	53.5	50.0	45.0	40.0	29.5
	1¼	31.8	53.5	50.0	45.5	39.5	29.0
	2⅛	54	52.5	48.5	44.0	39.0	28.0

4340 + Si: Cooling Transformation Diagram. Composition: 0.43 C, 0.83 Mn, 1.55 Si, 1.84 Ni, 0.91 Cr, 0.40 Mo, 0.12 V, 0.083 Al. Austenitized at 845 °C (1555 °F). Grain size: 8. Ac_3, 805 °C (1480 °F); Ac_1, 760 °C (1400 °F). A: austenite, F: ferrite, B: bainite, M: martensite. Source: Bethlehem Steel

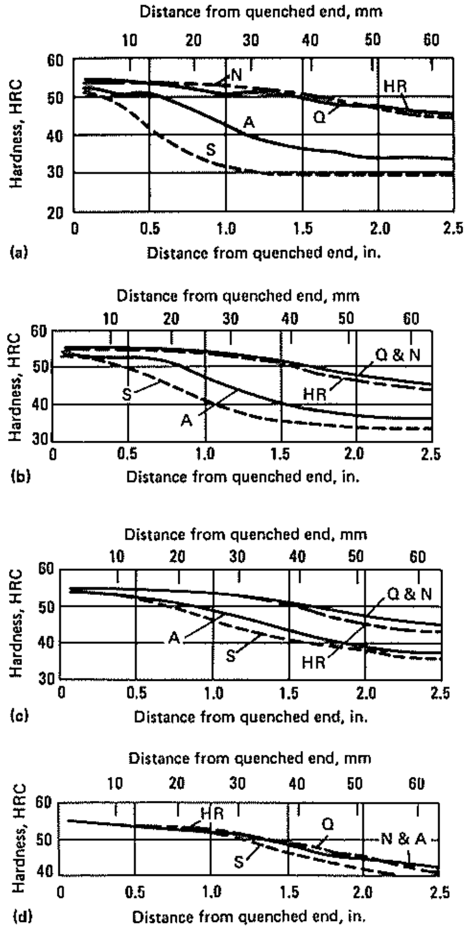


4340H: End-Quench Hardenability

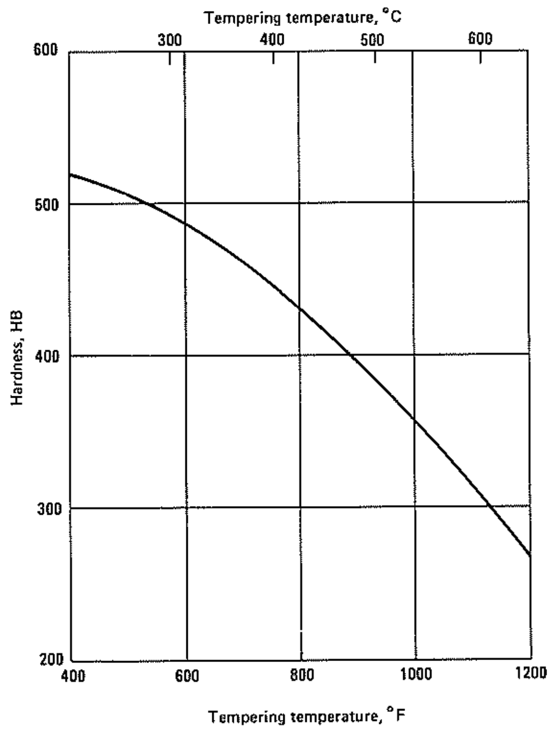
Distance from quenched surface		Hardness, HRC		Distance from quenched surface		Hardness, HRC	
1/16 in.	mm	max	min	1/16 in.	mm	max	min
1	1.58	60	53	13	20.54	59	50
2	3.16	60	53	14	22.12	58	49
3	4.74	60	53	15	23.70	58	49
4	6.32	60	53	16	25.28	58	48
5	7.90	60	53	18	28.44	58	47
6	9.48	60	53	20	31.60	57	46
7	11.06	60	53	22	34.76	57	45
8	12.64	60	52	24	37.92	57	44
9	14.22	60	52	26	41.08	57	43
10	15.80	60	52	28	44.24	56	42
11	17.38	59	51	30	47.40	56	41
12	18.96	59	51	32	50.56	56	40



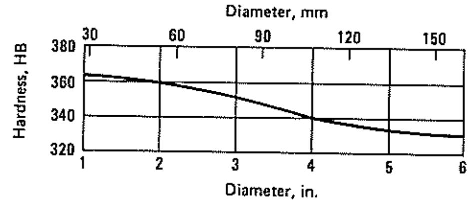
4340: End-Quench Hardenability. Influence of initial structure and time at 845 °C (1555 °F). HR: hot rolled, N: normalized, A: annealed, S: spheroidized. (a) 0 min; (b) 10 min; (c) 40 min; (d) 4 h



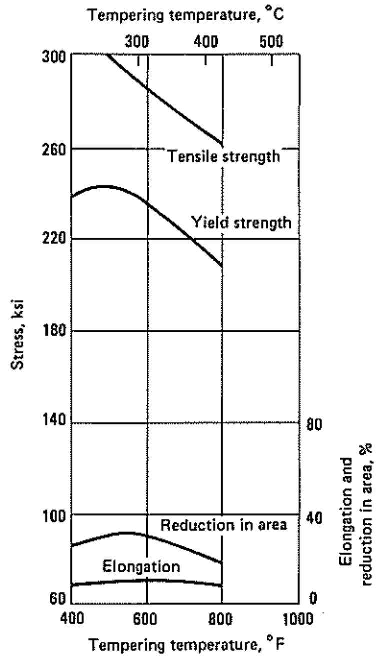
4340: Hardness vs Tempering Temperature. Normalized at 870 °C (1600 °F), quenched from 845 °C (1555 °F), and tempered in 56 °C (100 °F) intervals in 13.7 mm (0.540 in.) rounds. Tested in 12.8 mm (0.505 in.) rounds. Source: Republic Steel



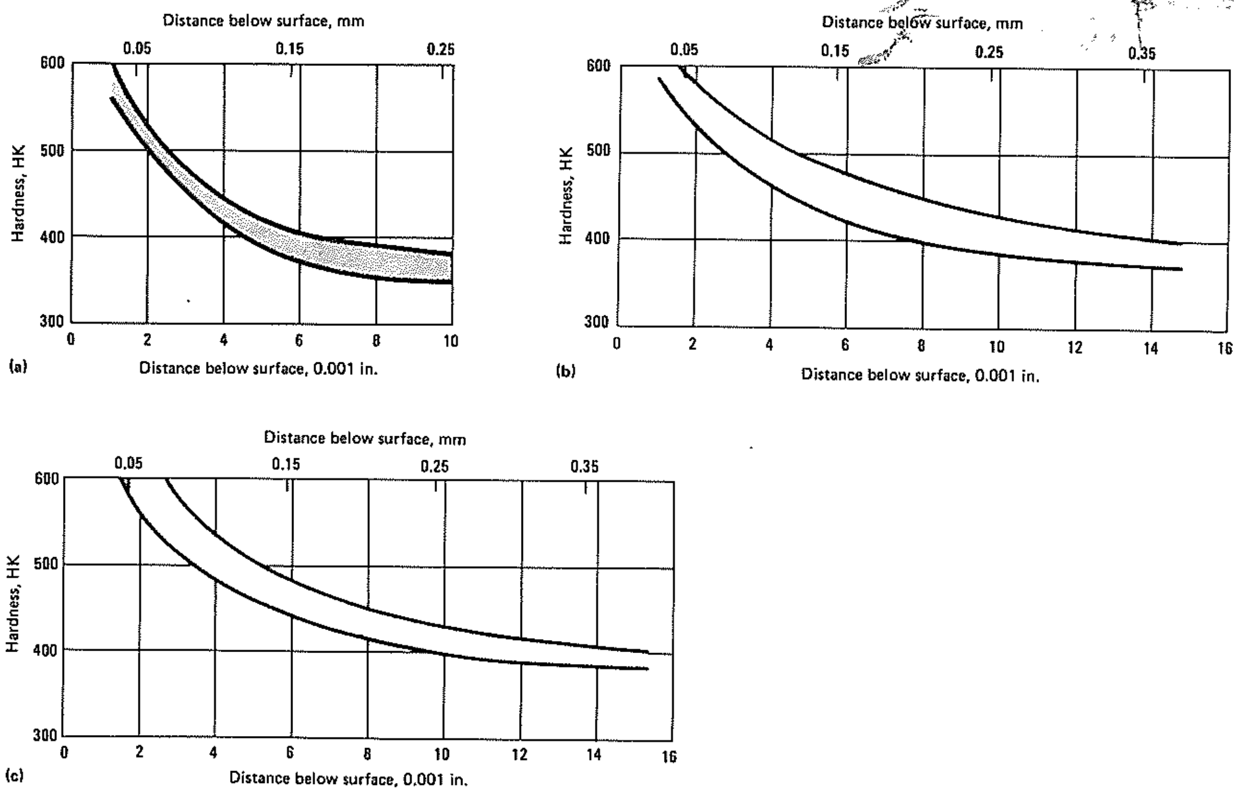
4340: Hardness vs Diameter. 0.38 to 0.43 C, 0.60 to 0.80 Mn, 0.040 P max, 0.040 S max, 0.20 to 0.35 Si, 1.65 to 2.00 Ni, 0.70 to 0.90 Cr, 0.20 to 0.30 Mo. Approximate critical points: Ac_1, 725 °C (1335 °F); Ac_3, 775 °C (1425 °F); Ar_3, 710 °C (1310 °F); Ar_1, 655 °C (1210 °F). Forge at 1230 °C (2250 °F) maximum; anneal at 595 to 660 °C (1105 to 1220 °F) for a maximum hardness of 223 HB; normalize at 845 to 900 °C (1555 to 1650 °F) for an approximate hardness of 415 HB; quench in oil from 830 to 855 °C (1525 to 1570 °F). Test specimens normalized at 870 °C (1600 °F) in over-sized rounds, quenched from 845 °C (1555 °F) in oil, tempered at 540 °C (1000 °F). Tested in 12.8 mm (0.505 in.) rounds. Tests from 38 mm (1.5 in.) diam bars and over are taken at half radius position. Source: Republic Steel



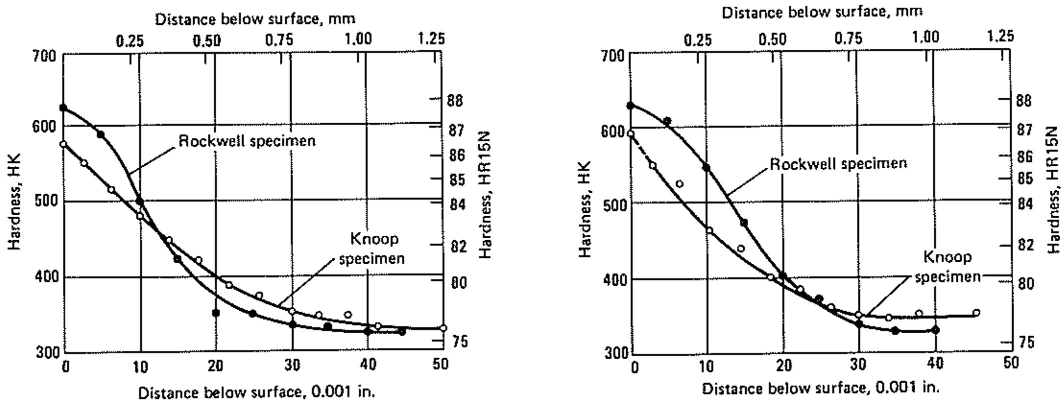
4340 + Si: Tensile Strength, Yield Strength Elongation, and Reduction in Area. Composition: 0.43 C, 0.83 Mn, 1.55 Si, 1.84 Ni, 0.91 Cr, 0.40 Mo, 0.12 V, 0.083 Al. Normalized at 900 °C (1650 °F), austenitized at 855 °C (1570 °F), quenched in agitated oil, tempered for 1 h. Source: Bethlehem Steel



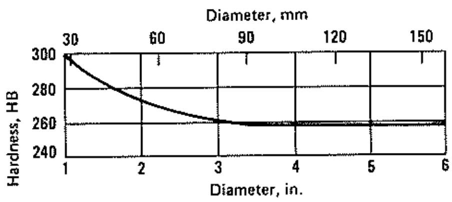
4340: Nitriding. 20 to 30% dissociation. (a) 7 h. (b) 24 h. (c) 48 h



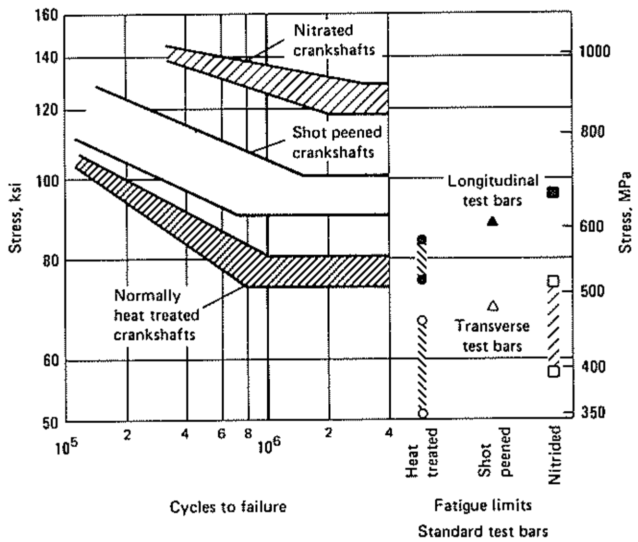
4340: Gas Nitriding. Two tests. Nitrided at 550 °C (1020 °F) for 20 h, 20 to 50% dissociation

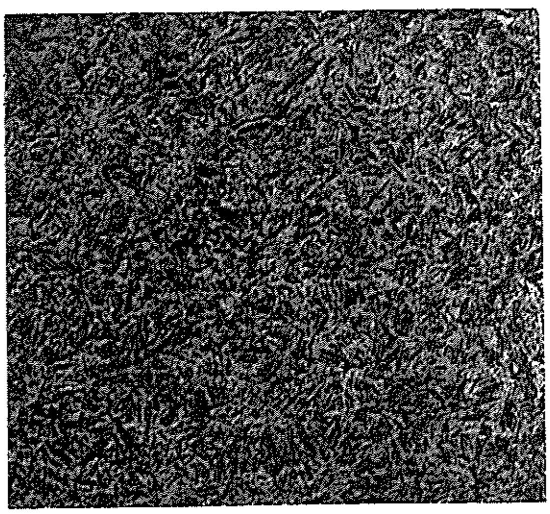


4340: Hardness vs Diameter. Composition: 0.38 to 0.43 C, 0.60 to 0.80 Mn, 0.040 P max, 0.040 S max, 0.20 to 0.35 Si, 1.65 to 2.00 Ni, 0.70 to 0.90 Cr, 0.20 to 0.30 Mo. Approximate critical points: Ac_1, 725 °C (1335 °F); Ac_3, 775 °C (1425 °F); Ar_3, 710 °C (1310 °F); Ar_1, 655 °C (1210 °F). Recommended thermal treatment: forge at 1230 °C (2250 °F) maximum; anneal at 595 to 660 °C (1105 to 1220 °F) for a maximum hardness of 223 HB; normalize at 845 to 900 °C (1555 to 1650 °F) for an approximate hardness of 415 HB; quench in oil from 830 to 855 °C (1525 to 1570 °F). Test specimens normalized at 870 °C (1600 °F) in over-sized rounds, quenched from 845 °C (1555 °F) in oil, tempered at 650 °C (1200 °F). Tested in 12.8 mm (0.505 in.) rounds. Tests from 38 mm (1 ½ in.) diam bars and over are taken at half radius position. Source: Republic Steel



4340: Effect of Nitriding and Shot Peening on Fatigue Behavior. Comparison between fatigue limits of crankshafts (S-N bands) and fatigue limits for separate test bars, indicated by plotted points at right





4340: Microstructure. 2% nital, 500×. Quenched in oil from 845 °C (1555 °F) and tempered at 315 °C (600 °F). Tempered martensite

E4340, E4340H

Chemical Composition. **E4340. AISI and UNS:** 0.38 to 0.43 C, 0.65 to 0.85 Mn, 0.025 P max, 0.025 S max, 0.15 to 0.30 Si, 1.65 to 2.00 Ni, 0.70 to 0.90 Cr, 0.20 to 0.30 Mo. **E4340H. AISI and UNS:** 0.37 to 0.44 C, 0.60 to 0.95 Mn, 0.025 P max, 0.025 S max, 0.15 to 0.30 Si, 1.55 to 2.00 Ni, 0.65 to 0.95 Cr, 0.20 to 0.30 Mo

Similar Steels (U.S. and/or Foreign). **E4340.** UNS G43406; ASTM A331, A505, A519; MIL SPEC MIL-S-5000; SAE J404, J770; (Ger.) DIN 1.6562; (Jap.) JIS 40 NiCrMo 7, 40 NiCrMo 7 KB; (U.K.) B.S. Type 8, S 139. **E4340H.** UNS H43406; ASTM A304; SAE J407; (Ger.) DIN 1.6562; (Ital.) UNI 40 NiCrMo 7, 40 NiCrMo 7 KB; (U.K.) B.S. Type 8, S 139

Characteristics. Basically a premium grade of 4340H. Prescribed composition carries lower maximums for both phosphorus and sulfur. Manganese range is slightly higher, but this is of little practical significance. Hardenability and other properties are the same as for conventional 4340H. Weldability and machinability are poor; forgeability is good. As-quenched hardness, 54 to 59 HRC

Forging. Heat to 1230 °C (2250 °F). Do not forge after temperature of forging stock drops below approximately 900 °C (1650 °F). Slow cooling from forging is recommended to prevent the possibility of cracking

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

Annealing. For a predominately pearlitic structure (not usually preferred for this grade), heat to 830 °C (1525 °F), cool rapidly to 705 °C (1300 °F), then to 565 °C (1050 °F) at a rate not to exceed 8 °C (15 °F) per h; or heat to 830 °C (1525 °F), cool rapidly to 650 °C (1200 °F), and hold for 8 h. For a predominately spheroidized structure, heat to 750 °C (1380 °F), cool rapidly to 705 °C (1300 °F), then to 565 °C (1050 °F) at a rate not to exceed 3 °C (5 °F) per h; or heat to 750 °C (1380 °F), cool rapidly to 650 °C (1200 °F), and hold for 12 h. A spheroidized structure is usually preferred, for both machining and heat treating

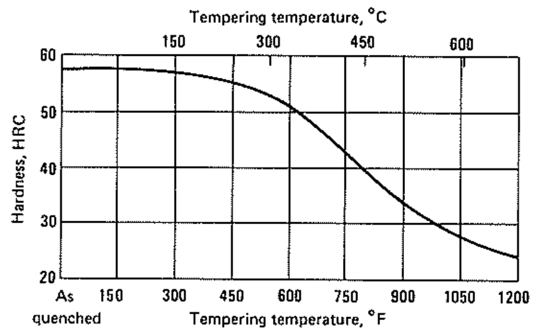
Hardening. Austenitize at 845 °C (1555 °F), and quench in oil. Thin sections may be fully hardened by air cooling

Tempering. These steels, in common with all high-hardenability steels, are susceptible to quench cracking. Before parts reach ambient temperature (38 to 49 °C, or 100 to 120 °F), they should be placed in the tempering furnace. Tempering temperature depends upon the desired hardness or combination of mechanical properties

Nitriding. Can be nitrided to produce high surface hardness and to increase fatigue strength. See processing procedure given for 4140H

Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize, quench, and temper
- Finish machine
- Nitride (optional)

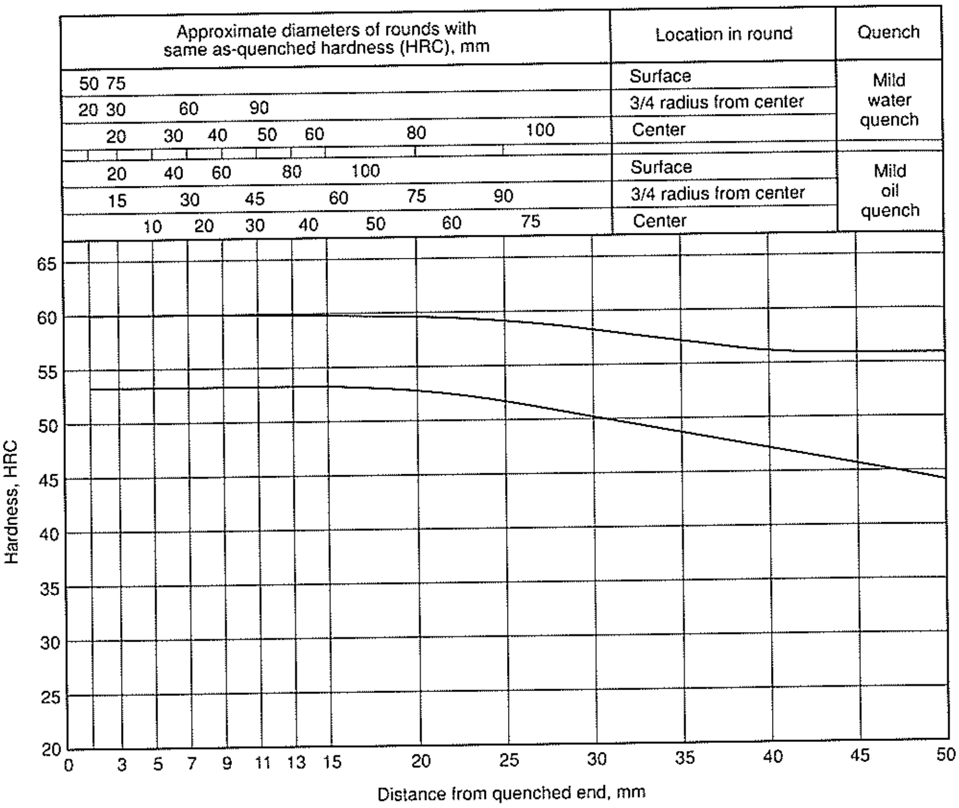


E4340, E4340H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

E4340H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870°C (1600 °F). Austenitize: 845 °C (1555 °F)

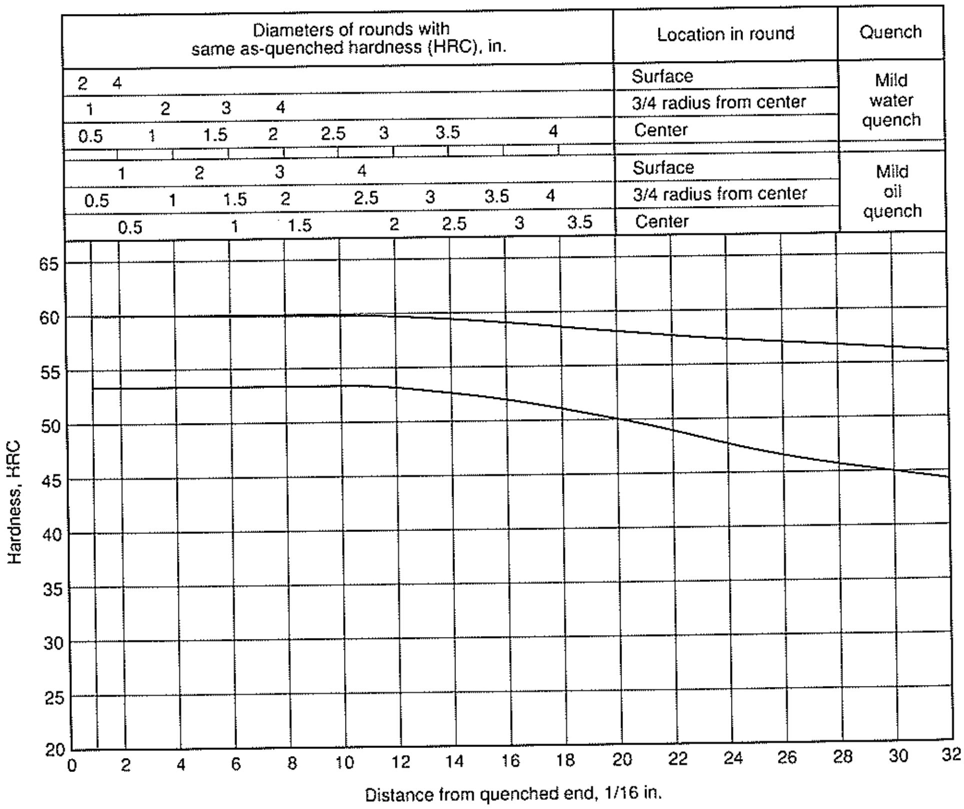
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	60	53
3	60	53
5	60	53
7	60	53
9	60	53
11	60	53
13	60	53
15	60	53
20	60	52
25	59	51
30	58	50
35	58	49
40	57	47
45	57	46
50	57	44



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	60	53
2	60	53
3	60	53
4	60	53
5	60	53
6	60	53
7	60	53
8	60	53
9	60	53
10	60	53
11	60	53
12	60	52
13	60	52
14	59	52
15	59	52
16	59	51
18	58	51
20	58	50
22	58	49
24	57	48
26	57	47
28	57	46
30	57	45
32	57	44



4615

Chemical Composition. **4615. AISI and UNS:** 0.13 to 0.18 C, 0.45 to 0.65 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 1.65 to 2.00 Ni, 0.20 to 0.30 Mo

Similar Steels (U.S. and/or Foreign). **4142.** UNS G46150; AMS 6290; ASTM A322, A331, A505; MIL SPEC MIL-S-7493; SAE J404, J412, J770. This steel is no longer in SAE J404 or J 412, but does appear in SAE J770, which is now J1397

Characteristics. Used extensively for making parts that will be case hardened by carburizing or carbonitriding. Over a period of years, however, use has declined in favor of carburizing grades that have slightly higher carbon (for better core properties), lower nickel content, or both. As-quenched surface hardness (not carburized) can be expected to be approximately 35 to 40 HRC, and the hardenability band should be nearly the same general pattern as the one for 4620H. No AISI hardenability band for 4615. The slight difference in range of nickel content for 4615 and 4620H is not significant. Grade 4615 forges easily and is weldable, although alloy steel practice, in terms of preheating and postheating, should be used

Forging. Heat to 1245 °C (2275 °F) maximum. Do not forge after temperature of forging stock drops below approximately 900 °C (1650 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Cool in air

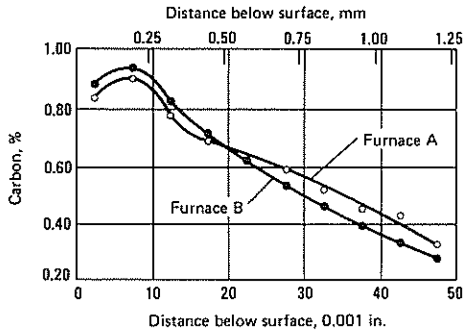
Annealing. Not usually required for this grade. Structures that are well suited to machining are generally obtained by normalizing or by isothermal annealing after rolling or forging. Isothermal annealing may be accomplished by heating to 700 °C (1290 °F) and holding for 8 h

Case Hardening. See recommended carburizing, carbonitriding, and tempering procedures described for 4118H. Flame hardening, liquid carburizing, austempering and martempering are alternative treatment processes

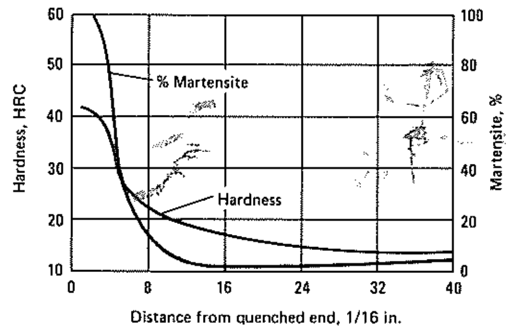
Recommended Processing Sequence

- Forge
- Normalize
- Anneal (optional)
- Rough and semifinish machine
- Case harden
- Temper
- Finish machine (carburized parts only)

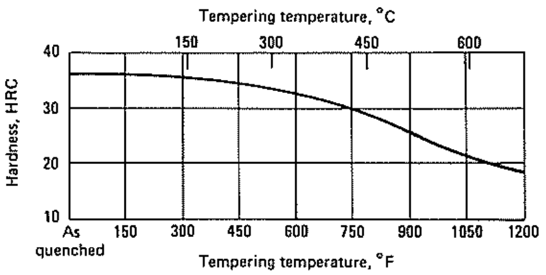
4615: Carbon Gradients Produced by Liquid Carburizing. 4615 mod (cast), carburized at 925 °C (1695 °F) for 7 h. Indicates slight differences in gradients obtained in two furnaces using the same carburizing conditions



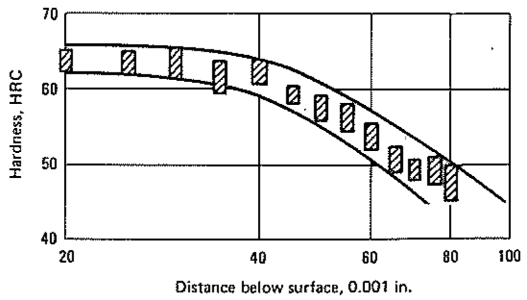
4615: End-Quench Hardenability. Composition: 0.15 C, 0.63 Mn, 1.90 Ni, 0.24 Mo. Austenitized at 925 °C (1695 °F). Grain size: 8



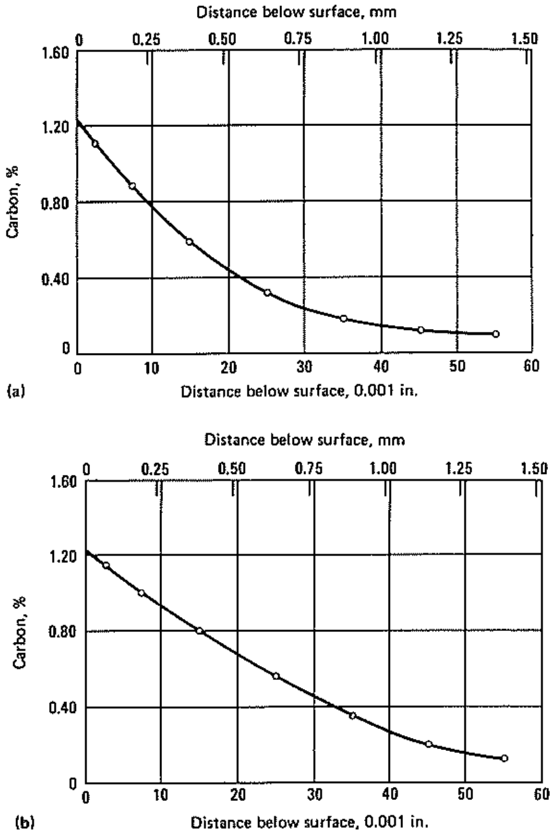
4615: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure



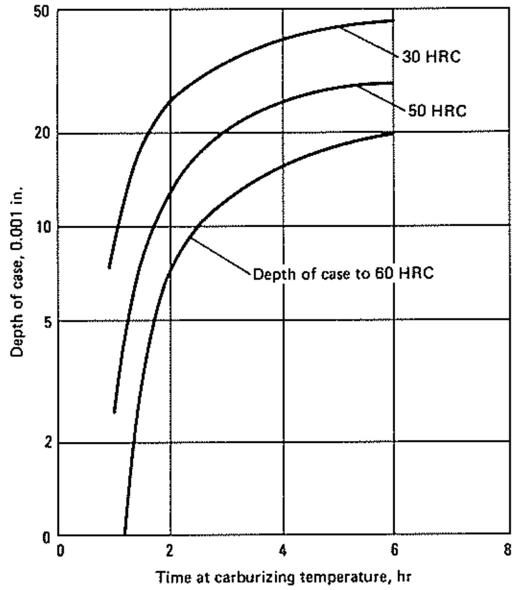
4615: Liquid Carburizing. Case hardness gradients after 10 tests



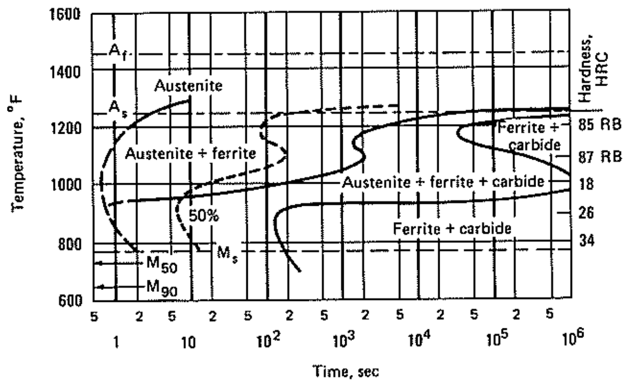
4615: Carbon Gradients After Carburizing. (a) Carburized for 4 h at 870 °C (1600 °F); (b) Carburized for 4 h at 925 °C (1695 °F)



4615: Depth of Case vs Time and Temperature. 25 mm (1 in.) round bars, carburized at 925 °C (1695 °F), oil quenched



4615: Isothermal Transformation Diagram. Composition: 0.15 C, 0.63 Mn, 1.90 Ni, 0.24 Mo. Austenitized at 925 °C (1695 °F). Grain size: 8



4620, 4620H, 4620RH

Chemical Composition. 4620. AISI and UNS: 0.17 to 0.22 C, 0.45 to 0.65 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 1.65 to 2.00 Ni, 0.20 to 0.30 Mo. **UNS H46200 and SAE/AISI 4620H:** 0.17 to 0.23 C, 0.35 to 0.75 Mn, 0.15 to 0.35 Si, 1.55 to 2.00 Ni, 0.20 to 0.30 Mo. **SAE 4620RH:** 0.17 to 0.22 C, 0.45 to 0.65 Mn, 0.15 to 0.35 Si, 1.65 to 2.00 Ni, 0.20 to 0.30 Mo

Similar Steels (U.S. and/or Foreign). 4620. UNS G46200; AMS 294; ASTM A322, A331, A505, A535; MIL SPEC MIL-S-7493; SAE J404, J412, J770. **4620H.** UNS H46200; ASTM A304, A914; SAE J1268, J1868

Characteristics. Used extensively for carburizing. Because of relatively high nickel content, it has been replaced in some areas with lower nickel alloys that have been developed and have hardenability and other properties equal to those of 4620H. Depending on the precise carbon content within the allowable range, as-quenched hardness without carburizing ranges between approximately 40 to 45 HRC. Has a reasonably high hardenability. Because of the relatively high nickel content, 4620H is strongly susceptible to retention of austenite. While retained austenite is usually considered as an undesirable constituent, some specific applications exist where retained austenite has proved to be an advantage

Forging. Heat to 1245 °C (2275 °F). Do not forge after temperature of forging stock drops below approximately 845 °C (1555 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Cool in air

Annealing. Structures with best machinability are developed by normalizing or by isothermal transformation after rolling or forging. Commonly used isothermal practice consists of heating to 775 °C (1425 °F), cooling rapidly to 650 °C (1200 °F), and holding for 6 h

Hardening. Seldom subjected to hardening treatments except carburizing and carbonitriding. See recommended carburizing, carbonitriding, and tempering procedures described for 4118H. Flame hardening and martempering are alternative processes

Recommended Processing Sequence

- Forge
- Normalize
- Anneal (optional)
- Rough and semifinish machine
- Case harden
- Temper
- Finish machine (carburized parts only)

4620: Carburizing, Single Heat Results

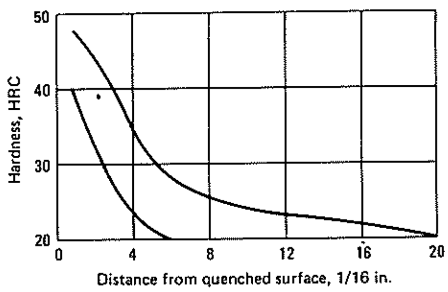
Specimens contained 0.17 C, 0.52 Mn, 0.017 P, 0.016 S, 0.26 Si, 1.81 Ni, 0.10 Cr, 0.21 Mo; grain size 6 to 8; critical points included Ac_1, 1300 °F (705 °C); Ac_3, 1490 °F (810 °C); Ar_3, 1335 °F (725 °C); Ar_1, 1220 °F (660 °C); 0.565-in. (14.4-mm) round treated, 0.505-in. (12.8-mm) round tested

	Case			Core properties						
	Hardness,	Depth		Tensile strength		Yield point		Elongation in 2 in.	Reduction of area,	Hardness,
Recommended practice	HRC	in.	mm	ksi	MPa	ksi	MPa	(50 mm), %	%	HB
For maximum case hardness										
Direct quench from pot(a)	60.5	0.075	1.91	148.25	1022.2	116.5	803.2	17.0	55.7	311
Single quench and temper(b)	62.5	0.075	1.91	119.25	822.2	83.5	576	19.5	59.4	277
Double quench and temper(c)	62	0.060	1.52	122	841	77.25	532.6	22.0	55.7	248
For maximum core toughness										
Direct quench from pot(d)	58.5	0.060	1.52	147.5	1017	115.75	798.07	16.8	57.9	302
Single quench and temper(e)	59	0.065	1.65	115.5	796.3	80.75	556.8	20.5	63.6	248
Double quench and temper(f)	59	0.060	1.65	115.25	794.63	77	531	22.5	62.1	235

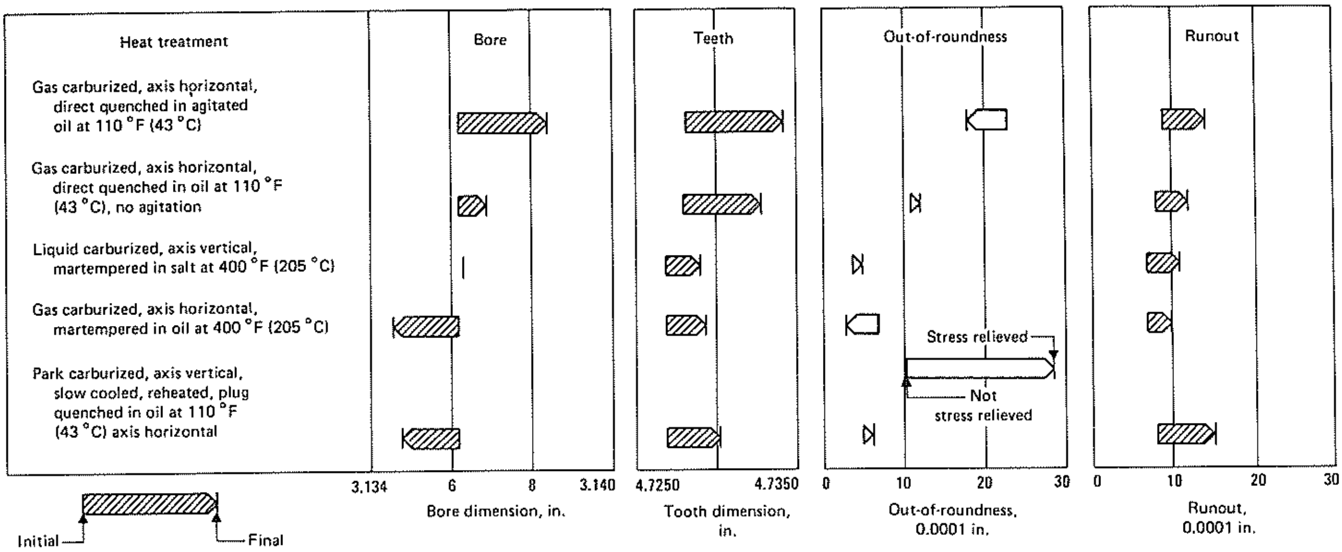
(a) Carburized at 1700 °F (925 °C) for 8 h, quenched in agitated oil, tempered at 300 °F (150 °C). (b) Carburized at 1700 °F (925 °C) for 8 h, pot cooled, reheated to 1500 °F (815 °C), quenched in agitated oil, tempered at 300 °F (150 °C). Good case and core properties. (c) Carburized at 1700 °F (925 °C) for 8 h, pot cooled, reheated to 1525 °F (830 °C), quenched in agitated oil, reheated to 1475 °F (800 °C), quenched in agitated oil, tempered at 300 °F (150 °C). Maximum refinement of case and core. (d) Carburized at 1700 °F (925 °C), quenched in agitated oil, tempered at 450 °F (230 °C). (e) Carburized at 1700 °F (925 °C), pot cooled, reheated to 1500 °F (815 °C), quenched in agitated oil, tempered at 450 °F (230 °C). Good case and core properties. (f) Carburized at 1700 °F (925 °C) for 8 h, pot cooled, reheated to 1525 °F (830 °C), quenched in agitated oil, reheated to 1475 °F (800 °C), quenched in agitated oil, tempered at 450 °F (230 °C). (Source: Bethlehem Steel)

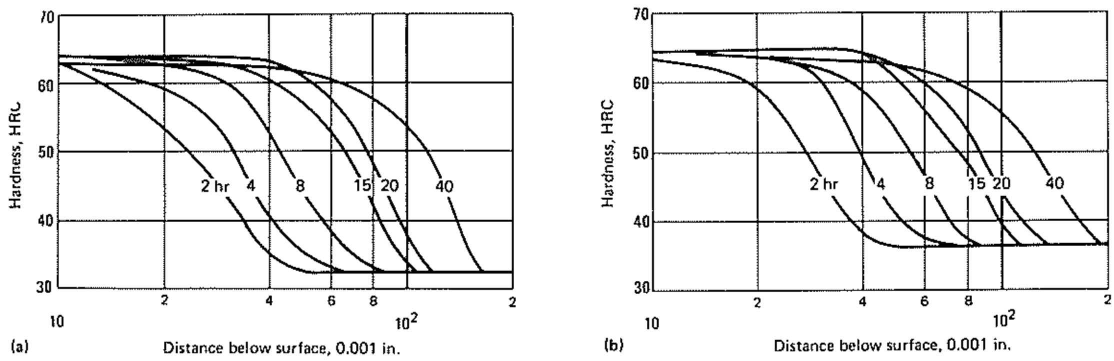
4620H: End-Quench Hardenability

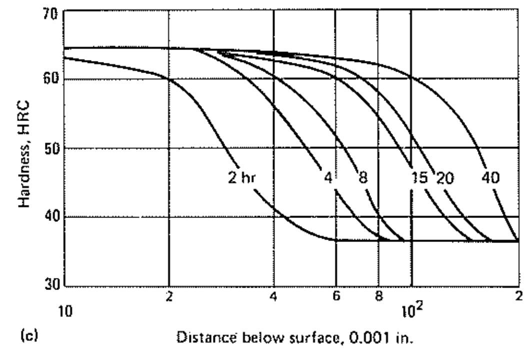
Distance from quenched surface		Hardness, HRC		Distance from quenched surface		Hardness, HRC
1/16 in.	mm	max	min	1/16 in.	mm	max
1	1.58	48	41	13	20.54	22
2	3.16	45	35	14	22.12	22
3	4.74	42	27	15	23.70	22
4	6.32	39	24	16	25.28	21
5	7.90	34	21	18	28.44	21
6	9.48	31	...	20	31.60	20
7	11.06	29	...	22	34.76	...
8	12.64	27	...	24	37.92	...
9	14.22	26	...	26	41.08	...
10	15.80	25	...	28	44.24	...
11	17.38	24	...	30	47.40	...
12	18.96	23	...	32	50.56	...



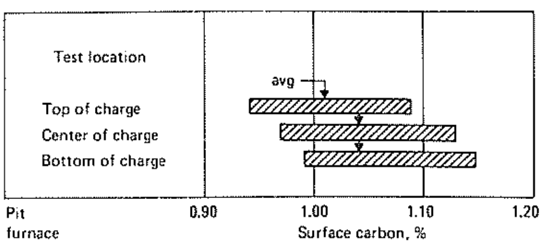
4620H: Effects of Carburizing and Quenching Methods on Dimensions. Gears, carburized 0.762 to 1.02 mm (0.030 to 0.040 in.), 58 to 63 HRC







4620: Liquid Carburizing. Specimens 19 mm (.75 in.) diam by 51 mm (2 in.), carburized, air cooled, reheated in neutral salt at 845 °C (1555 °F), quenched in salt at 180 °C (360 °F). (a) Carburized at 870 °C (1600 °F); (b) Carburized at 900 °C (1650 °F); (c) Carburized at 925 °C (1695 °F)



4620: Range of Surface Carbon vs Position in Furnace. Bearing races, carburized in a pit furnace 762 mm (30 in.) in diameter by 914 mm (36 in.) deep. Open load of races was carburized for 7 h in natural gas atmosphere; 3 ½ h diffusion cycle followed. Surface carbon aim was 1.00%. Each bar represents 14 heats of steel

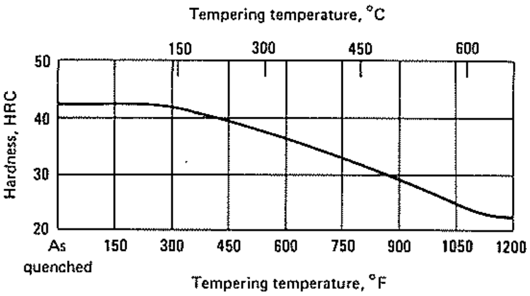
4630: As-Quenched Hardness

Specimens quenched in oil

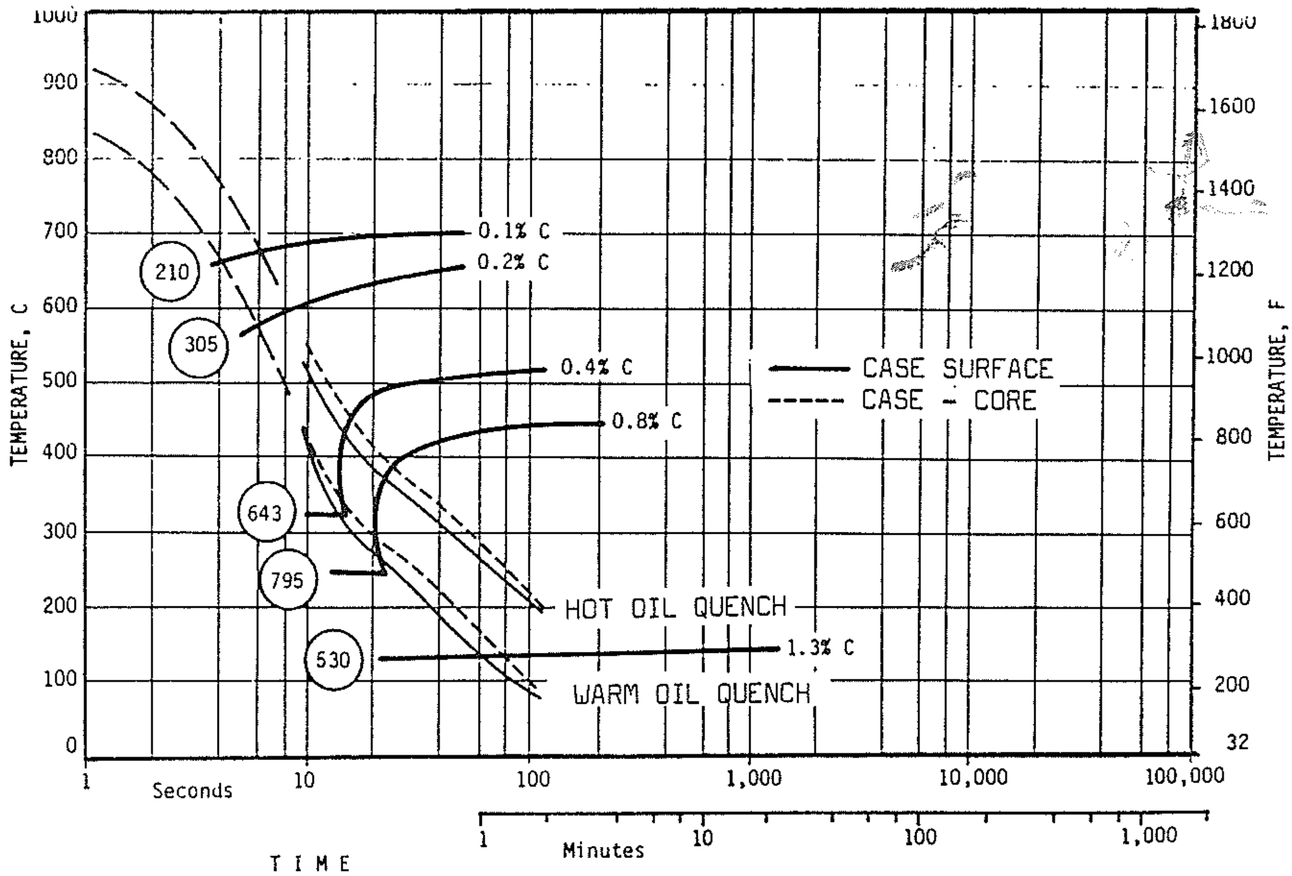
Size round		Hardness		
in.	mm	Surface	½ radius	Center
½	13	40 HRC	32 HRC	31 HRC
1	25	27 HRC	99 HRB	97 HRB
2	51	24 HRC	94 HRB	92 HRB
4	102	96 HRB	91 HRB	88 HRB

Source: Bethlehem Steel

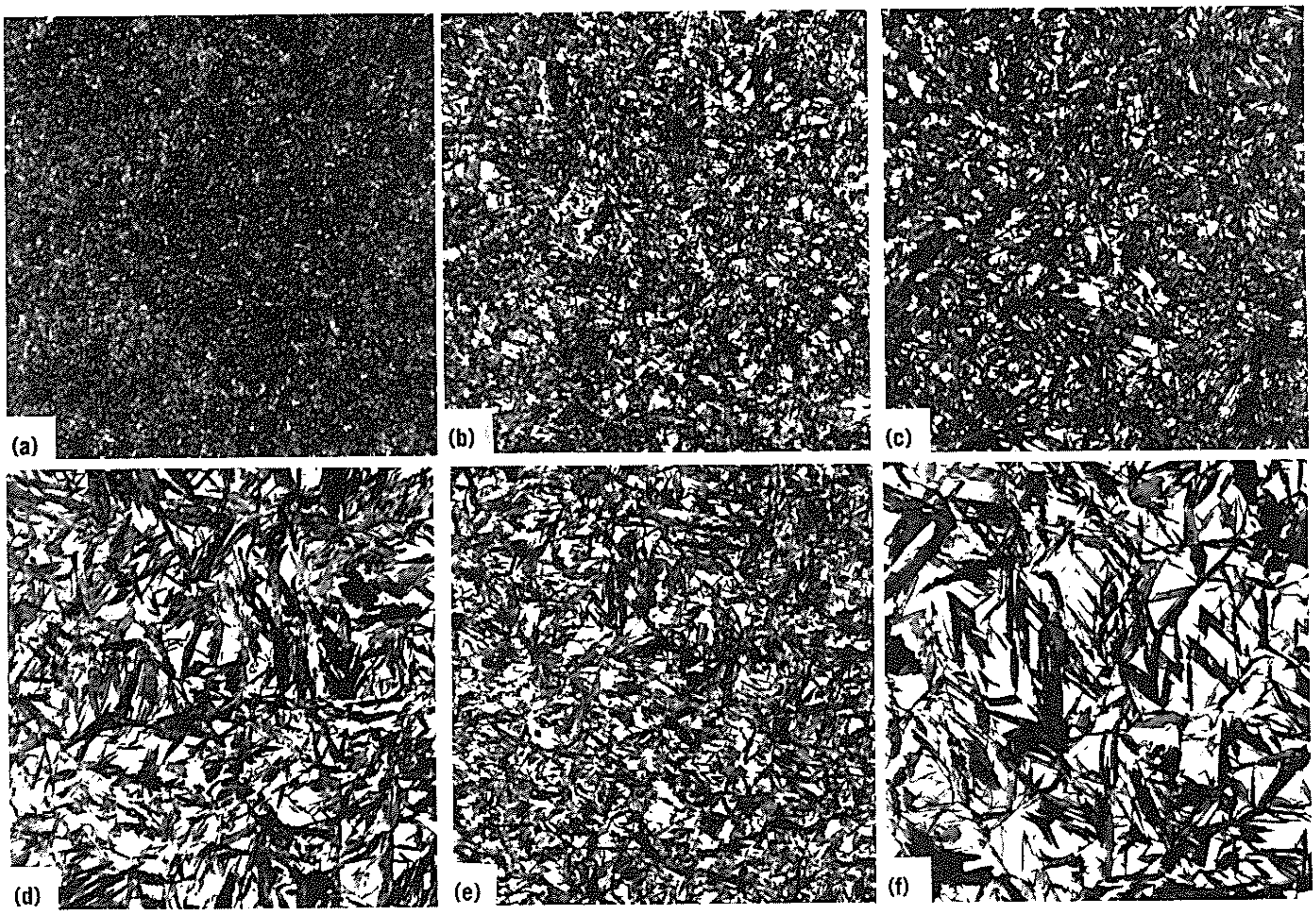
4620, 4620H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure



4620: CCT Diagram. Chemical composition: 0.20 C, 0.49 Mn, 0.016 P, 0.022 S, 0.23 Si, 1.78 Ni, 0.25 Mo, 0.076 Al. A laboratory induction air melted heat. Specimens 4 mm (0.16 in.) in diameter were through-carburized to various carbon levels by holding in a carburizing atmosphere at 1150 °C (2100 °F) for 16 to 20 h. Machined dilatometer specimens [3 mm (0.118 in.)] in diameter were austenitized and cooled at three different rates to define the partial CCT diagram at each carbon level. Cooling rates ranged from 357 to 3280 °C (675 to 5900 °F) per min. The cooling curves used to define the diagrams are not shown. Instead, the cooling curves shown were measured on impact-fracture specimens (gear tooth simulation) at locations corresponding to the surface and the case-core interface during quenching in warm oil [66 °C (150 °F)] or in hot oil [170 °C (340 °F). Specimens were austenitized at 900 °C (1650 °F) for 20 min. The objectives of the study were to obtain partial kinetic data on continuous-cooling transformation at various carbon levels in the carburized case. Hardness values (in circles on the diagram) were exhibited by specimens of each carbon level subjected to the fastest cooling rate used to define each CCT diagram. Source: Datasheet I-262, Climax Molybdenum Company



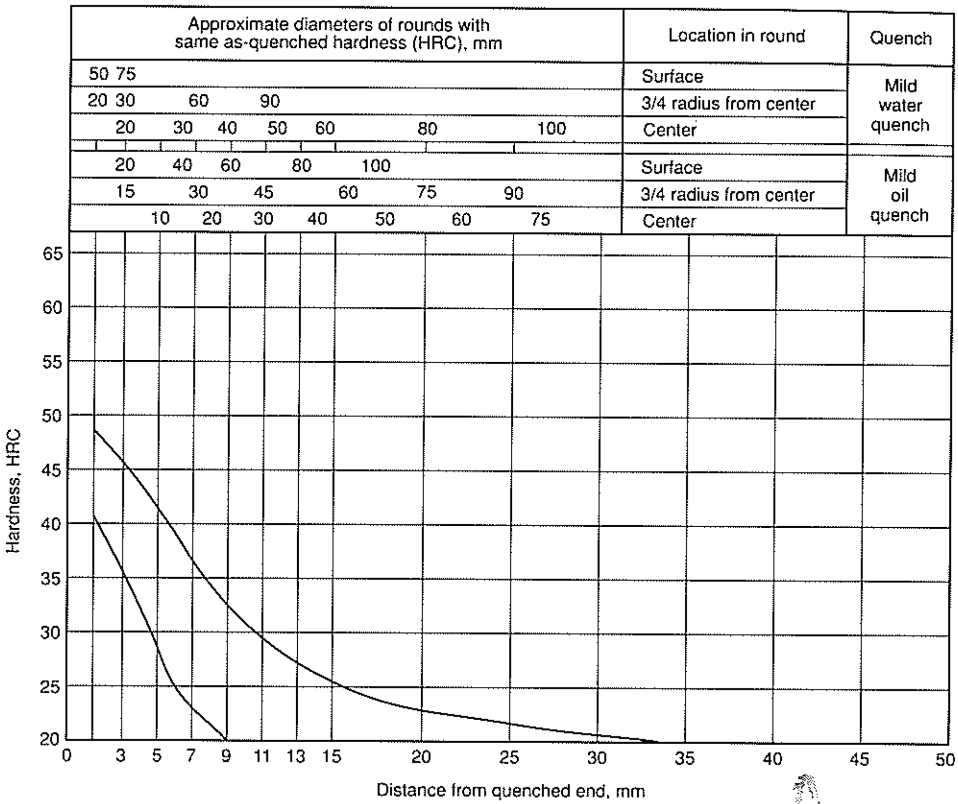
4620: Microstructures. (a) Nital, 1000×. Gas carburized at 1.00% carbon potential for 8 h at 940 °C (1725 °F), oil quenched, heated to 820 °C (1510 °F), oil quenched, tempered 1 h at 180 °C (355 °F), retempered 2 h at 260 °C (500 °F). Composition: 0.95 C. Retained austenite (by x-ray), tempered martensite, lower bainite, carbide. (b) Nital, 1000×. Gas carburized and heat treated before tempering under same conditions as (a), but tempered 1 h at 180 °C (355 °F) and retempered 2 h at 230 °C (450 °F). 10% retained austenite (by x-ray), tempered martensite, lower bainite, dispersed carbide particles. (c) Nital, 1000×. Gas carburized and heat treated before tempering under same conditions as (a) and (b), but tempered 1 h at 180 °C (355 °F) and retempered 2 h at 220 °C (425 °F). Composition: 0.95 C. 20% retained austenite (by x-ray), tempered martensite, lower bainite, carbide. (d) Nital, 1000×. Gas carburized at 1.00% carbon potential for 4 h at 940 °C (1725 °F), oil quenched, and tempered for 1 h at 180 °C (355 °F). Composition: 0.90 C. 35% retained austenite (by x-ray), and tempered martensite. (e) Nital, 1000×. Gas carburized at 1.00% carbon potential for 8 h at 940 °C (1725 °F), oil quenched, heated to 820 °C (1510 °F) for 30 min, oil quenched, tempered 20 min at 94 °C (200 °F). Composition: 0.95 C. 40% retained austenite (by x-ray), and tempered martensite. (f) Nital, 1000×. Gas carburized at 1.00% carbon potential for 8 h at 940 °C (1725 °F), oil quenched, and tempered for 1 h at 180 °C (355 °F). Composition: 0.95 C. 45% retained austenite (by x-ray), and tempered martensite.



4620H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 925 °C (1700 °F)

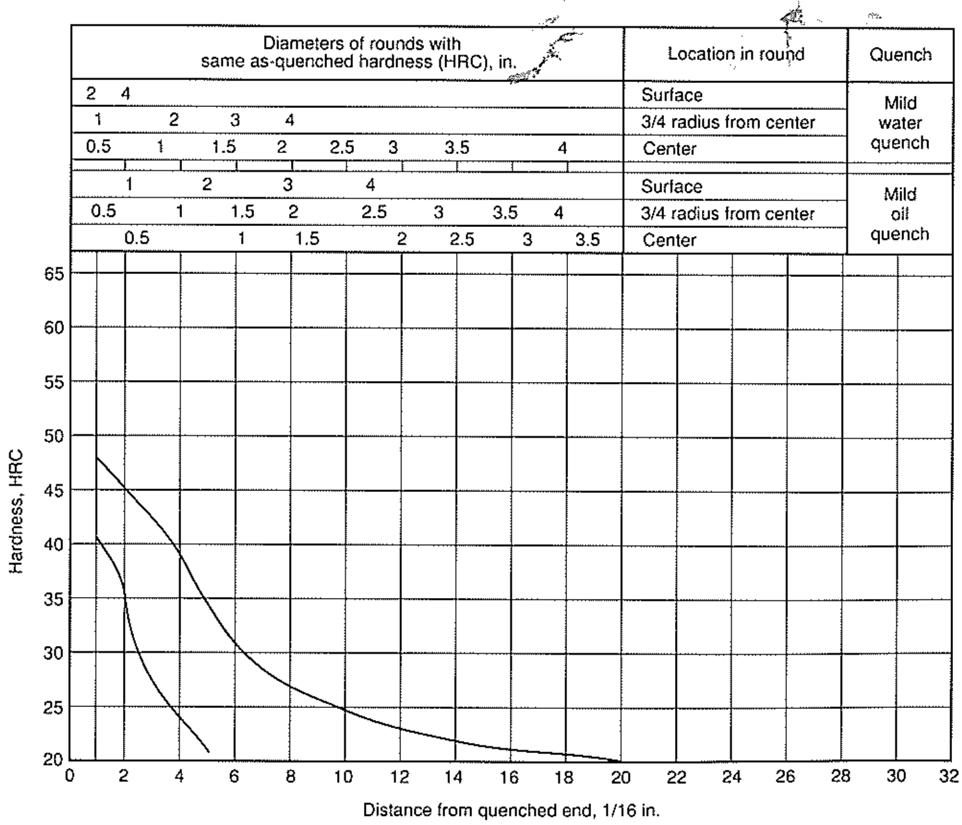
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	48	41
3	46	37
5	42	28
7	37	23
9	33	...
11	30	...
13	27	...
15	26	...
20	23	...
25	22	...
30	21	...
35	...	...



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	48	41
2	45	35
3	42	27
4	39	24
5	34	21
6	31	...
7	29	...
8	27	...
9	26	...
10	25	...
11	24	...
12	23	...
13	22	...
14	22	...
15	22	...
16	21	...
18	21	...
20	20	...
22	...	...



4626, 4626H

Chemical Composition. **4626. AISI and UNS:** 0.24 to 0.29 C, 0.45 to 0.65 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.70 to 1.00 Ni, 0.15 to 0.25 Mo. **4626H. AISI and UNS:** 0.23 to 0.29 C, 0.40 to 0.70 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.65 to 1.05 Ni, 0.15 to 0.25 Mo

Similar Steels (U.S. and/or Foreign). **4626.** UNS G46260; ASTM A322, A331; SAE J404, J412, J770. **4626H.** UNS H46260; ASTM A304. This steel is no longer in SAE J404 or J412, but does appear in SAE J770, which is now J1397

Characteristics. Usually used for carburizing or carbonitriding applications, although because of the as-quenched hardness of approximately 43 to 48 HRC that can be developed, it is sometimes used for parts that require strength and toughness without case hardening. To save energy, 4626H is sometimes used rather than lower carbon steels for carburizing, because the harder cores provided by 4626H often permit thinner cases, decreasing the required carburizing time. The hardenability of 4626H is slightly lower than shown for 4620H, because of the lower alloy content of 4626H. Can be welded, but alloy steel practice must be used

Forging. Heat to 1230 °C (2250 °F) maximum. Do not forge after temperature of forging stock drops below approximately 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F). Cool in air

Annealing. Best structures for machining are obtained either by normalizing or by isothermal treatment after rolling or forging. Isothermal treatment is accomplished by heating to 815 °C (1500 °F), cooling rapidly to 675 °C (1245 °F), and holding for 8 h

Direct Hardening. Heat to 870 °C (1600 °F) and quench in oil. Carbonitriding is a suitable hardening process

Tempering. Temper to at least 205 °C (400 °F) and preferably higher if some loss of hardness can be tolerated

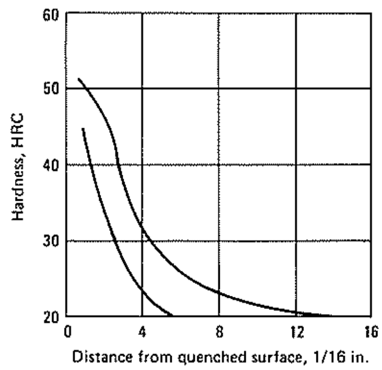
Case Hardening. See recommended carburizing, carbonitriding, and tempering procedures described for 4118H

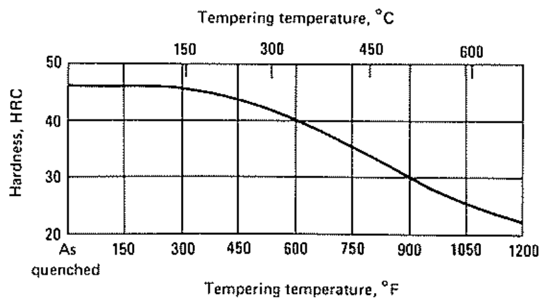
Recommended Processing Sequence

- Forge
- Normalize
- Anneal (optional)
- Rough and semifinish machine
- Case harden or direct harden
- Temper
- Finish machine (carburized parts only)

4626H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max
1	1.58	51	45	13	20.54	21
2	3.16	48	36	14	22.12	20
3	4.74	41	29	15	23.70	...
4	6.32	33	24	16	25.28	...
5	7.90	29	21	18	28.44	...
6	9.48	27	...	20	31.60	...
7	11.06	25	...	22	34.76	...
8	12.64	24	...	24	37.92	...
9	14.22	23	...	26	41.08	...
10	15.80	22	...	28	44.24	...
11	17.38	22	...	30	47.40	...
12	18.96	21	...	32	50.56	...



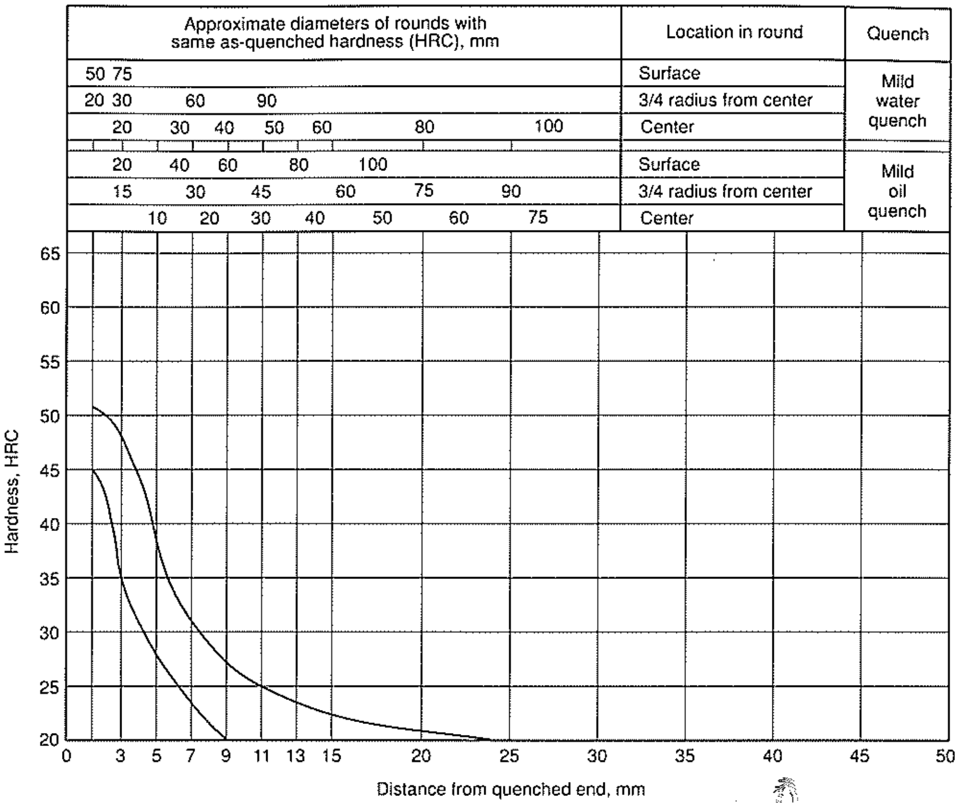


4626, 4626H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

4626H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 925 °C (1700 °F)

Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	51	45
3	48	36
5	38	29
7	31	23
9	27	20
11	25	...
13	24	...
15	23	...
20	21	...
25	...	...



Hardness limits for specification purposes

J distance, $\frac{1}{16}$ in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	51	45
2	48	36
3	41	29
4	33	24
5	29	21
6	27	...
7	25	...
8	24	...
9	23	...
10	22	...
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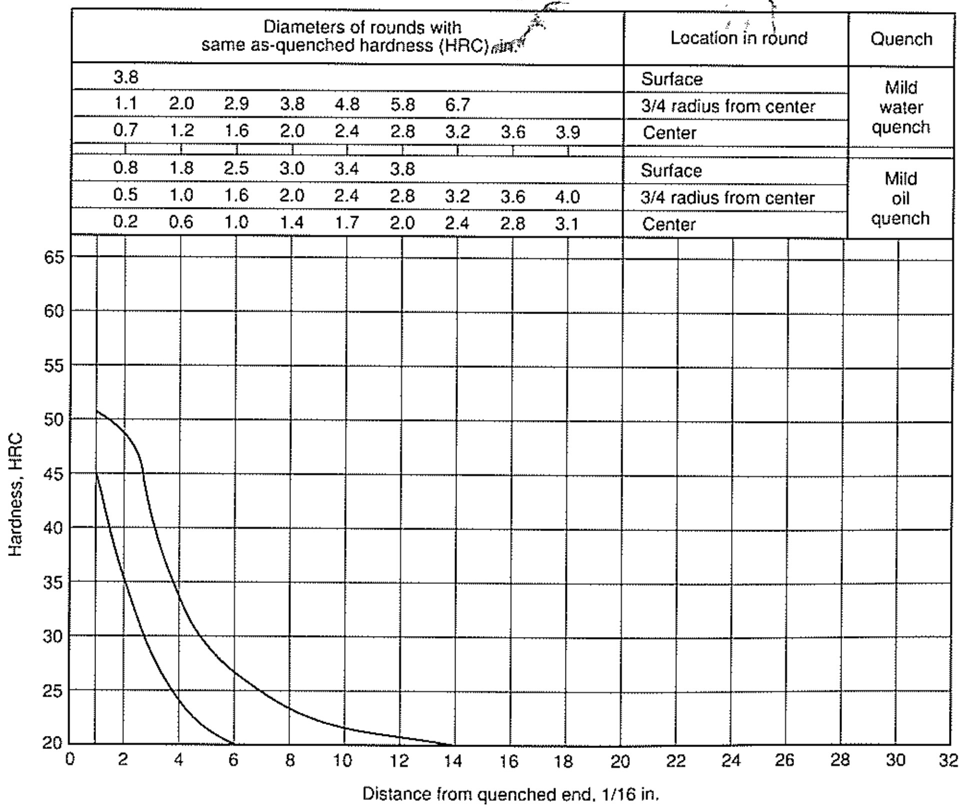
12	21	...
13	21	...
14	20	...
15	...	...



4718H

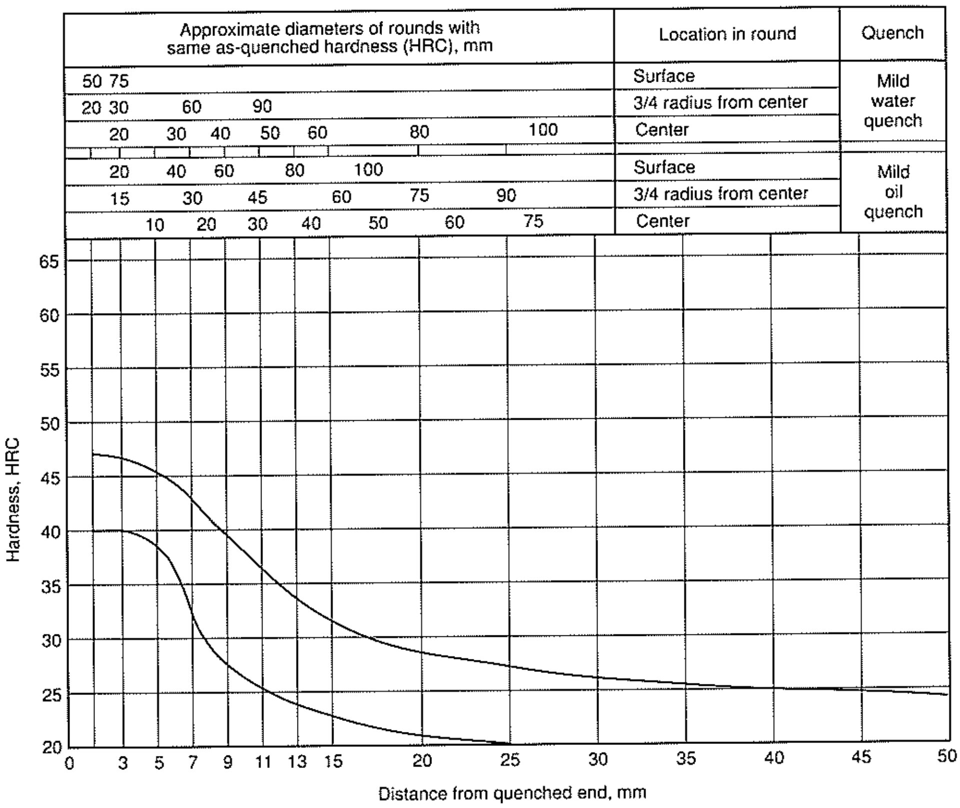
Chemical Composition. **UNS H47180 and SAE/AISI 4718H:** 0.15 to 0.21 C, 0.60 to 0.95 MN, 0.15 to 0.35 Si, 0.85 to 1.25 Ni, 0.30 to 0.60 Cr, 0.30 to 0.40 Mo

Similar Steels (U.S. and/or Foreign). This steel has been added to SAE J1268 and will appear in ASTM A304

4718H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 925 °C (1700 °F)

Hardness limits for specification purposes

J distance, mm	Hardness, HRC	
	Maximum	Minimum
1.5	47	40
3	47	40
5	46	38
7	43	31
9	39	28
11	36	25
13	34	23
15	32	22
20	29	21
25	27	20
30	26	...
35	26	...
40	25	...
45	25	...
50	24	...

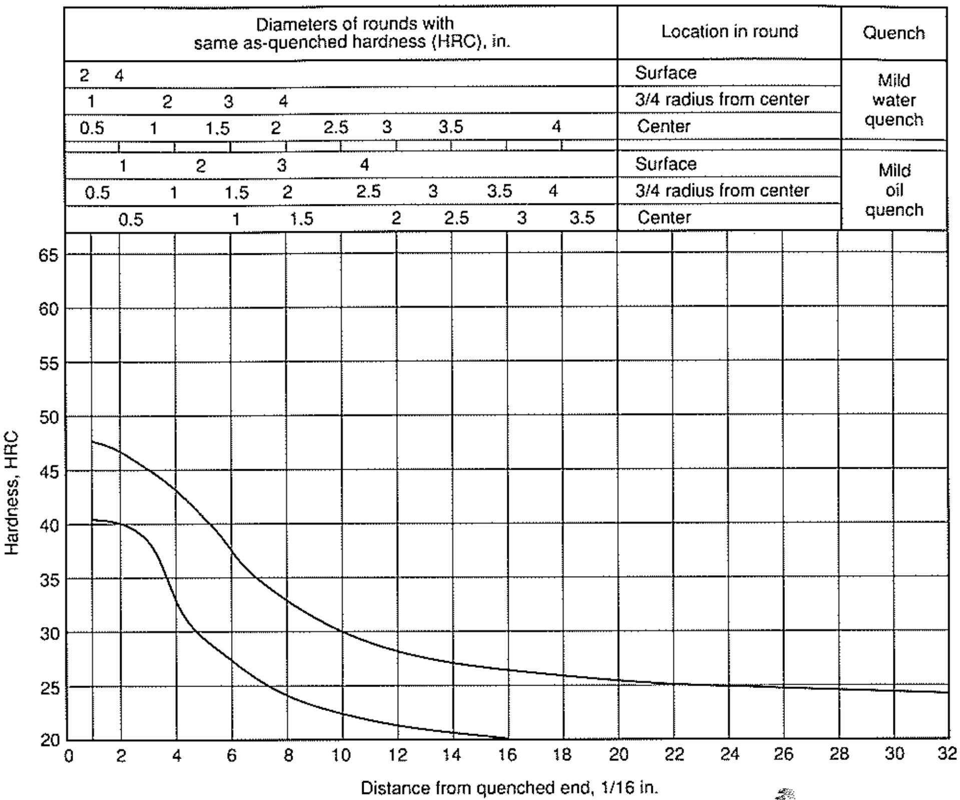


(continued)

4718H: Hardenability Curves. (continued) Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 925 °C (1700 °F)

Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	47	40
2	47	40
3	45	38
4	43	33
5	40	29
6	37	27
7	35	25
8	33	24
9	32	23
10	31	22
11	30	22
12	29	21
13	29	21
14	28	21
15	27	20
16	27	20
18	27	...
20	26	...
22	26	...
24	25	...
26	25	...
28	24	...
30	24	...
32	24	...



4720, 4720H

Chemical Composition. **4720. AISI and UNS:** 0.17 to 0.22 C, 0.50 to 0.70 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.90 to 1.20 Ni, 0.35 to 0.55 Cr, 0.15 to 0.25 Mo. **UNS H47200 and SAE/AISI 4720H:** 0.17 to 0.23 C, 0.45 to 0.75 Mn, 0.15 to 0.35 Si, 0.85 to 1.25 Ni, 0.30 to 0.60 Cr, 0.15 to 0.25 Mo

Similar Steels (U.S. and/or Foreign). **4720.** UNS G47200; ASTM A274, A322, A331, A519, A535; SAE J404, J412, J770. **4720H.** UNS H47200; ASTM A304; SAE J1268

Characteristics. Essentially the same as those for 4620H. The lesser nickel content of 4720H is compensated for by a chromium addition. As a result, hardenability for the two steels is nearly the same. As-quenched hardness of approximately 40 to 45 HRC is also the same. Because of the lower nickel content and the chromium addition, the tendency of 4720H to retain austenite in carburized cases is less than for 4620H. In many instances, 4720H has replaced 4620H as a carburizing steel

Forging. Heat to 1230 °C (2250 °F) maximum. Do not forge after temperature of forging stock drops below approximately 845 °C (1555 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Cool in air

Annealing. Best structures for machining are obtained either by normalizing or by isothermal treatment consisting of heating to 815 °C (1500 °F), cooling rapidly to 650 °C (1200 °F), and holding for 8 h

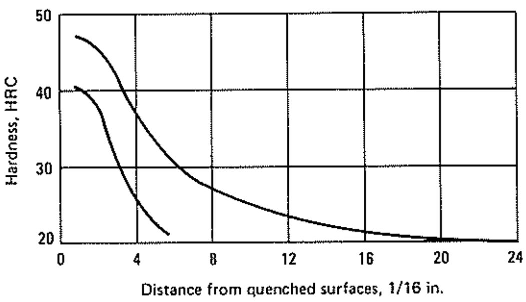
Case Hardening. See recommended carburizing, carbonitriding, and tempering procedures described for 4118H

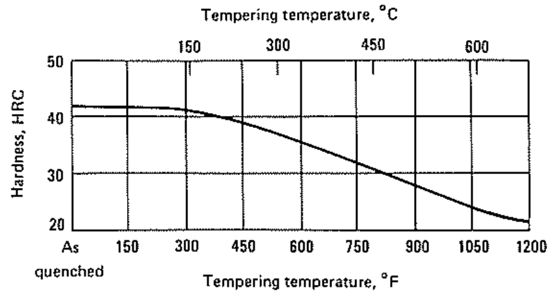
Recommended Processing Sequence

- Forge
- Normalize
- Anneal (optional)
- Rough and semifinish machine
- Case harden
- Temper
- Finish machine (carburized parts only)

4720H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max
1	1.58	48	41	13	20.54	24
2	3.16	47	39	14	22.12	23
3	4.74	33	31	15	23.70	23
4	6.32	39	27	16	25.28	22
5	7.90	35	23	18	28.44	21
6	9.48	32	21	20	31.60	21
7	11.06	29	...	22	34.76	21
8	12.64	28	...	24	37.92	20
9	14.22	27	...	26	41.08	...
10	15.80	26	...	28	44.24	...
11	17.38	25	...	30	47.40	...
12	18.96	24	...	32	50.56	...



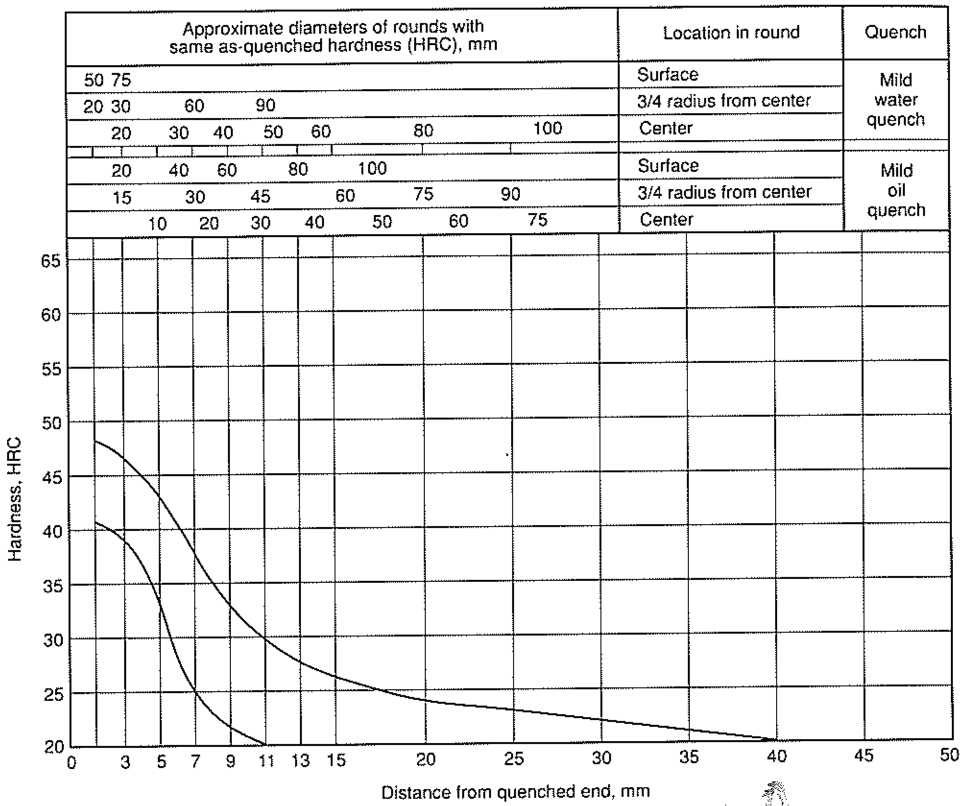


4720, 4720H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

4720H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 925 °C (1700 °F)

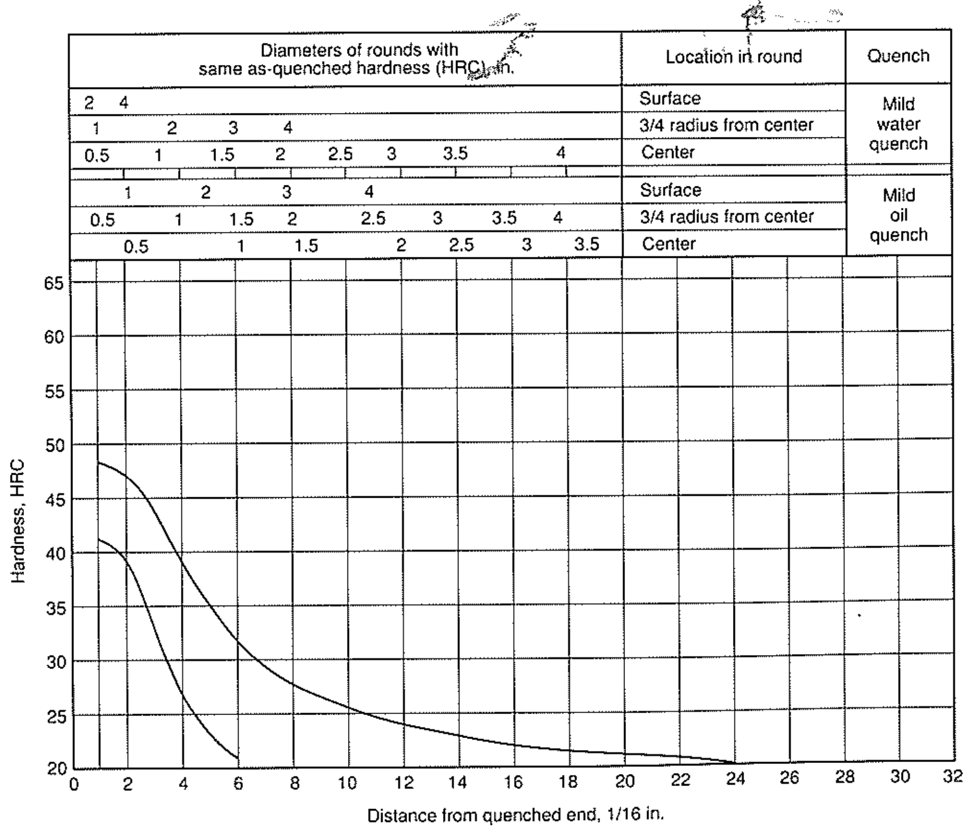
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	48	41
3	47	39
5	43	32
7	38	25
9	33	22
11	30	20
13	28	...
15	27	...
20	24	...
25	23	...
30	22	...
35	21	...
40	20	...
45	...	...



Hardness limits for specification purposes

J distance, $\frac{1}{16}$ in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	48	41
2	47	39
3	43	31
4	39	27
5	35	23
6	32	21
7	29	...
8	28	...
9	27	...
10	26	...
11	25	...
12	24	...
13	24	...
14	23	...
15	23	...
16	22	...
18	21	...
20	21	...
22	21	...
24	20	...
26	...	...



4815, 4815H

Chemical Composition. **4815. AISI and UNS:** 0.13 to 0.18 C, 0.40 to 0.60 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 3.25 to 3.75 Ni, 0.20 to 0.30 Mo. **UNS H48150 and SAE/AISI 4815H:** 0.12 to 0.18 C, 0.30 to 0.70 Mn, 0.15 to 0.35 Si, 3.20 to 3.80 Ni, 0.20 to 0.30 Mo

Similar Steels (U.S. and/or Foreign). **4815.** UNS G48150; ASTM A322, A331, A505; SAE J404, J412, J770. **4815H.** UNS H48150; ASTM A304; SAE J1268

Characteristics. Represents a relatively high alloy carburizing grade intended for use where sections are thick and relatively hard, and tough cores are mandatory. Depending on the precise carbon content, as-quenched hardness should be approximately 35 to 42 HRC. Hardenability is relatively high. As is true for other high-nickel carburizing steels, austenite may be retained in the carburized case. Amenable to welding, but alloy steel practice of preheating and postheating must be used

Forging. Heat to 1245 °C (2275 °F). Do not forge after temperature of forging stock drops below approximately 845 °C (1555 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Cool in air

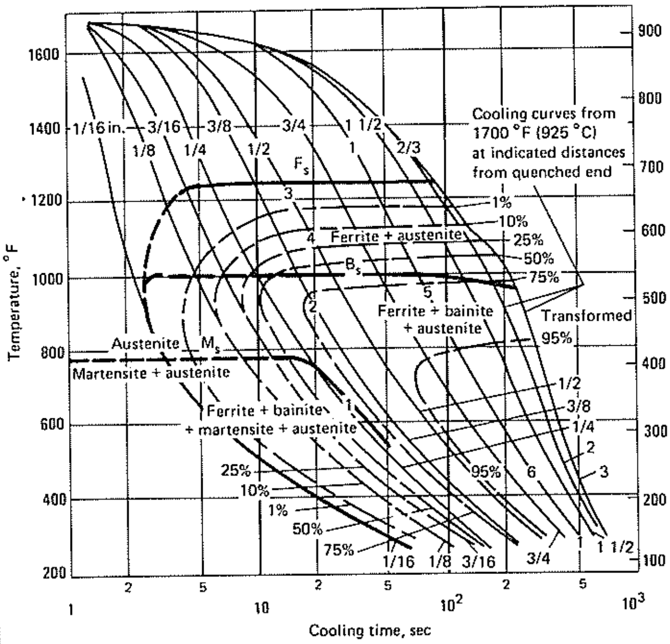
Annealing. After normalizing, heat to 650 °C (1200 °F), hold for 1 h per inch of section thickness. Cooling rate from this temperature is not critical. May also be isothermally annealed by heating to 745 °C (1370 °F), cooling rapidly to 605 °C (1125 °F), and holding for 8 h

Tempering. All parts made from this grade should be tempered at 150 °C (300 °F) or higher if some loss of hardness can be tolerated. Tempering will help in transforming retained austenite

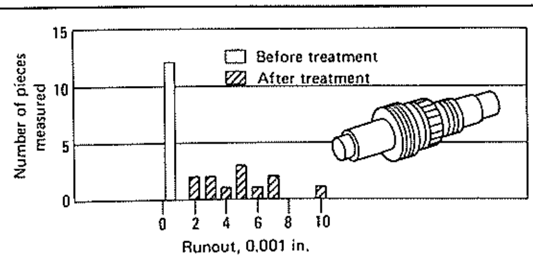
Case Hardening. See carburizing process described for 4118H. This grade is rarely subjected to carbonitriding. Liquid carburizing, gas carburizing, and martempering are suitable processes

Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough and semifinish machine
- Case harden
- Temper
- Finish machine (carburized parts only)



4815: Continuous Cooling Curves. Composition: 0.14 C, 0.45 Mn, 0.22 Si, 3.42 Ni, 0.21 Mo. Austenitized at 925 °C (1695 °F). Grain size: 9. Ac_3, 800 °C (1475 °F); Ac_1, 730 °C (1350 °F). A: austenite, F: ferrite, B: bainite, M: martensite. Source: Bethlehem Steel



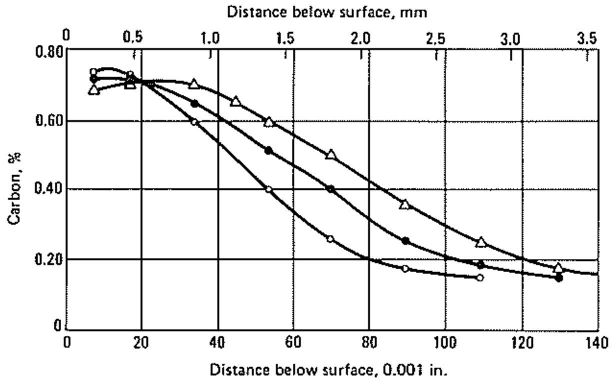
4815: Liquid Carburizing. Pinion liquid carburized at 900 °C (1650 °F) for 2.5 h, quenched in still oil, tempered at 205 °C (400 °F) for 0.5 h. Hardness, 58 to 60 HRC. 12 tests done to measure runout

4815: Carbon Gradients

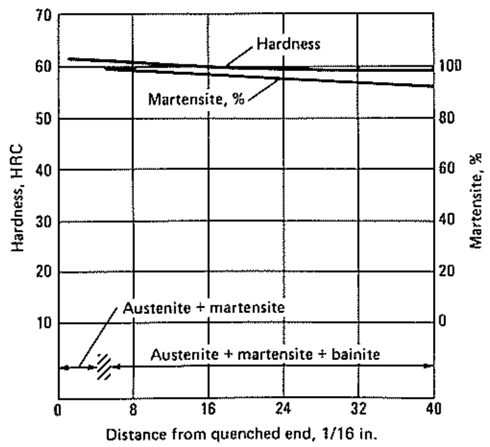
Zone	Temperature °F	°C	Atmosphere	Time in zone, h	Carbon potential, %C
Cycle 1(a)					
1	1690	920	Methane	8	1.25
2	1690	920	Methane	14	1.25
3	1670	910	Carrier gas, air	13	0.80(b), 0.55(c)
Cycle 2(d)					
1	1690	920	Methane	6	1.25
2	1690	920	Methane	10	1.25
3	1670	910	Carrier gas, air	9	0.80(b), 0.60(c)
Cycle 3(e)					
1	1690	920	Methane	4	1.25
2	1690	920	Methane	7	1.25
3	1670	910	Carrier gas, air	6	0.80(b), 0.75(c)

(a) Target, 0.110-in. (2.79-mm) case at 0.25% C. (b) At center of zone. (c) At discharge. (d) Target, 0.090-in. (2.29-mm) at 0.25% C. (e) Target, 0.070-in. (1.78-mm) case at 0.25% C

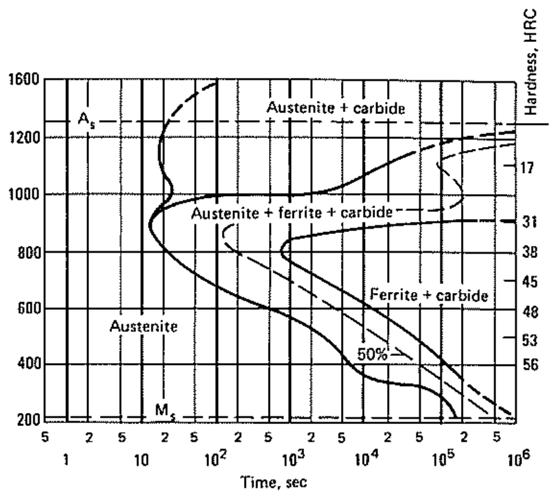
4815: Carbon Gradients. From three-zone continuous pusher-type carburizing furnace. Carbon potential was controlled manually. ▲: Cycle 1, 35 h; ●: Cycle 2, 25 h; O: Cycle 3, 17 h



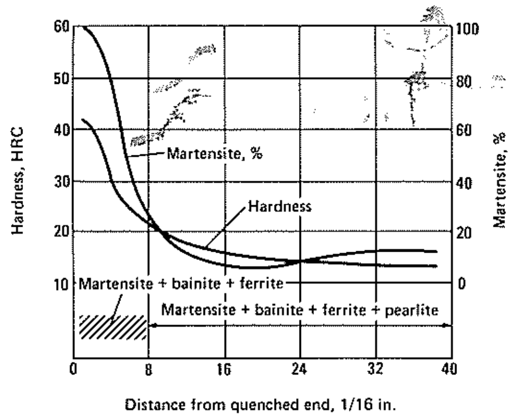
4815: End-Quench Hardenability. Carburized, 1.0% carbon. Composition: 0.97 C, 0.52 Mn, 3.36 Ni, 0.19 Mo. Austenitized at 980 °C (1795 °F). Grain size: 7



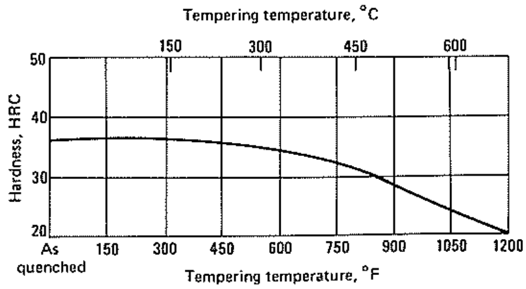
4815: Isothermal Transformation Diagram. Carburized, 1.0% carbon. Composition: 0.97 C, 0.52 Mn, 3.36 Ni, 0.19 Mo. Austenitized at 980 °C (1795 °F). Grain size: 7



4815: End-Quench Hardenability. Composition: 0.16 C, 0.52 Mn, 3.36 Ni, 0.19 Mo. Austenitized at 900 °C (1650 °F). Grain size: 8 to 9

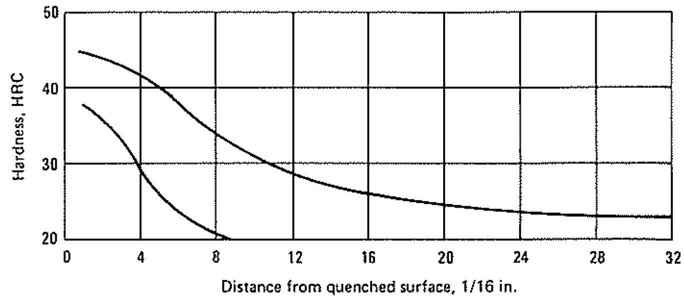


4815, 4815H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

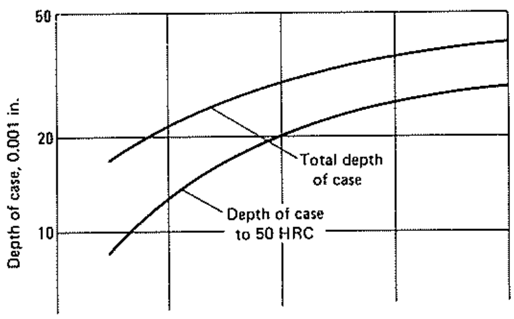


4815H: End-Quench Hardenability

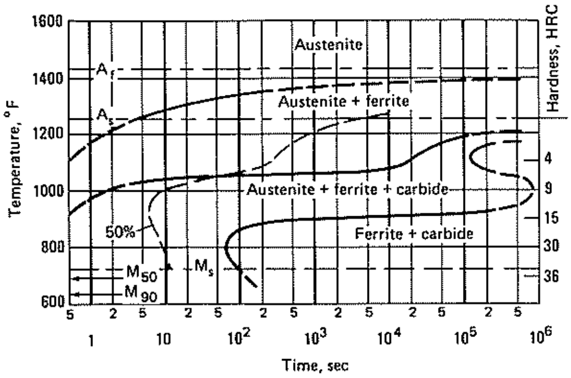
Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max
1	1.58	45	38	13	20.54	28
2	3.16	44	37	14	22.12	28
3	4.74	44	34	15	23.70	27
4	6.32	42	30	16	25.28	27
5	7.90	41	27	18	28.44	26
6	9.48	39	24	20	31.60	25
7	11.06	37	22	22	34.76	24
8	12.64	35	21	24	37.92	24
9	14.22	33	20	26	41.08	24
10	15.80	31	...	28	44.24	23
11	17.38	30	...	30	47.40	23
12	18.96	29	...	32	50.56	23



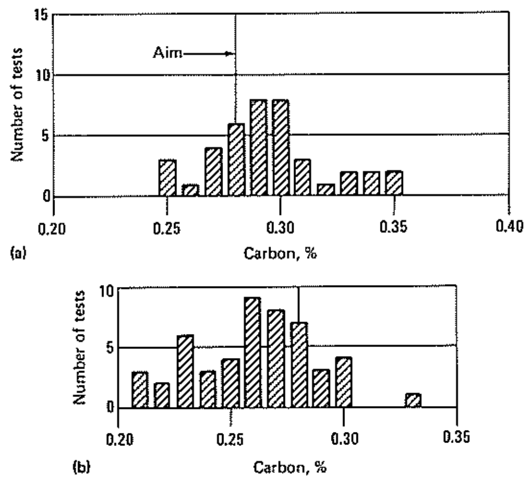
4815: Depth of Case vs Time and Temperature. 13 mm (0.5 in.) round bars, carburized at 900 °C (1650 °F), and oil quenched



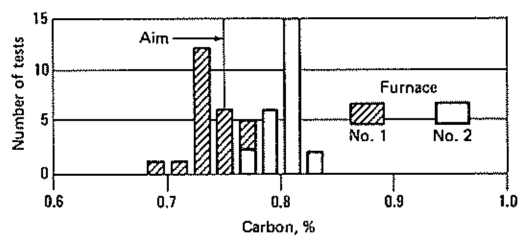
4815: Isothermal Transformation Diagram. Composition: 0.16 C, 0.52 Mn, 3.36 Ni, 0.19 Mo. Austenitized at 900 °C (1650 °F). Grain size: 8 to 9



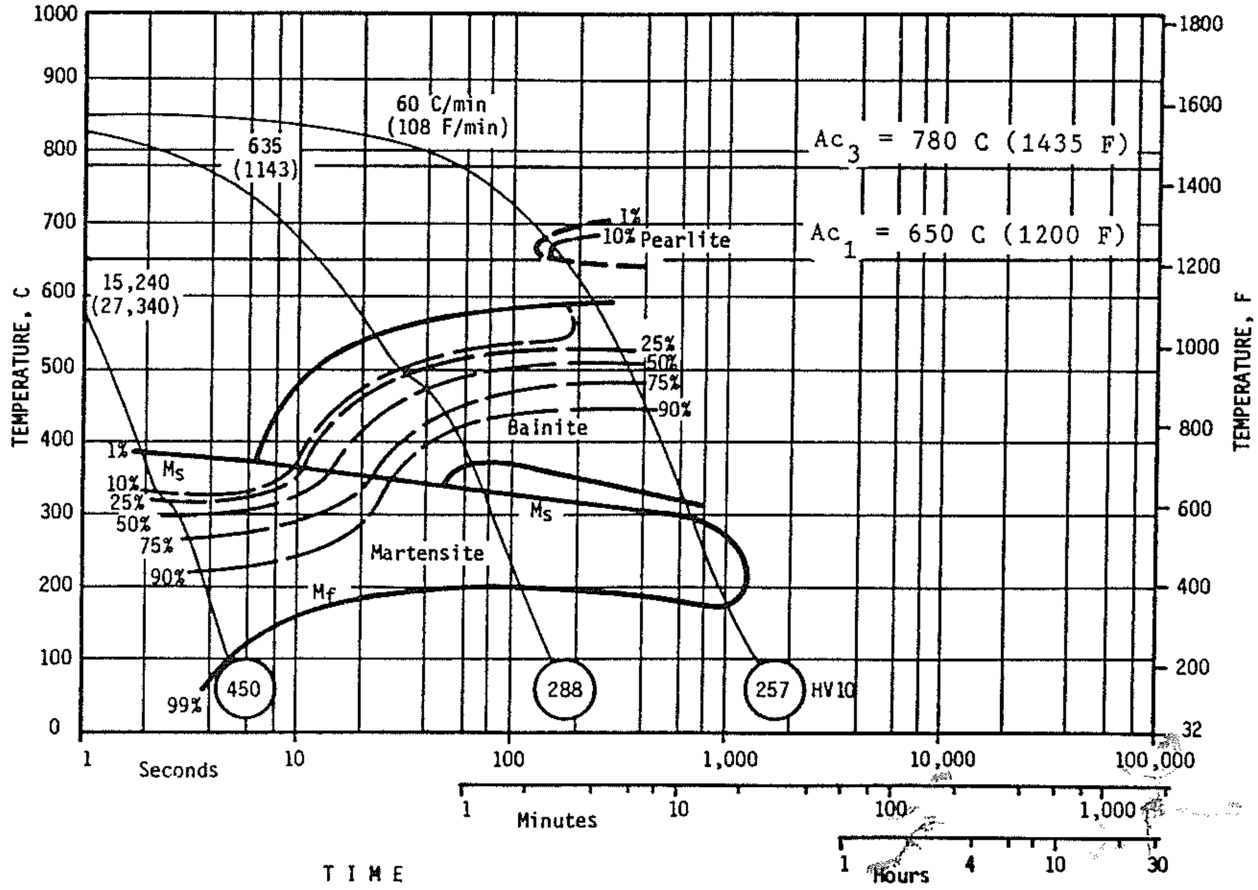
4815: Variation in Carbon Concentration. Steel rock bit cutters carburized at 925 °C (1695 °F). Pit-type furnace, 314 mm (36 in.) in diameter by 1829 mm (72 in.) deep, used a carburizing-diffusion cycle. Dew point controlled at the generator only. Each test represents one load of 1361 kg (3000 lb). (a) 40 tests. Carbon at 1.8 mm (0.070 in.) below surface; (b) 50 tests. Carbon at 2.42 mm (0.095 in.) below surface



4815: Variation of Surface Carbon Content. 50 tests of rock bit cutters carburized in two pit-type furnaces to an aim of 0.75% C. Furnaces were operated simultaneously, using the same gas generator. Each furnace was 914 mm (36 in.) in diameter by 1829 mm (72 in.) deep and contained a load of about 1361 kg (3000 lb). A carburize-diffuse cycle was used. An automatic dew point controller was employed on the generator, but not on the furnace



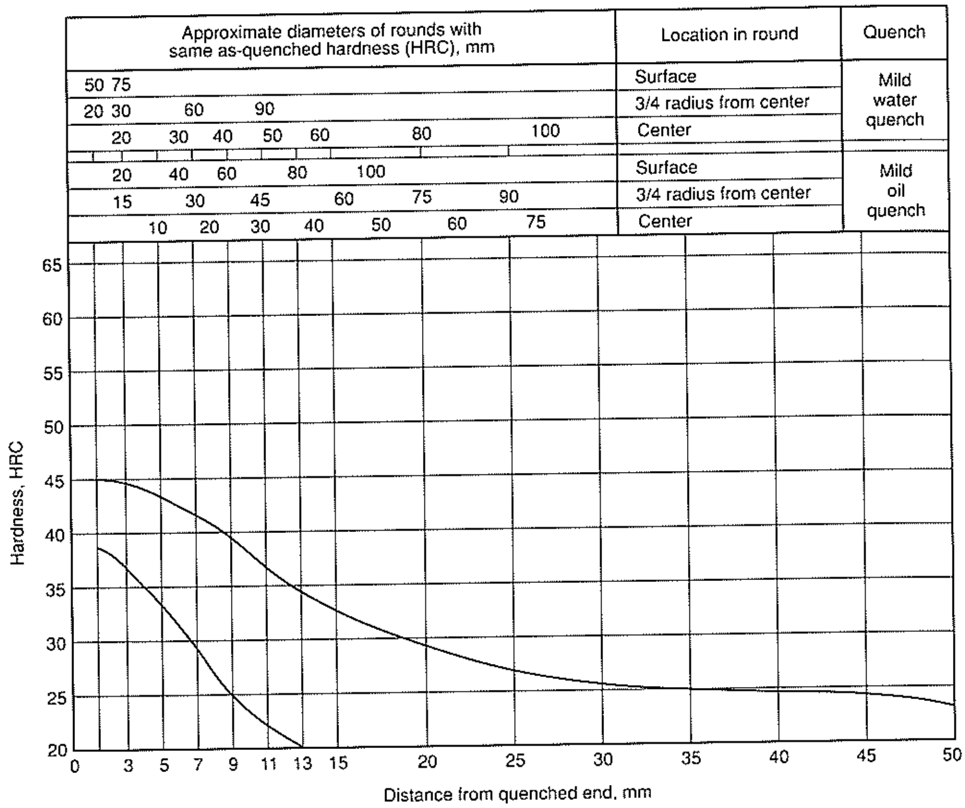
4815H: CCT Diagram. Composition for commercial SAE 4815 carburizing steel: 0.16 C, 0.63 Mn, 0.010 P, 0.012 S, 0.24 Si, 3.35 Ni, 0.21 Cr, 0.24 Mo, 0.19 Cu. In this study, slabs from commercial billet 76 mm (3 in.) square were normalized at 925 °C (1695 °F) for 1 h. Specimens were austenitized at 870 °C (1600 °F) for 20 min. The purpose of the study was to characterize a standard grade of carburizing steel for comparison with recently developed grades. Source: Datasheet I-257. Climax Molybdenum Company



4815H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 845 °C (1555 °F)

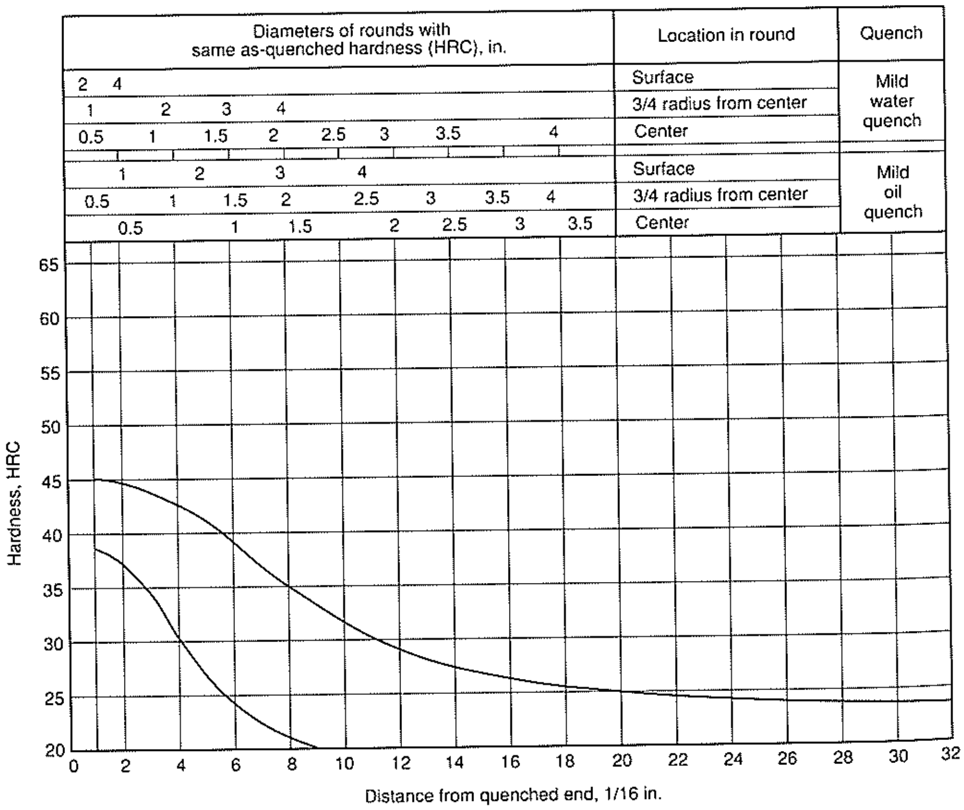
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	45	38
3	45	36
5	44	33
7	42	28
9	40	25
11	37	22
13	35	20
15	32	...
20	29	...
25	27	...
30	26	...
35	25	...
40	24	...
45	24	...
50	23	...



Hardness limits for specification purposes

J distance, $^1/_{16}$ in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	45	38
2	44	37
3	44	34
4	42	30
5	41	27
6	39	24
7	37	22
8	35	21
9	33	20
10	31	...
11	30	...
12	29	...
13	28	...
14	28	...
15	27	...
16	27	...
18	26	...
20	25	...
22	24	...
24	24	...
26	24	...
28	23	...
30	23	...
32	23	...



4817, 4817H

Chemical Composition. **4817. AISI and UNS:** 0.15 to 0.20 C, 0.40 to 0.60 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 3.25 to 3.75 Ni, 0.20 to 0.30 Mo. **UNS H48170 and SAE/AISI 4817H:** 0.14 to 0.20 C, 0.30 to 0.70 Mn, 0.15 to 0.35 Si, 3.20 to 3.80 Ni, 0.20 to 0.30 Mo

Similar Steels (U.S. and/or Foreign). **4817.** UNS G48170; ASTM A322, A331, A519; SAE J404, J412, J770. **4817H.** UNS H48170; ASTM A304; SAE J1268

Characteristics. With the exception of a slightly higher carbon content, steels 4815H and 4817H are identical, and their characteristics are essentially identical. As-quenched hardness (core hardness) should be slightly higher for 4817H (approximately 36 to 43 HRC). Hardenability patterns are nearly identical. Welding is possible, but preheating and postheating must be used

Forging. Heat to 1245 °C (2275 °F) maximum. Do not forge after temperature of forging stock drops below approximately 845 °C (1555 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Cool in air

Annealing. After normalizing, heat to 650 °C (1200 °F), hold for 1 h per inch of section thickness. Cooling rate from this temperature is not critical. May also be isothermally annealed by heating to 745 °C (1370 °F), cooling rapidly to 605 °C (1125 °F), and holding for 8 h

Tempering. All parts made from this grade should be tempered at 150 °C (300 °F) or higher if some loss of hardness can be tolerated. Tempering will help in transforming retained austenite

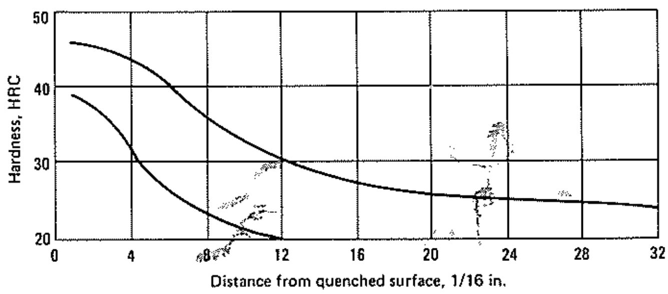
Case Hardening. See carburizing process described for 4118H. This grade is rarely subjected to carbonitriding

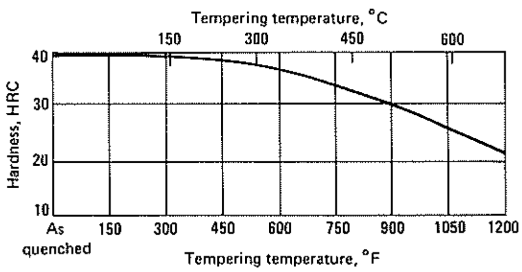
Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough and semifinish machine
- Case harden
- Temper
- Finish machine (carburized parts only)

4817H: End-Quench Hardenability

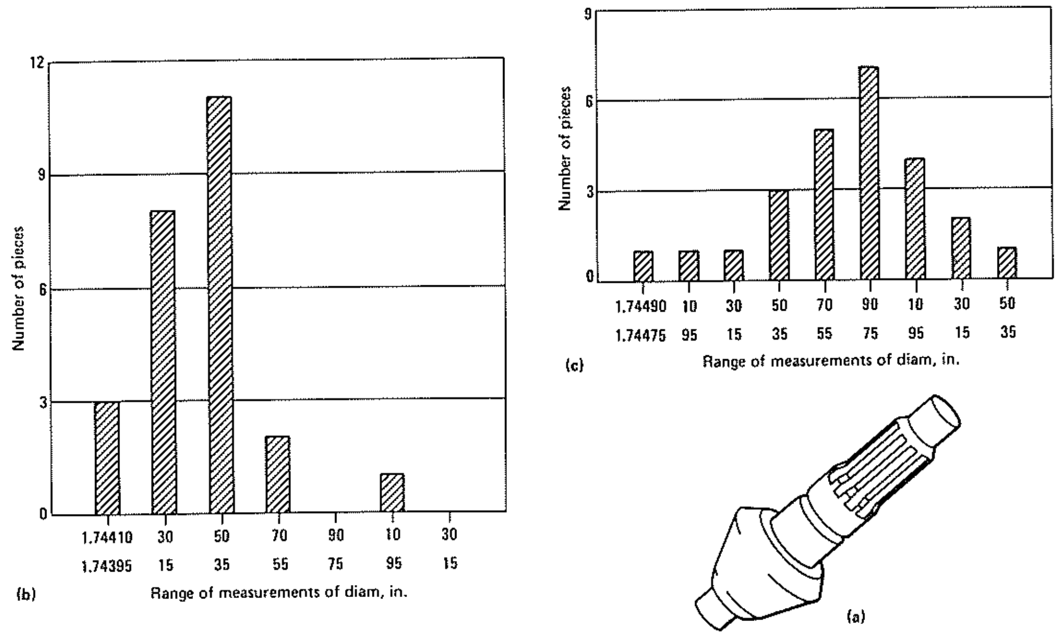
Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max
1	1.58	46	39	13	20.54	30
2	3.16	46	38	14	22.12	29
3	4.74	45	35	15	23.70	28
4	6.32	44	32	16	25.28	28
5	7.90	42	29	18	28.44	27
6	9.48	41	27	20	31.60	26
7	11.06	39	25	22	34.76	25
8	12.64	37	23	24	37.92	25
9	14.22	35	22	26	41.08	25
10	15.80	33	21	28	44.24	25
11	17.38	32	20	30	47.40	24
12	18.96	31	20	32	50.56	24



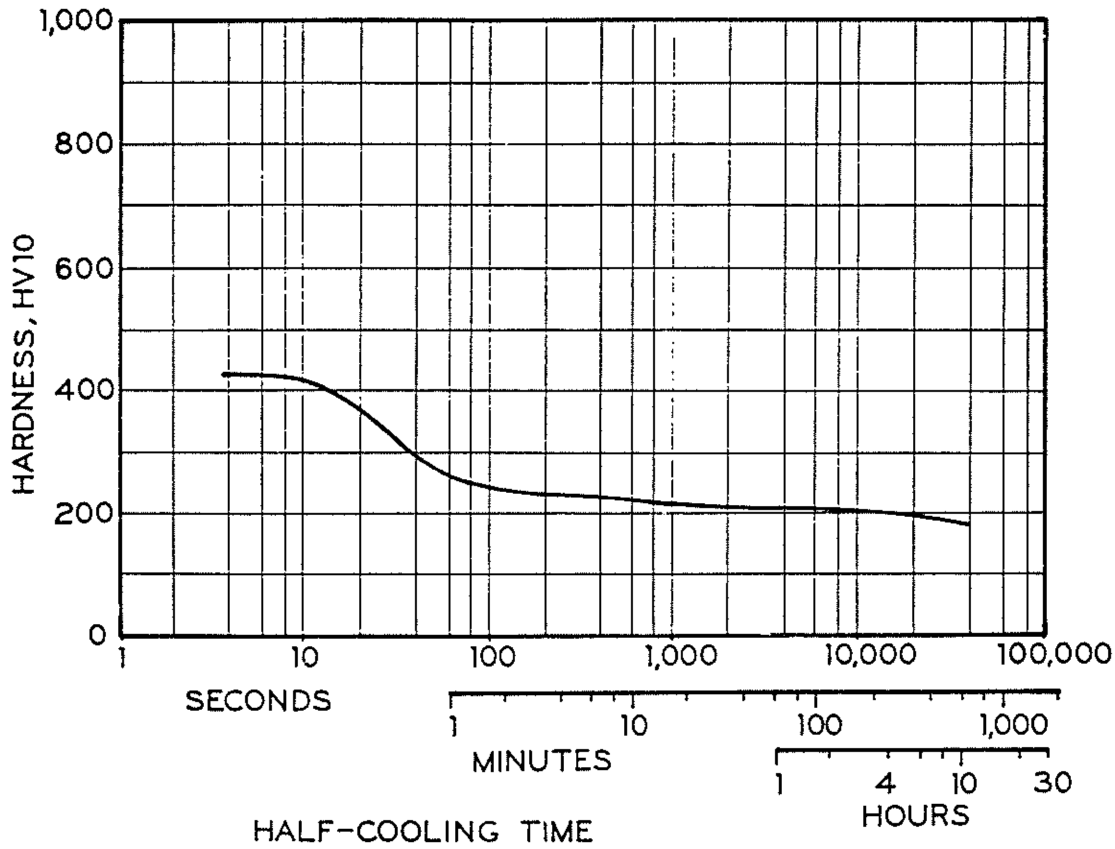


4817, 4817H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

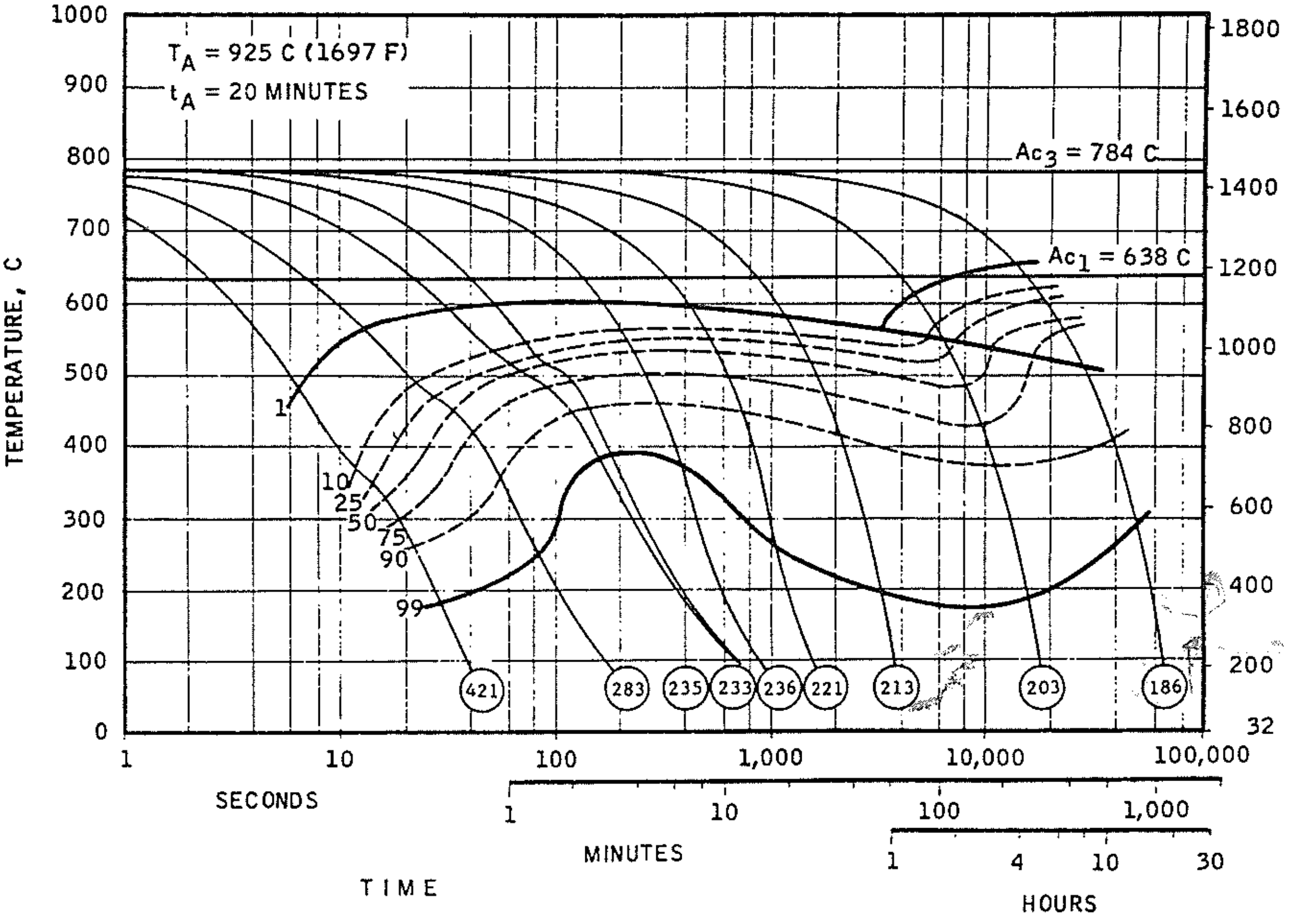
4817: Carburizing and Hardening vs Diametral Dimensions. Bevel drive pinion gear (a), carburized at 925 °C (1695 °F), tempered at 160 °C (320 °F). Depth of case, 1.27 to 1.65 mm (0.050 to 0.065 in.). Major spline diameter of twenty-five 4 kg (8 lb) gears (b) before treatment, (c) after treatment



4817: Cooling Curve. Half cooling time. Source: Datasheet I-50. Climax Molybdenum Company

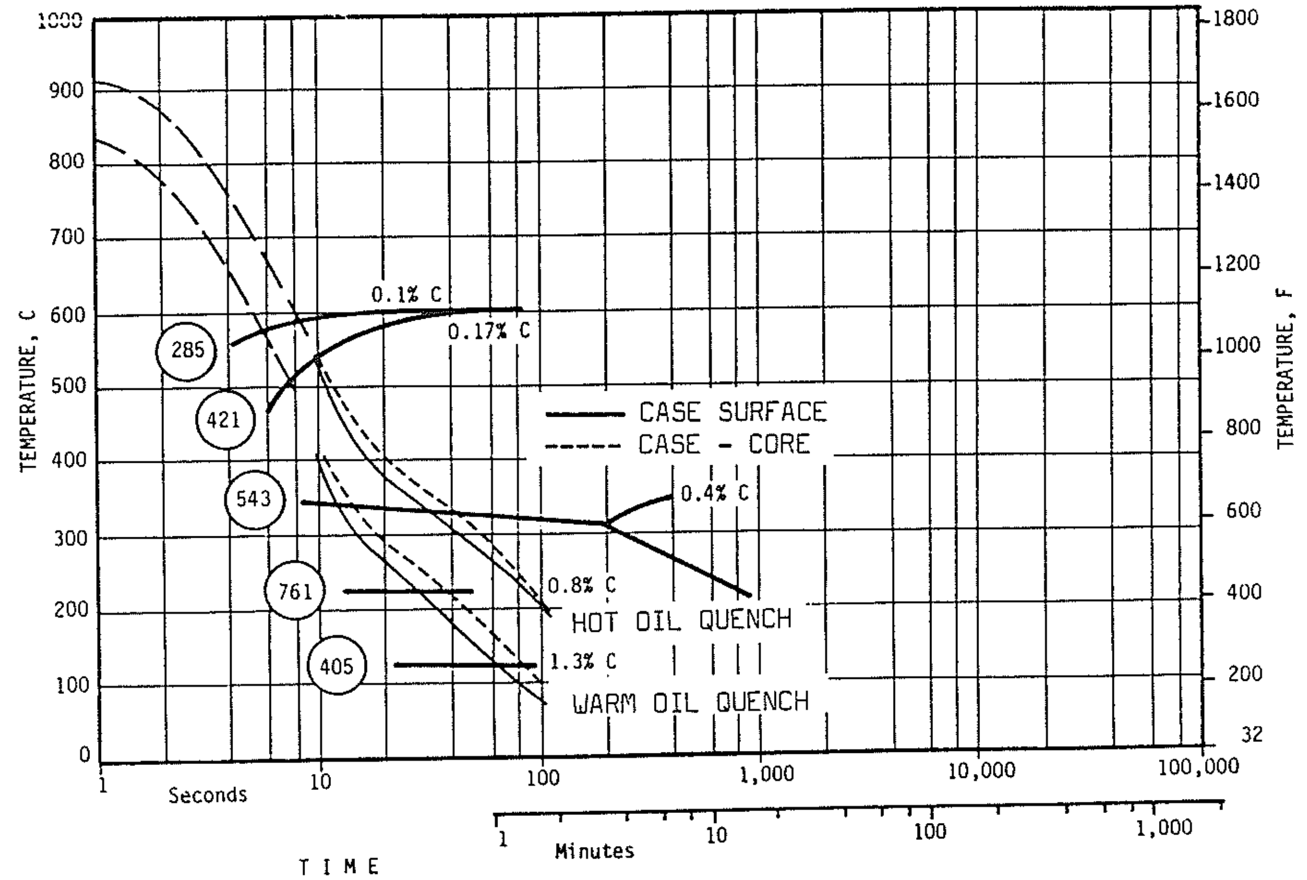


4817: CCT Diagram. Chemical composition: 0.17 C, 0.54 Mn, 0.015 P, 0.025 S, 0.33 Si, 0.087 Al. A laboratory induction air melted heat. Specimens 4 mm (0.16 in.) in diameter were through-carburized to various carbon levels by holding in a carburizing atmosphere at 1150 °C (2100 °F) for 16 to 20 h. Machined dilatometer specimens 3 mm (0.118) in diameter were austenitized and cooled at three different rates to define the partial CCT diagram at each carbon level. The cooling rates ranged from 375 to 3280 °C (675 to 5900 °F) per min. The cooling curves used to define the diagrams are not shown. Instead, the cooling curves shown were measured on impact-fracture specimens (gear tooth simulation) at locations corresponding to the surface and the case-core interface during quenching in warm oil 66 °C (150 °F) or in hot oil 170 °C (340 °F). Specimens were austenitized at 900 °C (1650 °F) for 20 min. The objectives of the study were to obtain partial kinetic data on continuous-cooling transformation at various carbon levels in the carburized case. Hardness values (in circles on the diagram) were exhibited by specimens of each carbon level subjected to the fastest cooling rate used to define each CCT diagram. Source: Datasheet I279. Climax Molybdenum Company



(continued)

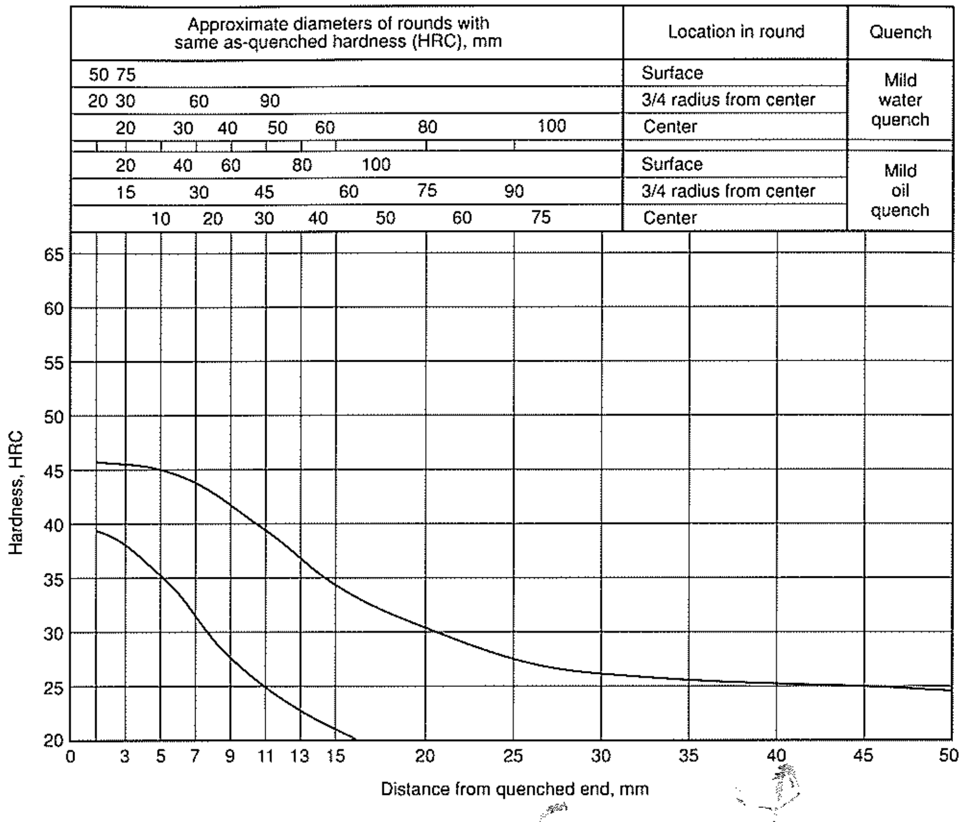
4817: CCT Diagram. (continued)



4817H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 845 °C (1555 °F)

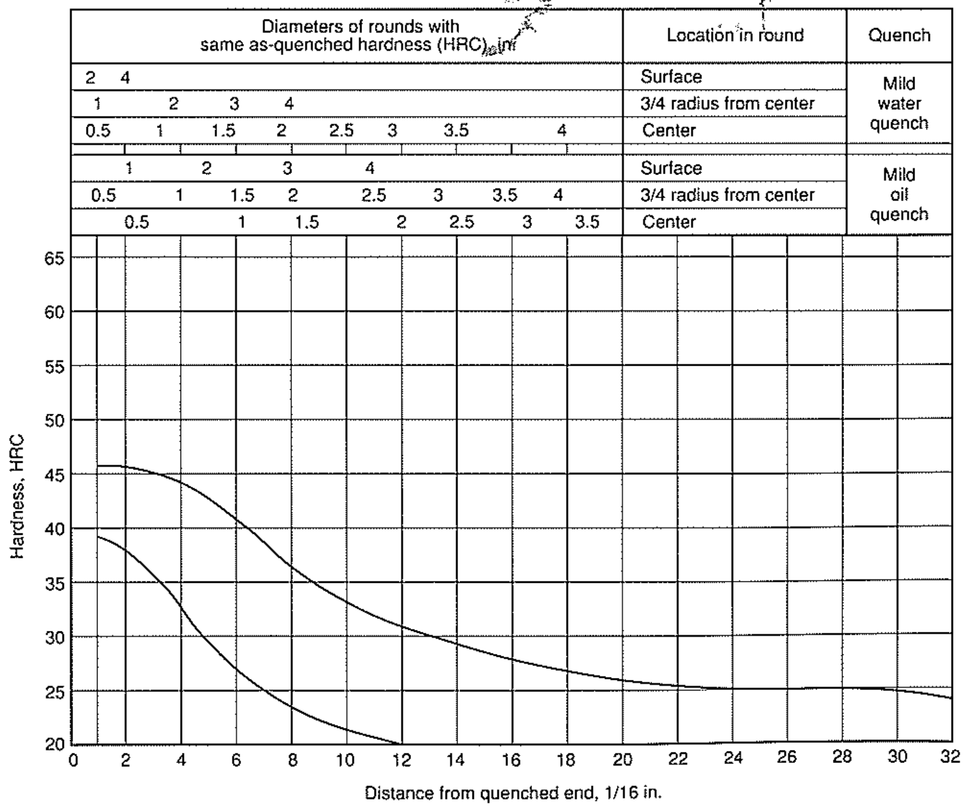
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	46	39
3	46	38
5	45	35
7	44	31
9	42	28
11	39	25
13	37	23
15	34	21
20	31	...
25	28	...
30	27	...
35	26	...
40	25	...
45	25	...
50	25	...



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	46	39
2	46	38
3	45	35
4	44	32
5	42	29
6	41	27
7	39	25
8	37	23
9	35	22
10	33	21
11	32	20
12	31	20
13	30	...
14	29	...
15	28	...
16	28	...
18	27	...
20	26	...
22	25	...
24	25	...
26	25	...
28	25	...
30	24	...
32	24	...



4820, 4820H, 4820RH

Chemical Composition. **4820. AISI and UNS:** 0.18 to 0.23 C, 0.50 to 0.70 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 3.25 to 3.75 Ni, 0.20 to 0.30 Mo. **UNS H48200 and SAE/AISI 4820H:** 0.17 to 0.23 C, 0.40 to 0.80 Mn, 0.15 to 0.35 Si, 3.20 to 3.80 Ni, 0.20 to 0.30 Mo. **SAE 4820RH:** 0.18 to 0.23 C, 0.50 to 0.70 Mn, 0.15 to 0.35 Si, 3.25 to 3.75 Ni, 0.20 to 0.30 Mo

Similar Steels (U.S. and/or Foreign). **4820.** UNS G48200; ASTM A322, A331, A505, A519, A535; SAE J404, J412, J770. **4820H.** UNS H48200; ASTM A304, A914; SAE J1268, J8668

Characteristics. In general, the characteristics of 4820H are similar to those described for 4815H and 4817H. Because of higher carbon content, as-quenched hardness of 4820H ranges from approximately 40 to 45 HRC. The hardenability band is shifted upward when compared with the bands for 4815H and 4817H. As is true for other high-nickel carburizing steels, there is a strong tendency for retention of austenite in the carburized cases of 4820 and 4820H. Amenable to welding, but alloy steel practice of preheating and postheating must be used

Forging. Heat to 1245 °C (2275 °F) maximum. Do not forge after temperature of forging stock drops below approximately 845 °C (1555 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Cool in air

Annealing. After normalizing, heat to 650 °C (1200 °F), hold for 1 h per inch of section thickness. Cooling rate from this temperature is not critical. May also be isothermally annealed by heating to 745 °C (1370 °F), cooling rapidly to 605 °C (1125 °F), and holding for 8 h

Tempering. All parts made from this grade should be tempered at 150 °C (300 °F) or higher if some loss of hardness can be tolerated. Tempering will help in transforming retained austenite

Case Hardening. See carburizing process described for 4118H. This grade is rarely subjected to carbonitriding. Austempering is an alternative process

Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough and semifinish machine
- Case harden
- Temper
- Finish machine (carburized parts only)

4820: Carburizing, Single Heat Results

Specimens contained 0.21 C, 0.51 Mn, 0.021 P, 0.018 S, 0.21 Si, 3.49 Ni, 0.18 Cr, 0.24 Mo; critical points included Ac_1, 1310 °F (710 °C); Ac_3, 1440 °F (780 °C); Ar_3, 1215 °F (655 °C); Ar_1, 780 °F (415 °C); grain size was 6 to 8; 0.565-in. (14.4-mm) round treated, 0.505-in. (12.8-mm) round tested

	Case									
	Hardness,	Depth		Tensile strength		Yield strength 0.2% offset		Elongation in 2 in.	Reduction of area,	Hardness,
Recommended practice	HRC	in.	mm	ksi	MPa	ksi	MPa	(50 mm), %	%	HB
For maximum case hardness										
Direct quench from pot(a)	60	0.039	...	205	1413	165.5	1141	13.3	53.3	415
Single quench and temper(b)	61	0.047	...	207.5	1431	167	1151	13.8	52.2	415
Double quench and temper(c)	60	0.047	...	204.5	1410	165.5	1141	13.8	52.4	415
For maximum core toughness										
Direct quench from pot(d)	56	0.039	...	200.5	1382	170	1172	12.8	53.0	401
Single quench and temper(e)	57.5	0.047	...	205	1413	184.5	1272	13.0	53.3	415
Double quench and temper(f)	56.5	0.047	...	196.5	1355	171.5	1182	13.0	53.4	401

(a) Carburized at 1700 °F (925 °C) for 8 h, quenched in agitated oil, tempered at 300 °F (150 °C). (b) Carburized at 1700 °F (925 °C) for 8 h, pot cooled, reheated to 1475 °F (800 °C), quenched in agitated oil, tempered at 300 °F (150 °C). Good case and core properties. (c) Carburized at 1700 °F (925 °C) for 8 h, pot cooled, reheated to 1500 °F (815 °C), quenched in agitated oil, reheated to 1450 °F (790 °C), quenched in agitated oil, tempered at 300 °F (150 °C). For maximum refinement of case and core. (d) Carburized at 1700 °F (925 °C) for 8 h, quenched in agitated oil, tempered at 450 °F (230 °C). (e) Carburized at 1700 °F (925 °C) for 8 h, pot cooled, reheated to 1475 °F (800 °C), quenched in agitated oil, tempered at 450 °F (230 °C). Good case and core properties. (f) Carburized at 1700 °F (925 °C) for 8 h, pot cooled, reheated to 1500 °F (815 °C), quenched in agitated oil, reheated to 1450 °F (790 °C), quenched in agitated oil, tempered at 450 °F (230 °C). (Source: Bethlehem Steel)

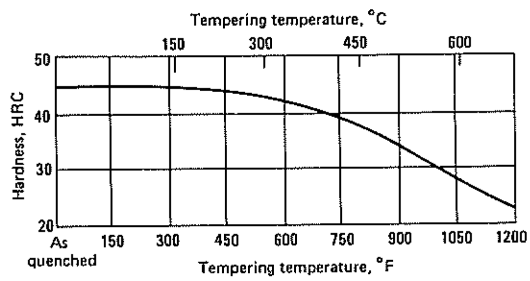
4820: As-Quenched Hardness (Oil)

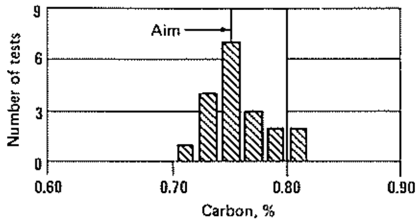
Grade: 0.18 to 0.23 C, 0.50 to 0.70 Mn, 0.20 to 0.35 Si, 3.25 to 3.75 Ni, 0.20 to 0.30 Mo; ladle: 0.20 C, 0.61 Mn, 0.027 P, 0.016 S, 0.29 Si, 3.47 Ni, 0.07 Cr, 0.22 Mo; grain size: 6 to 8

Size round		Hardness, HRC		
in.	mm	Surface	½ radius	Center
½	13	45	45	44
1	25	43	39	37
2	51	36	31	27
4	102	27	24	24

Source: Bethlehem Steel

4820: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

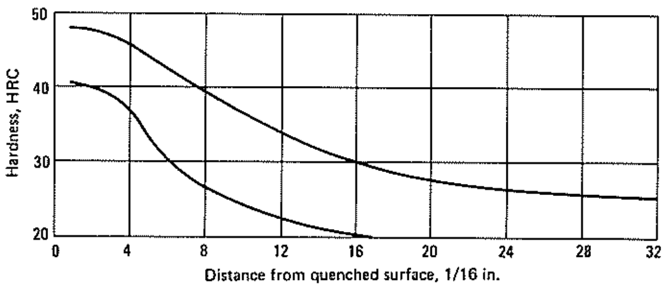




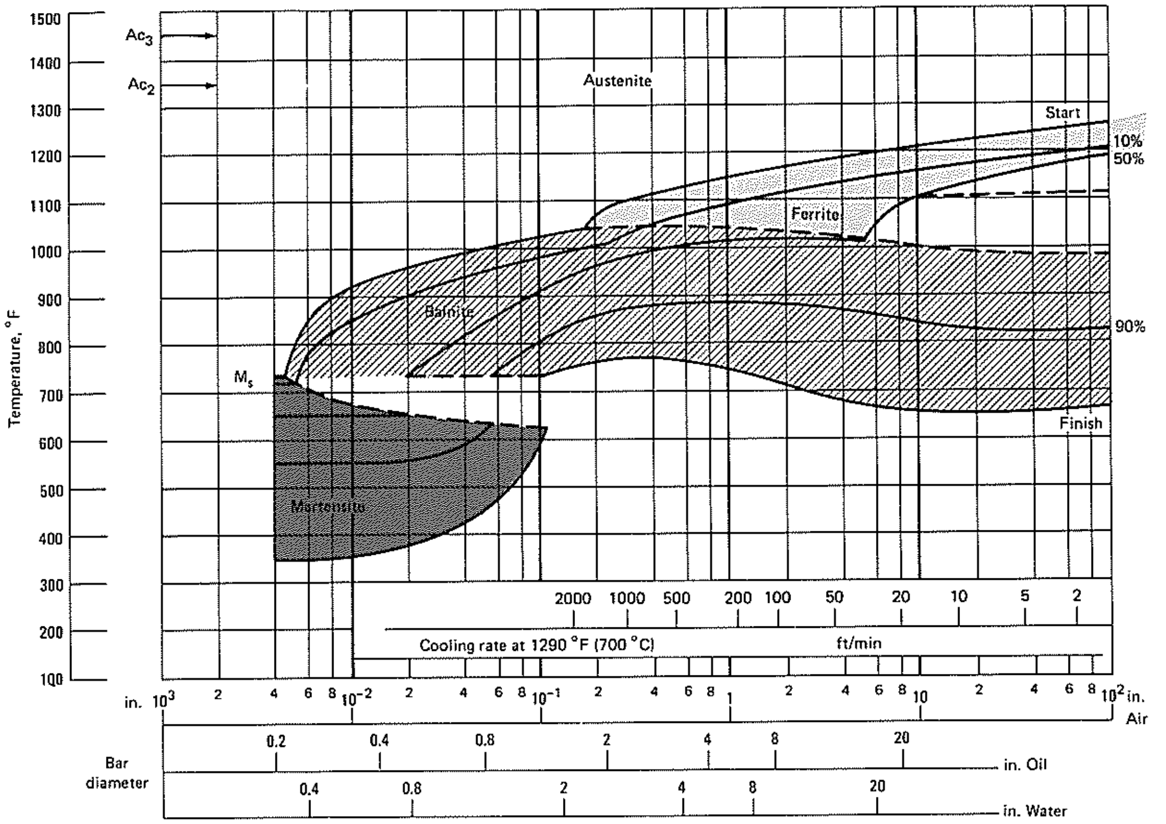
4820: Variation of Surface Carbon Content after Carburizing. Surface carbon concentration [first 0.076 mm (0.003 in.) depth of cut] in bars 19 25.4 mm (1 in.) diam, carburized with production parts in a two-row continuous furnace. Desired carbon content, 0.75 to 0.80%. Specimens were carburized at 925 °C (1695 °F) using a diffusion cycle, quenched from 815 °C (1500 °F) in oil at 60 °C (140 °F), tempered in lead at 620 °C (1150 °F) for 5 min, wire brushed, and liquid-abrasive cleaned. Atmosphere at the charge end of the furnace was automatically controlled at a dew point of −15 °C (5 °F) and at the discharge end at 3 °C (35 °F). Endothermic gas enriched with straight natural gas was used as the carburizing medium; air was added at the discharge end

4820H: End-Quench Hardenability

Distance from quenched surface		Hardness, HRC		Distance from quenched surface		Hardness, HRC	
1/16 in.	mm	max	min	1/16 in.	mm	max	min
1	1.58	48	41	13	20.54	34	22
2	3.16	48	40	14	22.12	33	22
3	4.74	47	39	15	23.70	32	21
4	6.32	46	38	16	25.28	31	21
5	7.90	45	34	18	28.44	29	20
6	9.48	43	31	20	31.60	28	20
7	11.06	42	29	22	34.76	28	...
8	12.64	40	27	24	37.92	27	...
9	14.22	39	26	26	41.08	27	...
10	15.80	37	25	28	44.24	26	...
11	17.38	36	24	30	47.40	26	...
12	18.96	35	23	32	50.56	25	...



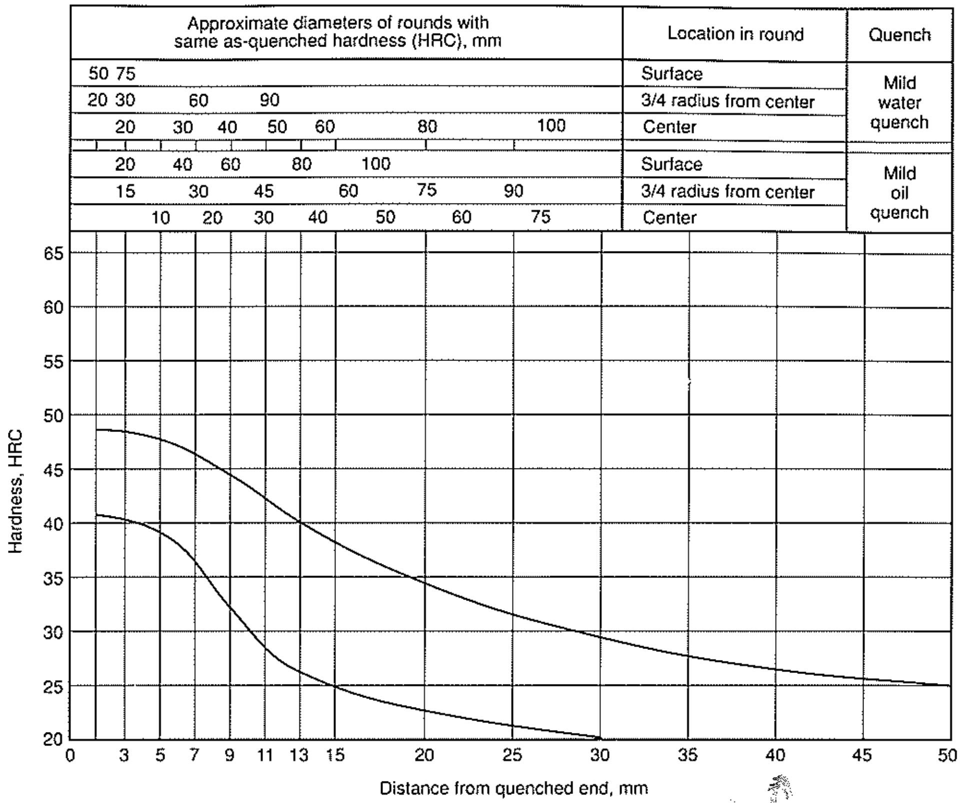
4820: Continuous Cooling Transformation Diagram. Composition: 0.18 C, 0.47 Mn, 0.009 P, 0.010 S, 0.27 Si, 3.33 Ni, 0.18 Cr, 0.23 Mo. Austenitized at 780 °C (1435 °F). Blank carburized at 900 to 920 °C (1650 to 1690 °F) for 4 h



4820H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 845 °C (1555 °F)

Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	48	41
3	48	40
5	48	39
7	46	36
9	45	32
11	43	29
13	40	27
15	39	25
20	35	22
25	32	21
30	29	20
35	28	...
40	27	...
45	26	...
50	26	...



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	48	41
2	48	40
3	47	39
4	46	38
5	45	34
6	43	31
7	42	29
8	40	27
9	39	26
10	37	25
11	36	24
12	35	23
13	34	22
14	33	22
15	32	21
16	31	21
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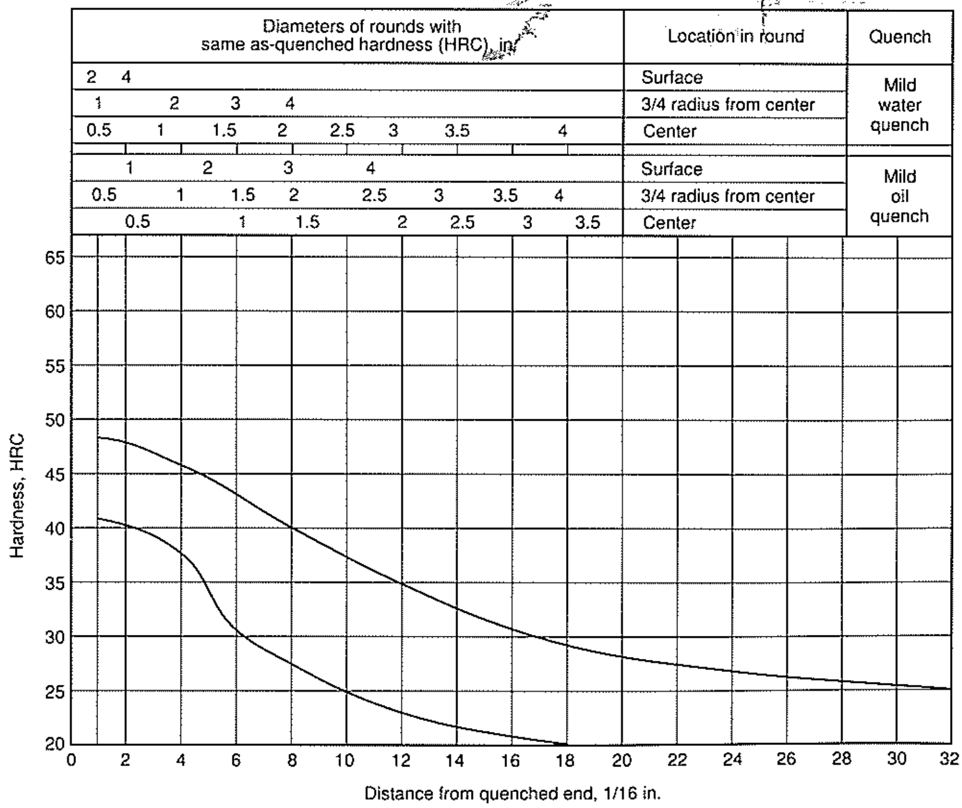
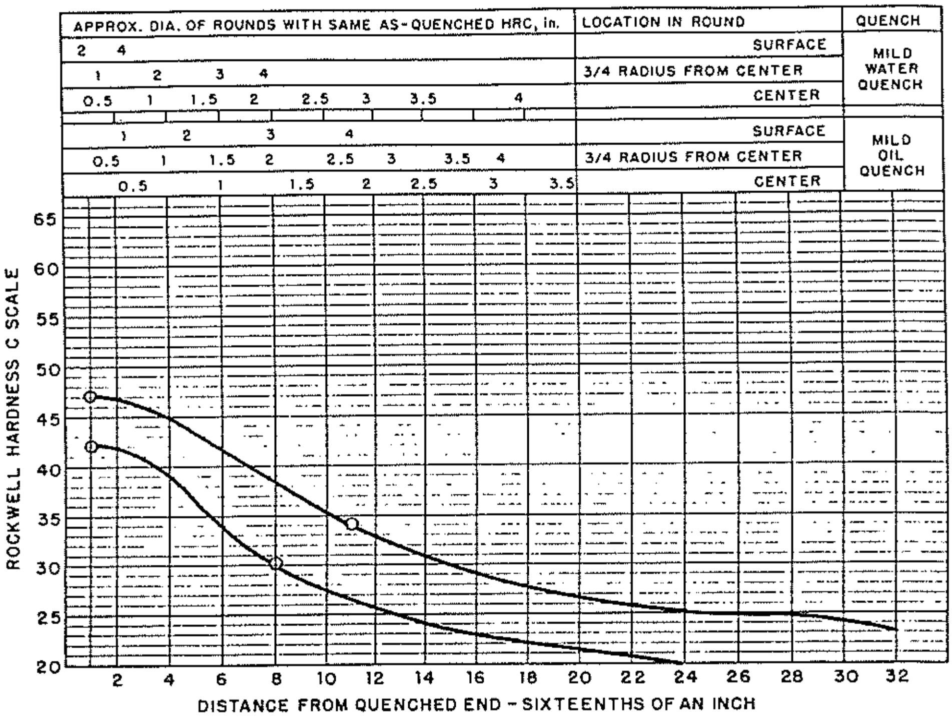
30	26	...
32	25	...



4820RH: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 845 °C (1555 °F)

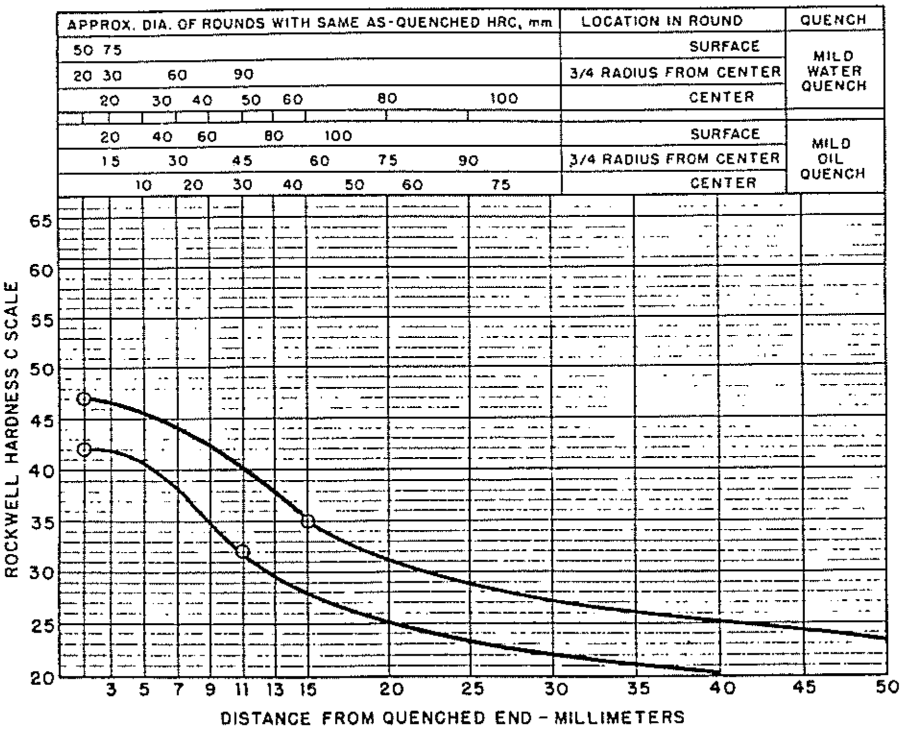
Hardness limits for specification purposes

distance, 1/16 in.	Hardness, HRC Maximum	Minimum
	47	42
	47	42
	46	41
	45	40
	43	36
	41	33
	40	32
	38	30
	36	28
0	35	27
1	34	26
2	33	25
3	32	24
4	31	24
5	30	23
6	29	23
8	28	22
20	27	22
22	26	21
24	25	20
26	25	20
28	25	...
30	24	...
32	23	...



Hardness limits for specification purposes

distance, mm	Hardness, HRC Maximum	Minimum
1.5	47	42
3	47	42
5	46	41
7	44	38
9	42	34
11	40	32
13	38	30
15	35	27
20	32	24
25	29	23
30	27	22
35	26	21
40	25	20
45	24	...
50	23	...



50B40, 50B40H, 50B40RH

Chemical Composition. **50B40. AISI:** 0.38 to 0.43 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.40 to 0.60 Cr, 0.0005 B min. **UNS:** 0.38 to 0.42 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.40 to 0.60 Cr, 0.0005 B min. **UNS H50401 and SAE/AISI 50B40H:** 0.37 to 0.44 C, 0.65 to 1.10 Mn, 0.15 to 0.35 Si, 0.30 to 0.70 Cr, B (can be expected to be 0.0005 to 0.003 percent). **SAE 50B40RH:** 0.38 to 0.43 C, 0.75 to 1.00 Mn, 0.15 to 0.35 Si, 0.40 to 0.60 Cr, B (can be expected to be 0.0005 to 0.003 percent)

Similar Steels (U.S. and/or Foreign). **50B40.** UNS G50401; ASTM A519; SAE J404, J412, J770; (Ger.) DIN 1.7007; (Ital.) UNI 38 CrB 1 KB. **50B40H.** UNS H50401; ASTM A304, A914; SAE J1268, J1868; (Ger.) DIN 1.7007; (Ital.) UNI 38 CrB 1 KB

Characteristics. A medium-carbon grade with an as-quenched surface hardness in the range of approximately 52 to 58 HRC, depending on whether the carbon is low or high on the allowable range. The hardenability band for 50B40H is nearly equal to that of 8640H, a higher alloy and more expensive steel. Is easily forged and responds readily to heat treatments that are used for other low-alloy steels of similar carbon content

Forging. Heat to 1230 °C (2250 °F) maximum. Do not forge after temperature of forging stock drops below approximately 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

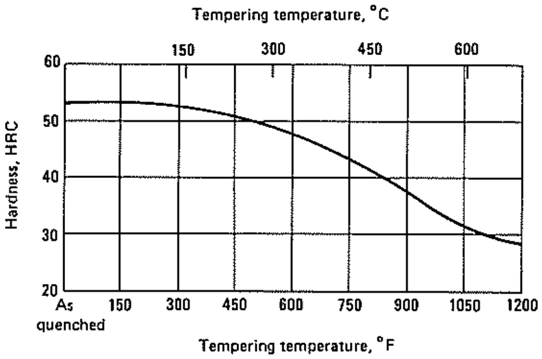
Annealing. For a predominately pearlitic structure, heat to 830 °C (1525 °F), cool rapidly to 740 °C (1365 °F), then to 670 °C (1240 °F) at a rate not to exceed 11 °C (20 °F) per h; or heat to 830 °C (1525 °F), cool rapidly to 675 °C (1245 °F), and hold for 6 h. For a predominately spheroidized structure, heat to 760 °C (1400 °F), cool to 665 °C (1230 °F) at a rate not to exceed 6 °C (10 °F) per h; or heat to 760 °C (1400 °F), cool rapidly to 665 °C (1230 °F), and hold for 8 h. For most subsequent operations such as machining and hardening, a predominately spheroidized structure is preferred

Hardening. Austenitize at 845 °C (1555 °F), and quench in oil

Tempering. Parts made from 50B40H should be tempered immediately after they have been uniformly quenched to near ambient temperature. Best practice is to place workpieces into the tempering furnace just before they have reached room temperature, ideally when they are in the range of 38 to 50 °C (100 to 120 °F). Tempering temperature must be selected based upon the final desired hardness

Recommended Processing Sequence

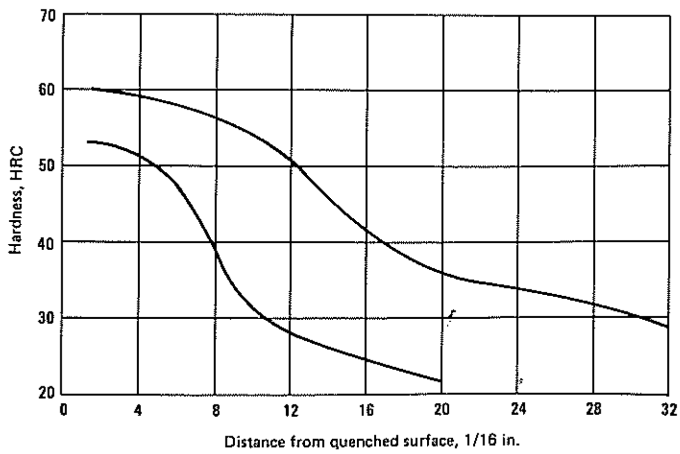
- Forge
- Normalize
- Anneal
- Rough and semifinish machine
- Austenitize and quench in oil
- Temper
- Finish machine



50B40, 50B40H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

50B40H: End-Quench Hardenability

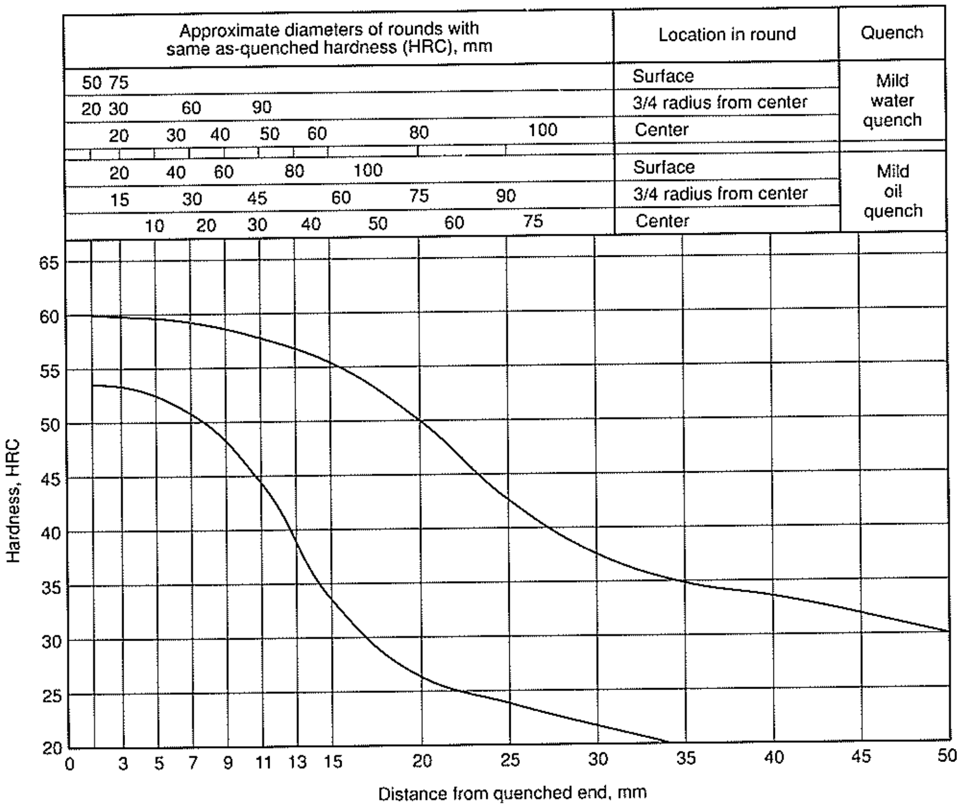
Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max	Hardness, HRC min
1	1.58	60	53	13	20.54	49	27
2	3.16	60	53	14	22.12	47	26
3	4.74	59	52	15	23.70	44	25
4	6.32	59	51	16	25.28	41	25
5	7.90	58	50	18	28.44	38	23
6	9.48	58	48	20	31.60	36	21
7	11.06	57	44	22	34.76	35	...
8	12.64	57	39	24	37.92	34	...
9	14.22	56	34	26	41.08	33	...
10	15.80	55	31	28	44.24	32	...
11	17.38	53	29	30	47.40	30	...
12	18.96	51	28	32	50.56	29	...



50B40H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

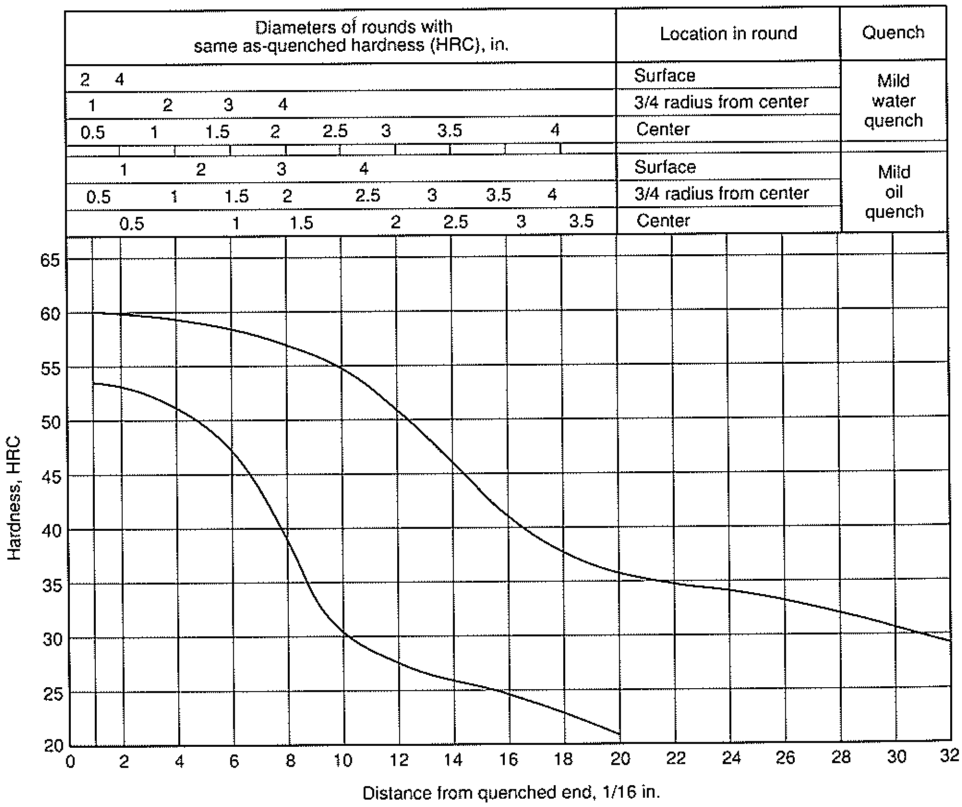
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	60	53
3	60	53
5	60	52
7	59	51
9	59	49
11	58	44
13	57	38
15	56	33
20	50	27
25	43	24
30	37	22
35	35	...
40	34	...
45	32	...
50	30	...



Hardness limits for specification purposes

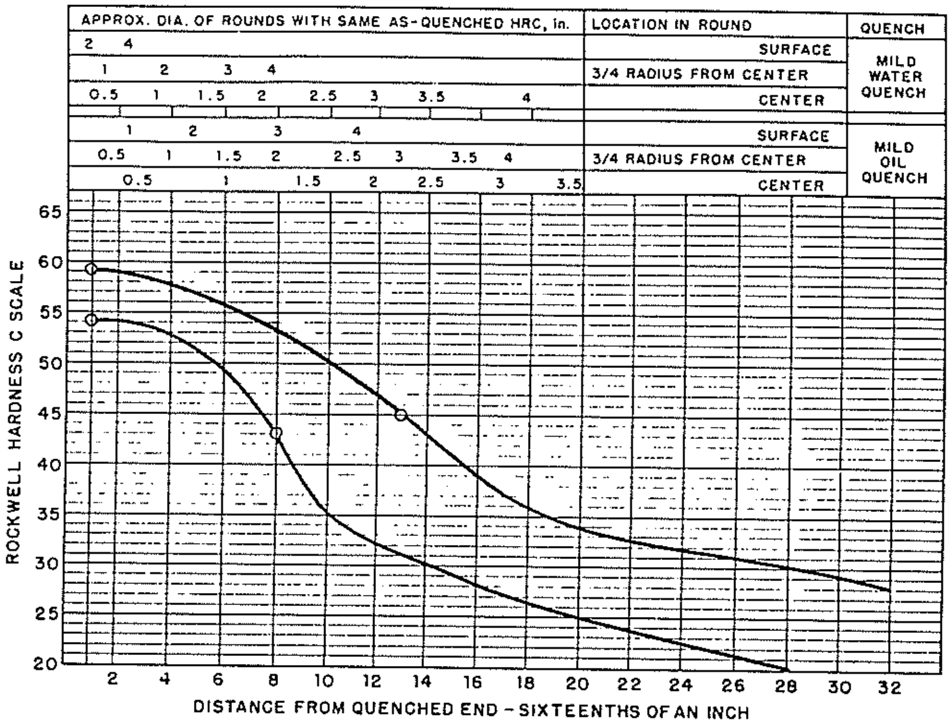
J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	60	53
2	60	53
3	59	52
4	59	51
5	58	50
6	58	48
7	57	44
8	57	39
9	56	34
10	55	31
11	53	29
12	51	28
13	49	27
14	47	26
15	44	25
16	41	25
18	38	23
20	36	21
22	35	...
24	34	...
26	33	...
28	32	...
30	30	...
32	29	...



50B40RH: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

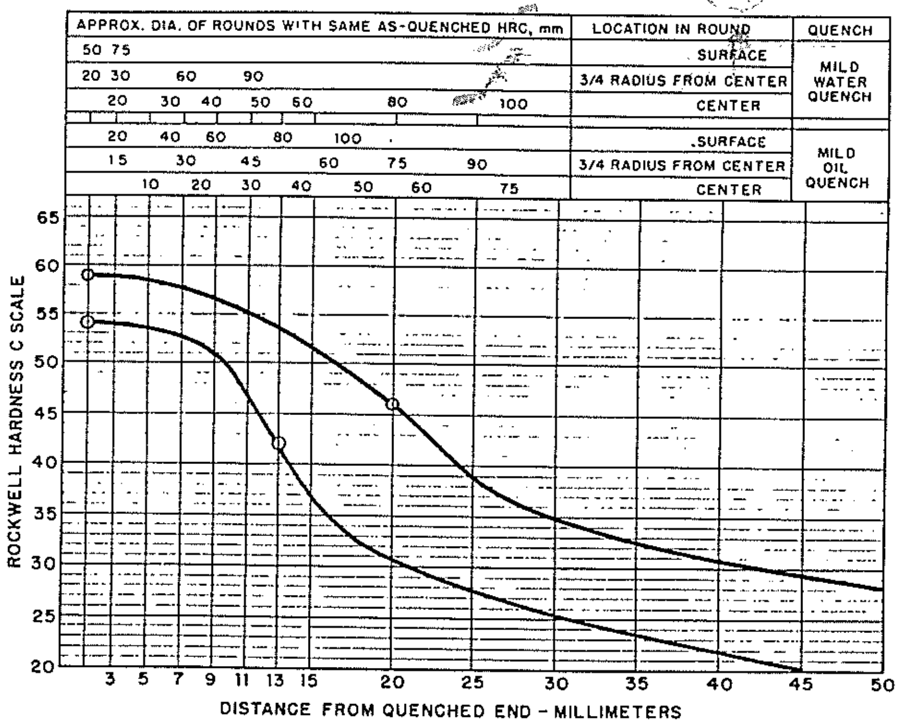
Hardness limits for specification purposes

J distance, $\frac{1}{16}$ in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	59	54
2	59	54
3	58	53
4	58	53
5	57	52
6	56	50
7	55	47
8	54	43
9	52	38
10	50	35
11	49	33
12	47	32
13	45	31
14	44	30
15	41	29
16	38	28
18	36	26
20	34	24
22	33	23
24	32	22
26	31	21
28	30	20
30	29	...
32	28	...



Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	59	54
3	59	54
5	58	53
7	58	53
9	56	51
11	55	47
13	54	42
15	51	36
20	46	31
25	39	28
30	35	25
35	33	23
40	31	21
45	29	20
50	28	...



50B44, 50B44H

Chemical Composition. **50B44. AISI:** 0.43 to 0.48 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.40 to 0.60 Cr, 0.0005 to 0.003 B. **UNS:** 0.43 to 0.48 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.40 to 0.60 Cr, 0.0005 B min. **UNS H50441 and SAE/AISI 50B44H:** 0.42 to 0.49 C, 0.65 to 1.10 Mn, 0.15 to 0.35 Si, 0.30 to 0.70 Cr, B (can be expected to be 0.0005 to 0.003 percent)

Similar Steels (U.S. and/or Foreign). **50B44.** UNS G50441; ASTM A519; SAE J404, J412, J770. **50B44H.** UNS H50441; ASTM A304; SAE J1268

Characteristics. Has the same general characteristics as 50B40H. Because of slightly higher carbon content, the as-quenched hardness of 50B44H will be higher, although the carbon ranges of the two steels overlap. The as-quenched hardness will range from approximately 54 to 60 HRC. Hardenability bands for the two grades are similar, the band for 50B44H shifted slightly upward. Is easily forged and responds readily to heat treatments that are used for other low-alloy steels of similar carbon content

Forging. Heat to 1230 °C (2250 °F) maximum. Do not forge after temperature of forging stock drops below approximately 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

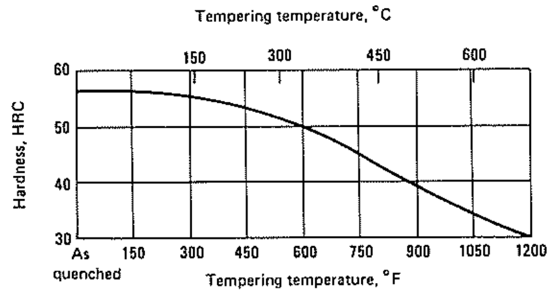
Annealing. For a predominately pearlitic structure, heat to 830 °C (1525 °F), cool rapidly to 740 °C (1365 °F), then to 670 °C (1240 °F) at a rate not to exceed 11 °C (20 °F) per h; or heat to 830 °C (1525 °F), cool rapidly to 675 °C (1245 °F), and hold for 6 h. For a predominately spheroidized structure, heat to 760 °C (1400 °F), cool to 665 °C (1230 °F) at a rate not to exceed 6 °C (10 °F) per h; or heat to 760 °C (1400 °F), cool rapidly to 665 °C (1230 °F), and hold for 8 h. For most subsequent operations such as machining and hardening, a predominately spheroidized structure is preferred

Hardening. Austenitize at 845 °C (1555 °F), and quench in oil

Tempering. Parts made from 50B44H should be tempered immediately after they have been uniformly quenched to near ambient temperature. Best practice is to place workpieces into the tempering furnace just before they have reached room temperature, ideally when they are in the range of 38 to 50 °C (100 to 120 °F). Tempering temperature must be selected based upon the final desired hardness

Recommended Processing Sequence

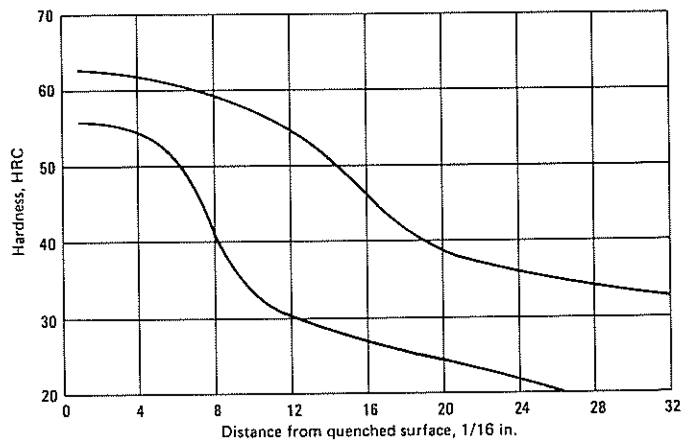
- Forge
- Normalize
- Anneal
- Rough and semifinish machine
- Austenitize and quench in oil
- Temper
- Finish machine



50B44, 50B44H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

50B44H: End-Quench Hardenability

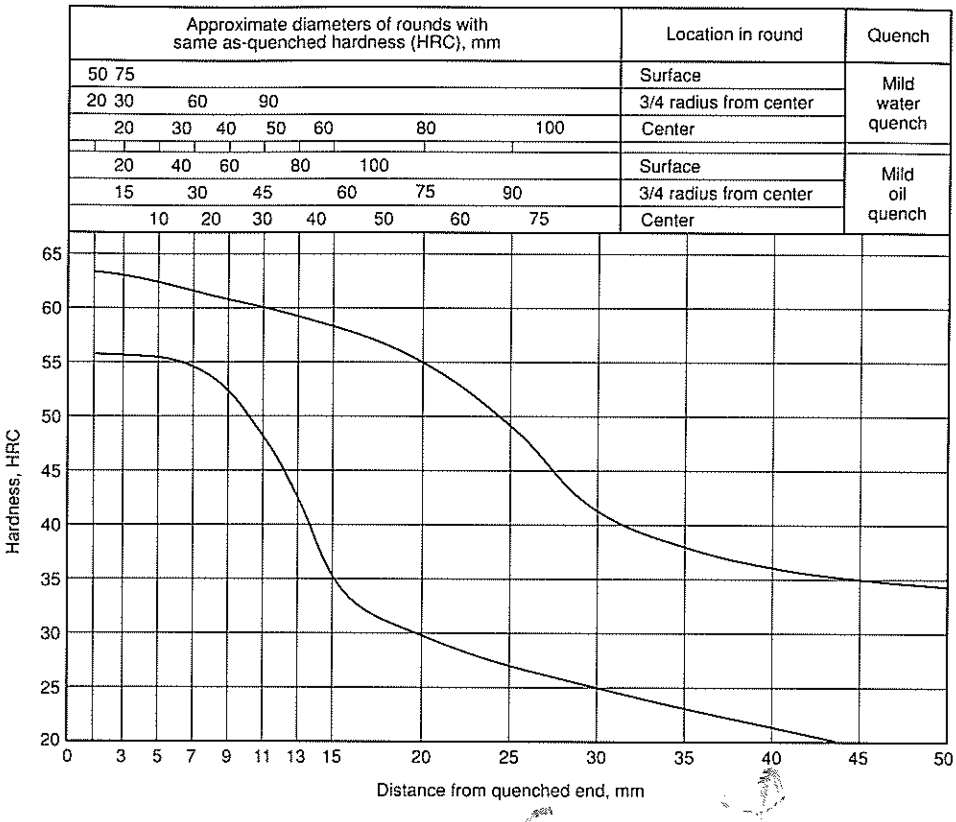
Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max	Hardness, HRC min
1	1.58	63	56	13	20.54	54	29
2	3.16	63	56	14	22.12	52	29
3	4.74	62	55	15	23.70	50	28
4	6.32	62	55	16	25.28	48	27
5	7.90	61	54	18	28.44	44	26
6	9.48	61	52	20	31.60	40	24
7	11.06	60	48	22	34.76	38	23
8	12.64	60	43	24	37.92	37	21
9	14.22	59	38	26	41.08	36	20
10	15.80	58	34	28	44.24	35	...
11	17.38	57	31	30	47.40	34	...
12	18.96	56	30	32	50.56	33	...



50B44H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

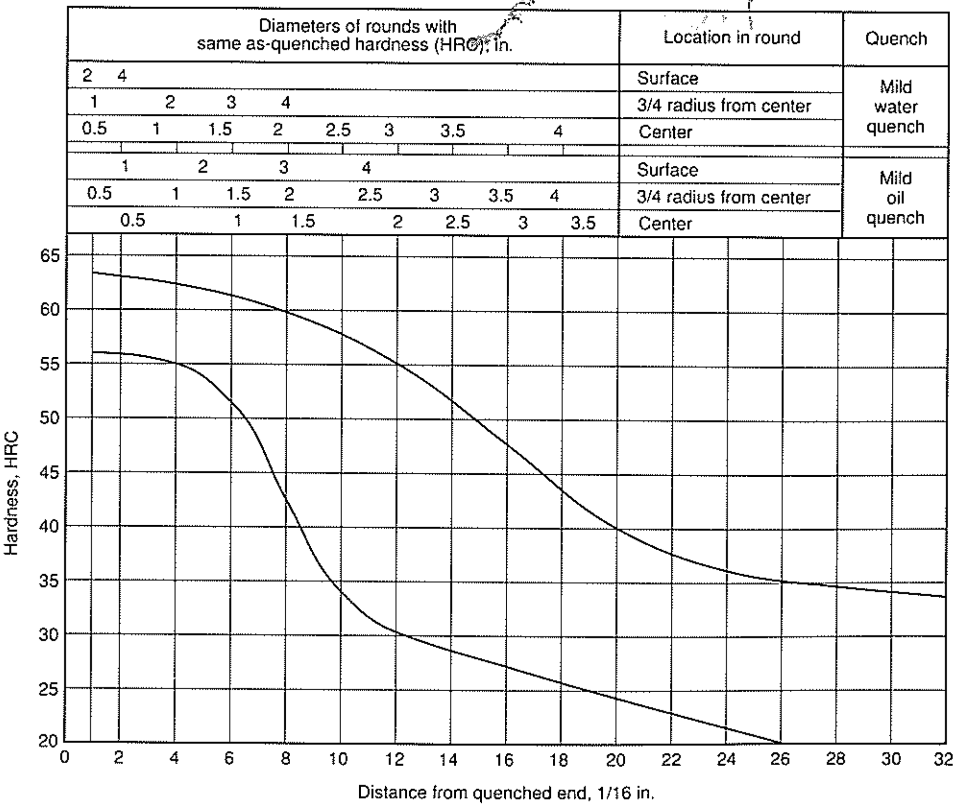
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	63	56
3	63	56
5	63	55
7	62	54
9	61	52
11	61	49
13	60	42
15	59	36
20	55	30
25	49	27
30	42	25
35	38	23
40	37	21
45	35	...
50	34	...



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	63	56
2	63	56
3	62	55
4	62	55
5	61	54
6	61	52
7	60	48
8	60	43
9	59	38
10	58	34
11	57	31
12	56	30
13	54	29
14	52	29
15	50	28
16	48	27
18	44	26
20	40	24
22	38	23
24	37	21
26	36	20
28	35	...
30	34	...
32	33	...



5046, 5046H

Chemical Composition. **5046. AISI:** 0.43 to 0.50 C, 0.75 to 1.00 Mn, 0.040 P max, 0.040 S max, 0.20 to 0.35 Si, 0.20 to 0.35 Cr. **UNS:** 0.43 to 0.50 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.20 to 0.35 Cr. **UNS H50460 and SAE/AISI 5046H:** 0.43 to 0.50 C, 0.65 to .10 Mn, 0.15 to 0.35 Si, 0.13 to 0.43 Cr

Similar Steels (U.S. and/or Foreign). **5046.** UNS G50460; ASTM A519; SAE J404, J412, J770. **5046H.** UNS H50460; ASTM A304; SAE J1268

Characteristics. A typical medium-carbon, very low-alloy steel. When both manganese and chromium are on the high side of their allowable ranges, 5046H has sufficient hardenability so that full hardness can be obtained in thin sections by oil quenching. As-quenched hardness typically ranges from approximately 53 to 58 HRC, depending on whether the carbon is on the low or the high side of the range

Forging. Heat to 1230 °C (2250 °F) maximum. Do not forge after temperature of forging stock drops below approximately 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

Annealing. For a predominately pearlitic structure, heat to 830 °C (1525 °F), cool rapidly to 755 °C (1390 °F), then cool from 755 °C (1390 °F) to 655 °C (1220 °F) at a rate not to exceed 11 °C (20 °F) per h; or heat to 830 °C (1525 °F), cool rapidly to 665 °C (1230 °F), and hold for 4 ½ h. For a predominately spheroidized structure, heat to 760 °C (1400 °F), cool to 665 °C (1230 °F) at a rate not to exceed 6 °C (10 °F) per h; or heat to 760 °C (1400 °F), cool rapidly to 660 °C (1220 °F), and hold for 8 h

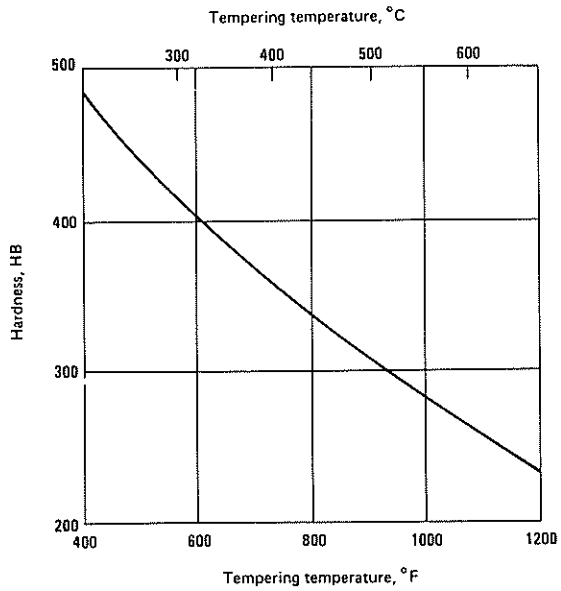
Hardening. Austenitize at 845 °C (1555 °F), and quench in oil for thin sections. Thicker sections will require a water or brine quench for full hardness

Tempering. After quenching, reheat to the temperature required to achieve the final desired hardness

Recommended Processing Sequence

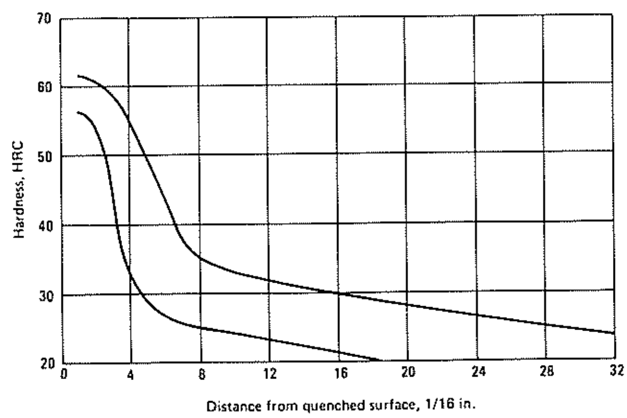
- Forge
- Normalize
- Anneal (preferably spheroidize)
- Rough machine
- Harden
- Temper
- Finish machine

5046: Hardness vs Tempering Temperature. Normalized at 870 °C (1600 °F), quenched from 845 °C (1555 °F), tempered in 56 °C (100 °F) intervals in 13.7 mm (0.540 in.) rounds. Tested in 12.8 mm (0.505 in.) rounds. Source: Republic Steel



5046H: End-Quench Hardenability

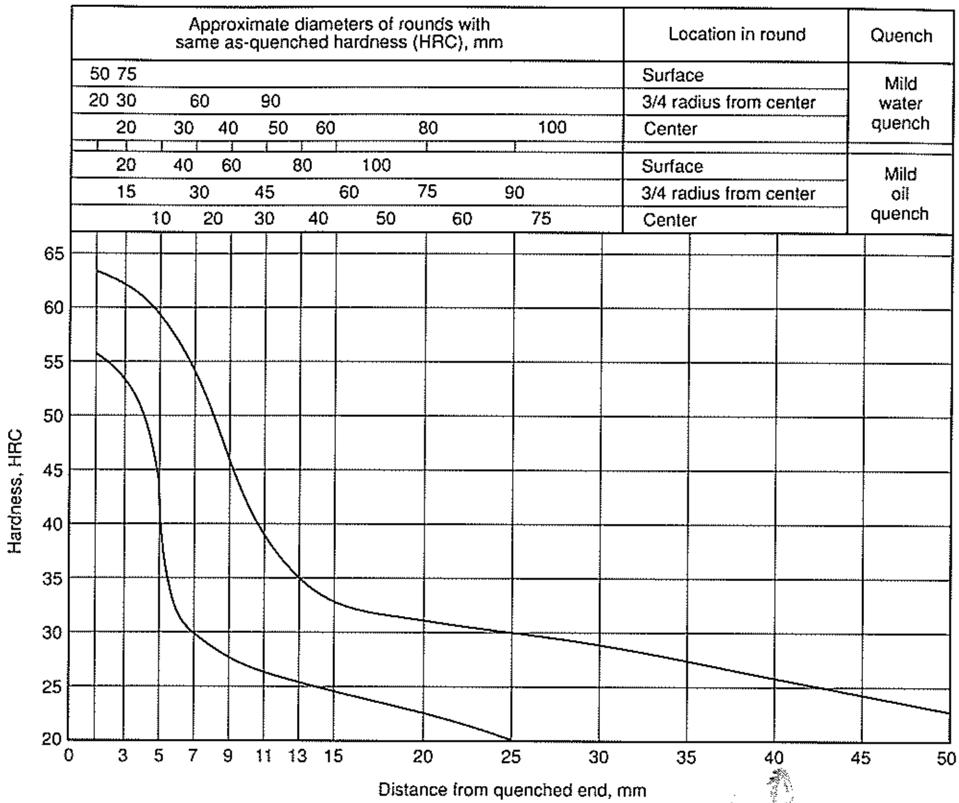
Distance from quenched surface		Hardness, HRC		Distance from quenched surface		Hardness, HRC	
1/16 in.	mm	max	min	1/16 in.	mm	max	min
1	1.58	63	56	13	20.54	32	22
2	3.16	62	55	14	22.12	31	22
3	4.75	60	45	15	23.70	31	21
4	6.32	56	32	16	25.28	30	21
5	7.90	52	28	18	28.44	29	20
6	9.48	46	27	20	31.60	28	...
7	1.06	39	26	22	34.76	27	...
8	12.64	35	25	24	37.92	26	...
9	14.22	34	24	26	41.08	25	...
10	15.80	33	24	28	44.24	24	...
11	17.38	33	23	30	47.40	23	...
12	18.96	32	23	32	50.56	23	...



5046H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

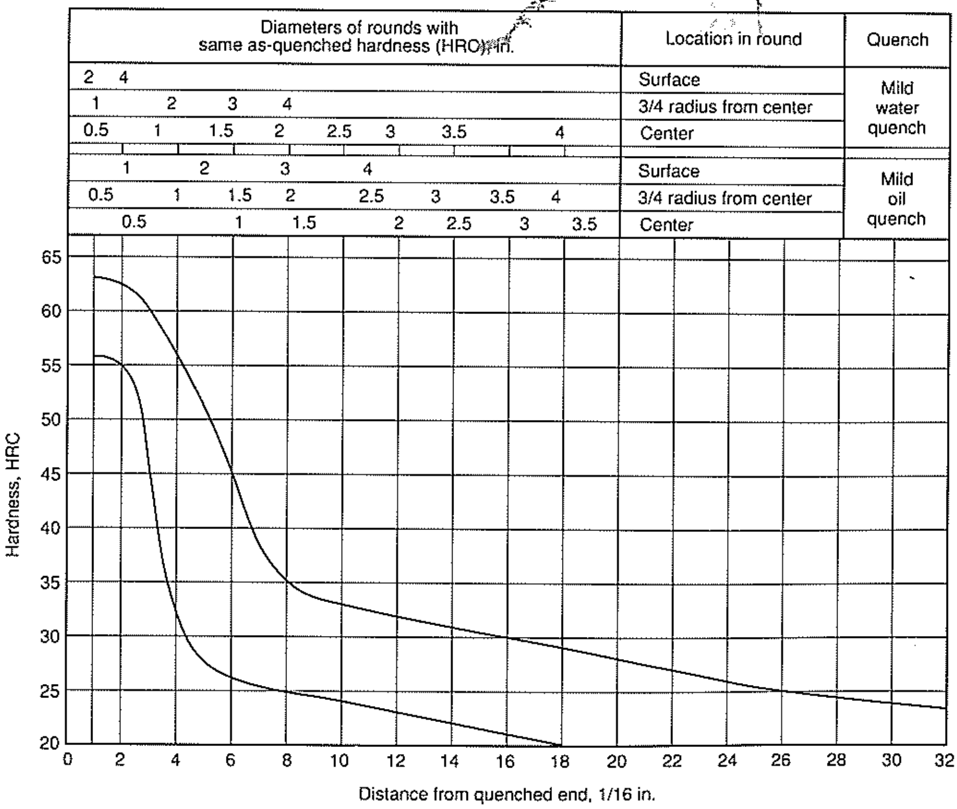
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	63	56
3	62	54
5	59	40
7	54	30
9	48	27
11	39	26
13	35	25
15	34	25
20	32	22
25	30	20
30	29	...
35	27	...
40	26	...
45	24	...
50	23	...



Hardness limits for specification purposes

J distance, $\frac{1}{16}$ in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	63	56
2	62	55
3	60	45
4	56	32
5	52	28
6	46	27
7	39	26
8	35	25
9	34	24
10	33	24
11	33	23
12	32	23
13	32	22
14	31	22
15	31	21
16	30	21
18	29	20
20	28	...
22	27	...
24	26	...
26	25	...
28	24	...
30	23	...
32	23	...



0B46, 50B46H

hemical Composition. 50B46. AISI: 0.44 to 0.49 C, 0.75 to 1.00 In, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.20 to 0.35 Cr, 0.0005 to .003 B. **UNS:** 0.44 to 0.49 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, .15 to 0.30 Si, 0.20 to 0.35 Cr, 0.0005 B min. **UNS H50461 and AE/AISI 50B46H:** 0.43 to 0.50 C, 0.65 to 1.10 Mn, 0.15 to 0.35 Si, 0.13 o 0.43 Cr, B (can be expected to be 0.0005 to 0.003 percent)

imilar Steels (U.S. and/or Foreign). 50B46. UNS G50461; STM A519; SAE J404, J412, J770. **50B46H.** UNS H50461; ASTM 304; SAE J1268

haracteristics. Boron influences 50B46H much the same as it affects 0B40H and 50B44H. 50B46H has a lower chromium content. When the hromium is low, approaching 0.13, the hardenability without the boron vould be little more than that of a plain carbon steel. Hardenability is lower vhen compared with 50B44H. As-quenched surface hardness for 50B46H an be expected to be about the same as for 50B44H, 54 to 60 HRC

orging. Heat to 1230 °C (2250 °F) maximum. Do not forge after emperature of forging stock drops below approximately 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

Annealing. For a predominately pearlitic structure, heat to 830 °C (1525 °F), cool rapidly to 740 °C (1365 °F), then cool to 670 °C (1240 °F) at a rate not to exceed 11 °C (20 °F) per h; or heat to 830 °C (1525 °F), cool rapidly to 675 °C (1245 °F), and hold for 6 h. For a predominately spheroidized structure, heat to 760 °C (1400 °F), cool to 665 °C (1230 °F) at a rate not to exceed 6 °C (10 °F) per h; or heat to 760 °C (1400 °F), cool rapidly to 665 °C (1230 °F), and hold for 8 h

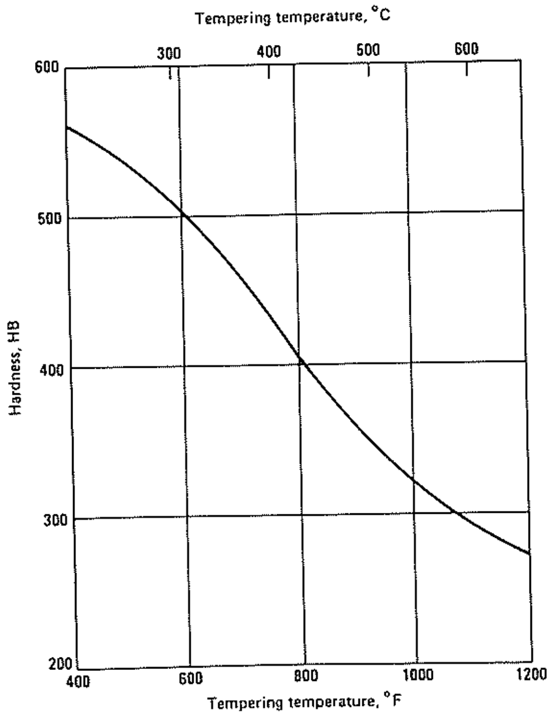
Hardening. Austenitize at 845 °C (1555 °F), and quench in oil

Tempering. Parts made from 50B44H should be tempered immediately after they have been uniformly quenched to near ambient temperature. Best practice is to place workpieces into the tempering furnace just before they have reached room temperature, ideally when they are in the range of 38 to 50 °C (100 to 120 °F). Tempering temperature must be selected based upon the final desired hardness

Recommended Processing Sequence

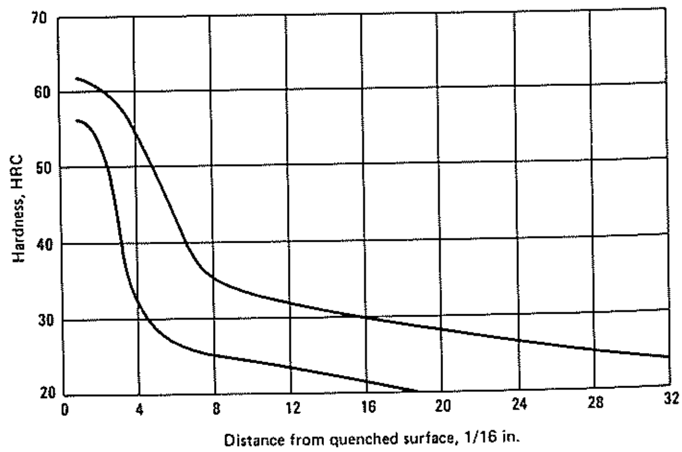
- Forge
- Normalize
- Anneal
- Rough and semifinish machine
- Austenitize and quench in oil
- Temper
- Finish machine

50B46: Hardness vs Tempering Temperature. Normalized at 870 °C (1600 °F), quenched from 845 °C (1555 °F) in oil and tempered in 56 °C (100 °F) intervals in 13.7 mm (0.540 in.) rounds. Tested in 12.8 mm (0.505 in.) rounds. Source: Republic Steel



50B46H: End-Quench Hardenability

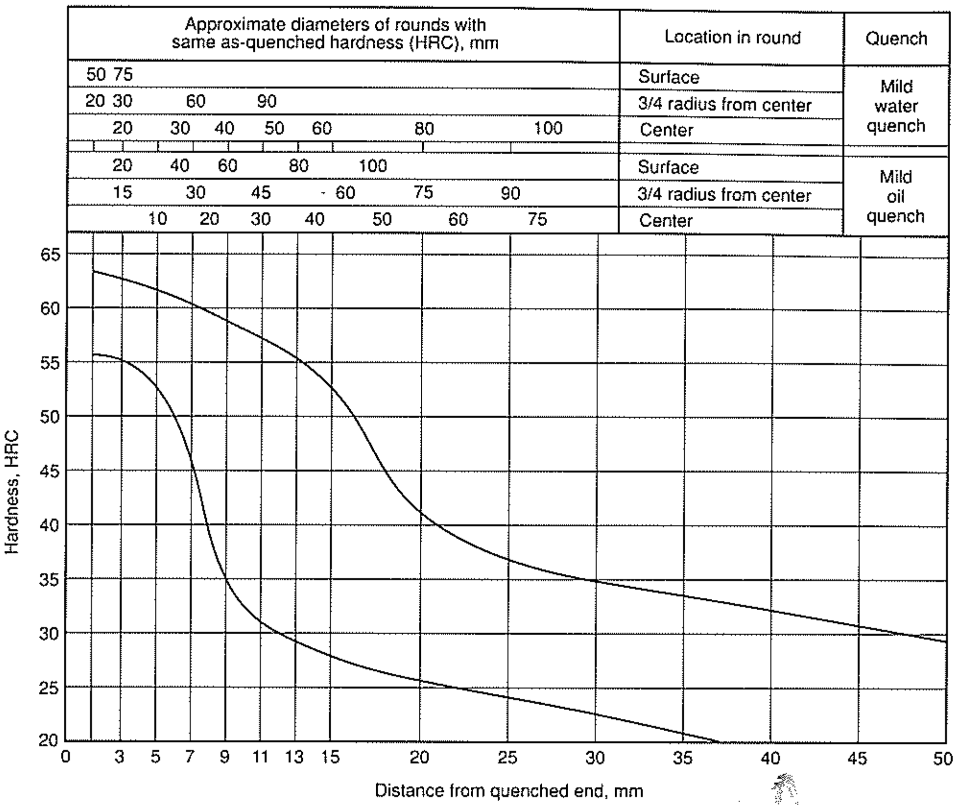
Distance from quenched surface		Hardness, HRC		Distance from quenched surface		Hardness, HRC	
1/16 in.	mm	max	min	1/16 in.	mm	max	min
1	1.58	63	56	13	20.54	40	26
2	3.16	62	54	14	22.12	38	25
3	4.74	61	52	15	23.70	37	25
4	6.32	60	50	16	25.28	36	24
5	7.90	59	41	18	28.44	35	23
6	9.48	58	32	20	31.60	34	22
7	11.06	57	31	22	34.76	33	21
8	12.64	56	30	24	37.92	32	20
9	14.22	54	29	26	41.08	31	...
10	15.80	51	28	28	44.24	30	...
11	17.38	47	27	30	47.40	29	...
12	18.96	43	26	32	50.56	28	...



50B46H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870°C (1600 °F). Austenitize: 845 °C (1555 °F)

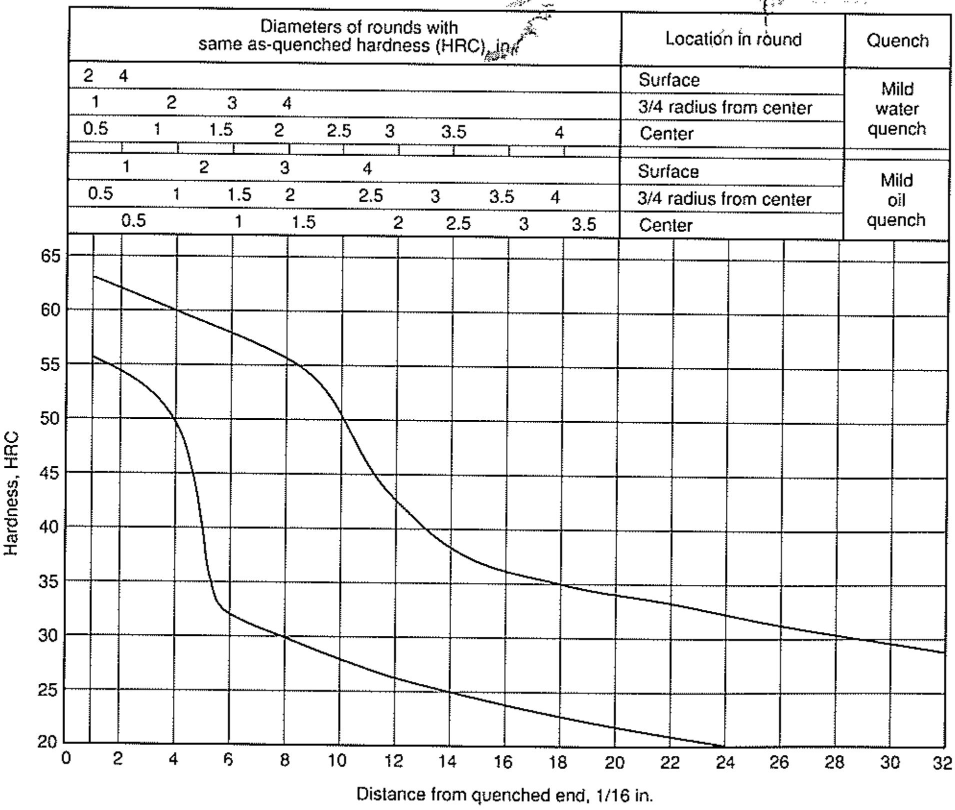
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	63	56
3	62	55
5	61	53
7	60	47
9	59	35
11	58	31
13	56	29
15	53	28
20	42	26
25	37	24
30	35	22
35	34	21
40	32	...
45	31	...
50	29	...



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	63	56
2	62	54
3	61	52
4	60	50
5	59	41
6	58	32
7	57	31
8	56	30
9	54	29
10	51	28
11	47	27
12	43	26
13	40	26
14	38	25
15	37	25
16	36	24
18	35	23
20	34	22
22	33	21
24	32	20
26	31	...
28	30	...
30	29	...
32	28	...



50B50, 50B50H

Chemical Composition. **50B50. AISI:** 0.48 to 0.53 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.40 to 0.60 Cr, 0.0005 to 0.003 B. **UNS:** 0.48 to 0.53 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.40 to 0.60 Cr, 0.0005 B min. **UNS H50501 and SAE/AISI 50B50H:** 0.47 to 0.54 C, 0.65 to 1.10 Mn, 0.15 to 0.35 Si, 0.30 to 0.70 Cr, B (can be expected to be 0.0005 to 0.003 percent)

Similar Steels (U.S. and/or Foreign). **50B50.** UNS G50501; ASTM A519; SAE J404, J412, J770; (Ger.) DIN 1.7138; (Jap.) JIS SUP 11. **50B50H.** UNS H50501; ASTM A304; SAE J1268; (Ger.) DIN 1.7138; (Jap.) JIS SUP 11

Characteristics. Borders between what is usually considered as a medium-carbon and a high-carbon steel, depending on the precise carbon content, which also controls the as-quenched surface hardness. A range of approximately 56 to 62 HRC can be expected. The 0.30 to 0.70% chromium and the boron treatment produce a relatively high hardenability. Used for a variety of applications, where its hardenability is advantageous, such as heavy-duty springs

Forging. Heat to 1230 °C (2250 °F) maximum. Do not forge after temperature of forging stock drops below approximately 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

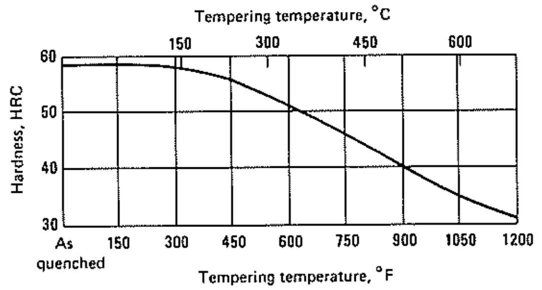
Annealing. For a predominately spheroidized structure, heat to 750 °C (1380 °F), cool rapidly to 705 °C (1300 °F), then cool to 650 °C (1200 °F), at a rate not to exceed 6 °C (10 °F) per h; or heat to 750 °C (1380 °F), cool rapidly to 675 °C (1245 °F), and hold for 12 h

Hardening. Austenitize at 845 °C (1555 °F), and quench in oil

Tempering. Parts made from 50B50H should be tempered immediately after they have been uniformly quenched to near ambient temperature. Best practice is to place workpieces into the tempering furnace just before they have reached room temperature, ideally when they are in the range of 38 to 50 °C (100 to 120 °F). Tempering temperature must be selected based upon the final desired hardness

Recommended Processing Sequence

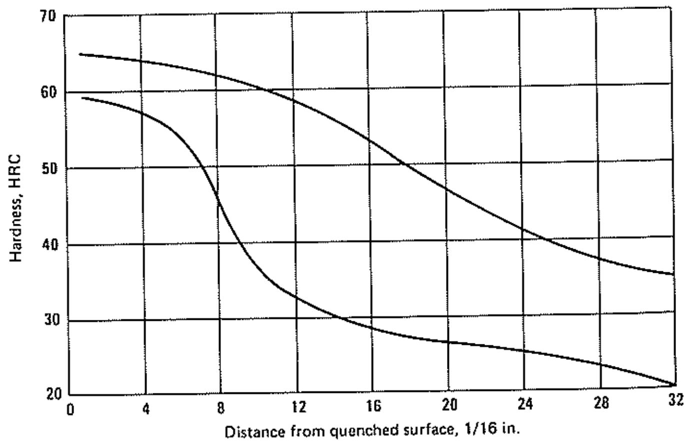
- Forge
- Normalize
- Anneal
- Rough and semifinish machine
- Austenitize and quench in oil
- Temper
- Finish machine



50B50, 50B50H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

50B50H: End-Quench Hardenability

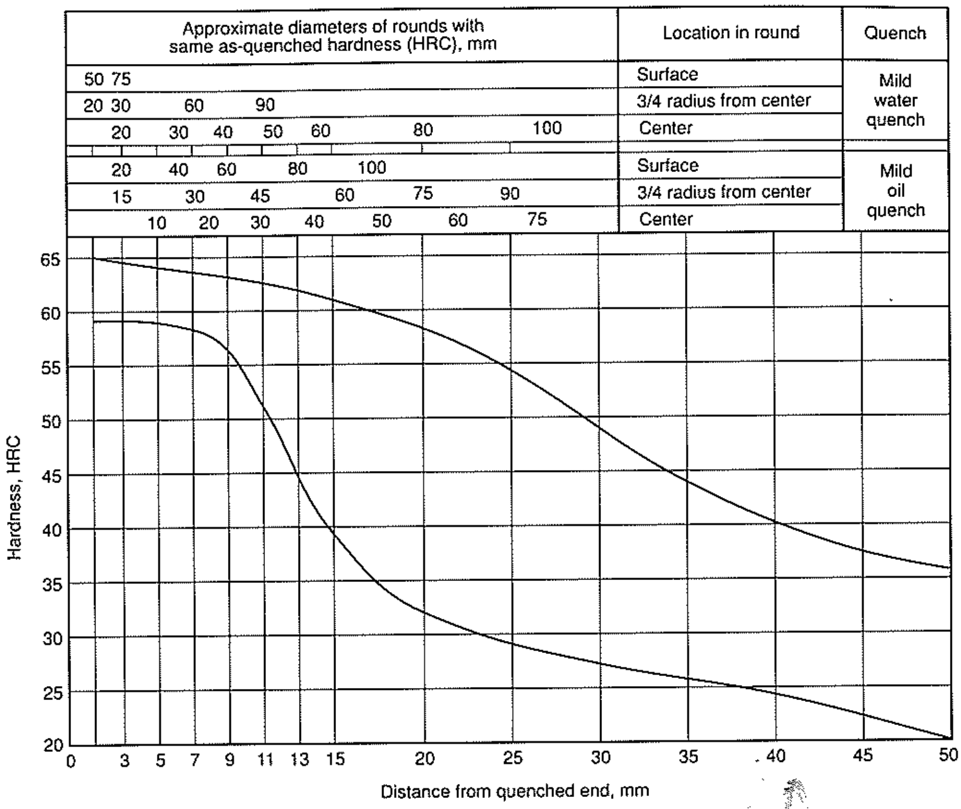
Distance from quenched surface, $\frac{1}{16}$ in.	mm	Hardness, HRC max	min	Distance from quenched surface, $\frac{1}{16}$ in.	mm	Hardness, HRC max	min
1	1.58	65	59	13	20.54	58	32
2	3.16	65	59	14	22.12	57	31
3	4.74	64	58	15	23.70	56	30
4	6.32	64	57	16	25.28	54	29
5	7.90	63	56	18	28.44	50	28
6	9.48	63	55	20	31.60	47	27
7	11.06	62	52	22	34.76	44	26
8	12.64	62	47	24	37.92	41	25
9	14.22	61	42	26	41.08	39	24
10	15.80	60	37	28	44.24	38	22
11	17.38	60	35	30	47.40	37	21
12	18.96	59	33	32	50.56	36	20



50B50H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

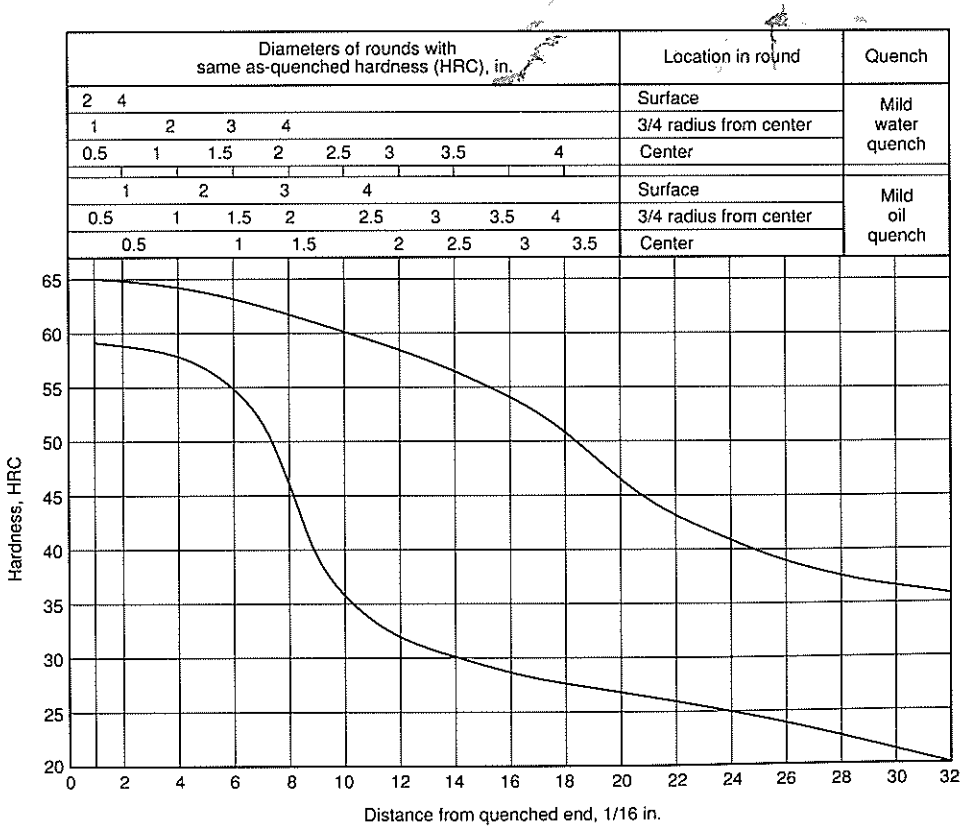
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	65	59
3	65	59
5	65	59
7	64	57
9	63	55
11	63	52
13	62	46
15	62	39
20	59	32
25	54	29
30	49	27
35	44	26
40	40	24
45	38	22
50	37	20



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	65	59
2	65	59
3	64	58
4	64	57
5	63	56
6	63	55
7	62	52
8	62	47
9	61	42
10	60	37
11	60	35
12	59	33
13	58	32
14	57	31
15	56	30
16	54	29
18	50	28
20	47	27
22	44	26
24	41	25
26	39	24
28	38	22
30	37	21
32	36	20



50B60, 50B60H

Chemical Composition. **50B60. AISI:** 0.56 to 0.64 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.40 to 0.60 Cr, 0.0005 to 0.003 B. **UNS:** 0.56 to 0.64 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.40 to 0.60 Cr, 0.0005 B min. **UNS H50601 and SAE/AISI 50B60H:** 0.55 to 0.65 C, 0.65 to 1.10 Mn, 0.15 to 0.35 Si, 0.30 to 0.70 Cr, B (can be expected to be 0.0005 to 0.003 percent)

Similar Steels (U.S. and/or Foreign). **50B60.** UNS G50601; ASTM A519; SAE J404, J412, J770. **50B60H.** UNS H50601; ASTM A304; SAE J1268

Characteristics. Has the same general characteristics as other boron-containing steels. With the higher carbon content, an as-quenched hardness in the range of approximately 58 to 63 HRC can be expected. The hardenability of this grade is quite high. Both the top and the bottom boundaries of the hardenability band are straight lines for significant distances from the quenched end. Used for parts that demand high hardenability, especially where economy is a factor. This steel, similar to other boron-containing steels, represents a cost-effective way of achieving high hardenability

Forging. Heat to 1205 °C (2200 °F) maximum. Do not forge after temperature of forging stock drops below approximately 925 °C (1695 °F). Because of high hardenability, forgings, especially complex shapes, should be cooled slowly from the forging operation to minimize the possibility of cracking. Forgings may be slow cooled by either placing them in a furnace or burying them in an insulating compound

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

Annealing. For a predominately spheroidized structure, which is usually favored for this grade, heat to 750 °C (1380 °F), cool rapidly to 700 °C (1290 °F), then cool to 655 °C (1210 °F), at a rate not to exceed 6 °C (10 °F) per h; or heat to 750 °C (1380 °F), cool rapidly to 650 °C (1200 °F), and hold for 12 h

Hardening. Austenitize at 845 °C (1555 °F), and quench in oil

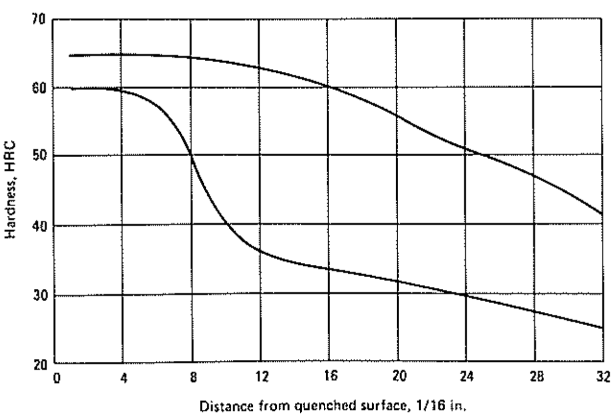
Tempering. Selection of tempering temperature depends on the final properties desired. To prevent cracking, make sure parts have reached a uniform temperature throughout each section, and then place them in a tempering furnace before ambient temperature is reached. 38 to 50 °C (100 to 120 °F) is considered ideal

Recommended Processing Sequence

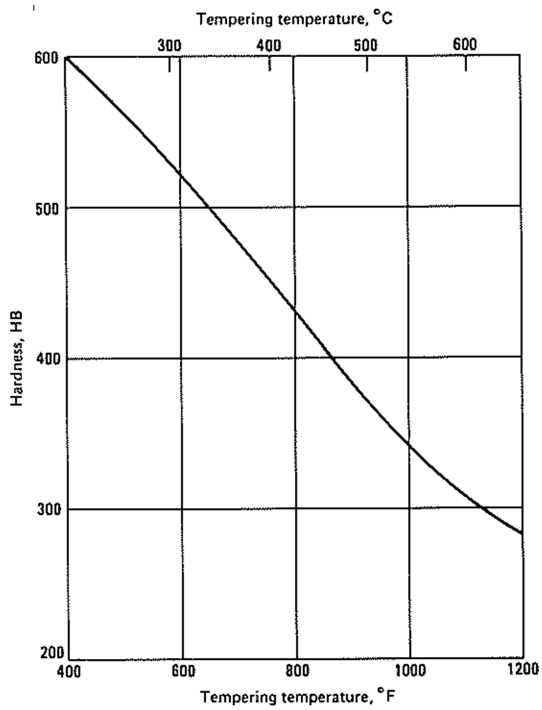
- Forge
- Normalize
- Anneal
- Rough and semifinish machine
- Austenitize and quench
- Temper
- Finish machine

50B60H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max	min	Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max	min
1	1.58	...	60	13	20.54	63	36
2	3.16	...	60	14	22.12	63	35
3	4.75	...	60	15	23.70	63	34
4	6.32	...	60	16	25.28	62	34
5	7.90	...	60	18	28.44	60	33
6	9.48	...	59	20	31.60	58	31
7	11.06	...	57	22	34.76	55	30
8	12.64	65	53	24	37.92	53	29
9	14.22	65	47	26	41.08	51	28
10	15.80	64	42	28	44.24	49	27
11	17.38	64	39	30	47.40	47	26
12	18.96	64	37	32	50.56	44	25



50B60: Hardness vs Tempering Temperature. Normalized at 870 °C (1600 °F), quenched from 845 °C (1555 °F) in oil, tempered in 56 °C (100 °F) intervals in 13.7 mm (0.540 in.) rounds. Tested in 12.8 mm (0.505 in.) rounds. Source: Republic Steel

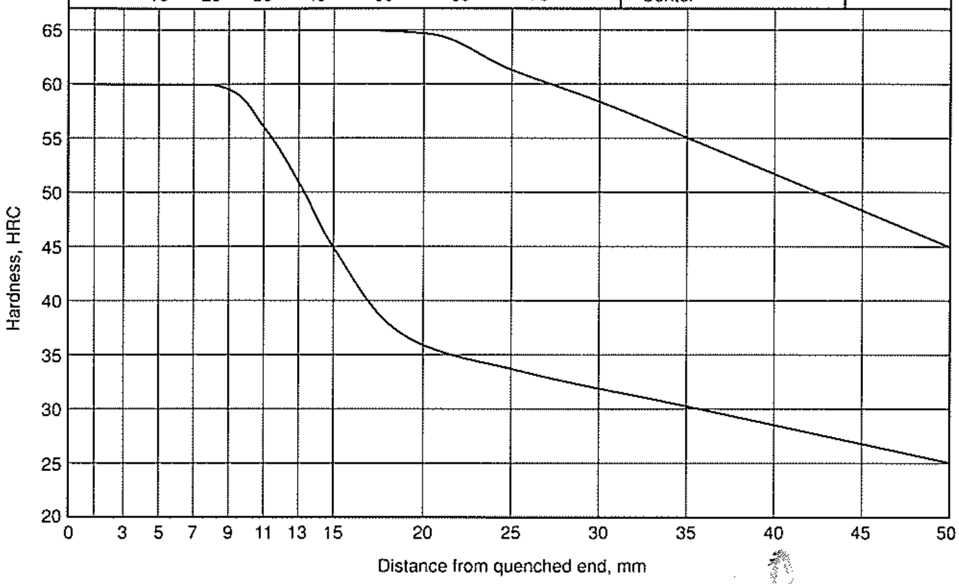


50B60H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	...	60
3	...	60
5	...	60
7	...	60
9	...	59
11	...	57
13	65	51
15	65	44
20	65	36
25	62	34
30	59	32
35	56	30
40	52	28
45	48	27
50	45	25

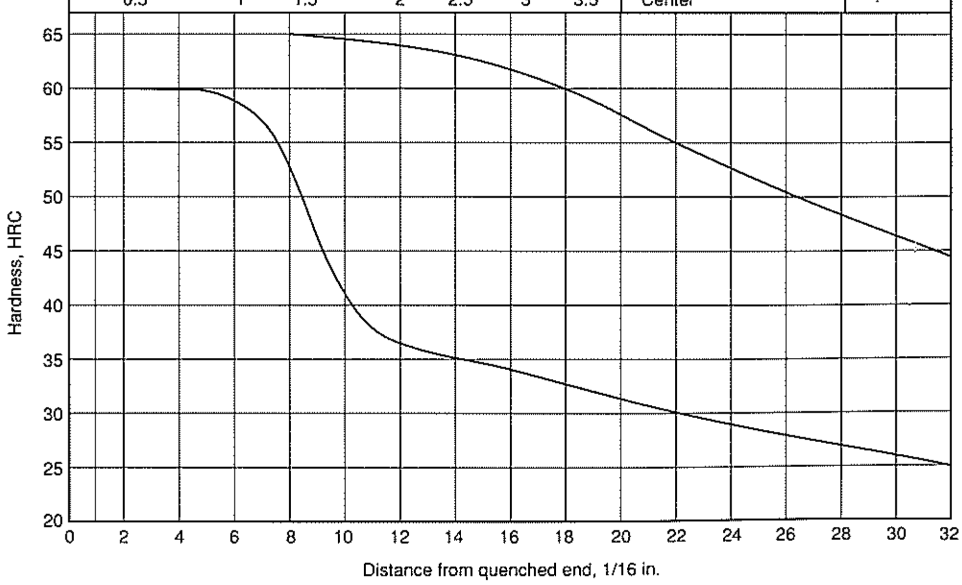
Approximate diameters of rounds with same as-quenched hardness (HRC), mm	Location in round	Quench
50 75	Surface	Mild water quench
20 30 60 90	3/4 radius from center	
20 30 40 50 60 80 100	Center	
20 40 60 80 100	Surface	Mild oil quench
15 30 45 60 75 90	3/4 radius from center	
10 20 30 40 50 60 75	Center	



Hardness limits for specification purposes

J distance, $\frac{1}{16}$ in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	...	60
2	...	60
3	...	60
4	...	60
5	...	60
6	...	59
7	...	57
8	65	53
9	65	47
10	64	42
11	64	39
12	64	37
13	63	36
14	63	35
15	63	34
16	62	34
18	60	33
20	58	31
22	55	30
24	53	29
26	51	28
28	49	27
30	47	26
32	44	25

Diameters of rounds with same as-quenched hardness (HRC), in.	Location in round	Quench
2 4	Surface	Mild water quench
1 2 3 4	3/4 radius from center	
0.5 1 1.5 2 2.5 3 3.5 4	Center	
1 2 3 4	Surface	Mild oil quench
0.5 1 1.5 2 2.5 3 3.5 4	3/4 radius from center	
0.5 1 1.5 2 2.5 3 3.5	Center	



5117

Chemical Composition. **5117. AISI and UNS:** 0.15 to 0.20 C, 0.70 to 0.90 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.70 to 0.90 Cr

Similar Steels (U.S. and/or Foreign). UNS G51170

Characteristics. A slightly modified version of 5120. The carbon range is lower, but the ranges for the two steels overlap. Although there is no H version of 5117, hardenability is expected to be very close to that of 5120H. As-quenched hardness for 5117 (no case) usually ranges from 36 to 41 HRC. Readily forgeable and weldable with alloy steel welding practice. Definitely a case hardening grade and is used for parts that require either carburizing or carbonitriding. For further details see 5120H

Forging. Heat to 1245 °C (2275 °F) maximum. Do not forge after temperature of forging stock drops below approximately 870 °C (1600 °F)

Recommended Heat Treating Practice

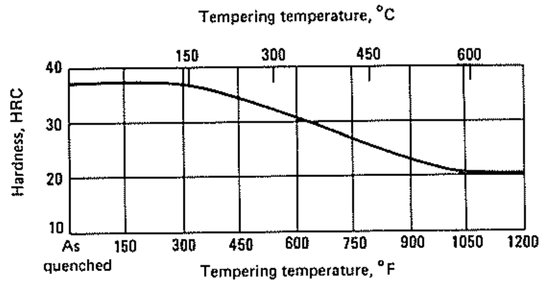
Normalizing. Heat to 925 °C (1695 °F). Cool in air

Annealing. Not usually required for this grade. Structures that are well suited to machining are generally obtained by normalizing or by isothermal annealing after rolling or forging. Isothermal annealing is accomplished by heating to 700 °C (1290 °F), and holding for 8 h

Case Hardening. See recommended carburizing, carbonitriding, and tempering procedures described for 4118H. Ion nitriding and gas nitriding are alternative processes

Recommended Processing Sequence

- Forge
- Normalize
- Anneal (optional)
- Rough and semifinish machine
- Case harden
- Temper
- Finish machine



5117: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

5120, 5120H

Chemical Composition. **5120. AISI and UNS:** 0.17 to 0.22 C, 0.70 to 0.90 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.70 to 0.90 Cr. **UNS H51200 and SAE/AISI 5120H:** 0.17 to 0.23 C, 0.60 to 1.00 Mn, 0.15 to 0.35 Si, 0.60 to 1.00 Cr

Similar Steels (U.S. and/or Foreign). **5120.** UNS G51200; ASTM A322, A331, A519; SAE J404, J770; (Ger.) DIN 1.7147; (Fr.) AFNOR 20 MC 5. **5120H.** UNS H51200; ASTM A304; SAE J1268; (Ger.) DIN 1.7147; (Fr.) AFNOR 20 MC 5

Characteristics. A low-alloy carburizing grade. An as-quenched hardness of approximately 38 to 44 HRC can normally be expected. This range represents the core hardness of carburized 5120H. Would not be considered a high hardenability steel, but it is similar to 4118H in hardenability

Forging. Heat to 1245 °C (2275 °F) maximum. Do not forge after temperature of forging stock drops below approximately 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Cool in air

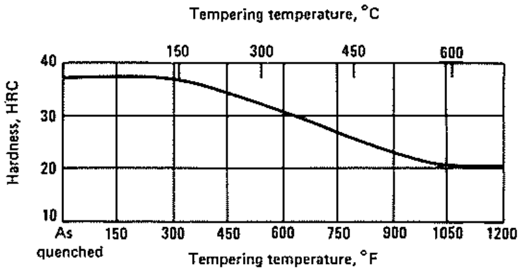
Annealing. Best machining structures are obtained by heating to 800 °C (1475 °F), cooling rapidly to 675 °C (1245 °F), and holding for 10 h

Tempering. Parts that have been carburized or carbonitrided should be tempered at 150 °C (300 °F), or higher if some loss of hardness can be tolerated

Case Hardening. See recommended carburizing, carbonitriding, and tempering procedures described for 4118H. Ion nitriding is an alternative process

Recommended Processing Sequence

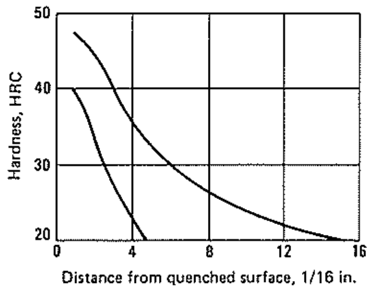
- Forge
- Normalize
- Anneal
- Rough and semifinish machine
- Carburize, diffuse and quench, or carbonitride and quench
- Temper
- Finish machine if required



5120, 5120H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

5120H: End-Quench Hardenability

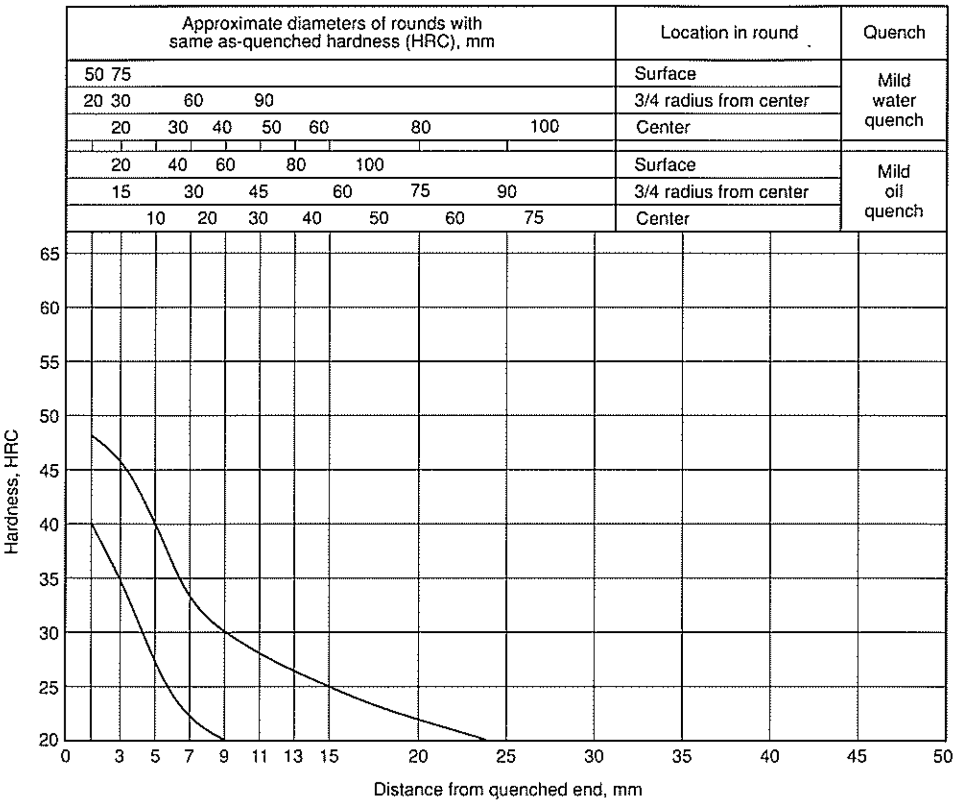
Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max
1	1.58	48	40	13	20.54	21
2	3.16	46	34	14	22.12	21
3	4.74	41	28	15	23.70	20
4	6.32	36	23	16	25.28	...
5	7.90	33	20	18	28.44	...
6	9.48	30	...	20	31.60	...
7	11.06	28	...	22	34.76	...
8	12.64	27	...	24	37.92	...
9	14.22	25	...	26	41.08	...
10	15.80	24	...	28	44.24	...
11	17.38	23	...	30	47.40	...
12	18.96	22	...	32	50.56	...



5120H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 925 °C (1700 °F)

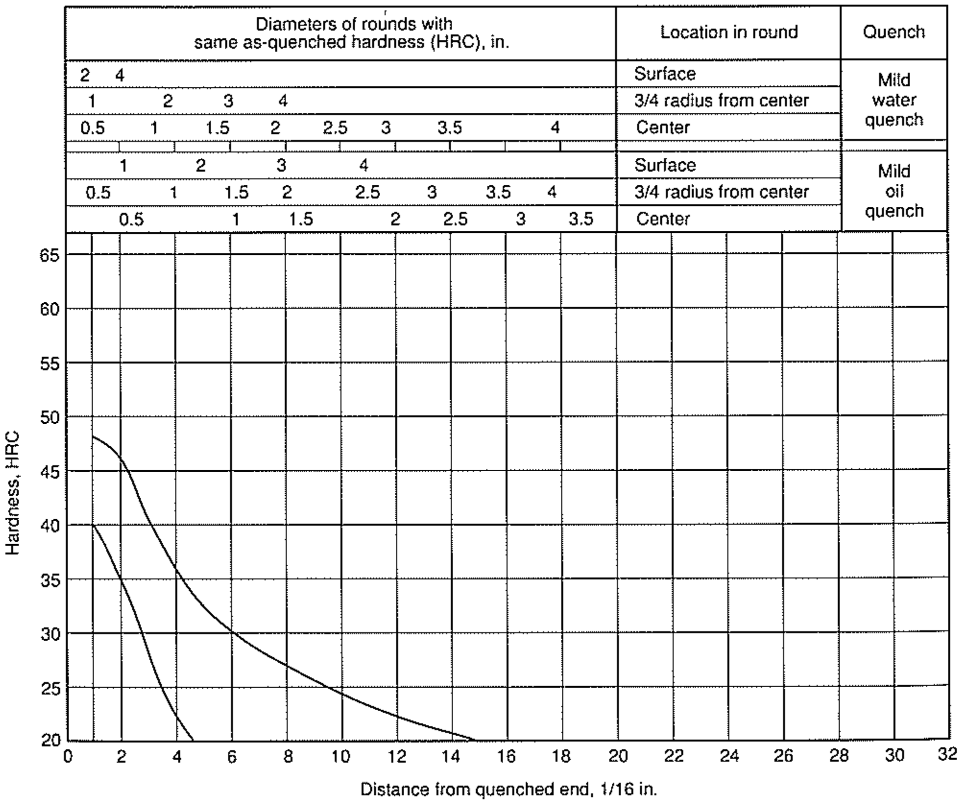
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	48	40
3	46	34
5	41	27
7	34	22
9	31	20
11	29	...
13	27	...
15	25	...
20	22	...
25	...	...



Hardness limits for specification purposes

J distance, $\frac{1}{16}$ in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	48	40
2	46	34
3	41	28
4	36	23
5	33	20
6	30	...
7	28	...
8	27	...
9	25	...
10	24	...
11	23	...
12	22	...
13	21	...
14	21	...
15	20	...
16	...	...



5130, 5130H, 5130RH

Chemical Composition. **5130. AISI and UNS:** 0.28 to 0.33 C, 0.70 to 0.90 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.80 to 1.10 Cr. **UNS H51300 and SAE/AISI 5130H:** 0.27 to 0.33 C, 0.60 to 1.00 Mn, 0.15 to 0.35 Si, 0.75 to 1.20 Cr. **SAE 5130RH:** 0.28 to 0.33 C, 0.70 to 0.90 Mn, 0.15 to 0.35 Si, 0.80 to 1.10 Cr

Similar Steels (U.S. and/or Foreign). **5130.** UNS G51300; SAE J404, J412, J770; (Ger.) DIN 1.7030; (U.K.) B.S. 530 A 30, 530 H 30. **5130H.** UNS H51300; ASTM A304, A914; SAE J1268, J1868; (Ger.) DIN 1.7033; (Fr.) AFNOR 32 C 4; (Ital.) UNI 34 Cr 4 KB; (Jap.) JIS SCr 2 H, SCr 2; (U.K.) B.S. 530 A 32, 530 H 32

Characteristics. A medium-carbon alloy steel. Chromium is the sole alloying element; manganese in the range of 5130H is not considered an alloy. Hardenability is considered fairly high. Depending on the specific carbon content, as-quenched hardness in the range of approximately 46 to 53 HRC can be expected. Can be welded, but alloy steel welding practice is mandatory

Forging. Heat to 1230 °C (2250 °F) maximum. Do not forge after temperature of forging stock drops below approximately 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F). Cool in air

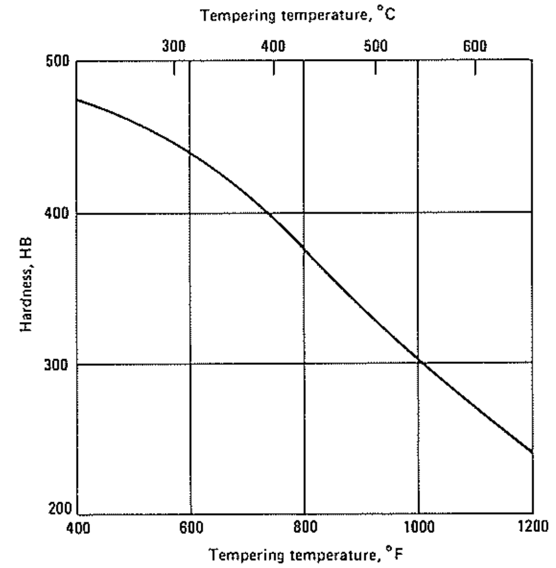
Annealing. For a predominately pearlitic structure, heat to 845 °C (1555 °F), cool rapidly to 755 °C (1390 °F), then cool to 670 °C (1240 °F), at a rate not to exceed 11 °C (20 °F) per h; or heat to 845 °C (1555 °F), cool rapidly to 675 °C (1245 °F), and hold for 6 h. For a largely spheroidized structure, heat to 790 °C (1455 °F), cool rapidly to 690 °C (1275 °F), and hold for 8 h

Hardening. Austenitize at 855 °C (1570 °F), and quench in oil. Ion nitriding, gas nitriding, liquid carburizing, and gas carburizing are suitable processes

Tempering. Reheat after quenching to the temperature that will result in the desired hardness

Recommended Processing Sequence

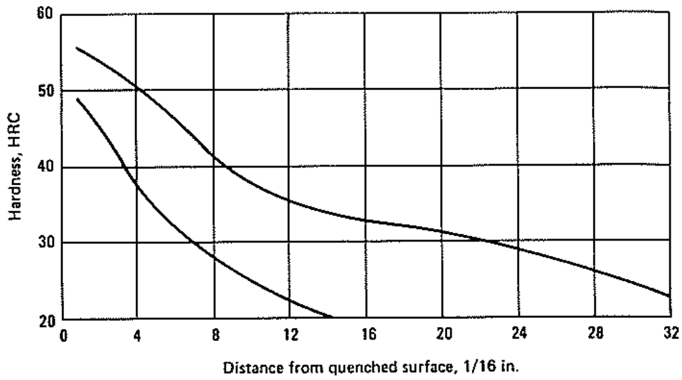
- Forge
- Normalize
- Anneal (preferably spheroidize)
- Rough machine
- Austenitize and quench
- Temper
- Finish machine

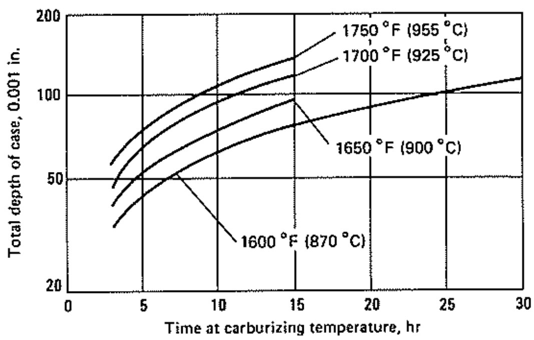


5130: Hardness vs Tempering Temperature. Normalized at 900 °C (1650 °F), quenched from 870 °C (1600 °F) in water, tempered in 56 °C (100 °F) intervals in 13.7 mm (0.540 in.) rounds. Tested in 12.8 mm (0.505 in.) rounds. Source: Republic Steel

5130H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min
1	1.58	56	49	13	20.54	35	21
2	3.16	55	46	14	22.12	34	20
3	4.74	53	42	15	23.70	34	...
4	6.32	51	39	16	25.28	33	...
5	7.90	49	35	18	28.44	32	...
6	9.48	47	32	20	31.60	31	...
7	11.06	45	30	22	34.76	30	...
8	12.64	42	28	24	37.92	29	...
9	14.22	40	26	26	41.08	27	...
10	15.80	38	25	28	44.24	26	...
11	17.38	37	23	30	47.40	25	...
12	18.96	36	22	32	50.56	24	...



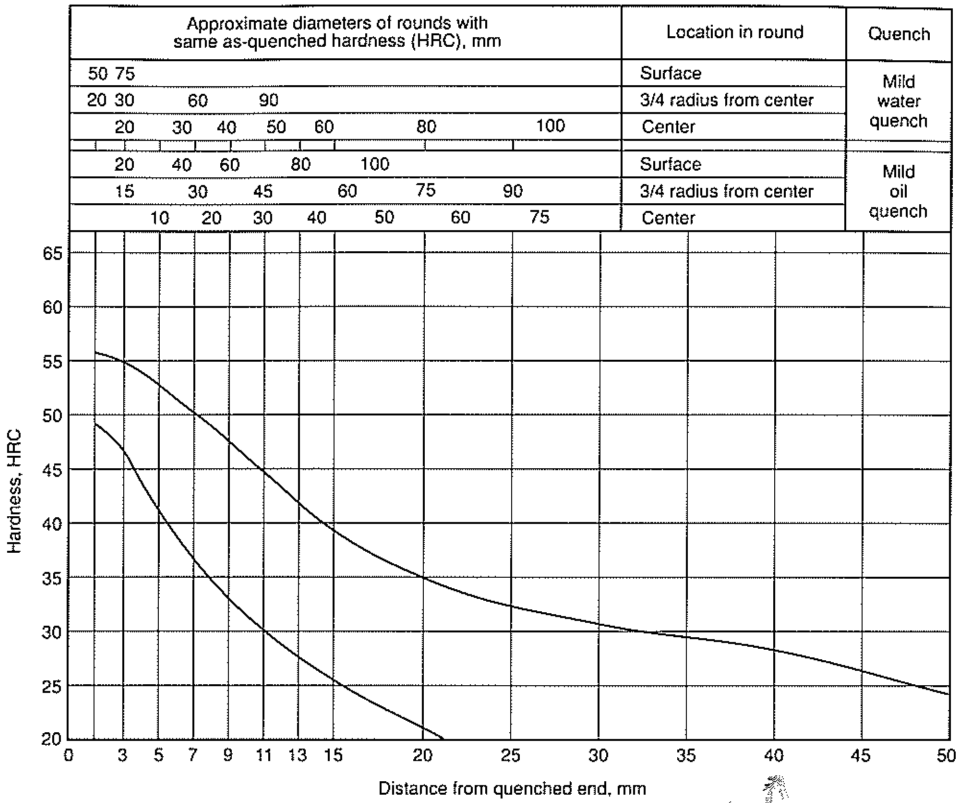


5130: Depth of Case vs Time and Temperature. 57.2 mm (2.25 in.) outside diameter by 165 mm (6.5 in.), oil quenched. Carburized at temperatures indicated

5130H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 900 °C (1650 °F). Austenitize: 870 °C (1600 °F)

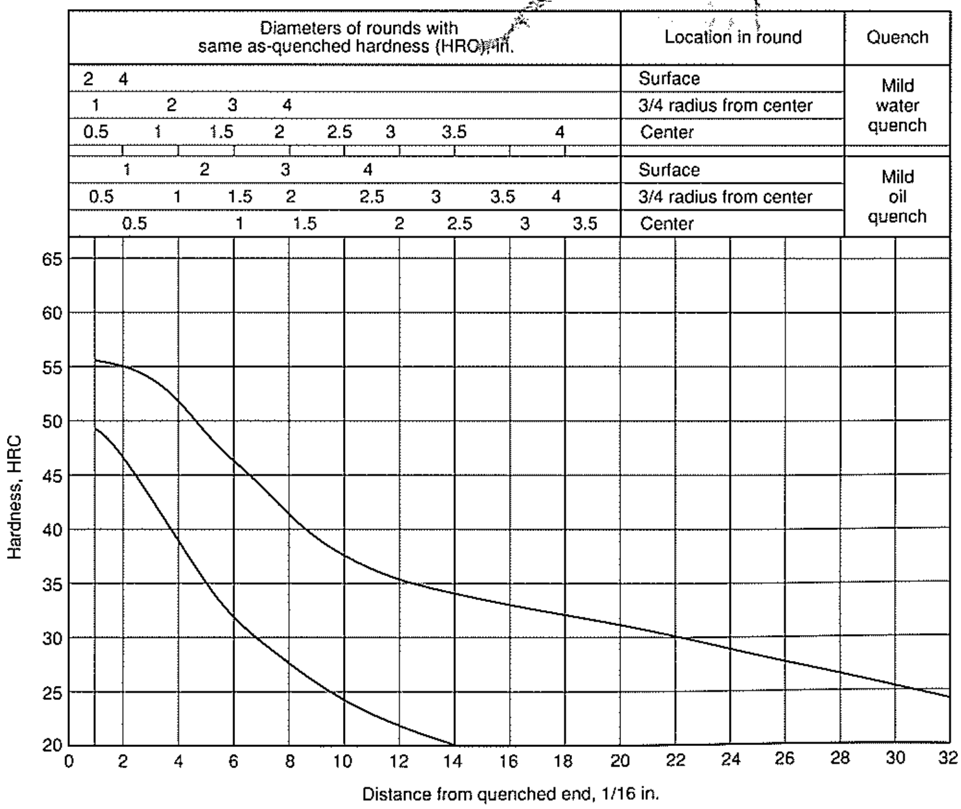
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	56	49
3	55	46
5	53	42
7	51	37
9	48	33
11	45	30
13	42	27
15	39	25
20	35	21
25	33	...
30	31	...
35	30	...
40	28	...
45	26	...
50	24	...



Hardness limits for specification purposes

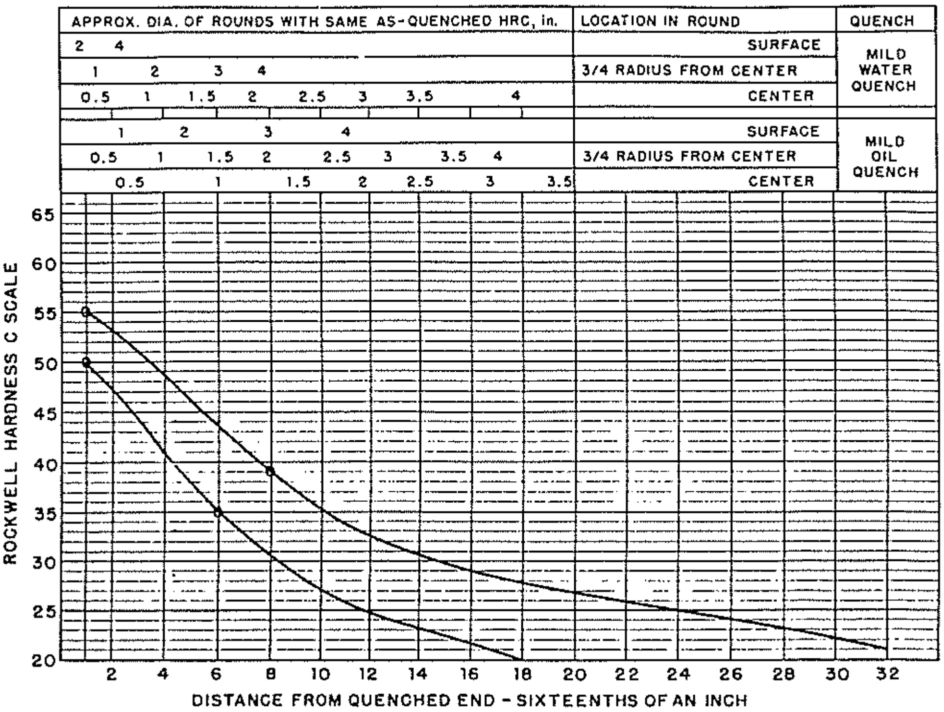
J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	56	49
2	55	46
3	53	42
4	51	39
5	49	35
6	47	32
7	45	30
8	42	28
9	40	26
10	38	25
11	37	23
12	36	22
13	35	21
14	34	20
15	34	...
16	33	...
18	32	...
20	31	...
22	30	...
24	29	...
26	27	...
28	26	...
30	25	...
32	24	...



5130RH: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 900 °C (1650 °F). Austenitize: 870 °C (1600 °F)

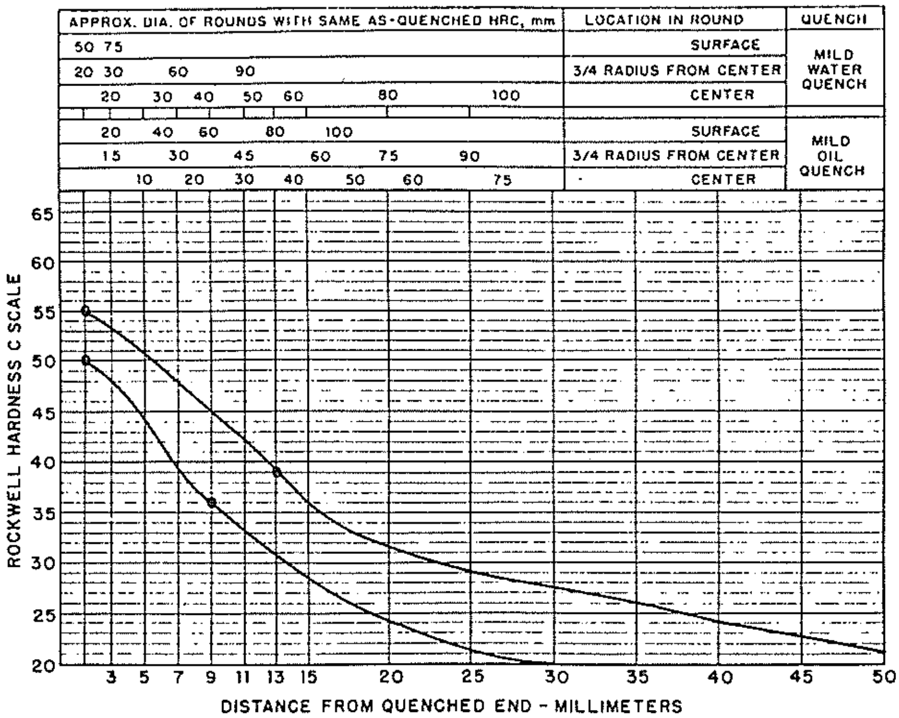
Hardness limits for specification purposes

J distance, $\frac{1}{16}$ in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	55	50
2	53	47
3	51	44
4	49	41
5	46	37
6	44	35
7	42	33
8	39	31
9	37	29
10	35	27
11	34	26
12	33	25
13	32	24
14	31	23
15	30	22
16	29	21
18	28	20
20	27	...
22	26	...
24	25	...
26	24	...
28	23	...
30	22	...
32	21	...



Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	55	50
3	53	47
5	51	44
7	48	39
9	45	36
11	42	33
13	39	31
15	36	28
20	32	24
25	29	21
30	28	20
35	26	...
40	24	...
45	23	...
50	21	...



5132, 5132H

Chemical Composition. **5132. AISI and UNS:** 0.30 to 0.35 C, 0.60 to 0.80 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.75 to 1.00 Cr. **UNS H51320 and SAE/AISI 5132H:** 0.29 to 0.35 C, 0.50 to 0.90 Mn, 0.15 to 0.35 Si, 0.65 to 1.10 Cr

Similar Steels (U.S. and/or Foreign). **5132.** UNS G51320; ASTM A322, A331, A505, A519; SAE J404, J412, J770; (Ger.) DIN 1.7033; (Fr.) AFNOR 32 C 4; (Ital.) UNI 34 Cr 4 KB; (Jap.) JIS SCr 2 H, SCr 2; (U.K.) B.S. 530 A 32, 530 H 32. **5132H.** UNS H51320; ASTM A304; SAE J1268; (Ger.) DIN 1.7034; (Fr.) AFNOR 38 C 4; (Ital.) UNI 38 Cr 4 KB; (Jap.) JIS SCr 3 H; (U.K.) B.S. 530 A 36, 530 H 36, Type 3

Characteristics. Varies only slightly in composition from 5130H. General characteristics are essentially the same as those for 5130H. The slightly higher carbon range of 5132H raises the maximum as-quenched hardness to approximately 48 to 55 HRC, although the hardenability of 5132H can be slightly less than that of 5130H because of the possibility of a lower chromium content. This grade can be welded, but alloy steel welding practice is mandatory

Forging. Heat to 1230 °C (2250 °F) maximum. Do not forge after temperature of forging stock drops below approximately 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F). Cool in air

Annealing. For a predominately pearlitic structure, heat to 845 °C (1555 °F), cool rapidly to 755 °C (1390 °F), then cool to 670 °C (1240 °F), at a rate not to exceed 11 °C (20 °F) per h; or heat to 845 °C (1555 °F), cool rapidly to 675 °C (1245 °F), and hold for 6 h. For a largely spheroidized structure, heat to 790 °C (1455 °F), cool rapidly to 690 °C (1275 °F), and hold for 8 h

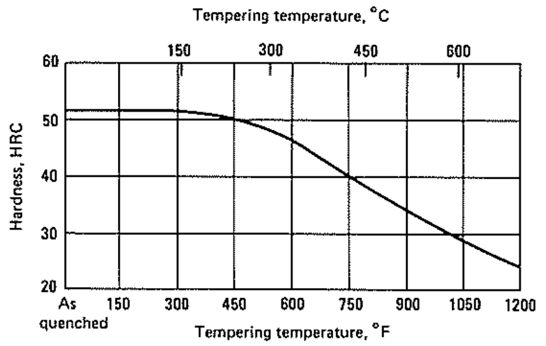
Hardening. Austenitize at 855 °C (1570 °F), and quench in oil. Ion nitriding and gas nitriding are suitable processes

Tempering. Reheat after quenching to the temperature that will result in the desired hardness

Recommended Processing Sequence

- Forge
- Normalize
- Anneal (preferably spheroidize)
- Rough machine
- Austenitize and quench
- Temper
- Finish machine

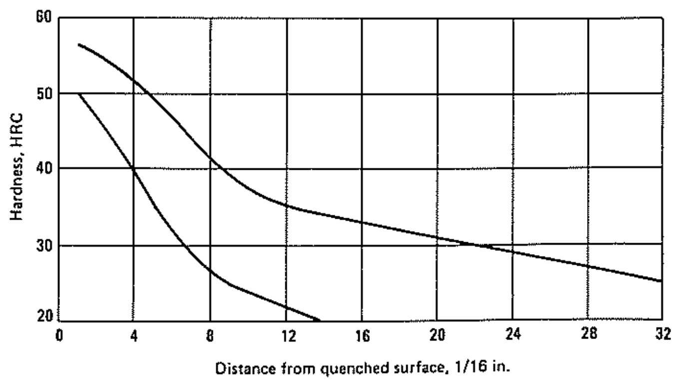
5132, 5132H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure



5132: Microstructure. Nital, 1650×. Steel forging, austenitized at 845 °C (1555 °F) and water quenched. Some blocky ferrite (light areas) and bainite (dark, feathery constituent) in a matrix of martensite

5132H: End-Quench Hardenability

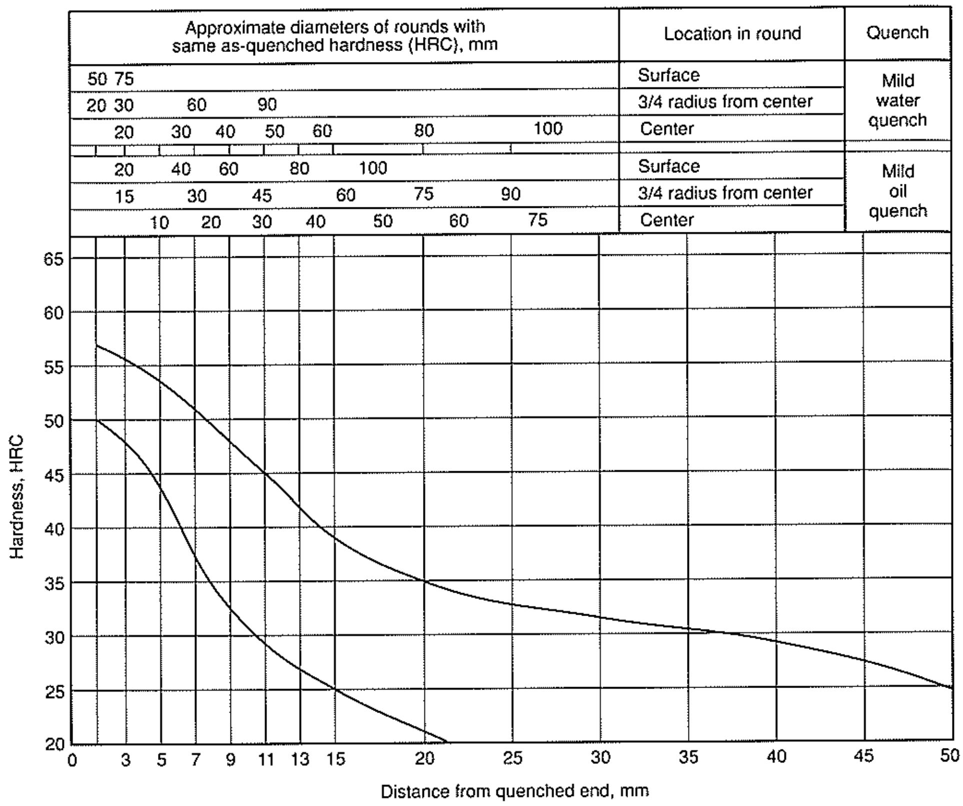
Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min
1	1.58	57	50	13	20.54	35	21
2	3.16	56	47	14	22.12	34	20
3	4.74	54	43	15	23.70	34	...
4	6.32	52	40	16	25.28	33	...
5	7.90	50	35	18	28.44	32	...
6	9.48	48	32	20	31.60	31	...
7	11.06	45	29	22	34.76	30	...
8	12.64	42	27	24	37.92	29	...
9	14.22	40	25	26	41.08	28	...
10	15.80	38	24	28	44.24	27	...
11	17.38	37	23	30	47.40	26	...
12	18.96	36	22	32	50.56	25	...



5132H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1650 °F). Austenitize: 845 °C (1555 °F)

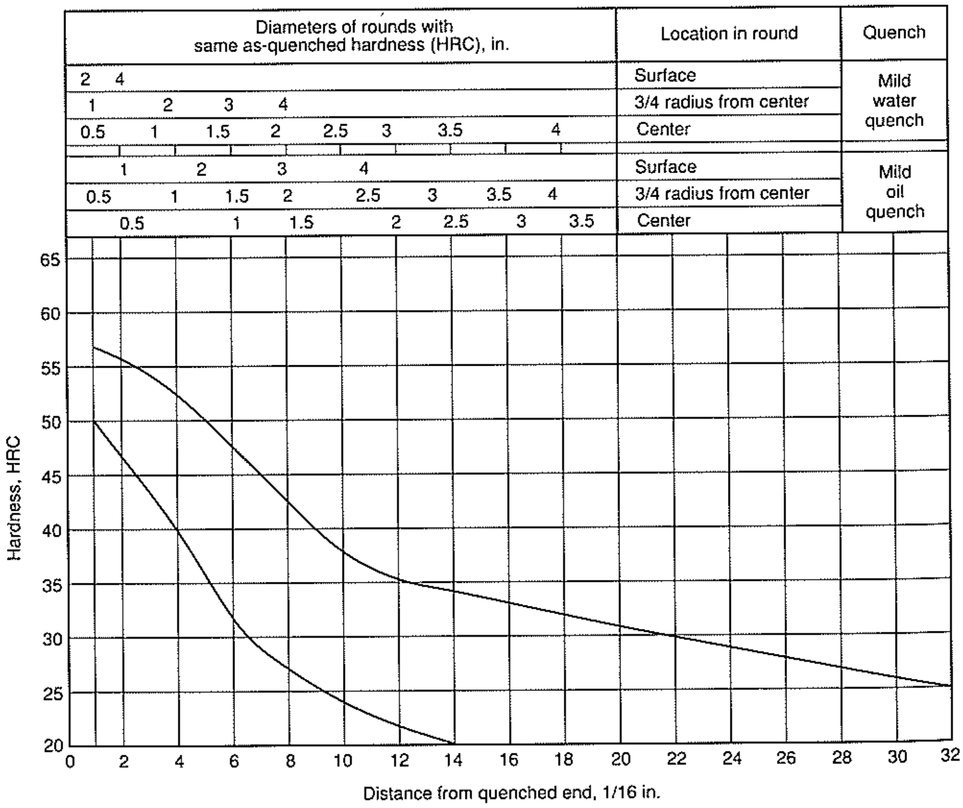
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	57	50
3	56	47
5	54	43
7	52	38
9	49	33
11	45	29
13	42	26
15	39	25
20	35	21
25	33	...
30	32	...
35	31	...
40	29	...
45	27	...
50	25	...



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	57	50
2	56	47
3	54	43
4	52	40
5	50	35
6	48	32
7	46	29
8	42	27
9	40	25
10	38	24
11	37	23
12	36	22
13	35	21
14	34	20
15	34	...
16	33	...
18	32	...
20	31	...
22	30	...
24	29	...
26	28	...
28	27	...
30	26	...
32	25	...



5135, 5135H

Chemical Composition. **5135. AISI and UNS:** 0.33 to 0.38 C, 0.60 to 0.80 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.80 to 1.05 Cr. **UNS H51350 and SAE/AISI 5135H:** 0.32 to 0.38 C, 0.50 to 0.90 Mn, 0.15 to 0.35 Si, 0.70 to 1.15 Cr

Similar Steels (U.S. and/or Foreign). **5135.** UNS G51350; ASTM A322, A331, A519; SAE J404, J412, J770; (Ger.) DIN 1.7034; (Fr.) AFNOR 38 C 4; (Ital.) UNI 38 Cr 4 KB; (Jap.) JIS SCr 3 H; (U.K.) B.S. 530 A 36, 530 H 3. **5135H.** UNS H51350; ASTM A304; SAE J1268; (Ger.) DIN 1.7035; (Fr.) AFNOR 42 C 4; (Ital.) UNI 41 Cr 4 KB, 40 Cr 4; (Jap.) JIS SCr 4 H; (U.K.) B.S. 530 A 40, 530 H 40, 530 M 40, 2 S 117

Characteristics. A low-alloy version of the carbon steels 1035 and 1038H. Because of the chromium addition, hardenability of 5135H is considerably greater than for 1038H. When fully quenched, an as-quenched hardness of approximately 50 to 56 HRC can be expected. Can be welded, but is susceptible to weld cracking

Forging. Heat to 1230 °C (2250 °F) maximum. Do not forge after temperature of forging stock drops below approximately 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

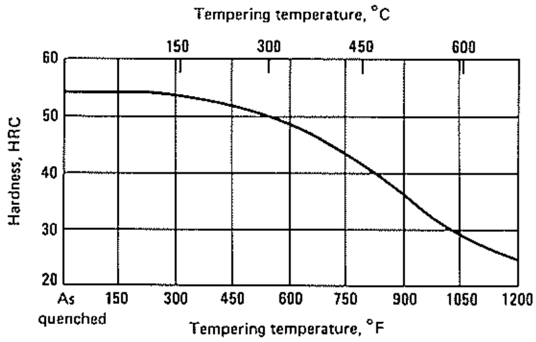
Annealing. For a predominately pearlitic structure, heat to 830 °C (1525 °F), cool rapidly to 740 °C (1365 °F), then cool to 670 °C (1240 °F), at a rate not to exceed 11 °C (20 °F) per h; or heat to 830 °C (1525 °F), cool rapidly to 675 °C (1245 °F), and hold for 6 h. For a predominately spheroidized structure, heat to 750 °C (1380 °F), cool rapidly to 690 °C (1275 °F), and hold for 8 h

Hardening. Austenitize at 845 °C (1555 °F), and quench in oil. Ion nitriding and gas nitriding are suitable processes

Tempering. After quenching, reheat to the temperature required for obtaining the desired hardness

Recommended Processing Sequence

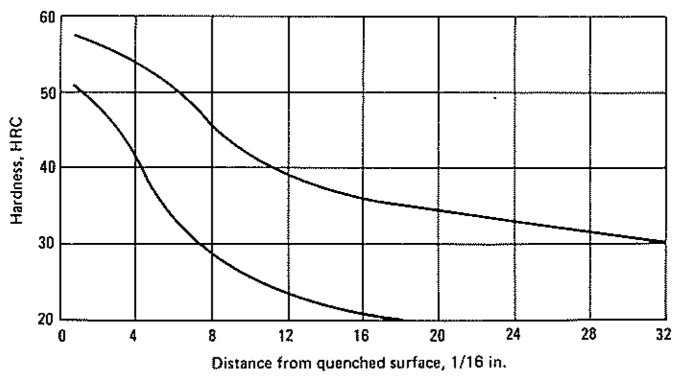
- Forge
- Normalize
- Anneal (preferably spheroidize)
- Rough machine
- Austenitize and quench
- Temper
- Finish machine



5135, 5135H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

5135H: End-Quench Hardenability

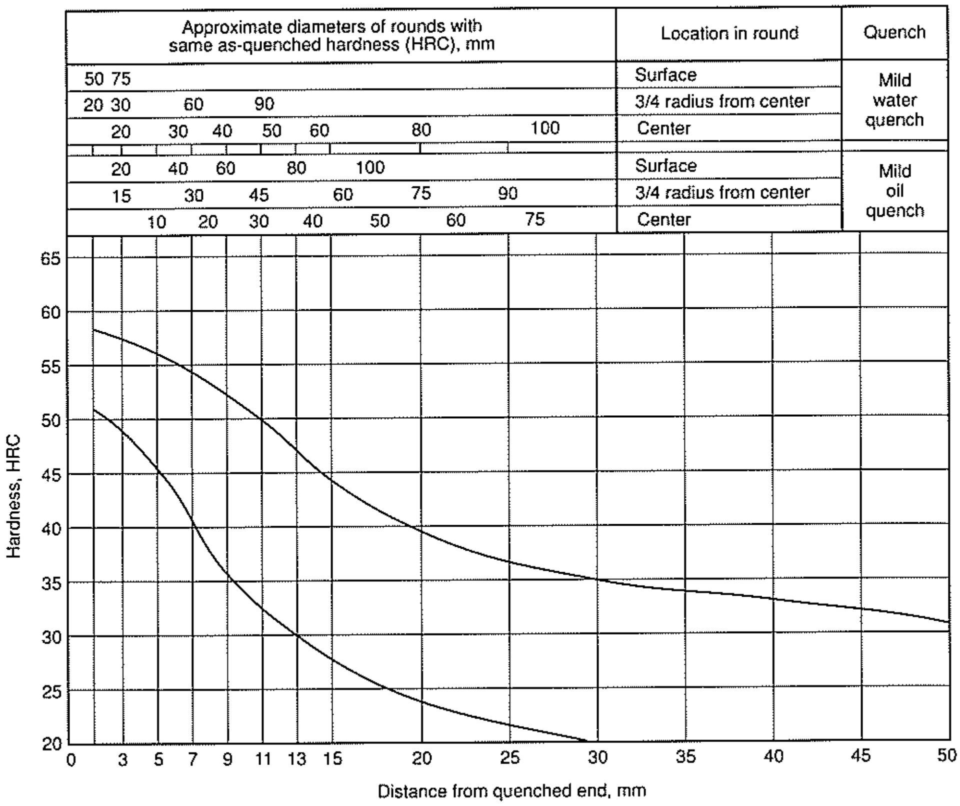
Distance from quenched surface		Hardness, HRC		Distance from quenched surface		Hardness, HRC	
1/16 in.	mm	max	min	1/16 in.	mm	max	min
1	1.58	58	51	13	20.54	39	23
2	3.16	57	49	14	22.12	38	22
3	4.74	56	47	15	23.70	37	21
4	6.32	55	43	16	25.28	37	21
5	7.90	54	38	18	28.44	36	20
6	9.48	52	35	20	31.60	35	...
7	11.06	50	32	22	34.76	34	...
8	12.64	47	30	24	37.92	33	...
9	14.22	45	28	26	41.08	32	...
10	15.80	43	27	28	44.24	32	...
11	17.38	41	25	30	47.40	31	...
12	18.96	40	24	32	50.56	30	...



5135H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1650 °F). Austenitize: 845 °C (1555 °F)

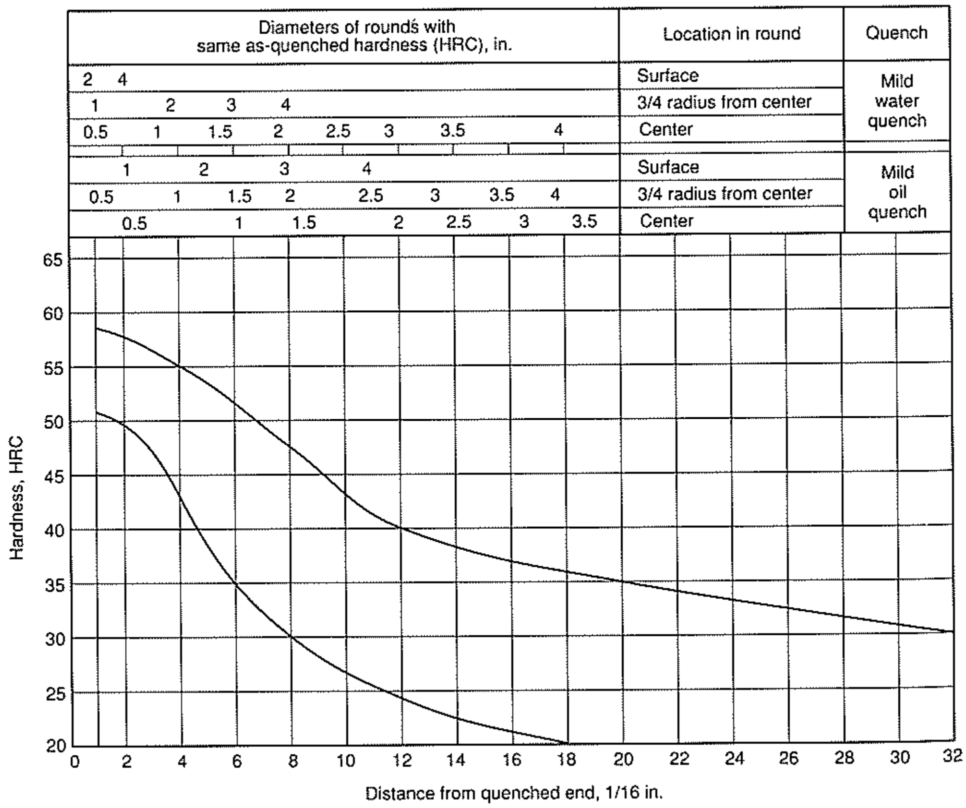
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	58	51
3	58	49
5	56	46
7	54	41
9	53	36
11	50	32
13	47	30
15	44	27
20	40	23
25	37	21
30	35	...
35	34	...
40	33	...
45	32	...
50	31	...



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	58	51
2	57	49
3	56	47
4	55	43
5	54	38
6	52	35
7	50	32
8	47	30
9	45	28
10	43	27
11	41	25
12	40	24
13	39	23
14	38	22
15	37	21
16	37	21
18	36	20
20	35	...
22	34	...
24	33	...
26	32	...
28	32	...
30	31	...
32	30	...



5140, 5140H, 5140RH

Chemical Composition. **5140. AISI and UNS:** 0.38 to 0.43 C, 0.70 to 0.90 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.70 to 0.90 Cr. **UNS H51400 and SAE/AISI 5140H:** 0.37 to 0.44 C, 0.60 to 1.00 Mn, 0.15 to 0.35 Si, 0.60 to 1.00 Cr. **SAE 5140RH:** 0.38 to 0.43 C, 0.70 to 0.90 Mn, 0.15 to 0.35 Si, 0.70 to 0.90 Cr

Similar Steels (U.S. and/or Foreign). **5140.** UNS G51400; ASTM A322, A331, A505, A519; SAE J404, J412, J770; (Ger.) DIN 1.7035; (Fr.) AFNOR 42 C 4; (Ital.) UNI 40 Cr 4, 41 Cr 4 KB; (Jap.) JIS SCr 4 H; (U.K.) B.S. 530 A 40, 530 H 40, 530 M 40, 2 S 117. **5140H.** UNS H51400; ASTM A304, A914; SAE J1268, J1868; (Ger.) DIN 1.7006; (Fr.) AFNOR 42 C 2, 45 C 2

Characteristics. The characteristics described for 5135H generally apply for 5140H. Because the carbon range is higher, slightly higher as-quenched hardness of approximately 51 to 57 HRC can be expected. The possibility of a slightly lower chromium content for 5140H makes no significant difference in hardenability. This grade can be welded, but is susceptible to weld cracking

Forging. Heat to 1230 °C (2250 °F) maximum. Do not forge after temperature of forging stock drops below approximately 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

Annealing. For a predominately pearlitic structure, heat to 830 °C (1525 °F), cool rapidly to 740 °C (1365 °F), then cool to 670 °C (1240 °F), at a rate not to exceed 11 °C (20 °F) per h; or heat to 830 °C (1525 °F), cool rapidly to 675 °C (1245 °F), and hold for 6 h. For a spheroidized structure, heat to 750 °C (1380 °F), cool rapidly to 690 °C (1275 °F), and hold for 8 h

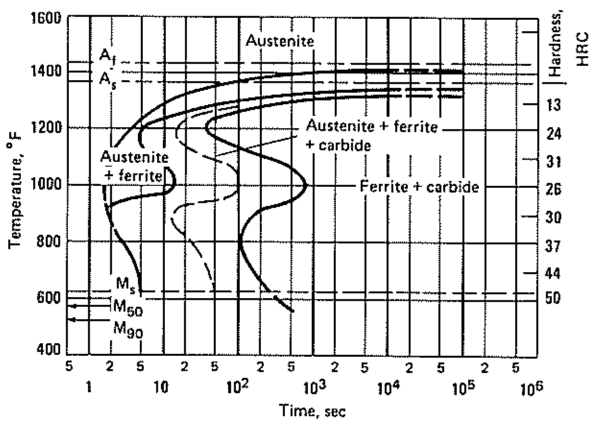
Hardening. Austenitize at 845 °C (1555 °F), and quench in oil. Ion nitriding, gas nitriding, carbonitriding, austempering and martempering are alternative processes

Tempering. After quenching, reheat to the temperature required for obtaining the desired hardness

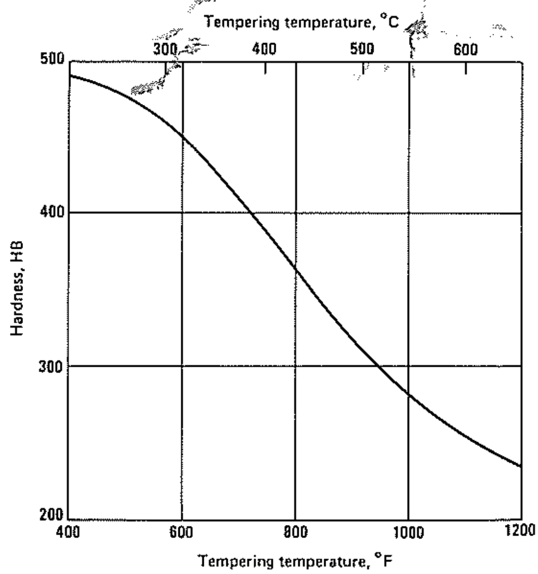
Recommended Processing Sequence

- Forge
- Normalize
- Anneal (preferably spheroidize)
- Rough machine
- Austenitize and quench
- Temper
- Finish machine

5140: Isothermal Transformation Diagram. Composition: 0.42 C, 0.68 Mn, 0.93 Cr. Austenitized at 845 °C (1555 °F). Grain size: 6 to 7

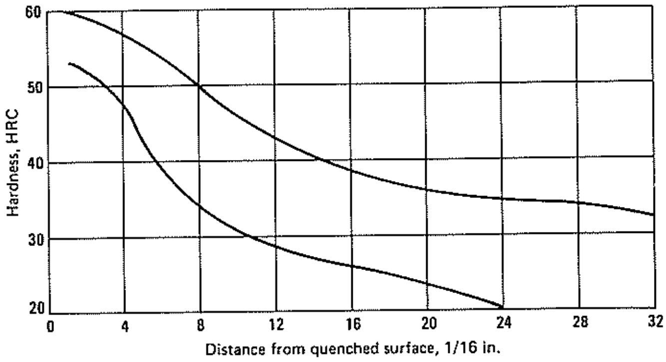


5140: Hardness vs Tempering Temperature. Normalized at 870 °C (1600 °F), quenched from 845 °C (1555 °F) in oil, tempered in 56 °C (100 °F) intervals in 13.8 mm (0.545 in.) rounds. Tested in 12.8 mm (0.505 in.) rounds. Source: Republic Steel

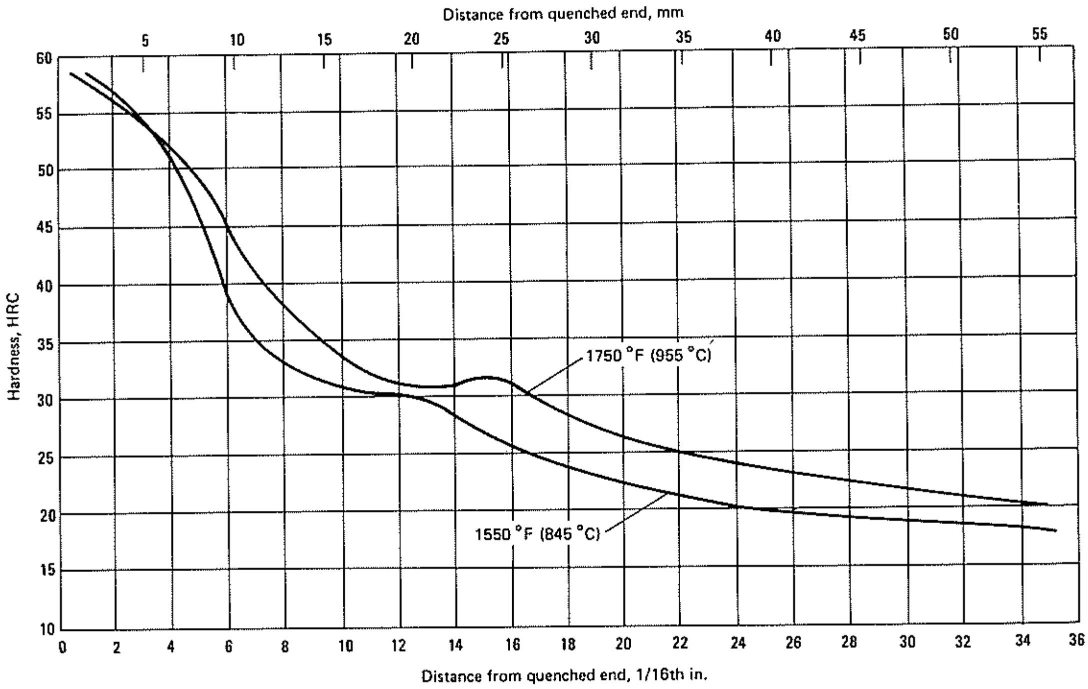


5140: End-Quench Hardenability

Distance from quenched surface ¹⁄₁₆ in.	mm	Hardness, HRC max	min	Distance from quenched surface ¹⁄₁₆ in.	mm	Hardness, HRC max	min
1	1.58	60	53	13	20.54	42	27
2	3.16	59	52	14	22.12	40	27
3	4.74	58	50	15	23.70	39	25
4	6.32	57	48	16	25.28	38	25
5	7.90	56	43	18	28.44	37	24
6	9.48	54	38	20	31.60	36	23
7	11.06	52	35	22	34.76	35	21
8	12.64	50	33	24	37.92	34	20
9	14.22	48	31	26	41.08	34	...
10	15.80	46	30	28	44.24	33	...
11	17.38	45	29	30	47.40	33	...
12	18.96	43	28	32	50.56	32	...



5140: End-Quench Hardenability. Composition: 0.43 C, 0.80 Mn, 0.010 P, 0.050 S, 0.26 Si, 0.02 Ni, 0.84 Cr, 0.02 Mo. Grain size: 7 to 8. Austenitized at 955 °C (1750 °F) as in production and austenitized at 845 °C (1555 °F) in accordance with hardenability specifications



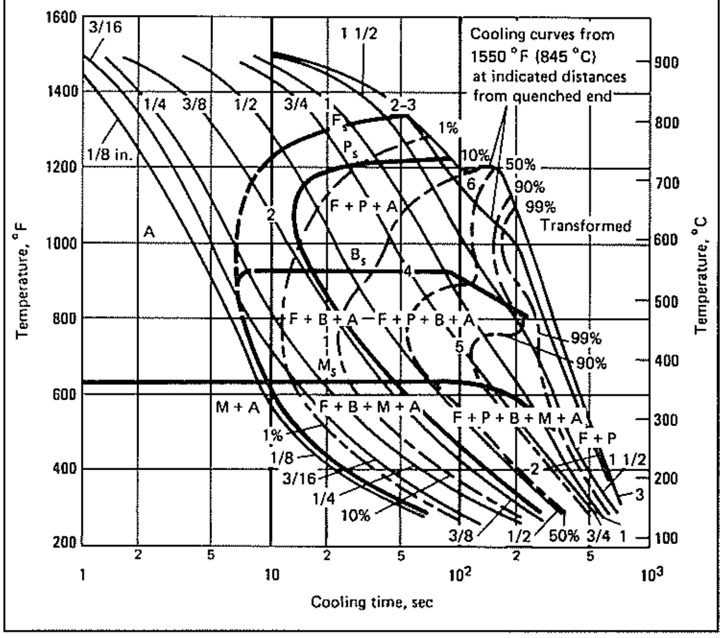
5140: As-Quenched Hardness (Oil)

Single heat results; grade: 0.38 to 0.43 C, 0.70 to 0.90 Mn, 0.20 to 0.35 Si, 0.70 to 0.90 Cr; ladle: 0.43 C, 0.78 Mn, 0.020 P, 0.033 S, 0.22 Si, 0.06 Ni, 0.74 Cr, 0.01 Mo; grain size 6 to 8

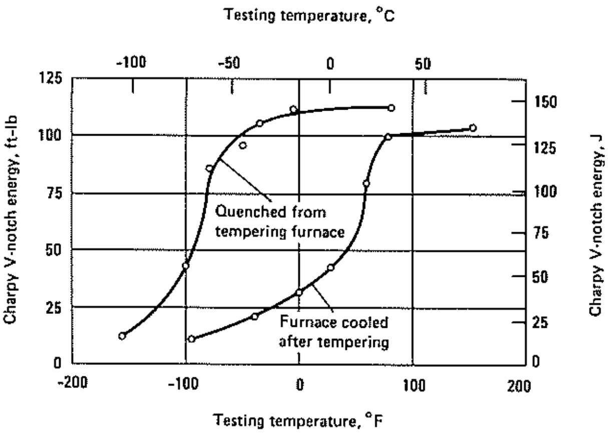
Size round in.	mm	Hardness, HRC Surface	½ radius	Center
½	13	57	57	56
1	25	53	48	45
2	51	46	38	35
4	102	35	29	20

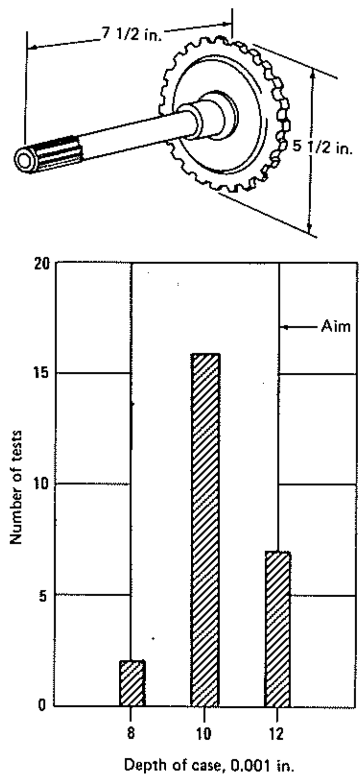
Source: Bethlehem Steel

5140: Continuous Cooling Curves. Composition: 0.42 C, 0.87 Mn, 0.25 Si, 0.89 Cr. Austenitized at 845 °C (1555 °F). Grain size: 8. Ac_3, 805 °C (1480 °F); Ac_1, 750 °C (1380 °F). A: austenite, F: ferrite, P: pearlite, B: bainite, M: martensite. Source: Bethlehem Steel



5140: Tempering Temperature vs Furnace Cooling and Water Quenching. Tempered at 620 °C (1150 °F) for 2 h. Source: Climax Molybdenum



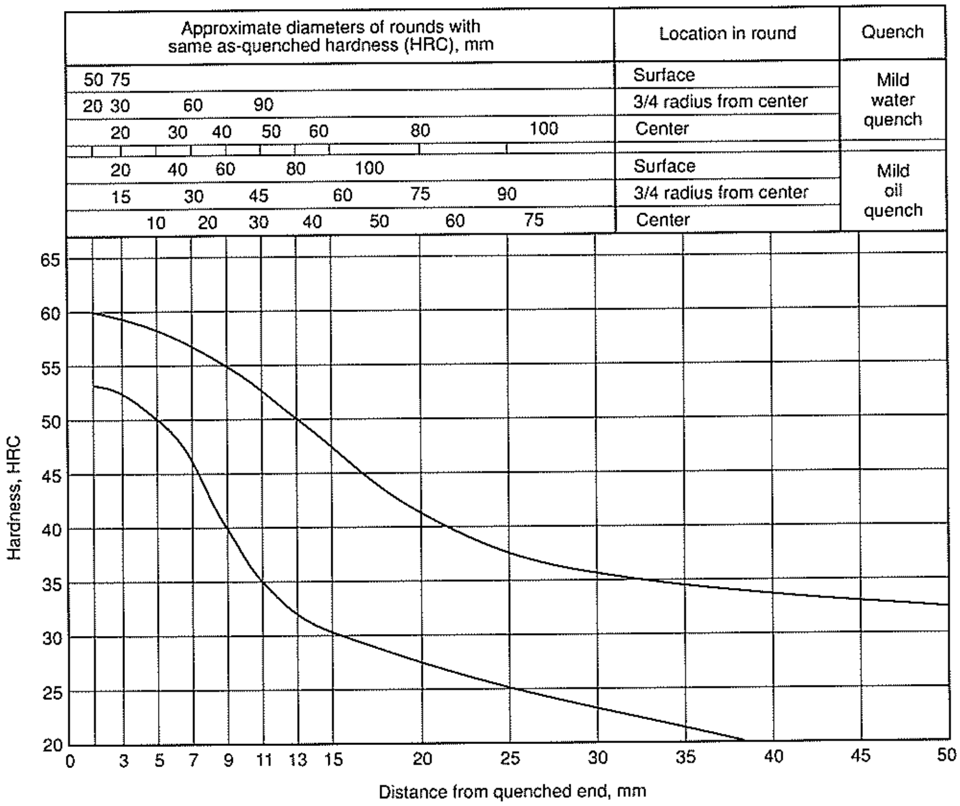


5140: Distribution of Case Depth after Carbonitriding. Carbonitrided at 775 °C (1425 °F) for 8 h and quenched in oil at 77 °C (170 °F). 25 tests on a steel pinion shaft

5140H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

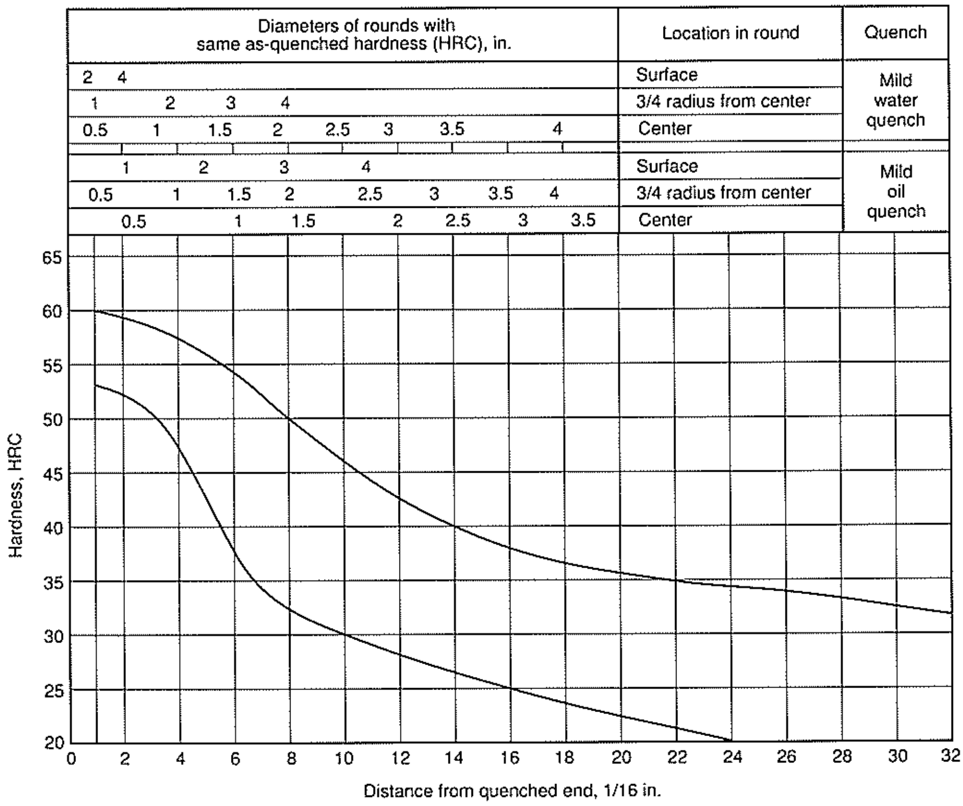
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	60	53
3	59	52
5	58	50
7	57	45
9	55	40
11	53	35
13	50	32
15	47	30
20	42	28
25	39	25
30	36	23
35	35	21
40	34	...
45	33	...
50	32	...



Hardness limits for specification purposes

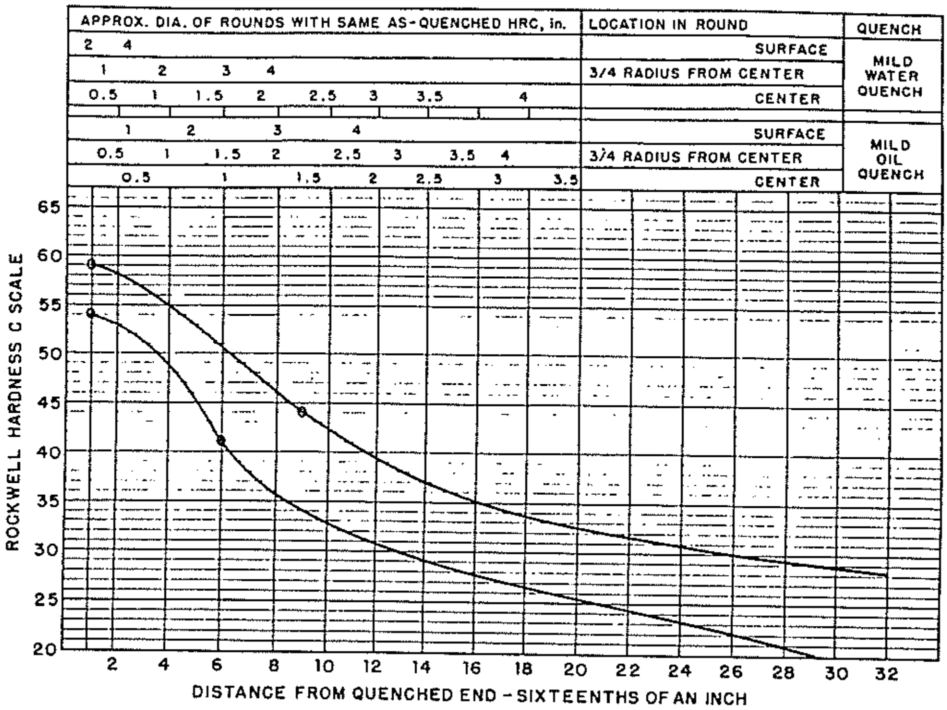
J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	60	53
2	59	52
3	58	50
4	57	48
5	56	43
6	54	38
7	52	35
8	50	33
9	48	31
10	46	30
11	45	29
12	43	28
13	42	27
14	40	27
15	39	26
16	38	25
18	37	24
20	36	23
22	35	21
24	34	20
26	34	...
28	33	...
30	33	...
32	32	...



5140RH: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

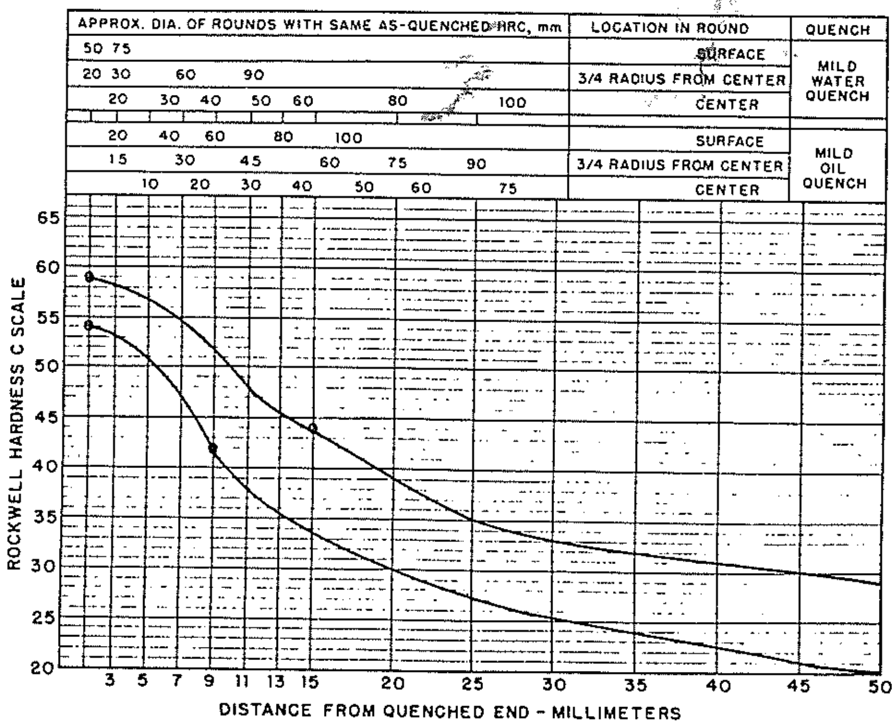
Hardness limits for specification purposes

J distance, $\frac{1}{16}$ in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	59	54
2	58	53
3	57	51
4	55	49
5	53	45
6	51	41
7	48	38
8	46	36
9	44	34
10	43	33
11	41	32
12	40	31
13	39	30
14	37	29
15	36	28
16	35	27
18	34	26
20	33	25
22	32	24
24	31	23
26	30	22
28	30	21
30	29	20
32	29	...



Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	59	54
3	58	53
5	57	51
7	55	47
9	52	42
11	48	38
13	46	36
15	44	34
20	39	30
25	35	27
30	33	25
35	32	24
40	31	22
45	30	21
50	29	20



ı147H

hemical Composition. UNS H51470 and SAE/AISI 5147H: 0.45 0.52 C, 0.60 to 1.05 Mn, 0.15 to 0.35 Si, 0.80 to 1.25 Cr

imilar Steels (U.S. and/or Foreign). This steel is no longer in ꓥE J404 or J412, but does appear in SAE J770, which is now J1397

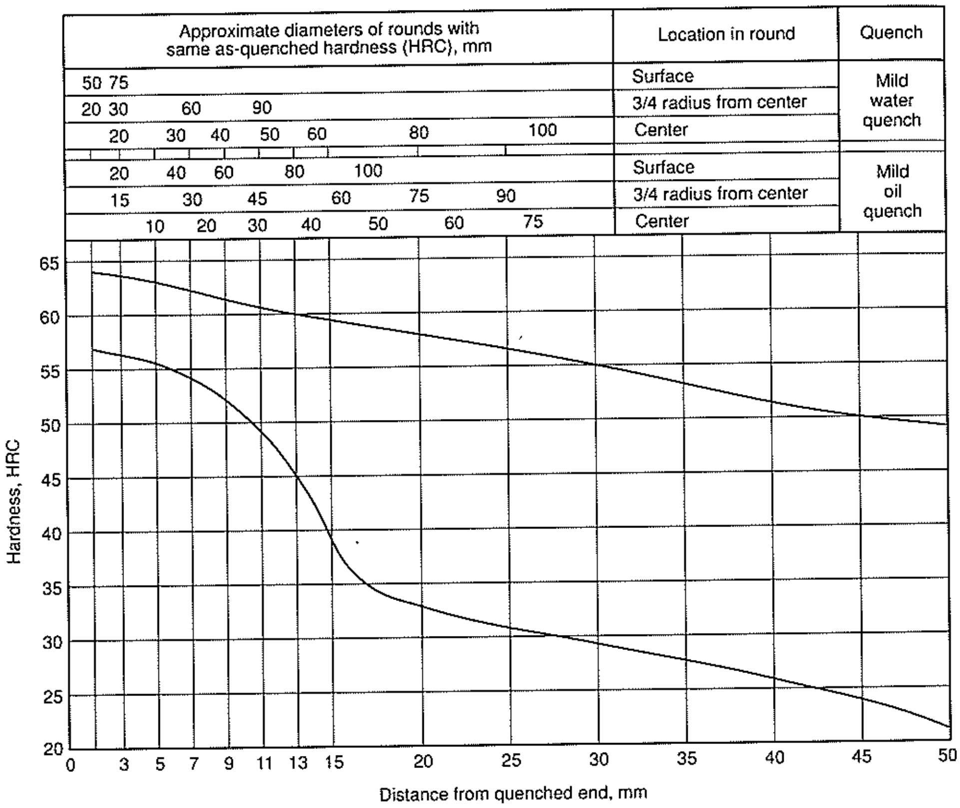
Recommended Heat Treating Practice

Hardening. Gas nitriding and ion nitriding are suitable processes

ı147H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

ıardness limits for specification ıurposes

distance, ım	Hardness, HRC Maximum	Minimum
.5	64	57
	64	56
	64	55
	63	53
	62	52
1	61	49
3	60	44
5	60	39
:0	58	33
:5	57	31
;0	55	29
;5	53	27
ł0	52	25
ł5	50	23
;0	49	21



(continued)

5147H: Hardenability Curves. (continued) Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	64	57
2	64	56
3	63	55
4	62	54
5	62	53
6	61	52
7	61	49
8	60	45
9	60	40
10	59	37
11	59	35
12	58	34
13	58	33
14	57	32
15	57	32
16	56	31
18	55	30
20	54	29
22	53	27
24	52	26
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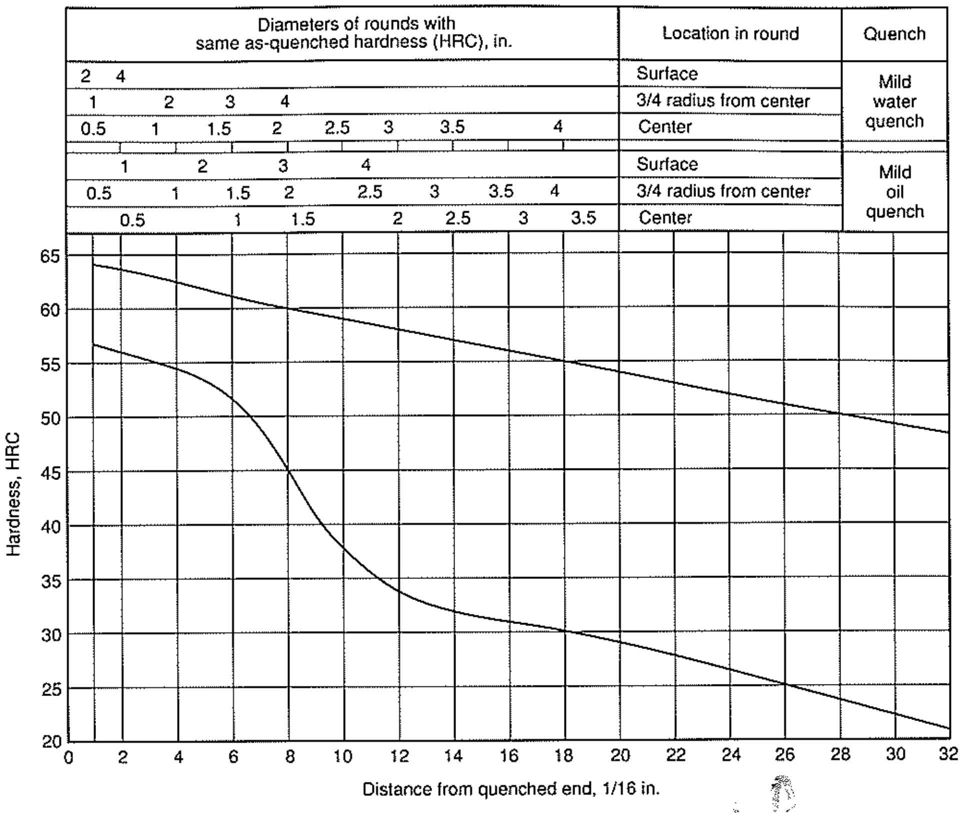
28	50	24
30	49	22
32	48	21



5150, 5150H

Chemical Composition. **5150. AISI and UNS:** 0.48 to 0.53 C, 0.70 to 0.90 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.70 to 0.90 Cr. **UNS H51500 and SAE/AISI 5150H:** 0.47 to 0.54 C, 0.60 to 1.00 Mn, 0.15 to 0.35 Si, 0.60 to 1.00 Cr

Similar Steels (U.S. and/or Foreign). **5150.** UNS G51500; ASTM A322, A331, A505, A519; SAE J404, J412, J770; (Ger.) DIN 1.7006; (Fr.) AFNOR 42 C 2, 45 C 2. **5150H.** UNS H51500; ASTM A304; SAE J1268

Characteristics. Has a borderline carbon content, between a medium-carbon and a high-carbon steel. When fully hardened, an as-quenched hardness of approximately 55 to 60 HRC is normal, slightly higher when the carbon is near the maximum of the allowable range. Hardenability is also considered as relatively high. Because of the high carbon content and the high hardenability, does not have good weldability

Forging. Heat to 1220 °C (2225 °F) maximum. Do not forge after temperature of forging stock drops below approximately 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

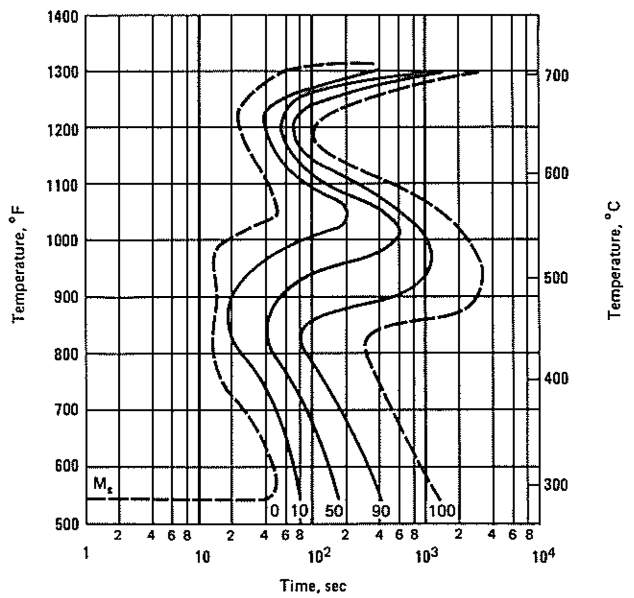
Annealing. For a predominately pearlitic structure, heat to 830 °C (1525 °F), cool rapidly to 705 °C (1300 °F), then cool to 650 °C (1200 °F), at a rate not to exceed 11 °C (20 °F) per h; or heat to 830 °C (1525 °F), cool rapidly to 675 °C (1245 °F), and hold for 6 h. For a predominately spheroidized structure, heat to 750 °C (1380 °F), cool rapidly to 705 °C (1300 °F), then cool to 650 °C (1200 °F), at a rate not to exceed 6 °C (10 °F) per h; or heat to 750 °C (1380 °F), cool rapidly to 675 °C (1245 °F), and hold for 10 h

Hardening. Austenitize at 830 °C (1525 °F), and quench in oil. Gas nitriding, fluidized bed nitriding, and ion nitriding are suitable processes

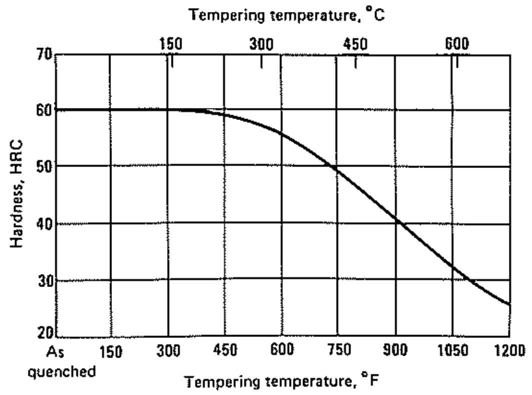
Tempering. After quenching, reheat to the temperature required to provide the desired hardness

Recommended Processing Sequence

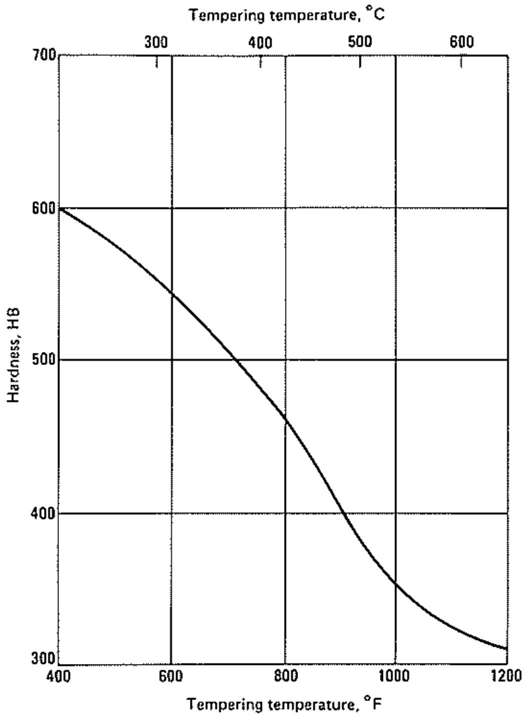
- Forge
- Normalize
- Anneal (preferably spheroidize)
- Rough machine
- Austenitize and quench
- Temper
- Finish machine



5150: Isothermal Transformation Diagram. Composition: 0.48 C, 0.86 Mn, 0.023 P, 0.021 S, 0.25 Si, 0.18 Ni, 0.98 Cr, 0.04 Mo, 0.09 Cu. Austenitized at 860 °C (1580 °F). Grain size 5 to 6



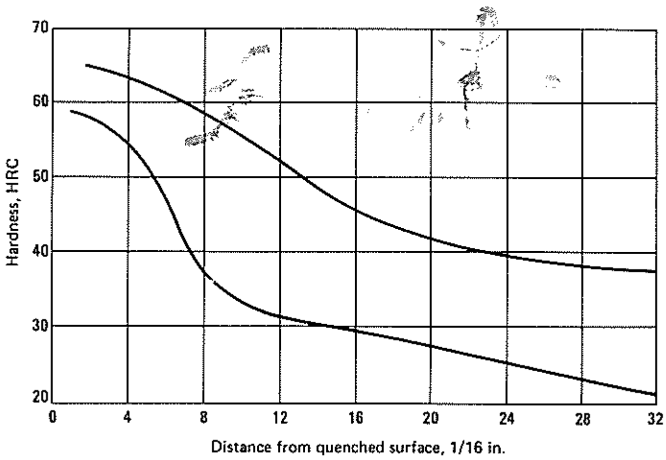
5150, 5150H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure



5150: Hardness vs Tempering Temperature. Normalized at 870 °C (1600 °F), quenched from 845 °C (1555 °F), tempered in 56 °C (100 °F) intervals in 13.7 mm (0.540 in.) rounds. Tested in 12.8 mm (0.505 in.) rounds. Source: Republic Steel

5150H: End-Quench Hardenability

Distance from quenched surface		Hardness, HRC		Distance from quenched surface		Hardness, HRC	
1/16 in.	mm	max	min	1/16 in.	mm	max	min
1	1.58	65	59	13	20.54	51	31
2	3.16	65	58	14	22.12	50	31
3	4.74	64	57	15	23.70	48	30
4	6.32	63	56	16	25.28	47	30
5	7.90	62	53	18	28.44	45	29
6	9.48	61	49	20	31.60	43	28
7	11.06	60	42	22	34.76	42	27
8	12.64	59	38	24	37.92	41	26
9	14.22	58	36	26	41.08	40	25
10	15.80	56	34	28	44.24	39	24
11	17.38	55	33	30	47.40	39	23
12	18.96	53	32	32	50.56	38	22



5150: As-Quenched Hardness (Oil)

Single heat results; grade: 0.48 to 0.53 C, 0.70 to 0.90 Mn, 0.20 to 0.35 Si, 0.70 to 0.90 Cr, ladle: 0.49 C, 0.75 Mn, 0.018 P, 0.018 S, 0.25 Si, 0.11 Ni, 0.80 Cr, 0.05 Mo; grain size 7 to 8

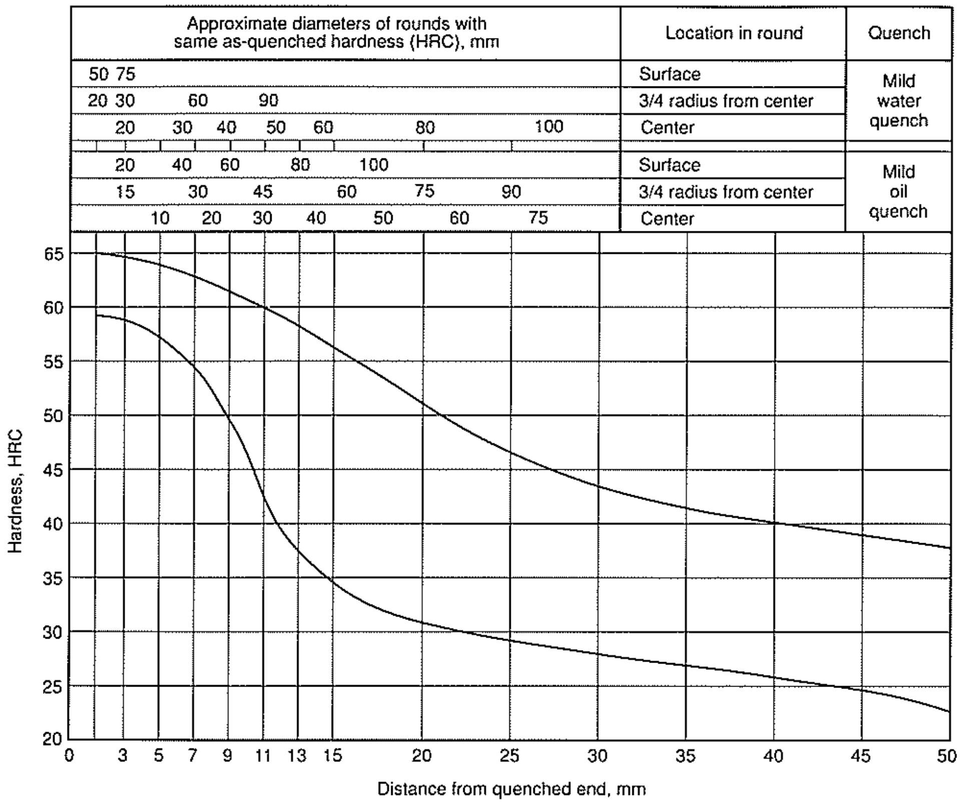
Size round		Hardness, HRC		
in.	mm	Surface	½ radius	Center
½	13	60	60	59
1	25	59	52	50
2	51	55	44	40
4	102	37	31	29

Source: Bethlehem Steel

5150H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

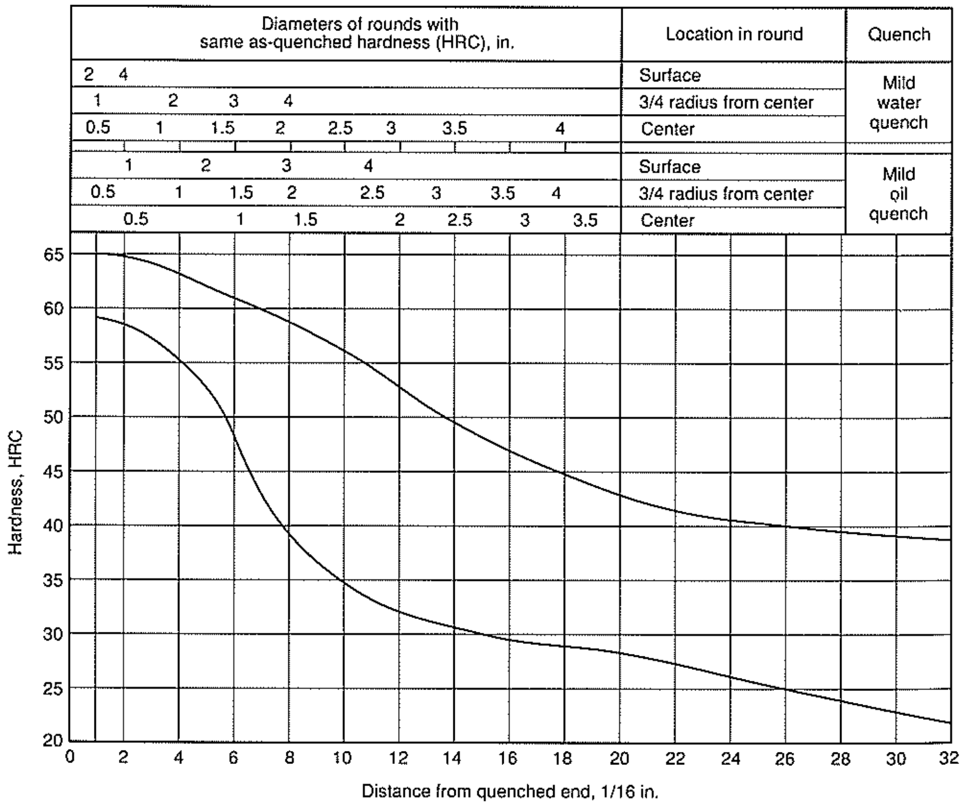
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	65	59
3	65	58
5	64	57
7	63	54
9	62	50
11	60	43
13	58	37
15	57	35
20	52	31
25	47	29
30	44	28
35	42	27
40	40	26
45	39	24
50	38	22



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	65	59
2	65	58
3	64	57
4	63	56
5	62	53
6	61	49
7	60	42
8	59	38
9	58	36
10	56	34
11	55	33
12	53	32
13	51	31
14	50	31
15	48	30
16	47	30
18	45	29
20	43	28
22	42	27
24	41	26
26	40	25
28	39	24
30	39	23
32	38	22



5155, 5155H

Chemical Composition. **5155. AISI and UNS:** 0.51 to 0.59 C, 0.70 to 0.90 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.70 to 0.90 Cr. **UNS H51550 and SAE/AISI 5155H:** 0.50 to 0.60 C, 0.60 to 1.00 Mn, 0.15 to 0.30 Si, 0.60 to 1.00 Cr

Similar Steels (U.S. and/or Foreign). **5155.** UNS G51550; ASTM A322, A331, A519; SAE J404, J412, J770; (Ger.) DIN 1.7176; (Fr.) AFNOR 55 C 3. **5155H.** UNS H51550; ASTM A304; SAE J1268; (Ger.) DIN 1.7176; (Fr.) AFNOR 55 C 3

Characteristics. In general, the characteristics of 5155H are the same as those discussed for 5150H. However, the slightly higher carbon range of 5155H makes a higher as-quenched hardness possible. 57 to 63 HRC is normal for fully quenched 5155H. Although the hardenability patterns of 5150H and 5155H are similar, the entire band is slightly higher for 5155H. Because of the high carbon content and the high hardenability, this grade does not have good weldability

Forging. Heat to 1220 °C (2225 °F) maximum. Do not forge after temperature of forging stock drops below approximately 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

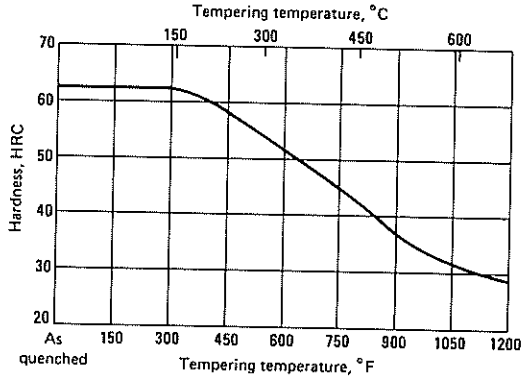
Annealing. For a predominately pearlitic structure, heat to 830 °C (1525 °F), cool rapidly to 705 °C (1300 °F), then cool to 650 °C (1200 °F), at a rate not to exceed 11 °C (20 °F) per h; or heat to 830 °C (1525 °F), cool rapidly to 675 °C (1245 °F), and hold for 6 h. For a predominately spheroidized structure, heat to 750 °C (1380 °F), cool rapidly to 705 °C (1300 °F), then cool to 650 °C (1200 °F), at a rate not to exceed 6 °C (10 °F) per h; or heat to 750 °C (1380 °F), cool rapidly to 675 °C (1245 °F), and hold for 10 h

Hardening. Austenitize at 830 °C (1525 °F), and quench in oil. Gas nitriding and ion nitriding are suitable processes

Tempering. After quenching, reheat to the temperature required to provide the desired hardness

Recommended Processing Sequence

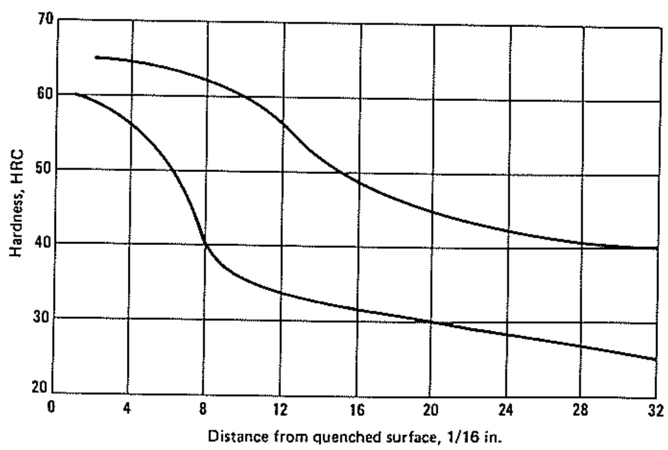
- Forge
- Normalize
- Anneal (preferably spheroidize)
- Rough machine
- Austenitize and quench
- Temper
- Finish machine



5155, 5155H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

5155H: End-Quench Hardenability

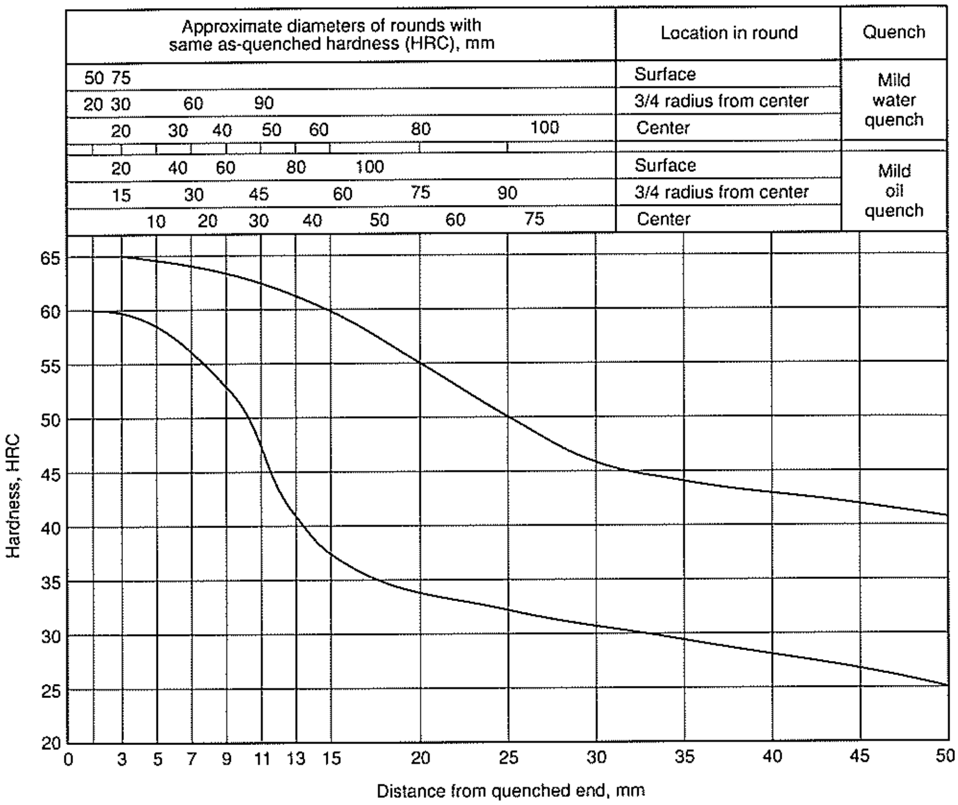
Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min
1	1.58	...	60	13	20.54	55	34
2	3.16	65	59	14	22.12	52	33
3	4.74	64	58	15	23.70	51	33
4	6.32	64	57	16	25.28	49	32
5	7.90	63	55	18	28.44	47	31
6	9.48	63	52	20	31.60	45	31
7	11.06	62	47	22	34.76	44	30
8	12.64	62	41	24	37.92	43	29
9	14.22	61	37	26	41.08	42	28
10	15.80	60	36	28	44.24	41	27
11	17.38	59	35	30	47.40	41	26
12	18.96	57	34	32	50.56	40	25



5155H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

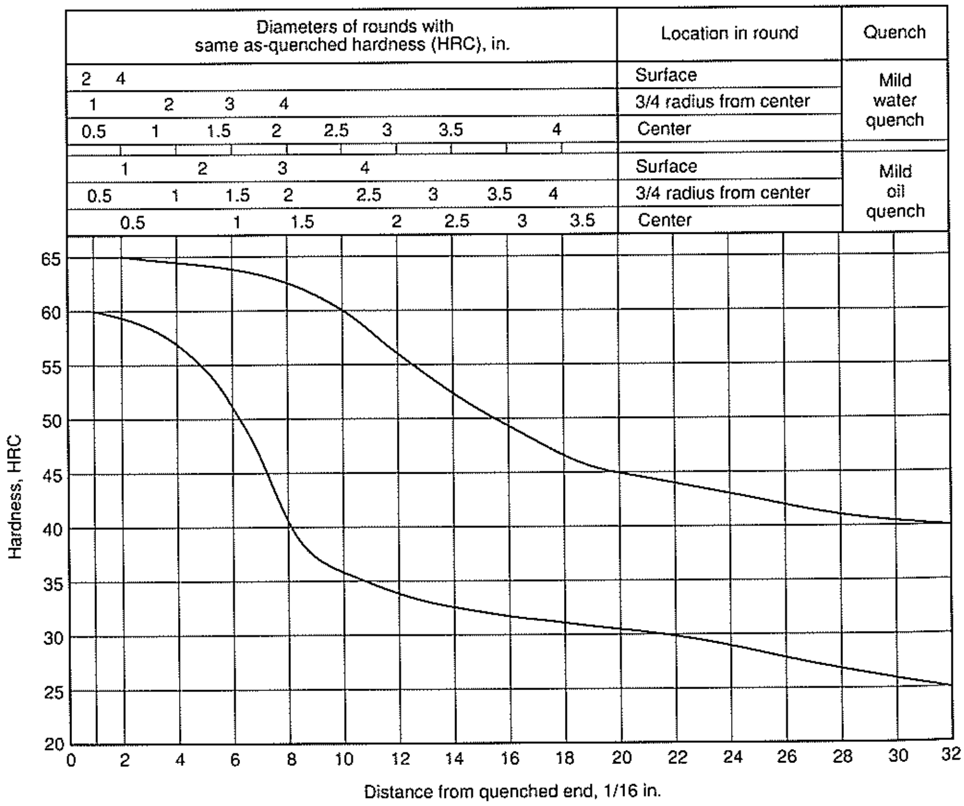
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Minimum
1.5	...	60
3	65	60
5	65	59
7	64	56
9	64	53
11	63	48
13	61	40
15	60	37
20	56	34
25	50	32
30	46	30
35	44	29
40	43	28
45	42	27
50	41	25



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Minimum
1	...	60
2	65	59
3	64	58
4	64	57
5	63	55
6	63	52
7	62	47
8	62	41
9	61	37
10	60	36
11	59	35
12	57	34
13	55	34
14	52	33
15	51	33
16	49	32
18	47	31
20	45	31
22	44	30
24	43	29
26	42	28
28	41	27
30	41	26
32	40	25



5160, 5160H, 5160RH

Chemical Composition. **5160. AISI and UNS:** 0.56 to 0.64 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.70 to 0.90 Cr. **UNS H51600 and SAE/AISI 5160H:** 0.55 to 0.65 C, 0.65 to 1.00 Mn, 0.15 to 0.35 Si, 0.60 to 1.00 Cr. **SAE 5160RH:** 0.56 to 0.64 C, 0.75 to 1.00 Mn, 0.15 to 0.35 Si, 0.70 to 0.90 Cr

Similar Steels (U.S. and/or Foreign). **5160.** UNS G51600; ASTM A322, A331, A505, A519; SAE J404, J412, J770. **5160H.** UNS H51600; ASTM A304, A914; SAE J1268, J1868

Characteristics. Definitely considered a high-carbon alloy steel. As-quenched hardness of 58 to 63 HRC is considered normal. Sometimes values higher than this range are obtained, depending on the precise carbon content. Hardenability is slightly higher than that of 5155H. Used for a variety of spring applications, notably flat springs. Often uses austempering as a method of heat treating

Forging. Heat to 1205 °C (2200 °F) maximum. Do not forge after temperature of forging stock drops below approximately 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

Annealing. For a predominately pearlitic structure, heat to 830 °C (1525 °F), cool rapidly to 705 °C (1300 °F), then cool to 650 °C (1200 °F), at a rate not to exceed 11 °C (20 °F) per h; or heat to 830 °C (1525 °F), cool rapidly to 675 °C (1245 °F), and hold for 6 h. For a predominately spheroidized structure, heat to 750 °C (1380 °F), cool rapidly to 705 °C (1300 °F), then cool to 650 °C (1200 °F), at a rate not to exceed 6 °C (10 °F) per h; or heat to 750 °C (1380 °F), cool rapidly to 675 °C (1245 °F), and hold for 10 h

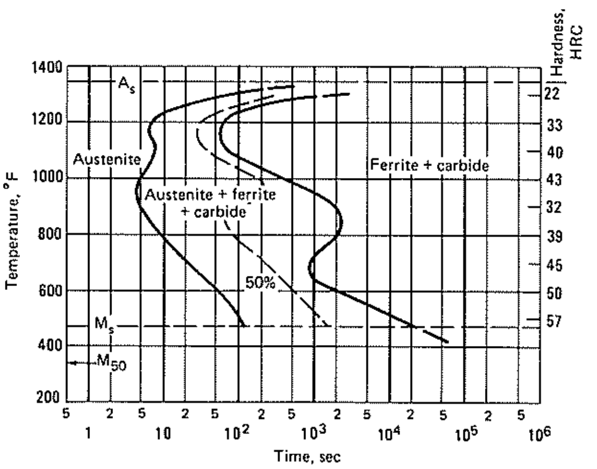
Hardening. Austenitize at 830 °C (1525 °F), and quench in oil or polymer. Gas nitriding and ion nitriding are suitable processes

Tempering. After quenching, reheat to the temperature required to provide the desired hardness

Austempering. Austenitize at 845 °C (1555 °F), quench in molten salt at 315 °C (600 °F), and hold for 1 h. Parts are cooled in air from 315 °C (600 °F) and need no tempering. A spring temper hardness within the range of approximately 46 to 52 HRC is obtained

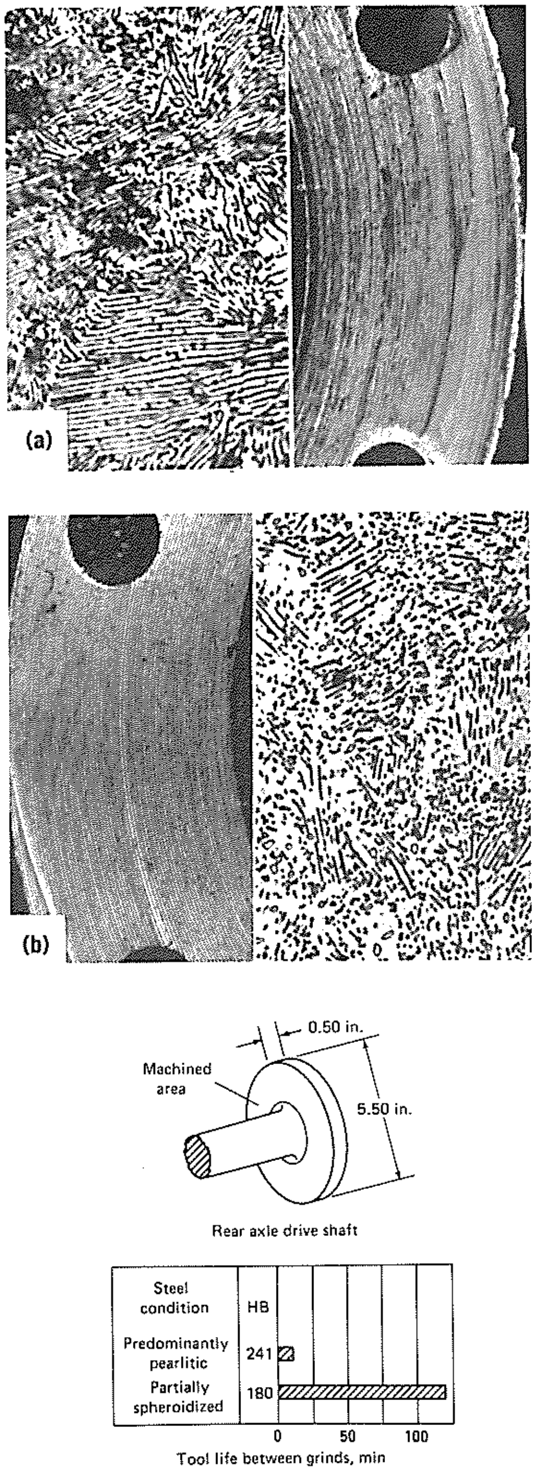
Recommended Processing Sequence

- Forge
- Normalize
- Anneal (preferably spheroidize)
- Rough machine
- Austenitize and quench (or austemper)
- Temper (or austemper)
- Finish machine

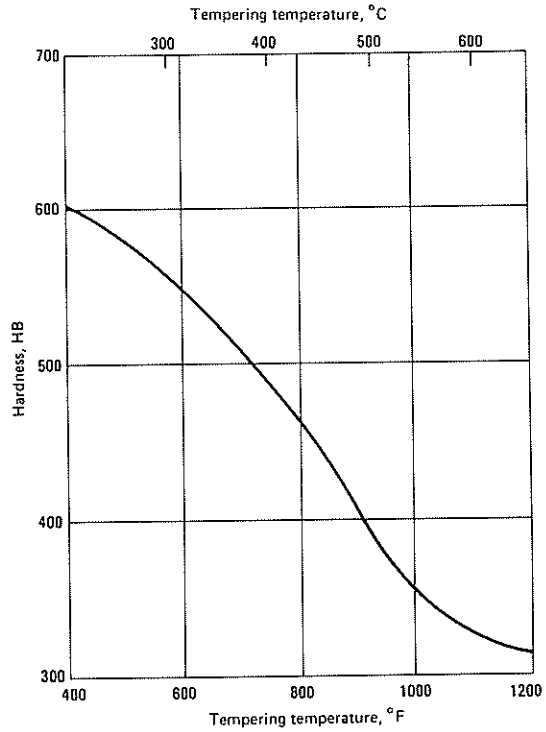


5160: Isothermal Transformation Diagram. Composition: 0.61 C, 0.94 Mn, 0.88 Cr, 0.22 Mo. Austenitized at 845 °C (1555 °F). Grain size 7

5160: Correlation of Annealing Practice with Surface Finish and Tool Life in Subsequent Machining. (a) Annealed (pearlitic) microstructure, 241 HB, and surface finish of flange after machining eight pieces. (b) Partially spheroidized microstructure, 180 HB, and surface finish of flange after machining 123 pieces



5160: Hardness vs Tempering Temperature. Normalized at 870 °C (1600 °F), quenched from 845 °C (1555 °F) in oil, tempered in 56 °C (100 °F) intervals in 13.7 mm (0.540 in.) rounds. Tested in 12.8 mm (0.505 in.) rounds. Source: Republic Steel



5160: As-Quenched Hardness (Oil)

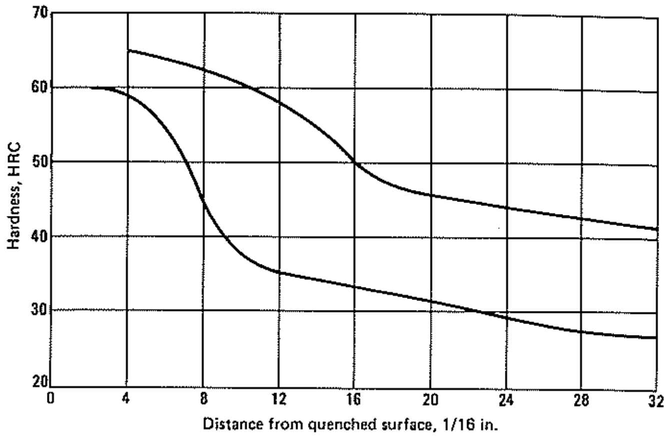
Single heat results; grade: 0.56 to 0.64 C, 0.75 to 1.00 Mn, 0.20 to 0.30 Si, 0.70 to 0.90 Cr; ladle: 0.62 C, 0.84 Mn, 0.010 P, 0.034 S, 0.24 Si, 0.04 Ni, 0.74 Cr, 0.01 Mo; grain size: 6 to 8

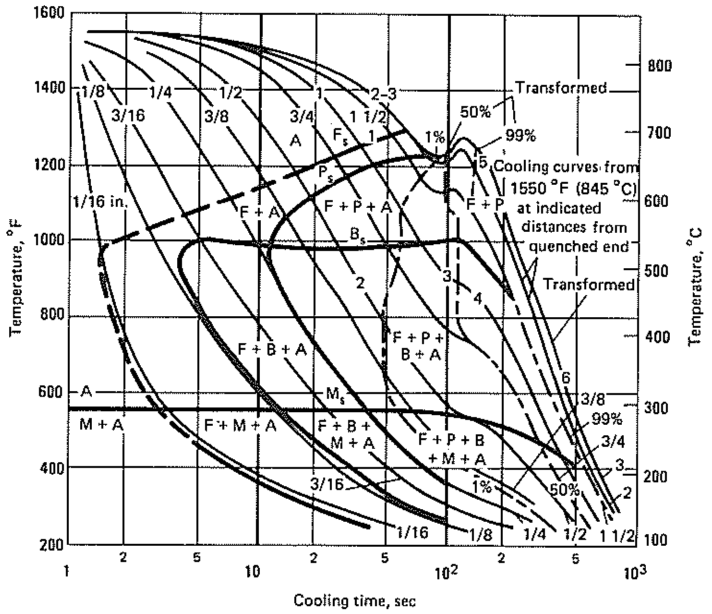
Size round		Hardness, HRC		
in.	mm	Surface	½ radius	Center
½	13	63	62	62
1	25	62	61	60
2	51	53	46	43
4	102	40	32	29

Source: Bethlehem Steel

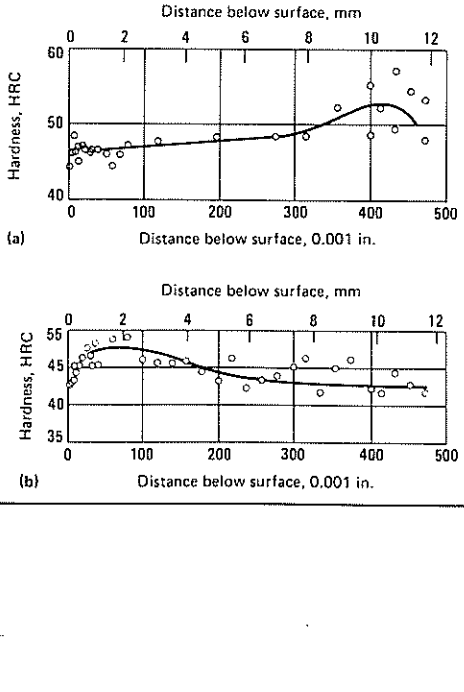
5160H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min
1	1.58	...	60	13	20.54	58	35
2	3.16	...	60	14	22.12	56	35
3	4.74	...	60	15	23.70	54	34
4	6.32	65	59	16	25.28	52	34
5	7.90	65	58	18	28.44	48	33
6	9.48	64	56	20	31.60	47	32
7	11.06	64	52	22	34.76	46	31
8	12.64	63	47	24	37.92	45	30
9	14.22	62	42	26	41.08	44	29
10	15.80	61	39	28	44.24	43	28
11	17.38	60	37	30	47.40	43	28
12	18.96	59	36	32	50.56	42	27



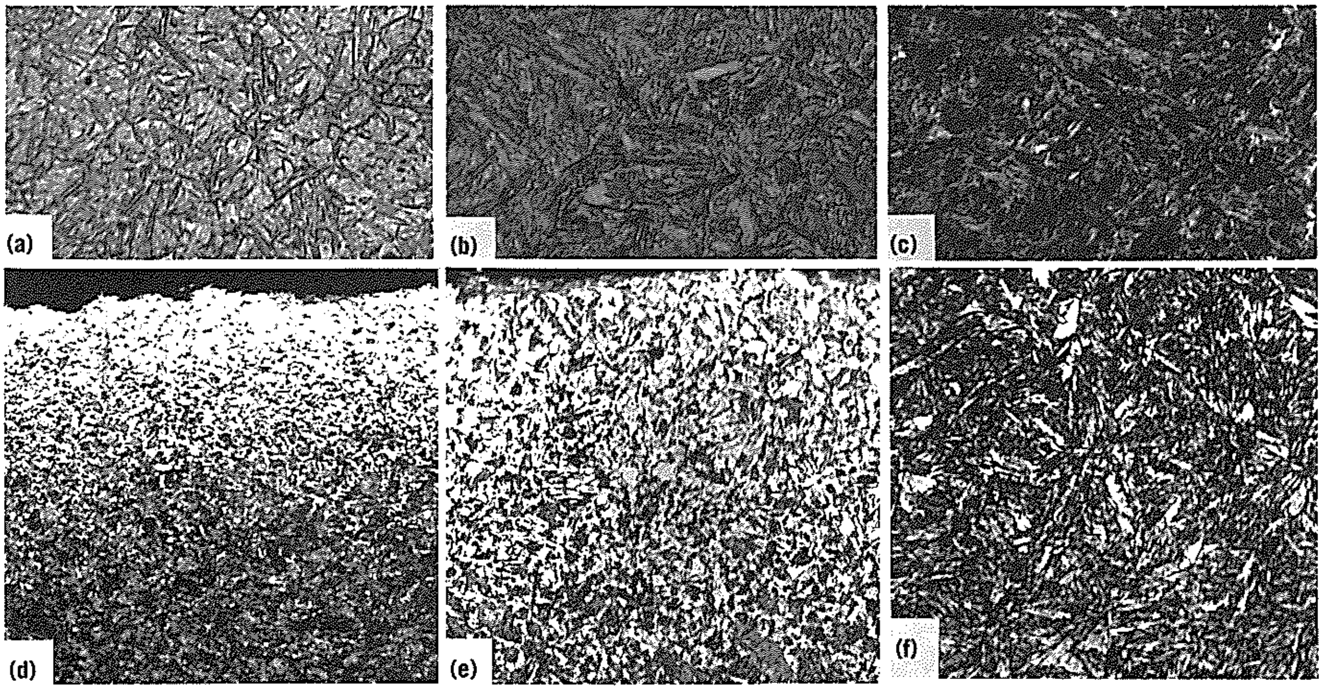


5160: Continuous Cooling Curves. Composition: 0.63 C, 0.86 Mn, 0.23 Si, 0.83 Cr. Austenitized at 845 °C (1555 °F). Grain size: 7 ½. Ac_3, 780 °C (1435 °F); Ac_1, 755 °C (1390 °F). A: austenite, F: ferrite, P: pearlite, B: bainite, M: martensite. Source: Bethlehem Steel



5160: Section Thickness vs Austempered Hardness. Quenched in agitated salt containing some water. Rockwell C hardness values converted from microhardness readings taken with a 100 g (3.53 oz) load. Low values of surface hardness result from decarburization. (a) 24.6 mm (0.967 in.) diam. Austenitized at 900 °C (1650 °F) and quenched in salt at 300 °C (570 °F) for 15 min. High hardness at center because of segregation. (b) 26.29 mm (1.035 in.) diam. Austenitized at 940 °C (1725 °F) and quenched in salt at 315 °C (600 °F) for 15 min

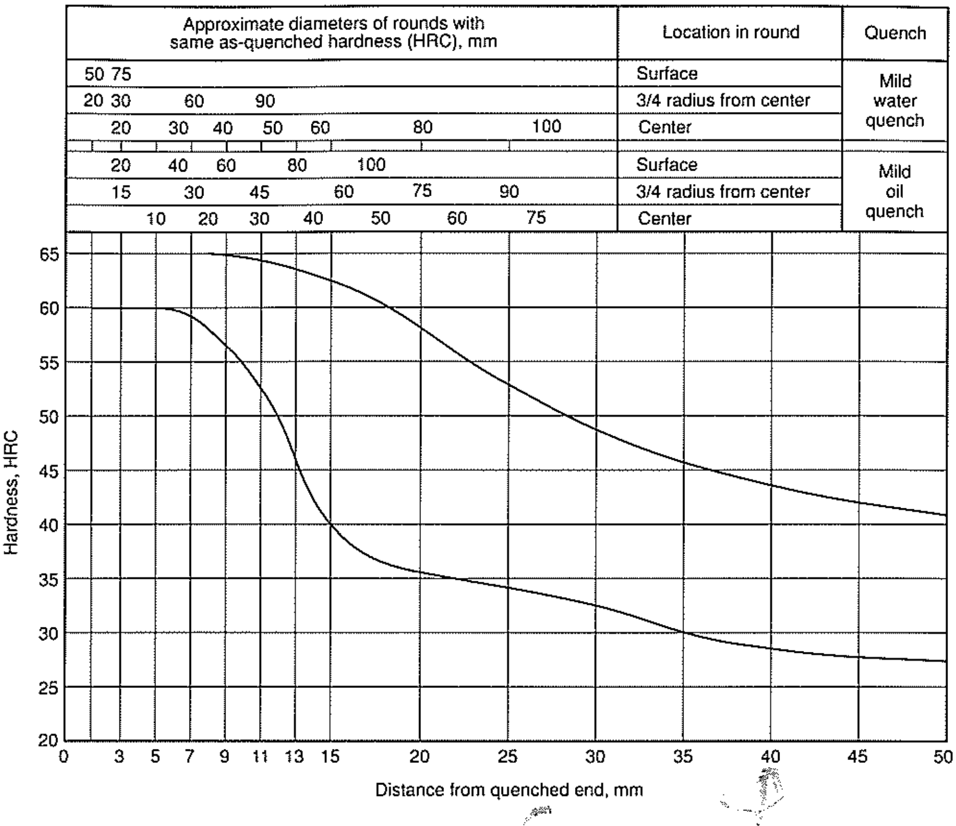
5160: Microstructures. (a) 4% picral with 0.05% HCl, 500x. Hot rolled coil-spring steel, austenitized at 870 °C (1600 °F) for 30 min and oil quenched. Untempered martensite (dark, needlelike constituent) and retained austenite (light constituent). (b) 4% nital, 4% picral, mixed 1 to 1; 1000×. Same steel and heat treatment as (a), except at a higher magnification. Untempered martensite (dark gray constituent) and the retained austenite (light constituent are now more clearly resolved). (c) 4% nital, 4% picral, mixed 1 to 1; 1000×. Same steel as (a), except tempered at 205 °C (400 °F) after austenitizing and quenching. Predominantly tempered martensite (dark), with small particles of ferrite (white). (d) 2% nital, 110×. Spring steel, 16.1 mm (0.632 in.) diam, austenitized at 870 °C (1600 °F) for 5 min, hot coiled, oil quenched at 60 °C (140 °F), tempered at 425 °C (795 °F) for 40 min. Note tempered martensite and decarburization. (e) 2% nital, 275×. Same steel and treatment as (d), except at a higher magnification. Surface decarburization (white area near top of micrograph) occurred in the bar mill, while the steel was at about 1150 °C (2100 °F). (f) 4% nital, 4% picral, mixed 1 to 1; 1000×. Hot rolled steel, austenitized at 870 °C (1600 °F) for 30 min, oil quenched, tempered at 540 °C (1000 °F) for 1 h. Predominantly tempered martensite (dark), with some ferrite (white)



5160H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

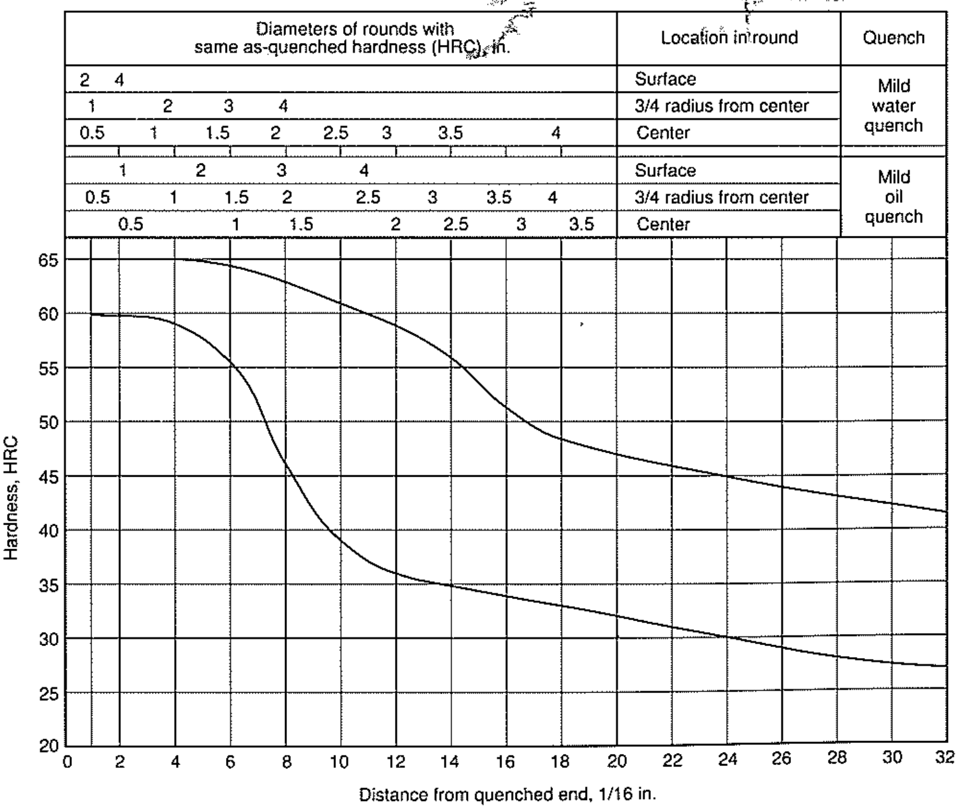
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	...	60
3	...	60
5	...	60
7	...	59
9	65	57
11	64	52
13	64	46
15	62	40
20	58	36
25	53	34
30	49	32
35	46	30
40	44	28
45	42	27
50	41	27



Hardness limits for specification purposes

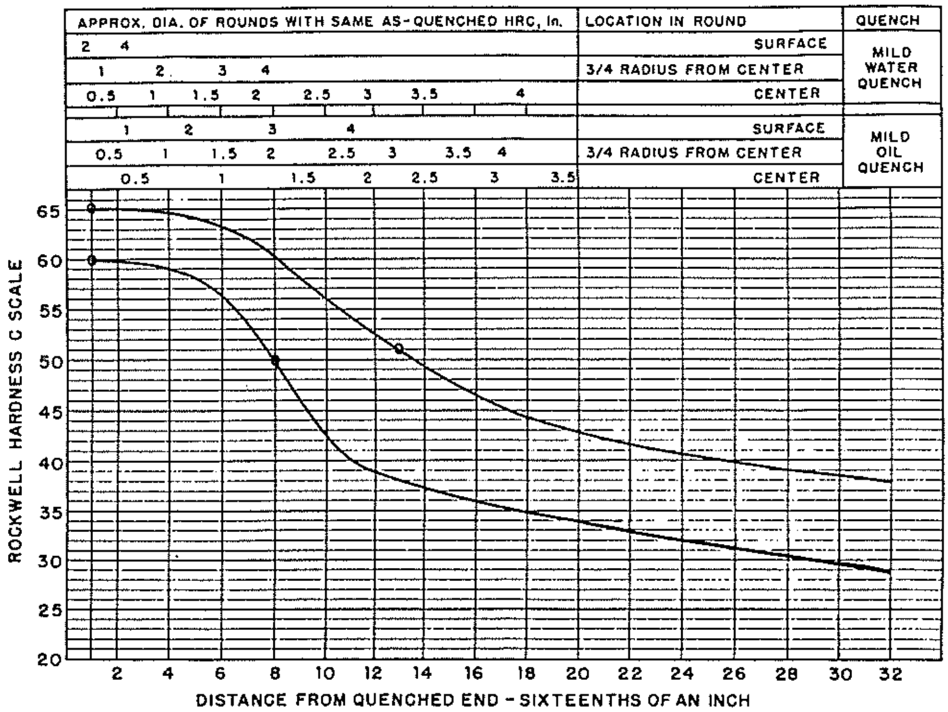
J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	...	60
2	...	60
3	...	60
4	65	59
5	65	58
6	64	56
7	64	52
8	63	47
9	62	42
10	61	39
11	60	37
12	59	36
13	58	35
14	56	35
15	54	34
16	52	34
18	48	33
20	47	32
22	46	31
24	45	30
26	44	29
28	43	28
30	43	28
32	42	27



5160RH: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

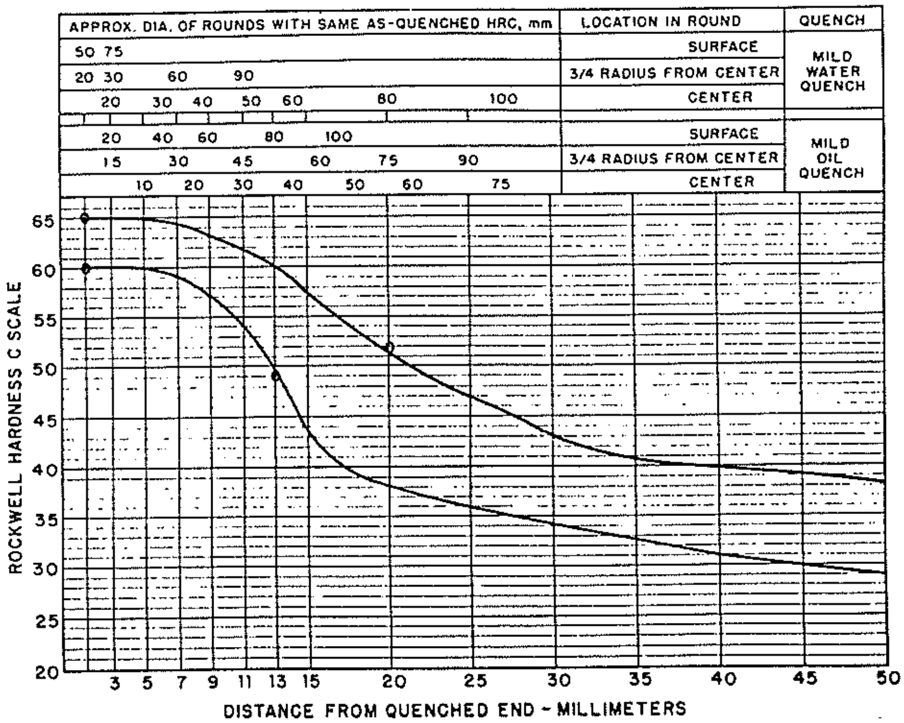
Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Minimum
1	65	60
2	65	60
3	65	60
4	65	59
5	64	58
6	63	57
7	62	54
8	60	50
9	58	45
10	56	42
11	55	40
12	53	39
13	51	38
14	50	37
15	48	36
16	47	36
18	44	35
20	43	34
22	42	33
24	41	32
26	40	31
28	39	30
30	39	29
32	38	29



Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Minimum
1.5	65	60
3	65	60
5	65	60
7	65	59
9	63	57
11	62	54
13	60	49
15	57	43
20	52	38
25	47	36
30	43	34
35	41	32
40	40	31
45	39	30
50	38	29



51B60, 51B60H

Chemical Composition. **51B60. AISI:** 0.56 to 0.64 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.70 to 0.90 Cr, 0.0005 to 0.003 B. **UNS:** 0.56 to 0.64 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.70 to 0.90 Cr, 0.0005 B min. **UNS H51601 and SAE/AISI 51B60H:** 0.55 to 0.65 C, 0.65 to 1.10 Mn, 0.15 to 0.35 Si, 0.60 to 1.00 Cr, B (can be expected to be 0.0005 to 0.003 percent)

Similar Steels (U.S. and/or Foreign). **51B60.** UNS G51601; ASTM A519; SAE J404, J412, J770. **51B60H.** UNS H51601; ASTM A304; SAE J1268

Characteristics. With the exception of a slightly higher chromium content, 51B60H has practically the same characteristics as 50B60H. As-quenched hardness of 58 to 63 HRC can be expected. Hardenability of 51B60H is slightly higher, because of the increase in chromium

Forging. Heat to 1205 °C (2200 °F) maximum. Do not forge after temperature of forging stock drops below approximately 925 °C (1695 °F). Because of high hardenability, forgings, especially complex shapes, should be cooled slowly from the forging operation to minimize the possibility of cracking. Forgings may be slow cooled by either placing them in a furnace or burying them in an insulating compound

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

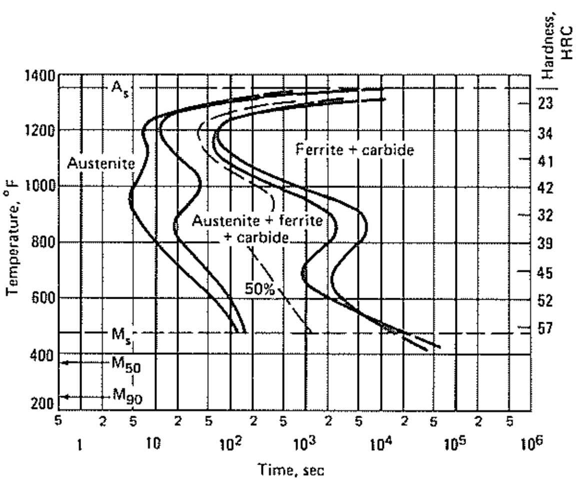
Annealing. For a predominately spheroidized structure which is usually favored for this grade of steel, heat to 750 °C (1380 °F), cool rapidly to 700 °C (1290 °F), then cool to 655 °C (1210 °F), at a rate not to exceed 6 °C (10 °F) per h; or heat to 750 °C (1380 °F), cool rapidly to 650 °C (1200 °F), and hold for 12 h

Hardening. Austenitize at 845 °C (1555 °F), and quench in oil. Gas nitriding and ion nitriding are suitable processes

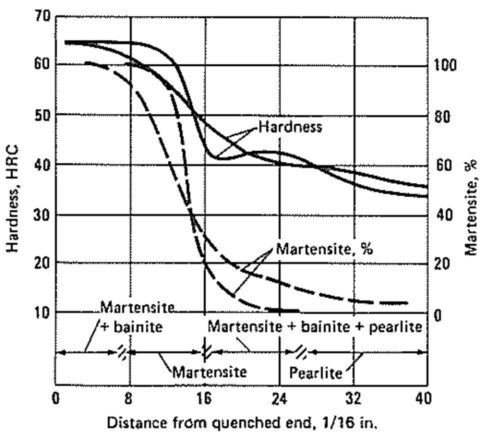
Tempering. Selection of tempering temperature depends on the final properties desired. To prevent cracking, make sure parts have reached a uniform temperature throughout each section, and then place them in a tempering furnace before ambient temperature is reached. 38 to 50 °C (100 to 120 °F) is considered ideal

Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough and semifinish machine
- Austenitize and quench
- Temper
- Finish machine

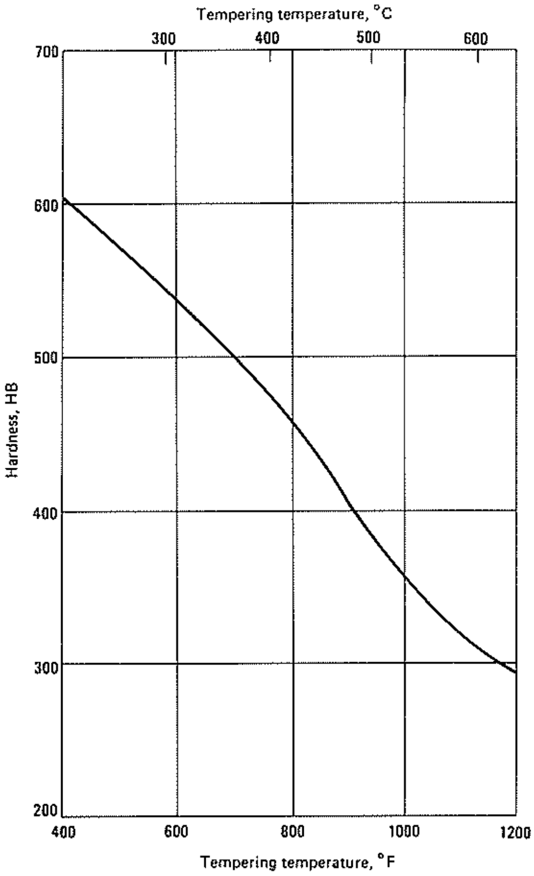


51B60: Isothermal Transformation Diagram. Composition: 0.64 C, 0.88 Mn, 0.83 Cr, 0.0006 B. Austenitized at 845 °C (1555 °F). Grain size 6 to 7

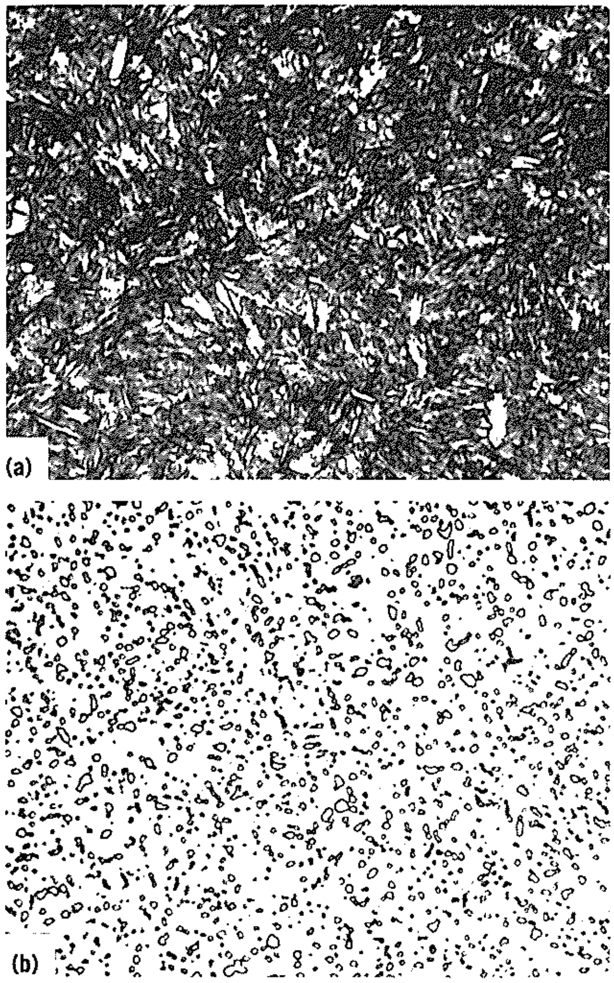


51B60: End-Quench Hardenability. Composition: 0.64 C, 0.88 Mn, 0.83 Cr, 0.0006 B. Austenitized at 845 °C (1555°F). Grain size 6 to 7

51B60: Hardness vs Tempering Temperature. Normalized at 870 °C (1600 °F), quenched from 845 °C (1555 °F) in oil, tempered in 56 °C (100 °F) intervals in 13.7 mm (0.540 in.) rounds. Tested in 12.8 mm (0.505 in.) rounds. Source: Republic Steel

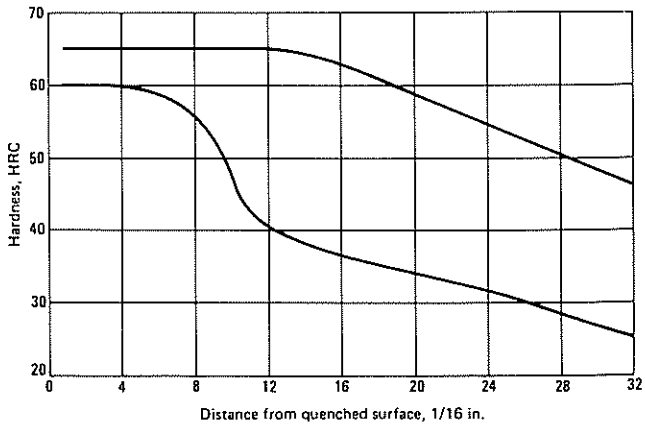


51B60: Microstructures. (a) Picral, 1000×. Hot rolled steel bar, 31.8 mm (1 ¼ in.) diam, austenitized at 870 °C (1600 °F), air cooled (normalized); austenitized at 815 °C (1500 °F), water quenched. Untempered martensite, some retained austenite (white), fine spheroidal carbide. (b) Nital, 1000×. Hot rolled steel bar, 13.8 mm (1 ¼ in.) diam, austenitized and quenched to obtain a martensitic structure, then heated to 675 °C (1245 °F) for 15 h. Spheroidal carbide particles in a matrix of ferrite



51B60H: End-Quench Hardenability

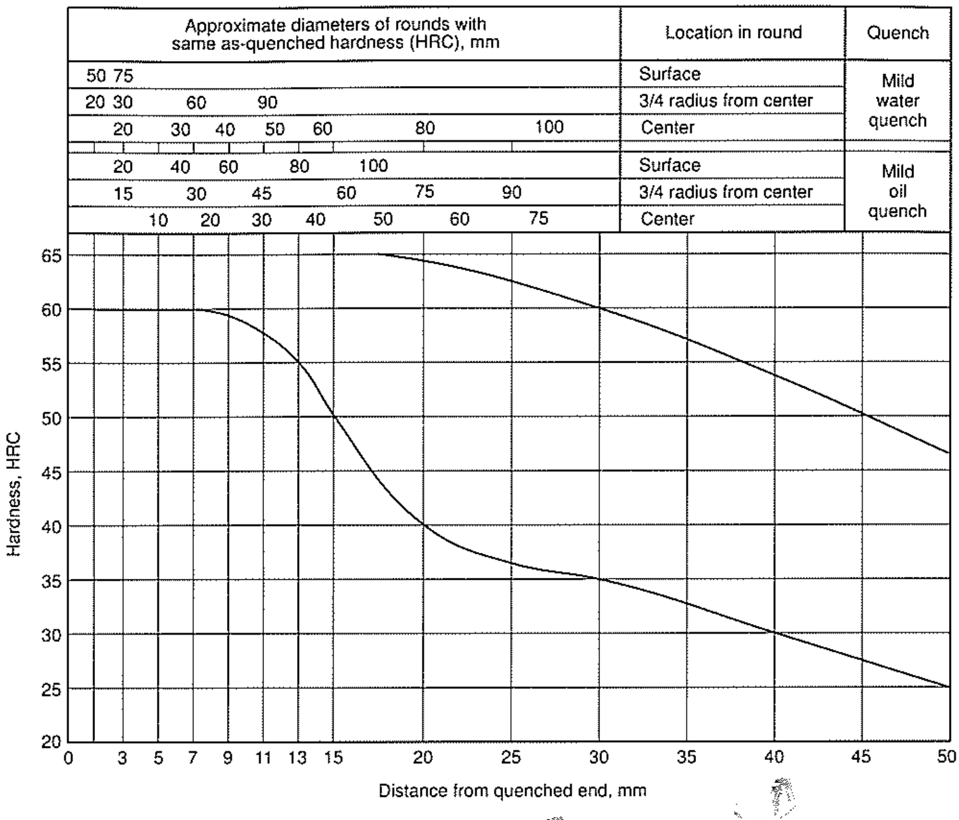
Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min
1	1.58	...	60	13	20.54	65	40
2	3.16	...	60	14	22.12	64	39
3	4.75	...	60	15	23.70	64	38
4	6.32	...	60	16	25.28	63	37
5	7.90	...	60	18	28.44	61	36
6	9.48	...	59	20	31.60	59	34
7	11.06	...	58	22	34.76	57	33
8	12.64	...	57	24	37.92	55	31
9	14.22	...	54	26	41.08	53	30
10	15.80	...	50	28	44.24	51	28
11	17.38	...	44	30	47.40	49	27
12	18.96	65	41	32	50.56	47	25



51B60H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

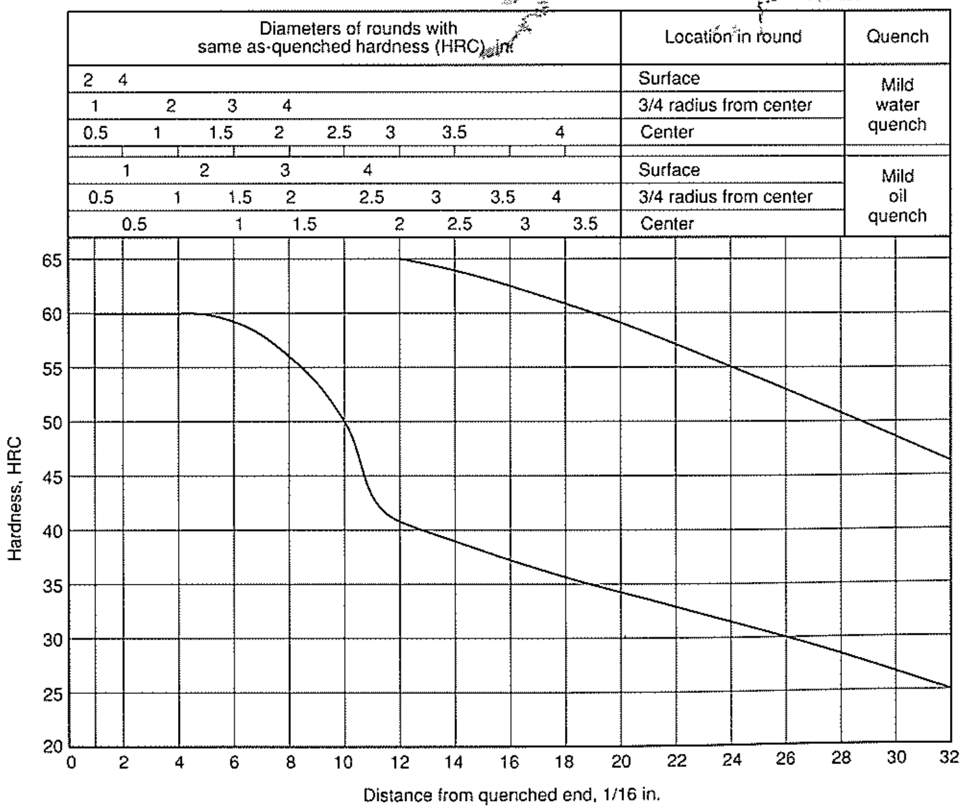
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	...	60
3	...	60
5	...	60
7	...	60
9	...	59
11	...	58
13	...	55
15	...	51
20	65	40
25	63	37
30	61	35
35	57	32
40	54	30
45	51	28
50	47	25



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	...	60
2	...	60
3	...	60
4	...	60
5	...	60
6	...	59
7	...	58
8	...	57
9	...	54
10	...	50
11	...	44
12	65	41
13	65	40
14	64	39
15	64	38
16	63	37
18	61	36
20	59	34
22	57	33
24	55	31
26	53	30
28	51	28
30	49	27
32	47	25



E51100

Chemical Composition. **AISI and UNS:** 0.98 to 1.10 C, 0.25 to 0.45 Mn, 0.025 P max, 0.025 S max, 0.15 to 0.30 Si, 0.90 to 1.15 Cr

Similar Steels (U.S. and/or Foreign). UNS G51986; AMS 6443, 6446, 6449; ASTM A295, A322, A505, A519; SAE J404, J412, J770; (Ger.) DIN 1.3503

Characteristics. One of only two alloy steels listed by AISI which contain carbon of near 1.0% or higher. The E prefix in the designation indicates that it is manufactured only by the electric furnace process, which is further indicated by the low contents of phosphorus and sulfur. This grade and its companion, E52100, are sometimes called tool steels because their composition is nearly identical with L2 grade of tool steel. However, neither E51100 or E52100 is made by what is commonly considered as tool steel practice; they are both made in relatively large quantities.

Although E51100 does serve many commercial applications, it is used most extensively as a material for ball and ball race rolling element bearings, for which extremely high hardness is needed.

There is no H version of this steel because the end-quench test is not often used to evaluate hardenability of the very high-carbon grades. It is, however, generally considered an oil-hardening steel, so that its hardenability is considered as fairly high. As-quenched hardness generally ranges from 62 to 66 HRC, depending on the cooling power of the quenchant

Forging. Heat to 1150 °C (2100 °F) maximum. Do not forge after temperature of forging stock drops below approximately 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 885 °C (1625 °F). Cool in air

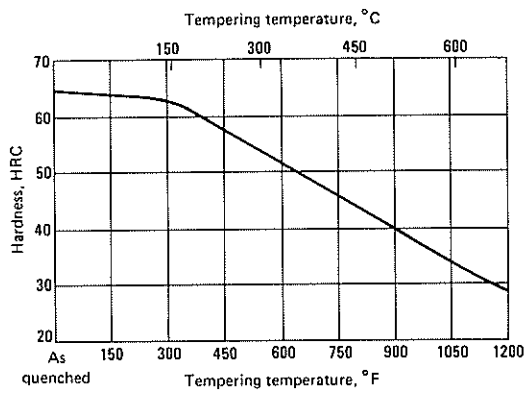
Annealing. For a predominantly spheroidized structure, which is generally desired for machining as well as heat treating, heat to 795 °C (1460 °F), cool rapidly to 750 °C (1380 °F), then cool to 675 °C (1245 °F), at a rate not to exceed 6 °C (10 °F) per h; or heat to 795 °C (1460 °F), cool rapidly to 690 °C (1275 °F), and hold for 16 h

Hardening. Austenitize at 845 °C (1555 °F) in a neutral salt bath or in a gaseous atmosphere with a carbon potential of near 1.0%, and quench in oil

Tempering. After quenching, parts should be tempered as soon as they have uniformly reached near ambient temperature, 38 to 50 °C (100 to 120 °F) is ideal. Because of the high carbon content, parts must be tempered to at least 120 °C (250 °F) to convert the tetragonal martensite to cubic martensite. Most commercial practice calls for tempering at 150 °C (300 °F), which does not reduce the as-quenched hardness to any significant amount. When a reduction in hardness from the as-quenched value of approximately two points HRC can be tolerated, a tempering temperature of 175 °C (345 °F) is recommended. Sometimes subjected to higher tempering temperatures, with an accompanying loss of hardness

Recommended Processing Sequence

- Forge
- Normalize
- Anneal (spheroidize)
- Machine, including rough grinding
- Austenitize and quench
- Temper
- Finish grind



E51100: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

E52100

Chemical Composition. **AISI:** 0.98 to 1.10 C, 0.25 to 0.45 Mn, 0.025 P max, 0.025 S max, 0.15 to 0.30 Si, 1.30 to 1.60 Cr. **UNS:** 0.98 to 1.10 C, 0.25 to 0.45 Mn, 0.025 P max, 0.025 S max, 0.20 to 0.30 Si, 1.30 to 1.60 Cr

Similar Steels (U.S. and/or Foreign). UNS G52986; AMS 6440, 6444, 6447; ASTM A274, A322, A331, A505, A519, A535, A636; MIL SPEC MIL-S-980, MIL-S-7420, MIL-S-22141; SAE J404, J412, J770; (Ger.) DIN 1.3505; (Fr.) AFNOR 100 C 6; (Ital.) UNI 100 Cr 6; (U.K.) B.S. 534 A 99, 535 A 99

Characteristics. Because E52100 has the same composition as 5110 except for a modest increase in chromium, the characteristics and commercial applications are similar. The as-quenched hardnesses for the two steels can be the same (62 to 66 HRC), depending mainly on section thickness. Because of higher chromium content, the hardenability of E52100 is somewhat higher. Sometimes an attempt is made to evaluate hardness by the end-quench method. E52100 is selected when greater section sizes and the increased hardenability are needed

Forging. Heat to 1150 °C (2100 °F) maximum. Do not forge after temperature of forging stock drops below approximately 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 885 °C (1625 °F). Cool in air. In aerospace practice this alloy is normalized at 900 °C (1650 °F)

Annealing. For a predominantly spheroidized structure which is generally desired for machining as well as heat treating, heat to 795 °C (1460 °F), cool rapidly to 750 °C (1380 °F), then cool to 675 °C (1245 °F), at a rate not to exceed 6 °C (10 °F) per h; or heat to 795 °C (1460 °F), cool rapidly to 690 °C (1275 °F), and hold for 16 h. Parts are annealed at 775 °C (1425 °F) for 20 min, cooled to 740 °C (1365 °F) at a rate not to exceed 10 °C (20 °F) per h, and air cooled to ambient temperature

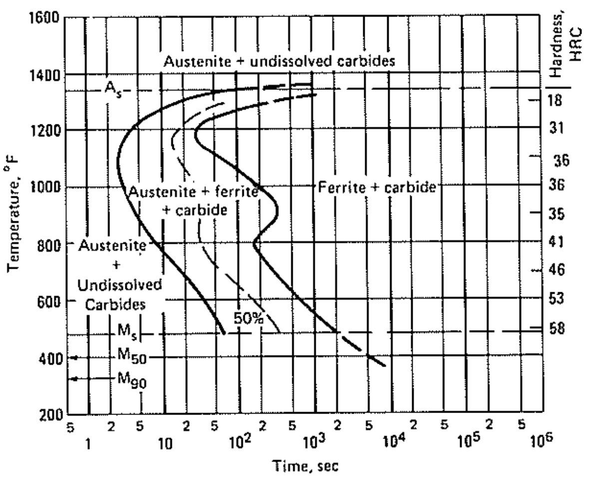
Hardening. Austenitize at 845 °C (1555 °F) in a neutral salt bath or in a gaseous atmosphere with a carbon potential of near 1.0%, and quench in oil.

In aerospace practice, this alloy is austenitized at 845 °C (1555 °F). However, 815 °C (1500 °F) is permissible for parts requiring distortion control. Parts are hardened from the spheroidize annealed condition or normalized condition. Parts are quenched in oil or polymer. Immediately after quenching, parts are refrigerated at -70 °C (-95 °F) or lower, held for 1 h minimum, then air warmed to room temperature. If parts have high propensity for cracking during refrigeration, a snap temper is recommended

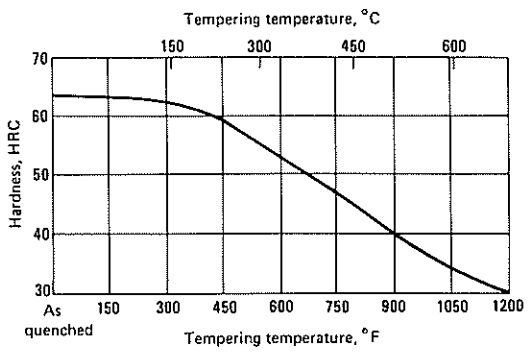
Tempering. After quenching, parts should be tempered as soon as they have uniformly reached near ambient temperature, 38 to 50 °C (100 to 120 °F) is ideal. Because of the high carbon content, parts must be tempered to at least 120 °C (250 °F) to convert the tetragonal martensite to cubic martensite. Most commercial practice calls for tempering at 150 °C (300 °F), which does not reduce the as-quenched hardness to any significant amount. When a reduction in hardness from the as-quenched value of approximately two points HRC can be tolerated, a tempering temperature of 175 °C (345 °F) is recommended. Sometimes subjected to higher tempering temperatures, with an accompanying loss of hardness. In aerospace practice, at least two tempering operations are required. For hardness in the range of 58 to 65 HRC, parts are tempered at 170 to 230 °C (340 to 450 °F)

Recommended Processing Sequence

- Forge
- Normalize
- Anneal (spheroidize)
- Machine, including rough grinding
- Austenitize and quench
- Temper
- Finish grind

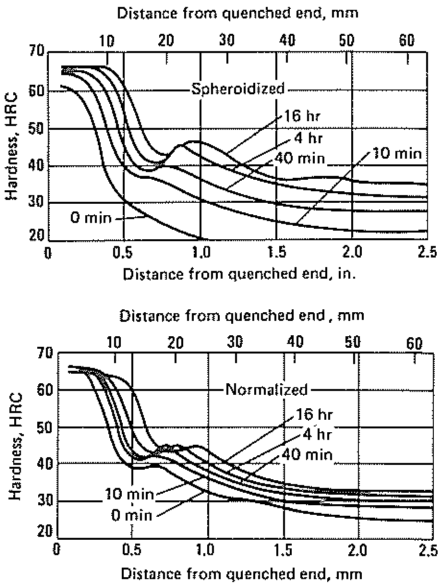


E52100: Isothermal Transformation Diagram. Composition: 1.02 C, 0.36 Mn, 0.20 Ni, 1.41 Cr. Austenitized at 845 °C (1555 °F). Grain size: 9

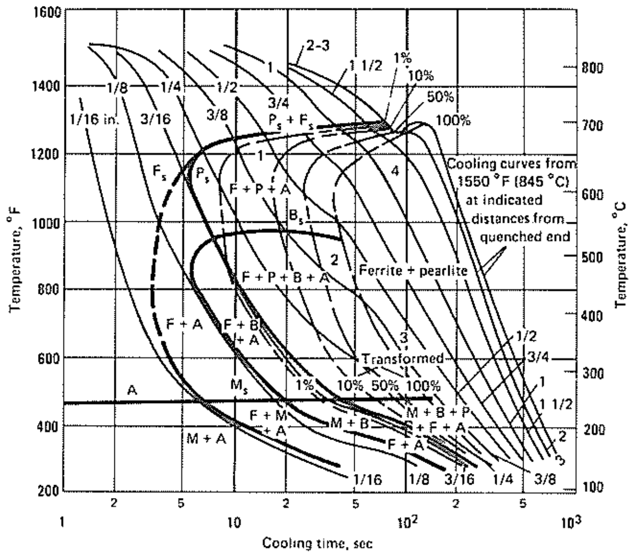


E52100: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

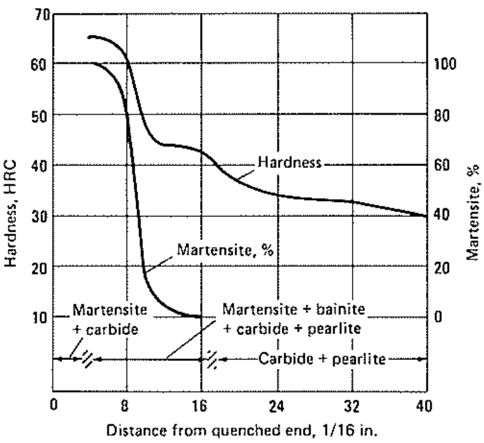
E52100: End-Quench Hardenability. Austenitized at 845 °C (1555 °F). Insufficient time to permit full carbide solubility in austenite



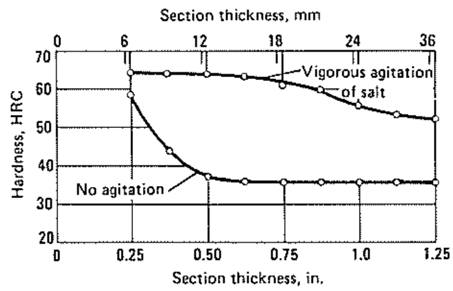
E52100: Continuous Cooling Curves. Composition: 1.06 C, 0.33 Mn, 0.32 Si, 1.44 Cr. Austenitized at 845 °C (1555 °F). Grain size: 9. Ac_3, 780 °C (1440 °F); Ac_1, 755 °C (1390 °F). A: austenite, F: ferrite, P: pearlite, B: bainite, M: martensite. Source: Bethlehem Steel



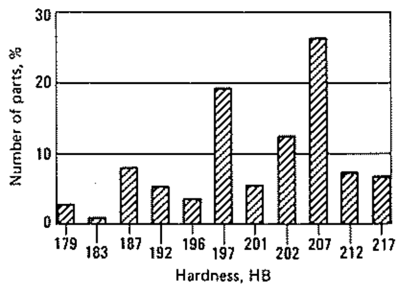
E52100: End-Quench Hardenability. 13 mm (0.5 in.) diam bar. Composition: 1.02 C, 0.36 Mn, 0.20 Ni, 1.41 Cr. Austenitized at 845 °C (1555 °F). Grain size: 9



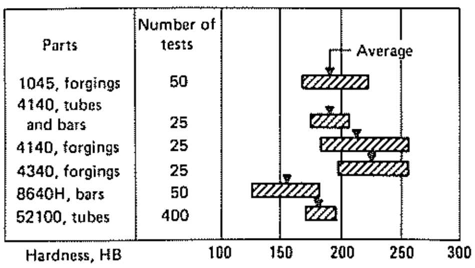
E52100: Influence of Agitation of Surface Hardness. Various section thicknesses, martempered in hot salt



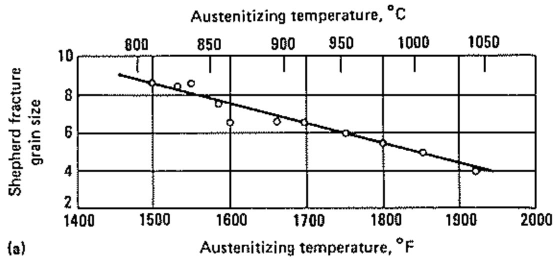
E52100: Hardness Distribution. Steel rings, 100 heats. Heated at 790 °C (1455 °F) for 3 h, cooled rapidly to 725 °C (1335 °F), then cooled to 695 °C (1280 °F) at 8 °C (15 °F) per h, and air cooled. Hardness measurements were made on rings located at extreme positions in furnace load. Treatment resulted in spheroidized structure. Composition: 0.90 to 1.05 C, 0.95 to 1.25 Mn, 0.50 to 0.70 Si, 0.90 to 1.15 Cr

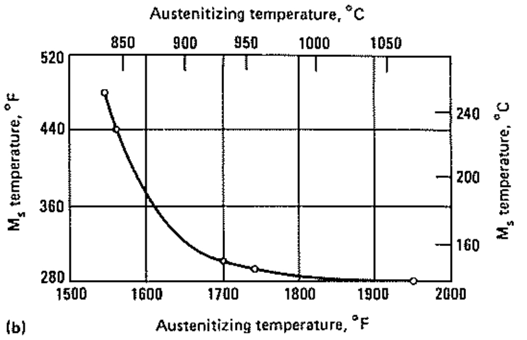


E52100: Variation of Brinell Hardness Measurements on Annealed Plain Carbon and Low-Alloy Steels. 52100 seamless tubes were austenitized at 790 °C (1445 °F), rapid furnace cooled to 750 °C (1380 °F), then cooled to 695 °C (1280 °F) at 6 °C (10 °F) per h, and air cooled

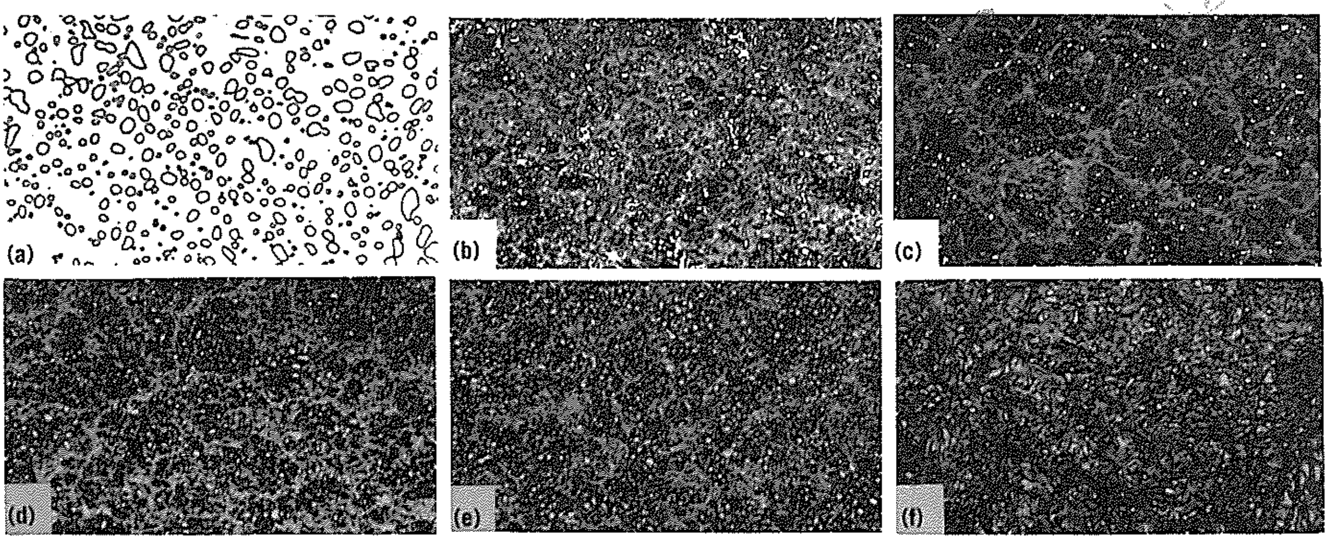


E52100: Austenitizing Temperature vs Grain Size and M_s Temperature. (a) Grain size; (b) Ms temperature



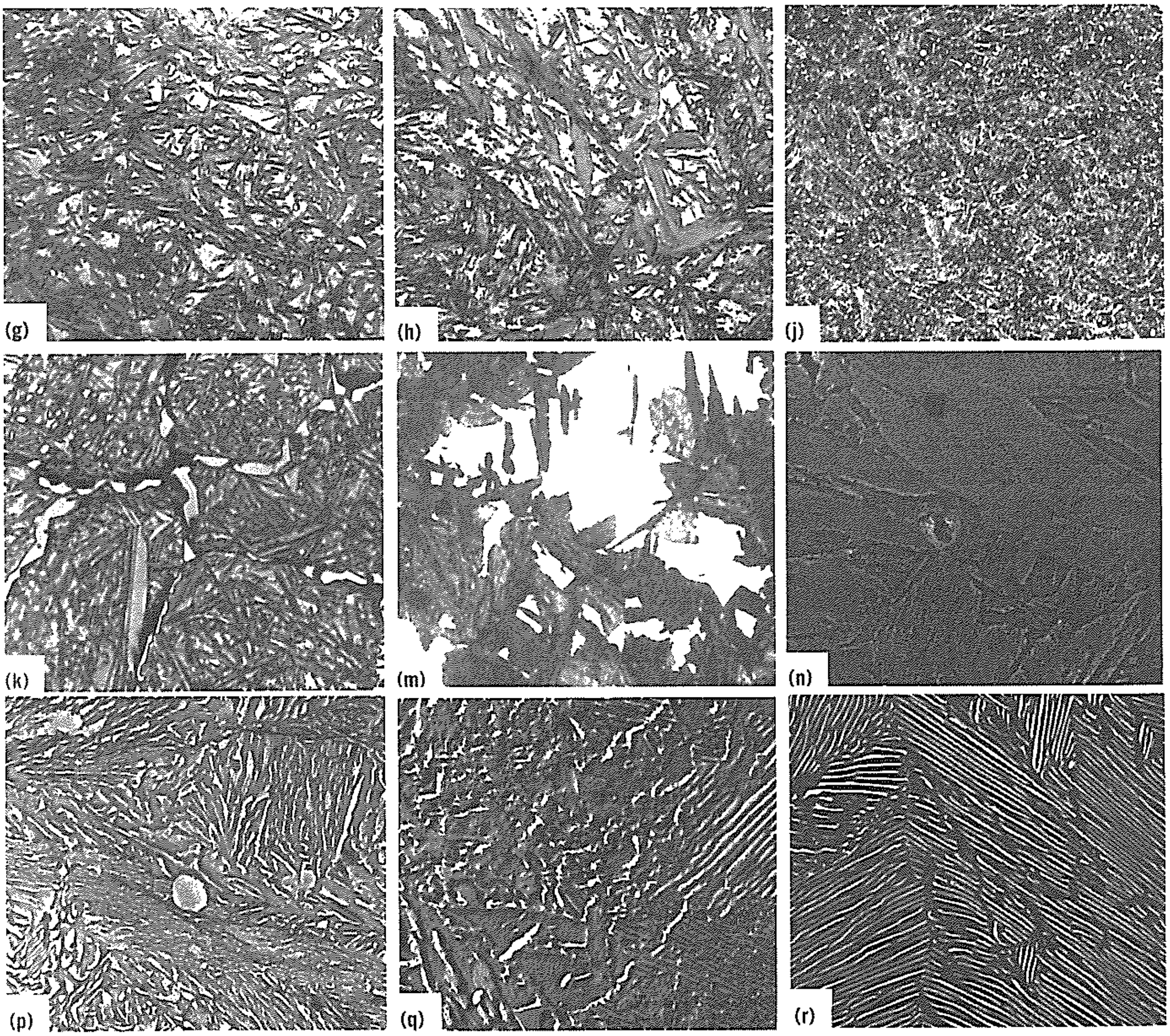


E52100: Microstructures. (a) 4% picral with 0.05% HCl, 1000×. Steel bar, 123.8 mm (4.875 in.) diam, heated to 770 °C (1420 °F) for 10 h, held for 5 h, cooled to 650 °C (1200 °F) at 11 °C (20 °F) per h, furnace cooled to 28 °C (80 °F). Fine dispersion of spheroidal carbide in a matrix of ferrite. Prior structure for (b) to (k). (b) 4% nital, 4% picral, mixed 1 to 1; 500×. See (a). Austenitized at 790 °C (1455 °F) for ½ h, oil quenched, tempered at 175 °C (345 °F) for 1 h. Black areas are bainite, gray areas tempered martensite, white dots are carbide particles that did not dissolve during austenitizing. (c) 4% nital, 4% picral, mixed 1 to 1; 500×. See (a), austenitized ½ h at 845 °C (1555 °F) and oil quenched, then tempered same as (b). Tempered martensite and carbide particles (white) undissolved during austenitizing. Ghost lines are because of inhomogeneous distribution of carbon and chromium. (d) 4% nital, 4% picral, mixed 1 to 1; 500×. See (a), austenitized at 855 °C (1570 °F) for ½ h, oil quenched, tempered at 260 °C (500 °F) for 1 h. Tempered martensite and undissolved carbide particles. Ghost lines less prominent because of higher austenitizing and tempering temperatures. See (c). (e) 4% nital, 4% picral, mixed 1 to 1; 500×. See (a). Austenitized at 845 °C (1555 °F) for ½ h, oil quenched, tempered at 750 °C (400 °F) for 1 h. Tempered martensite and a dispersion of carbide particles not dissolved during austenitizing. Ghost lines have nearly disappeared. Compare with (c) and (d). (f) 4% nital, 4% picral, mixed 1 to 1; 500×. See (a). Austenitized at 925 °C (1695 °F) for ½ h, oil quenched, tempered at 175 °C (345 °F) for 1 h. Mainly tempered martensite. High austenitizing temperature resulted in some retained austenite (angular white areas) and a few carbide particles. Compare to (c) and (e).



(continued)

E52100: Microstructures (continued). (g) 4% nital, 4% picral, mixed 1 to 1; 1000×. Same specimen as (f) shown at higher magnification. Dark areas are tempered martensite. Retained austenite (angular light gray areas) is well resolved. A few undissolved carbide particles remain from the original structure (a). (h) 4% nital, 4% picral, 1000×. See (a). Austenitized at 980 °C (1795 °F) for ½ h, oil quenched, tempered at 175 °C (345 °F) for 1 h. Coarse plates (needles) of tempered martensite and retained austenite (white). Carbide particles are almost wholly dissolved. (j) 4% nital, 4% picral, mixed 1 to 1; 500×. See (a). Austenitized at 855 °C (1570 °F) for ½ h, quenched in a salt bath at 260 °C (500 °F), held for ½ h, air cooled to room temperature. Spheroidal carbide particles in lower bainite, some retained austenite. (k) 4% nital, 4% picral, mixed 1 to 1; 1000×. See (a). Austenitized at 955 °C (1750 °F) for 2 h, cooled slowly to 705 °C (1300 °F), oil quenched. Note dark gray needles of martensite, carbide rejected to grain boundaries (light gray), bainite (black), and retained austenite (small light areas). (m) 4% nital, 500×. Steel rod austenitized at 900 °C (1650 °F) for 20 min and slack quenched in oil to room temperature. Dark areas (etched) are a mixture of fine pearlite and bainite. Light areas (almost unetched) are untempered martensite. (n) 4% nital, 10 000×. Steel rod, austenitized at 1125 °C (2060 °F) for 15 min, oil quenched. Electron micrograph of a replica rotary-shadowed with chromium. Coarse, untempered martensite. Note cracks in martensite platelets (upper left, upper right). (p) 4% nital, 5000×. Steel rod, austenitized at 980 °C (1795 °F) for 1 h, quenched in a lead bath at 357 °C (675 °F), held for 2 h, air cooled. Electron micrograph of a replica rotary-shadowed with chromium. Bainite, probably upper bainite. (q) 4% nital, 10 000×. Steel wire, austenitized at 900 °C (1650 °F) for 30 sec, quenched in a lead bath at 530 °C (990 °F), held for 30 sec, air cooled. Electron micrograph of a replica rotary-shadowed with chromium. Lamellar pearlite and bainite. (r) 4% nital, 10 000×. Steel rod, austenitized at 1150 °C (2100 °F) for 3 min, quenched in a lead bath at 575 °C (1065 °F), held for 5 min, air cooled. Electron micrograph of a replica static-shadowed with chromium. Fine lamellar pearlite.



6118, 6118H

Chemical Composition. **6118. AISI and UNS:** 0.16 to 0.21 C, 0.50 to 0.70 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.50 to 0.70 Cr, 0.10 to 0.15 V. **UNS H61180 and SAE/AISI 6118H:** 0.15 to 0.21 C, 0.40 to 0.80 Mn, 0.15 to 0.35 Si, 0.40 to 0.80 Cr, 0.10 to 0.15 V

Similar Steels (U.S. and/or Foreign). **6118.** UNS G61180; SAE J404, J770; (Ger.) DIN 1.7511. **6118H.** UNS H61180; ASTM A304; SAE 1268; (Ger.) DIN 1.7511

Characteristics. A chromium-vanadium carburizing-carbonitriding steel. Its characteristics are approximately the same as those for 4118H. Because of the slightly lower carbon range of 6118H, the as-quenched hardness is likely to be lower, approximately 36 to 42 HRC. The chromium contents of these two steels are nearly the same, and their hardenability bands are nearly the same. The small amount of vanadium contained in 6118H acts as a grain refiner and does not increase hardenability. Is readily forgeable and weldable (using alloy steel practice). Machines reasonably well

Forging. Heat to 1245 °C (2275 °F) maximum. Do not forge after temperature of forging stock drops below approximately 900 °C (1650 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Cool in air

Annealing. Structures having best machinability are normally obtained by normalizing or by isothermal treatment which consists of heating to 885 °C (1625 °F), cooling rapidly to 690 °C (1275 °F), and holding for 4 h

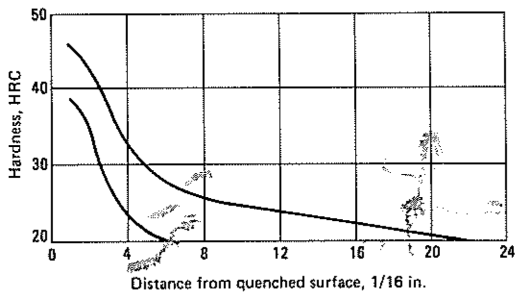
Case Hardening. See recommended carburizing, carbonitriding, and tempering procedures described for 4118H. Ion nitriding is an alternative process

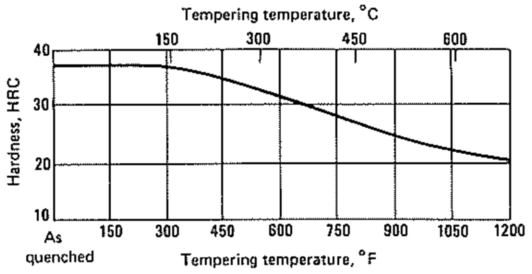
Recommended Processing Sequence

- Forge
- Normalize
- Anneal (optional)
- Rough and semifinish machine
- Case harden
- Temper
- Finish machine

6118H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max
1	1.58	46	39	13	20.54	24
2	3.16	44	36	14	22.12	23
3	4.74	38	28	15	23.70	23
4	6.32	33	24	16	25.28	22
5	7.90	30	22	18	28.44	22
6	9.48	28	20	20	31.60	21
7	11.06	27	...	22	34.76	21
8	12.64	26	...	24	37.92	20
9	14.22	26	...	26	41.08	...
10	15.80	25	...	28	44.24	...
11	17.38	25	...	30	47.40	...
12	18.96	24	...	32	50.56	...





6118, 6118H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

6150, 6150H

Chemical Composition. **6150. AISI and UNS:** 0.48 to 0.53 C, 0.70 to 0.90 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.80 to 1.10 Cr, 0.15 V min. **6150H. AISI and UNS:** 0.47 to 0.54 C, 0.60 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.75 to 1.20 Cr, 0.15 V min.

Similar Steels (U.S. and/or Foreign). **6150.** UNS G61500; AMS 6448, 6450, 6455; ASTM A322, A331; MIL SPEC MIL-S-8503; SAE J404, J412, J770; (Ger.) DIN 1.8159; (Fr.) AFNOR 50 CV 4; (Ital.) UNI 50 CrV 4; (Jap.) JIS SUP 10; (Swed.) SS_{14} 2230; (U.K.) B.S. 735 A 50, En. 47. **6150H.** UNS H61500; ASTM A304; SAE J407; (Ger.) DIN 1.8159; (Fr.) AFNOR 50 CV 4; (Ital.) UNI 50 CrV 4; (Jap.) JIS SUP 10; (Swed.) SS_{14} 2230; (U.K.) B.S. 735 A 50, En. 47

Characteristics. A medium high-carbon chromium-vanadium alloy steel which has been used for numerous applications including premium quality springs. Its as-quenched hardness is generally 55 to 60 HRC, depending on the precise carbon content. Hardenability is relatively high, approximately the same as for 4140H. The chromium content is mainly responsible for the hardenability. The vanadium serves as a grain refiner and has no significant effect on hardenability. Is forgeable, but is not recommended for welding

Forging. Heat to 1230 °C (2250 °F) maximum. Do not forge after temperature of forging stock drops below approximately 900 °C (1650 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F). Cool in air

Annealing. For a predominantly pearlitic structure, heat to 830 °C (1525 °F), cool rapidly to 760 °C (1400 °F), then cool to 675 °C (1245 °F), at a rate not to exceed 8 °C (15 °F) per h; or heat to 830 °C (1525 °F), cool rapidly to 675 °C (1245 °F), and hold for 6 h. For a predominantly spheroidized structure, heat to 760 °C (1400 °F), and cool to 675 °C (1245 °F) at a rate not to exceed 6 °C (10 °F) per h; or heat to 760 °C (1400 °F), cool rapidly to 650 °C (1200 °F), and hold for 10 h

Hardening. Heat to 870 °C (1600 °F), and quench in oil

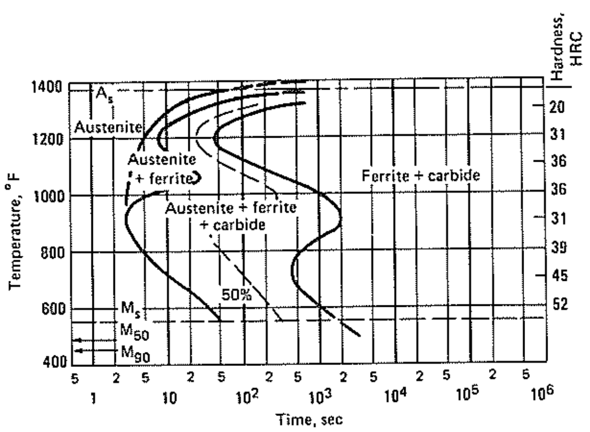
Tempering. Reheat immediately after quenching [preferably before the temperature of the parts drops below the range of 38 to 50 °C (100 to 120 °F)] to the temperature required to obtain the desire combination of mechanical properties

Austempering. For many spring applications, this steel is austempered by austenitizing at 870 °C (1600 °F), quenching in an agitated molten salt bath at 315 °C (600 °F), holding for 1 h, and air cooling. No tempering is required. Hardness after this treatment generally ranges from approximately 46 to 51 HRC

Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize and quench (or austemper)
- Temper (or austemper)
- Finish machine

6150: Isothermal Transformation Diagram. Composition: 0.53 C, 0.67 Mn, 0.93 Cr, 0.18 V. Austenitized at 845 °C (1555 °F). Grain size: 9

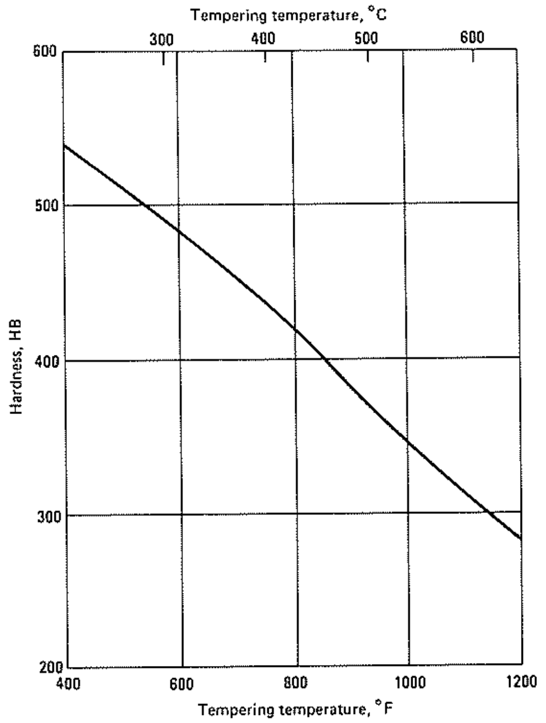


6150: Equipment requirements for salt martempering gears

Production requirements	
Weight of each piece	0.9 kg (2 lb)
Pieces per furnace load	32
Production per hour(a):	
Number of pieces	128
Net work load	116 kg (256 lb)
Gross furnace load(b)	152 kg (336 lb)
Equipment requirements	
Martempering furnace	Immersion-heated salt pot(c)
Size of salt pot	610 by 381 by 838 mm (24 by 15 by 33 in.)
Capacity of salt pot	272 kg (600 lb)
Type of salt	Nitrate-nitrite (2% water added)
Quenching capacity of salt pot	181 kg/h (400 lb/h)
Operating temperature	205 °C (400 °F)
Agitation	Air-operated stirrer

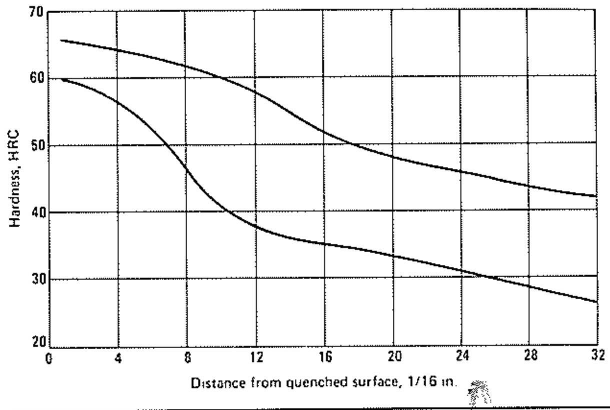
(a) Cycle time, 15 min. (b) Work and fixtures. Each fixture weighed 9.1 kg (20 lb) empty and contained eight gears. (c) Salt pot rated at 21 kV · A (3 phase, 60 cycle, 220 to 440 V) for heating to temperature range of 175 to 400 °C (350 to 750 °F). Blower (½ hp, 3 phase, 60 cycles, 220 V) used for cooling by driving room-temperature air between wall of pot and exterior shell of furnace

6150: Hardness vs Tempering Temperature. Normalized at 900 °C (1650 °F), quenched from 870 °C (1600 °F) in oil, tempered in 56 °C (100 °F) intervals in 13.7 mm (0.540 in.) rounds. Tested in 12.8 mm (0.505 in.) rounds. Source: Republic Steel



6150H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min
1	1.58	65	59	13	20.54	57	37
2	3.16	65	58	14	22.12	55	36
3	4.74	64	57	15	23.70	54	35
4	6.32	64	56	16	25.28	52	35
5	7.90	63	55	18	28.44	50	34
6	9.48	63	53	20	31.60	48	32
7	11.06	62	50	22	34.76	47	31
8	12.64	61	47	24	37.92	46	30
9	14.22	61	43	26	41.08	45	29
10	15.80	60	41	28	44.24	44	27
11	17.38	59	39	30	47.40	43	26
12	18.96	58	38	32	50.56	42	25



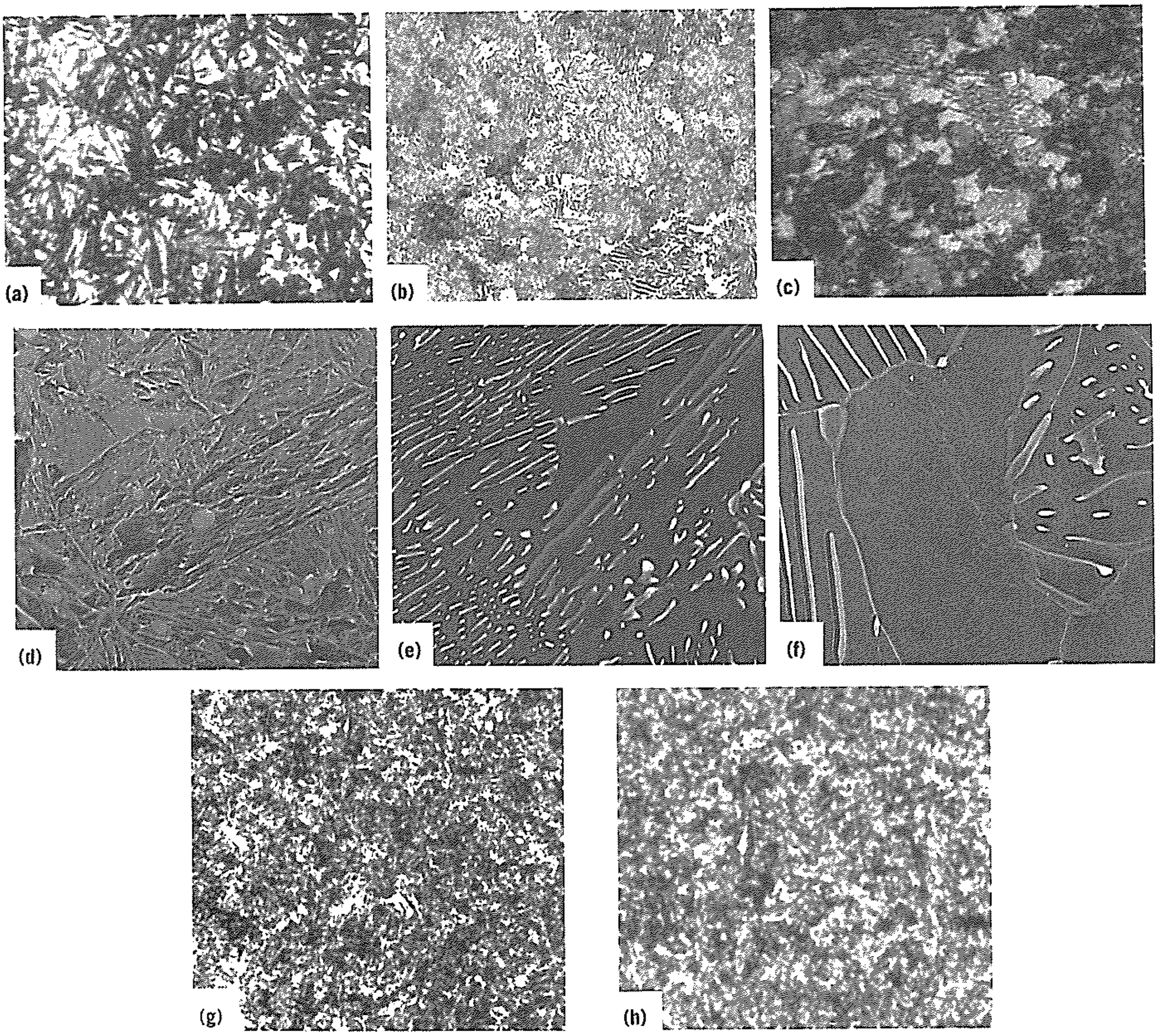
6150: As-Quenched Hardness (Oil)

Single heat results; grade: 0.48 to 0.53 C, 0.70 to 0.90 Mn, 0.20 to 0.35 Si, 0.80 to 1.10 Cr, 0.15 V minimum; ladle: 0.51 C, 0.80 Mn, 0.014 P, 0.015 S, 0.35 Si, 0.11 Ni, 0.95 Cr, 0.01 Mo, 0.18 V; grain size: 5 to 6 for 70%, 2 to 4 for 30%

Size round, in.	Size round, mm	Hardness, HRC Surface	Hardness, HRC ½ radius	Hardness, HRC Center
½	13	61	60	60
1	25	60	58	57
2	51	54	47	44
4	102	42	36	35

Source: Bethlehem Steel

6150: Microstructures. (a) 2% nital, 550×. Steel wire, austenitized at 900 °C (1650 °F) for 20 min and slack quenched in oil to room temperature. Lower bainite (dark) and untempered martensite (light). (b) Picral, 550×. Austenitized at 880 °C (1620 °F) for ½ h, cooled to 730 °C (1350 °F) held 5 h, cooled to 650 °C (1200 °F) at 28 °C (50 °F) per h, held 1 h, air cooled. Pearlite and ferrite. (c) 4% nital, 500×. Steel wire, austenitized at 885 °C (1625 °F) for 20 min, quenched to 675 °C (1245 °F) for 20 min, oil quenched to room temperature. Structure mainly pearlite. (d) 4% nital, 5000×. Steel wire, austenitized at 845 °C (1555 °F) for ½ h, oil quenched, tempered at 150 °C (300 °F). An electron micrograph of a replica rotary-shadowed with chromium. Tempered martensite and some spheroidal carbide particles. (e) 4% nital, 10,000×. Steel wire, austenitized at 870 °C (1600 °F), held for 2 h, quenched in lead to 650 °C (1200 °F), held for 2 h, water quenched. An electron micrograph of a replica rotary-shadowed with chromium. Partly spheroidized carbide in a ferrite matrix. (f) 4% nital, 10,000×. Steel wire, austenitized at 870 °C (1600 °F) for 2 h, quenched in lead to 720 °C (1330 °F), held 2 h, water quenched. An electron micrograph of a replica rotary-shadowed with chromium. Partly spheroidized and partly lamellar pearlite in ferrite. (g) Nital, 535×. Steel rod, 13 mm (½ in.) diam, austenitized at 845 °C (1555 °F) for 1 h, quenched to 315 °C (600 °F), held 16 min, air cooled. Mostly bainite, probably lower bainite. (h) Nital, 1000×. Same steel, rod diameter, and heat treatment as (g), except at higher magnification. Austempering was the heat treatment used



81B45, 81B45H

Chemical Composition. **81B45. AISI:** 0.43 to 0.48 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.20 to 0.40 Ni, 0.35 to 0.55 Cr, 0.08 to 0.15 Mo, 0.0005 to 0.003 B. **UNS:** 0.43 to 0.48 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.20 to 0.40 Ni, 0.35 to 0.55 Cr, 0.08 to 0.15 Mo, 0.0005 B min. **UNS H81451 and SAE/AISI 81B45H:** 0.42 to 0.49 C, 0.70 to 1.05 Mn, 0.15 to 0.35 Si, 0.15 to 0.45 Ni, 0.30 to 0.60 Cr, 0.08 to 0.15 Mo, B (can be expected to be 0.0005 to 0.003 percent)

Similar Steels (U.S. and/or Foreign). **81B45.** UNS G81451; ASTM A519; SAE J404, J412, J770. **81B45H.** UNS H81451; ASTM A304; SAE J1268

Characteristics. A slightly modified version of 86B45H. Ni, Cr, and Mo are slightly lower. The as-quenched hardnesses of the two steels are essentially the same, approximately 54 to 60 HRC. Hardenability of the two grades is nearly the same

Forging. Heat to 1230 °C (2250 °F) maximum. Do not forge after temperature of forging stock drops below approximately 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

Annealing. For a predominantly pearlitic structure, heat to 830 °C (1525 °F), cool rapidly to 725 °C (1335 °F), then cool to 640 °C (1185 °F), at a rate not to exceed 11 °C (20 °F) per h; or heat to 830 °C (1525 °F), cool rapidly to 660 °C (1220 °F), and hold for 7 h. For a predominantly spheroidized structure, heat to 750 °C (1380 °F), and cool rapidly to 725 °C (1335 °F), then continue cooling to 640 °C (1185 °F) at a rate not to exceed 6 °C (10 °F); or heat to 750 °C (1380 °F), cool rapidly to 660 °C (1220 °F), and hold for 10 h

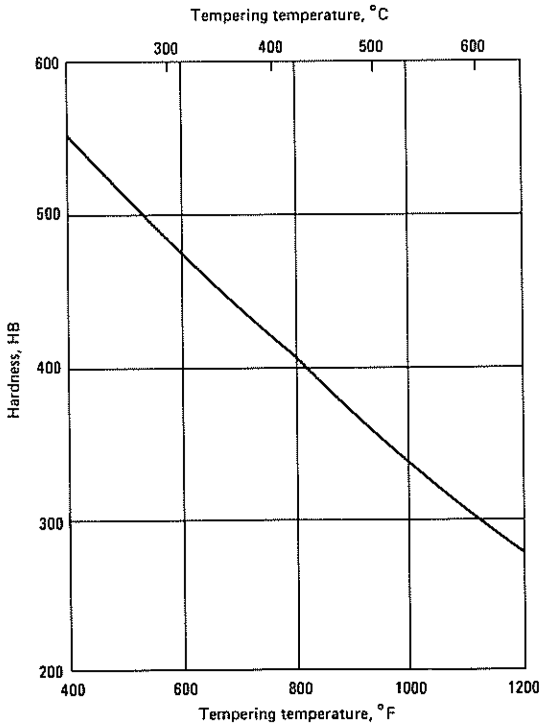
Hardening. Heat to 845 °C (1555 °F), and quench in oil

Tempering. After quenching, parts should be tempered immediately. Selection of tempering temperature depends upon the desired mechanical properties

Recommended Processing Sequence

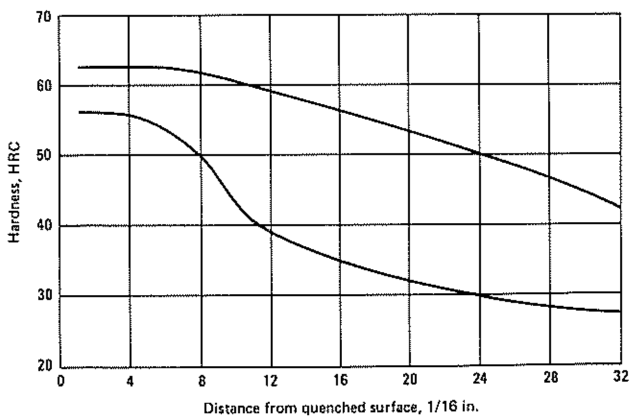
- Forge
- Normalize
- Anneal
- Rough and semifinish machine
- Austenitize and quench
- Temper
- Finish machine

81B45: Hardness vs Tempering Temperature. Normalized at 870 °C (1600 °F), quenched from 845 °C (1555 °F) in oil, tempered in 56 °C (100 °F) intervals in 13.7 mm (0.540 in.) rounds. Tested in 12.8 mm (0.505 in.) rounds. Source: Republic Steel



81B45H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max	min	Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max	min
1	1.58	63	56	13	20.54	58	38
2	3.16	63	56	14	22.12	57	37
3	4.74	63	56	15	23.70	57	36
4	6.32	63	56	16	25.28	56	35
5	7.90	63	55	18	28.44	55	34
6	9.48	63	54	20	31.60	53	32
7	11.06	62	53	22	34.76	52	31
8	12.64	62	51	24	37.92	50	30
9	14.22	61	48	26	41.08	49	29
10	15.80	60	44	28	44.24	47	28
11	17.33	60	41	30	47.40	45	28
12	18.96	59	39	32	50.56	43	27



3615

:hemical Composition. 8615. **AISI and UNS:** 0.13 to 0.18 C, 0.70 › 0.90 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.40 to 0.70 Ni, 0.40 › 0.60 Cr, 0.15 to 0.25 Mo

;imilar Steels (U.S. and/or Foreign). UNS G86150; AMS 333; ASTM A322; MIL SPEC MIL-S-866; SAE J404, J770

:haracteristics. Similar to 8617H and 8620H, except with a lower arbon range. Extensively used for parts processed by carburizing and arbonitriding. Although there is no published AISI hardenability band for 615, the hardenability pattern for 8615 should be very similar to that for 617H, adjusted down slightly because 8615 has a lower carbon range. ıs-quenched surface hardness for 8615 usually ranges from 35 to 40 HRC. 'orgeable and weldable; machinability is fairly good

'orging. Heat to 1245 °C (2275 °F) maximum. Do not forge after ːmperature of forging stock drops below approximately 900 °C (1650 °F)

ɫecommended Heat Treating Practice

ɫormalizing. Heat to 925 °C (1695 °F). Cool in air

ɩnnealing. Structures with best machinability are developed by norıalizing or by heating to 885 °C (1625 °F), cooling rapidly to 660 °C (1220 °F), then holding for 4 h. Another technique is to heat to 790 °C (1455 °F), cool rapidly to 660 °C (1220 °F), and hold for 8 h

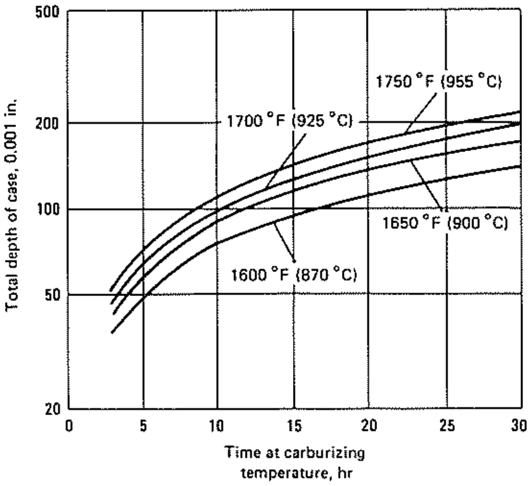
Tempering. Temper all carburized or carbonitrided parts at 150 °C (300 °F), and no case hardness will be lost as a result. If some decrease in hardness can be tolerated, toughness can be increased by tempering at somewhat higher temperatures, up to 260 °C (500 °F)

Case Hardening. See carburizing and carbonitriding practices described for 8620H. Flame hardening and ion nitriding are alternative processes

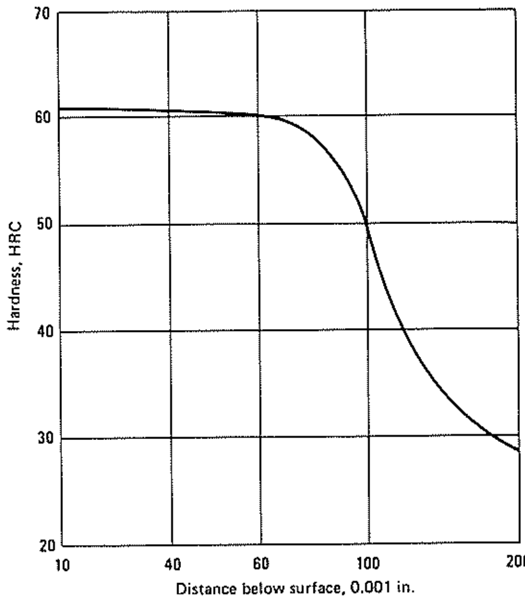
Recommended Processing Sequence

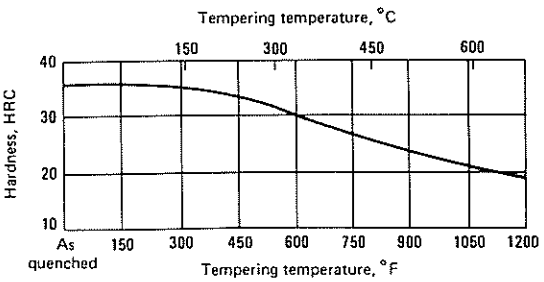
- Forge
- Normalize
- Anneal (if required)
- Rough machine
- Semifinish machine allowing only grinding stock, no more than 10% of the case depth per side for carburized parts. In most instances, carbonitrided parts are completely finished in this step
- Carburize or carbonitride and quench
- Temper

8615: Case Depth of Liquid Carburized Steel vs Time and Temperature. 19 mm (0.75 in.) outside diam by 121 mm (4.75 in.), oil quenched. Carburized at indicated temperatures



8615: Liquid Carburizing. Specimens 190 mm (0.75 in.) by 120.65 mm (4.75 in.), carburized at 925 ° C (1695 °F) for 15 h, air cooled, reheated in neutral salt at 845 ° C (1555 °F), quenched in salt at 180 ° C (355 °F)





8615: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

8617, 8617H

Chemical Composition. **8617. AISI and UNS:** 0.15 to 0.20 C, 0.70 to 0.90 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.15 to 0.25 Mo. **UNS H86170 and SAE/AISI 8617H:** 0.14 to 0.20 C, 0.60 to 0.95 Mn, 0.15 to 0.35 Si, 0.35 to 0.75 Ni, 0.35 to 0.65 Cr, 0.15 to 0.25 Mo

Similar Steels (U.S. and/or Foreign). **8617.** UNS G86170; AMS 6272; SAE J404, J770; (Ger.) DIN 1.6523; (Fr.) AFNOR 20 NCD 2, 22 NCD 2; (Ital.) UNI 20 NiCrMo 2; (Jap.) JIS SNCM 21 H, SNCM 21; (U.K.) B.S. 805 H 20, 805 M 20. **8617H.** UNS H86170; ASTM A304; SAE J1268; (Ger.) DIN 1.6523; (Fr.) AFNOR 20 NCD 2, 22 NCD 2; (Ital.) UNI 20 NiCrMo 2; (Jap.) JIS SNCM 21 H, SNCM 21; (U.K.) B.S. 805 H 20, 805 M 20

Characteristics. A carburizing grade of the multiple alloy series, Ni-Cr-Mo. Not as widely used for case hardening as 8620H and 8622H. An as-quenched hardness of approximately 35 to 40 HRC can be expected without carburizing. Hardenability is reasonably high. Has excellent forgeability, can be welded using alloy steel practice, and has fairly good machinability

Forging. Heat to 1245 °C (2275 °F) maximum. Do not forge after temperature of forging stock drops below approximately 900 °C (1650 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Cool in air

Annealing. Structures with best machinability are developed by normalizing or by heating to 885 °C (1625 °F), cooling rapidly to 660 °C (1220 °F), and holding for 4 h; or heat to 790 °C (1455 °F), cool rapidly to 660 °C (1220 °F), and hold for 8 h.

Tempering. Temper all carburized or carbonitrided parts at 150 °C (300 °F) and no loss of case hardness will result. If some decrease in hardness can be tolerated, toughness can be increased by tempering at somewhat higher temperatures, up to 260 °C (500 °F)

Case Hardening. See carburizing and carbonitriding practices described for 8620H. Flame hardening, ion nitriding, gas nitriding, gas carburizing, austempering and martempering are alternative processes

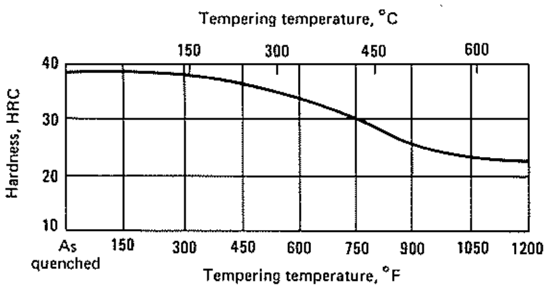
Recommended Processing Sequence

- Forge
- Normalize
- Anneal (if required)
- Rough machine
- Semifinish machine allowing only grinding stock, no more than 10% of the case depth per side for carburized parts. In most instances, carbonitrided parts are completely finished in this step
- Carburize or carbonitride and quench
- Temper

8617: Equipment requirements for oil martempering carburized parts

Production requirements	
Weight of load	453.6 kg (1000 lb net)
Weight of each piece	1.5 kg (3.3 lb)
Number of pieces treated per hour	75
Equipment requirements	
Capacity of quench tank	7511 L (2000 gal)
Type of oil	Mineral oil with additives (viscosity, 250 SUS)
Temperature of oil	150 °C (300 °F)
Agitation	Direct flow(a)

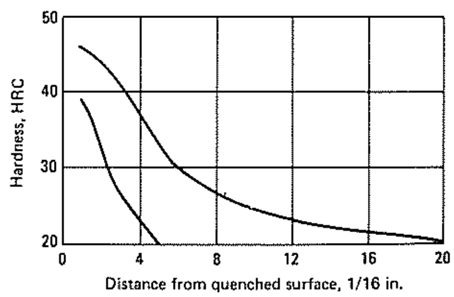
(a) Agitation provided by two 5-hp motors driving 457-mm (18-in.) propellers at 370 rpm, causing the oil to flow at a rate of 914 mm/sec (36 in./sec)



8617, 8617H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

8617H: End-Quench Hardenability

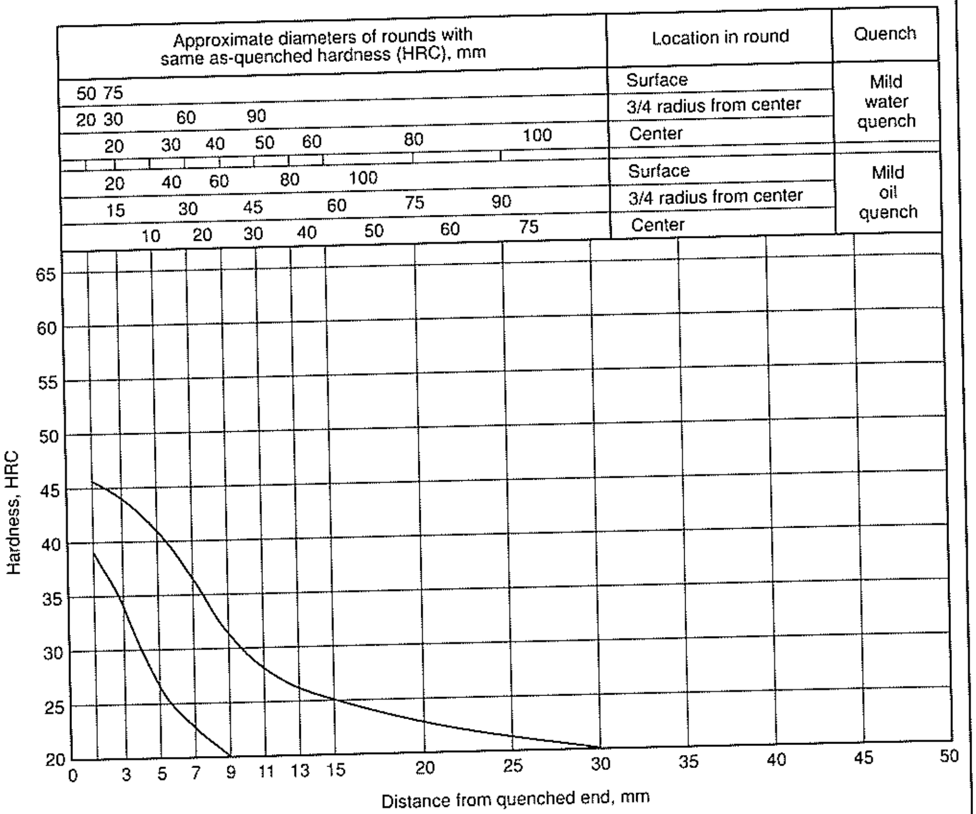
Distance from quenched surface		Hardness, HRC		Distance from quenched surface		Hardness, HRC
1/16 in.	mm	max	min	1/16 in.	mm	max
1	1.58	46	39	13	20.54	23
2	3.16	44	33	14	22.12	22
3	4.74	41	27	15	23.70	22
4	6.32	38	24	16	25.28	21
5	7.90	34	20	18	28.44	21
6	9.48	31	...	20	31.60	20
7	11.06	28	...	22	34.76	...
8	12.64	27	...	24	37.92	...
9	14.22	26	...	26	41.08	...
10	15.80	25	...	28	44.24	...
11	17.38	24	...	30	47.40	...
12	18.96	23	...	32	50.56	...



8617H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 925 °C (1700 °F)

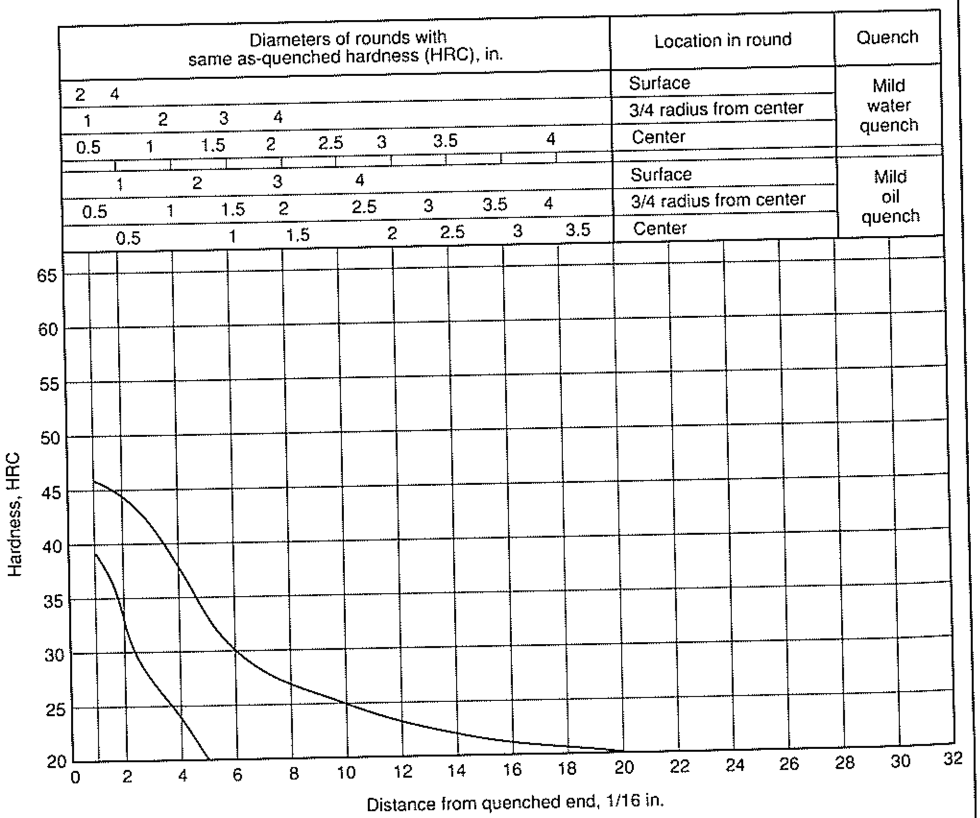
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	46	39
3	44	33
5	42	27
7	37	23
9	32	20
11	29	...
13	27	...
15	25	...
20	23	...
25	22	...
30	20	...
35	...	...

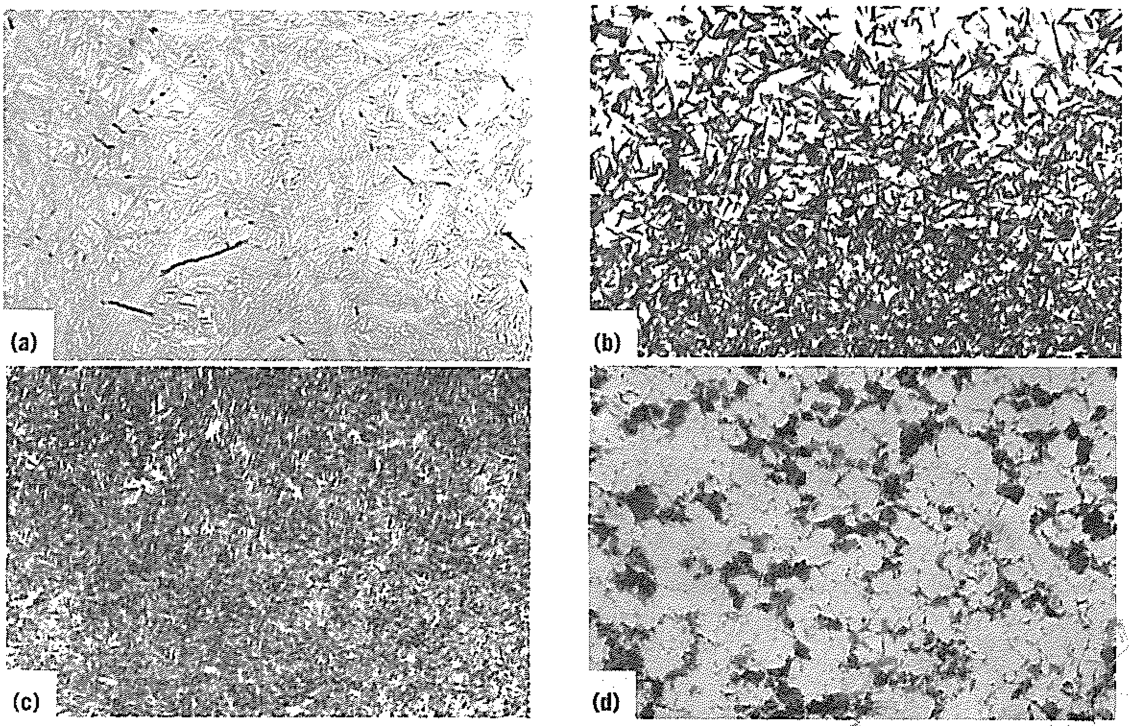


Hardness limits for specification purposes

J distance, 1/16 mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1	46	39
2	44	33
3	41	27
4	38	24
5	34	20
6	31	...
7	28	...
8	27	...
9	26	...
10	25	...
11	24	...
12	23	...
13	23	...
14	22	...
15	22	...
16	21	...
18	21	...
20	20	...
22	...	...



8617: Microstructures. (a) 1% nital, 500×. 8617H, gas carburized for 3 ¾ h at 925 °C (1695 °F), cooled in the furnace to 540 °C (1000 °F), air cooled, heated to 840 °C (1545 °F), quenched in oil, tempered for 2 h at 150 °C (300 °F), quenched in oil, tempered for 2 h at 150 °C (300 °F). Numerous microcracks (small black streaks), are present both at the boundaries and across martensite plates. (b) 3% nital, 200×. 8617, carbonitrided 4 h at 845 °C (1555 °F) in 8% ammonia, 8% propane, remainder endothermic gas, oil quenched, tempered 1 ½ h at 150 °C (300 °F). Tempered martensite (dark) and retained austenite. (c) 3% nital, 200×. 8617 steel bar, carbonitrided and tempered same as (b), except held at -73 °C (-100 °F) for 2 h between quenching and tempering to transform most of the retained austenite. Scattered carbide and small amounts of retained austenite in a matrix of tempered martensite. (d) Picral, 200×. 8617 steel bar, annealed by being austenitized at 870 °C (1600 °F) for 2 h, furnace cooled. Fine pearlite (dark) in ferrite matrix (light). Magnification too low for good resolution of structure



8620, 8620H

Chemical Composition. 8620. AISI and UNS: Nominal. 0.18 to 0.23 C, 0.70 to 0.90 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.15 to 0.25 Mo. **8620H. AISI and UNS:** Nominal. 0.17 to 0.23 C, 0.60 to 0.95 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.35 to 0.75 Ni, 0.35 to 0.65 Cr, 0.15 to 0.25 Mo

Similar Steels (U.S. and/or Foreign). 8620. UNS G86200; AMS 6274, 6276, 6277; ASTM A322, A331, A513, A914; MIL SPEC MIL-S-16974; SAE J1268, J1868; (W. Ger.) DIN 1.6523; (Fr.) AFNOR 20 NCD 2, 22 NCD 2; (Ital.) UNI 20 NiCrMo 2; (Jap.) JIS SNCM 21 H, SNCM 21; (U.K.) B.S. 805 H 20, 805 M 20. **8620H.** UNS H86200; ASTM A304; SAE J407; (W. Ger.) DIN 1.6523; (Fr.) AFNOR 20 NCD 2, 22 NCD 2; (Ital.) UNI 20 NiCrMo 2; (Jap.) JIS SNCM 21 H, SNCM 21; (U.K.) B.S. 805 H 20, 805 M 20

Characteristics. Used extensively as a case hardening steel for both carburizing and carbonitriding. As-quenched surface hardness usually ranges from approximately 37 to 43 HRC. Reasonably high hardenability. Excellent forgeability and weldability, although alloy steel practice should be used in welding to minimize susceptibility to weld cracking. Machinability is fairly good. Because 8620H and 8620 are high-tonnage steels, some mills produce them with lead additions. This significantly improves machinability without sacrificing heat treating response

Forging. Heat to 1245 °C (2275 °F) maximum, and do not forge after the temperature of the forging stock has dropped below approximately 900 °C (1650 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1700 °F) and cool in air

Annealing. Structures with best machinability are developed by normalizing or by heating to 885 °C (1625 °F), cooling rapidly to 660 °C (1225 °F), and holding for 4 h. Another technique is to heat to 790 °C (1450 °F), cool rapidly to 660 °C (1225 °F), and hold for 8 h

Carburizing. In general, carburizing practice for 8620H (and 8620) is the same as for other low-carbon, plain carbon, and alloy steels. Because of its inefficiency, the pack method is used only for highly specialized applications. Carburizing by immersion is often used, although mainly for developing relatively thin cases. Any one of a number of proprietary molten salt baths can be used, usually within the temperature range of 870 to 925 °C (1600 to 1700 °F). As a rule, workpieces are quenched directly from the carburizing temperature. 8620H and other carbon and alloy steels are most frequently gas carburized, a far more efficient method that is easier to control

ias Carburizing. Although a number of different cycles can be used ffectively for 8620 and 8620H, the one listed below is a cycle used xtensively:

- Carburize at 925 °C (1700 °F) in a prepared carbonaceous atmosphere with the desired carbon potential (commonly about 0.90 carbon) for 4 h
- Reduce temperature to 845 °C (1555 °F), reduce carbon potential to near eutectoid, and diffuse for 1 h
- Quench in oil
- Temper for 1 h at 150 °C (300 °F)

This cycle will result in a total case of approximately 1.3 mm (0.050 in.). Deeper cases can be obtained with longer cycles, but this is a matter of diminishing returns. Obtaining greater case depths by increasing time cycles is costly in terms of energy consumption. Case depth can be increased exponentially by increasing the carburizing temperature, but this approach becomes a matter of economics as well, because the rate of deterioration on furnace alloys and refractories above about 925 °C (1700 °F) may become intolerable because of the high cost of furnace maintenance. The most economical approach for deep-case carburizing is the use of the vacuum furnace, which operates as high as 1095 °C (2000 °F)

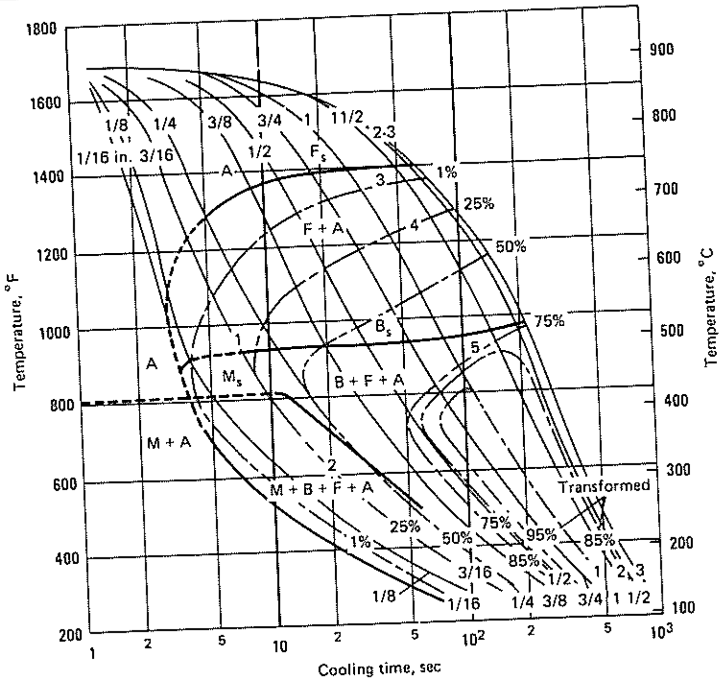
Carbonitriding. For thin, file-hard cases, parts made of 8620 or 8620H are often carbonitrided at 845 °C (1550 °F) in a carbonaceous atmosphere with an addition of 10% anhydrous ammonia. Temperatures of 790 to 900 °C (1450 to 1650 °F) have been used, but 845 °C (1555 °F) seems to be the most common. Parts are oil quenched directly from the carbonitriding temperature. Just as is true for carburizing, the case depth increases with time at temperature. Using a carbonitriding temperature of 845 °C (1555 °F), it is possible to obtain a case depth of approximately 0.305 mm (0.012 in.) in about 45 min

Other Processes. Flame hardening, austempering, martempering, ion nitriding, gas nitriding ion carburizing, vacuum carburizing, liquid carburizing

Tempering. Temper all carburized or carbonitrided parts at 150 °C (300 °F) and virtually no loss of case hardness results. If some decrease in hardness can be tolerated, toughness can be increased by tempering at somewhat higher temperatures, up to 260 °C (500 °F)

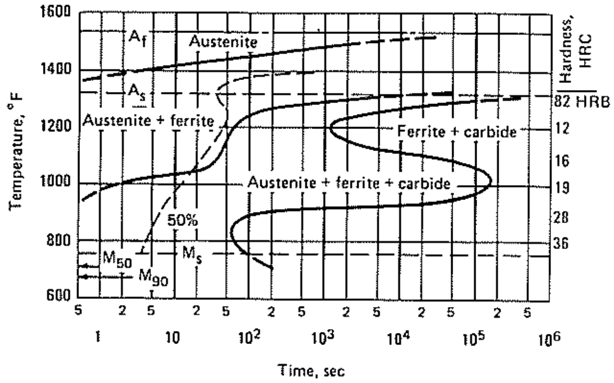
Recommended Processing Sequence

- Forge
- Normalize
- Anneal (if required)
- Rough machine
- Semifinish machine, allowing only grinding stock, no more than 10% of the case depth per side for carburized parts. In most instances, carbonitrided parts are completely finished in this step
- Carburize or carbonitride and quench
- Temper

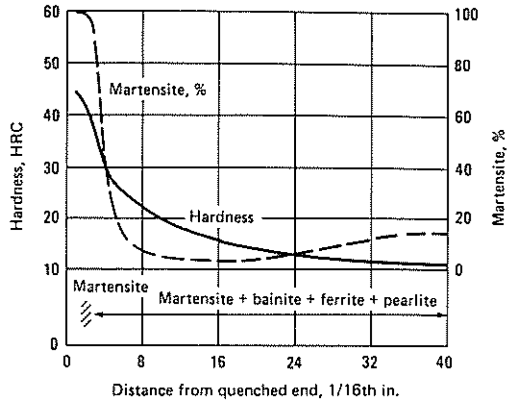


8620: Continuous Cooling Curves. Composition: 0.17 C, 0.82 Mn, 0.31 Si, 0.52 Ni, 0.50 Cr, 0.20 Mo. Austenitized at 925 °C (1700 °F). Grain size: 9. Ac_3, 825 °C (1520 °F); Ac_1, 745 °C (1370 °F). A: austenite, F: ferrite, B: bainite, M: martensite

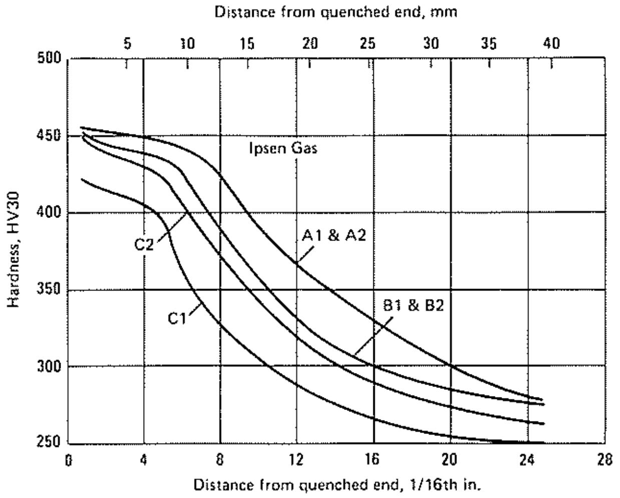
8620: Isothermal Transformation Diagram. Composition: 0.18 C, 0.79 Mn, 0.52 Ni, 0.56 Cr, 0.19 Mo. Austenitized at 900 °C (1650 °F). Grain size: 9 to 10



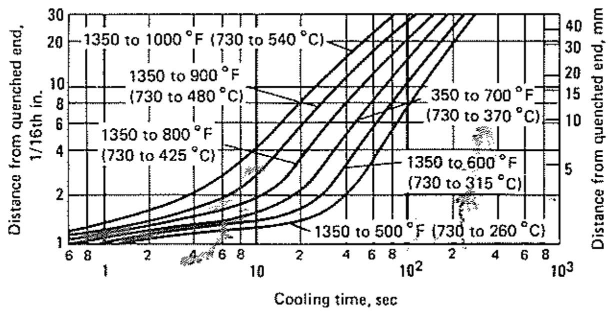
8620: End-Quench Hardenability. Composition: 0.18 C, 0.79 Mn, 0.52 Ni, 0.56 Cr, 0.19 Mo. Austenitized at 900 °C (1650 °F). Grain size: 9 to 10



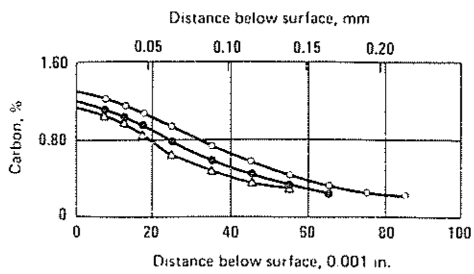
8620: Austenitizing Temperature vs Depth of Hardness. Cast RL7911. Heat treatment: A: 900 °C (1650 °F), 15 min, Ipsen Furnace; B: 1000 °C (1830 °F), 15 min, Ipsen Furnace; C: 1100 °C (2010 °F), 15 min, Muffle and Ipsen. Depth below surface: 1: 0.3 mm (0.012 in.); 2: 2.5 mm (0.1 in.)



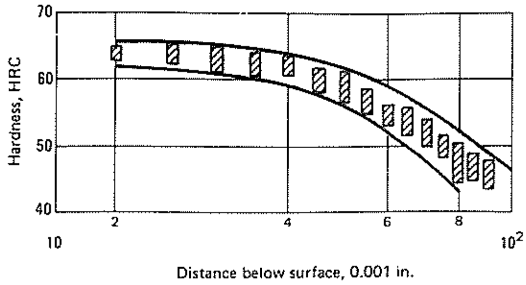
8620: Cooling Time vs Depth of Hardness. Time to cool from 730 °C (1350 °F) to temperatures of 540 to 260 °C (1000 to 500 °F), quenched from 845 °C (1555 °F)



8620: Gas Carburizing. Carburized in a recirculating pit furnace. 7.5 h at temperature. 12% CH_4. Core: 0.22% C. O: 925 °C (1700 °F); ●: 900 °C (1650 °F); Δ: 870 °C (1600 °F)

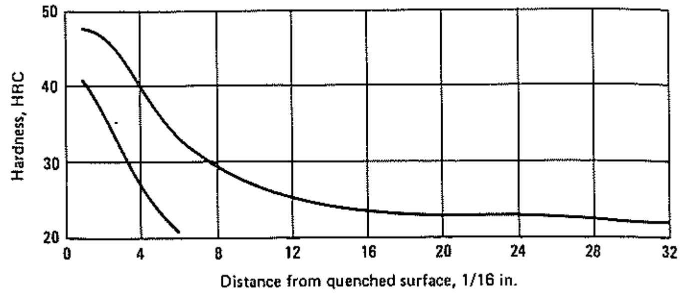


8620: Liquid Carburizing, Case Hardness Gradients. Nine tests. Scatter resulting from normal variations

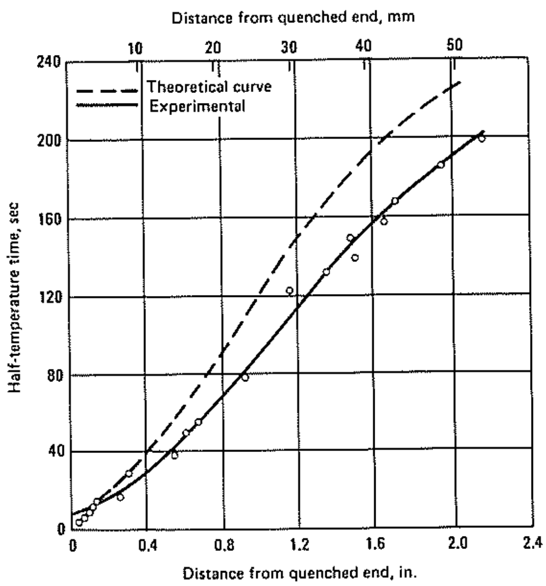


8620H: End-Quench Hardenability

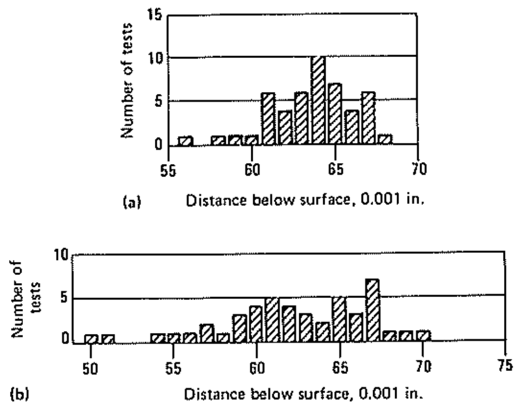
Distance from quenched surface, $^1/_{16}$ in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, $^1/_{16}$ in.	Distance from quenched surface, mm	Hardness, HRC max
1	1.58	48	41	13	20.54	25
2	3.16	47	37	14	22.12	25
3	4.74	44	32	15	23.70	24
4	6.32	41	27	16	25.28	24
5	7.90	37	23	18	28.44	23
6	9.48	34	21	20	31.60	23
7	11.06	32	...	22	34.76	23
8	12.64	30	...	24	37.92	23
9	14.22	29	...	26	41.08	23
10	15.80	28	...	28	44.24	22
11	17.38	27	...	30	47.40	22
12	18.96	26	...	32	50.56	22



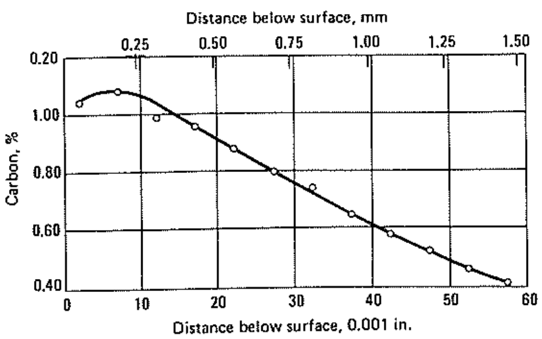
8620: End-Quench Hardenability. Jominy results compared with theoretical curve (constant H)



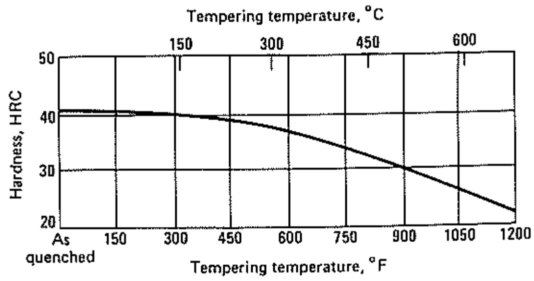
8620: Depth of Case vs 0.40% C and 59 HRC. Test specimens 25-mm (1-in.) diam were processed with production gears in a two-row continuous gas carburizing furnace using a diffusion cycle and an atmosphere of endothermic gas enriched with natural gas; air was added to the discharge end. Effective case depth to 50 HRC was measured on a microhardness traverse taken midway between the ends of a cross section of the gear tooth at the junction of the involute profile and root fillet. (a) Depth of case to 0.40% C, 48 tests. 25-mm (1-in.) diam bar tempered in lead at 650 °C (1200 °F). (b) Depth of case to 50 HRC, 47 tests. Gears tempered at 160 °C (325 °F)



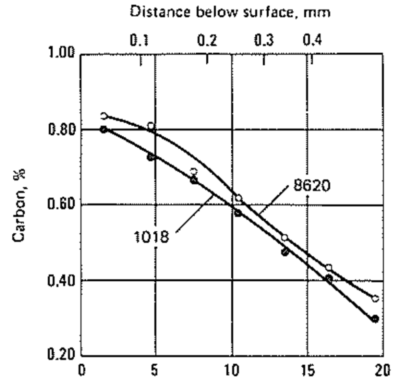
8620: Carbon Gradients Produced by Liquid Carburizing. 19-mm (0.75-in.) diam by 51 mm (2 in.), carburized at 910 °C (1675 °F) for 8 h



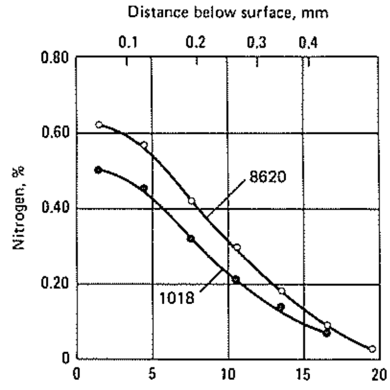
8620, 8620H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure



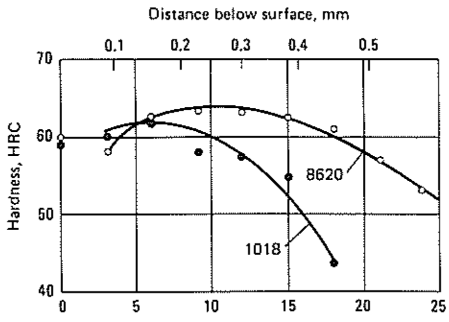
8620: Carbon, Nitrogen, and Hardness Gradients. 8620 and 1018 carbonitrided at 845 °C (1555 °F) for 4 h in a batch radiant-tube furnace. Test data were obtained in a construction-equipment manufacturing plant under normal production conditions, using a standard carbonitriding cycle. Test specimens were carbonitrided in production loads containing 23 kg (50 lb) of gears and shafts. The carbonitriding atmosphere, which was controlled by an infrared control unit, consisted of endothermic gas at 14.1 m³/h (500 ft³/h), ammonia at 0.71 m³/h (25 ft³/h), propane at 0.01 to 0.02 m³/h (0.25 to 0.75 ft³/h), and 0.32 to 0.34% CO_2. Dew point of the atmosphere was maintained at −7 to −6 °C (19 to 21 °F) throughout the carbonitriding cycle. All specimens were quenched from the carbonitriding temperature (845 °C or 1555 °F) in warm (54 °C or 130 °F) oil. (a) Carbon; (b) Nitrogen; (c) Hardness. Quenched in oil at 54 °C (130 °F). Hardness converted from Tukon



(a)

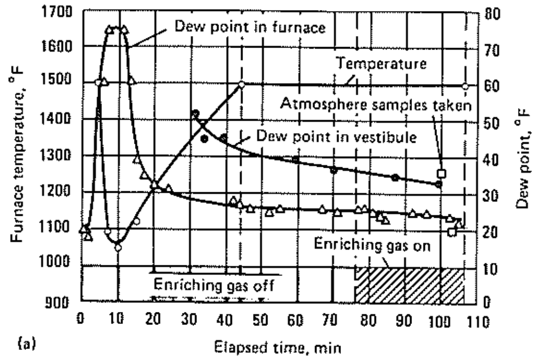


(b)

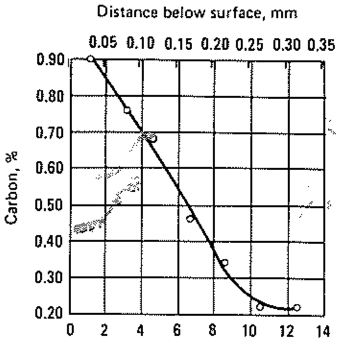


(c)

8620H: Carbonitriding. Load: gears, 342 kg (753 lb) net, 459 kg (1011 lb) gross. Batch-type furnace with brick-lined heating chamber, heated by radiant tubes; vestibule-enclosed quench. Dimensions of furnace chamber: 1422 mm wide, 1676 mm long, 1092 mm high (56 by 66 by 43 in.). Carrier gas: endothermic gas at 21.2 m³/h (750 ft³/h), including 63 min at temperature. Enriching gas: additions of propane at 0.1 m³/h (5 ft³/h), and of ammonia at 1.1 m³/h (38 ft³/h), started after 33 min at temperature. Generator dew point: −15 to −14 °C (5 to 7 °F) throughout carbonitriding process cycle. Heating chamber pressure: 1.5 to 2.0 mm (0.06 to 0.08 in.) H_2O. Carbonitriding temperature: 815 °C (1500 °F). Quenching temperature: 815 °C (1500 °F). (a) Temperature and dew-point variations. (b) resulting carbon gradient



(a)



(b)

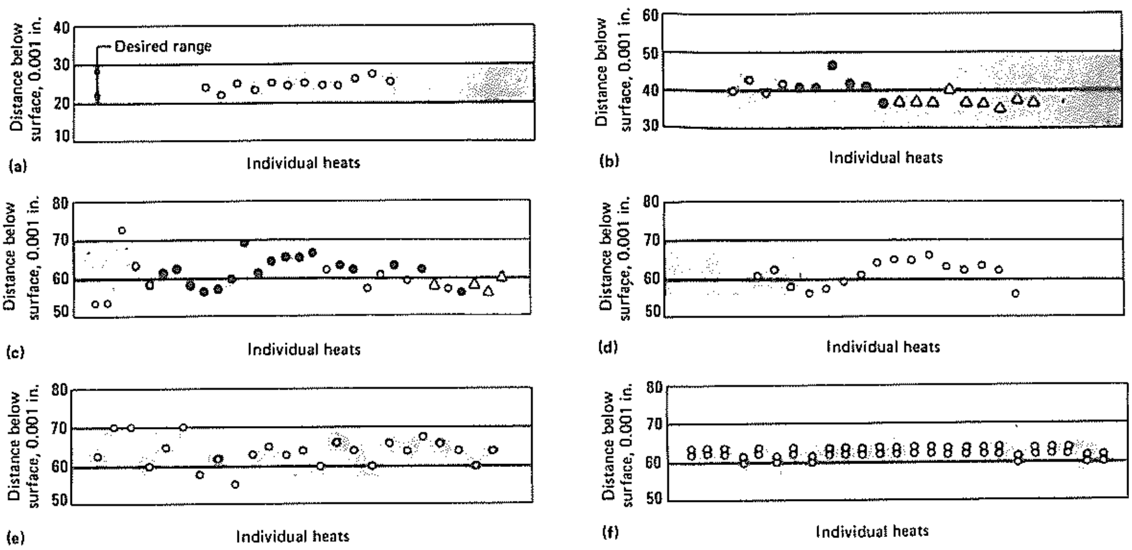
Analysis of Atmosphere Near End of Cycle

Constituent	Amount in furnace, %	Amount in vestibule, %
CO_2	0.4	0.8
O_2	...	0.0
CO	20.4	22.4
CH_4	1.2	1.2
H_2	34.2	34.2
N_2	rem	rem

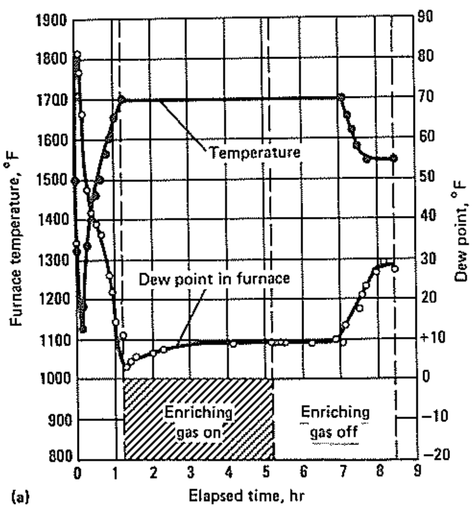
8620: Approximate Critical Points

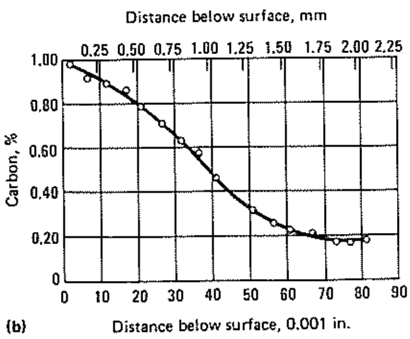
Critical point	Temperature °F	Temperature °C
Ac_1	1350	730
Ac_3	1525	830
Ar_3	1415	770
Ar_1	1220	660

8620: Depth of Case After Gas Carburizing. Depth of case to 0.40% C. O: Furnace A. 762 by 1219 by 457 mm (30 by 48 by 18 in.). Atmosphere control dew cell with manual reset. Rated gross load, 680 kg (1500 lb). ●: Furnace B, same as Furnace A. Δ: Furnace C. 914 by 1829 by 610 mm (36 by 72 by 24 in.). Atmosphere control infrared analyzer controlling carbon dioxide, automatic reset. Rated gross load, 1588 kg (3500 lb) (a) 25-mm (1-in.) rounds carburized at 925 °C (1700 °F) for 1.75 h. Quenched in oil from 845 °C (1555 °F). Diffusion cycle used. Dew points of −15 °C (5 °F) for first part of 925 °C (1700 °F) cycle, −12 °C (10 °F) for diffusion cycle at 925 °C (1700 °F), and −3 °C (27 °F) for time at 845 °C (1555 °F) before quenching. Endothermic plus straight natural gas as enriching gas. Tempered in lead at 650 °C (1200 °F), wire brushed, and liquid abrasive cleaned. (b) 25-mm (1-in.) diam bar. Endothermic with straight natural gas as enriching gas. Carburized at 925 °C (1700 °F), using diffusion cycle. Dew point of −15 °C (5 °F) for 3 h at 925 °C (1700 °F), a dew point of −12 °C (10 °F) for the diffusion portion, and −3 °C (27 °F) for 1 h at 845 °C (1555 °F). (c) 25-mm (1-in.) diam bar. Total cycle at 925 °C (1700 °F) was 10.5 h, 5 h with a −15 °C (5 °F) dew point, and 5.5 h with a −12 °C (10 °F) dew point. Equalizing time at 845 °C (1555 °F) was 1 h, with a dew point of −3 °C (27 °F). (d) 25-mm (1-in.) diam bar. Diffusion time with a −12 °C (10 °F) dew point was 6 h. (e) Gears, carburized at 925 °C (1700 °F) in a continuous furnace. (f) 25-mm (1-in.) diam by 38 mm (1.5 in.), batch-type carburizing

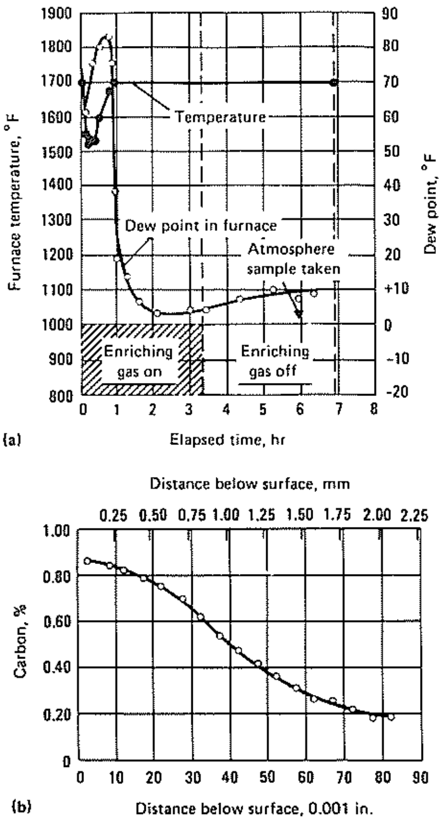


8620H: Gas Carburizing. Shafts, 171 kg (376 lb), 440 kg (969 lb) gross. Vestibule, enclosed-quench, brick-lined heating chamber, radiant-tube heated. Carrier gas: 21.8 m³/h (770 ft³/h) endothermic gas for 5 h 53 min at temperature. Enriching gas: 0.28 m³/h (10 ft³/h) propane, 3 h 59 min at temperature (66% of cycle). Generator dew point: 1 to 4 °C (33 to 39 °F). Heating chamber pressure: 2.5 to 3.6 mm (0.10 to 0.14 in.) water column. Carburized at 925 °C (1700 °F) and quenched from 845 °C (1555 °F). (a) Furnace temperature and atmosphere conditions for carburizing. (b) Resulting carbon gradient

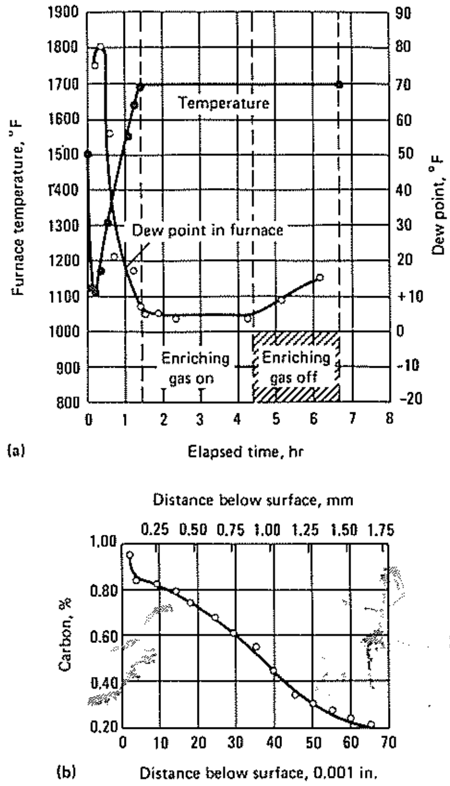


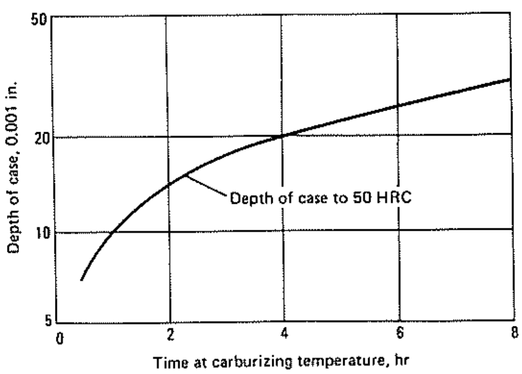


8620H: Gas Carburizing. Load: ring gears, 231 kg (510 lb) net, 390 kg (860 lb) gross. Metallic-retort pit furnace, electrically heated. 0.34 m^3/h (100 ft^3/h) endothermic gas throughout the cycle, including 5 h 59 min at temperature. Enriching gas: 0.34 m^3/h (12 ft^3/h) natural gas for 2.5 h at temperature (42% of at-temperature cycle). Generator dew point: −6 to −4 °C (22 to 25 °F). Heating chamber pressure: 5.1 to 7.9 mm (0.20 to 0.31 in.), water column. Carburizing temperature: 925 °C (1700 °F). Slow cooled from 925 °C (1700 °F) in cooling pit. Atmosphere at the end of cycle: 20.8% CO, 0.4% CO_2, 34.0% H_2, 0% O_2, 0.8% CH_4. (a) Furnace temperature and atmosphere conditions for carburizing. (b) Resulting carbon gradient



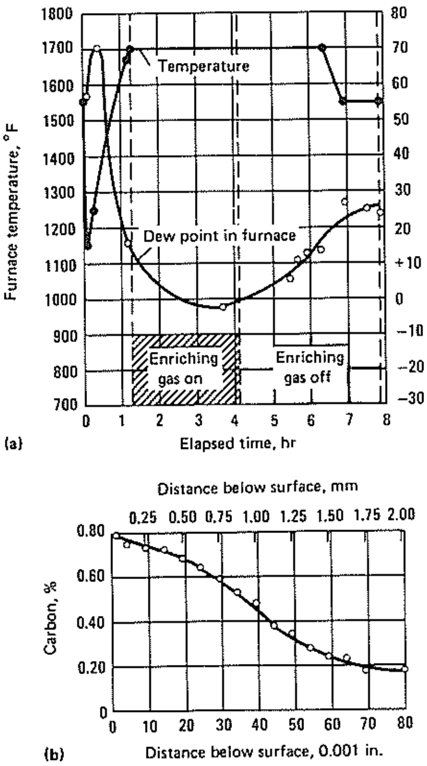
8620H: Gas Carburizing. Ring gears, 231 kg (510 lb) net, 390 kg (860 lb) gross. Metallic-retort pit furnace, electrically heated. 2.83 m^3/h (100 ft^3/h) endothermic gas for 5 h 15 min at temperature, carrier gas. Enriching gas: 0.34 m^3/h (12 ft^3/h) started at temperature and shut off after 3 h (57% of cycle). Generator dew point: −4 to −3 °C (24 to 26 °F). Heating chamber pressure: 8.6 to 11 mm (0.34 to 0.44 in.) water column. Carburized at 925 °C (1700 °F) and slow cooled in cooling pit. (a) Furnace temperature and atmosphere conditions for carburizing. (b) Resulting carbon gradient



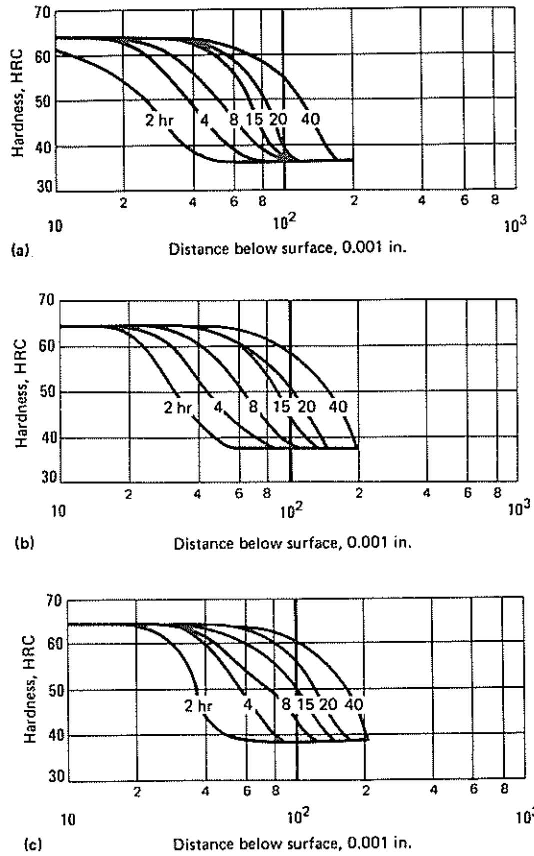


8620: Depth of Case vs Time and Temperature. 12-mm (0.5-in.) diam by 6.4 mm (0.25 in.). Carburized at 855 °C (1575 °F), oil quenched, tempered at 150 °C (300 °F), treated at 49 °C (120 °F)

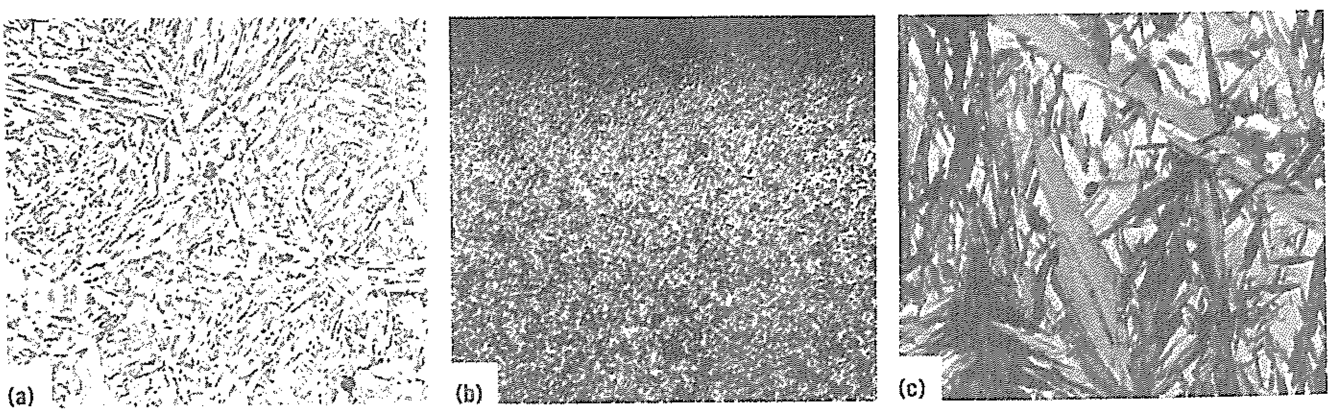
8620H: Gas Carburizing. Shafts, 245 kg (320 lb) net, 298 kg (569 lb) gross. Metallic-retort pit furnace, electrically heated. Carrier gas: 2.83 m^3/h (100 ft^3/h) endothermic gas for 5 h 5 min at temperature. Enriching gas: 0.3 m^3/h (9 ft^3/h) natural gas, for 2 h 50 min from start of cycle (56% of cycle). Generator dew point: –4 to –3 °C (24 to 27 °F). Heating chamber pressure: 9.9 to 12 mm (0.39 to 0.49 in.) water column. Carburized at 925 °C (1700 °F) and quenched from 845 °C (1555 °F). (a) Furnace temperature and atmosphere conditions for carburizing. (b) Resulting carbon gradient



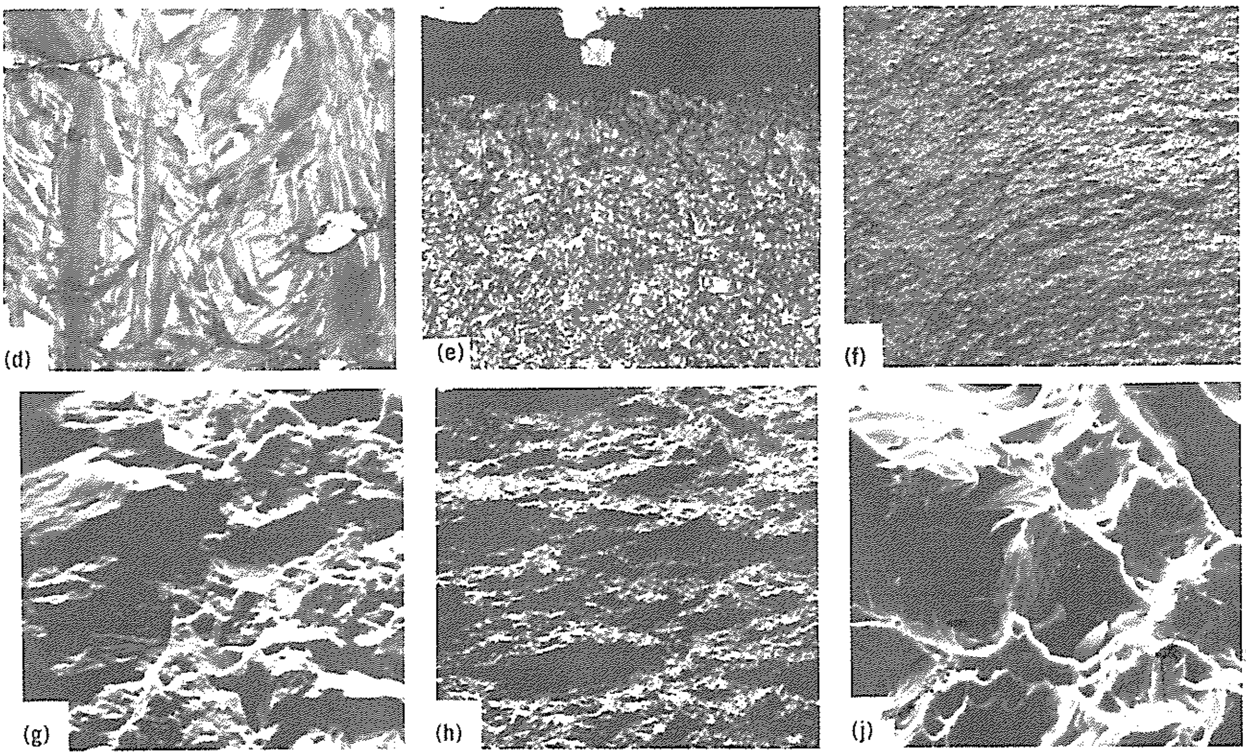
8620: Effect of Carburizing Time and Temperature. Specimens 19-mm (0.75-in.) diam by 51 mm (2 in.), carburized, air cooled, reheated in neutral salt at 845 °C (1555 °F), quenched in salt at 180 °C (360 °F). (a) Carburized at 870 °C (1600 °F); (b) carburized at 900 °C (1650 °F); (c) carburized at 925 °C (1700 °F)



8620: Microstructures. (a) Picral, 200×. Steel bar normalized by being austenitized at 900 °C (1650 °F) for 2 h and cooled in still air. Mixture of ferrite and carbide. Cooling too rapid to produce an annealed structure. (b) Nital, 100×. Steel bar carbonitrided for 4 h at 845 °C (1555 °F), oil quenched, not tempered, and stabilized by subzero treatment. Conventional case structure with martensite, carbide particles, and a small amount of retained austenite. (c) Picral, 1000×. Coarse grain steel, gas carburized 11 h at 925 °C (1700 °F), furnace cooled at 845 °C (1555 °F), oil quenched, tempered 2 h at 195 °C (380 °F). Tempered martensite and retained austenite. A large martensite plate contains several microcracks



8620: Microstructures (continued). (d) Picral, 1000×. Same steel, carburizing and heat treatments, and structure as (c), but specimen was subjected to maximum compressive stress of 4137 MPa (600 ksi) for 11.4 million cycles in a contact fatigue test. Butterfly structural alterations developed at microcracks. (e) 4% picral, 500×. Steel gas carburized for 18 h at 925 °C (1700 °F), reheated to 830 °C (1540 °F) and held 40 min, oil quenched, tempered 1 h at 175 °C (350 °F). Near surface are grain-boundary oxides and, less visible because of dark etching, bainite and pearlite. Remaining structure is carbide particles and retained austenite in a matrix of tempered martensite. (f) Not polished, not etched; 23×. Steel tubing, gas carburized 8 h at 925 °C (1700 °F), hardened, and tempered. Scanning electron micrograph of fractured carburized case. See (g). (g) Not polished, not etched, 1100×. Same as (f), but a higher magnification. Fractured carburized case consists of carbide, retained austenite, and tempered martensite. (h) Not polished, not etched; 23×. Same as (f), except a scanning electron micrograph of fractured uncarburized core material (low-carbon martensite). Fracture surface is fibrous. (j) Not polished, not etched; 1100×. Same as (h), but at higher magnification, showing that fractured uncarburized core material has elongated dimples formed during transgranular rupture



8622, 8622H, 8622RH

Chemical Composition. **8622. AISI and UNS:** 0.20 to 0.25 C, 0.70 to 0.90 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.15 to 0.25 Mo. **UNS H86220 and SAE/AISI 8622H:** 0.19 to 0.25 C, 0.60 to 0.95 Mn, 0.15 to 0.35 Si, 0.35 to 0.75 Ni, 0.35 to 0.65 Cr, 0.15 to 0.25 Mo. **SAE 8622RH:** 0.20 to 0.25 C, 0.70 to 0.90 Mn, 0.15 to 0.35 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.15 to 0.25 Mo

Similar Steels (U.S. and/or Foreign). **8622.** UNS G86220; SAE J404, J770; (Ger.) DIN 1.6543; (U.K.) B.S. 805 A 20. **8622H.** UNS H86220; ASTM A304; SAE J407; (Ger.) DIN 1.6543; (U.K.) B.S. 805 A 20

Characteristics. Except for a slightly higher carbon range, 8622H has an identical composition to 8620H, and the characteristics for 8622H are approximately the same as those for 8620H. Because of the higher carbon range, as-quenched surface hardness is slightly higher for 8622H, approximately 39 to 45 HRC. The hardenability band for 8622H, is adjusted upward just slightly when compared with 8620H. In some carburizing applications, steels that are higher in carbon content have been used to attain a higher core hardness which permits thinner cases. These steels use shorter carburizing cycles and save energy

Forging. Heat to 1245 °C (2275 °F) maximum. Do not forge after temperature of forging stock drops below approximately 900 °C (1650 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Cool in air

Annealing. Structures having best machinability are developed by normalizing; or by heating to 885 °C (1625 °F), cooling rapidly to 660 °C (1220 °F), and holding for 4 h; or by heating to 790 °C (1455 °F), cooling rapidly to 660 °C (1220 °F), and holding for 8 h

Tempering. Temper all carburized or carbonitrided parts at 150 °C (300 °F), and virtually no loss of case hardness will result. If some decrease in hardness can be tolerated, toughness can be increased by tempering at somewhat higher temperatures, up to 260 °C (500 °F)

Case Hardening. See carburizing and carbonitriding practices described for 8620H. Gas nitriding and ion nitriding are alternative processes

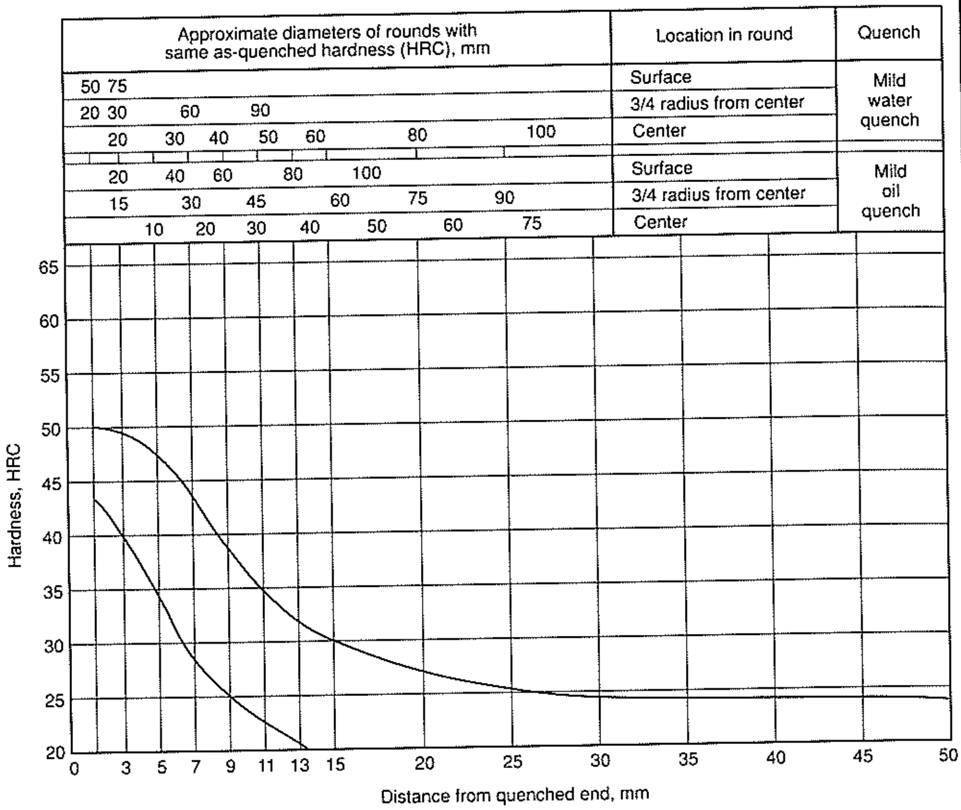
Recommended Processing Sequence

- Forge
- Normalize
- Anneal (if required)
- Rough machine
- Semifinish machine, allowing only grinding stock, no more than 10% or the case depth per side for carburized parts. In most instances, carbonitrided parts are completely finished in this step
- Carburize or carbonitride and quench
- Temper

8622H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 925 °C (1700 °F)

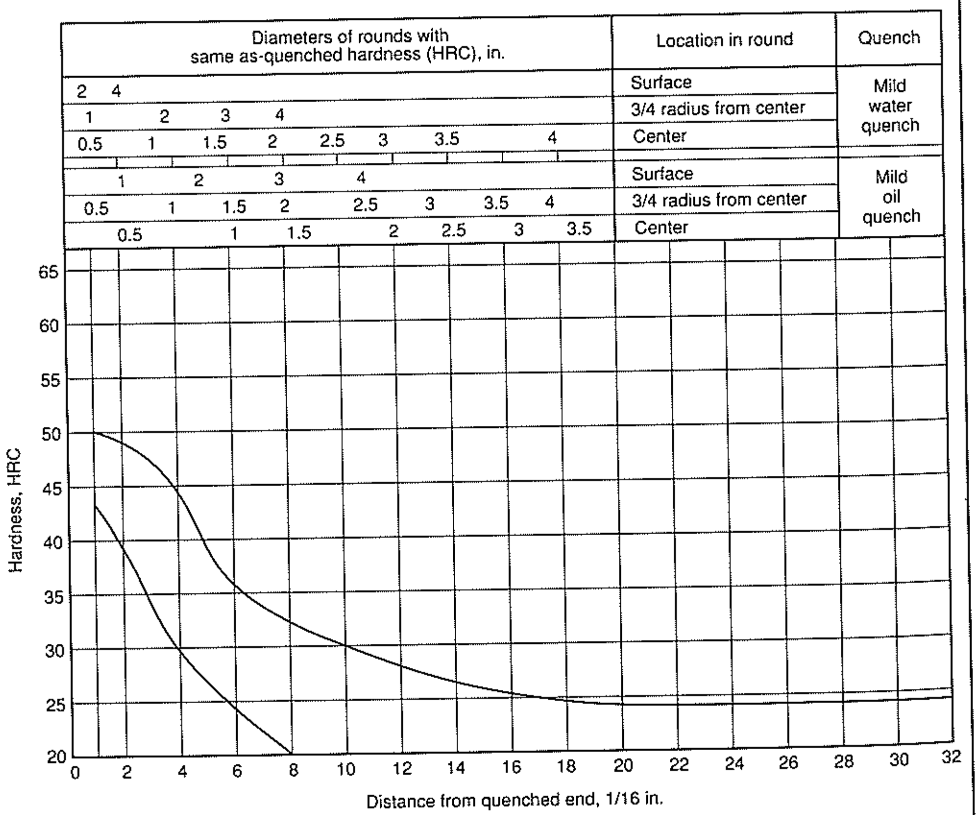
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	50	43
3	50	39
5	47	34
7	43	28
9	39	25
11	35	22
13	32	20
15	31	...
20	28	...
25	26	...
30	25	...
35	24	...
40	24	...
45	24	...
50	24	...



Hardness limits for specification purposes

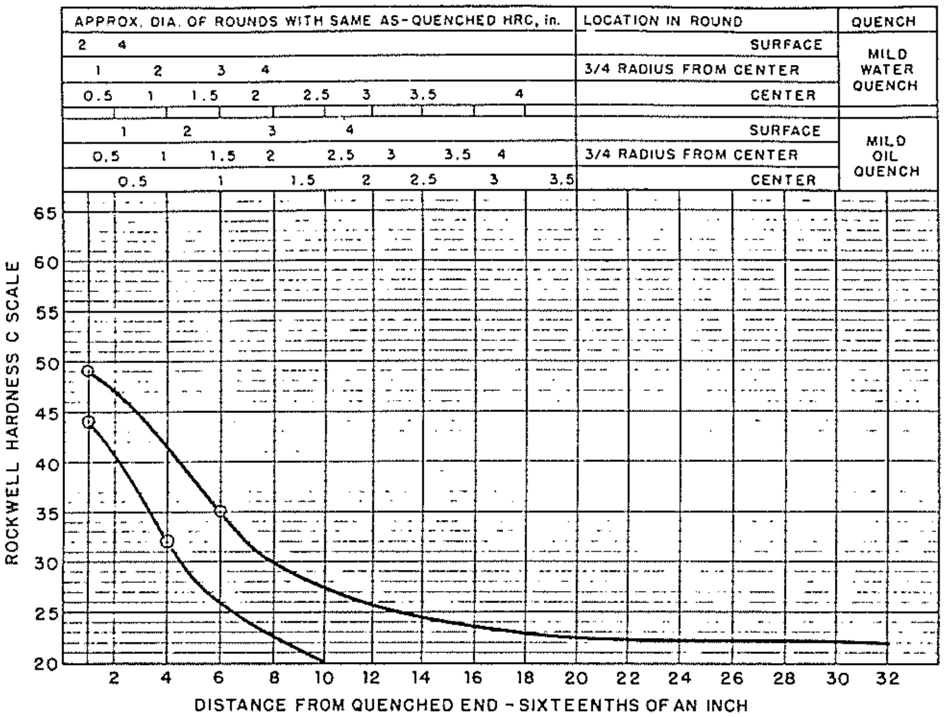
J distance, $1/16$ in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	50	43
2	49	39
3	47	34
4	44	30
5	40	26
6	37	24
7	34	22
8	32	20
9	31	...
10	30	...
11	29	...
12	28	...
13	27	...
14	26	...
15	26	...
16	25	...
18	25	...
20	24	...
22	24	...
24	24	...
26	24	...
28	24	...
30	24	...
32	24	...



8622RH: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 925 °C (1700 °F).

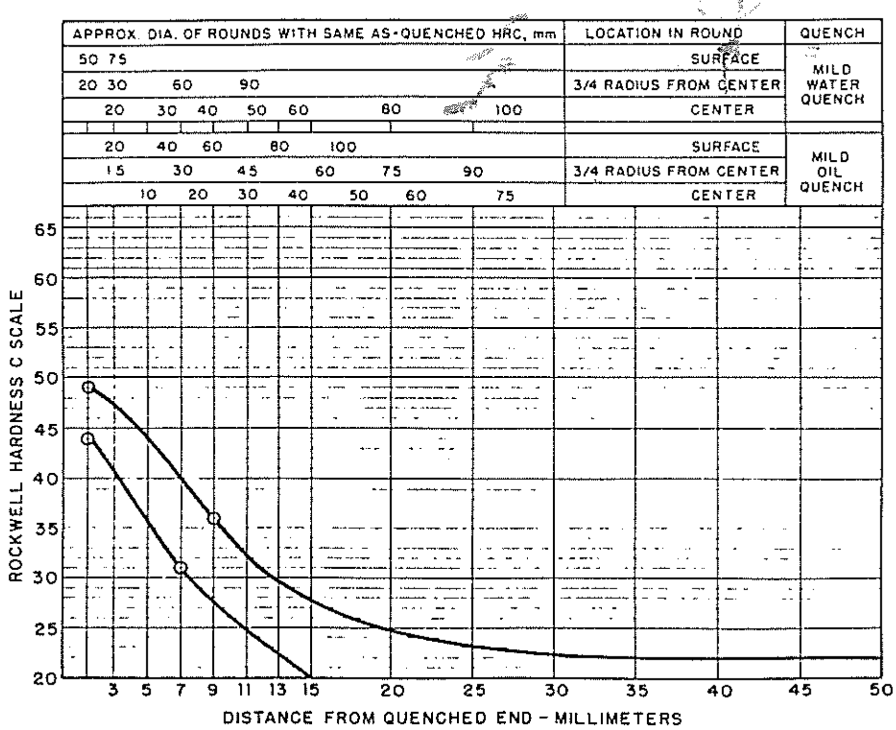
Hardness limits for specification purposes

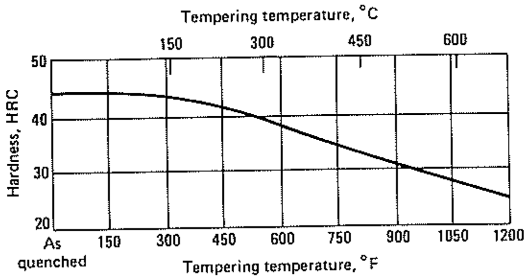
J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	49	44
2	47	41
3	45	37
4	41	32
5	38	29
6	35	27
7	32	24
8	30	22
9	29	21
10	28	20
11	27	...
12	26	...
13	25	...
14	24	...
15	24	...
16	23	...
18	23	...
20	22	...
22	22	...
24	22	...
26	22	...
28	22	...
30	22	...
32	22	...



Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	49	44
3	47	41
5	44	36
7	40	31
9	36	28
11	32	24
13	30	22
15	28	20
20	25	...
25	23	...
30	22	...
35	22	...
40	22	...
45	22	...
50	22	...

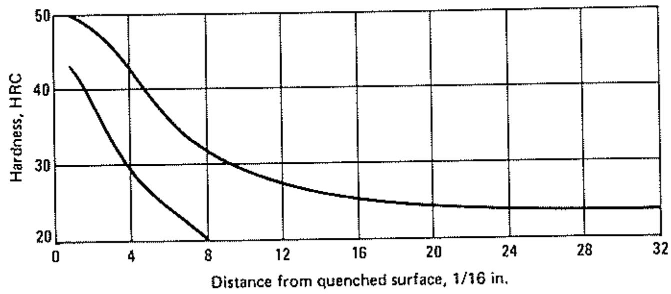




8622, 8622H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

8622H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max
1	1.58	50	43	13	20.54	27
2	3.16	49	39	14	22.12	26
3	4.74	47	34	15	23.70	26
4	6.32	44	30	16	25.28	25
5	7.90	40	26	18	28.44	25
6	9.48	37	24	20	31.60	24
7	11.06	34	22	22	34.76	24
8	12.64	32	20	24	37.92	24
9	14.22	31	...	26	41.08	24
10	15.80	30	...	28	44.24	24
11	17.38	29	...	30	47.40	24
12	18.96	28	...	32	50.56	24



8625, 8625H

Chemical Composition. **8625. AISI and UNS:** 0.23 to 0.28 C, 0.70 to 0.90 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.15 to 0.25 Mo. **UNS H86250 and SAE/AISI 8625H:** 0.22 to 0.28 C, 0.60 to 0.95 Mn, 0.15 to 0.35 Si, 0.35 to 0.75 Ni, 0.35 to 0.65 Cr, 0.15 to 0.25 Mo

Similar Steels (U.S. and/or Foreign). **8625.** UNS G86250; MIL SPEC MIL-S-16974; SAE J404, J770. **8625H.** UNS H86250; ASTM A304; SAE J1268

Characteristics. Identical to 8620H except for higher carbon range, which results in a higher as-quenched hardness (approximately 40 to 46 HRC), and somewhat higher hardenability. Case hardening by carburizing or carbonitriding are the heat treatments most often used. Has come into more extensive use to save energy in carburizing. Weldable, but alloy steel welding practice must be used

Forging. Heat to 1245 °C (2275 °F) maximum. Do not forge after temperature of forging stock drops below approximately 900 °C (1650 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Cool in air

Annealing. Structures having best machinability are developed by normalizing; or by heating to 885 °C (1625 °F), cooling rapidly to 660 °C (1220 °F), and holding for 4 h; or by heating to 790 °C (1455 °F), cooling rapidly to 660 °C (1220 °F), and holding for 8 h

Tempering. Temper all carburized or carbonitrided parts at 150 °C (300 °F), and virtually no loss of case hardness will result. If some decrease in hardness can be tolerated, toughness can be increased by tempering at somewhat higher temperatures, up to 260 °C (500 °F)

Case Hardening. See carburizing and carbonitriding practices described for 8620H. Ion nitriding and gas nitriding are alternative processes

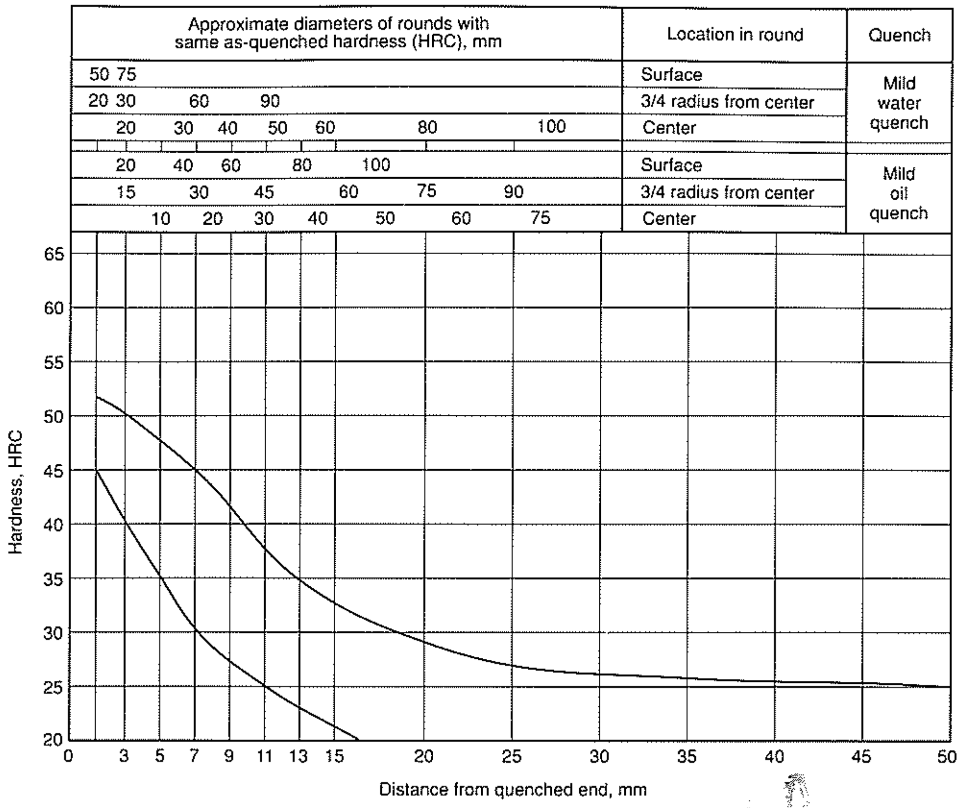
Recommended Processing Sequence

- Forge
- Normalize
- Anneal (if required)
- Rough machine
- Semifinish machine, allowing only grinding stock, no more than 10% of the case depth per side for carburized parts. In most instances, carbonitrided parts are completely finished in this step
- Carburize or carbonitride and quench
- Temper

8625: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 900 °C (1650 °F). Austenitize: 870 °C (1600 °F)

Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Minimum
1.5	52	45
3	51	40
5	48	35
7	45	31
9	41	28
11	38	25
13	35	23
15	33	21
20	29	...
25	28	...
30	27	...
35	26	...
40	26	...
45	26	...
50	25	...



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Minimum
1	52	45
2	51	41
3	48	36
4	46	32
5	43	29
6	40	27
7	37	25
8	35	23
9	33	22
10	32	21
11	31	20
12	30	...
13	29	...
14	28	...
15	28	...
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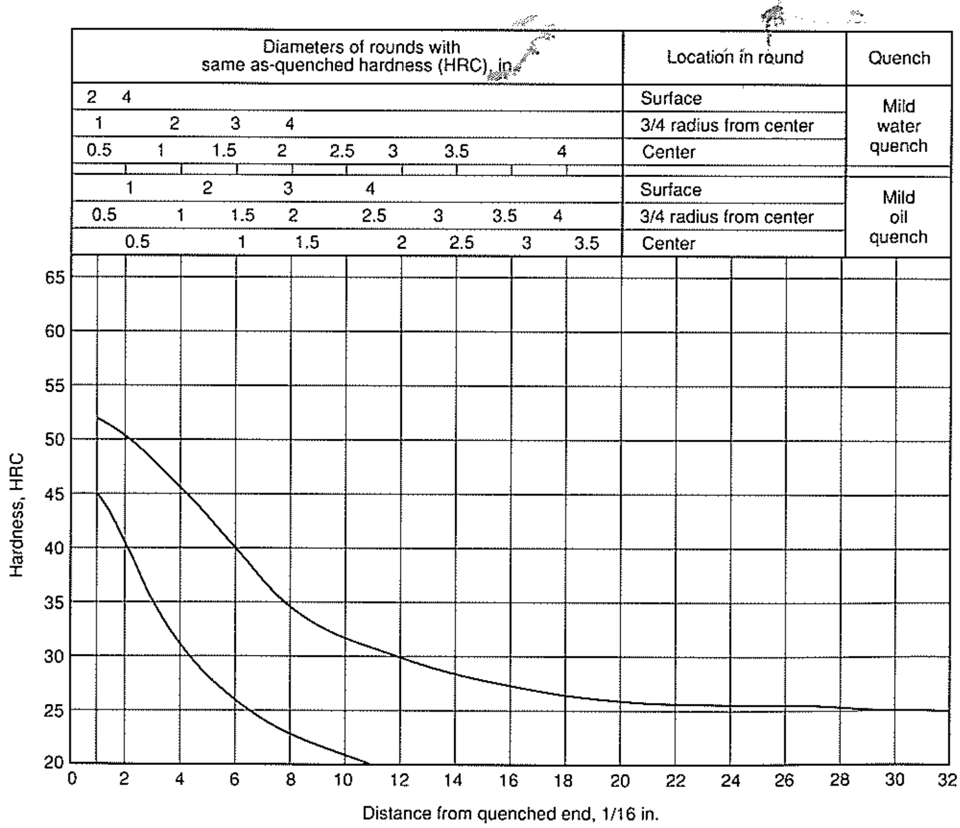
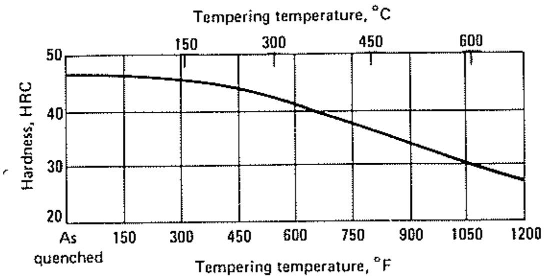
30	25	...
32	25	...

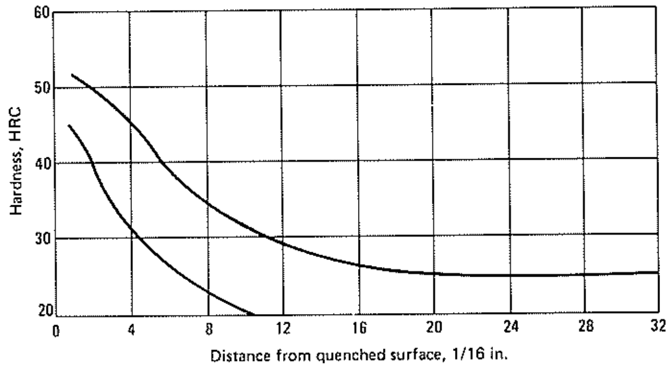




8625, 8625H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

8625H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max
1	1.58	52	45	13	20.54	29
2	3.16	51	41	14	22.12	28
3	4.74	48	36	15	23.70	28
4	6.32	46	32	16	25.28	27
5	7.90	43	29	18	28.44	27
6	9.48	40	27	20	31.60	26
7	11.06	37	25	22	34.76	26
8	12.64	35	23	24	37.92	26
9	14.22	33	22	26	41.08	26
10	15.80	32	21	28	44.24	25
11	17.38	31	20	30	47.40	25
12	18.96	30	...	32	50.56	25



8627, 8627H

Chemical Composition. **8627. AISI and UNS:** 0.25 to 0.30 C, 0.70 to 0.90 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.15 to 0.25 Mo. **UNS H86270 and SAE/AISI 8627H:** 0.24 to 0.30 C, 0.60 to 0.95 Mn, 0.15 to 0.35 Si, 0.35 to 0.75 Ni, 0.35 to 0.65 Cr, 0.15 to 0.25 Mo

Similar Steels (U.S. and/or Foreign). **8627.** UNS G86270; SAE J404, J770. **8627H.** UNS H86270; ASTM A304; SAE J1268

Characteristics. Has a borderline composition, with a carbon content near the maximum used for case hardening, but at about the minimum suitable for direct hardening. Used for both as demanded, however. As-quenched surface hardness of approximately 42 to 48 HRC can be expected. Hardenability band for 8627H is slightly higher than for 8625H

Forging. Heat to 1230 °C (2250 °F) maximum. Do not forge after temperature of forging stock drops below approximately 900 °C (1650 °F). For direct hardening, see tempering curve

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F). Cool in air

Annealing. For a predominantly pearlitic structure, heat to 845 °C (1555 °F), cool rapidly to 730 °C (1350 °F), then cool to 640 °C (1185 °F), at a rate not to exceed 11 °C (20 °F) per h; or heat to 845 °C (1555 °F), cool rapidly to 665 °C (1230 °F), and hold for 6 h. For a predominantly spheroidized structure, heat to 760 °C (1400 °F), cool rapidly to 730 °C (1350 °F), then cool to 650 °C (1200 °F), at a rate not to exceed 6 °C (10 °F) per h; or heat to 760 °C (1400 °F), cool rapidly to 665 °C (1230 °F), and hold for 8 h

Direct Hardening. Austenitize at 870 °C (1600 °F), and quench in oil

Tempering. After direct hardening. After quenching, reheat to the temperature required to provide the desired hardness

Case Hardening. See carburizing and carbonitriding practice described for 8620H. Ion nitriding and gas nitriding are suitable processes

Tempering. After case hardening. Temper all carburized or carbonitrided parts at 150 °C (300 °F), and virtually no loss of case hardness will result. If some decrease in hardness can be tolerated, toughness can be increased by tempering at somewhat higher temperatures, up to 260 °C (500 °F). For direct hardening, see tempering curve

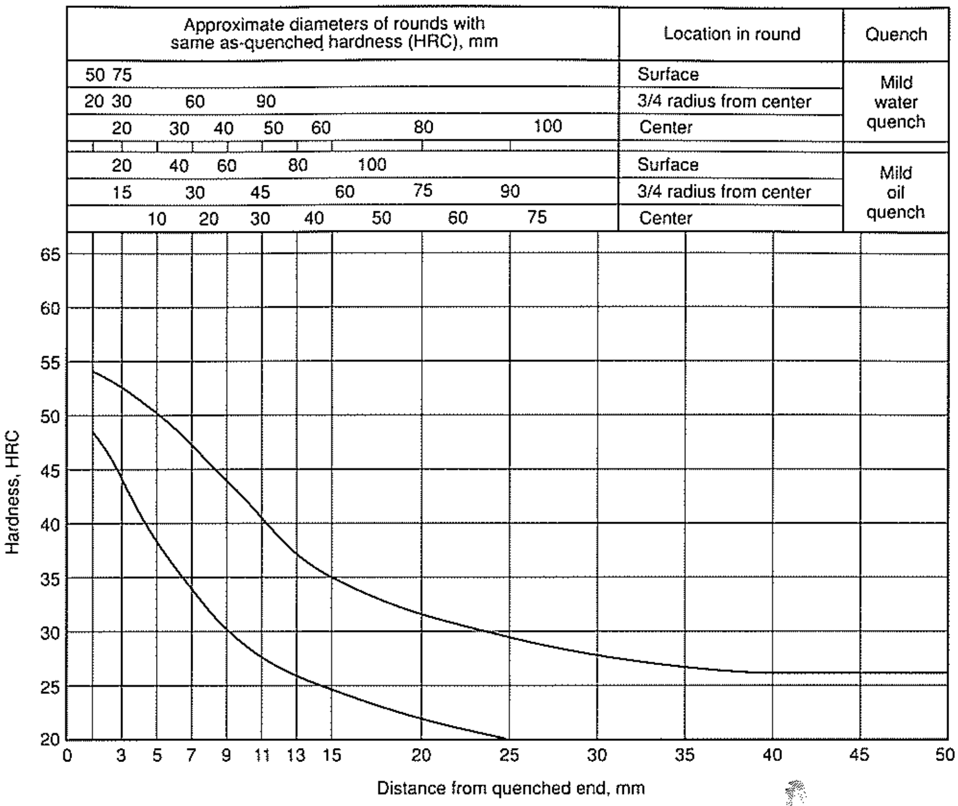
Recommended Processing Sequence

- Forge
- Normalize
- Anneal (if required)
- Rough machine
- Semifinish machine, allowing only grinding stock, no more than 10% of the case depth per side for carburized parts. In most instances, carbonitrided parts are completely finished in this step
- Case harden or direct harden
- Quench
- Temper

8627H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 900 °C (1650 °F). Austenitize: 870 °C (1600 °F)

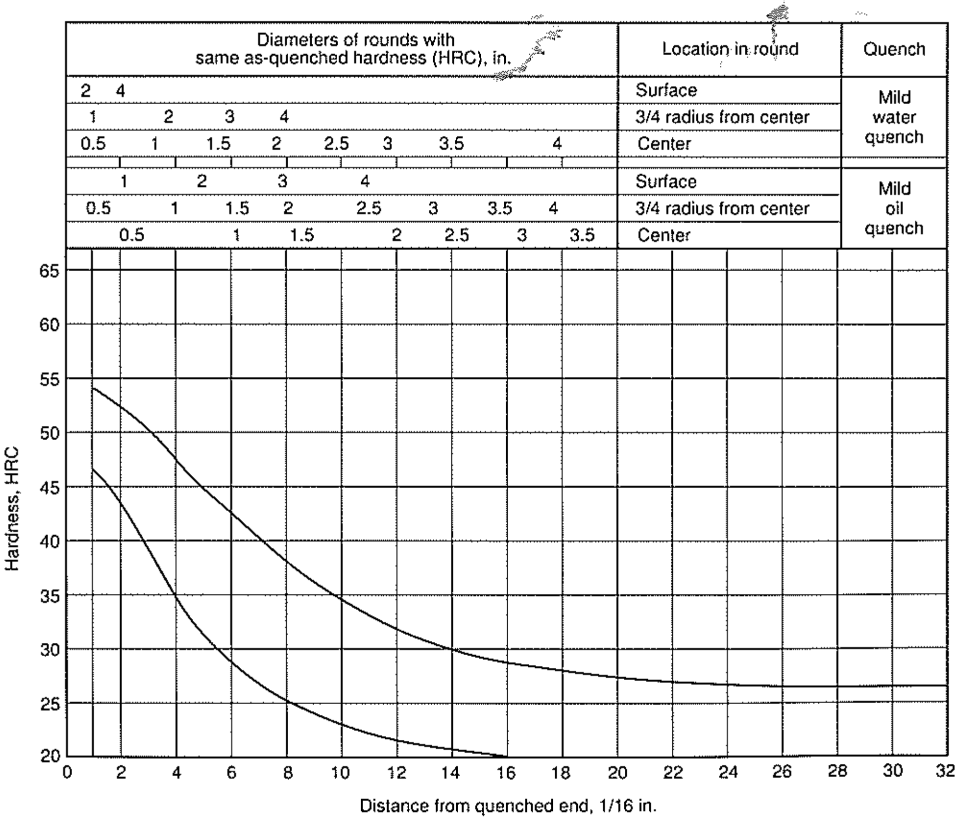
Hardness limits for specification purposes

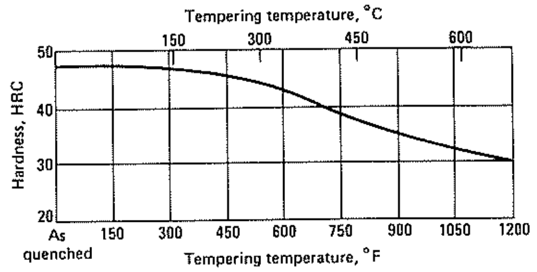
J distance, mm	Hardness, HRC Maximum	Minimum
1.5	54	47
3	53	43
5	50	38
7	47	34
9	44	31
11	41	27
13	38	25
15	35	24
20	32	21
25	30	20
30	28	...
35	27	...
40	27	...
45	27	...
50	27	...



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Minimum
1	54	47
2	52	43
3	50	38
4	48	35
5	45	32
6	43	29
7	40	27
8	38	26
9	36	24
10	34	24
11	33	23
12	32	22
13	31	21
14	30	21
15	30	20
16	29	20
18	28	...
20	28	...
22	28	...
24	27	...
26	27	...
28	27	...
30	27	...
32	27	...

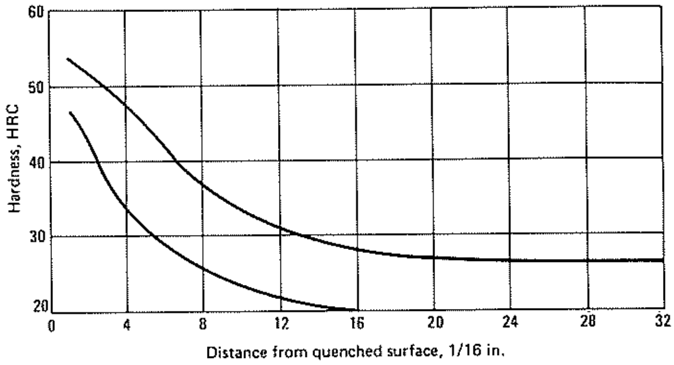




8627, 8627H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

8627H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min
1	1.58	54	47	13	20.54	31	21
2	3.16	52	43	14	22.12	30	21
3	4.74	50	38	15	23.70	30	20
4	6.32	48	35	16	25.28	29	20
5	7.90	45	32	18	28.44	28	...
6	9.48	43	29	20	31.60	28	...
7	11.06	40	27	22	34.76	28	...
8	12.64	38	26	24	37.92	27	...
9	14.22	36	24	26	41.08	27	...
10	15.80	34	24	28	44.24	27	...
11	17.38	33	23	30	47.40	27	...
12	18.96	32	22	32	50.56	27	...



8630, 8630H

Chemical Composition. 8630. AISI and UNS: 0.28 to 0.33 C, 0.70 to 0.90 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.15 to 0.25 Mo. **UNS H86300 and SAE/AISI 8630H:** 0.27 to 0.33 C, 0.60 to 0.95 Mn, 0.15 to 0.35 Si, 0.35 to 0.75 Ni, 0.35 to 0.65 Cr, 0.15 to 0.25 Mo

Similar Steels (U.S. and/or Foreign). 8630. UNS G86300; AMS 6280, 6281, 6355, 6530, 6550; ASTM A322, A331; MIL SPEC MIL-S-16974; SAE J404, J412, J770; (Ger.) DIN 1.6545; (Ital.) UNI 30 NiCrMo 2 KB. **8630H.** UNS H86300; ASTM A304; SAE J1268; (Ger.) DIN 1.6545; (Ital.) UNI 30 NiCrMo 2 KB

Characteristics. A medium-carbon steel. Responds readily to direct hardening. As-quenched surface hardness usually ranges from approximately 46 to 52 HRC. Its hardenability band is similar to other 86XXH steels. Seldom used for case hardening by carburizing or carbonitriding because of its carbon content. Generally available in various product forms including seamless tubing used in producing welded structures. Forges easily and can be welded by virtually any of the well-known techniques. Because of its relatively high hardenability, alloy steel practice must be used in welding

Forging. Heat to 1230 °C (2250 °F) maximum. Do not forge after temperature of forging stock drops below approximately 900 °C (1650 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F). Cool in air.

In aerospace practice, parts are normalized at 900 °C (1650 °F)

Annealing. For a predominantly pearlitic structure, heat to 845 °C (1555 °F), cool rapidly to 730 °C (1350 °F), then cool to 640 °C (1180 °F), at a rate not to exceed 11 °C (20 °F) per h; or heat to 845 °C (1555 °F), cool rapidly to 665 °C (1230 °F), and hold for 6 h. For a predominantly spheroidized structure, heat to 760 °C (1400 °F), cool rapidly to 730 °C (1350 °F), then cool to 650 °C (1200 °F), at a rate not to exceed 6 °C (10 °F) per h; or heat to 760 °C (1400 °F), cool rapidly to 665 °C (1230 °F), and hold for 8 h

In aerospace practice, parts are annealed at 845 °C (1555 °F), then cooled to below 540 °C (1000 °F) at a rate not to exceed 95 °C (205 °F) per h

Hardening. Austenitize at 870 °C (1600 °F), and quench in oil. Flame hardening, gas nitriding, ion nitriding, carbonitriding, and martempering are alternative processes. Quenchants include water and polymers. In aerospace practice, austenitize at 855 °C (1570 °F), and quench in oil or polymer

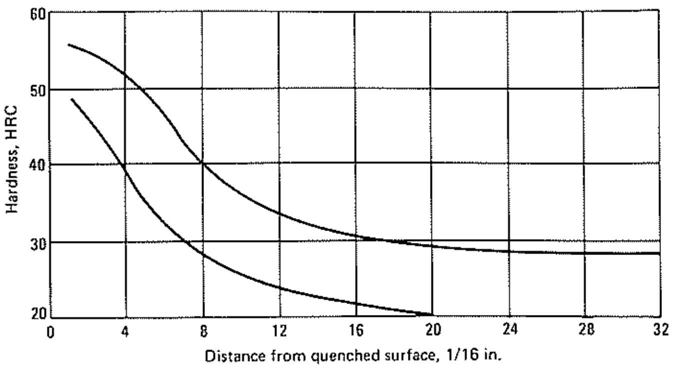
Tempering. After quenching, reheat to the temperature required for providing the desired hardness or other mechanical properties

Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough and semifinish machine
- Austenitize and quench
- Temper
- Finish machine

8630H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min
1	1.58	56	49	13	20.54	33	23
2	3.16	55	46	14	22.12	33	22
3	4.74	54	43	15	23.70	32	22
4	6.32	52	39	16	25.28	31	21
5	7.90	50	35	18	28.44	30	21
6	9.48	47	32	20	31.60	30	20
7	11.06	44	29	22	34.76	29	20
8	12.64	41	28	24	37.92	29	...
9	14.22	39	27	26	41.08	29	...
10	15.80	37	26	28	44.24	29	...
11	17.38	35	25	30	47.40	29	...
12	18.96	34	24	32	50.56	29	...

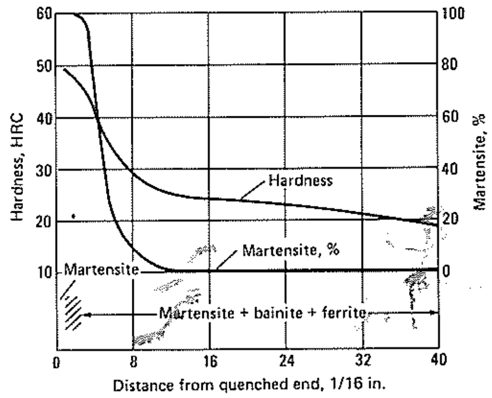


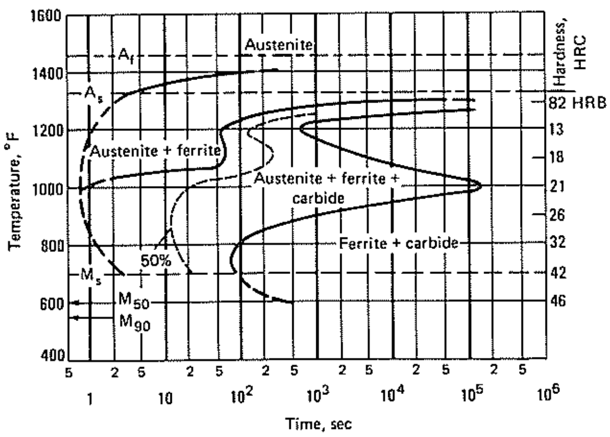
8630: Approximate Critical Points

Critical point	Temperature °C	Temperature °F
Ac_1	735	1355
Ac_3	795	1460
Ar_3	745	1370
Ar_1	660	1220

Source: Republic Steel

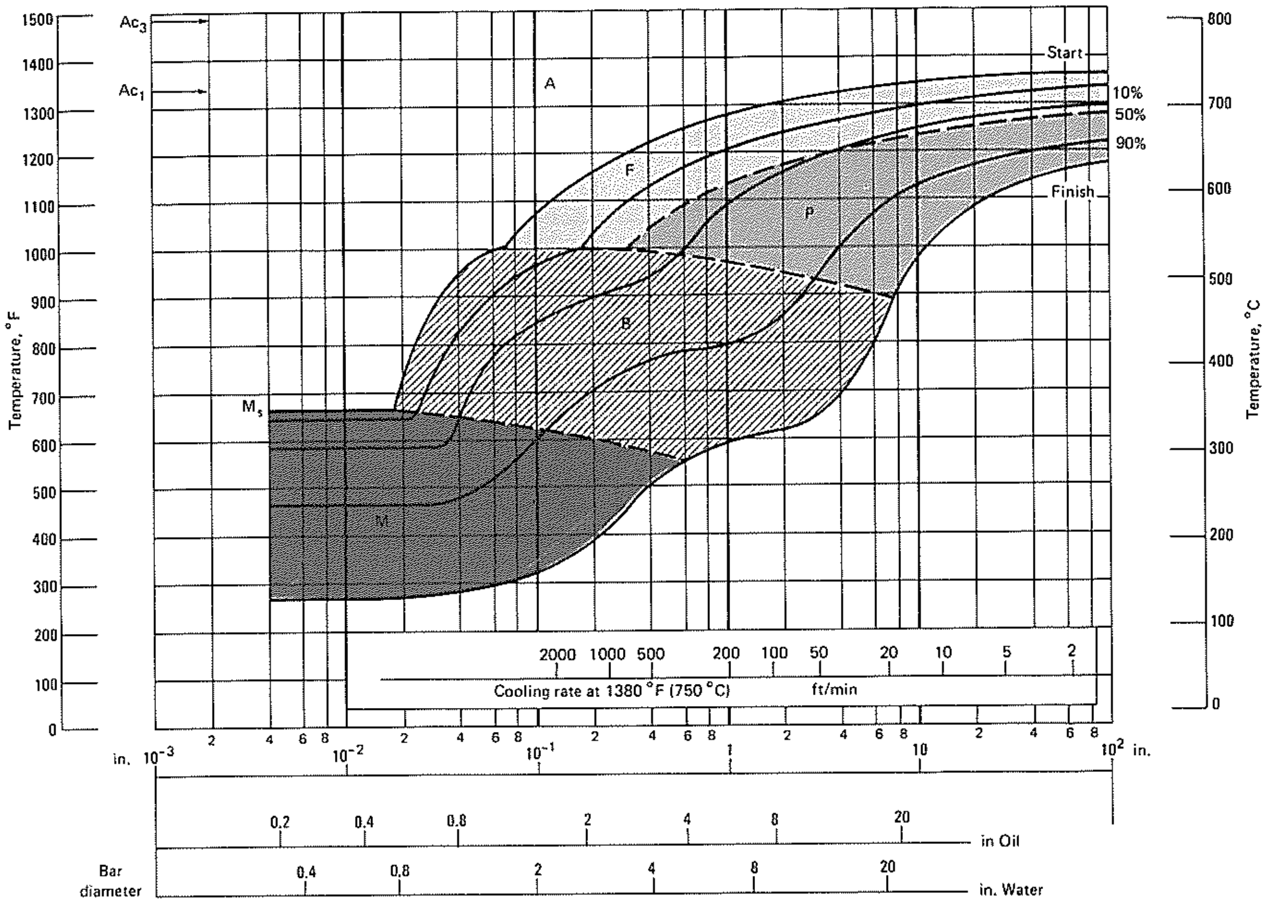
8630: End-Quench Hardenability. Composition: 0.30 C, 0.80 Mn, 0.54 Ni, 0.55 Cr, 0.21 Mo. Austenitized at 870 °C (1600 °F). Grain size: 9





8630: Isothermal Transformation Diagram. Composition: 0.30 C, 0.80 Mn, 0.54 Ni, 0.55 Cr, 0.21 Mo. Austenitized at 870 °C (1600 °F). Grain size: 9

8630: Continuous Cooling Transformation Diagram. Composition: 0.30 C, 0.80 Mn, 0.020 P, 0.020 S, 0.25 Si, 0.55 Ni, 0.50 Cr, 0.20 Mo. Austenitized at 850 °C (1560 °F)



8630: Effect of Heat Treatment on Hardness

Heat treatment	Hardness, HB Size round measured in ½ in. (13 mm)	1 in. (25 mm)	2 in. (51 mm)	4 in. (102 mm)
Annealed(a)	...	156	...	...
Normalized(b)	201	187	187	187
Water quenched from 845 °C (1555 °F), tempered at 480 °C (900 °F)	302	293	269	235
Water quenched from 845 °C (1555 °F), tempered at 540 °C (1000 °F)	285	269	235	217
Water quenched from 845 °C (1555 °F), tempered at 595 °C (1100 °F)	269	241	223	197

(a) Heated to 845 °C (1555 °F), furnace cooled at 11 °C (20 °F) per hour to 625 °C (1155 °F), cooled in air. (b) Heated to 870 °C (1600 °F), cooled in air. Source: Republic Steel

8630: Suggested Tempering Temperatures (Aerospace Practice)

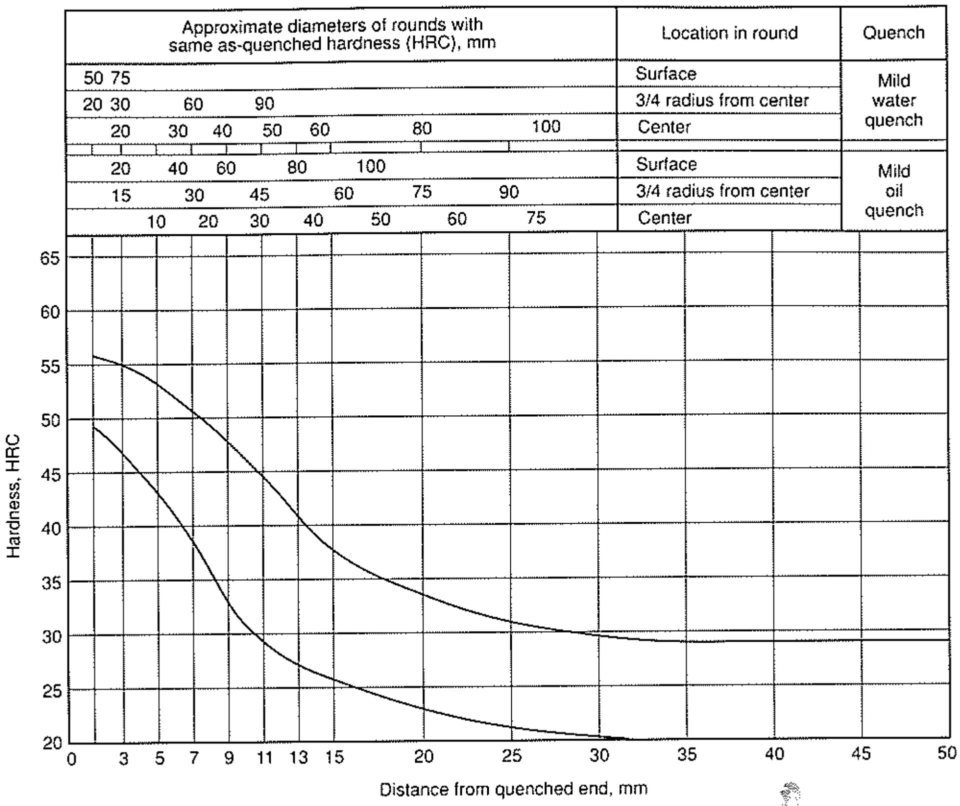
Tensile strength range 620-860 MPa (90-125 ksi)	865-1035 MPa (125-150 ksi)	1035-1175 MPa (150-170 ksi)	1175-1240 MPa (160-180 ksi)	1240-1380 MPa (180-200 ksi)
(1) 650 °C (1200 °F)	550 °C (1025 °F)	485 °C (925 °F)	440 °C (825 °F)	370 °C (700 °F)
(2) 650 °C (1200 °F)	550 °C (1025 °F)	510 °C (950 °F)	440 °C (825 °F)	370 °C (700 °F)

(1) Quench in oil or polymer. (2) Quench in water. Source: AMS 2759/1

8630H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 900 °C (1650 °F). Austenitize: 870 °C (1600 °F)

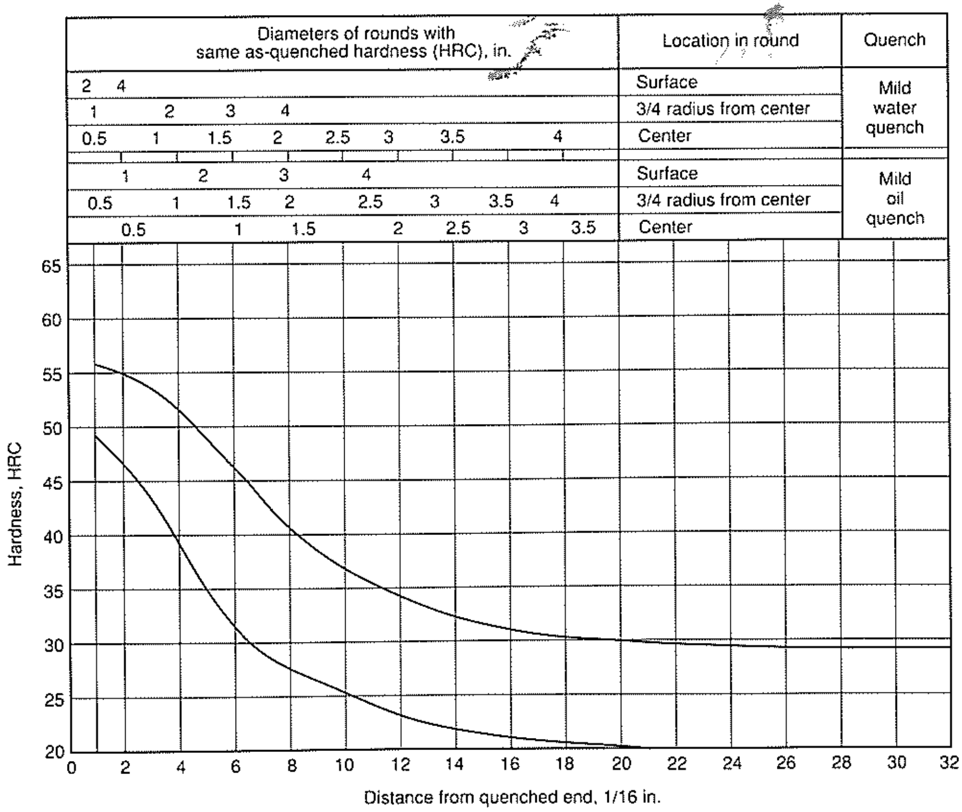
Hardness limits for specification purposes

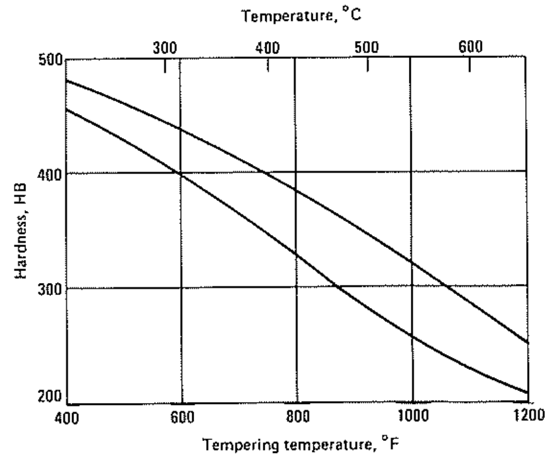
J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	56	49
3	55	46
5	54	42
7	51	38
9	48	33
11	44	29
13	41	27
15	38	26
20	34	23
25	31	21
30	30	20
35	29	...
40	29	...
45	29	...
50	29	...



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	56	49
2	55	46
3	54	43
4	52	39
5	50	35
6	47	32
7	44	29
8	41	28
9	39	27
10	37	26
11	35	25
12	34	24
13	33	23
14	33	22
15	32	22
16	31	21
18	30	21
20	30	20
22	29	20
24	29	...
26	29	...
28	29	...
30	29	...
32	29	...





8630: Hardness vs Tempering Temperature. Composition: 0.28 to 0.33 C, 0.70 to 0.90 Mn, 0.20 to 0.35 Si, 0.40 to 0.70 Ni, 0.40 to 60 Cr, 0.15 to 0.25 Mo. Forged at 1230 °C (2250 °F). Normalized at 900 °C (1650 °F). Furnace cooled from 815 to 870 °C (1500 to 1600 °F). Tempered 2 h. Maximum annealed hardness, 179 HB. Hardness normalized in test size, 225 HB. Source: Republic Steel

86B30H

Chemical Composition. **SAE/AISI 86B30H:** 0.27 to 0.33 C, 0.60 to 0.95 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.35 to 0.75 Ni, 0.35 to 0.65 Cr, 0.15 to 0.25 Mo, 0.0005 to 0.003 B. **UNS H86301 and SAE/AISE 86B30H:** 0.27 to 0.33 C, 0.60 to 0.95 Mn, 0.15 to 0.35 Si, 0.35 to 0.75 Ni, 0.35 to 0.65 Cr, 0.15 to 0.25 Mo, B (can be expected to be 0.0005 to 0.003 percent)

Similar Steels (U.S. and/or Foreign). UNS G86301; ASTM A304; SAE J1268

Characteristics. Identical in composition to 8630H with boron added. The applications of 86B30H are also similar to those for 8630H. 86B30H is selected for its increased hardenability, which is a result of the boron addition. As-quenched surface hardness of 86B30H generally ranges from 46 to 52 HRC, about the same as for 8630H. Forging and heat treating procedures for 86B30H are essentially the same as those used for 8630H

Forging. Heat to 1230 °C (2250 °F) maximum. Do not forge after temperature of forging stock drops below approximately 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F). Cool in air

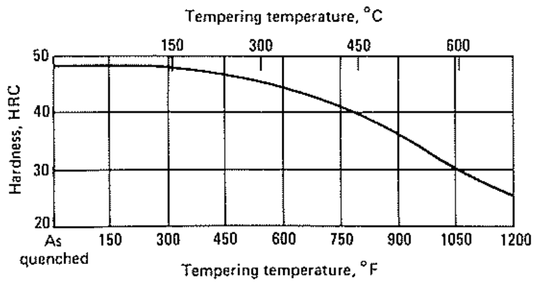
Annealing. For a predominantly pearlitic structure, heat to 845 °C (1555 °F), cool slowly to 730 °C (1350 °F), then cool to 640 °C (1185 °F), at a rate not to exceed 11 °C (20 °F) per h; or heat to 845 °C (1555 °F), cool rapidly to 665 °C (1230 °F), and hold for 7 h. For a predominantly spheroidized structure, heat to 760 °C (1400 °F), cool rapidly to 730 °C (1350 °F), then cool to 650 °C (1200 °F), at a rate not to exceed 6 °C (10 °F) per h; or heat to 760 °C (1400 °F), cool rapidly to 665 °C (1230 °F), and hold for 10 h

Hardening. Austenitize at 870 °C (1600 °F), and quench in oil. Flame hardening, gas nitriding, carbonitriding, and ion nitriding are suitable processes

Tempering. Parts should be tempered immediately after quenching at the temperature which will provide the required hardness

Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough and semifinish machine
- Austenitize and quench
- Temper
- Finish machine

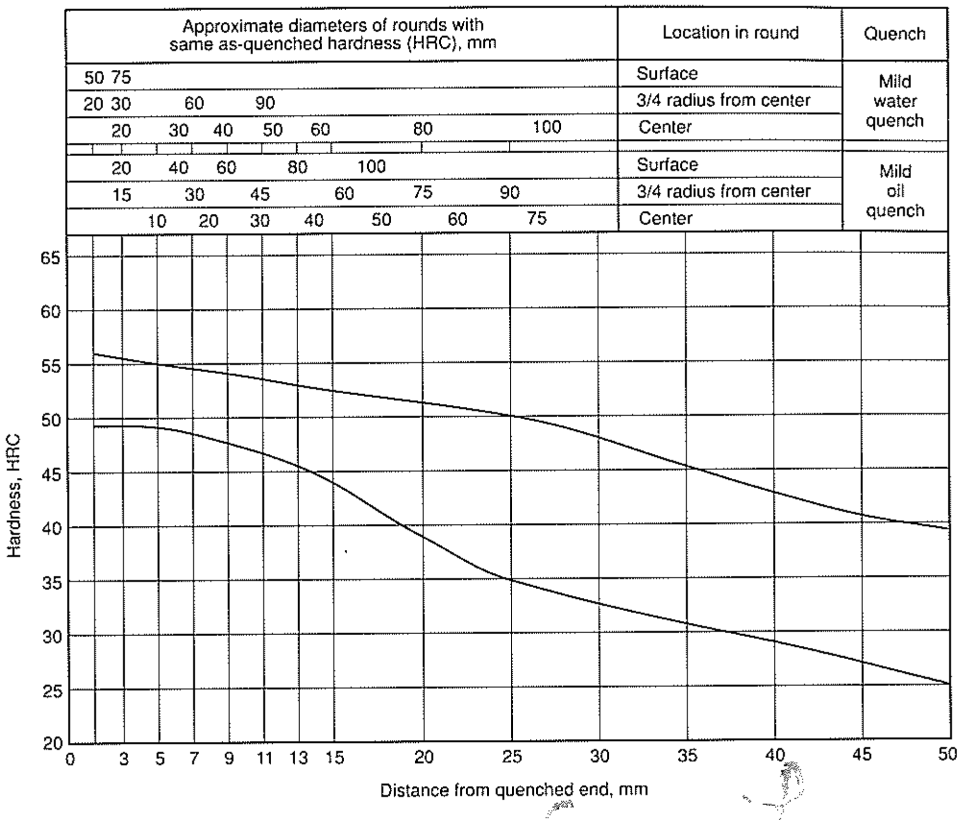


86B30H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

86B30H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 900 °C (1650 °F). Austenitize: 870 °C (1600 °F)

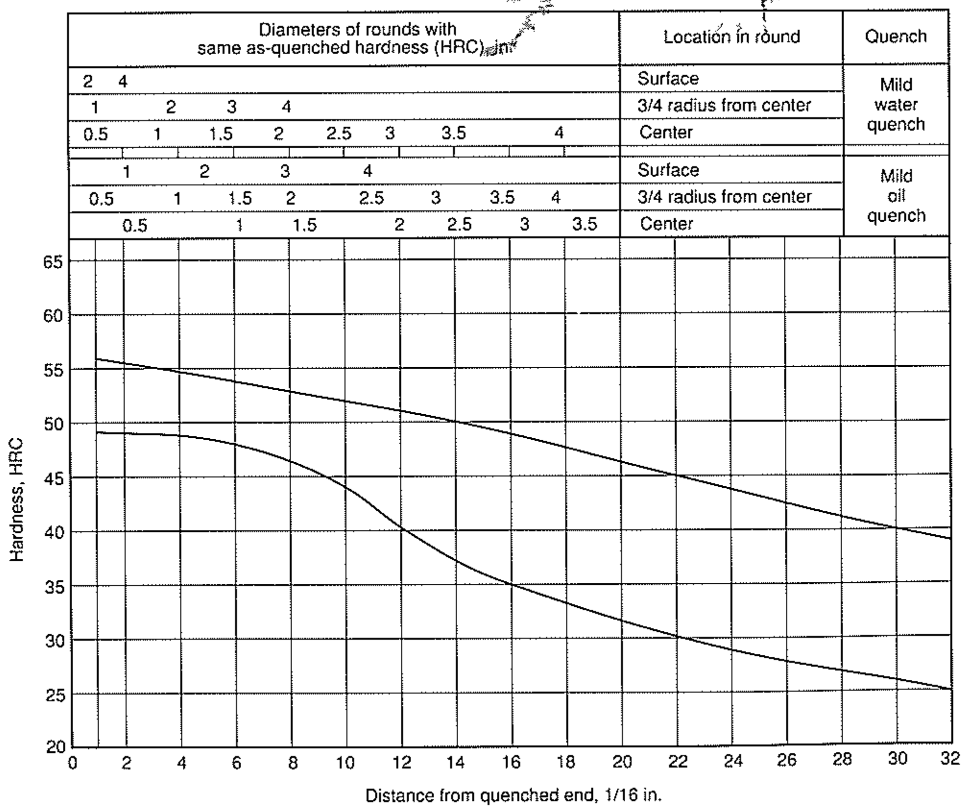
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	56	49
3	56	49
5	55	48
7	55	48
9	54	48
11	54	47
13	53	46
15	53	44
20	52	39
25	50	35
30	48	33
35	46	30
40	43	28
45	41	27
50	40	25



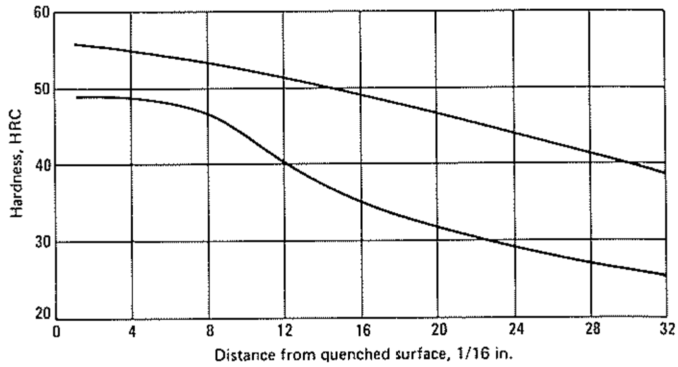
Hardness limits for specification purposes

J distance, $\frac{1}{16}$ in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	56	49
2	55	49
3	55	48
4	55	48
5	54	48
6	54	48
7	53	48
8	53	47
9	52	46
10	52	44
11	52	42
12	51	40
13	51	39
14	50	38
15	50	36
16	49	35
18	48	34
20	47	32
22	45	31
24	44	29
26	43	28
28	41	27
30	40	26
32	39	25



86B30H: End-Quench Hardenability

Distance from quenched surface		Hardness, HRC		Distance from quenched surface		Hardness, HRC	
1/16 in.	mm	max	min	1/16 in.	mm	max	min
1	1.58	56	49	13	20.54	51	39
2	3.16	55	49	14	22.12	50	38
3	4.74	55	48	15	23.70	50	36
4	6.32	55	48	16	25.28	49	35
5	7.90	54	48	18	28.44	48	34
6	9.48	54	48	20	31.60	47	32
7	11.06	53	48	22	34.76	45	31
8	12.64	53	47	24	37.92	44	29
9	14.22	52	46	26	41.08	43	28
10	15.80	52	44	28	44.24	41	27
11	17.38	52	42	30	47.40	40	26
12	18.96	51	40	32	50.56	39	25



8637, 8637H

Chemical Composition. **8637. AISI and UNS:** 0.35 to 0.40 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.15 to 0.25 Mo. **UNS H86370 and SAE/AISI 8637H:** 0.34 to 0.41 C, 0.70 to 1.05 Mn, 0.15 to 0.35 Si, 0.35 to 0.75 Ni, 0.35 to 0.65 Cr, 0.15 to 0.25 Mo

Similar Steels (U.S. and/or Foreign). **8637.** UNS G86370; SAE J404, J412, J770. **8637H.** UNS H86370; ASTM A304; SAE J1268

Characteristics. A medium-carbon, low-alloy steel, which is widely used for a variety of machinery components because of its ability to be heat treated for high strength and toughness. Used for shafts requiring high fatigue strength. Amenable to nitriding for resistance to surface wear and for greater fatigue strength. As-quenched surface hardness ranges from 50 to 55 HRC. Its hardenability is considered fairly high. Is readily forged

Forging. Heat to 1230 °C (2250 °F) maximum. Do not forge after temperature of forging stock drops below approximately 900 °C (1650 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

Annealing. For a predominantly pearlitic structure, heat to 830 °C (1525 °F), cool rapidly to 725 °C (1335 °F), then cool to 640 °C (1185 °F), at a rate not to exceed 11 °C (20 °F) per h; or heat to 830 °C (1525 °F), cool rapidly to 665 °C (1230 °F), and hold for 6 h. For a predominantly spheroidized structure, heat to 750 °C (1380 °F), cool rapidly to 725 °C (1335 °F), then cool to 640 °C (1185 °F), at a rate not to exceed 6 °C (10 °F) per h; or heat to 750 °C (1380 °F), cool rapidly to 665 °C (1230 °F), and hold for 8 h

Direct Hardening. Austenitize at 855 °C (1570 °F), and quench in oil

Tempering. After quenching, reheat immediately to the tempering temperature that will provide the desired combination of mechanical properties

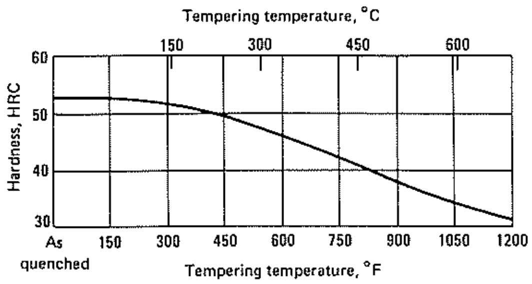
Nitriding. Responds well to ammonia gas nitriding as well as to nitriding in any one of several proprietary molten salt baths. The following is a commonly used cycle for ammonia gas nitriding:

- Parts are austenitized, quenched, and tempered at 540 °C (1000 °F) or higher. (Tempering temperature must always be higher than the nitriding temperature)
- Finish machine
- Nitride in ammonia gas for 10 to 12 h with an ammonia gas dissociation of 25 to 30%

See processing data for 4140H for other nitriding cycles

Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough and semifinish machine
- Austenitize and quench
- Temper
- Finish machine (grind if required)
- Nitride (optional)

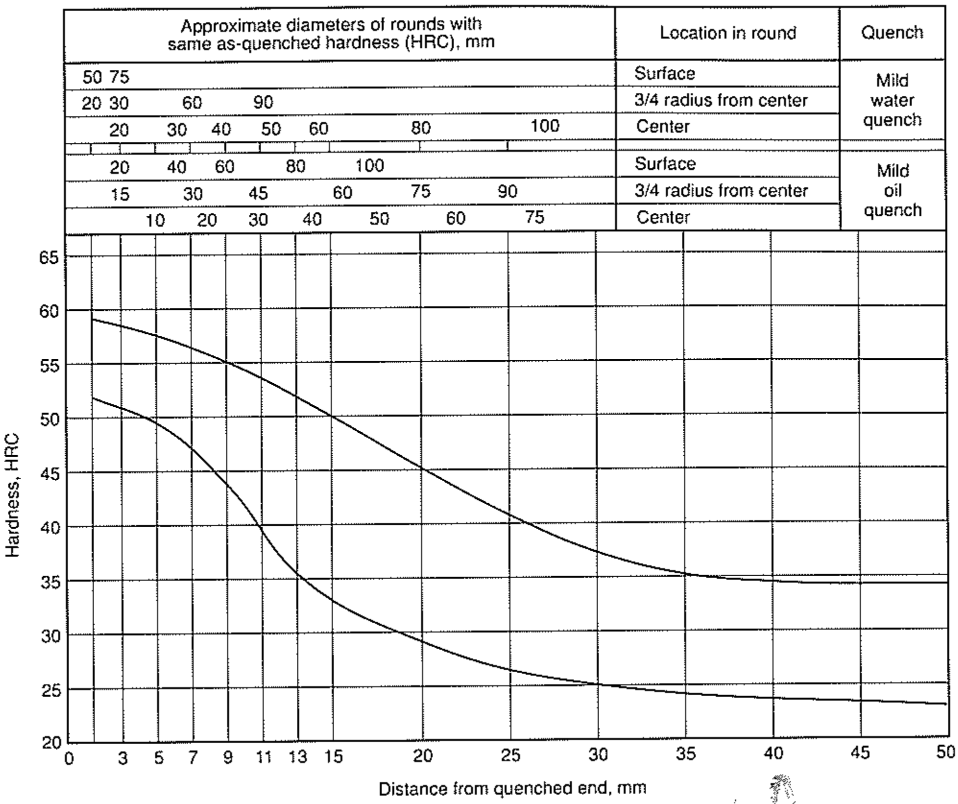


8637, 8637H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

8637H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

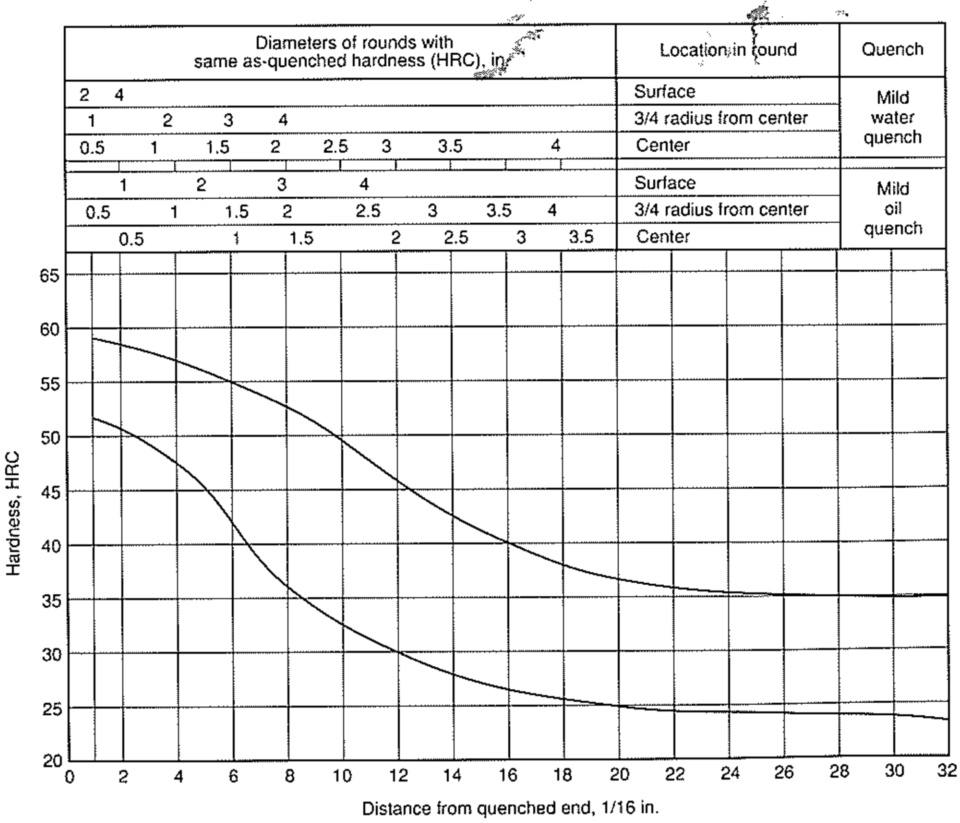
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	59	52
3	59	51
5	58	49
7	57	47
9	55	43
11	54	39
13	52	36
15	50	33
20	45	29
25	41	27
30	38	25
35	36	24
40	35	24
45	35	23
50	35	23



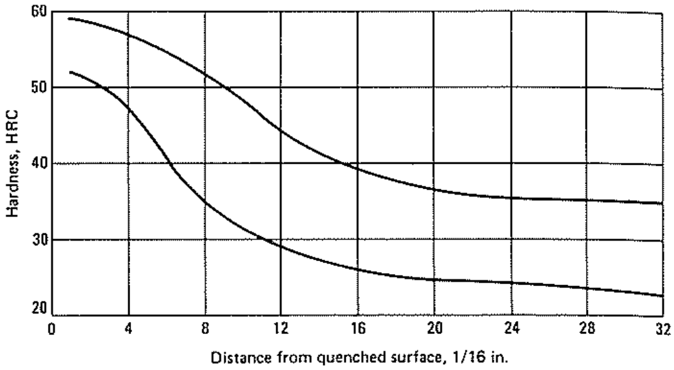
Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	59	52
2	58	51
3	58	50
4	57	48
5	56	45
6	55	42
7	54	39
8	53	36
9	51	34
10	49	32
11	47	31
12	46	30
13	44	29
14	43	28
15	41	27
16	40	26
18	39	25
20	37	25
22	36	24
24	36	24
26	35	24
28	35	24
30	35	23
32	35	23



8637H: End-Quench Hardenability

Distance from quenched surface		Hardness, HRC		Distance from quenched surface		Hardness, HRC	
1/16 in.	mm	max	min	1/16 in.	mm	max	min
1	1.58	59	52	13	20.54	44	29
2	3.16	58	51	14	22.12	43	28
3	4.74	58	50	15	23.70	41	27
4	6.32	57	48	16	25.28	40	26
5	7.90	56	45	18	28.44	39	25
6	9.48	55	42	20	31.60	37	25
7	11.06	54	39	22	34.76	36	24
8	12.64	53	36	24	37.92	36	24
9	14.22	51	34	26	41.08	35	24
10	15.80	49	32	28	44.24	35	24
11	17.38	47	31	30	47.40	35	23
12	18.96	46	30	32	50.56	35	23



8640, 8640H

Chemical Composition. **8640. AISI and UNS:** 0.38 to 0.43 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.15 to 0.25 Mo. **8640H. AISI and UNS:** 0.37 to 0.44 C, 0.70 to 1.05 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.35 to 0.75 Ni, 0.35 to 0.65 Cr, 0.15 to 0.25 Mo

Similar Steels (U.S. and/or Foreign). **8640.** UNS G86400; ASTM A304, A322; MIL SPEC MIL-S-16974; SAE J404, J412, J770; (Ger.) DIN 1.6546; (Ital.) UNI 40 NiCrMo 2 KB; (U.K.) B.S. Type 7. **8640H.** UNS H86400; ASTM A304; SAE J407; (Ger.) DIN 1.6546; (Ital.) UNI 40 NiCrMo 2 KB; (U.K.) B.S. Type 7

Characteristics. Probably the most widely used medium-carbon, low-alloy steel. Available in various product forms. Can be heat treated to high values of strength and toughness and, if desired, can be nitrided to achieve surfaces that help to resist abrasion and further increase fatigue strength. Depending on the precise carbon content, an as-quenched surface hardness of approximately 52 to 57 HRC can be expected. Hardenability is relatively high. Can be forged by any one of the various forging methods

Forging. Heat to 1230 °C (2250 °F) maximum. Do not forge after temperature of forging stock drops below approximately 900 °C (1650 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

Annealing. For a predominantly pearlitic structure, heat to 830 °C (1525 °F), cool rapidly to 725 °C (1335 °F), then cool to 640 °C (1185 °F), at a rate not to exceed 11 °C (20 °F) per h; or heat to 830 °C (1525 °F), cool rapidly to 665 °C (1230 °F), and hold for 6 h. For a predominantly spheroidized structure, heat to 750 °C (1380 °F), cool rapidly to 725 °C (1335 °F), then cool to 640 °C (1185 °F), at a rate not to exceed 6 °C (10 °F) per h; or heat to 750 °C (1380 °F), cool rapidly to 665 °C (1230 °F), and hold for 8 h

Hardening. Austenitize at 855 °C (1570 °F), and quench in oil

Tempering. After quenching, reheat immediately to the tempering temperature that will provide the desired combination of mechanical properties

Nitriding. Responds well to ammonia gas nitriding as well as to nitriding in any one of several proprietary molten salt baths. The following is a commonly used cycle for ammonia gas nitriding:

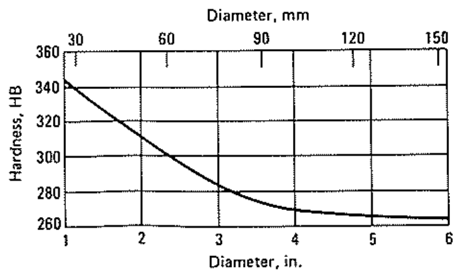
- Parts are austenitized, quenched, and tempered at 540 °C (1000 °F) or higher. (Tempering temperature must always be higher than the nitriding temperature)
- Finish machine
- Nitride in ammonia gas for 10 to 12 h with an ammonia gas dissociation of 25 to 30%

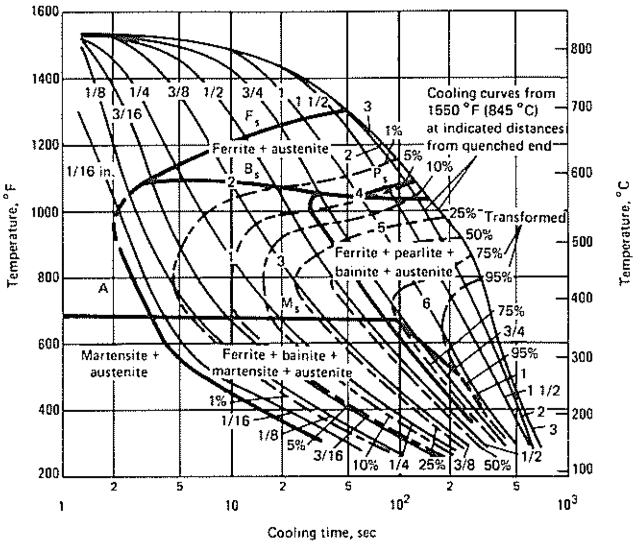
See processing data for 4140H for other nitriding cycles

Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough and semifinish machine
- Austenitize and quench
- Temper
- Finish machine (grind if required)
- Nitride (optional)

8640: Hardness vs Diameter. Composition: 0.38 to 0.43 C, 0.75 to 1.00 Mn, 0.040 P max, 0.040 S max, 0.20 to 0.35 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.15 to 0.25 Mo. Test specimens were normalized at 870 °C (1600 °F) in over-sized rounds, quenched from 845 °C (1555 °F) in oil in sizes shown, tempered at 540 °C (1000 °F). Tested in 12.8 mm (0.505 in.) rounds. Tested from bars 38 mm (1.50 in.) diam taken at half radius position. Source: Republic Steel

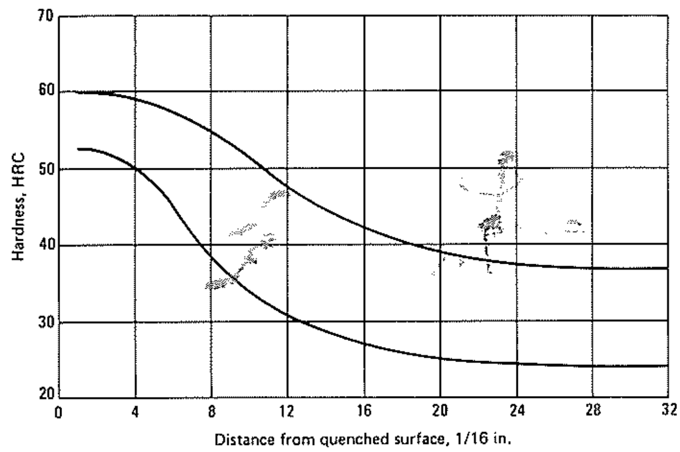




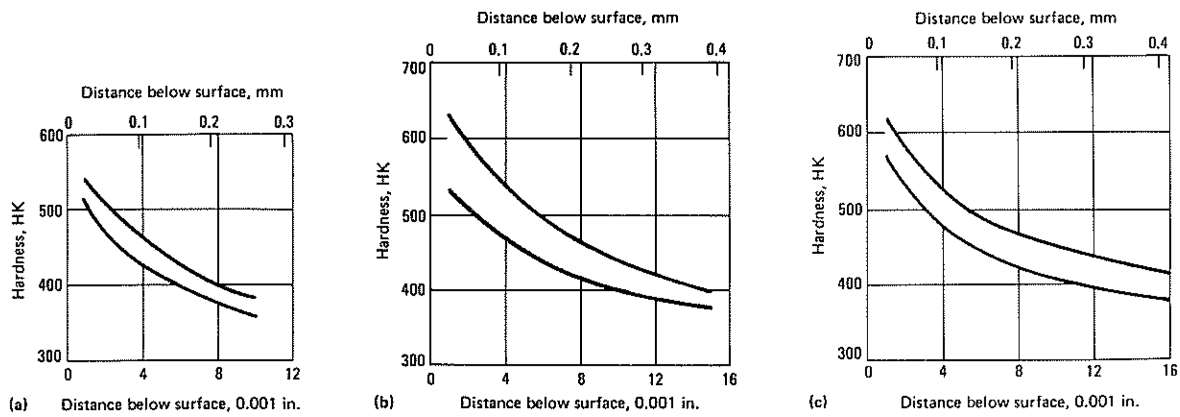
8640: Continuous Cooling Curves. Composition: 0.37 C, 0.87 Mn, 0.25 Si, 0.56 Ni, 0.44 Cr, 0.18 Mo. Austenitized at 845 °C (1555 °F). Grain size: 7. Ac_3, 795 °C (1460 °F); Ac_1, 745 °C (1370 °F). A: austenite, F: ferrite, P: pearlite, B: bainite, M: martensite

8640H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min
1	1.58	60	53	13	20.54	47	30
2	3.16	60	53	14	22.12	45	29
3	4.74	60	52	15	23.70	44	28
4	6.32	59	51	16	25.28	42	28
5	7.90	59	49	18	28.44	41	26
6	9.48	58	46	20	31.60	39	26
7	11.06	57	42	22	34.76	38	25
8	12.64	55	39	24	37.92	38	25
9	14.22	54	36	26	41.08	37	24
10	15.80	52	34	28	44.24	37	24
11	17.38	50	32	30	47.40	37	24
12	18.96	49	31	32	50.56	37	24



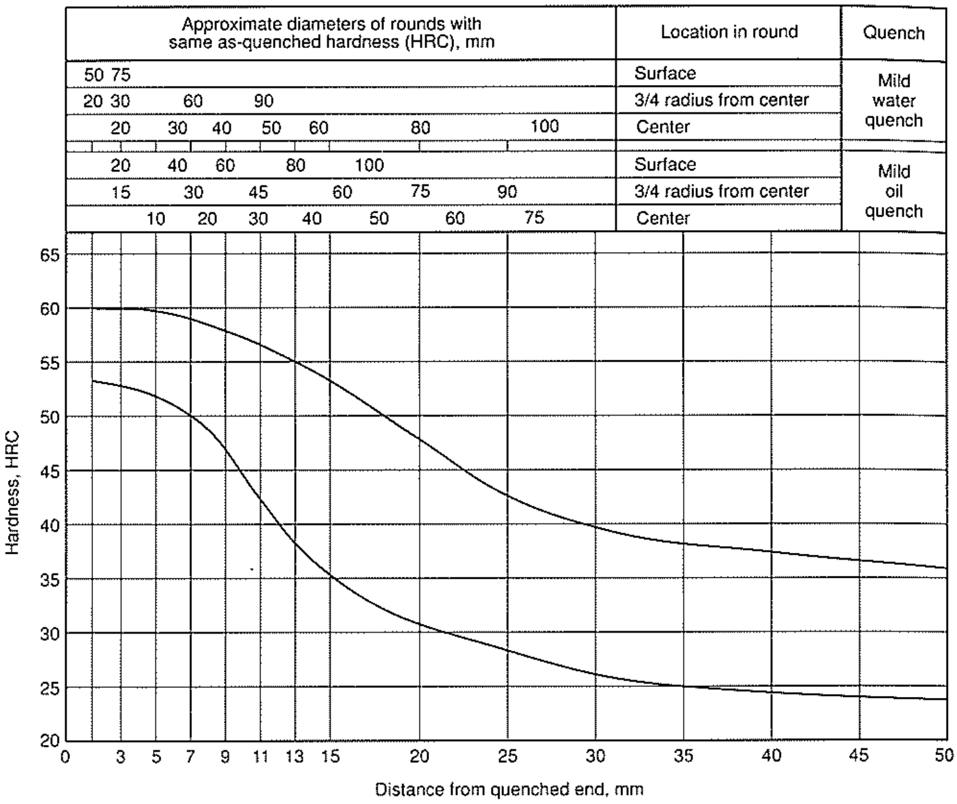
8640: Hardness Gradients. Nitrided to 20 to 30% dissociation. (a) Nitrided for 7 h; (b) nitrided for 24 h; (c) nitrided for 48 h



8640H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

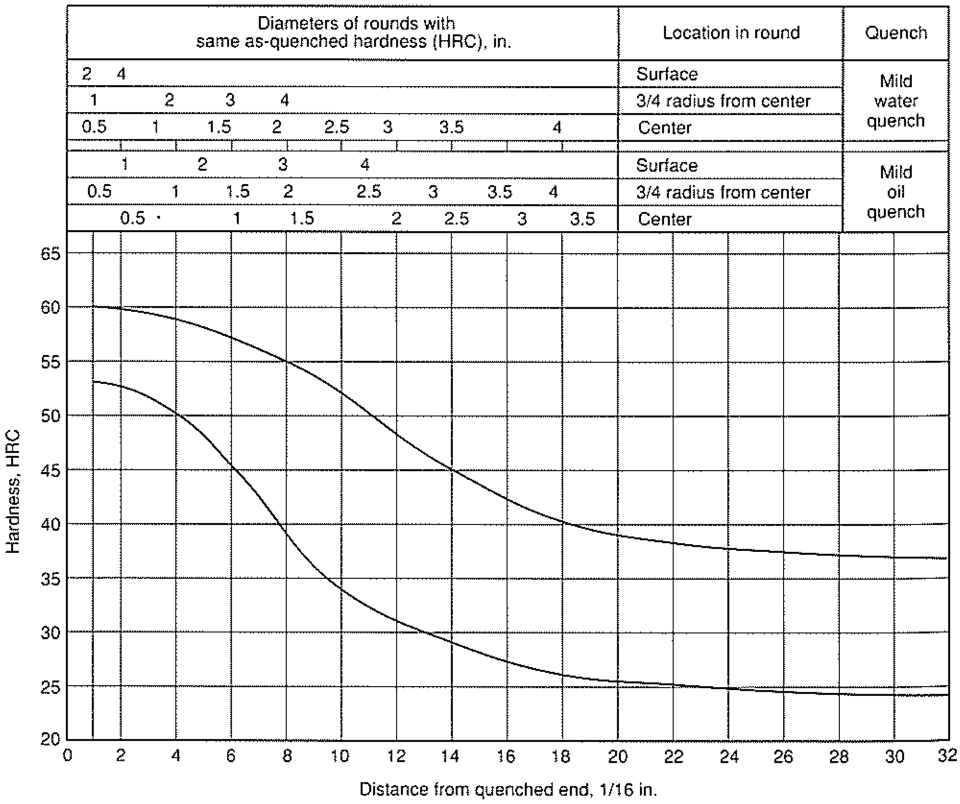
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	60	53
3	60	53
5	60	52
7	60	50
9	58	47
11	57	42
13	55	38
15	54	36
20	48	31
25	43	27
30	40	26
35	39	25
40	38	24
45	37	24
50	37	24



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	60	53
2	60	53
3	60	52
4	59	51
5	59	49
6	58	46
7	57	42
8	55	39
9	54	36
10	52	34
11	50	32
12	49	31
13	47	30
14	45	29
15	44	28
16	42	28
18	41	26
20	39	26
22	38	25
24	38	25
26	37	24
28	37	24
30	37	24
32	37	24

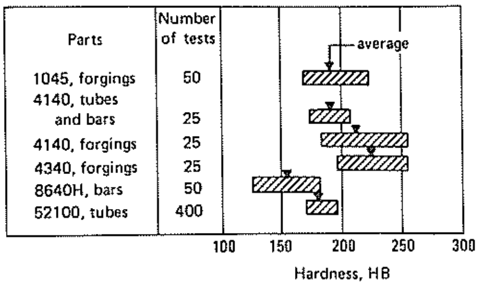


8640: Approximate Critical Points

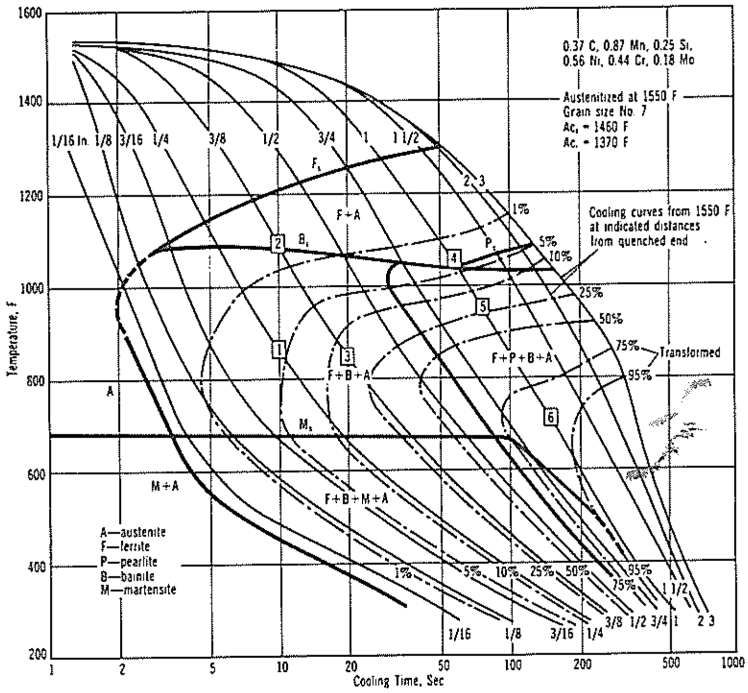
Critical point	Temperature °F	°C
Ac_1	1350	730
Ac_3	1435	780
Ar_3	1340	725
Ar_1	1230	665

Source: Republic Steel

8640H: Variation of Brinell Hardness Measurements. Tests done on annealed plain carbon and low-alloy steels



8640: Cooling Curves. Composition: 0.37 C, 0.87 Mn, 0.25 Si, 0.56 Ni, 0.44 Cr, 0.18 Mo. Grain size: 7. Austenitized at 845 °C (1555 °F) (using interrupted Jominy method)



8642, 8642H

Chemical Composition. 8642. AISI and UNS: 0.40 to 0.45 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.15 to 0.25 Mo. **UNS H86420 and SAE/AISI 8642H:** 0.39 to 0.46 C, 0.70 to 1.05 Mn, 0.15 to 0.35 Si, 0.35 to 0.75 Ni, 0.35 to 0.65 Cr, 0.15 to 0.25 Mo

Similar Steels (U.S. and/or Foreign). 8642. UNS G86420; SAE J404, J412, J770. **8642H.** UNS H86420; ASTM A304; SAE J1268

Characteristics. Change in composition from 8640H is slight. Has essentially the same characteristics as described for 8640H. As-quenched surface hardness for 8642H, because the carbon content is slightly higher, is approximately 53 to 59 HRC. Hardenability band is shifted upward slightly for 8642H. Can be forged by any one of the various forging methods

Forging. Heat to 1230 °C (2250 °F) maximum. Do not forge after temperature of forging stock drops below approximately 900 °C (1650 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

Annealing. For a predominantly pearlitic structure, heat to 830 °C (1525 °F), cool rapidly to 725 °C (1335 °F), then cool to 640 °C (1185 °F), at a rate not to exceed 11 °C (20 °F) per h; or heat to 830 °C (1525 °F), cool rapidly to 665 °C (1230 °F), and hold for 6 h. For a predominantly spheroidized structure, heat to 750 °C (1380 °F), cool rapidly to 725 °C (1335 °F), then cool to 640 °C (1185 °F), at a rate not to exceed 6 °C (10 °F) per h; or heat to 750 °C (1380 °F), cool rapidly to 665 °C (1230 °F), and hold for 8 h

Direct Hardening. Austenitize at 855 °C (1570 °F), and quench in oil

Nitriding. Responds well to ammonia gas nitriding as well as to nitriding in any one of several proprietary molten salt baths. The following is a commonly used cycle for ammonia gas nitriding:

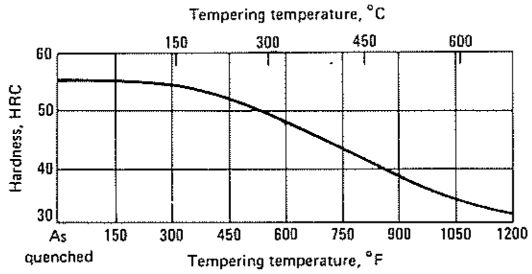
- Parts are austenitized, quenched, and tempered at 540 °C (1000 °F) or higher. (Tempering temperature must always be higher than the nitriding temperature)
- Finish machine
- Nitride in ammonia gas for 10 to 12 h with an ammonia gas dissociation of 25 to 30%

See processing data for 4140H for other nitriding cycles. Flame hardening and ion nitriding are alternative processes

Tempering. After quenching, reheat immediately to the tempering temperature that will provide the desired combination of mechanical properties

Recommended Processing Sequence

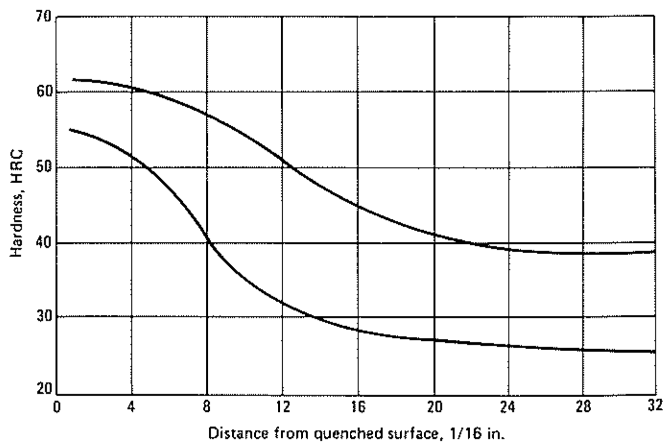
- Forge
- Normalize
- Anneal
- Rough and semifinish machine
- Austenitize and quench
- Temper
- Finish machine (grind if required)
- Nitride (optional)



8642, 8642H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

8642H: End-Quench Hardenability

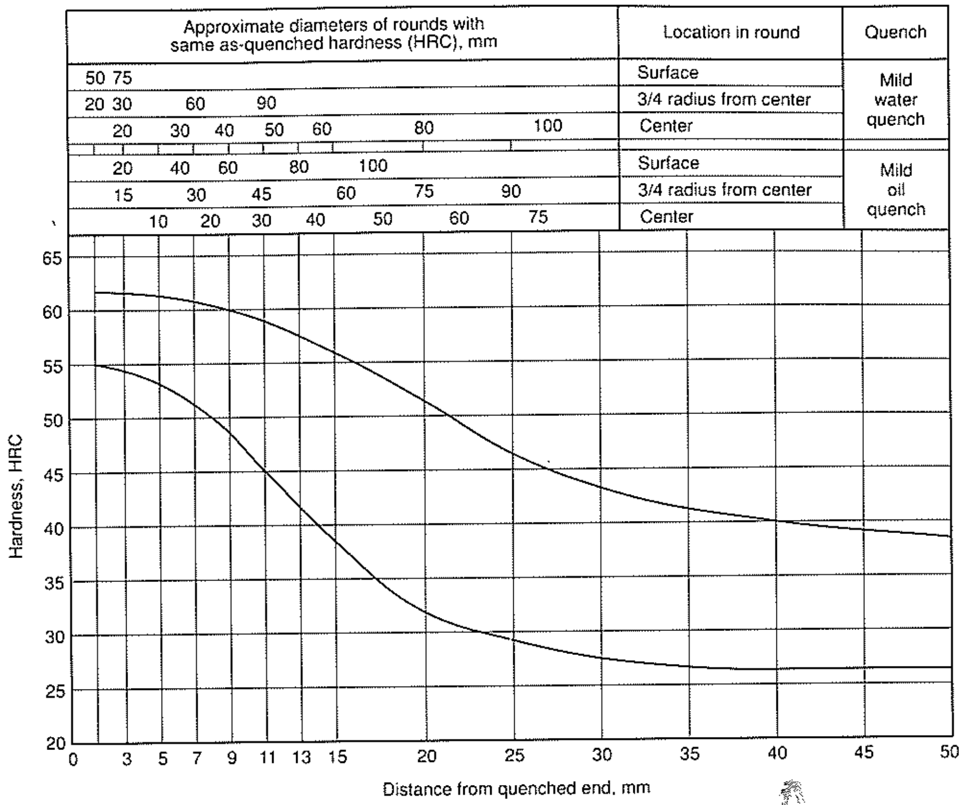
Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min
1	1.58	62	55	13	20.54	50	32
2	3.16	62	54	14	22.12	49	31
3	4.74	62	53	15	23.70	48	30
4	6.32	61	52	16	25.28	46	29
5	7.90	61	50	18	28.44	44	28
6	9.48	60	48	20	31.60	42	.28
7	11.06	59	45	22	34.76	41	27
8	12.64	58	42	24	37.92	40	27
9	14.22	57	39	26	41.08	40	26
10	15.80	55	37	28	44.24	39	26
11	17.38	54	34	30	47.40	39	26
12	18.96	52	33	32	50.56	39	26



8642H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

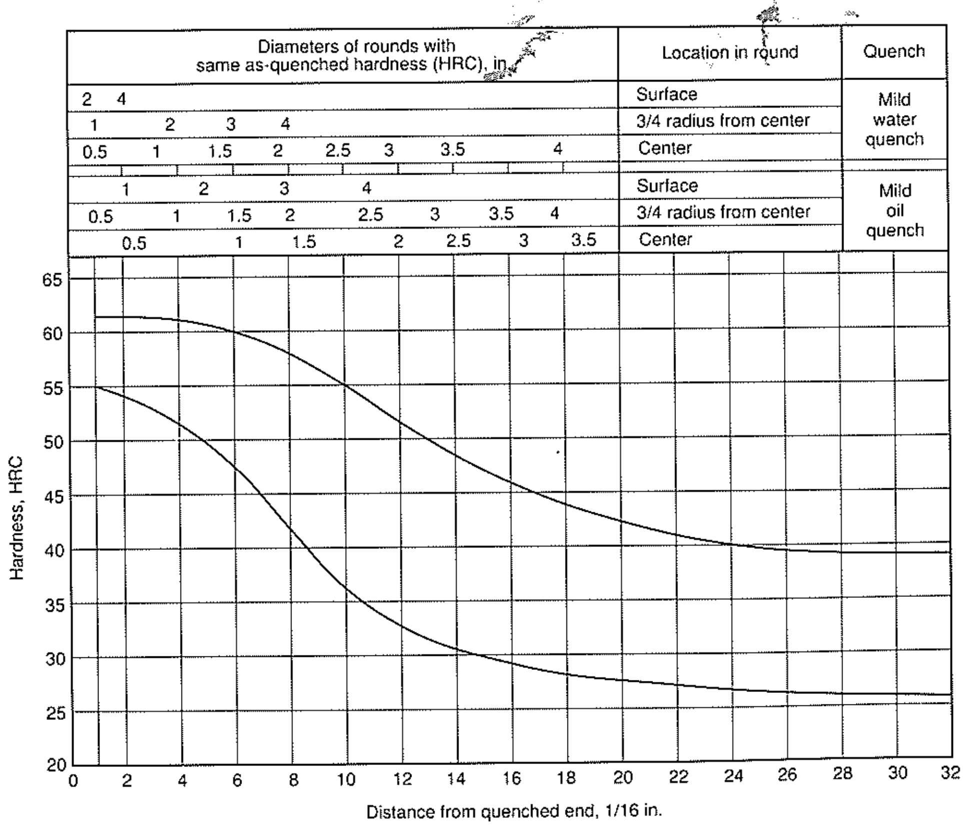
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Minimum
1.5	62	55
3	62	54
5	62	53
7	61	51
9	60	49
11	59	46
13	58	42
15	56	38
20	52	32
25	47	29
30	44	28
35	41	27
40	40	27
45	39	26
50	39	26



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Minimum
1	62	55
2	62	54
3	62	53
4	61	52
5	61	50
6	60	48
7	59	45
8	58	42
9	57	39
10	55	37
11	54	34
12	52	33
13	50	32
14	49	31
15	48	30
16	46	29
18	44	28
20	42	28
22	41	27
24	40	27
26	40	26
28	39	26
30	39	26
32	39	26



8645, 8645H

Chemical Composition. **8645. AISI and UNS:** 0.43 to 0.48 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.15 to 0.25 Mo. **UNS H86450 and SAE/AISI 8645H:** 0.42 to 0.49 C, 0.70 to 1.05 Mn, 0.035 P max, 0.40 S max, 0.15 to 0.30 Si, 0.35 to 0.75 Ni, 0.35 to 0.65 Cr, 0.15 to 0.25 Mo

Similar Steels (U.S. and/or Foreign). **8645.** UNS G86450; MIL SPEC MIL-S-16974; SAE J404, J412, J770. **8645H.** UNS H86450; ASTM A304; SAE J1268

Characteristics. A slightly lower carbon version of 8650H. As-quenched hardness generally ranges from approximately 54 to 60 HRC, depending on the precise carbon content within the allowable range. Considered a relatively high-hardenability steel. Used extensively for a variety of machinery parts where high strength is required for rigorous service, including highly stressed shafts and springs. Can be forged, although just as is true for other higher carbon, high-hardenability steels, forgings of complex shape should be cooled slowly from the forging temperature to minimize the possibility of cracking

Forging. Heat to 1230 °C (2250 °F) maximum. Do not forge after temperature of forging stock drops below approximately 925 °C (1695 °F). Cool slowly from the forging temperature

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

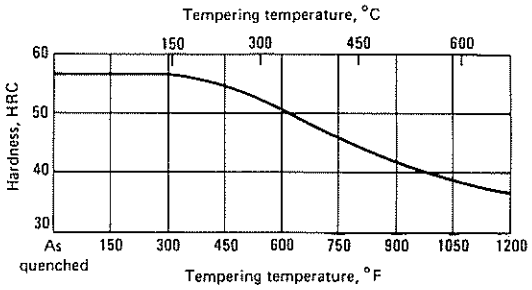
Annealing. For a predominantly pearlitic structure, heat to 830 °C (1525 °F), cool slowly to 710 °C (1310 °F), then cool to 650 °C (1200 °F), at a rate not to exceed 8 °C (15 °F) per h; or heat to 830 °C (1525 °F), cool rapidly to 650 °C (1200 °F), and hold for 8 h. For a predominantly spheroidized structure, heat to 750 °C (1380 °F), cool rapidly to 715 °C (1320 °F), then cool to 650 °C (1200 °F), at a rate not to exceed 6 °C (10 °F) per h; or heat to 750 °C (1380 °F), cool rapidly to 650 °C (1200 °F), and hold for 10 h

Hardening. Austenitize at 845 °C (1555 °F), and quench in oil. Flame hardening, gas nitriding, ion nitriding, and carbonitriding are suitable processes

Tempering. After quenching, parts should be tempered immediately, preferably when they are still warm to the touch, at 150 °C (300 °F) or higher. For most purposes, higher tempering temperatures are used. Selection of tempering temperature is based on the desired combination of mechanical properties

Recommended Processing Sequence

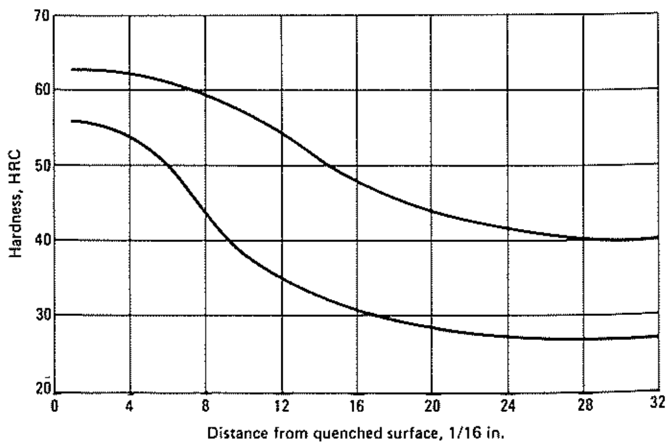
- Forge
- Normalize
- Anneal
- Rough and semifinish machine
- Austenitize and quench
- Temper
- Finish machine



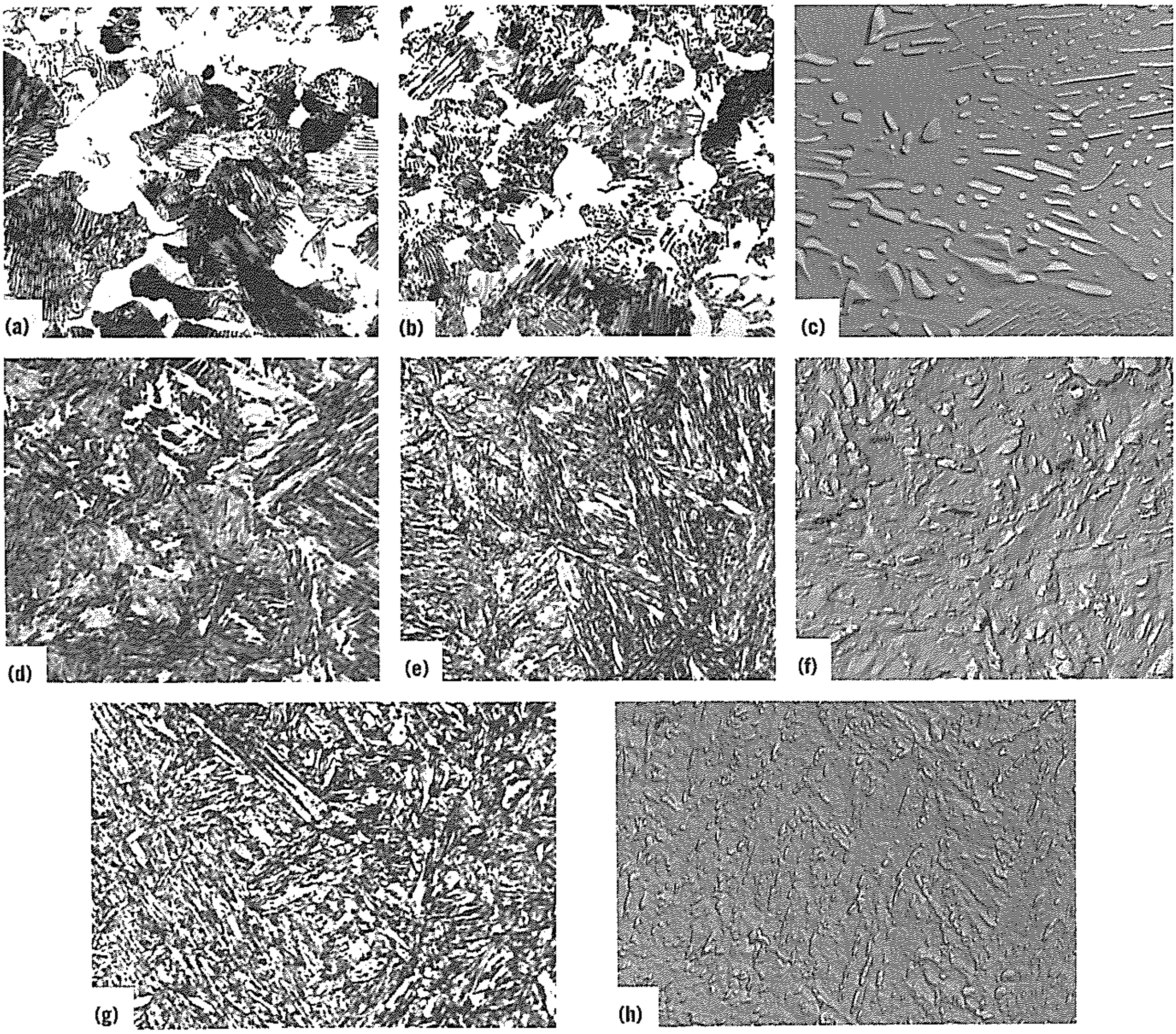
8645, 8645H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

8645H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min
1	1.58	63	56	13	20.54	54	34
2	3.16	63	56	14	22.12	52	33
3	4.74	63	55	15	23.70	51	32
4	6.32	63	54	16	25.28	49	31
5	7.90	62	52	18	28.44	47	30
6	9.48	61	50	20	31.60	45	29
7	11.06	61	48	22	34.76	43	28
8	12.64	60	45	24	37.92	42	28
9	14.22	59	41	26	41.08	42	27
10	15.80	58	39	28	44.24	41	27
11	17.38	56	37	30	47.40	41	27
12	18.96	55	35	32	50.56	41	27



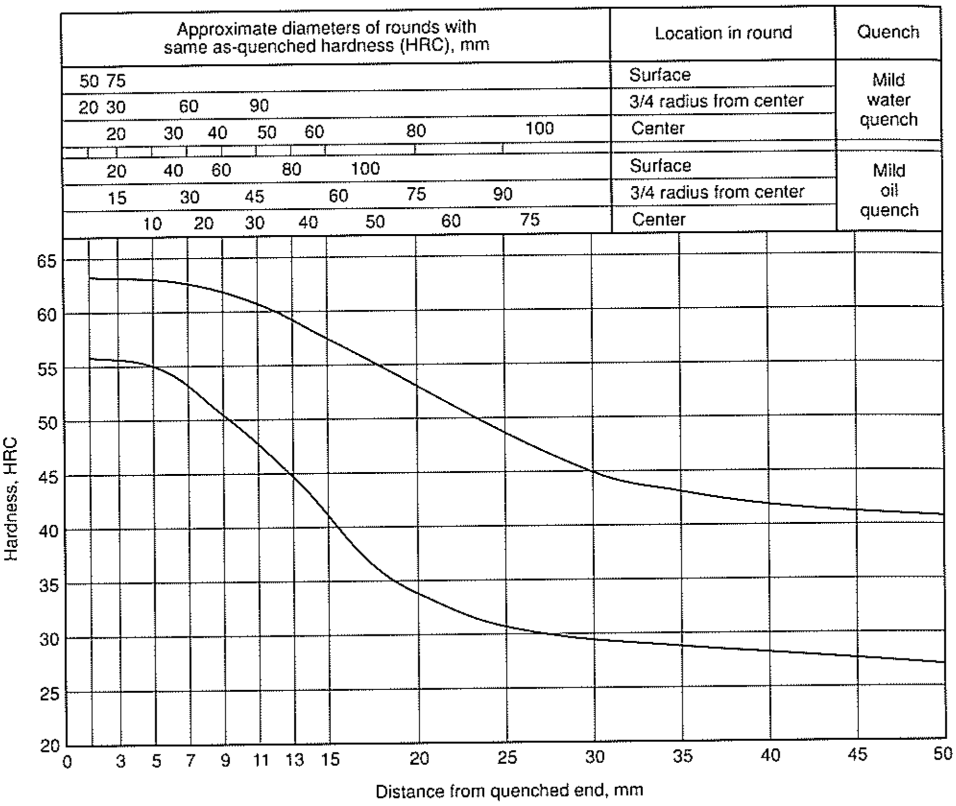
8645: Microstructures. (a) 2% nital, 825×. Hot rolled steel bar, 25 mm (1 in.) diam, austenitized at 815 °C (1500 °F) for 1 h and furnace cooled, resulting in a fully annealed structure. Dark areas lamellar pearlite, white areas ferrite. (b) 2% nital, 750×. Same steel and bar size as (a). Austenitized at 815 °C (1500 °F) for 1 h, cooled to 675 °C (1245 °F), and held for 8 h (for spheroidizing). Dark areas, partly spheroidized pearlite, white areas ferrite. See (c). (c) 5% picric acid, 2 ½% HNO_3, in ethanol; 5000×. Same bar size as (a) and (b), same heat treatment as (b). Replica electron micrograph shows a structure that consists of partly spheroidized pearlite. (d) 2% nital, 1000×. Same bar size as (a), (b), and (c). Austenitized at 845 °C (1555 °F), water quenched, tempered at 260 °C (500 °F) for 1 h. Tempered martensite. See (e). (e) 2% nital, 1000×. Same bar size as (a), (b), (c) and (d). Heat treatment same as (d), except tempered at 370 °C (700 °F). Tempered martensite. See (f). (f) 5% picric acid, 2 ½% HNO_3, in ethanol; 10 000×. Same bar size and heat treatment as (e). Electron micrograph of platinum-carbon-shadowed two-stage carbon replica, showing carbide particles that precipitated from the martensite matrix. (g) 2% nital, 1000×. Same bar size as (f), austenitized at 845 °C (1555 °F) for 1 h, water quenched, tempered at 480 °C (895 °F) for 1 h. Compare with (d) and (e); increasing tempering temperature has little effect on the appearance of the tempered martensite. (h) 5% picric acid, 2 ½% HNO_3, in ethanol; 10 000×. Same bar size and heat treatment as (g). Electron micrograph, made using a platinum-carbon-shadowed two-stage carbon replica, shows particles of carbide that have precipitated from the matrix of tempered martensite



8645H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	63	56
3	63	56
5	63	55
7	63	53
9	62	51
11	61	48
13	59	45
15	58	41
20	54	34
25	49	31
30	46	29
35	43	28
40	42	27
45	42	27
50	41	27



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	63	56
2	63	56
3	63	55
4	63	54
5	62	52
6	61	50
7	61	48
8	60	45
9	59	41
10	58	39
11	56	37
12	55	35
13	54	34
14	52	33
15	51	32
16	49	31
18	47	30
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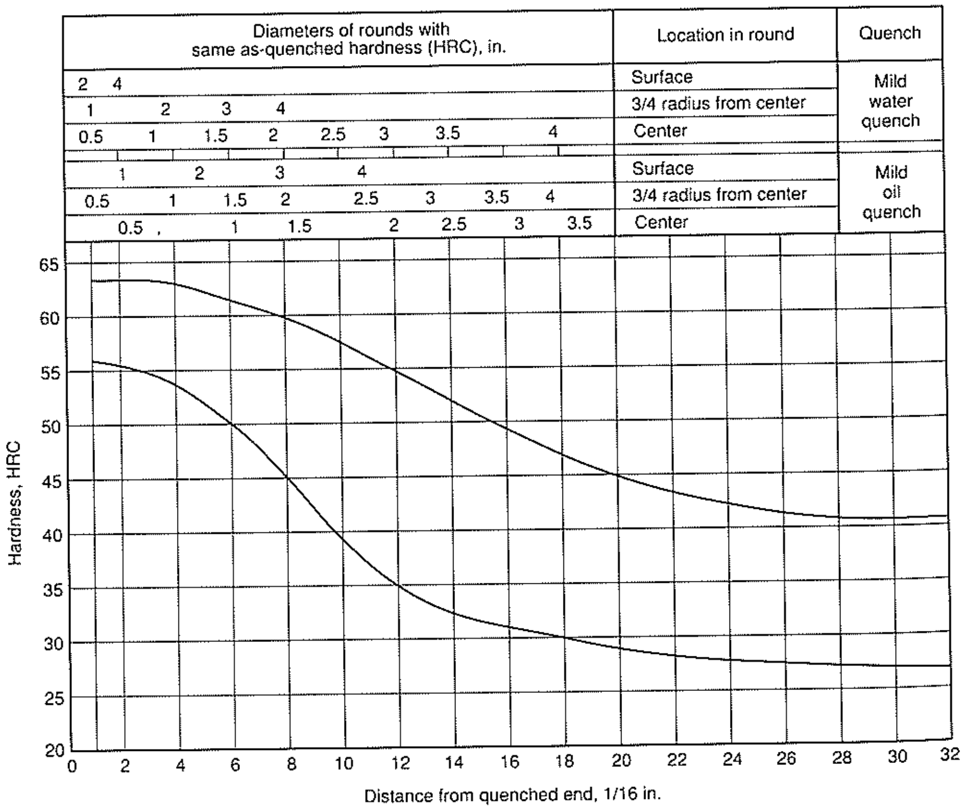
24	42	28
26	42	27
28	41	27
30	41	27
32	41	27



86B45, 86B45H

Chemical Composition. 86B45. AISI: 0.43 to 0.48 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.20 to 0.35 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.15 to 0.25 Mo, 0.0005 B min. **UNS:** 0.43 to 0.48 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.15 to 0.25 Mo, 0.0005 B min. **UNS H86451 and SAE/AISI 86B45H:** 0.42 to 0.49 C, 0.70 to 1.05 Mn, 0.15 to 0.35 Si, 0.35 to 0.75 Ni, 0.35 to 0.65 Cr, 0.15 to 0.25 Mo, B (can be expected to be 0.0005 to 0.003 percent)

Similar Steels (U.S. and/or Foreign). 86B45. UNS G86451; ASTM A519; SAE J404, J412, J770. **86B45H.** UNS H86451; ASTM A304; SAE J1268

Characteristics. With the exception of the boron addition, 86B45H is identical in composition to 8645H. Commercial applications for these two steels are similar. 86B45H is chosen when more hardenability is needed than can be provided by 8645H. 86B45H is significantly higher in hardenability. As-quenched surface hardness is the same for the two steels, usually ranging from 54 to 60 HRC. Compares favorably with 8645H in forgeability and response to heat treatment

Forging. Heat to 1230 °C (2250 °F) maximum. Do not forge after temperature of forging stock drops below approximately 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

Annealing. For a predominantly pearlitic structure, heat to 830 °C (1525 °F), cool rapidly to 725 °C (1335 °F), then cool to 640 °C (1185 °F), at a rate not to exceed 11 °C (20 °F) per h; or heat to 830 °C (1525 °F), cool rapidly to 665 °C (1230 °F), and hold for 7 h. For a predominantly spheroidized structure, heat to 750 °C (1380 °F), cool rapidly to 725 °C (1335 °F), then cool to 640 °C (1185 °F), at a rate not to exceed 6 °C (10 °F) per h; or heat to 750 °C (1380 °F), cool rapidly to 665 °C (1230 °F), and hold for 10 h

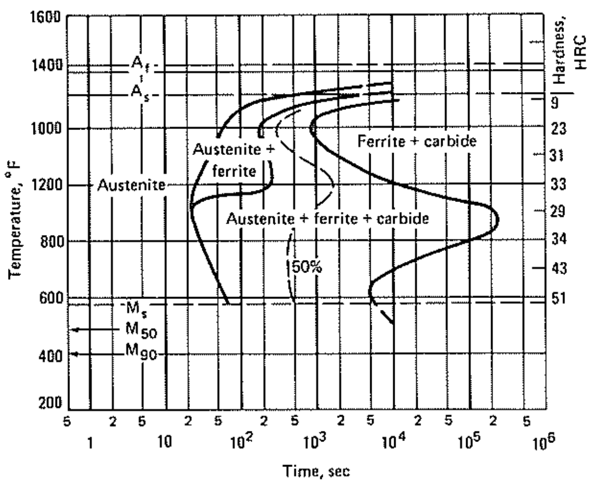
Hardening. Austenitize at 845 °C (1555 °F), and quench in oil. Flame hardening, gas nitriding, ion nitriding, carbonitriding, and fluidized bed nitriding are suitable processes

Tempering. After quenching, parts should be tempered immediately. Selection of tempering temperature depends on the desired mechanical properties

Recommended Processing Sequence

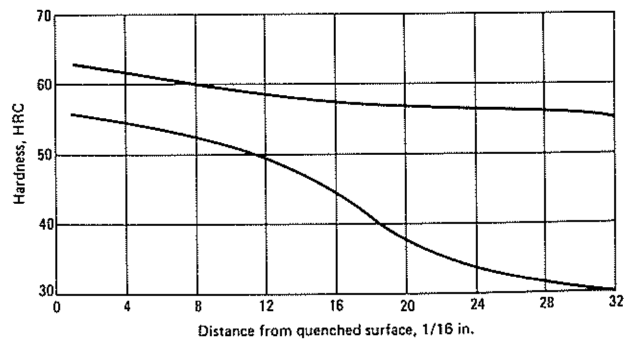
- Forge
- Normalize
- Anneal
- Rough and semifinish machine
- Austenitize and quench
- Temper
- Finish machine

86B45: Isothermal Transformation Diagram. Composition: 0.45 C, 0.89 Mn, 0.59 Ni, 0.66 Cr, 0.12 Mo, 0.0015 B. Austenitized at 845 °C (1555 °F). Grain size: 6 to 7



86B45H: End-Quench Hardenability

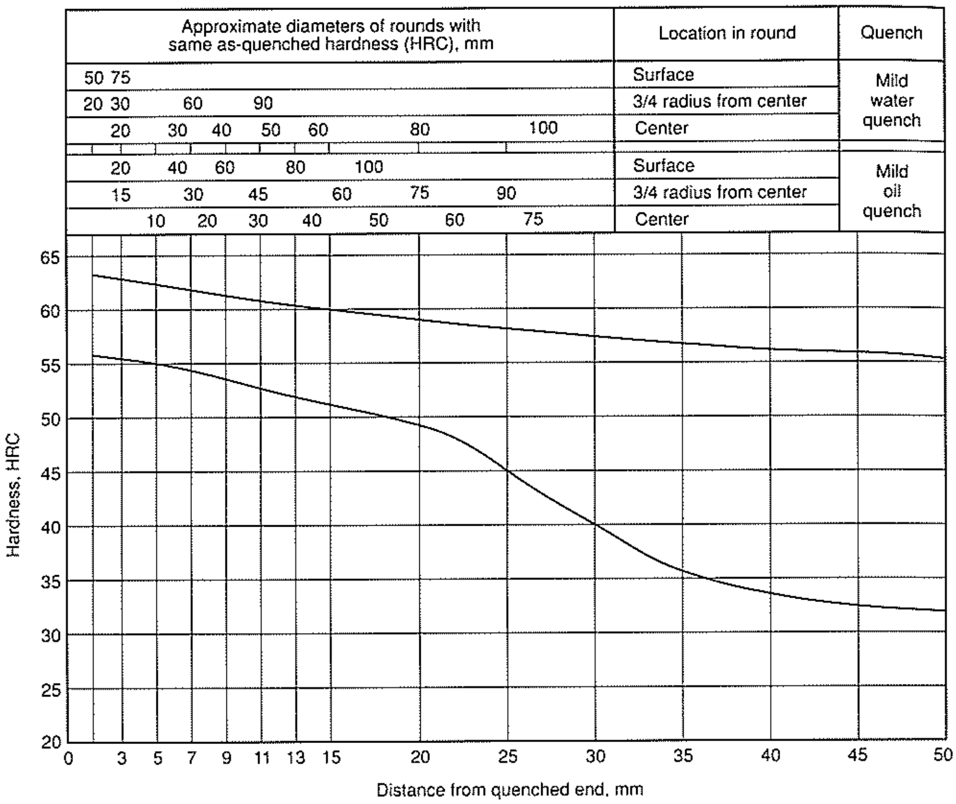
Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max	min	Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max	min
1	1.58	63	56	13	20.54	59	49
2	3.16	63	56	14	22.12	59	48
3	4.74	62	55	15	23.70	58	46
4	6.32	62	54	16	25.28	58	45
5	7.90	62	54	18	28.44	58	42
6	9.48	61	53	20	31.60	58	39
7	11.06	61	52	22	34.76	57	37
8	12.64	60	52	24	37.92	57	35
9	14.22	60	51	26	41.08	57	34
10	15.80	60	51	28	44.24	57	32
11	17.38	59	50	30	47.40	56	32
12	18.96	59	50	32	50.56	56	31



86B45H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

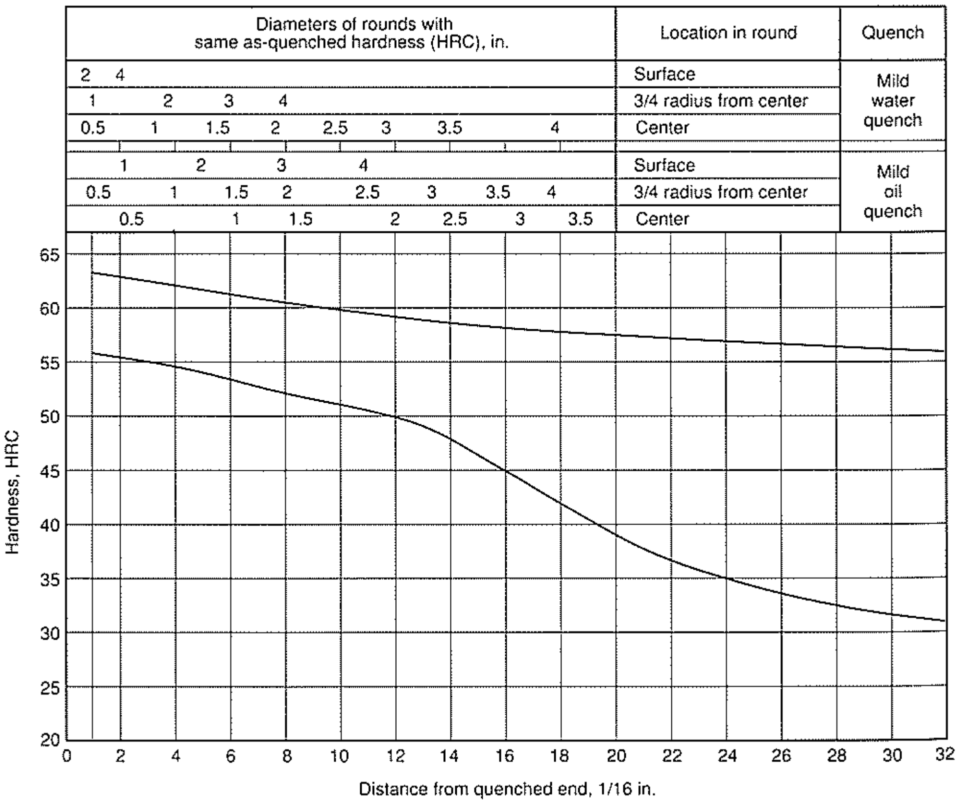
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Minimum
1.5	63	56
3	63	56
5	63	55
7	62	54
9	62	53
11	61	52
13	61	51
15	60	51
20	59	49
25	58	45
30	58	40
35	57	36
40	57	33
45	56	32
50	56	31

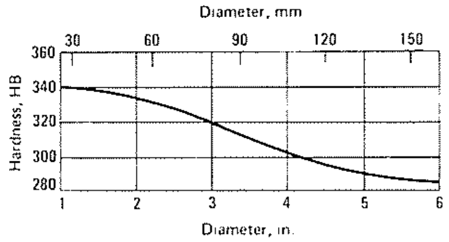


Hardness limits for specification purposes

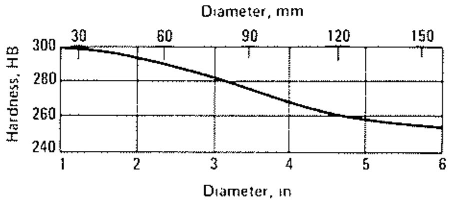
J distance, 1/16 in.	Hardness, HRC Maximum	Minimum
1	63	56
2	63	56
3	62	55
4	62	54
5	62	54
6	61	53
7	61	52
8	60	52
9	60	51
10	60	51
11	59	50
12	59	50
13	59	49
14	59	48
15	58	48
16	58	45
18	58	42
20	58	39
22	57	37
24	57	35
26	57	34
28	57	32
30	56	32
32	56	31



86B45: Hardness vs Diameter. Composition: 0.43 to 0.48 C, 0.75 to 1.00 Mn, 0.040 P max, 0.040 S max, 0.20 to 0.35 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.15 to 0.25 Mo, 0.0005 B min. Approximate critical points: Ac_1, 720 °C (1330 °F). Ac_3, 770 °C (1420 °F); Ar_3, 695 °C (1280 °F); Ar_1, 650 °C (1200 °F). Recommended thermal treatment: forge at 1205 °C (2200 °F) maximum, anneal at 790 to 845 °C (1455 to 1555 °F) for a maximum hardness of 207 HB, normalize at 845 to 900 °C (1555 to 1650 °F) for an approximate hardness of 277 HB, quench from 830 to 855 °C (1525 to 1570 °F) in oil. Test specimens were normalized at 870 °C (1600 °F) in over-sized rounds, quenched from 845 °C (1555 °F) in oil, tempered at 540 °C (1000 °F), and tested in 12.8 mm (0.505 in.) rounds. Tests from bars 38 mm (1.50 in.) and over are taken at half radius position. Source: Republic Steel



86B45: Hardness vs Diameter. Composition: 0.43 to 0.48 C, 0.75 to 1.00 Mn, 0.040 P max, 0.040 S max, 0.20 to 0.35 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.15 to 0.25 Mo, 0.0005 B min. Approximate critical points: Ac_1, 720 °C (1330 °F). Ac_3, 770 °C (1420 °F); Ar_3, 695 °C (1280 °F); Ar_1, 650 °C (1200 °F). Recommended thermal treatment: forge at 1205 °C (2200 °F) maximum, anneal at 790 to 845 °C (1455 to 1555 °F) for a maximum hardness of 207 HB, normalize at 845 to 900 °C (1555 to 1650 °F) for an approximate hardness of 277 HB, quench from 830 to 855 °C (1525 to 1570 °F) in oil. Test specimens were normalized at 870 °C (1600 °F) in over-sized rounds, quenched from 845 °C (1555 °F) in oil, tempered at 650 °C (1200 °F), and tested in 12.8 mm (0.505 in.) rounds. Tests from specimens 38 mm (1 ½ in.) and over were taken at half radius position. Source: Republic Steel



8650, 8650H

Chemical Composition. **8650. AISI:** 0.48 to 0.53 C, 0.75 to 1.00 Mn, 0.040 P max, 0.040 S max, 0.20 to 0.35 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.15 to 0.25 Mo. **UNS:** 0.48 to 0.53 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.15 to 0.25 Mo. **UNS H86500 and SAE/AISI 8650H:** 0.47 to 0.54 C, 0.70 to 1.05 Mn, 0.15 to 0.35 Si, 0.35 to 0.75 Ni, 0.35 to 0.65 Cr, 0.15 to 0.25 Mo

Similar Steels (U.S. and/or Foreign). **8650.** UNS G86500; ASTM A322, A519; SAE J404, J412, J770. **8650H.** UNS H86500; ASTM A304; SAE J1268

Characteristics. Borderline between what is usually considered a medium-carbon grade and a high-carbon grade alloy steel. When the carbon is on the lower side of the allowable range, oil-quenched hardness of approximately 56 HRC can be expected. When the carbon content is near 0.54, an as-quenched hardness of approximately 61 HRC can be expected. Hardenability is relatively high. Used extensively for a variety of machinery parts where high strength is required for rigorous service, notably for highly stressed shafts and springs. Can be forged, although as is true for other higher carbon, high-hardenability steels, forgings of complex shape should be cooled slowly from the forging temperature to minimize the possibility of cracking

Forging. Heat to 1230 °C (2250 °F) maximum. Do not forge after temperature of forging stock drops below approximately 925 °C (1695 °F). Cool slowly from the forging temperature

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

Annealing. For a predominantly pearlitic structure, heat to 830 °C (1525 °F), cool slowly to 710 °C (1310 °F), then cool to 650 °C (1200 °F), at a rate not to exceed 8 °C (15 °F) per h; or heat to 830 °C (1525 °F), cool rapidly to 650 °C (1200 °F), and hold for 8 h. For a predominantly spheroidized structure, heat to 750 °C (1380 °F), cool rapidly to 715 °C (1320 °F), then cool to 650 °C (1200 °F), at a rate not to exceed 6 °C (10 °F) per h; or heat to 750 °C (1380 °F), cool rapidly to 650 °C (1200 °F), and hold for 10 h

Hardening. Austenitize at 845 °C (1555 °F), and quench in oil. Flame hardening, gas nitriding, ion nitriding, and carbonitriding are suitable processes

Tempering. After quenching, parts should be tempered immediately (preferably when they are still warm to the touch) at 150 °C (300 °F) or higher. For most purposes, higher tempering temperatures are used. Selection of tempering temperature is based on the desired combination of mechanical properties

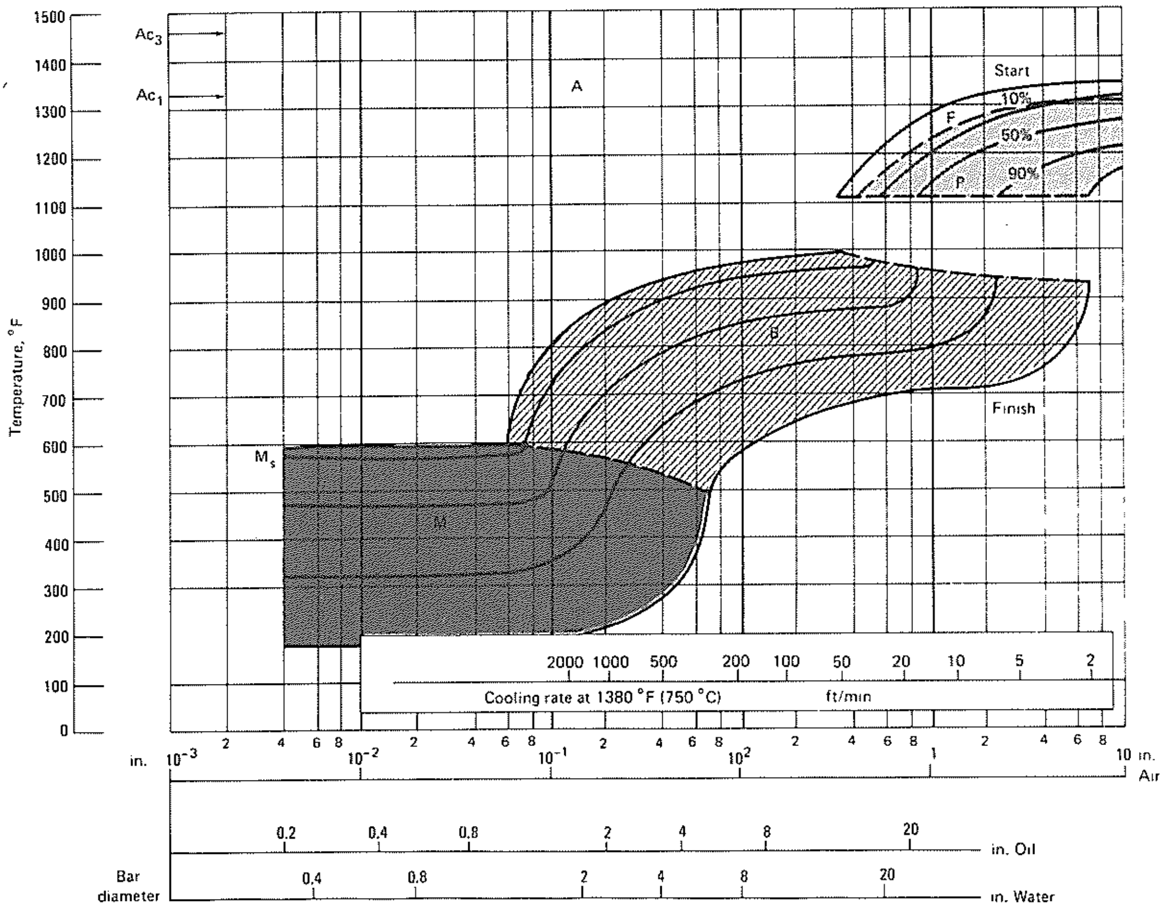
Recommended Processing Sequence

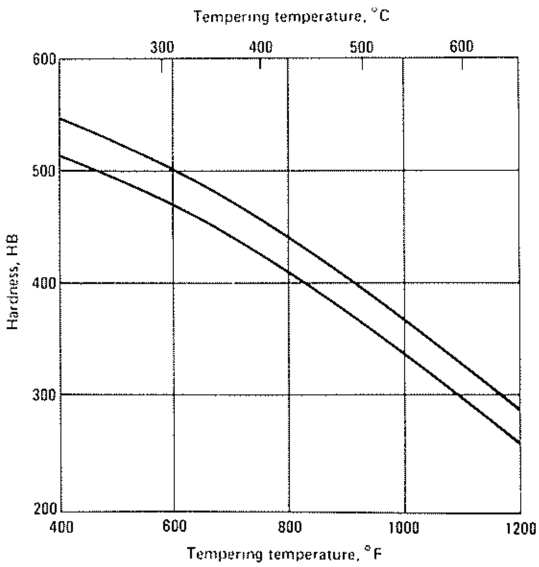
- Forge
- Normalize
- Anneal
- Rough and semifinish machine
- Austenitize and quench
- Temper
- Finish machine

8650: Approximate Critical Points

Critical point	Temperature °C	Temperature °F
Ac_1	730	1350
Ac_3	770	1420
Ar_3	700	1295
Ar_1	655	1210

8650: Continuous Cooling Transformation Diagram. Composition: 0.48 C, 0.75 Mn, 0.020 P, 0.010 S, 0.34 Si, 0.60 Ni, 0.58 Cr, 0.20 Mo. Austenitized at 850 °C (1560 °F)



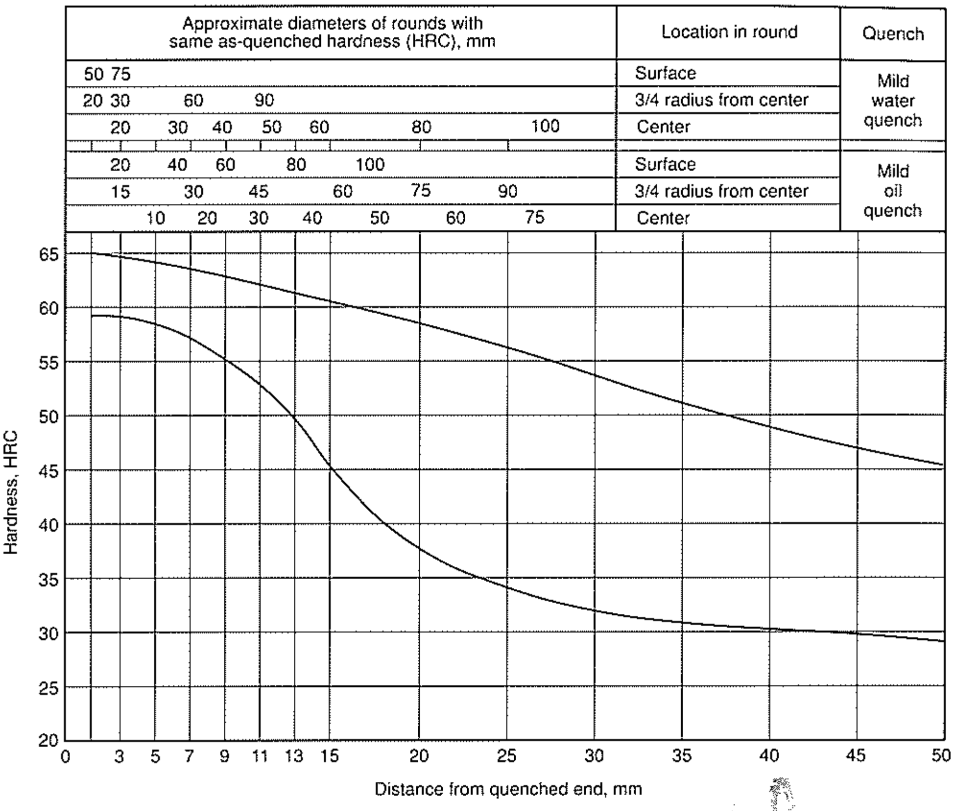


8650: Hardness vs Tempering Temperature. Composition: 0.48 to 0.53 C, 0.75 to 1.00 Mn, 0.20 to 0.35 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.15 to 0.25 Mo. Forged at 1175 °C (2150 °F) maximum and annealed by furnace cooling from 815 to 925 °C (1500 to 1695 °F). Maximum annealed hardness, 212 HB. Normalized at 870 °C (1600 °F) with a hardness of 355 HB for test size. Quenched in oil at 845 °C (1555 °F) and tempered for 2 h. Source: Republic Steel

8650H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

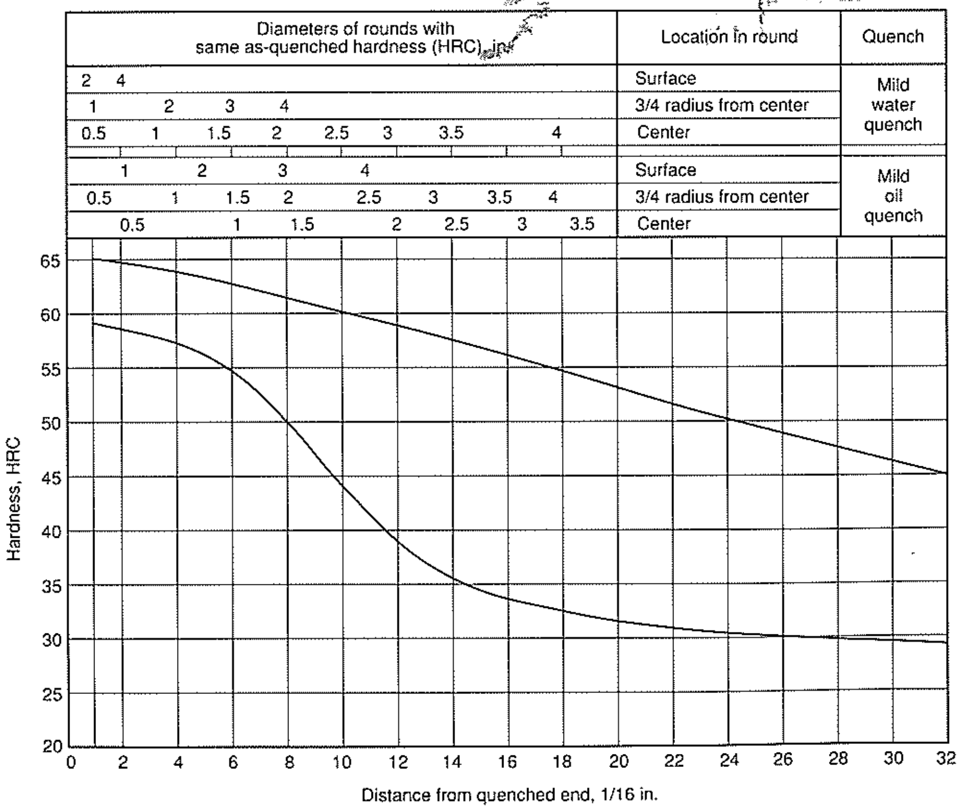
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	65	59
3	65	59
5	65	58
7	65	56
9	64	55
11	63	53
13	62	50
15	61	46
20	59	38
25	57	34
30	54	32
35	52	31
40	49	30
45	47	29
50	46	29



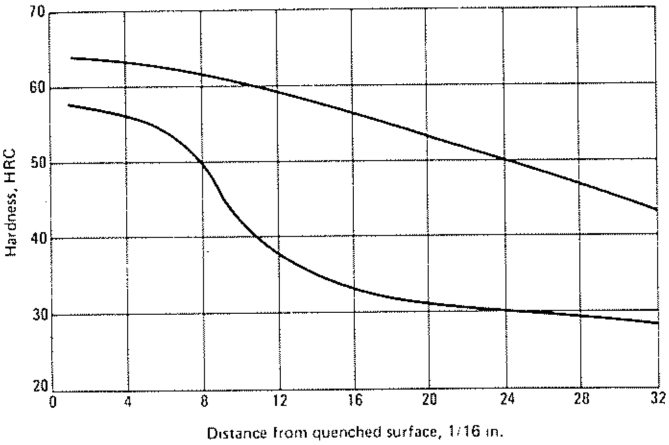
Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	65	59
2	65	58
3	65	57
4	64	57
5	64	56
6	63	54
7	63	53
8	62	50
9	61	47
10	60	44
11	60	41
12	59	39
13	58	37
14	58	36
15	57	35
16	56	34
18	55	33
20	53	32
22	52	31
24	50	31
26	49	30
28	47	30
30	46	29
32	45	29

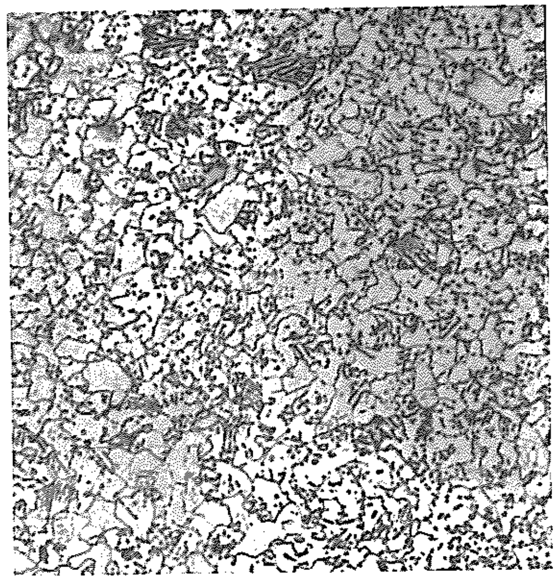


8650H: End-Quench Hardenability

Distance from quenched surface		Hardness, HRC		Distance from quenched surface		Hardness, HRC	
1/16 in.	mm	max	min	1/16 in.	mm	max	min
1	1.58	65	59	13	20.54	58	37
2	3.16	65	58	14	22.12	58	36
3	4.74	65	57	15	23.70	57	35
4	6.32	64	57	16	25.28	56	34
5	7.90	64	56	18	28.44	55	33
6	9.48	63	54	20	31.60	53	32
7	11.06	63	53	22	34.76	52	31
8	12.64	62	50	24	37.92	50	31
9	14.22	61	47	26	41.08	49	30
10	15.80	60	44	28	44.24	47	30
11	17.38	60	41	30	47.40	46	29
12	18.96	59	39	32	50.56	45	29



8650: Microstructure. 2% nital, 500×. Hot rolled steel bar, 7.936 mm (0.31 in.) hexagonal, austenitized at 750 °C (1380 °F) 3 h, furnace cooled to 665 °C (1230 °F) and held 6 h, air cooled, cold drawn, reheated to 665 °C (1230 °F) for 10 h, furnace cooled. Spheroidized cementite and lamellar pearlite in ferrite



8655, 8655H

Chemical Composition. 8655. **AISI and UNS:** 0.51 to 0.59 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.15 to 0.25 Mo. **UNS H86550 and SAE/AISI 8655H:** 0.50 to 0.60 C, 0.70 to 1.05 Mn, 0.15 to 0.35 Si, 0.35 to 0.75 Ni, 0.15 to 0.25 Mo

Similar Steels (U.S. and/or Foreign). 8655. UNS G86550; ASTM A322, A331; SAE J404, J412, J770. **8655H.** UNS H86550; ASTM A304; SAE J1268

Characteristics. A high-carbon steel. A spring steel, although it is used to fabricate a variety of machinery parts not related to springs. As-quenched hardness after quenching in oil usually ranges from 57 to 62 HRC, depending on exact carbon content. A high-hardenability steel, although the band is generally wide. Is forgeable, but not recommended for welding because of its high carbon content and high hardenability

Forging. Heat to 1200 °C (2190 °F) maximum. Do not forge after temperature of forging stock drops below approximately 925 °C (1695 °F). Forgings of this grade should be cooled slowly from the forging operation, especially if they have complex shapes. Bury them in an insulating compound or place them in a furnace

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

Annealing. For a predominantly spheroidized structure, which is preferred for machining and heat treating 8655H, heat to 750 °C (1380 °F), cool rapidly to 700 °C (1290 °F), then cool to 655 °C (1210 °F), at a rate not to exceed 6 °C (10 °F) per h; or heat to 750 °C (1380 °F), cool rapidly to 650 °C (1200 °F), and hold for 10 h

Direct Hardening. Austenitize at 830 °C (1525 °F), and quench in oil. Flame hardening, gas nitriding, ion nitriding, and carbonitriding are suitable processes

Tempering. After quenching to near ambient temperature, temper immediately at 150 °C (300 °F) or higher. The selection of tempering temperature depends on the required hardness or mechanical properties. 8655H is sensitive to quench cracking, and tool steel practice should be observed in tempering. Parts should not be allowed to become too cold after quenching before they are placed in the tempering furnace. A uniform temperature of approximately 38 to 50 °C (100 to 120 °F) is preferred

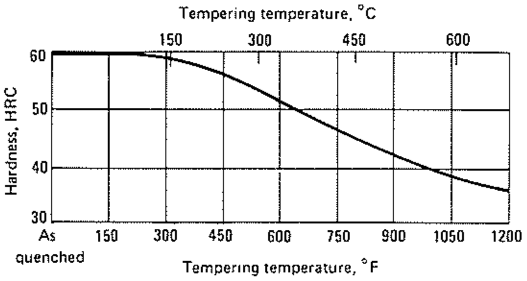
Austempering. When used for applications such as heavy-duty springs, 8655H is austempered in a procedure such as the one that follows:

- Austenitize at 830 °C (1525 °F)
- Quench in an agitated molten salt bath held at 345 °C (655 °F)
- Hold at 345 °C (655 °F) for 1 h
- Air cool to room temperature
- Wash in hot water

No tempering is required. Hardness for parts should range from approximately 47 to 52 HRC

Recommended Processing Sequence

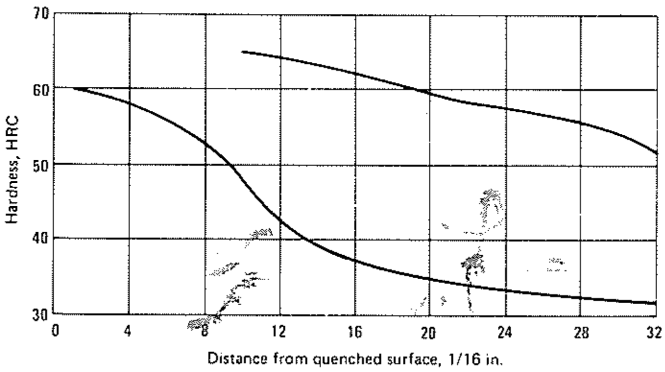
- Forge
- Normalize
- Anneal
- Rough and semifinish machine
- Austenitize and quench (or austemper)
- Temper (or austemper)
- Finish machine (usually grinding)



8655, 8655H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

8655H: End-Quench Hardenability

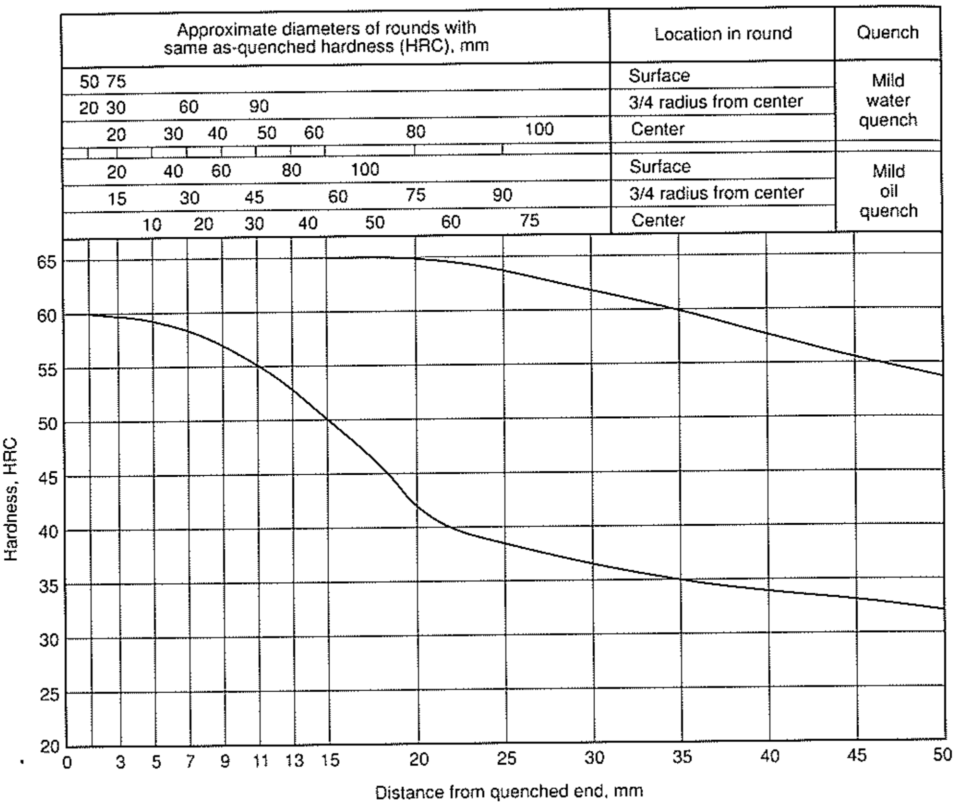
Distance from quenched surface		Hardness, HRC		Distance from quenched surface		Hardness, HRC	
1/16 in.	mm	max	min	1/16 in.	mm	max	min
1	1.58	...	60	13	20.54	64	41
2	3.16	...	59	14	22.12	63	40
3	4.74	...	59	15	23.70	63	39
4	6.32	...	58	16	25.28	62	38
5	7.90	...	57	18	28.44	61	37
6	9.48	...	56	20	31.60	60	35
7	11.06	...	55	22	34.76	59	34
8	12.64	...	54	24	37.92	58	34
9	14.22	...	52	26	41.08	57	33
10	15.80	65	49	28	44.24	56	33
11	17.38	65	46	30	47.40	55	32
12	18.96	64	43	32	50.56	53	32



8655H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

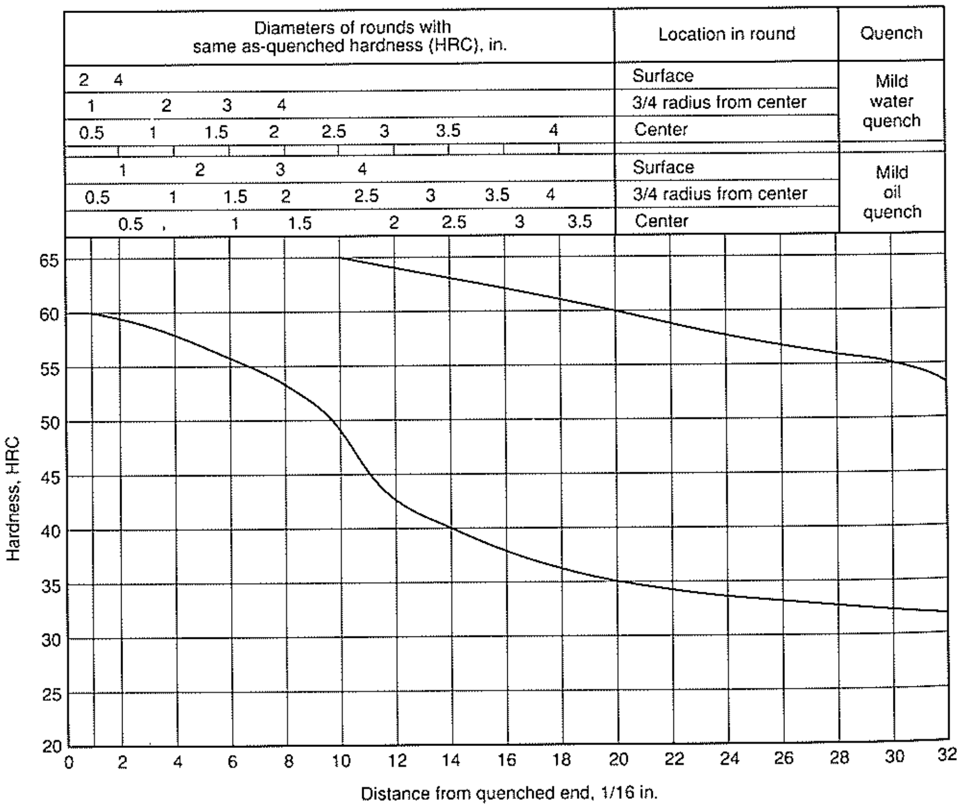
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	...	60
3	...	60
5	...	59
7	...	57
9	...	56
11	...	55
13	...	53
15	65	51
20	65	42
25	64	39
30	62	36
35	60	34
40	58	34
45	56	33
50	54	32



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	...	60
2	...	59
3	...	59
4	...	58
5	...	57
6	...	56
7	...	55
8	...	54
9	...	52
10	65	49
11	65	46
12	64	43
13	64	41
14	63	40
15	63	39
16	62	38
18	61	37
20	60	35
22	59	34
24	58	34
26	57	33
28	56	33
30	55	32
32	53	32



8660, 8660H

Chemical Composition. 8660. AISI: 0.55 to 0.65 C, 0.75 to 1.00 Mn, 0.040 P max, 0.040 S max, 0.20 to 0.35 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.15 to 0.25 Mo. **UNS:** 0.55 to 0.65 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.15 to 0.25 Mo. **UNS H86600 and SAE/AISI 8660H:** 0.55 to 0.65 C, 0.70 to 1.05 Mn, 0.15 to 0.35 Si, 0.35 to 0.75 Ni, 0.35 to 0.65 Cr, 0.15 to 0.25 Mo

Similar Steels (U.S. and/or Foreign). 8660. UNS G86600; ASTM A274, A322, A332, A519; SAE J404, J412, J770. **8660H.** UNS H86600; ASTM A304; SAE J1268

Characteristics. A spring steel used for a wide variety of machinery parts where high strength and high hardenability are important. Also used for a variety of metal working tools including cold work dies. When the carbon is on the low side of the allowable range, the as-quenched hardness for an oil-quenched part may be no higher than about 59 HRC, but when the carbon approaches the upper limit, the as-quenched hardness can be as high as 65 HRC. The hardenability band is relatively wide, but the hardenability can be very high, actually approaching that of an air-hardening steel

Forging. Heat to 1200 °C (2190 °F) maximum. Do not forge after temperature of forging stock drops below approximately 925 °C (1695 °F). Forgings of this grade should be cooled slowly from the forging operation, especially if they have complex shapes. Bury them in an insulating compound or place them in a furnace

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air

Annealing. For a predominantly spheroidized structure, which is usually preferred for machining as well as heat treating, heat to 750 °C (1380 °F), cool rapidly to 700 °C (1290 °F), then cool to 655 °C (1210 °F), at a rate not to exceed 6 °C (10 °F) per h; or heat to 750 °C (1380 °F), cool rapidly to 650 °C (1200 °F), and hold for 10 h

Direct Hardening. Austenitize at 830 °C (1525 °F), and quench in oil. Flame hardening, gas nitriding, and ion nitriding, are alternative processes

Tempering. After quenching to near ambient temperature, temper immediately at 150 °C (300 °F) or higher. The selection of tempering temperature depends on the required hardness or mechanical properties. 8660H is sensitive to quench cracking, and tool steel practice should be observed in tempering. Parts should not be allowed to become too cold after quenching before they are placed in the tempering furnace. A uniform temperature of approximately 38 to 50 °C (100 to 120 °F) is preferred

Austempering. When used for applications such as heavy-duty springs, 8655H is austempered in a procedure such as the one that follows:

- Austenitize at 830 °C (1525 °F)
- Quench in an agitated molten salt bath held at 345 °C (655 °F)
- Hold at 345 °C (655 °F) for 1 h
- Air cool to room temperature
- Wash in hot water

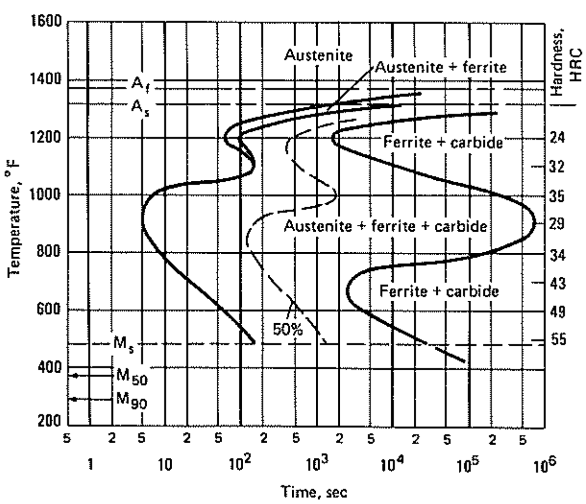
No tempering is required. Hardness for parts should range from approximately 47 to 52 HRC

Recommended Processing Sequence

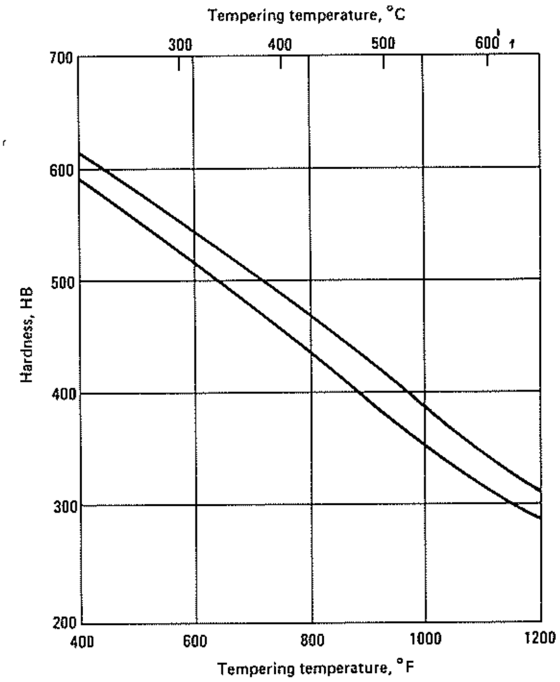
- Forge
- Normalize
- Anneal
- Rough and semifinish machine
- Austenitize and quench (or austemper)
- Temper (or austemper)
- Finish machine (usually grinding)

8660: Approximate Critical Points

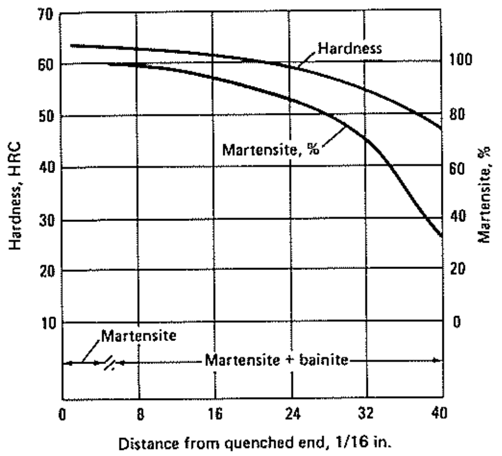
Critical point	Temperature °C	Temperature °F
Ac_1	730	1345
Ac_3	765	1410
Ar_3	690	1270
Ar_1	665	1230



8660: Isothermal Transformation Diagram. Composition: 0.59 C, 0.89 Mn, 0.53 Ni, 0.64 Cr, 0.22 Mo. Austenitized at 845 °C (1555 °F). Grain size: 8



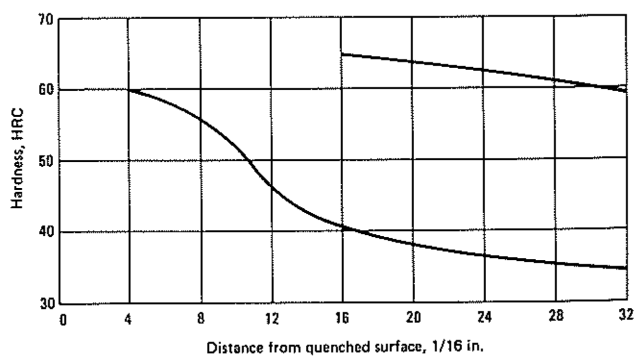
8660: Hardness vs Tempering Temperature. Composition: 0.55 to 0.65 C, 0.75 to 1.00 Mn, 0.20 to 0.35 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.15 to 0.25 Mo. Forge at 1175 °C (2150 °F), anneal from 815 to 925 °C (1500 to 1695 °F) for a maximum hardness of 229 HB. Hardness after normalizing in test size, 321 HB. Normalized at 870 °C (1600 °F), quenched in oil from 845 °C (1555 °F), tempered 2 h. Source: Republic Steel



8660: End-Quench Hardenability. Composition: 0.59 C, 0.89 Mn, 0.53 Ni, 0.64 Cr, 0.22 Mo. Austenitized at 845 °C (1555 °F). Grain size 8

8660H: End-Quench Hardenability

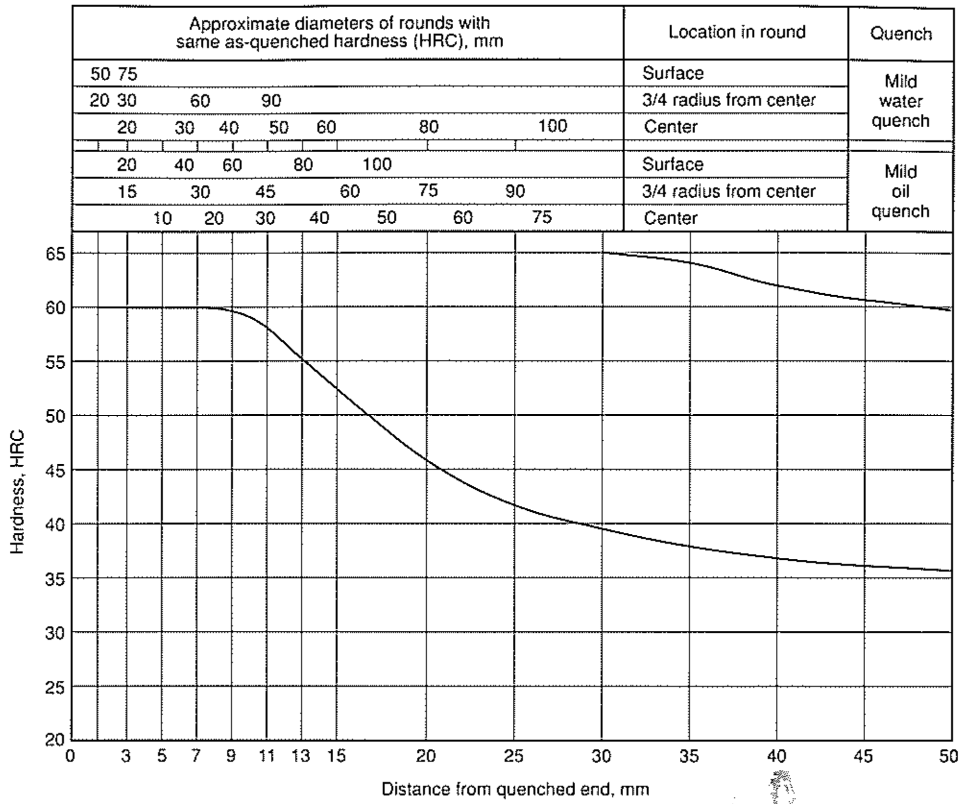
Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max	Hardness, HRC min
1	1.58	...	60	13	20.54	...	45
2	3.16	...	60	14	22.12	...	44
3	4.74	...	60	15	23.70	...	43
4	6.32	...	60	16	25.28	65	42
5	7.90	...	60	18	28.44	64	40
6	9.48	...	59	20	31.60	64	39
7	11.06	...	58	22	34.76	63	38
8	12.64	...	57	24	37.92	62	37
9	14.22	...	55	26	41.08	62	36
10	15.80	...	53	28	44.24	61	36
11	17.38	...	50	30	47.40	60	35
12	18.96	...	47	32	50.56	60	35



8660H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

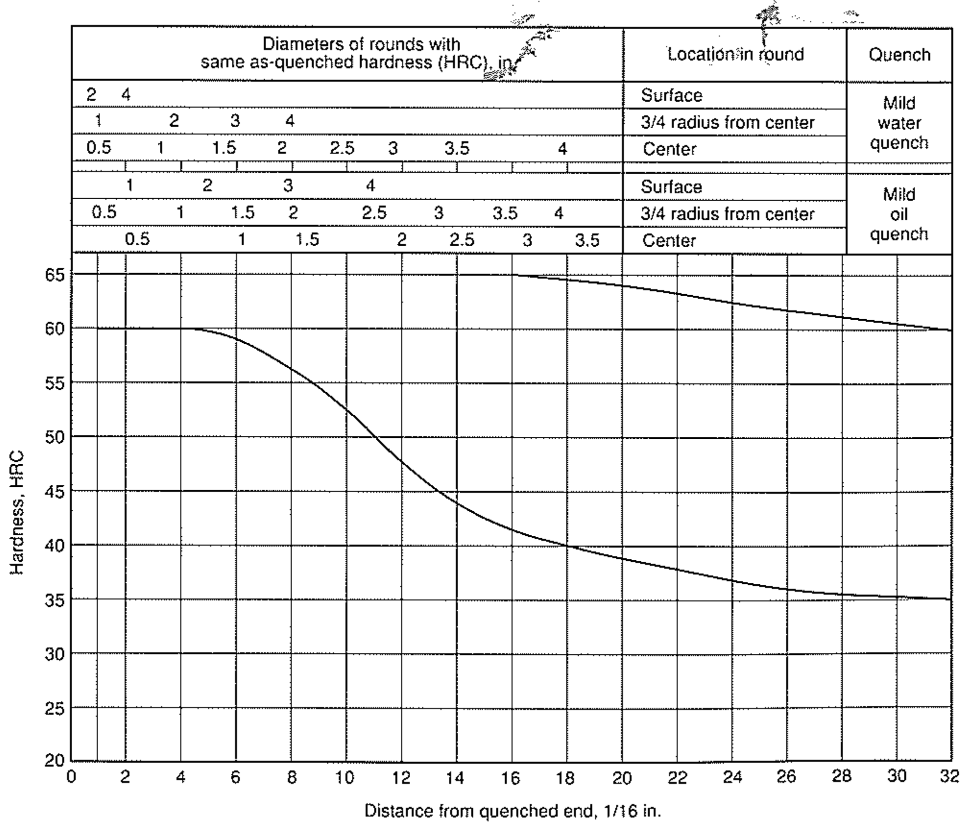
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	...	60
3	...	60
5	...	60
7	...	60
9	...	59
11	...	58
13	...	56
15	...	53
20	...	46
25	...	42
30	65	39
35	64	38
40	62	37
45	61	36
50	60	35



Hardness limits for specification purposes

J distance, $^1/_{16}$ in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	...	60
2	...	60
3	...	60
4	...	60
5	...	60
6	...	59
7	...	58
8	...	57
9	...	55
10	...	53
11	...	50
12	...	47
13	...	45
14	...	44
15	...	43
16	65	42
18	64	40
20	64	39
22	63	38
24	62	37
26	62	36
28	61	36
30	60	35
32	60	35



8720RH: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 925 °C (1700 °F)

Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Minimum
1	47	42
2	45	39
3	43	37
4	40	32
5	36	28
6	33	26
7	31	24
8	29	23
9	28	22
10	27	21
11	26	20
12	25	...
13	25	...
14	24	...
15	24	...
16	23	...
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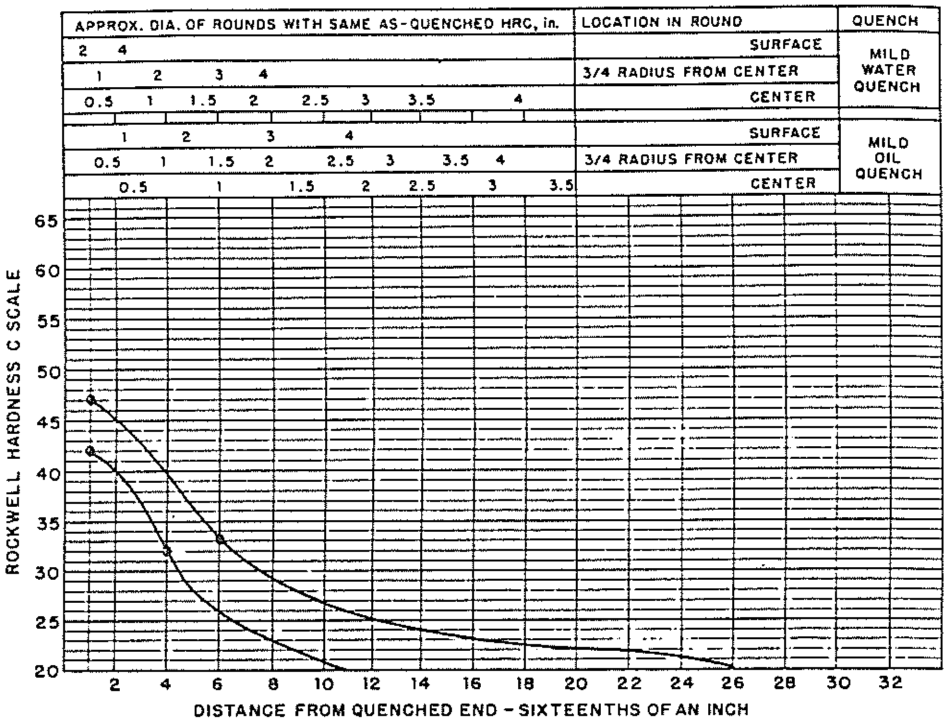
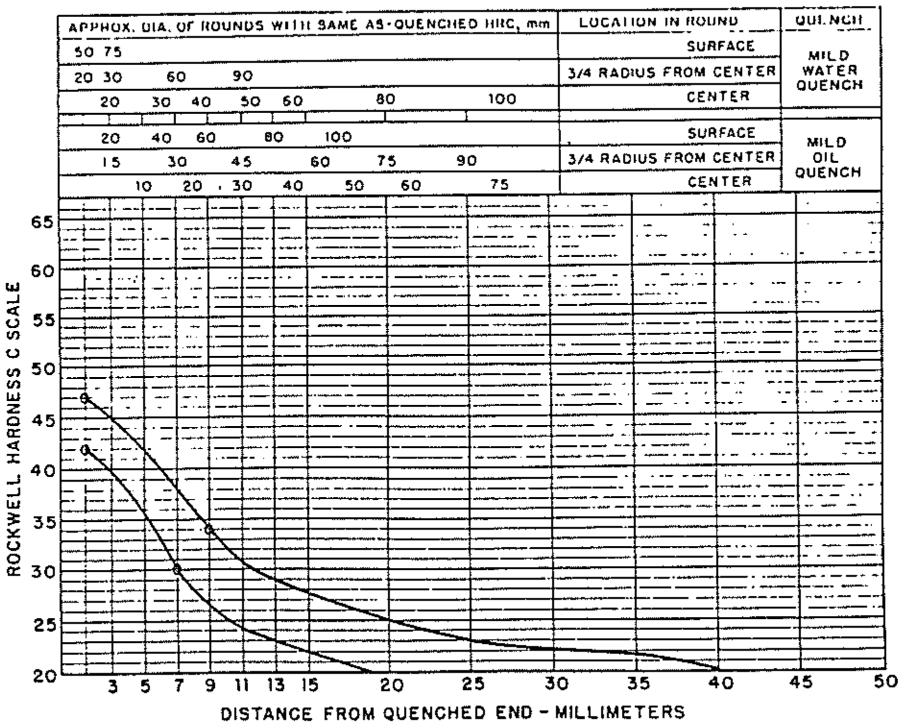
24	21	...
26	20	...
28	...	...
30	...	...
32	...	...

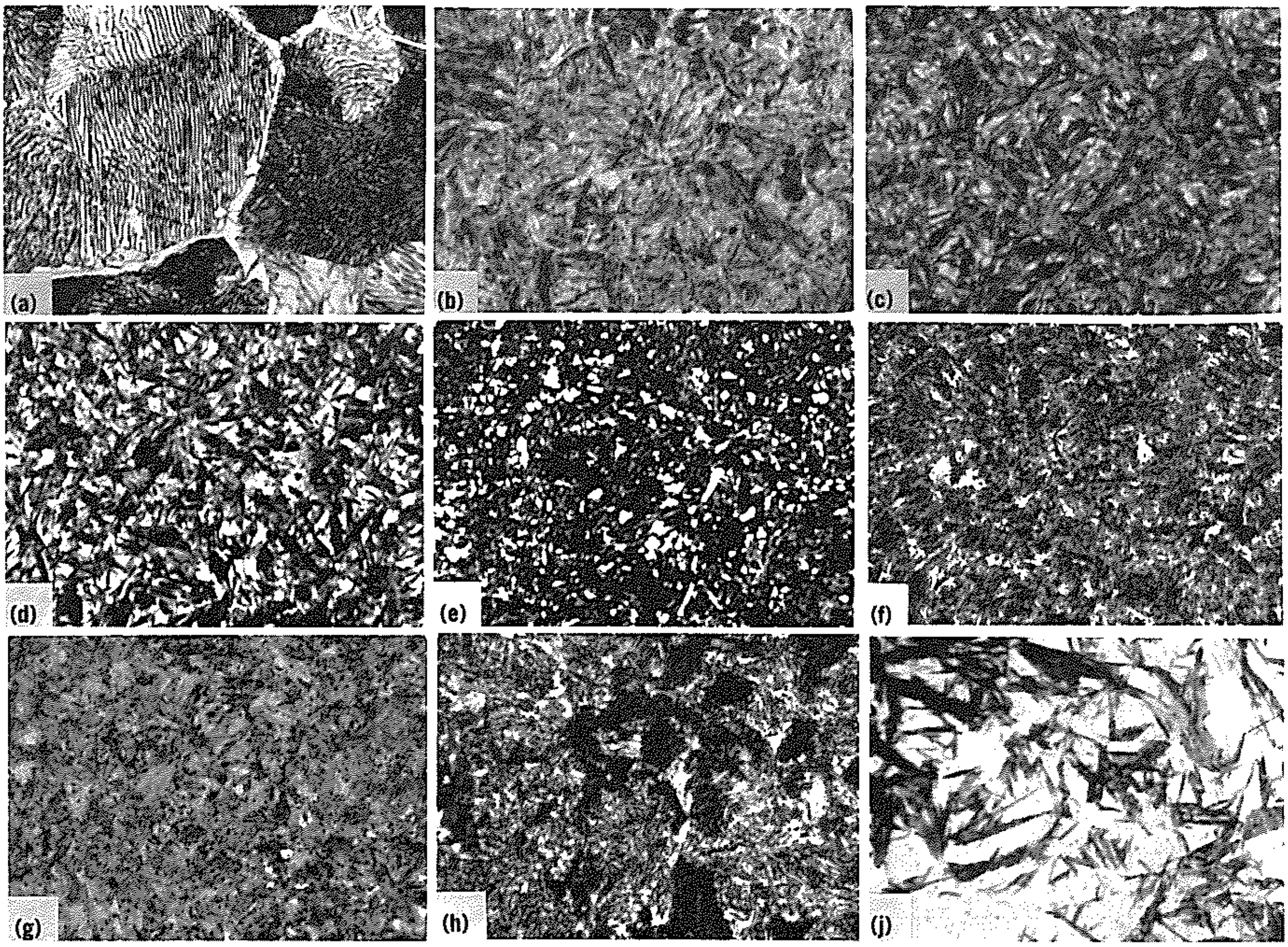


Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Minimum
1.5	47	42
3	45	39
5	42	35
7	38	30
9	34	27
11	31	24
13	29	23
15	28	22
20	25	...
25	23	...
30	23	...
35	22	...
40	20	...
45	...	...
50	...	...



8720: Microstructures. Note: All microstructures for 8720 were hot rolled specimens treated uniformly before described heat treatments: gas carburized for 9 h at 925 °C (1695 °F) at 1.35% carbon potential and diffused for 2 h at the same temperature at 0.90% carbon potential. The center of the field in the micrographs ranges from 0.127 to 0.254 mm (0.005 to 0.010 in.) beneath the carburized surface. (a) 5% nital, 1000×. Slowly cooled in the furnace from the carburizing temperature. Light carbide network in a matrix of lamellar pearlite. (b) 5% nital, 1000×. Austenitized at 0.90% carbon potential for 1 h at 815 °C (1500 °F), oil quenched, tempered for 1 h at 190 °C (375 °F). Relatively low-carbon tempered martensite. (c) 5% nital, 1000×. Same austenitizing and tempering treatments as (b). Globular carbide, retained austenite in tempered martensite of higher carbon content than (b). (d)5% nital, 1000×. Austenitized at 0.65% carbon potential for 1 h at 815 °C (1500 °F), oil quenched, tempered for 1 h at 190 °C (375 °F). Retained austenite (white constituent) in a matrix of tempered martensite. (e) 5% nital, 1000×. Austenitized at 1.35% carbon potential for 1 h at 815 °C (1500 °F), oil quenched, tempered 1 h at 190 °C (375 °F). Carbide (light network, globular particles) in a matrix of tempered martensite, retained austenite not visible. (f) 5% nital, 1000×. Austenitized at 0.90% carbon potential for 1 h at 815 °C (1500 °F), quenched in oil, tempered for 1 h at 260 °C (500 °F). Small amount of retained austenite (white areas) visible in a matrix of overtempered martensite. (g) 5% nital, 1000×. Austenitized at 0.90% carbon potential for 1 h at 815 °C (1500 °F), quenched in oil, tempered for 1 h at 120 °C (250 °F). Tempered martensite, showing effects of undertempering. (h) 5% nital, 1000×. Austenitized at 0.90% carbon potential for 1 h at 815 °C (1500 °F), rapidly air cooled, tempered for 1 h at 190 °C (375 °F). Fine pearlite (dark constituent) in a matrix of bainite. (j) 5% nital, 1000×. Same as (h), except oil quenched. Surface was improperly ground, being heated above the critical temperature and then rapidly cooled. Retained austenite (white) and untempered martensite result



8740, 8740H

Chemical Composition. 8740. AISI and UNS: 0.38 to 0.43 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.20 to 0.30 Mo. **UNS H87400 and SAE/AISI 8740H:** 0.37 to 0.44 C, 0.70 to 1.05 Mn, 0.15 to 0.35 Si, 0.35 to 0.75 Ni, 0.35 to 0.65 Cr, 0.20 to 0.30 Mo

Similar Steels (U.S. and/or Foreign). 8740. UNS G87400; AMS 6322, 6323, 6325, 6327, 6358; ASTM A322, A331; MIL SPEC MIL-S-6049; SAE J404, J412, J770; (Ger.) DIN 1.6546; (Ital.) UNI 40 NiCrMo 2 KB; (U.K.) B.S. Type 7. **8740H.** UNS H87400; ASTM A304; SAE J1268; (Ger.) DIN 1.6546; (Ital.) UNI 40 NiCrMo 2 KB; (U.K.) B.S. Type 7

Characteristics. Nearly identical in composition to 8640H. The only difference is a slightly higher molybdenum range, 0.20 to 0.30% for 8740H as opposed to 0.15 to 0.25% for 8640H. This minor difference does not change the as-quenched hardness, but does offer a light increase in hardenability. If desired, can be nitrided to achieve surfaces that help to resist abrasion and further increase fatigue strength. An as-quenched surface hardness of approximately 52 to 57 HRC can be expected, depending on the precise carbon content. Can be forged by any one of the various forging methods

Forging. Heat to 1230 °C (2250 °F) maximum. Do not forge after temperature of forging stock drops below approximately 900 °C (1650 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Cool in air.

In aerospace practice, parts are normalized at 900 °C (1650 °F)

Annealing. For a predominantly pearlitic structure, heat to 830 °C (1525 °F), cool rapidly to 725 °C (1335 °F), then cool to 640 °C (1185 °F), at a rate not to exceed 11 °C (20 °F) per h; or heat to 830 °C (1525 °F), cool rapidly to 665 °C (1230 °F), and hold for 6 h. For a predominantly spheroidized structure, heat to 750 °C (1380 °F), cool rapidly to 725 °C (1335 °F), then cool to 640 °C (1185 °F), at a rate not to exceed 6 °C (10 °F) per h; or heat to 750 °C (1380 °F), cool rapidly to 665 °C (1230 °F), and hold for 8 h

In aerospace practice, parts are annealed at 845 °C (1555 °F), cooled to below 540 °C (1000 °F) at a rate not to exceed 95 °C (200 °F) per h

Direct Hardening. Austenitize at 855 °C (1570 °F), and quench in oil

Nitriding. Responds well to ammonia gas nitriding as well as to nitriding in any one of several proprietary molten salt baths. The following is a cycle used with ammonia gas nitriding:

- Parts are austenitized, quenched, and tempered at 540 °C (1000 °F) or higher. (Tempering temperature must always be higher than the nitriding temperature)
- Finish machine (must be done before nitriding, because of resulting thin case)
- Nitride in ammonia gas for 10 to 12 h with an ammonia gas dissociation of 25 to 30%

See processing data for 4140H for other nitriding cycles

Tempering. After quenching, reheat immediately to the tempering temperature that will provide the desired combination of mechanical properties

Other Processes. Ion nitriding, austempering and martempering are alternative processes.

In aerospace practice, parts are austenitized at 845 °C (1555 °F), then quenched in oil or polymers

Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough and semifinish machine
- Austenitize and quench
- Temper
- Finish machine (grind if required)
- Nitride (optional)

8740: As-Quenched Hardness

Specimens quenched in oil

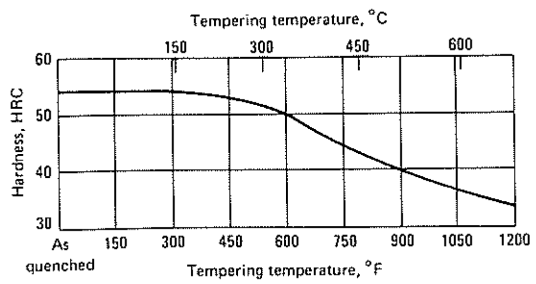
Size round, in.	Size round, mm	Hardness, HRC Surface	Hardness, HRC ½ radius	Hardness, HRC Center
½	13	57	56	55
1	25	56	55	54
2	51	52	49	45
4	102	42	37	36

Source: Republic Steel

8740: Effect of Heat Treating on Hardness

Condition	Hardness, HB Size round ½ in. (13 mm)	1 in. (25 mm)	2 in. (51 mm)	4 in. (102 mm)
Annealed(a)	...	201	...	...
Normalized(b)	269	269	262	255
Oil quenched(c)	352	352	331	277
Oil quenched(d)	311	302	277	248
Oil quenched(e)	285	285	255	229

(a) Heated to 1500 °F (815 °C), furnace cooled 20 °F (11 °C) to 1100 °F (595 °C), cooled in air. (b) Heated to 1600 °F (870 °C), cooled in air. (c) From 1525 °F (830 °C), tempered at 1000 °F (540 °C). (d) From 1525 °F (830 °C), tempered at 1100 °F (595 °C). (e) From 1525 °F (830 °C), tempered at 1200 °F (650 °C). Source: Republic Steel

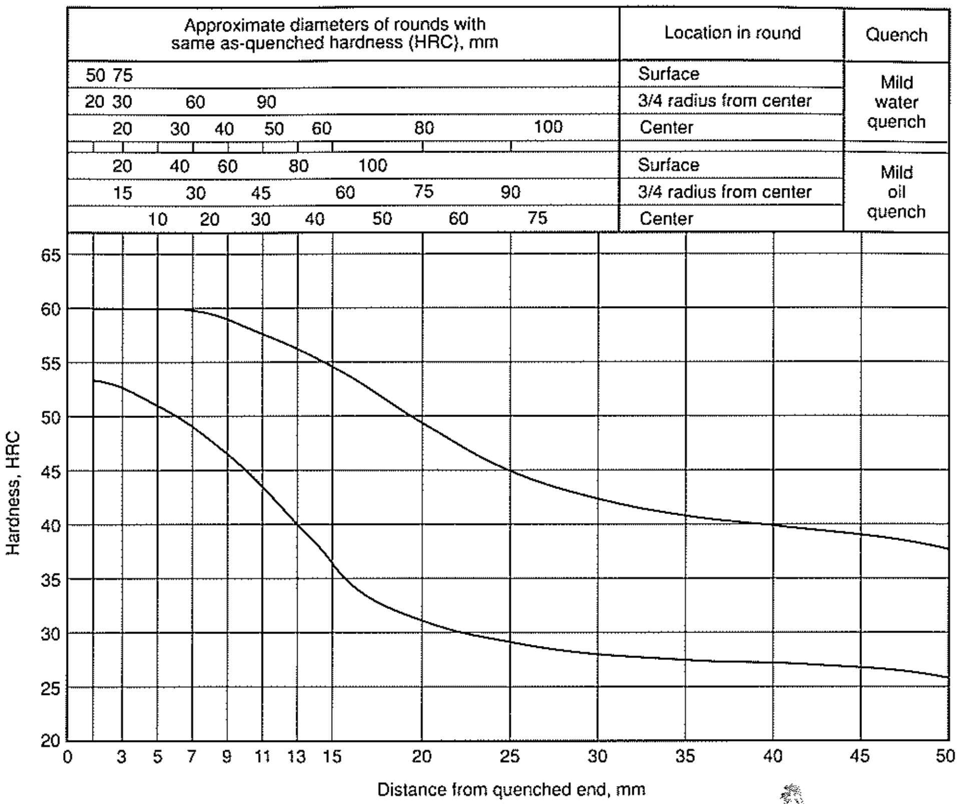


8740, 8740H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

8740H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

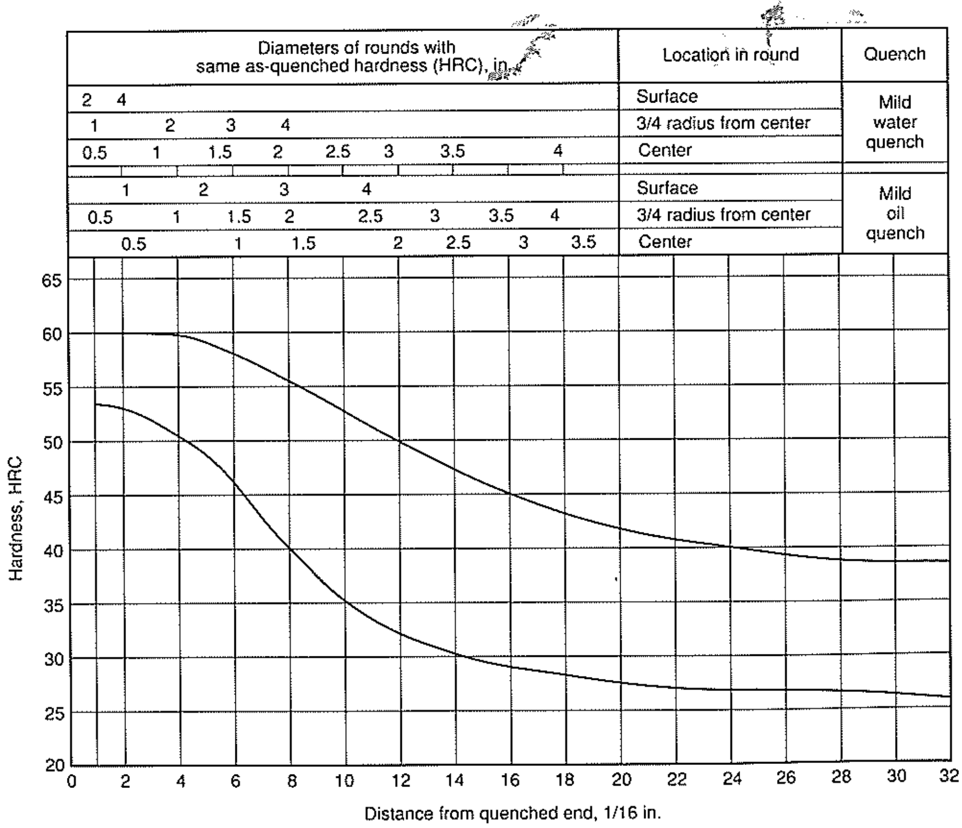
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	60	53
3	60	52
5	60	51
7	60	49
9	59	46
11	58	43
13	56	39
15	54	36
20	50	31
25	45	29
30	43	28
35	41	27
40	40	27
45	39	26
50	38	26



Hardness limits for specification purposes

J distance, $\frac{1}{16}$ in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	60	53
2	60	53
3	60	52
4	60	51
5	59	49
6	58	46
7	57	43
8	56	40
9	55	37
10	53	35
11	52	34
12	50	32
13	49	31
14	48	31
15	46	30
16	45	29
18	43	28
20	42	28
22	41	27
24	40	27
26	39	27
28	39	27
30	38	26
32	38	26



8740: Suggested Tempering Temperatures (Aerospace Practice)*

Tensile Strength Range					
620-860 MPa (90-125 ksi)	860-1035 MPa (125-150 ksi)	1035-1175 MPa (150-170 ksi)	1175-1240 MPa (160-180 ksi)	1240-1380 MPa (180-200 ksi)	1380-1520 MPa (200-220 ksi)
690 °C (1275 °F)	635 °C (1175 °F)	580 °C (1075 °F)	525 °C (975 °F)	455 °C (850 °F)	385 °C (725 °F)

* Quench in oil or polymer. Source: AMS 2759/1

8740: Suggested Tempering Temperatures Based on As-Quenched Hardness (Aerospace Practice)

Tensile strength range	RC 47-49	RC 50-52	RC 53-55	RC 56-58
620-1035 MPa 125-150 ksi)	595 °C (1100 °F)	620 °C (1150 °F)	(650 °C) (1200 °F)	675 °C (1250 °F)
965-1105 MPa (140-160 ksi)	525 °C (975 °F)	550 °C (1025 °F)	595 °C (1100 °F)	635 °C (1175 °F)
1035-1175 MPa (150-170 ksi)	470 °C (875 °F)	510 °C (950 °F)	550 °C (1025 °F)	595 °C (1100 °F)
1105-1240 MPa (160-190 ksi)	...	480 °C (900 °F)	525 °C (975 °F)	565 °C (1050 °F)
1175-1310 MPa (180-200 ksi)	...	440 °C (775 °F)	495 °C (875 °F)	540 °C (950 °F)
1240-1380 MPa (190-210 ksi)	...	410 °C (725 °F)	470 °C (825 °F)	510 °C (925 °F)
1380-1515 MPa (200-220 ksi)	...	...	410 °C (775 °F)	470 °C (875 °F)

Source: AMS 2759/1

8822, 8822H, 8822RH

Chemical Composition. 8822. **AISI and UNS:** 0.20 to 0.25 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.30 to 0.40 Mo. **UNS H88220 and SAE/AISI 8822H:** 0.19 to 0.25 C, 0.70 to 1.05 Mn, 0.15 to 0.35 Si, 0.35 to 0.75 Ni, 0.35 to 0.65 Cr, 0.30 to 0.40 Mo. **SAE 8822RH:** 0.20 to 0.25 C, 0.75 to 1.00 Mn, 0.15 to 0.35 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.30 to 0.40 Mo

Similar Steels (U.S. and/or Foreign). **8822.** UNS G88220; SAE J404, J770; (Ger.) DIN 1.6543; (U.K.) B.S. 805 A 20. **8822H.** UNS H88220; ASTM A304; SAE J407; (Ger.) DIN 1.6543; (U.K.) B.S. 805 A 20

Characteristics. A modification of 8620H, with a higher carbon range (same as 8622H) and a substantially higher molybdenum content (0.30 to 0.40% as opposed to 0.15 to 0.25% for 8620 and 8622H). This increase in molybdenum content results in a significant increase in hardenability. As-quenched hardness usually ranges from approximately 41 to 47 HRC. Can be processed by carbonitriding, but usually is not used for producing parts that will be carbonitrided because most carbonitrided parts are relatively small, and the higher hardenability of 8822H is not required. Used principally for producing parts with heavy sections for which grades 8620H and 8622H do not have sufficient hardenability, such as heavy-duty gears and pinions. Such parts are subjected to carburizing treatments. Forges easily, and forging is often used to produce gear blanks and similar parts. Is readily weldable, although alloy steel practice should be used in welding to minimize susceptibility to weld cracking. Machinability is considered fairly good

Forging. Heat to 1245 °C (2275 °F) maximum. Do not forge after temperature of forging stock drops below approximately 900 °C (1650 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Cool in air

Annealing. Structures having best machinability are developed by normalizing; or by heating to 885 °C (1625 °F), cooling rapidly to 665 °C (1230 °F), and holding for 4 h; or heat to 790 °C (1455 °F), cool rapidly to 665 °C (1230 °F), and hold for 8 h

Tempering. Parts made from 50B44H should be tempered immediately after they have been uniformly quenched to near ambient temperature. Best practice is to place workpieces into the tempering furnace just before they have reached room temperature, ideally when they are in the range of 38 to 50 °C (100 to 120 °F). Tempering temperature must be selected based upon the final desired hardness.

After quenching to near ambient temperature, temper immediately at 150 °C (300 °F) or higher. The selection of tempering temperature depends on the required hardness or mechanical properties. 8655H is sensitive to quench cracking, and tool steel practice should be observed In tempering. Parts should not be allowed to become too cold after quenching before they are placed in the tempering furnace. A uniform temperature of approximately 38 to 50 °C (100 to 120 °F) is preferred. Temper all carburized or carbonitrided parts at 150 °C (300 °F), and virtually no loss of case hardness results. If some decrease in hardness can be tolerated, toughness can be increased by tempering at somewhat higher temperatures; such as up to 260 °C (500 °F)

Case Hardening. See carburizing and carbonitriding, practices described for 8620H

Recommended Processing Sequence

- Forge
- Normalize
- Anneal (if required)
- Rough machine
- Semifinish machine allowing only grinding stock, no more than 10% of the case depth per side for carburized parts. In most instances, carbonitrided parts are completely finished in this step
- Carburize or carbonitride and quench
- Temper

8822: Approximate Critical Points

Critical point	Temperature °C	Temperature °F
Ac_1	720	1330
Ac_3	840	1540
Ar_3	785	1445
Ar_1	645	1195

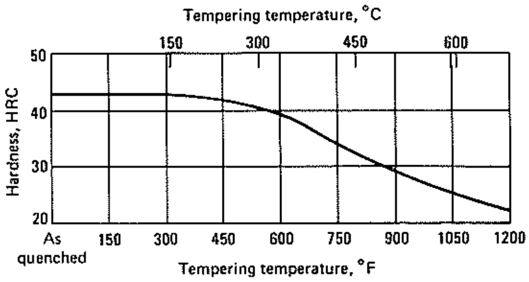
Source: Republic Steel

8822: Approximate Core Hardness

Normalized at 1700 °F (925 °C) in 1.25-in. (31.8-mm) rounds; machined to 1-in. (25-mm) or 0.540-in. (13.7-mm) rounds; pseudocarburized at 1700 °F (925 °C) for 8 h; box cooled to room temperature, reheated and oil quenched; tempered at 300 °F (150 °C); tested 0.505-in. (12.8-mm) rounds

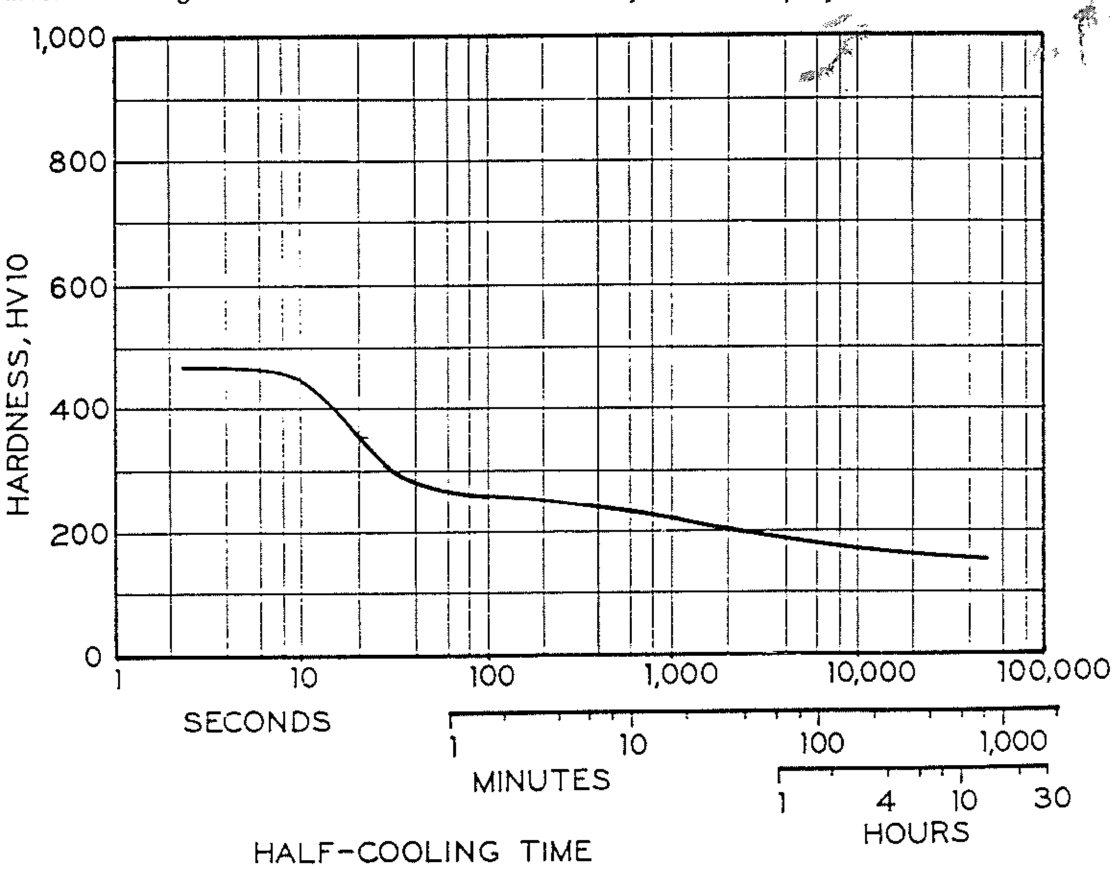
Reheat temperature °F	Reheat temperature °C	Hardness, HB, Heat treated in rounds: 1 in. (25 mm)	Hardness, HB, Heat treated in rounds: 0.540 in. (13.7 mm)
1425	775	352	352
1510	820	363	415
1590	865	388	429
1700(a)	925(a)	388	429

(a) Quenched from 1700 °F (925 °C) after pseudocarburizing for 8 h



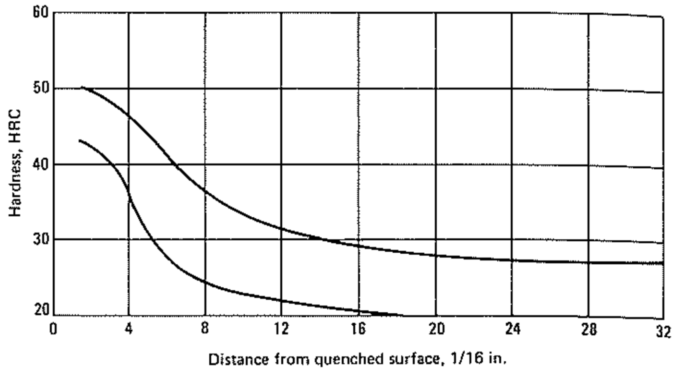
8822, 8822H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

8822: Cooling Curve. Half cooling time. Source: Datasheet I-60. Climax Molybdenum Company

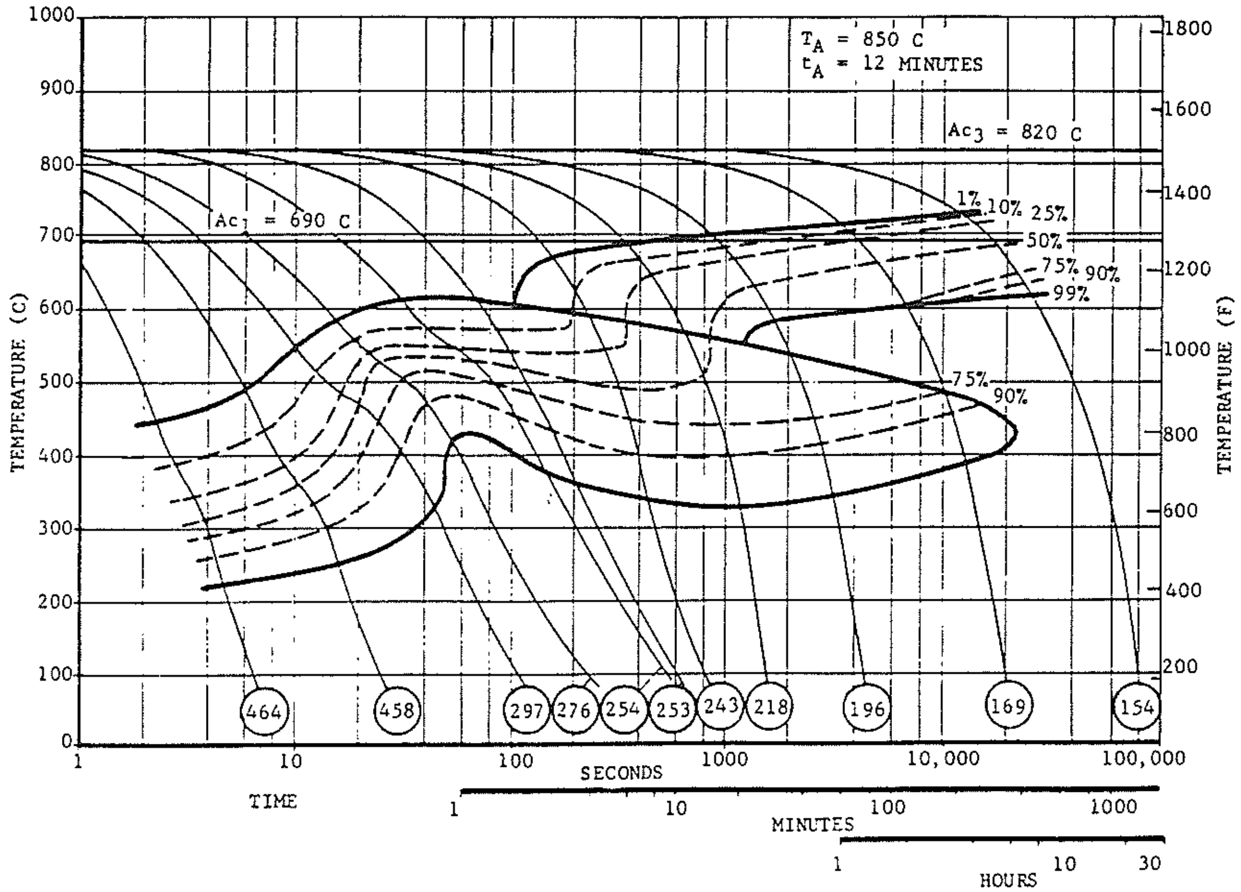


8822H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min
1	1.58	50	43	13	20.54	31	22
2	3.16	49	42	14	22.12	30	22
3	4.74	48	39	15	23.70	30	21
4	6.32	46	33	16	25.28	29	21
5	7.90	43	29	18	28.44	29	20
6	9.48	40	27	20	31.60	28	...
7	11.06	37	25	22	34.76	27	...
8	12.64	35	24	24	37.92	27	...
9	14.22	34	24	26	41.08	27	...
10	15.80	33	23	28	44.24	27	...
11	17.38	32	23	30	47.40	27	...
12	18.96	31	22	32	50.56	27	...



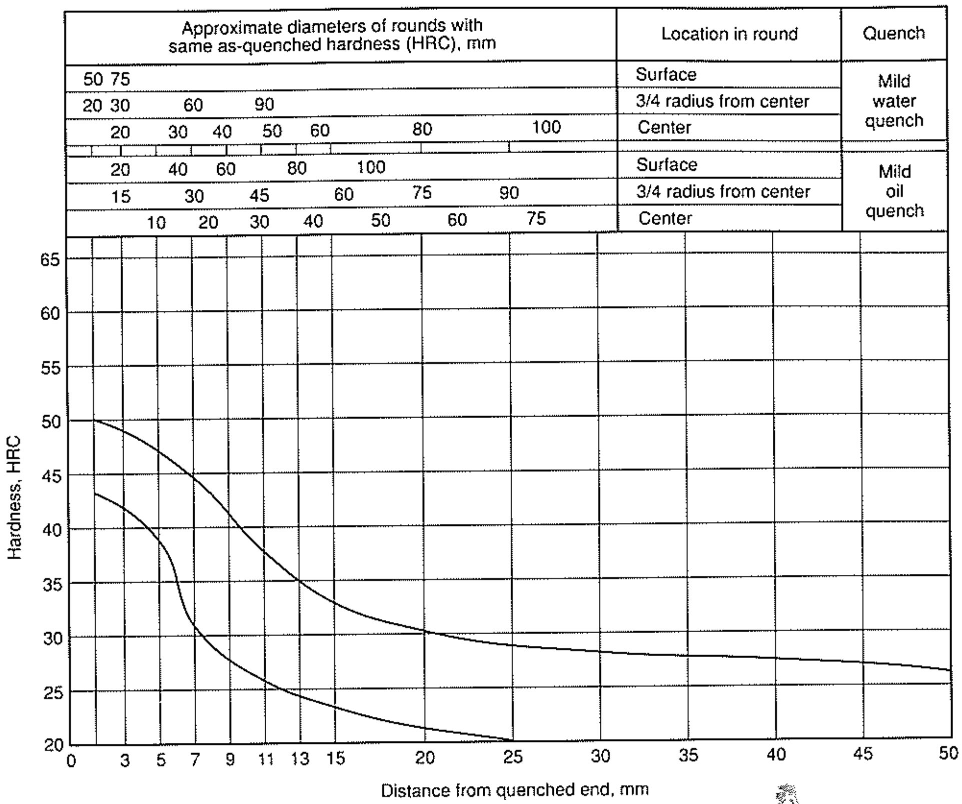
8822: CCT Diagram. Composition for AISI, constructional alloy steel: 0.24 C, 0.95 Mn, 0.28 Si, 0.019 P, 0.025 S, 0.44 Ni, 0.31 Mo. Steel was from commercial heat, and was austenitized at 850 °C (1560 °F) for 12 min. Determining heavy section hardenability was objective of study. Source: Datasheet I-60. Climax Molybdenum Company



8822H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 925 °C (1700 °F)

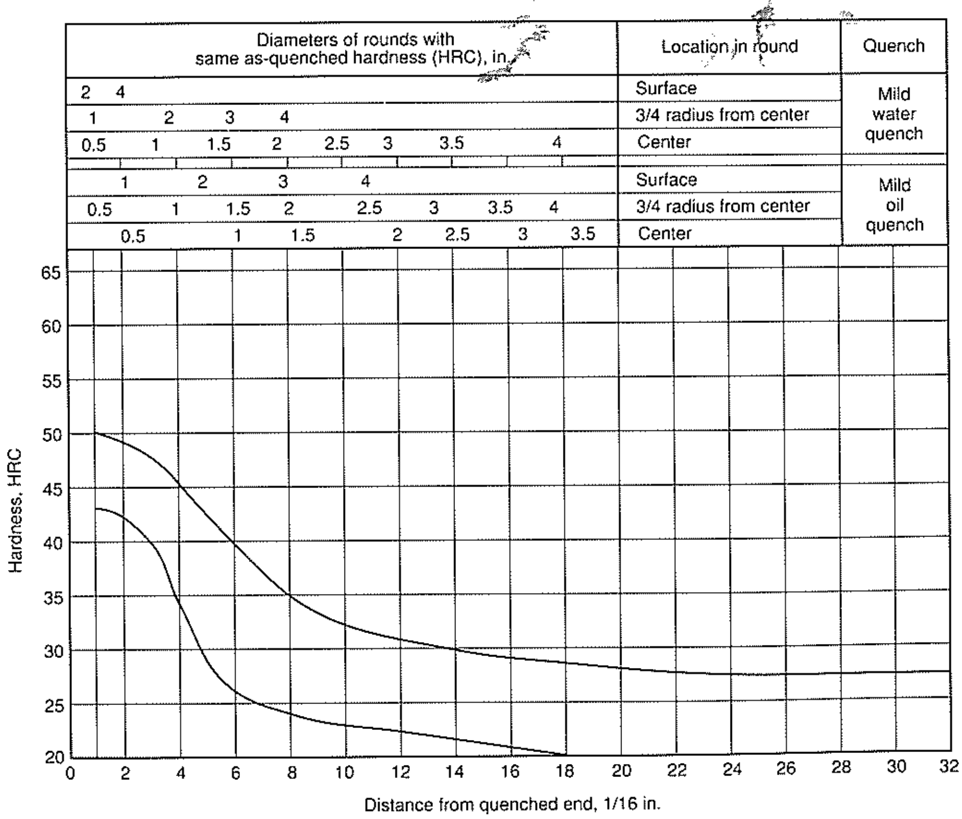
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	50	43
3	49	42
5	47	38
7	45	31
9	41	28
11	38	26
13	35	24
15	33	23
20	31	21
25	29	20
30	29	...
35	28	...
40	27	...
45	27	...
50	27	...



Hardness limits for specification purposes

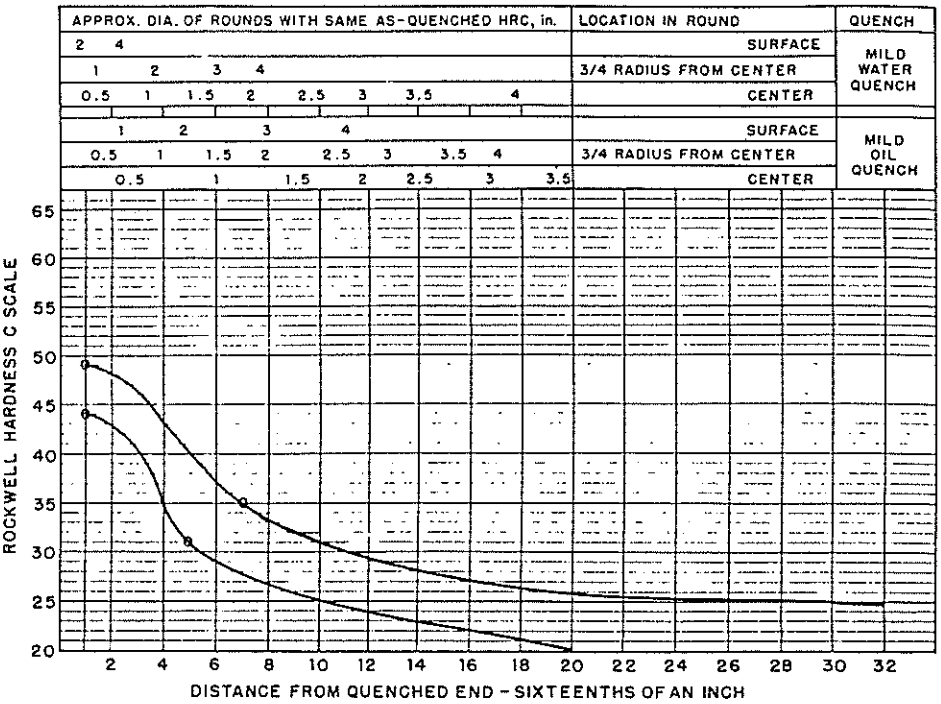
J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	50	43
2	49	42
3	48	39
4	46	33
5	43	29
6	40	27
7	37	25
8	35	24
9	34	24
10	33	23
11	32	23
12	31	22
13	31	22
14	30	22
15	30	21
16	29	21
18	29	20
20	28	...
22	27	...
24	27	...
26	27	...
28	27	...
30	27	...
32	27	...



8822RH: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 925 °C (1700 °F)

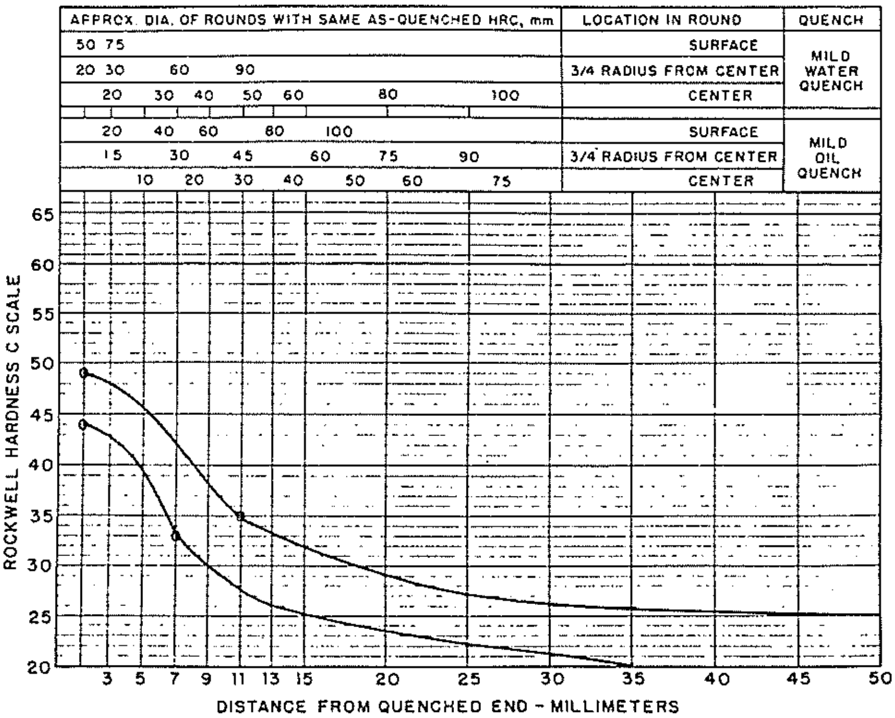
Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	49	44
2	48	43
3	47	40
4	43	35
5	40	31
6	37	29
7	35	27
8	33	26
9	32	25
10	31	25
11	30	24
12	30	23
13	29	23
14	28	23
15	28	22
16	27	22
18	27	21
20	26	20
22	26	...
24	26	...
26	26	...
28	25	...
30	25	...
32	25	...



Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	49	44
3	48	43
5	46	39
7	42	33
9	38	30
11	35	27
13	33	26
15	32	25
20	29	23
25	27	22
30	27	21
35	26	20
40	26	...
45	25	...
50	25	...



9260, 9260H

Chemical Composition. 9260. AISI and UNS: 0.56 to 0.64 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 1.80 to 2.20 Si. **UNS H92600 and SAE/AISI 9260H:** 0.55 to 0.65 C, 0.65 to 1.10 Mn, 1.70 to 2.20 Si

Similar Steels (U.S. and/or Foreign). 9260. UNS G92600; ASTM A29, A59, A322, A331; SAE J404, J412, J770; (Ger.) DIN 1.0909; (Fr.) AFNOR 60 S 7, 61 SC 7; (U.K.) B.S. 250 A 58. **9260H.** UNS H92600; ASTM A304; SAE J1268; (Ger.) DIN 1.0909; (Fr.) AFNOR 60 S 7, 61 SC 7; (U.K.) B.S. 250 A 58

Characteristics. A special composition, the only steel in the present AISI list where the silicon content (1.7 to 2.2%) is high enough to be considered an alloy. Principal use is for heavy-duty springs, notably coil springs that are hot wound. Is nearly identical in composition to S4, shock-resisting tool steel. 9260H is used for tooling as well as nontooling applications, such as coining dies, where impact resistance is important. As-quenched hardness can be expected to fall within the range of approximately 58 to 63 HRC. Hardenability is considered fairly high

Forging. Heat to 1205 °C (2200 °F) maximum. Do not forge after temperature of forging stock drops below approximately 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F). Cool in air

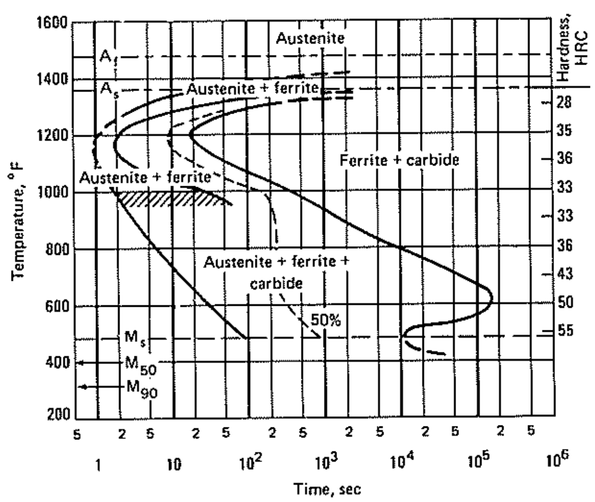
Annealing. For a predominantly spheroidized structure (usually preferred), heat to 760 °C (1400 °F), then cool to 705 °C (1300 °F), at a rate not to exceed 6 °C (10 °F) per h; or heat to 760 °C (1400 °F), cool rapidly to 665 °C (1230 °F), and hold for 10 h

Direct Hardening. Austenitize at 870 °C (1600 °F), and quench in oil. Martempering is an alternative process. Quenchants include polymers

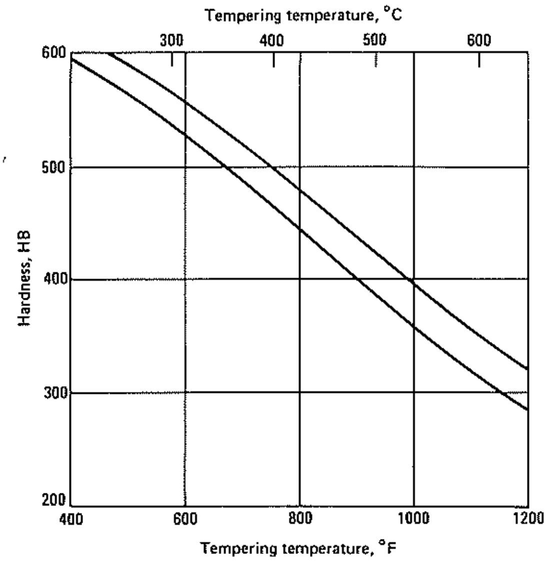
Tempering. After parts have been uniformly quenched to near ambient temperature, they should be placed in a tempering furnace immediately, preferably when their temperature is within the range of 38 to 50 °C (100 to 120 °F). The tempering temperature must be at least 150 °C (300 °F). Higher tempering temperatures are usually used to develop maximum toughness in this steel

Recommended Processing Sequence

- Forge, or hot wind if producing springs
- Normalize
- Anneal
- Rough and semifinish machine (if applicable)
- Austenitize and quench
- Temper
- Finish machine



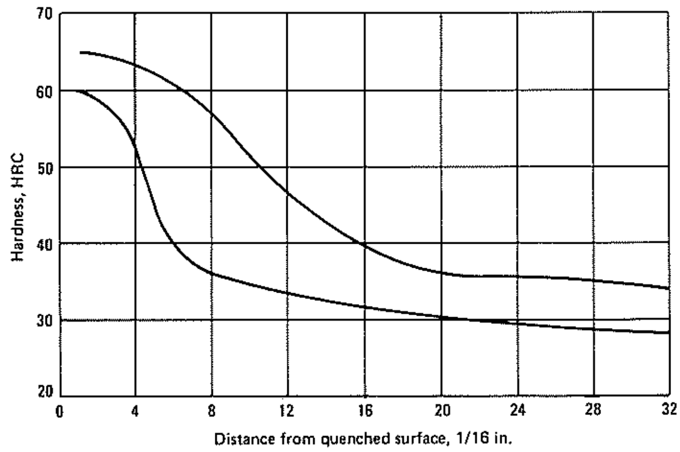
9260: Isothermal Transformation Diagram. Composition: 0.62 C, 0.82 Mn, 2.01 Si, 0.07 Cr. Austenitized at 870 °C (1600 °F). Grain size: 6 to 7

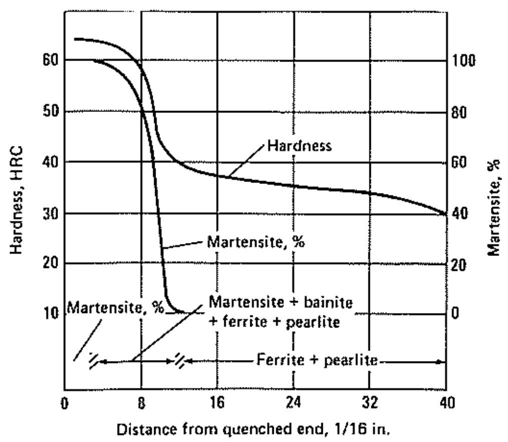


9260: Hardness vs Tempering Temperature. Composition: 0.55 to 0.65 C, 0.70 to 1.00 Mn, 1.80 to 2.20 Si. Forged at 1205 °C (2200 °F) maximum, furnace cooled from 815 to 925 °C (1500 to 1695 °F). Maximum annealed hardness, 229 HB. Hardness when normalized in test size, 302 HB. Normalized at 900 °C (1650 °F), quenched in oil from 870 °C (1600 °F), tempered for 2 h. Source: Republic Steel

9260H: End-Quench Hardenability

Distance from quenched surface		Hardness, HRC		Distance from quenched surface		Hardness, HRC	
1/16 in.	mm	max	min	1/16 in.	mm	max	min
1	1.58	...	60	13	20.54	45	33
2	3.16	...	60	14	22.12	43	33
3	4.74	65	57	15	23.70	42	32
4	6.32	64	53	16	25.28	40	32
5	7.90	63	46	18	28.44	38	31
6	9.48	62	41	20	31.60	37	31
7	11.06	60	38	22	34.76	36	30
8	12.64	58	36	24	37.92	36	30
9	14.22	55	36	26	41.08	35	29
10	15.80	52	35	28	44.24	35	29
11	17.38	49	34	30	47.40	35	28
12	18.96	47	34	32	50.56	34	28



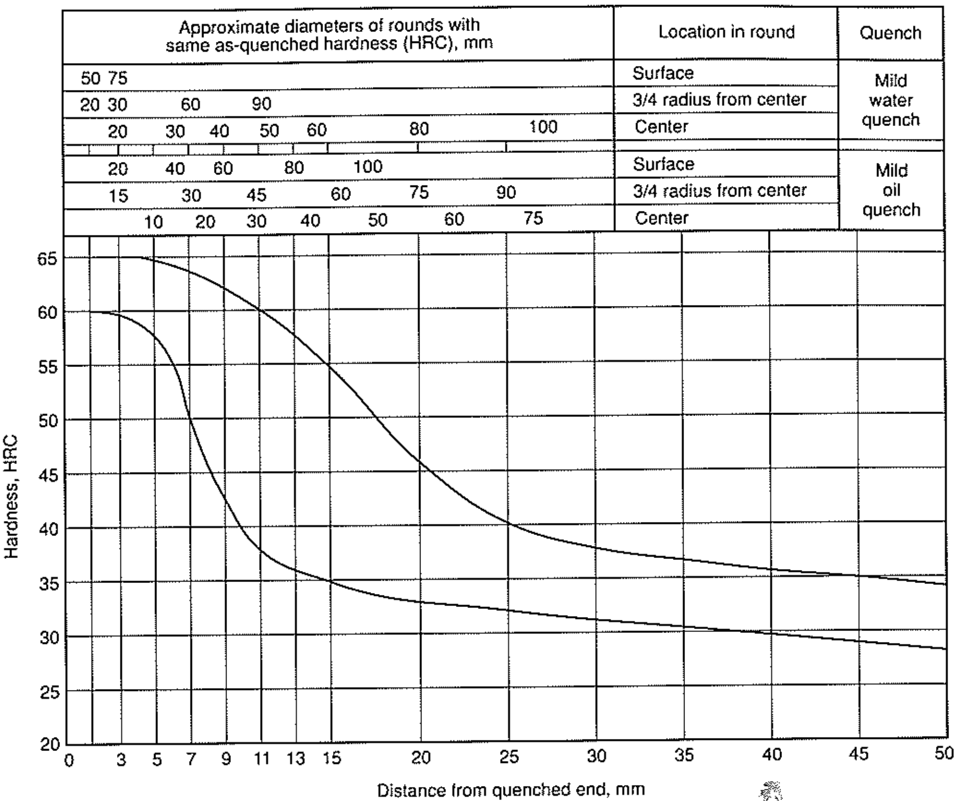


9260: End-Quench Hardenability. Composition: 0.62 C, 0.82 Mn, 2.01 Si, 0.07 Cr. Austenitized at 870 °C (1600 °F). Grain size: 6 to 7

9260H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 900 °C (1650 °F). Austenitize: 870 °C (1600 °F)

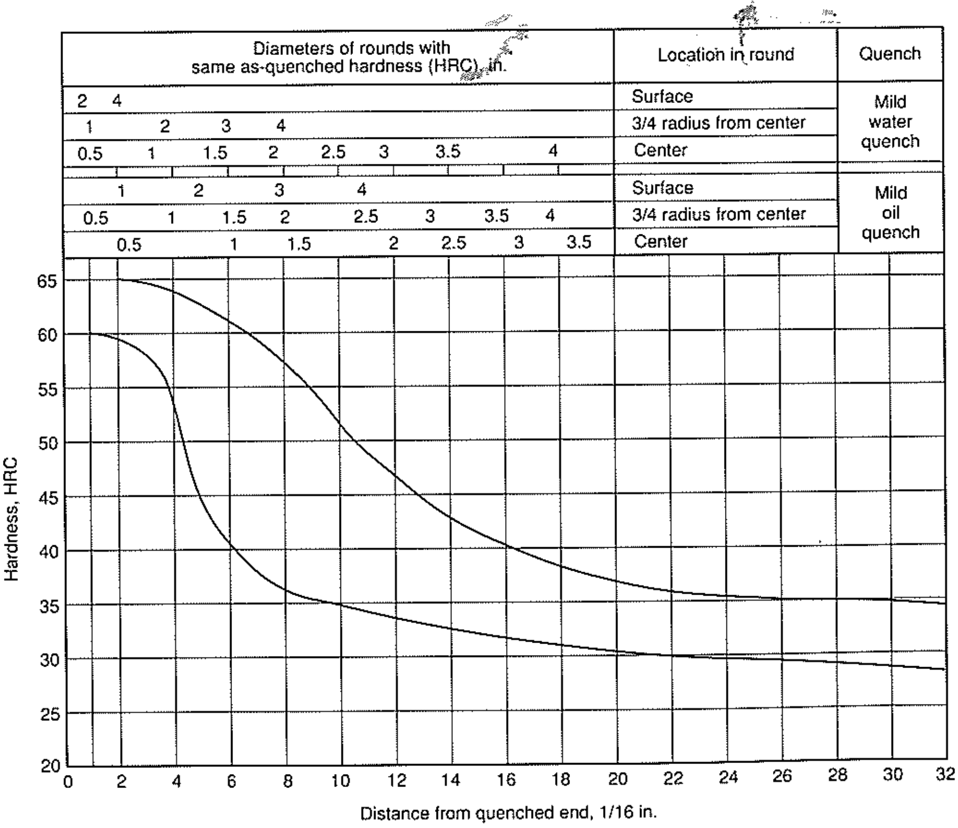
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	...	60
3	...	60
5	65	58
7	63	50
9	62	42
11	60	38
13	58	36
15	54	35
20	47	33
25	40	32
30	38	31
35	37	30
40	36	29
45	35	28
50	35	28

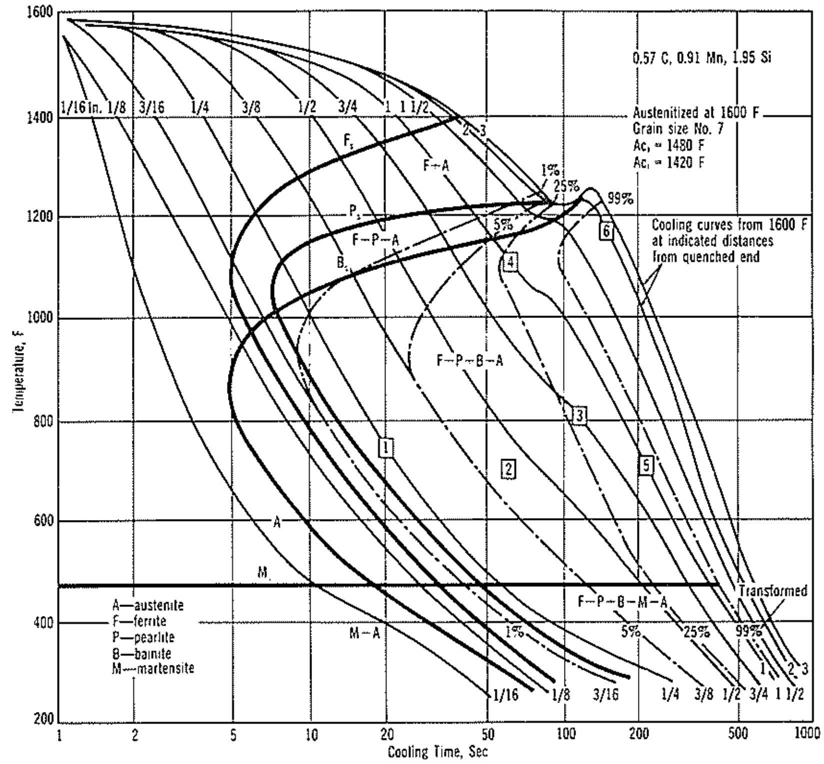


Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	...	60
2	...	60
3	65	57
4	64	53
5	63	46
6	62	41
7	60	38
8	58	36
9	55	36
10	52	35
11	49	34
12	47	34
13	45	33
14	43	33
15	42	32
16	40	32
18	38	31
20	37	31
22	36	30
24	36	30
26	35	29
28	35	29
30	35	28
32	34	28



9260: CCT Diagram. Composition: 0.57 C, 0.91 Mn, 1.95 Si. Grain size: 7. Austenitized at 870 °C (1600 °F) (using interrupted Jominy method)



9310H, 9310RH

Chemical Composition. **UNS H93100 and SAE/AISI 9310H:** 0.07 to 0.13 C, 0.40 to 0.70 Mn, 0.15 to 0.30 Si, 2.95 to 3.55 Ni, 1.00 to 1.45 Cr, 0.08 to 0.15 Mo. **SAE 9310RH:** 0.08 to 0.13 C, 0.45 to 0.65 Mn, 0.15 to 0.35 Si, 3.00 to 3.50 Ni, 1.00 to 1.40 Cr, 0.08 to 0.15 Mo

Similar Steels (U.S. and/or Foreign). UNS G93100; ASTM A304; SAE J1268

Characteristics. A relatively high-alloy, high-quality, and high-hardenability case hardening steel. Usually carburized. Because of its relatively low carbon content, as-quenched hardness is not usually higher than approximately 32 to 38 HRC, depending on whether the carbon is near the low side or the high side of the allowable range. Hardenability, however, is high. Used for such applications as premium quality gears, such as aircraft engines and pinions for which high hardenability and an unusually high degree of toughness are mandatory. Relatively expensive and has a high nickel content, which can be a scarce alloy. The use of 9310H has gradually declined in favor of higher carbon, lower alloy grades of carburizing steels. Can be case hardened by carbonitriding, but economics usually exclude the use of 9310H for parts that would require carbonitriding

Forging. Heat to 1260 °C (2300 °F) maximum. Do not forge after temperature of forging stock drops below approximately 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Cool in air

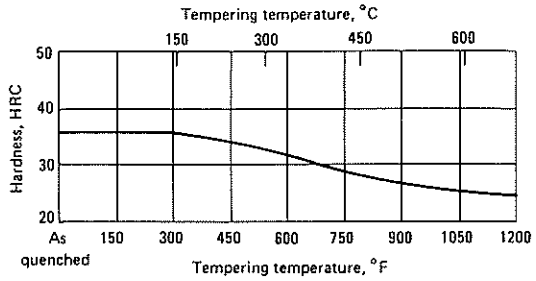
Annealing. Because of the sluggish transformation characteristics of this steel, conventional annealing is not usually practical. A better means of obtaining a spheroidized structure in 9310H is by tempering for approximately 18 h at a subcritical temperature, usually 600 °C (1110 °F)

Tempering. Temper all carburized parts at 150 °C (300 °F), and virtually no loss of case hardness results. If some decrease in hardness can be tolerated, toughness can be increased by tempering at somewhat higher temperatures, up to 260 °C (500 °F)

Case Hardening. See carburizing practice described for 8620H. Vacuum carburizing, ion nitriding, austempering, and martempering are suitable processes

Recommended Processing Sequence

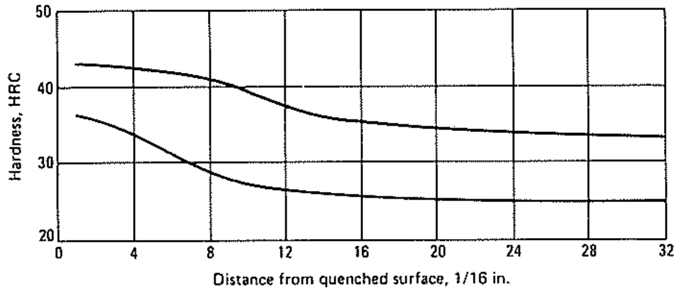
- Forge
- Normalize
- Anneal (if required)
- Rough machine
- Semifinish machine, allowing only grinding stock, no more than 10% of the case depth per side for carburized parts
- Carburize and quench
- Temper



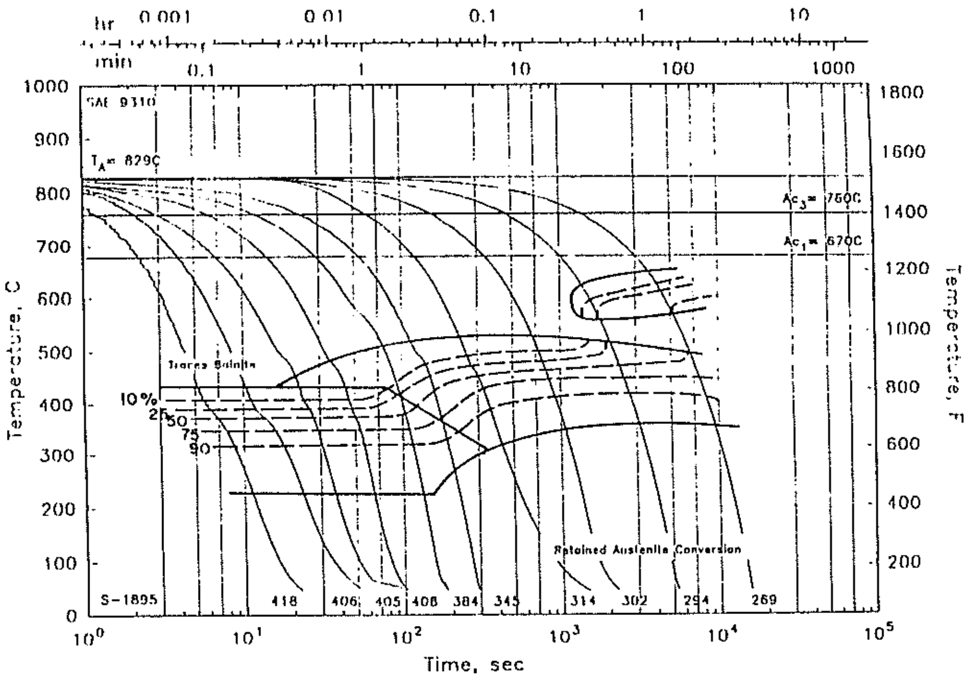
9310H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

9310H: End-Quench Hardenability

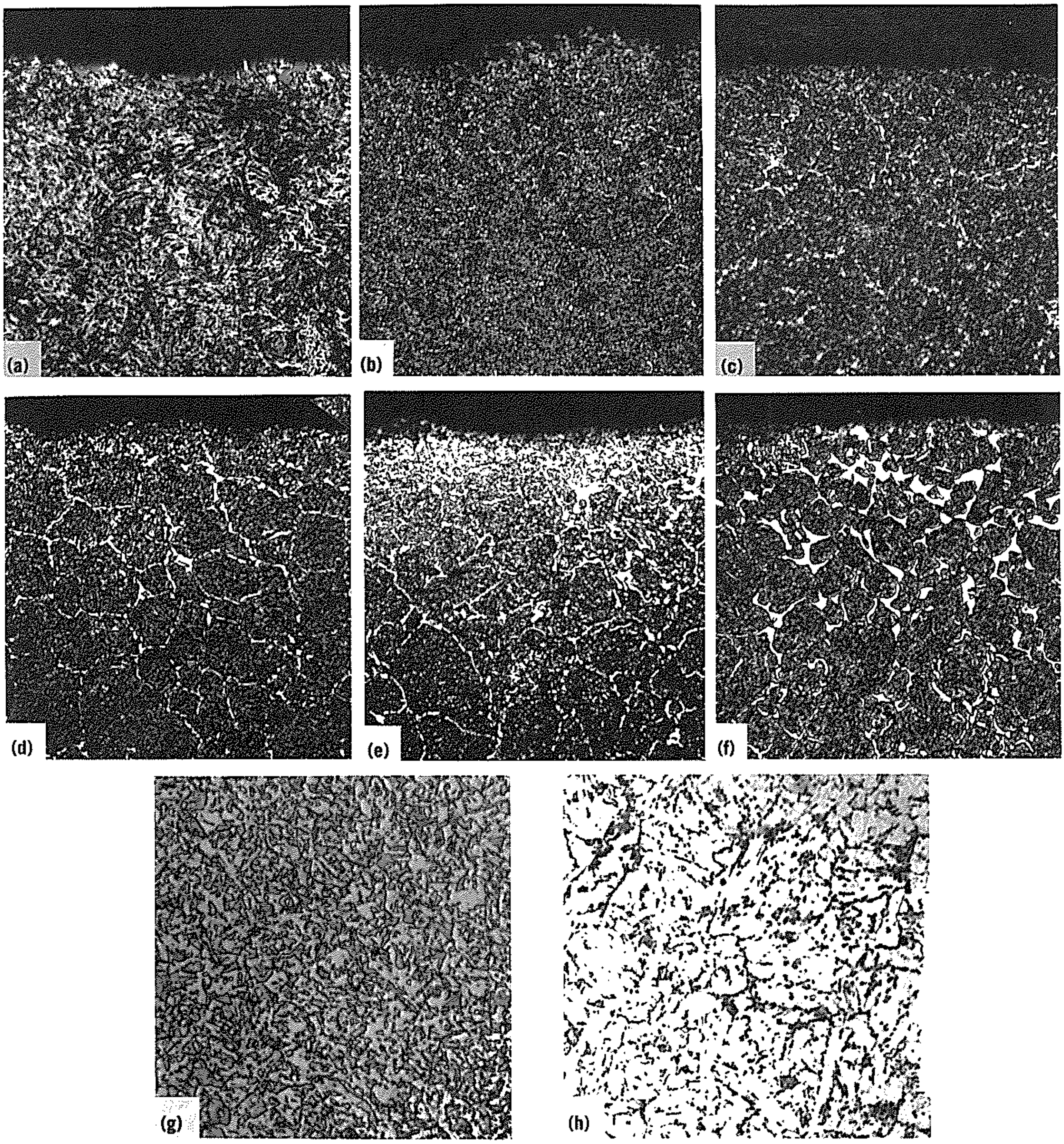
Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min
1	1.58	43	36	13	20.54	37	26
2	3.16	43	35	14	22.12	36	26
3	4.74	43	35	15	23.70	36	26
4	6.32	42	34	16	25.28	35	26
5	7.90	42	32	18	28.44	35	26
6	9.48	42	31	20	31.60	35	25
7	11.06	42	30	22	34.76	34	25
8	12.64	41	29	24	37.92	34	25
9	14.22	40	28	26	41.08	34	25
10	15.80	40	27	28	44.24	34	25
11	17.38	39	27	30	47.40	33	24
12	18.96	38	26	32	50.56	33	24



9310: CCT Diagram. Austenitized 20 min at 829 °C (1525 °F). Source: Climax Molybdenum Company



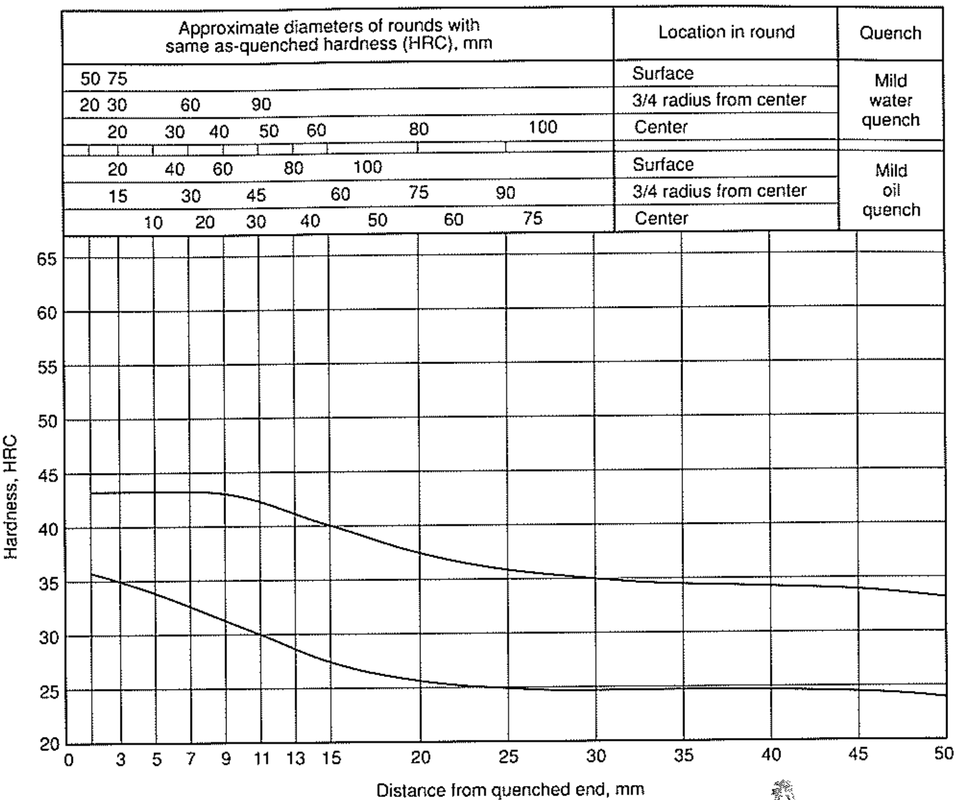
9310: Microstructures. Note: For (a to g), specimens were gas carburized at 925 to 940 °C (1695 to 1725 °F) for 4 h in a pit-type furnace, furnace cooled, austenitized at 815 to 830 °C (1500 to 1525 °F), oil quenched, and tempered at 150 °C (300 °F) for 4 h. Case carbon contents vary because of variations in the carbon potential of the carburizing atmosphere. (a) 2% nital, 500×. Gas carburized to a maximum case carbon content of 0.60% (lean). (b) 2% nital, 500×. Gas carburized to a maximum case carbon content of 0.85%. (c) 2% nital, 500×. Gas carburized to a maximum case carbon content of 0.95% (optimum). (d) 2% nital, 500×. Gas carburized to a maximum case carbon content of 1.05%. (e) 2% nital, 500×. Gas carburized to a maximum case carbon content of 1.10%. (f) 2% nital, 500×. Gas carburized to a maximum case carbon content of 1.20%. (g) Picral, 200×. Normalized by austenitizing 2 h at 885 °C (1625 °F) and cooling in still air. Scattered carbide particles and unresolved pearlite in a matrix of ferrite (light constituent). (h) 3% nital, 500×. Annealed by austenitizing 2 h at 885 °C (1625 °F) and cooling slowly in a furnace. Scattered carbide particles (dark constituent) in a matrix of ferrite (light constituent)



9310H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 845 °C (1555 °F)

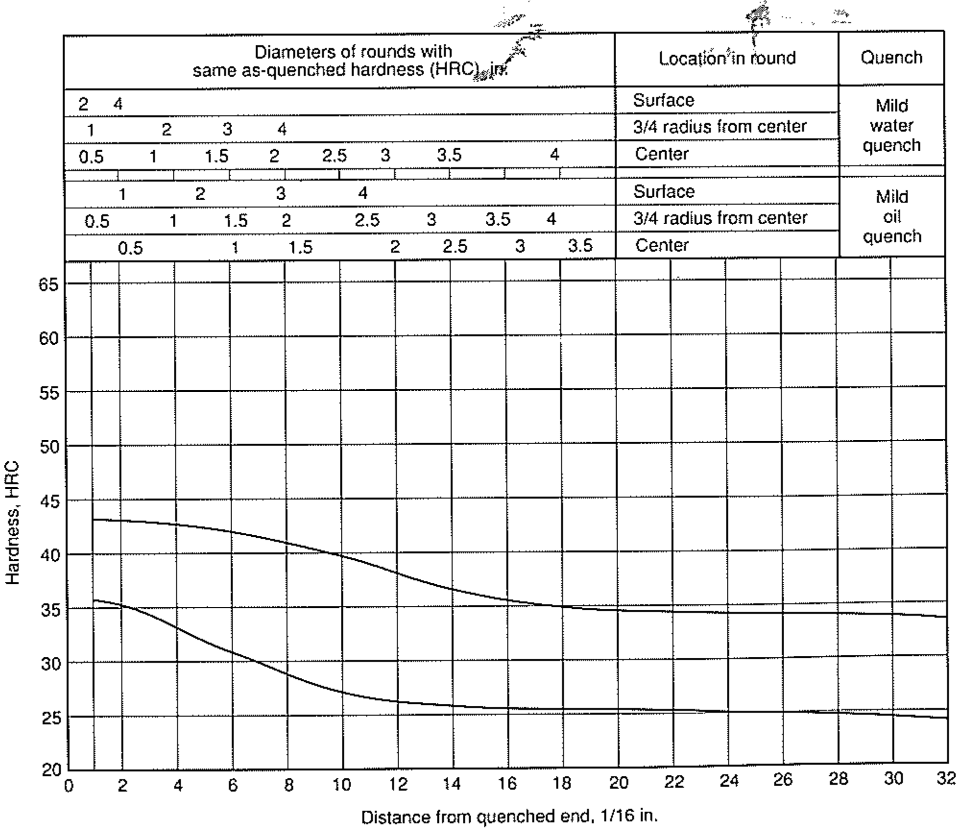
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	43	36
3	43	35
5	43	34
7	43	33
9	43	31
11	42	30
13	41	28
15	40	27
20	38	26
25	36	25
30	35	25
35	35	25
40	34	25
45	34	24
50	33	24



Hardness limits for specification purposes

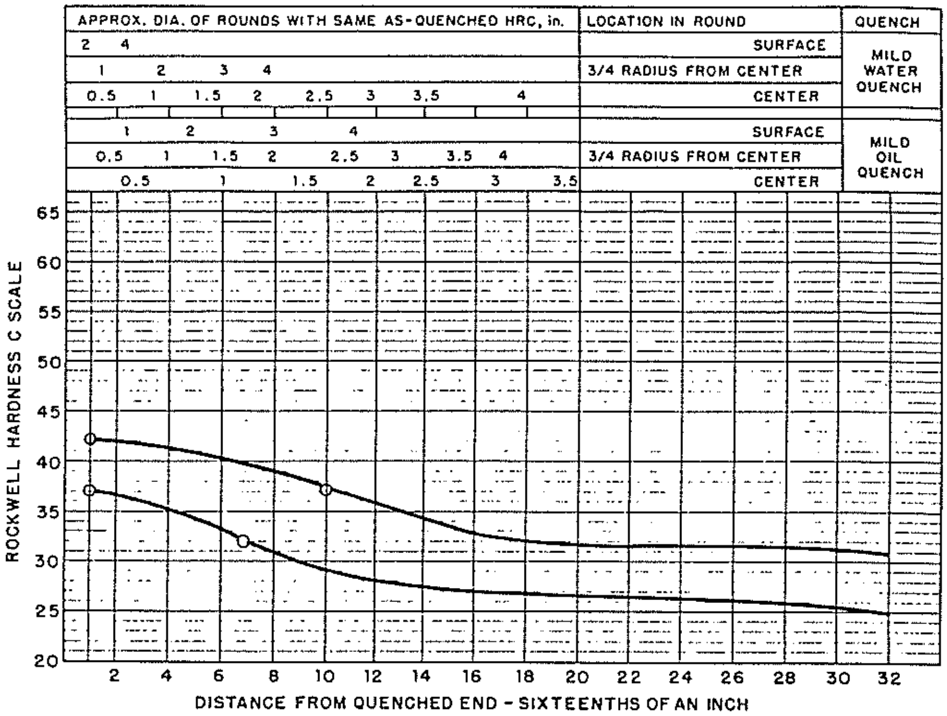
J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	43	36
2	43	35
3	43	35
4	42	34
5	42	32
6	42	31
7	42	30
8	41	29
9	40	28
10	40	27
11	39	27
12	38	26
13	37	26
14	36	26
15	36	26
16	35	26
18	35	26
20	35	25
22	34	25
24	34	25
26	34	25
28	34	25
30	33	24
32	33	24



9310RH: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 °C (1700 °F). Austenitize: 845 °C (1555 °F)

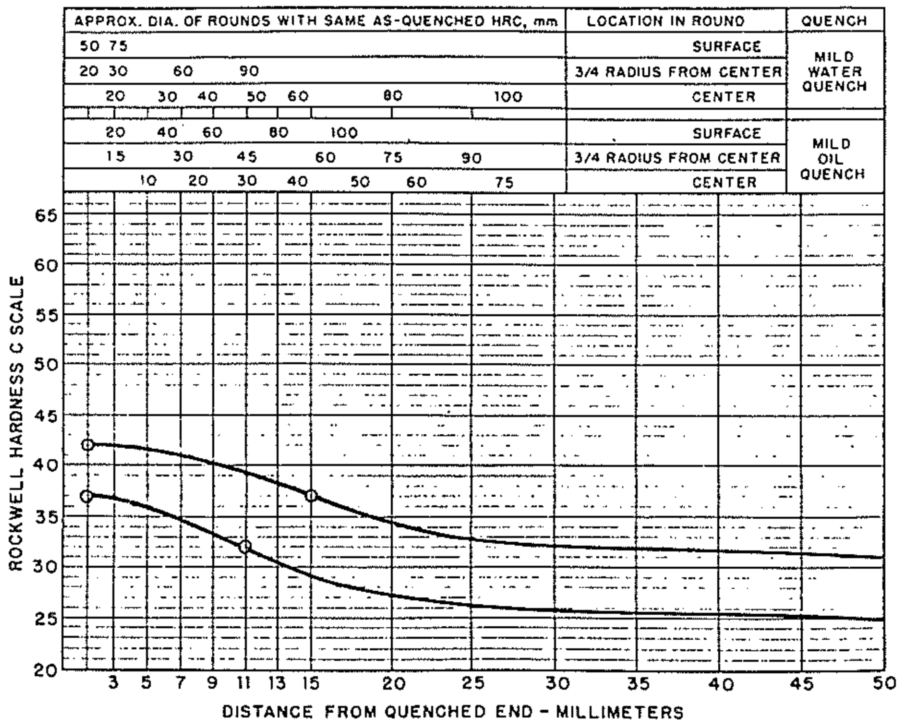
Hardness limits for specification purposes

J distance, $\frac{1}{16}$ in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	42	37
2	42	36
3	42	36
4	41	35
5	41	34
6	40	33
7	40	32
8	39	31
9	38	30
10	37	29
11	37	29
12	36	28
13	35	28
14	34	28
15	34	28
16	33	27
18	33	27
20	32	26
22	32	26
24	32	26
26	32	26
28	32	26
30	31	25
32	31	25



Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	42	37
3	42	36
5	42	36
7	41	35
9	40	33
11	40	32
13	39	31
15	37	29
20	35	28
25	33	27
30	32	26
35	32	26
40	32	26
45	32	25
50	31	25



94B15, 94B15H

Chemical Composition. **94B15. AISI:** 0.13 to 0.18 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.30 to 0.60 Ni, 0.30 to 0.50 Cr, 0.08 to 0.15 Mo, 0.0005 B min. **UNS:** 0.13 to 0.18 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.30 to 0.60 Ni, 0.30 to 0.50 Cr, 0.08 to 0.15 Mo, 0.0005 B min. **UNS H94151 and SAE/AISI 94B15H:** 0.12 to 0.18 C, 0.70 to 1.05 Mn, 0.15 to 0.35 Si, 0.25 to 0.65 Ni, 0.25 to 0.55 Cr, 0.08 to 0.15 Mo, B (can be expected to be 0.0005 to 0.003 percent)

Similar Steels (U.S. and/or Foreign). **94B15.** UNS G94151; AMS 6275 A; ASTM A519; SAE J404, J770. **94B15H.** UNS H94151; ASTM A304; SAE J1268

Characteristics. One of the two principal boron-containing grades used for case hardening, either carburizing or carbonitriding. Depending on the precise carbon content within the allowable range, as-quenched hardness (without case) usually ranges from 35 to 40 HRC. However, because of the boron addition, the hardenability of this grade is higher than that of an 8600H grade of similar carbon content, although the ranges of Ni, Cr, and Mo are lower for 94B15H. Used for carburized parts which have heavy sections and need the higher hardenability. Cost is generally less than that of a higher alloy grade not containing boron which would be required to provide the same hardenability

Forging. Heat to 1245 °C (2275 °F) maximum. Do not forge after temperature of forging stock drops below approximately 900 °C (1650 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Cool in air

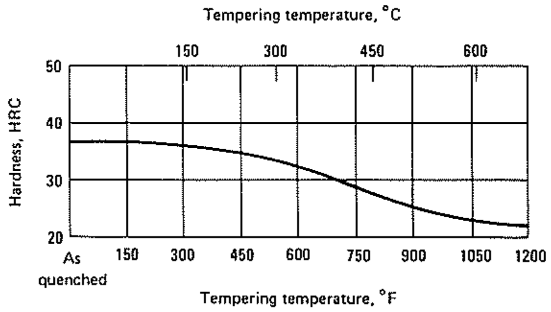
Annealing. For a predominantly pearlitic structure, heat to 900 °C (1650 °F), cool rapidly to 665 °C (1230 °F) and hold for 5 h. For a predominantly spheroidized structure, heat to 800 °C (1475 °F), cool rapidly to 665 °C (1230 °F), and hold for 10 h

Tempering. Temper all carburized or carbonitrided parts at 150 °C (300 °F), and virtually no loss of case hardness results. If some decrease in hardness can be tolerated, toughness can be increased by tempering at somewhat higher temperatures, up to 260 °C (500 °F)

Case Hardening. See carburizing and carbonitriding, processes described for 8620H

Recommended Processing Sequence

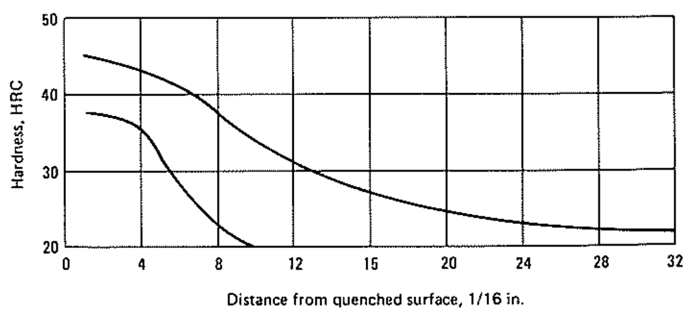
- Forge
- Normalize
- Anneal (if required)
- Rough machine
- Carburize or carbonitride and quench
- Semifinish machine, allowing only grinding stock, no more than 10% of the case depth per side for carburized parts. In most instances, carbonitrided parts are completely finished in this step
- Temper



94B15, 94B15H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

94B15H: End-Quench Hardenability

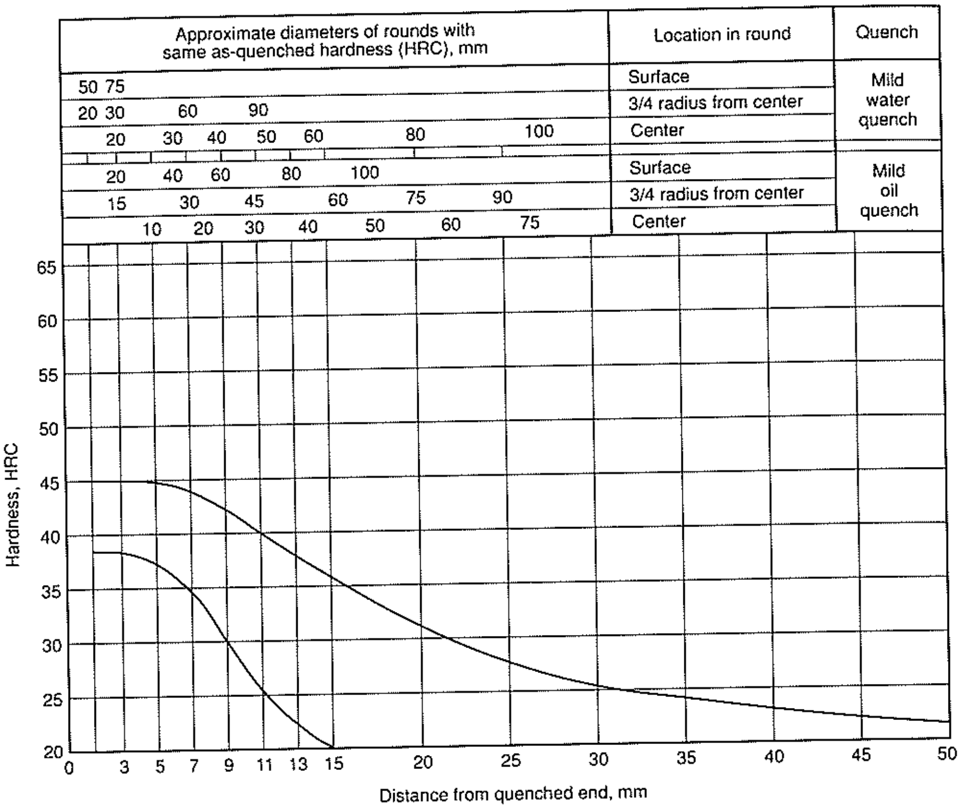
Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max
1	1.58	45	38	13	20.54	30
2	3.16	45	38	14	22.12	29
3	4.74	44	37	15	23.70	28
4	6.32	44	36	16	25.28	27
5	7.90	43	32	18	28.44	26
6	9.48	42	28	20	31.60	25
7	11.06	40	25	22	34.76	24
8	12.64	38	23	24	37.92	23
9	14.22	36	21	26	41.08	23
10	15.80	34	20	28	44.24	22
11	17.38	33	...	30	47.40	22
12	18.96	31	...	32	50.56	22



ı4B15H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 C (1700 °F). Austenitize: 925 °C (1700 °F)

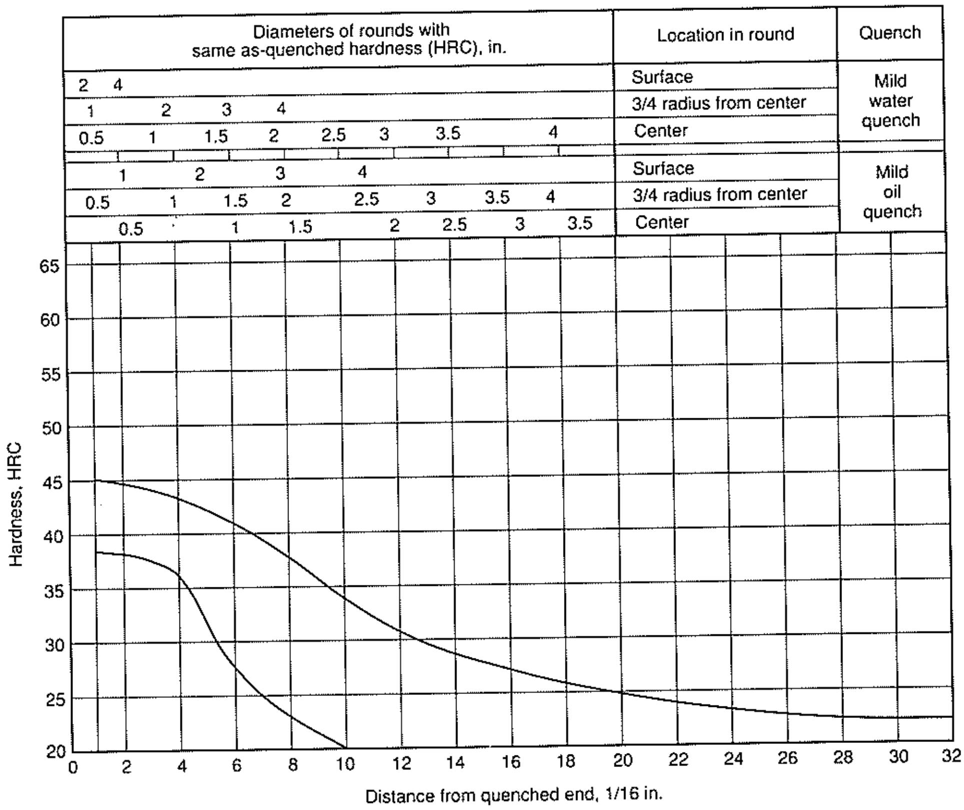
ardness limits for specification urposes

distance, ım	Hardness, HRC Maximum	Minimum
5	45	38
	45	38
	45	37
	44	34
	42	30
1	40	26
3	38	22
5	36	20
0	31	...
5	28	...
0	26	...
5	24	...
0	23	...
5	22	...
0	22	...



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Minimum
1	45	38
2	45	38
3	44	37
4	44	36
5	43	32
6	42	28
7	40	25
8	38	23
9	36	21
10	34	20
11	33	...
12	31	...
13	30	...
14	29	...
15	28	...
16	27	...
18	26	...
20	25	...
22	24	...
24	23	...
26	23	...
28	22	...
30	22	...
32	22	...



94B17, 94B17H

Chemical Composition. **94B17. AISI:** 0.15 to 0.20 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.30 to 0.60 Ni, 0.30 to 0.50 Cr, 0.08 to 0.15 Mo, 0.0005 to 0.003 B. **UNS:** 0.15 to 0.20 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.30 to 0.60 Ni, 0.30 to 0.50 Cr, 0.08 to 0.15 Mo, 0.0005 B min. **UNS H94171 and SAE/AISI 94B17H:** 0.14 to 0.20 C, 0.70 to 1.05 Mn, 0.15 to 0.35 Si, 0.25 to 0.65 Ni, 0.25 to 0.55 Cr, 0.08 to 0.15 Mo, B (can be expected to be 0.0005 to 0.003 percent)

Similar Steels (U.S. and/or Foreign). **94B17.** UNS G94171; AMS 6275; ASTM A519; SAE J404, J770. **94B17H.** UNS H494171; ASTM A304; SAE J1268

Characteristics. The compositions of 94B17H and 94B15H are identical, except for a slightly higher carbon range from 94B17H. The characteristics of these two grades are essentially the same. Because of the higher carbon range, as-quenched hardness range without case is slightly higher for 94B17H, approximately 37 to 42 HRC. The hardenability pattern for 94B17H is the same as for 94B15H, except the entire band for 94B17H is shifted upward because of the higher carbon content. Grade 94B17H is often used instead of 94B15H when a higher core hardness is needed for carburized parts

Forging. Heat to 1245 °C (2275 °F) maximum. Do not forge after temperature of forging stock drops below approximately 900 °C (1650 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 925 °C (1695 °F). Cool in air

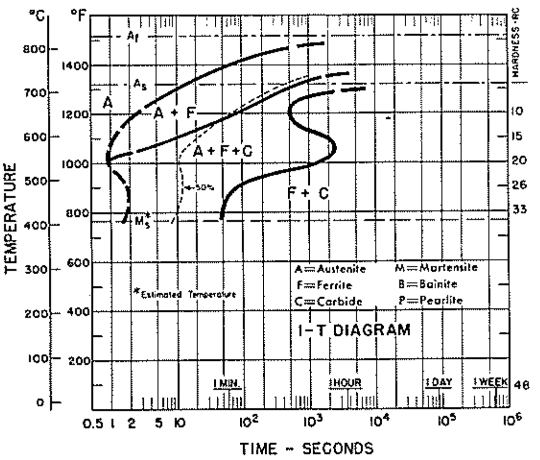
Annealing. For a predominantly pearlitic structure, heat to 900 °C (1650 °F), cool rapidly to 665 °C (1230 °F), and hold for 4 h. For a predominantly spheroidized structure, heat to 800 °C (1475 °F), cool rapidly to 665 °C (1230 °F), and hold for 10 h

Tempering. Temper all carburized or carbonitrided parts at 150 °C (300 °F), and virtually no loss of case hardness results. If some decrease in hardness can be tolerated, toughness can be increased by tempering at somewhat higher temperatures, up to 260 °C (500 °F)

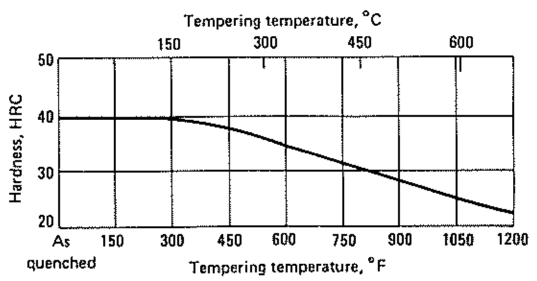
Case Hardening. See carburizing and carbonitriding processes described for 8620H

Recommended Processing Sequence

- Forge
- Normalize
- Anneal (if required)
- Rough machine
- Semifinish machine, allowing only grinding stock, no more than 10% of the case depth per side for carburized parts. In most instances, carbonitrided parts are completely finished in this step
- Carburize or carbonitride and quench
- Temper



94B17: Isothermal Transformation Diagram. Composition: 0.19 C, 0.77 Mn, 0.42 Ni, 0.40 Cr, 0.12 Mo, 0.0018 B. Austenitized at 925 °C (1695 °F). Grain size: 7 to 8

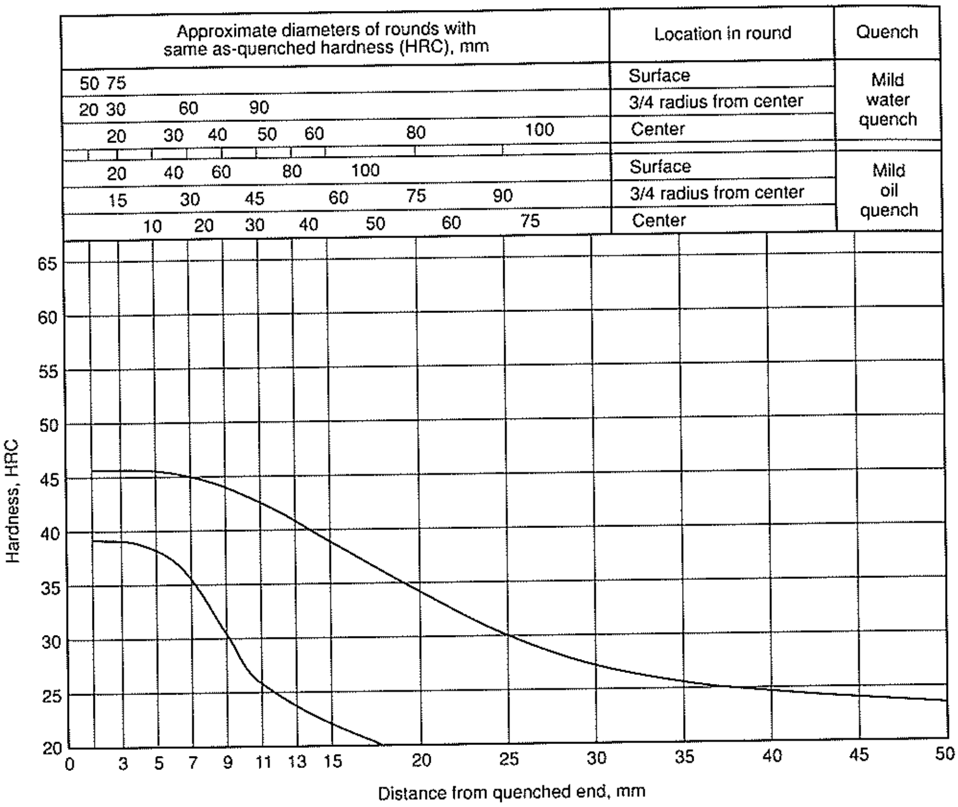


94B17, 94B17H: Hardness vs Tempering Temperature. Represents an average based on a fully quenched structure

)4B17H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 925 C (1700 °F). Austenitize: 925 °C (1700 °F)

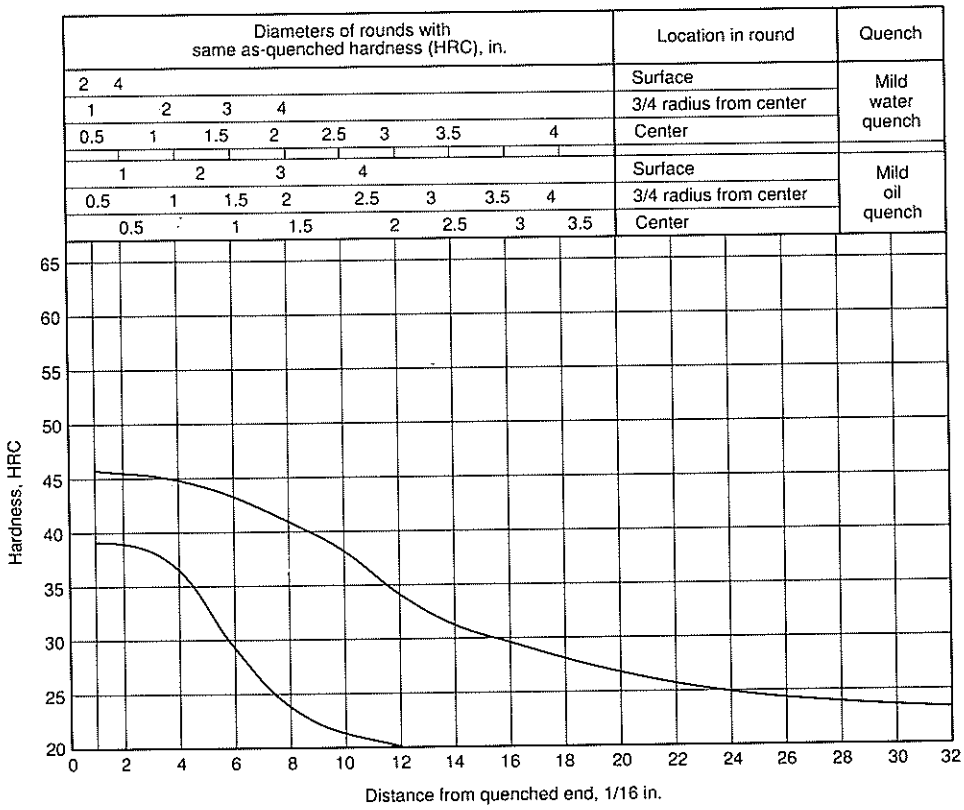
.ardness limits for specification urposes

distance, .m	Hardness, HRC Maximum	Minimum
5	46	39
	46	39
	46	38
	45	36
	44	31
l	43	26
3	41	24
5	39	22
0	34	...
5	30	...
0	28	...
5	26	...
0	25	...
5	24	...
0	23	...



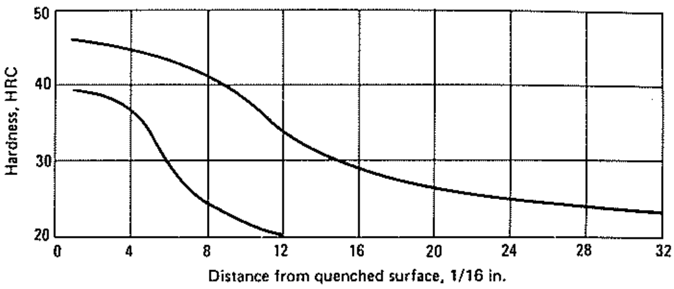
ɨardness limits for specification ɔurposes

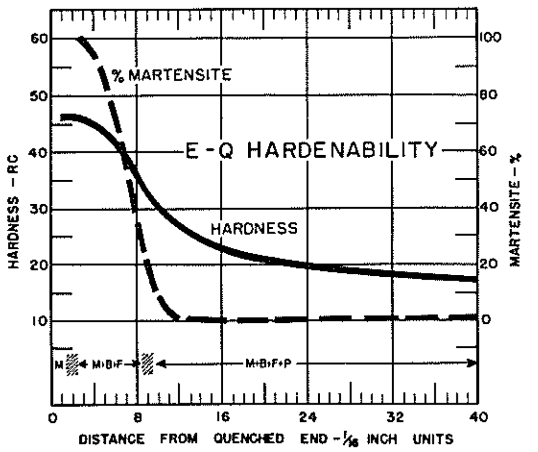
l distance, ⁄16 in.	Hardness, HRC Maximum	Minimum
1	46	39
2	46	39
3	45	38
4	45	37
5	44	34
6	43	29
7	42	26
8	41	24
9	40	23
10	38	21
11	36	20
12	34	...
13	33	...
14	32	...
15	31	...
16	30	...
18	28	...
20	27	...
22	26	...
24	25	...
26	24	...
28	24	...
30	23	...
32	23	...



94B17H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max
1	1.58	46	39	13	20.54	33
2	3.16	46	39	14	22.12	32
3	4.74	45	38	15	23.70	31
4	6.32	45	37	16	25.28	30
5	7.90	44	34	18	28.44	28
6	9.48	43	29	20	31.60	27
7	11.06	42	26	22	34.76	26
8	12.64	41	24	24	37.92	25
9	14.22	40	23	26	41.08	24
10	15.80	38	21	28	44.24	24
11	17.38	36	20	30	47.40	23
12	18.96	34	...	32	50.56	23





94B17: End-Quench Hardenability. Composition: 0.19 C, 0.77 Mn, 0.42 Ni, 0.40 Cr, 0.12 Mo, 0.0018 B. Austenitized at 925 °C (1695 °F). Grain size: 7 to 8

94B30, 94B30H

Chemical Composition. **94B30. AISI:** 0.28 to 0.33 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.30 to 0.60 Ni, 0.30 to 0.50 Cr, 0.08 to 0.15 Mo, 0.0005 to 0.003 B. **UNS:** 0.28 to 0.33 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.30 to 0.60 Ni, 0.30 to 0.50 Cr, 0.08 to 0.15 Mo, 0.0005 B min. **UNS H94301 and SAE/AISI 94B30H:** 0.27 to 0.33 C, 0.70 to 1.05 Mn, 0.15 to 0.35 Si, 0.25 to 0.65 Ni, 0.25 to 0.55 Cr, 0.08 to 0.15 Mo, B (can be expected to be 0.0005 to 0.003 percent)

Similar Steels (U.S. and/or Foreign). **94B30.** UNS G94301; ASTM A519; SAE J404, J412, J770. **94B30H.** UNS H94301; ASTM A304; SAE J1268

Characteristics. Clearly demonstrates the effects of boron upon hardenability. 94B30H is nearly identical with 86B30H, although the alloy ranges (Ni, Cr, Mo) are slightly lower for 94B30H. The hardenability because of the boron addition is nearly as high for 86B30H. As-quenched hardness, which is controlled mainly by carbon content, is the same for 94B30H as for 86B30H, approximately 46 to 52 HRC

Forging. Heat to 1230 °C (2250 °F) maximum. Do not forge after temperature of forging stock drops below approximately 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F). Cool in air

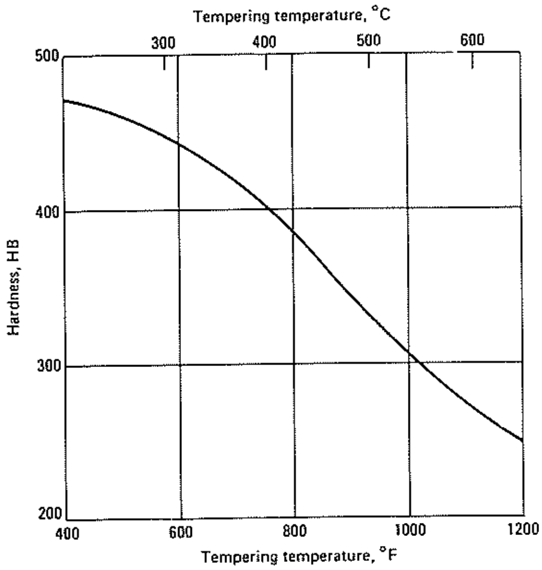
Annealing. For a predominantly pearlitic structure, heat to 845 °C (1555 °F), cool slowly to 730 °C (1350 °F), then cool to 640 °C (1185 °F), at a rate not to exceed 11 °C (20 °F) per h; or heat to 845 °C (1555 °F), cool rapidly to 665 °C (1230 °F), and hold for 7 h. For a predominantly spheroidized structure, heat to 760 °C (1400 °F), cool rapidly to 730 °C (1350 °F), then cool to 650 °C (1200 °F), at a rate not to exceed 6 °C (10 °F) per h; or heat to 760 °C (1400 °F), cool rapidly to 665 °C (1230 °F), and hold for 10 h

Hardening. Austenitize at 870 °C (1600 °F), and quench in oil

Tempering. Parts should be tempered immediately after quenching at the temperature which will provide the required hardness

commended Processing Sequence

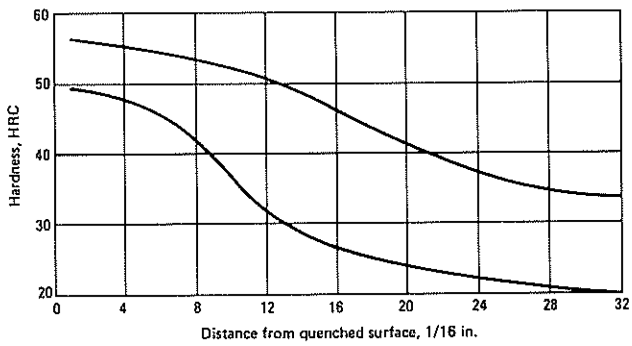
- orge
- ormalize
- nneal
- Rough and semifinish machine
- Austenitize and quench
- Temper
- Finish machine



94B30: Hardness vs Tempering Temperature. Composition: 0.28 to 0.33 C, 0.75 to 1.00 Mn, 0.040 P max, 0.040 S max, 0.20 to 0.35 Si, 0.30 to 0.60 Ni, 0.30 to 0.50 Cr, 0.08 to 0.15 Mo, 0.0005 B min. Approximate critical points: Ac_1, 720 °C (1330 °F); Ac_3, 805 °C (1480 °F); Ar_3, 750 °C (1380 °F); Ar_1, 655 °C (1210 °F). Recommended thermal treatment: forge at 1230 °C (2250 °F), anneal at 815 to 870 °C (1500 to 1600 °F) for a maximum hardness of 174 HB, normalize at 870 to 925 °C (1600 to 1695 °F) for an approximate hardness of 217 HB, quench from 855 to 885 °C (1570 to 1625 °F) in oil. Test specimens were normalized at 900 °C (1650 °F), quenched from 870 °C (1600 °F) in oil, tempered at 56 °C (100 °F) intervals in 13.7 mm (0.540 in.) rounds. Tested in 12.8 mm (0.505 in.) rounds. Source: Republic Steel

4B30H: End-Quench Hardenability

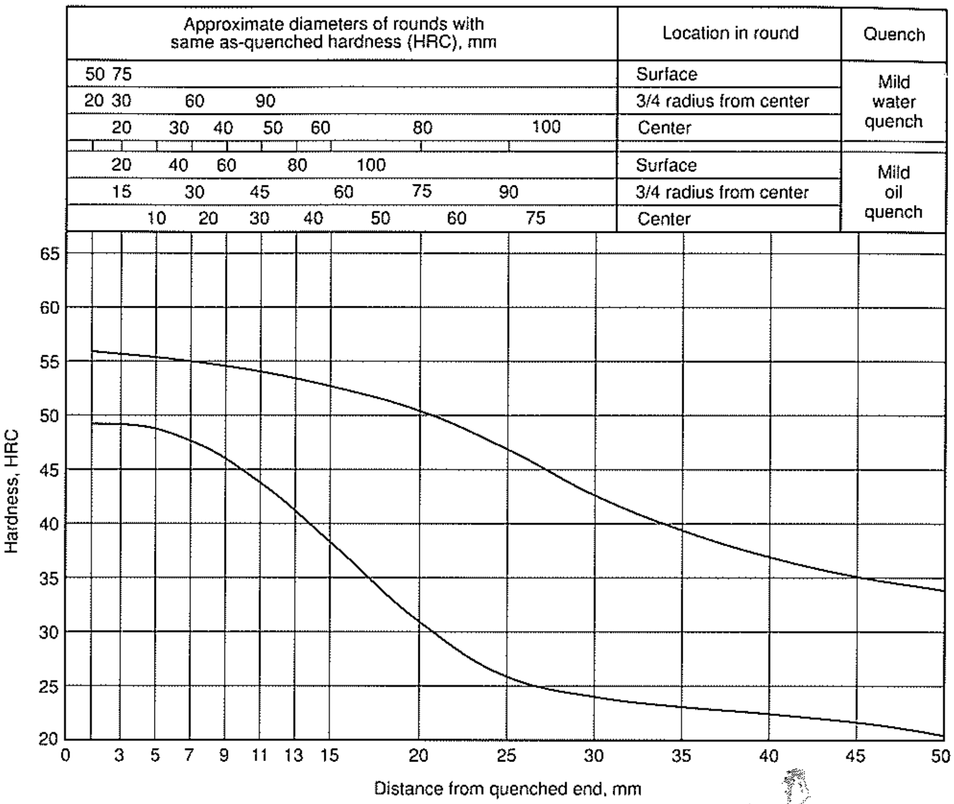
istance from quenched surface		Hardness, HRC		Distance from quenched surface		Hardness, HRC	
16 in.	mm	max	min	1/16 in.	mm	max	min
1	1.58	56	49	13	20.54	50	30
2	3.16	56	49	14	22.12	49	29
3	4.74	55	48	15	23.70	48	28
4	6.32	55	48	16	25.28	46	27
5	7.90	54	47	18	28.44	44	25
6	9.48	54	46	20	31.60	42	24
7	11.06	53	44	22	34.76	40	23
8	12.64	53	42	24	37.92	38	23
9	14.22	52	39	26	41.08	37	22
10	15.80	52	37	28	44.24	35	21
11	17.38	51	34	30	47.40	34	21
12	18.96	51	32	32	50.56	34	20



94B30H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 900 °C (1650 °F). Austenitize: 870 °C (1600 °F)

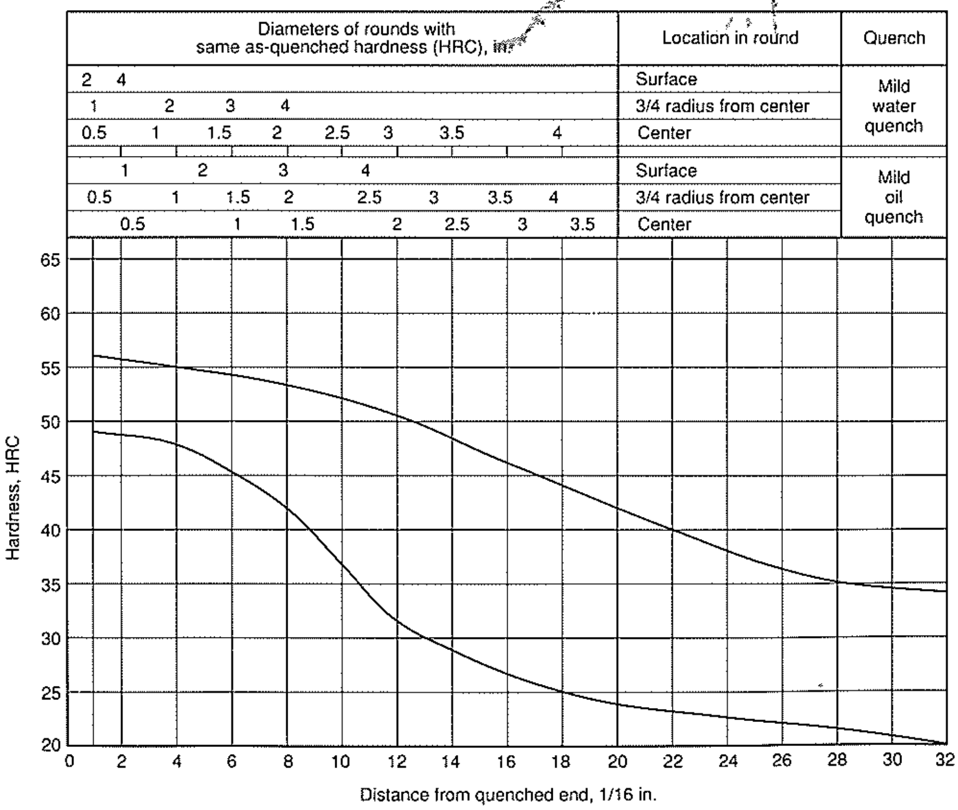
Hardness limits for specification purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	56	49
3	56	49
5	56	48
7	55	47
9	55	46
11	54	44
13	53	41
15	53	38
20	51	31
25	47	26
30	43	24
35	40	23
40	37	22
45	36	21
50	34	20



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	56	49
2	56	49
3	55	48
4	55	48
5	54	47
6	54	46
7	53	44
8	53	42
9	52	39
10	52	37
11	51	34
12	51	32
13	50	30
14	49	29
15	48	28
16	46	27
18	44	25
20	42	24
22	40	23
24	38	23
26	37	22
28	35	21
30	34	21
32	34	20



lo. 5-317

hemical Composition. 0.50 C, 0.50 Mn, 0.25 Si, 1.75 Ni, 1.00 Cr

haracteristics. A cold melt, grain controlled, electric furnace steel :at treatable to combination of hardness and toughness for machine parts two classes:

1. Hard tempering group, for gears and other hard parts, hardened and tempered between 205 to 345 °C (400 to 655 °F)
2. Tough tempering group for parts such as shafts, hardened and tempered between 370 to 595 °C (700 to 1105 °F)

eel has no special tendencies to decarburize. Machinability is 65 to 75 percent ' 1 percent carbon, water hardening tool steel, or about 50 percent that of 1112

orging. Heat to 1150 °C (2100 °F) maximum. Air cool in dry place. Do ɔt forge after temperature of forging stock drops below approximately 815 ℃ (1500 °F)

lecommended Heat Treating Practice

lormalizing. Heat to 845 to 900 °C (1555 to 1650 °F). Cool in air

.nnealing. Pack steel in container, using neutral packing compound, or eat in controlled atmosphere furnace. Heat parts to 760 °C (1400 °F), cool owly in furnace at a rate not to exceed 11 °C (20 °F) per h until furnace is :ack, and may then be turned off and allowed to cool naturally. Parts have ıaximum hardness of 201 HB

Hardening. Heat to 790 to 815 °C (1455 to 1500 °F), and quench in oil

Tempering. Temperature used depends on service conditions. Lower temperatures (see table below) are used when greater surface hardness and strength are required. Higher temperatures are used for greater toughness

No. 5-317: Effect of Tempering

Tempering temperature		
°F	°C	Rockwell "C"
As quenched	As quenched	56
300	149	56
350	177	55
400	204	54
450	232	53
500	260	53
550	288	52
600	316	50
700	371	46
800	427	44
900	482	40
1000	538	35
1100	593	31

25 mm (1 in.), section, oil quenched from 790 °C (1450 °F)

꞉RB-7

꞉hemical Composition. 1.10 C, 0.40 Mn, 0.30 Si, 14.00 Cr, 2.00 lo, 1.00V, 0.25 Cb

꞉haracteristics. A corrosion resistant, wear resistant, and secondary ardening, high temperature bearing steel, which has high heat treated ardness that is maintained at elevated temperatures

'orging. Preheat slowly to 815 to 870 °C (1500 to 1600 °F), then ıcrease furnace temperature to full heat of 1095 to 1120 °C (2005 to 2050 ⁼). Do not forge after temperature of forging stock drops below approxi- ıately 980 °C (1795 °F). Can be reheated as often as necessary. Slow cool ɔrgings to room temperature in dry ash, vermiculite, or in a furnace when ɔrging cooling. First set furnace at about 760 to 790 °C (1400 to 1455 °F), soak forging at this temperature until temperature of forging is uniform, then shut off heat, let forging cool in furnace. Annealing follows

Recommended Heat Treating Practice

Normalizing. Not recommended

Annealing. Two methods are available:

1. Pack parts in container, using clean, cast iron borings
2. Anneal in a controlled atmosphere furnace with a dew point of 1.5 to 8 °C (35 to 45 °F). Heat uniformly to 870 to 900 °C (1600 to 1650 °F), cool slowly in furnace to about 595 °C (1105 °F) at a rate not to exceed 6 °C (20 °F) per h, air cool to room temperature.

꞉RB-7: Effect of Tempering Temperatures

Tempering temperature		Rockwell C
°F	°C	Hardness
As quenched + refrigerated		64.0
300	149	63.5
400	204	61.0
500	260	59.5
600	316	58.0
700	371	58.0
800	427	58.0
900	482	60.5
1000	538	62.0
1100	593	53.5

arts were oil quenched from 1150 °C (2100 °F), refrigerated at −75 °C (−105 °F), and ːmpered 1 h at temperature. Source: Carpenter Technology Corporation

CRB-7: Elevated Temperature Hardness

Test temperature		Rockwell C
°F	°C	Hardness
Room temperature		62.5
500	260	59.0
600	316	58.5
700	371	58.0
800	427	57.0
900	482	56.0
1000	538	54.0

Hardnesses were measured on specimens heat treated as follows: salt quenched from 1150 °C (2100 °F) to 540 °C (1000 °F), equalized, then air cooled to room temperature, stress relieved at 150 °C (300 °F) 1 h, refrigerated at −75 °C (−105 °F), double tempered 2 + 2 h at 525 °C (975 °F). Source: Carpenter Technology Corporation

Average hardness of parts will be 241 HB

Hardening. Parts are treated in neutral salt baths or in controlled atmosphere furnaces. For the latter, a dew point of -12 °C (+10 °F) is suggested. For the furnace procedure, parts are preheated to 800 to 830 °C (1475 to 1525 °F), then transferred to a superheating furnace maintained at 1140 to 1155 °C (2085 to 2110 °F). Small parts may be oil quenched to room temperature. Preferred practice is to harden by quenching in molten salt at a temperature of 540 to 595 °C (1000 to 1100 °F), followed by air cooling to room temperature. Parts are then stress relief tempered at 150 °C (300 °F) for 1 h. For higher hardness and dimensional stability, parts are allowed to return to room temperature before tempering

Tempering. Double tempering is recommended for maximum hardness and dimensional stability. Parts are allowed to return to room temperature before tempering

Tool Steels

Introduction

Tool steels represent a small, but important segment of the total production of steel. These steels are made and processed to meet extremely high standards of quality control and are used principally for tools, dies, and components of mechanical devices that demand steels with special properties. Well over 100 different kinds of tool steels are produced at the present time, and if all the trade names were added together, the total would far exceed 100.

Tool steels vary in composition from plain carbon steels containing iron and up to 1.2% carbon with no significant amounts of alloying elements, to very highly alloyed grades, in which the total alloy content approaches 50%. Many tool steels are identical in composition to carbon and alloy steels that are produced in large tonnages. The differences lie in the small amount produced and the high level of quality control involved.

Classification of Tool Steels. Tool steels do not lend themselves to the type of classification used by the Society of Automotive Engineers (SAE) and the American Iron and Steel Institute (AISI) for low-alloy steels, because in these systems an entire series of steels is defined numerically, based upon a variation of carbon content alone. While some carbon tool steels and low-alloy tool steels are made in a wide range of carbon contents, most of the higher alloyed tool steels have a comparatively narrow carbon range making such a classification meaningless. Instead a mixed classification system is used with tool steels, in which some steels are grouped by use, others by composition or by certain mechanical properties, and still others by the method of heat treatment (precisely by the quenching technique). High-speed steels are grouped together because they have certain common properties, the water-hardening steels because they are hardened in a common manner, the hot work steels because they have certain common properties, and the high-carbon, high-chromium steels because they have similar compositions and similar applications.

The American Iron and Steel Institute System. The table at the end of this introduction includes compositions for most of the proprietary tool steels—Unified Numbering System (UNS) specifications are also given. Elements are listed in nominal amounts which may vary somewhat for different tool steel producers. When heat treating shops receive tools for heat treatment that are identified only by proprietary name, the AISI identification should be obtained before attempting to perform any heat treating operation. A number of grades have been deleted from the AISI list because they were no longer manufactured in significant quantities, and the steels listed in the table cover every conceivable tooling requirement. Statistics show that over 50% of the total tonnage of tool steels produced is confined to no more than about 12 or 15 of the compositions included in the Table.

The grouping of tool steels published by AISI has proved workable, and the nine main groups and their corresponding symbols are given as follows:

Name	Identifying symbol
Water-hardening tool steels	W
Shock-resisting tool steels	S
Oil-hardening cold work tool steels	O
Air-hardening, medium-alloy cold work tool steels	A
High-carbon, high-chromium cold work tool steels	D
Mold steels	P
Hot work tool steels, chromium, tungsten, and molybdenum	H
Tungsten high-speed tool steels	T
Molybdenum high-speed tool steels	M

Water-Hardening Tool Steels. The grades listed in the Table under the symbol W are essentially carbon steels and are among the least expensive of tool steels. They must be water quenched to attain the necessary hardness, and except in very small sizes, will harden with a hard case and a soft core. These steels may be used for a wide variety of tools, but they do have limitations. W steels are available in a range of carbon contents, and the selection of carbon content is based upon whether maximum toughness or maximum wear resistance is the more important. A lower carbon content provides maximum toughness. Although all W steels have relatively low hardenability, these grades are usually available as shallow, medium, or deep hardening, and this property is controlled by the manufacturer. Of the three compositions listed, W1 is the most extensively used.

Shock-Resisting Tool Steels. Steels are listed under the symbol S. As may be noted in the Table, the alloy content in these steels varies widely, resulting in a wide variation in hardenability among the grades. However, all S steels are intended for applications that require extreme toughness including punches, shear knives, and air-operated chisels. Grades S1 (tungsten bearing), and S5 (high silicon) are most widely used.

Oil-Hardening, Cold Work Tool Steels. These grades are listed in the table under the symbol O. As a group, the hardenability of these steels is much higher than that of the W grades; therefore, they can be hardened by quenching in oil. Grade O1 is by far the most popular of this group. A portion of the carbon in O6 is in the form of graphite, which allows better machinability, a factor in making intricate dies. In addition, the graphite particles in its microstructure provide a built-in lubricant, giving these steels a better die life for deep drawing operations. O7 is sometimes used for certain dies where it is essential to retain keen cutting edges because these steels have a higher carbon and the tungsten addition.

Air-Hardening, Medium-Alloy Cold Work Tool Steels. The cold work tool steels listed under the symbol A cover a wide range of carbon and alloy contents, but all have high hardenability and exhibit a high degree of dimensional stability in heat treatment. The low-carbon types, A8 and A9, offer greater shock resistance than the other steels in this group, but are lower in their wear resistance. Type A7, which has high carbon and vanadium contents, exhibits maximum abrasion resistance, but should be restricted to applications where toughness is not a prime consideration. As may be noted in the Table, A10 is also a graphitic steel, and it has properties similar to O6 except that A10 is higher in hardenability. Of the grades listed in this group, A2 is the most widely used.

High-Carbon, High-Chromium Cold Work Tool Steels. The cold work steels listed under the symbol D are all characterized by a high carbon content (1.5 to 2.5%) and a nominal 12.0% chromium content. Types containing molybdenum can be air hardened. All grades of this group have extremely high resistance to abrasive wear, which increases as the carbon and vanadium increase. Grade D7 is one of the most abrasion-resisting steels known, and it is often used for such rigorous applications as brick molds. However, the characteristics which provide its abrasion resistance make it very difficult to machine or grind. Grade D5, because of its cobalt addition, can be used for hot forming or shearing operations at temperatures up to 480 °C (895 °F). Of the five grades listed in this group, D2 is the most widely used.

Low-Alloy, Special-Purpose Tool Steels. The tool steels listed under the symbol L cover a wide range of alloy content and mechanical properties. They are widely used for die components and machinery parts. Both L6 and the lower carbon versions of L2 are often used for

lassification and approximate compositions of principal types of tool steels

SI	UNS No.	Identifying elements, % C	Mn	Si	Cr	V	W	Mo	Co	Ni
ater-hardening tool steels										
1	T72301	0.60-1.40(a)	...	...	...	...	...	...	...	...
2	T72302	0.60-1.40(a)	...	...	...	0.25	...	...	...	...
5	T72305	1.10	...	...	0.50	...	...	...	...	...
ock-resisting tool steels										
	T41901	0.50	...	...	1.50	...	2.50	...	...	...
	T41902	0.50	...	1.00	...	...	...	0.50	...	...
	T41905	0.55	0.80	2.00	...	...	...	0.40	...	...
	T41906	0.45	1.40	2.25	1.50	...	...	0.40	...	...
	T41907	0.50	...	...	3.25	...	...	1.40	...	...
il-hardening, cold work tool steels										
1	T31501	0.90	1.00	...	0.50	...	0.50	...	...	...
2	T31502	0.90	1.60	...	...	...	...	...	...	...
5(b)	T31506	1.45	0.80	1.00	...	...	...	0.25	...	...
7	T31507	1.20	...	...	0.75	...	1.75	...	...	...
ir-hardening, medium-alloy cold work tool steels										
2	T30102	1.00	...	...	5.00	...	...	1.00	...	...
3	T30103	1.25	...	...	5.00	1.00	...	1.00	...	...
4	T30104	1.00	2.00	...	1.00	...	...	1.00	...	...
5	T30106	0.70	2.00	...	1.00	...	...	1.25	...	...
7	T30107	2.25	...	...	5.25	4.75	1.00(c)	1.00	...	...
8	T30108	0.55	...	...	5.00	...	1.25	1.25	...	...
9	T30109	0.50	...	...	5.00	1.00	...	1.40	...	1.50
10(b)	T30110	1.35	1.80	1.25	...	...	...	1.50	...	1.80
igh-carbon, high-chromium cold work steels										
2	T30402	1.50	...	...	12.00	1.00	...	1.00	...	...
3	T30403	2.25	...	...	12.00	...	...	...	...	...
4	T30404	2.25	...	...	12.00	...	...	1.00	...	...
5	T30405	1.50	...	...	12.00	...	...	1.00	3.00	...
7	T30407	2.35	...	...	12.00	4.00	...	1.00	...	...
ow-alloy, special-purpose tool steels										
2	T61202	0.50-1.10(a)	...	...	1.00	0.20	...	...	...	...
6	T61206	0.70	...	...	0.75	...	...	0.25(c)	...	1.50
lold steels										
2	T51602	0.07	...	...	2.00	...	...	0.20	...	0.50
3	T51603	0.10	...	...	0.60	...	...	...	...	1.25
4	T51604	0.07	...	...	5.00	...	...	0.75	...	...
5	T51605	0.10	...	...	2.25	...	...	...	...	...
6	T51606	0.10	...	...	1.50	...	...	...	...	3.50
20	T51620	0.35	...	...	1.70	...	...	0.40	...	...
21	T51621	0.20	1.20 (Al)	...	...	...	...	...	...	4.00
hromium hot work tool steels										
I10	T20810	0.40	...	...	3.25	0.40	...	2.50	...	...
I11	T20811	0.35	...	...	5.00	0.40	...	1.50	...	...
I12	T20812	0.35	...	...	5.00	0.40	1.50	1.50	...	...
I13	T20813	0.35	...	...	5.00	1.00	...	1.50	...	...
I14	T20814	0.40	...	...	5.00	...	5.00	...	...	...
I19	T20819	0.40	...	...	4.25	2.00	4.25	...	4.25	...
ungsten hot work tool steels										
I21	T20821	0.35	...	...	3.50	...	9.00	...	...	...
I22	T20822	0.35	...	...	2.00	...	11.00	...	...	...
I23	T20823	0.30	...	...	12.00	...	12.00	...	...	...
I24	T20824	0.45	...	...	3.00	...	15.00	...	...	...
I25	T20825	0.25	...	...	4.00	...	15.00	...	...	...
I26	T20826	0.50	...	...	4.00	1.00	18.00	...	...	...
lolybdenum hot work tool steel										
I42	T20842	0.60	...	...	4.00	2.00	6.00	5.00	...	...
ungsten high-speed tool steels										
[1	T12001	0.75(a)	...	...	4.00	1.00	18.00	...	...	...
[2	T12002	0.80	...	...	4.00	2.00	18.00	...	...	...

(continued)

a) Available with different carbon contents. (b) Contains graphite. (c) Optional

Classification and approximate compositions of principal types of tool steels (continued)

AISI	UNS No.	Identifying elements, % C	Mn	Si	Cr	V	W	Mo	Co	Ni
Tungsten high-speed tool steels										
T4	T12004	0.75	...	...	4.00	1.00	18.00	...	5.00	...
T5	T12005	0.80	...	...	4.00	2.00	18.00	...	8.00	...
T6	T12006	0.80	...	...	4.50	1.50	20.00	...	12.00	...
T8	T12008	0.75	...	...	4.00	2.00	14.00	...	5.00	...
T15	T12015	1.50	...	...	4.00	5.00	12.00	...	5.00	...
Molybdenum high-speed tool steels										
M1	T11301	0.80(a)	...	...	4.00	1.00	1.50	8.00	...	...
M2	T11302	0.85-1.00(a)	...	...	4.00	2.00	6.00	5.00	...	...
M3, class 1	T11313	1.05	...	...	4.00	2.40	6.00	5.00	...	...
M3, class 2	T11323	1.20	...	...	4.00	3.00	6.00	5.00	...	...
M4	T11304	1.30	...	...	4.00	4.00	5.50	4.50	...	...
M6	T11306	0.80	...	...	4.00	2.00	4.00	5.00	12.00	...
M7	T11307	1.00	...	...	4.00	2.00	1.75	8.75	...	...
M10	T11310	0.85-1.00(a)	...	...	4.00	2.00	...	8.00	...	...
M30	T11330	0.80	...	...	4.00	1.25	2.00	8.00	5.00	...
M33	T11333	0.90	...	...	4.00	1.15	1.50	9.50	8.00	...
M34	T11334	0.90	...	...	4.00	2.00	2.00	8.00	8.00	...
M35	T11335	0.82-0.88	0.15-0.40	0.20-0.45	3.75-4.50	1.75-2.20	5.50-6.75	...	4.50-5.50	0.30 max
M36	T11336	0.80	...	...	4.00	2.00	6.00	5.00	8.00	...
Ultrahard high-speed tool steels										
M41	T11341	1.10	...	...	4.25	2.00	6.75	3.75	5.00	...
M42	T11342	1.10	...	...	3.75	1.15	1.50	9.50	8.00	...
M43	T11343	1.20	...	...	3.75	1.60	2.75	8.00	8.25	...
M44	T11344	1.15	...	...	4.25	2.00	5.25	6.25	12.00	...
M46	T11346	1.25	...	...	4.00	3.20	2.00	8.25	8.25	...
M47	T11347	1.10	...	...	3.75	1.25	1.50	9.50	5.00	...
M48	T11348	1.42-1.52	0.15-0.40	0.15-0.40	3.50-4.00	2.75-3.25	9.50-10.50	0.15-0.40	8.00-10.00	0.30 max
M50	T11350	0.78-0.88	0.15-0.45	0.20-0.60	3.75-4.50	0.80-1.25	...	3.90-4.75	...	0.30 max
M52	T11352	0.85-0.95	0.15-0.45	0.20-0.60	3.50-4.30	1.65-2.25	0.75-1.50	4.00-4.90	...	0.30 max
M62	T11362	1.25-1.35	0.15-0.40	0.15-0.40	3.50-4.00	1.80-2.00	5.75-6.50	10.00-11.00	...	0.30 max

(a) Available with different carbon contents. (b) Contains graphite. (c) Optional

applications requiring extreme toughness including punches and heading tools.

Mold Steels. Tool steels listed under the symbol P are generally intended for mold applications. Types P2 and P6 are low in carbon content and are usually supplied at low hardness to facilitate cold hubbing of the impressions. They are then carburized to develop the required surface properties for injection and compression molds for plastics.

Types P20 and P21 are usually supplied in the pre-hardened condition, to allow the cavity to be machined and the mold to be placed directly in service. These grades may be used for plastic molds, zinc die casting dies, and holder blocks.

Hot Work Steels. Hot work steels are divided into three groups: chromium, tungsten, and molybdenum.

Of the grades of chromium hot work steels listed in the Table, grades H11 and H13 are the most widely used. Both of them are also used for nontooling applications, notably in the aerospace industry. Principal tooling applications include forging dies and die inserts, blades for hot shearing, and dies for die casting of aluminum alloys. Grades H14 and H19 are sometimes used for applications where greater heat resistance is required, including dies for die casting brass.

The tungsten types are intended for hot work applications where resistance to the softening effect of elevated temperature is of greatest importance, and a lesser degree of toughness can be tolerated. Of the grades listed in the Table, H21 and H26 are most often used. Die casting dies for the copper-base alloys and hot extrusion tools are typical examples of their applications.

The molybdenum types are low-carbon modifications of molybdenum high-speed steels. They offer excellent resistance to the softening effect of elevated temperature, but similar to the tungsten types, should be restricted to those applications where less ductility is acceptable. These steels are not readily available except on a mill delivery basis.

High-Speed Steels. The high-speed steels are divided into three groups: (a) those bearing the symbol T where tungsten is the major alloying element; (b) those bearing the symbol M indicating that molybdenum is the principal alloying element; (c) a group of more highly alloyed steels that are capable of attaining unusually high hardness values.

T1 was one of the original high-speed steels, although all tungsten grades are used to a limited extent because of the cost and questionable availability of tungsten. Of the T steels, general purpose T1 and high-vanadium-cobalt T15 are most commonly used. T15 is used for cutting tools that are exposed to extremely rigorous heat or abrasion in service.

The M tool steels generally are considered to have molybdenum as the principal alloying element, although several contain an equal or a slightly greater amount of such elements as tungsten or cobalt. Types with higher carbon and vanadium contents offer improved abrasion resistance, but machinability and grindability may be adversely affected. The series beginning with M41 is characterized by the capability of attaining exceptionally high hardness in heat treatment, reaching hardnesses as high as Rockwell C. In addition to being used for cutting tools, some of the M high-speed steels are successfully used for such cold work applications as cold header die inserts, thread rolling dies, and blanking dies. For such applications, the high-speed steels are hardened from a lower temperature than that used for cutting tools to increase toughness.

Water-Hardening Tool Steels (W Series)

ntroduction

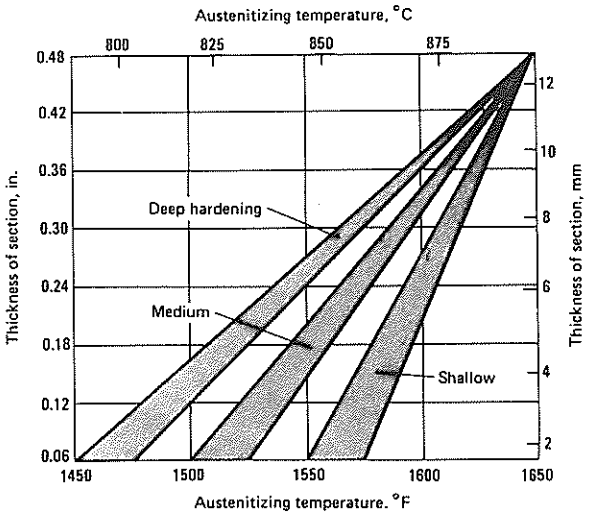
The water-hardening tool steels considered here (W1, W2, and W5) are ;entially carbon steels and are among the least expensive tool steels. As :lass, these steels are relatively low in hardenability, although they are ›itrarily classified and available as shallow-hardening, medium-harden- ;, and deep-hardening types. Except in very small sizes, W steels will rden with a hard case and a soft core. Their low hardenability is fre- ently an advantage, because it allows tough core properties in combina- n with high surface hardness. They are available in a range of carbon ntent, allowing for maximum toughness with lower carbon content or ıximum wear resistance with higher carbon content, depending on ınned use.

Water-hardening tool steels are most commonly hardened by quench- ; in water or brine. However, thin sections may be hardened suitably by quenching with less distortion and danger of cracking than if the :tions were quenched in water or brine. In general, these steels are not rmalized except after forging or before reheating treatment, for refining : grain and producing a more uniform structure. Parts should be protected ainst decarburization during air cooling.

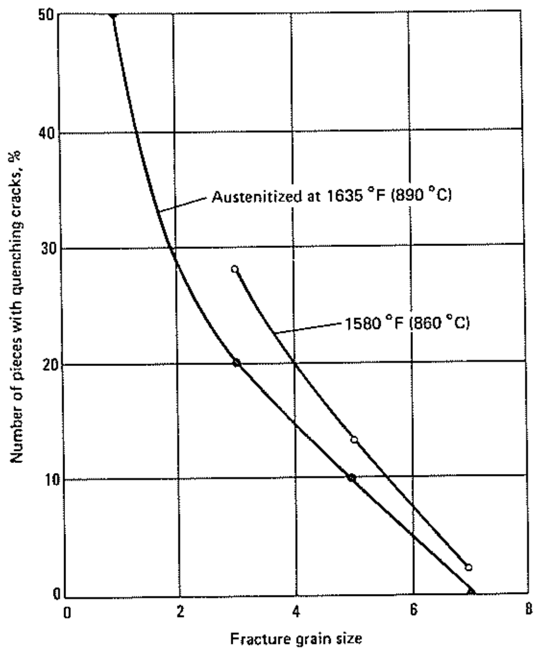
These steels are received from the supplier in the annealed condition, d further annealing is generally not required. Stress relieving prior to hardening is sometimes employed to minimize distortion and cracking, particularly when tools are complex or have been severely cold worked. Similarly, preheating prior to austenitizing is unusual except for very large tools or those with intricate cross sections.

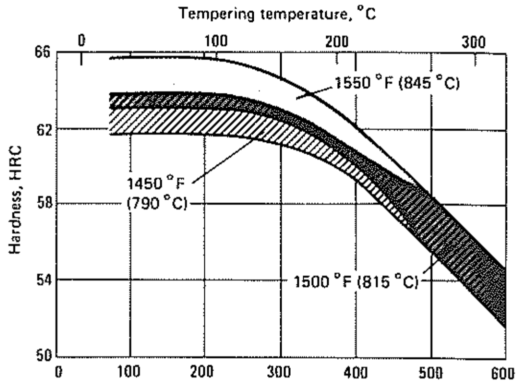
To produce maximum depth of hardness in water-hardening tool steels, it is essential that they be quenched as rapidly as possible. In most instances, water or a brine solution consisting of 10 wt % NaCl in water is used. For an even faster quench, an iced brine solution may be used. These steels should be tempered immediately after hardening, preferably before they reach room temperature. Salt baths, oil baths, and air furnaces are all satisfactory for tempering. However, working temperatures for both oil and salt are limited; the minimum for salt is approximately 165 °C (330 °F), and the maximum for oil is approximately 205 °C (400 °F). Tools should be placed in a warm furnace of 94 to 120 °C (200 to 250 °F) and then brought to the tempering temperature with the furnace. The resistance to fracture by impact initially increases with tempering temperature to approximately 180 °C (355 °F) but falls off rapidly to a minimum at approximately 260 °C (500 °F). Double tempering may be required to temper any martensite that may have formed from retained austenite during cooling in the first tempering cycle.

Vater-Hardening Tool Steels: Section Thickness vs Mininum Hardness. Oil quenched to 60 HRC

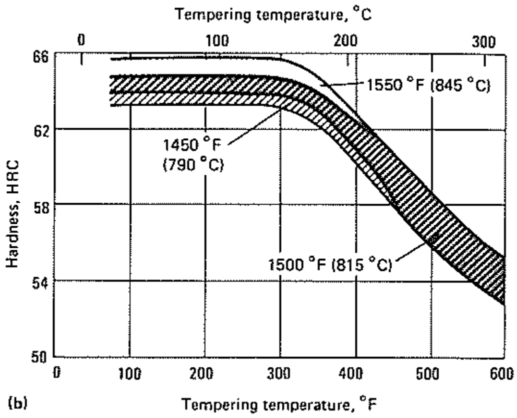


Water-Hardening Tool Steels: Fracture Grain Size vs Quench Cracking

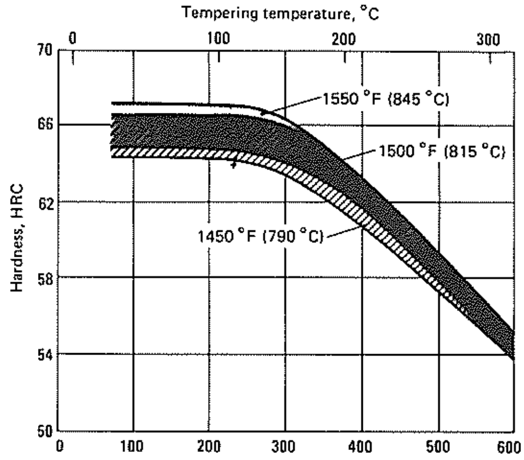




(a)

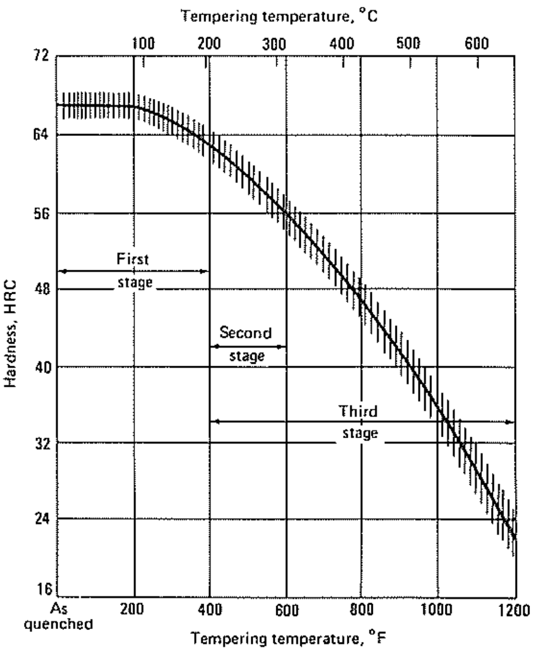


(b)



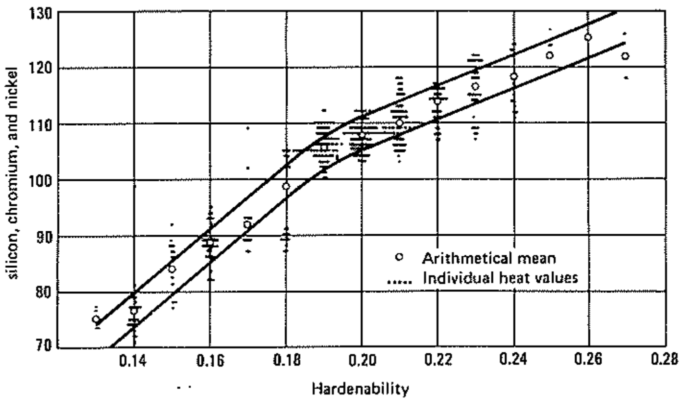
(c)

Water-Hardening Tool Steels: Hardness vs Tempering Temperature. Specimens held for 1 h at the tempering temperature in a recirculating-air furnace. Cooled in air to room temperature. Data represent 20 25 mm (1 in.) diam specimens for each steel. Each quenched from temperatures indicated. (a) Shallow hardening: 0.90 to 1.00 C, 0.18 to 0.22 Mn, 0.20 to 0.22 Si, 0.18 to 0.22 V. (b) Medium hardening: 0.90 to 1.00 C, 0.25 Mn, 0.25 Si, no alloying elements. (c) Deep hardening: 0.90 to 1.00 C, 0.30 to 0.35 Mn, 0.20 to 0.25 Si, 0.23 to 0.27 Cr

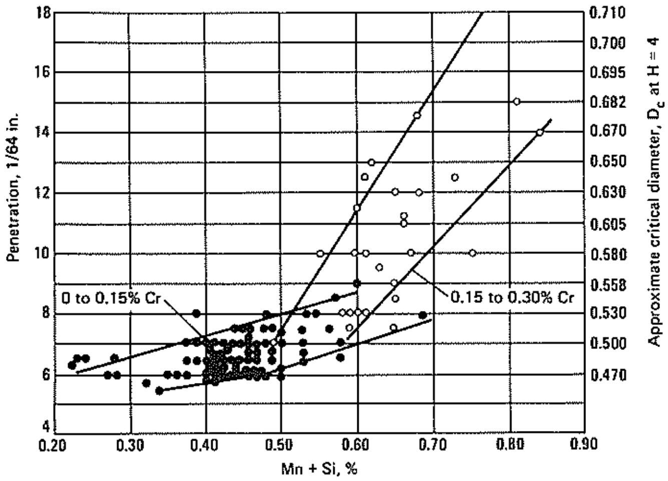


Water-Hardening Tool Steels: Hardness vs Tempering Temperature. 1% C. Size: 25 mm (1 in.) round by 51 mm (2 in.) long. Valid for tempering times from ½ to 2 h. Quench temperature: 790 °C (1455 °F) in water. **First stage:** The decomposition of martensite into low-carbon martensite (about 0.25 C) and epsilon carbide ($Fe_{2.4}C$). Epsilon carbide precipitates in the form of film at subgrains, 4 to 8 μin. in diam in the martensite. In steels containing more than 0.8 C, the early part of the first stage reaction results in a slight increase in hardness; however, the later portion of this stage is accompanied by a gradual decrease of hardness. Specific volume decreases during this stage. **Second stage:** Decomposition of retained austenite to bainite takes place over the temperature range from approximately 205 to 315 °C (400 to 600 °F). Hardness continues to decrease during this stage, while specific volume increases. **Third stage:** Epsilon carbide and low-carbon martensite (0.25 C) react to form ferrite (body-centered cubic) plus cementite. This process is accompanied by softening. Even after the complete disappearance of epsilon carbide, cementite continues to precipitate, depleting the ferritic matrix of carbon and resulting in further softening. Coalescence of cementite particles also contributes to this softening.

Nater-Hardening Tool Steels: Alloy Content vs Hardenability. Effect of total manganese, silicon, chromium, and nickel contents on the hardenability of 1 C steels quenched in brine from 790 °C 1455 °F) for 1 h at temperature. Hardenability expressed as lepth of penetration in inches for 25 mm (1 in.) round bars



Water-Hardening Tool Steels: Manganese Plus Silicon Content vs Penetration of Hardness. 19 mm (3/4 in.) round bars containing 1 to 1.10 C, 0.02 to 0.04 Ni, 0.010 to 0.015 S, 0.012 to 0.016 P. Quenched in brine from 790 °C (1455 °F). Source: Teledyne VASCO



'ater-Hardening Tool Steels: Effect of 1% Additions of lloying Elements on Hardenability

elative hardenability factors for alloy additions to 1% carbon tool eel, austenitized at normal temperatures with incomplete carbide lution. Treatment: 40 min at 870 °C (1600 °F) oil quench; 12 min at 0 °C (1450 °F), agitated brine quench (H = 5.0)

eel	Penetration in 1¼-in. round, 1/64 in.	Corresponding D_I	Multiplying factor for 1% addition	Fracture grain size
6 carbon (base)	5½	0.67	...	9
6 silicon	18	1.16	2.30	9
6 manganese	16	1.09	2.17	8¾
6 tungsten	4½	0.62	0.93	9¾
6 chromium	16	1.09	1.63	10
6 molybdenum	22	1.45	2.16	9¾
6 nickel	10	0.89	1.33	9¼

Water-Hardening Tool Steels: Composition vs Calculated Hardenability

Heat No.	Composition, % C	Mn	Si	Cr	Ni	Mo	Critical diameter for brine quench, in. (H = 5.0) Calculated	Observed approx
1(a)	1.02	0.09	0.03	0.05	0.02	0.03	0.15	<0.5
2	1.03	0.28	0.15	0.04	0.02	nil	0.35	<0.5
3	1.07	0.15	0.09	0.05	0.10	nil	0.20	<0.5
4	1.07	0.34	0.22	0.10	0.03	nil	0.45	<0.5
5	1.00	0.24	0.17	0.09	0.07	0.01	0.45	0.5
6	1.09	0.26	0.26	0.17	0.20	nil	0.45	0.5
7	1.04	0.29	0.16	0.15	0.14	0.03	0.50	0.6
8	1.00	0.31	0.28	0.13	0.07	0.03	0.60	0.7
9	0.97	0.46	0.29	0.17	0.05	nil	0.80	0.8
10	0.99	0.36	0.31	0.15	0.17	0.03	0.75	0.8
11	0.98	0.50	0.37	0.23	0.12	0.03	0.90	1.0
12	0.94	0.45	0.36	0.21	0.16	nil	1.0	1.0

(a) 0.03% vanadium

V1

hemical Composition. **AISI:** Nominal. 0.60 to 1.40 C, 1.50 Cr, .50 W. **AISI/UNS (T72301):** 0.70 to 1.50 C*, 0.10 to 0.40 Mn, 0.10 to .40 Si, 0.20 Ni max, 0.15 Cr max, 0.10 Mo max, 0.10 V max, 0.50 W max specified carbon ranges are designated by suffix numbers

imilar Steels (U.S. and/or Foreign). ASTM A686 (W-1); SAE 137 (W108), (W109), (W110), (W112), J438 (W108), (W109), (W110), V112); (Ger.) DIN 1.1525, 1.1545, 1.1625, 1.1654, 1.1663, 1.1673, .1744, 1.1750, 1.1820, 1.1830; (Fr.) AFNOR A35-590 1102 Y(1) 105, 35-590 1103 Y (1) 90, A35-590 1104 Y (1) 80, A35-590 1105 Y (1) 70, A35-590 1200 Y (2) 140, A35-590 1201 Y (2) 120, A36-596 Y75, A35-596 Y90; (Jap.) JIS G4401 SK 1, G4401 SK 2, G4401 SK 3, G4401 SK 4, G4401 SK 5, G4401 SK 6, G4401 SK 7, G4401 SKC 3; (U.K.) B.S. 4659 (SA W1), 4559 BW1A, 4659 BW1B, 4659 BW1C

Characteristics. Capable of hardening to high surface hardness and soft core which is useful in some shock applications. Low cost tool steels with fair to good wear resistance as carbon content increases. Water quenched with poor dimensional stability. Use limited to fairly uniform sections with minimum amount of stress raisers or quench cracking can occur

Forging. Start forging at 980 to 1065 °C (1795 to 1950 °F). Use upper temperature of range for 0.60 to 1.25 C, and lower temperature of range for 1.25 to 1.50 C. Do not forge below 815 °C (1500 °F)

Recommended Heat Treating Practice

Normalizing. For 0.60 to 0.75 C, heat to 815 °C (1500 °F); for 0.75 to 0.90 C, 790 °C (1455 °F); for 0.90 to 1.10 C, 870 °C (1600 °F); for 1.10 to 1.50 C, 870 to 925 °C (1600 to 1695 °F). After uniform through heating, holding time varies from approximately 15 min for small sections to approximately 1 h for large sections. Work is cooled from temperature in still air

Annealing. For 0.60 to 0.90 C, heat to 740 to 760 °C (1365 to 1400 °F); for 0.90 to 1.50 C, heat to 760 to 790 °C (1400 to 1455 °F). Use lower limit for small sections and upper limit for large sections. Holding time varies. Sections up to 25 mm (1 in.) require at least 20 min; 203 mm (8 in.) sections require 2 ½ h. For pack annealing, hold for 1 h per inch of cross section. Cool to 540 °C (1000 °F) at a rate not to exceed 28 °C (50 °F) per h, after which controlled cooling is not necessary. Hardness after annealing, 156 to 201 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

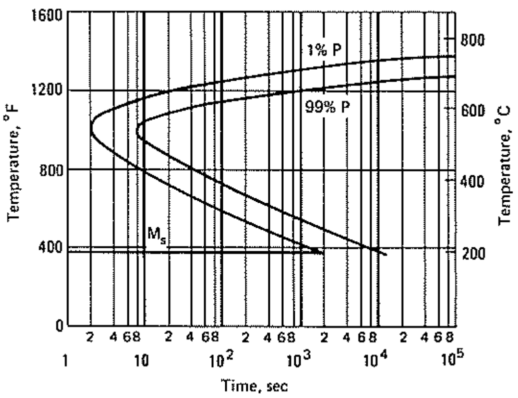
Hardening. Preheating is necessary only for intricate sections or large sections where temperatures would differ appreciably from surface to center. Heat slowly to 760 to 845 °C (1400 to 1555 °F), using the upper end of the temperature range for low carbon contents and lower end of the temperature range for high carbon contents. Using temperatures at the upper end of the temperature range will increase hardenability. Austenitized for 10 min for small sections to 30 min for large sections. Quench in agitated water or brine. A spray directed into a recessed configuration, such as a die cavity, or at the working end of a punch is often used to obtain maximum hardness and residual compressive stress in a desired area. Approximate quenched hardness, 65 to 68 HRC

Tempering. Temper immediately after hardening, preferably before tool reaches room temperature; approximately 50 °C (120 °F) is optimum. Allowing quenched tools to stand at room temperature or placing them in a cold furnace will lead to cracking. Therefore, place tools in a warm furnace at 94 to 120 °C (200 to 250 °F) immediately after quenching and bring to tempering temperature with the furnace. Except for large pieces, work will heat at approximately the same rate as the furnace. Temper at temperatures not lower than 175 °C (345 °F) and up to approximately 345 °C (655 °F). One hour at temperature is usually adequate; additional soaking time will further lower hardness. A double temper may be required. The low temperatures used in tempering eliminate the need for atmosphere control. Approximate tempered hardness, 50 to 64 HRC

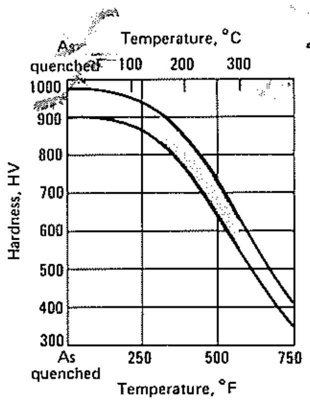
Recommended Processing Sequence

- Normalize
- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Temper (double temper, optional)
- Final grind to size

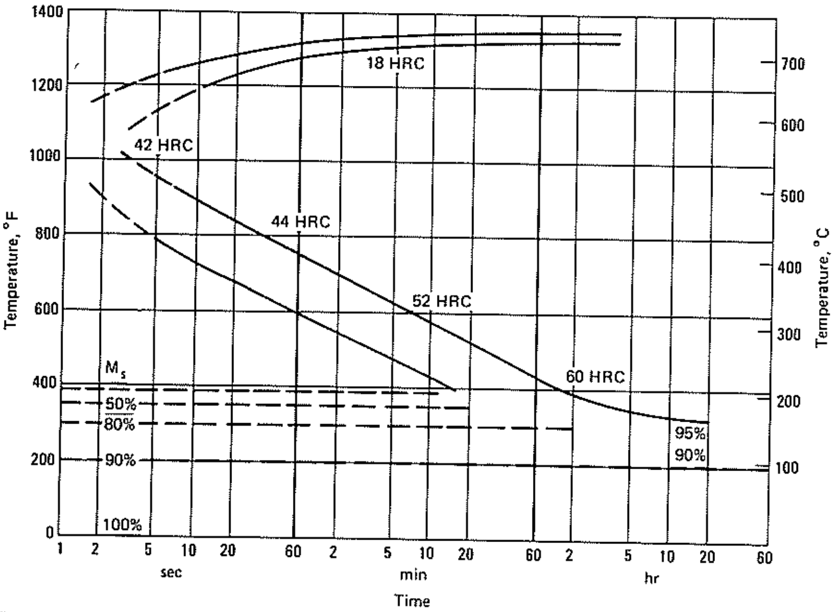
W1: Isothermal Transformation Diagram. Source: British Iron and Steel Institute



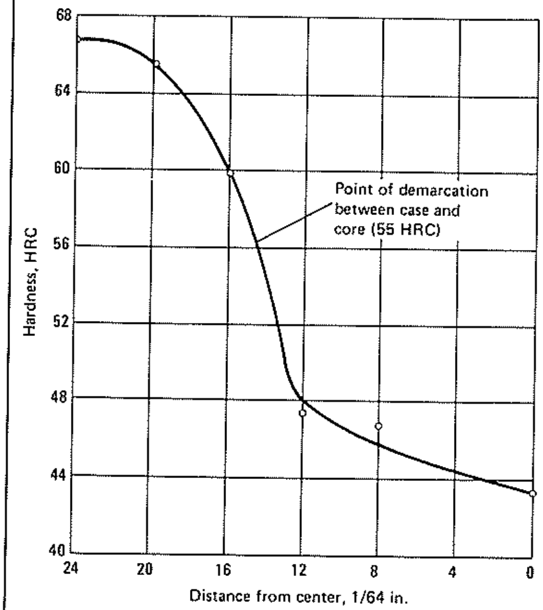
W1: Hardness vs Tempering Temperature. Source: British Steel



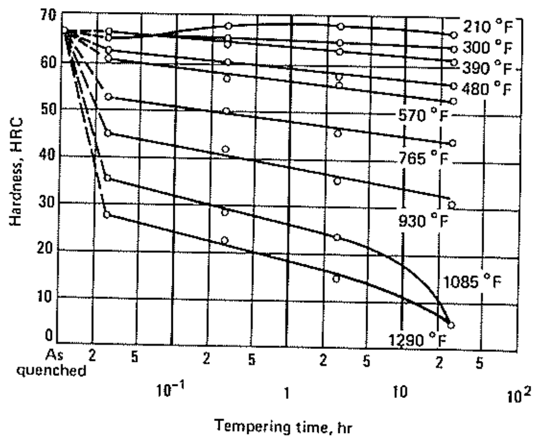
W1: Isothermal Transformation Diagram. Composition: 1.14 C, 0.22 Mn, 0.61 Si. Austenitized at 790 °C (1455 °F)



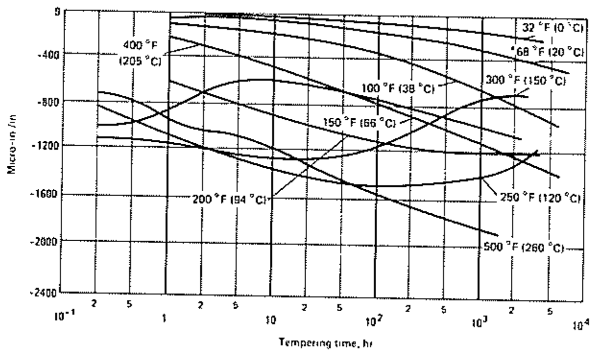
W1: Case and Core Hardness. Composition: 1.06 C, 0.36 Mn, 0.27 Si, 0.01 S, 0.015 P, 0.05 Cr. 19 mm (3/4 in.) round bar, brine quenched from 815 °C (1500 °F). Pretreated by oil quenching after 40 min at 870 °C (1600 °F). Source: Teledyne VASCO



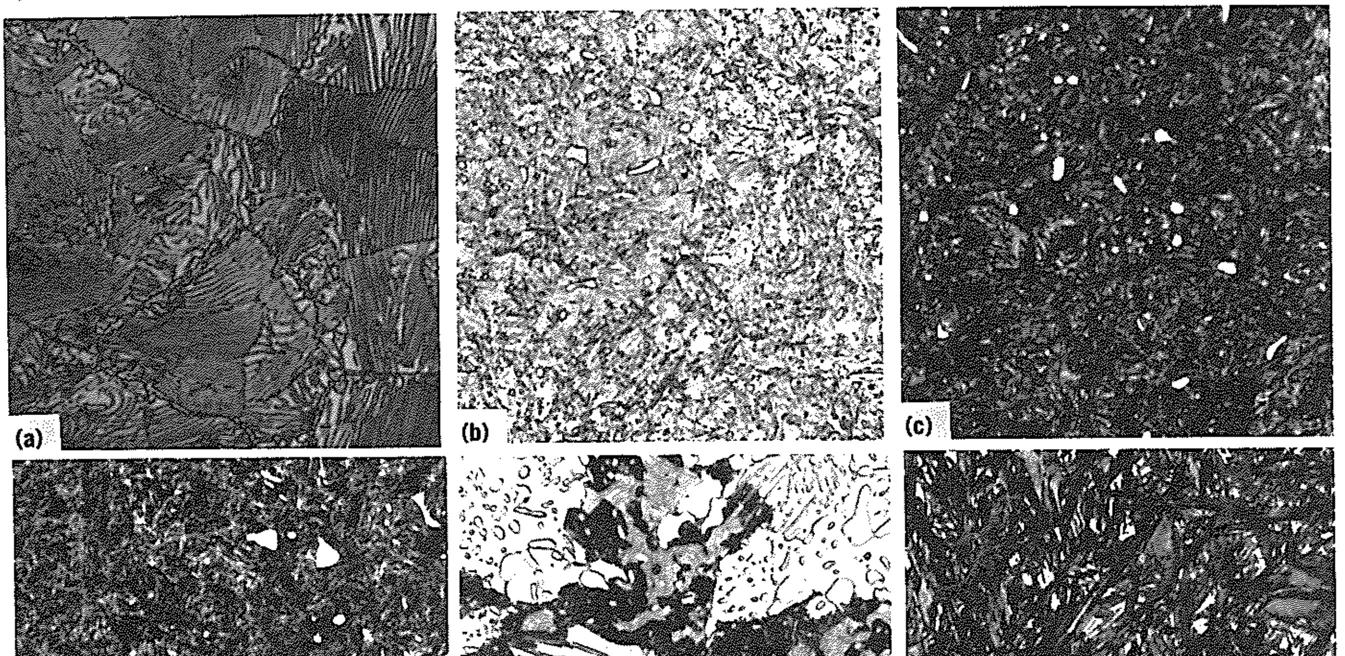
W1: Hardness vs Tempering Temperature. Composition: 0.98 C, 0.30 Mn, 0.30 Si. Specimens hardened by brine quenching after 1 h at 870 °C (1600 °F) and cooling to -71 °C (-95 °F) in dry ice and alcohol



W1: Length Changes. Contains 1.07 C. Tempering time is considered to begin 1 1/2 h after hardening



W1: Microstructures. (a) 4% picral, 1000×. 1.10 C, 0.30 Mn. Normalized by austenitizing at 925 °C (1695 °F) and air cooling. 227 HB. Lamellar pearlite with thin envelopes of cementite at grain boundaries. (b) 3% nital, 1000×. 0.94 C, 0.21 Mn. Austenitized at 790 °C (1455 °F) and quenched in brine (not tempered). 65 HRC. Largely untempered martensite with some undissolved carbide particles. (c) 3% nital, 1000×. Same steel and heat treatment as (b), after tempering at 165 °C (330 °F). 64 HRC. Tempered martensite (dark background) with a few spheroidal particles of carbide (white dots). (d) 3% nital, 1000×. Same steel and heat treatment as (b), after tempering at 260 °C (500 °F). 58 HRC. Gray constituent is tempered martensite. Its appearance has changed from (**c**). White spots are carbide particles. (e) 3% nital, 1000×. Same steel as (b), austenitized at 760 °C (1400 °F), Quenched in brine, tempered at 160 °C (320 °F). 44 HRC. Mixture of pearlite (dark), tempered martensite (gray), and ferrite indicates underheating. (f) 3% nital, 1000×. Same steel as (b), austenitized at 855 °C (1570 °F), quenched in brine, tempered at 160 °C (320 °F). Coarse-grained tempered martensite and retained austenite (white), the result of overheating. (g) 2% nital, 1000×. Case of hardened W1, 1.05 C, 0.31 Mn. Austenitized at 800 °C (1475 °F), water quenched, and tempered at 175 °C (345 °F). 64 HRC. Spheroidal cementite in tempered martensite. (h) 2% nital, 1000×. Transition zone between case and core of hardened W1, heat treated as for (g). 47 HRC. Fine spheroidal cementite in a matrix of martensite (light) and pearlite (dark). (j) 2% nital, 1000×. Core of hardened W1, heat treated as for (g). 36 HRC. Fine spheroidal particles of cementite in a matrix of fine pearlite (dark-etching constituent)



V2

ıemical Composition. **AISI:** Nominal. 0.60 to 1.40 C, 0.25 V. **SI/UNS (T72302):** 0.85 to 1.50 *C, 0.10 to 0.40 Mn, 0.10 to 0.40 Si, !0 Ni max, 0.15 Cr max, 0.10 Mo max, 0.15 to 0.35 V, 0.15 W max
* specified carbon ranges are designated by suffix numbers

milar Steels (U.S. and/or Foreign). ASTM A686 (W-2); FED Q-T-580 (W-2); SAE J437 (W209), (W210), J438 (W209), (W210); er.) DIN 1.1645, 1.2206, 1.2833; (Fr.) AFNOR A35-590 1161 Y 120 V, 35-590 1162 Y 105 V, A35-590 1163 Y 90 V, A35-590 1164 Y 75 V, 35-590 2130 Y 100 C 2, A35-590 1232 Y 105 C; (Jap.) JIS G4404 SKS , G4404 SKS 44; (U.K.) B.S. 4659 BW 2; (Swed.) SS (USA W2A), (USA 2B), (USA W2C)

ıaracteristics. Capable of hardening to high surface hardness and ft core which is useful in some shock applications. Low cost tool steels th fair to good wear resistance as carbon content increases. Water enched with poor dimensional stability. Use limited to fairly uniform :tions with minimum amount of stress raisers or quench cracking can cur

ɔrging. Start forging at 980 to 1065 °C (1795 to 1950 °F). Use upper nperature of range for 0.60 to 1.25 C, and lower temperature of range for !5 to 1.50 C. Do not forge below 815 °C (1500 °F)

ecommended Heat Treating Practice

ɔrmalizing. For 0.60 to 0.75 C, heat to 815 °C (1500 °F); for 0.75 to)0 C, 790 °C (1455 °F); for 0.90 to 1.10 C, 870 °C (1600 °F); for 1.10 to 50 C, 870 to 925 °C (1600 to 1695 °F). After uniform through heating, lding time varies from approximately 15 min for small sections to proximately 1 h for large sections. Work is cooled from temperature in ll air

ınealing. For 0.60 to 0.90 C, heat to 740 to 760 °C (1360 to 1400 °F); · 0.90 to 1.50 C, heat to 760 to 790 °C (1400 to 1455 °F). Use lower limit · small sections and upper limit for large sections. Holding time varies. ctions up to 25 mm (1 in.) require at least 20 min; 203 mm (8 in.) sections quire 2 ½ h. For pack annealing, hold for 1 h per inch of cross section. ɔol to 540 °C (1000 °F) at a rate not to exceed 28 °C (50 °F) per h, after ıich controlled cooling is not necessary. Hardness after annealing, 156 to 1 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

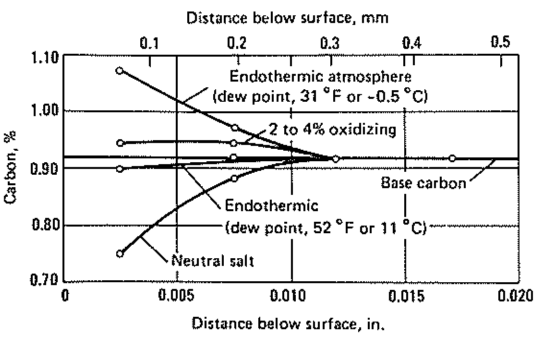
Hardening. Preheating is necessary only for intricate sections or large sections where temperatures would differ appreciably from surface to center. Heat slowly to 760 to 845 °C (1400 to 1555 °F), using the upper end of the temperature range for low carbon contents and lower end of the temperature range for high carbon contents. Using temperatures at the upper end of the temperature range will increase hardenability. Austenitized for 10 min for small sections to 30 min for large sections. Quench in agitated water or brine. A spray directed into a recessed configuration, such as a die cavity or at the working end of a punch, is often used to obtain maximum hardness and residual compressive stress in a desired area. Approximate quenched hardness, 65 to 68 HRC

Tempering. Temper immediately after hardening, preferably before tool reaches room temperature; approximately 50 °C (120 °F) is optimum. Allowing quenched tools to stand at room temperature or placing them in a cold furnace will lead to cracking. Therefore, place tools in a warm furnace at 94 to 120 °C (200 to 250 °F) immediately after quenching and bring to tempering temperature with the furnace. Except for large pieces, work will heat at approximately the same rate as the furnace. Temper at temperatures not lower than 175 °C (345 °F) and up to approximately 345 °C (655 °F). One hour at temperature is usually adequate; additional soaking time will further lower hardness. A double temper may be required. The low temperatures used in tempering eliminate the need for atmosphere control. Approximate tempered hardness, 50 to 64 HRC

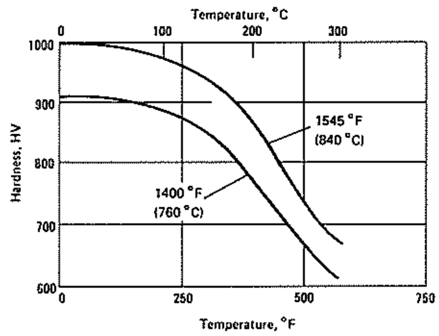
Recommended Processing Sequence

- Normalize
- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Temper (double temper, optional)
- Final grind to size

V2: Effect of Furnace Atmosphere on Surface Carbon Content. Specimens heated at 790 °C (1455 °F) for 1 h, quenched in ɔrine, annealed in lead at 705 °C (1300 °F), and machined in).127 mm (0.005 in.) cuts for analysis



W2: Hardness vs Time and Tempering Temperature. Tempering band for W2 and W5, containing 0.90 to 1.10 C. Austenitized at 760 °C (1400 °F) and 840 °C (1545 °F). Shaded portion indicates optimum tempering range. Source: British Steel



W5

:hemical Composition. **AISI:** Nominal. 1.10 C, 0.50 Cr. **.ISI/UNS (T72305):** 1.05 to 1.15 *C, 0.10 to 0.40 Mn, 0.10 to 0.40 Si, .20 Ni max, 0.40 to 0.60 Cr, 0.10 Mo max, 0.10 V max, 0.15 W max

* specified carbon ranges are designated by suffix numbers

;imilar Steels (U.S. and/or Foreign). ASTM A686 (W-5)

:haracteristics. Capable of hardening to high surface hardness and oft core which is useful in some shock applications. Low cost tool steels 'ith fair to good wear resistance as carbon content increases. Water uenched with poor dimensional stability. Use limited to fairly uniform ections with minimum amount of stress raisers or quench cracking can ccur

'orging. Start forging at 980 to 1065 °C (1795 to 1950 °F). Use upper emperature of range for 0.60 to 1.25 C, and lower temperature of range for .25 to 1.50 C. Do not forge below 815 °C (1500 °F)

Recommended Heat Treating Practice

Iormalizing. For 0.60 to 0.75 C, heat to 815 °C (1500 °F); for 0.75 to .90 C, 790 °C (1455 °F); for 0.90 to 1.10 C, 870 °C (1600 °F); for 1.10 to .50 C, 870 to 925 °C (1600 to 1695 °F). After uniform through heating, olding time varies from approximately 15 min for small sections to pproximately 1 h for large sections. Work is cooled from temperature in till air

\nnealing. For 0.60 to 0.90 C, heat to 740 to 760 °C (1365 to 1400 °F); or 0.90 to 1.50 C, heat to 760 to 790 °C (1400 to 1455 °F). Use lower limit or small sections and upper limit for large sections. Holding time varies. ;ections up to 25 mm (1 in.) require at least 20 min; 203 mm (8 in.) sections equire 2 ½ h. For pack annealing, hold for 1 h per inch of cross section. :ool to 540 °C (1000 °F) at a rate not to exceed 28 °C (50 °F) per h, after vhich controlled cooling is not necessary. Hardness after annealing, 156 to :01 HB

;tress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) nd hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Preheating is necessary only for intricate sections or large sections where temperatures would differ appreciably from surface to center. Heat slowly to 760 to 845 °C (1400 to 1555 °F), using the upper end of the temperature range for low carbon contents and lower end of the temperature range for high carbon contents. Using temperatures at the upper end of the temperature range will increase hardenability. Austenitized for 10 min for small sections to 30 min for large sections. Quench in agitated water or brine. A spray directed into a recessed configuration, such as a die cavity or at the working end of a punch, is often used to obtain maximum hardness and residual compressive stress in a desired area. Approximate quenched hardness, 65 to 68 HRC

Tempering. Temper immediately after hardening, preferably before tool reaches room temperature; approximately 50 °C (120 °F) is optimum. Allowing quenched tools to stand at room temperature or placing them in a cold furnace will lead to cracking. Therefore, place tools in a warm furnace at 94 to 120 °C (200 to 250 °F) immediately after quenching and bring to tempering temperature with the furnace. Except for large pieces, work will heat at approximately the same rate as the furnace. Temper at temperatures not lower than 175 °C (345 °F) and up to approximately 345 °C (655 °F). One hour at temperature is usually adequate; additional soaking time will further lower hardness. A double temper may be required. The low temperatures used in tempering eliminate the need for atmosphere control. Approximate tempered hardness, 50 to 64 HRC

Recommended Processing Sequence

- Normalize
- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Temper (double temper, optional)
- Final grind to size

Shock-Resisting Tool Steels (S Series)

ntroduction

The principal steels in this group (S1, S2, S5, S6, and S7) may be ›tained with several variations in composition for specific applications. ıese variations may require modifications in heat treating which may be ›tained from the steel supplier or determined by actual tests for those :els not described below. All of these steels contain from 0.40 to 0.60% rbon to ensure a sufficiently high hardness without impairing impact :ength and shock resistance.

The S steels are not normalized and, when annealed, the recommended ınealing temperature must not be exceeded. This is especially important hen annealing those steels with high silicon content. The high-silicon :els are susceptible to graphitization and decarburization, with graphitition occurring at excessively high annealing temperatures. Like all tool :els, S series steels must be protected against decarburization. The silicon :els should not be soaked at temperature.

Except for extremely intricate tools of widely varying section thick:ss, stress relieving before hardening is seldom required. When stress relieving is employed, the steel should be furnace cooled to approximately 510 °C (950 °F) and then cooled in air.

Preheating prior to austenitizing is not mandatory, but it can be desirable for large tools, to minimize distortion, to shorten time at austenitizing temperature, and to speed up production. For austenitizing temperatures below 870 °C (1600 °F), a slightly oxidizing atmosphere is best, but a reducing atmosphere is required for temperatures above 870 °C (1600 °F). Atmosphere furnaces, neutral salt baths, and packing media without contaminants are widely used for austenitizing.

Types S2 and S5 should be quenched almost as soon as they reach the austenitizing temperature; however, S1 and S7, which have the highest hardenability of these steels, are held at temperatures for 15 to 45 min before being quenched. All of the shock-resisting steels should be tempered immediately after quenching to prevent cracking. Type S1 is often carburized or carbonitrided to increase surface hardness and wear resistance without detracting from impact strength to any extent.

;1

hemical Composition. **AISI:** Nominal. 0.50 C, 1.50 Cr, 2.50 W. **[SI/UNS (T41901):** 0.40 to 0.55 C, 0.10 to 0.40 Mn, 0.15 to 1.20 Si, 0.30 ı max, 1.00 to 1.80 Cr, 0.50 Mo max, 0.15 to 0.30 V, 1.50 to 3.00 W

imilar Steels (U.S. and/or Foreign). ASTM A681 (S-1); FED Q-T-570 (S-1); SAE J438(S-1); (Ger.) DIN 1.2542, 1.2550; (Fr.) AFNOR ; WC 20, A35-590 2341 55 WC 20; (Ital.) UNI 58 W Cr 9 KU (Jap.) JIS 4404 SKS 41; (Swed.) SS 2710; (U.K.) B.S. 4659 BS1

haracteristics. Available in a variety of chemical compositions. ırying carbon, silicon, tungsten, and chromium contents affect response heat treatment. Modifications in heat treatment should be obtained from :el supplier, if not covered in the following data. Higher silicon contents omote graphitization at excessively high annealing temperatures

ɔrging. Start forging at 1010 to 1120 °C (1850 to 2050 °F). Do not rge below 870 °C (1600 °F)

ecommended Heat Treating Practice

ormalizing. Do not normalize

nnealing. Heat to 790 to 830 °C (1455 to 1525 °F). Use lower limit for ıall sections and upper limit for large sections. Holding time varies from proximately 1 h for light sections and small furnace charges, to approxiately 4 h for heavy sections and large charges. Cool at a rate not to exceed : °C (40 °F) per h. Maximum rate not critical after cooling to approxiately 510 °C (950 °F). Typical annealed hardness, 183 to 235 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Heat slowly. Preheat at 650 °C (1200 °F). Austenitize at 900 to 955 °C (1650 to 1750 °F), hold for 15 to 45 min, then quench in oil. As-quenched hardness, 57 to 59 HRC

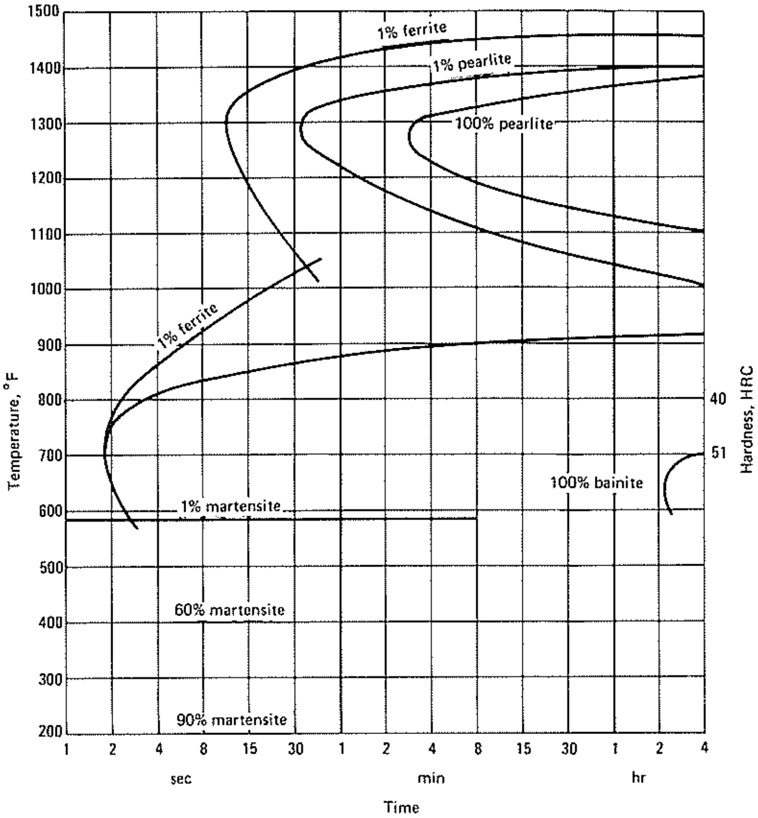
Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to –320 °F). Temper immediately after part reaches room temperature

Tempering. To prevent cracking, temper within 30 min if quenched from 900 °C (1650 °F), 15 min if quenched from 955 °C (1750 °F). Time may vary with size and shape. Temper at 205 to 650 °C (400 to 1200 °F). Approximate tempered hardness as it corresponds to tempering temperature, 58 to 40 HRC

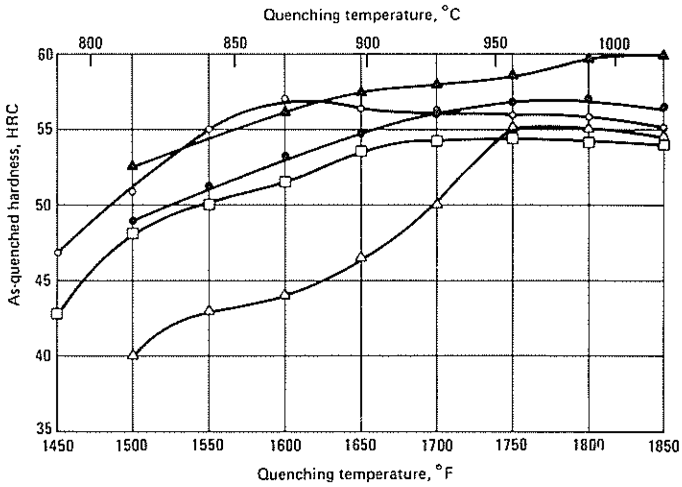
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size

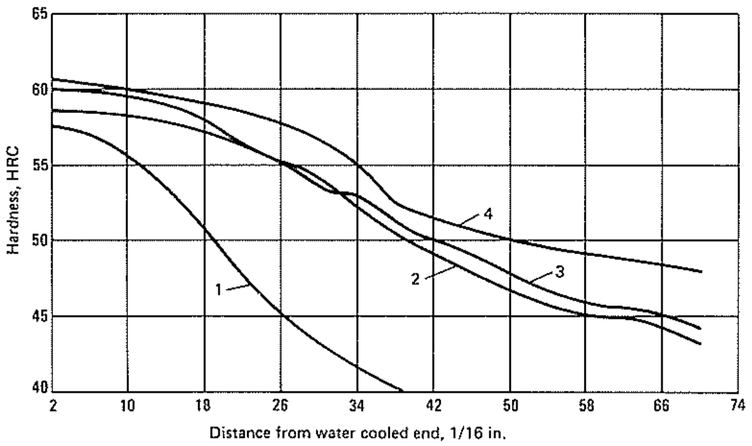
S1: Isothermal Transformation Diagram. Containing 0.50 C, 0.25 Mn, 0.75 Si, 1.25 Cr, 0.20 V, 2.50 W. Austenitized at 925 °C (1695 °F). Source: Uddeholm



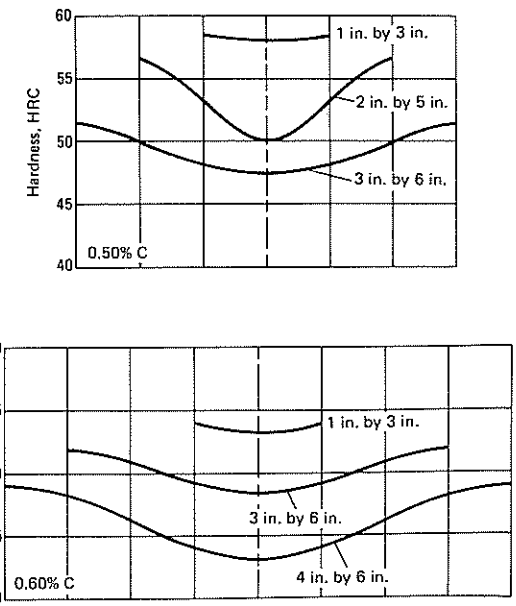
S1: Hardness vs Austenitizing Temperature. ○: 0.45 C, 1.50 Cr, 2.41 W, quenched in water; specimen, 25 mm (1 in.) by 127 mm (5 in.) ●: 0.55 C, 1.35 Cr, 0.25 V, 2.00 W, quenched in oil. △: 0.43 C, 1.30 Cr, 0.25 V, 2.00 W, quenched in oil; specimen, 22.2 mm (7/8 in.) diam by 76 mm (3 in.) ▲: 0.52 C, 0.85 Si, 1.30 Cr, 0.25 V, 2.25 W. Quenched in oil; specimen, 22.2 mm (7/8 in.) diam by 63.5 mm (2 1/2 in.) □: 0.45 C, 1.50 Cr, 2.41 W. Quenched in oil; 25 mm (1 in.) diam by 127 mm (5 in.). Sources: Allegheny Ludlum, Bethlehem Steel, Latrobe Steel



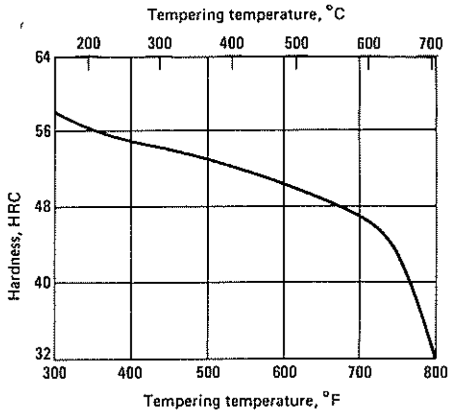
S1: End-Quench Hardenability. **1**: S1 containing 0.53 C, 0.38 Mn, 0.26 Si, 1.42 Cr, 2.13 W. **2**: S1 containing 0.54 C, 0.41 Mn, 1.02 Si, 1.40 Cr, 2.20 W. **3**: S1 containing 0.51 C, 0.39 Mn, 0.26 Si, 1.43 Cr, 0.30 V, 2.15 W, 0.51 Mo. **4**: S1 containing 0.52 C, 0.42 Mn, 1.04 Si, 1.46 Cr, 0.32 V, 2.14 W, 0.53 Mo. All austenitized at 950 °C (1740 °F)



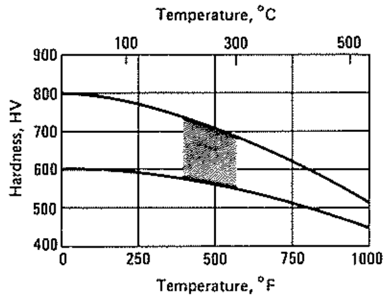
S1: Cross-Sectional Hardness. S1 containing 0.50% and 0.60% C, austenitized at 925 °C (1695 °F) and quenched in oil. Source: Columbia Tool Steel



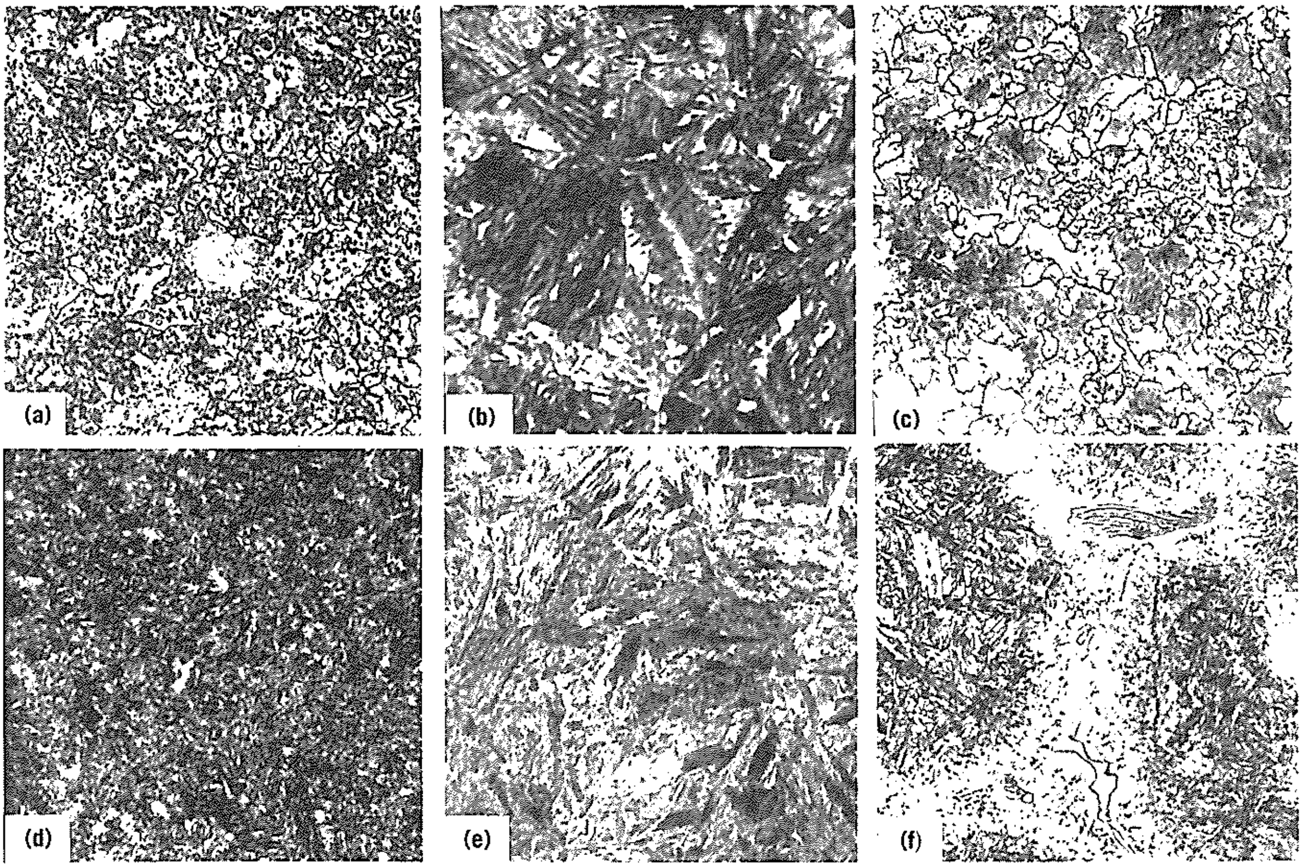
'1: Hardness vs Tempering Temperature. S1 austenitized at 55 °C (1750 °F) and quenched in oil. As-quenched hardness, 59 IRC. Source: Universal-Cyclops



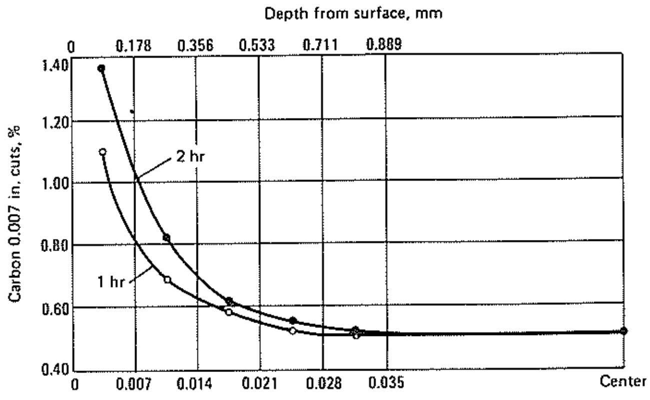
S1: Hardness vs Tempering Temperature. Shaded portion shows optimum range for best combination of hardness and toughness



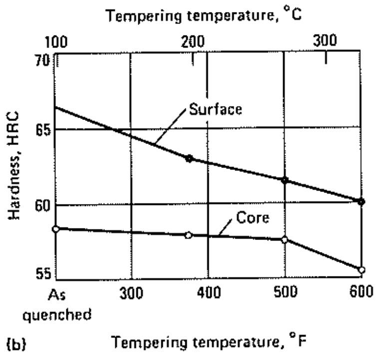
1: Microstructures. (a) 3% nital, 1000×. As received (mill annealed). Hardness, 183 HB. Dispersion of fine spheroidal particles of carbide lark spots) in matrix of ferrite. (b) Nital, 1000×. Normalized by austenitizing at 980 °C (1795 °F) for 1 h and air cooling. Carbide particles are ispersed in martensite, probably some bainite, and retained austenite. (c) 3% nital, 1000×. Austenitized at 815 °C (1500 °F) and oil uenched. Dispersion of fine carbide particles in the ferrite matrix indicates underheating during austenitizing. Some untempered marten-ite is present. (d) 3% nital, 1000×. Austenitized at 955 °C (1750 °F), oil quenched, tempered at 425 °C (795 °F). Tempered martensite and pheroidal carbide particles. (e) 3% nital, 1000×. Austenitized at 1040 °C (1905 °F), oil quenched, tempered at 220 °C (425 °F). Tempered ıartensite, coarse because of overheating. (f) 3% nital, 1000×. As cast and tempered at 425 °C (795 °F). Tempered martensite with retained ustenite and cellular carbide



S1: Carburizing Data. S1 containing 0.50 C, 1.65 Cr, 0.25 V, 2.00 W, after pack carburizing. (a) Carbon penetration curves after pack carburizing 1 and 2 h at 900 °C (1650 °F). (b) Effect of tempering temperature on the surface and core hardness of samples oil quenched after pack carburizing 1 h at 900 °C (1650 °F). Samples were 51 by 76 by 31.6 mm (2 by 3 by 1 ¼ in.). Source: Teledyne VASCO



(a)



(b)

S2

Chemical Composition. **AISI:** Nominal. 0.50 C, 1.00 Si, 0.50 Mo. **AISI/UNS (T41902):** 0.40 to 0.55 C, 0.30 to 0.50 Mn, 0.90 to 1.20 Si, 0.30 Ni max, 0.30 to 0.60 Mo, 0.50 V max

Similar Steels (U.S. and/or Foreign). ASTM A681 (S-2); FED QQ-T-570 (S-2); SAE J437(S2), J438(S2); (Ger.) DIN 1.2103; (Fr.) AFNOR A35-590 2324 Y 45 SCD 6; (U.K.) B.S. 4659 BS2

Characteristics. Among the most shock resistant of the S series. Has low safety in hardening because cracking in water or brine quenchants is possible. Overheating or oversoaking during austenitizing will lower ductility and promote grain growth. Will decarburize readily if not adequately protected

Forging. Start forging at 1010 to 1120 °C (1850 to 2050 °F). Do not forge below 870 °C (1600 °F) or above 1150 °C (2100 °F). Cool forgings in dry air

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat to 760 to 790 °C (1400 to 1455 °F). Use lower limit for small sections and upper limit for large sections. Holding time varies from approximately 1 h for light sections and small furnace charges, to approximately 4 h for heavy sections and large charges. Cool at a rate not to exceed 22 °C (40 °F) per h. Maximum rate not critical after cooling to approximately 510 °C (950 °F). Typical annealed hardness, 192 to 217 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Heat slowly. Preheat at 650 °C (1200 °F). Austenitize at 845 to 900 °C (1555 to 1650 °F), hold for 5 to 20 min, then quench in brine or water. As-quenched hardness, 60 to 62 HRC

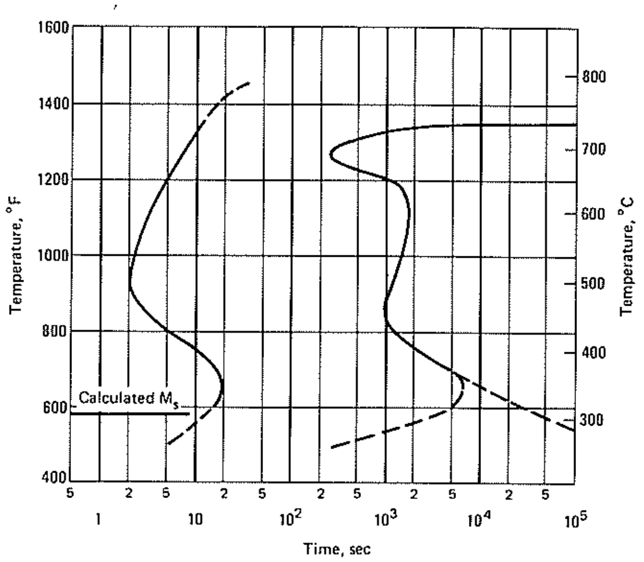
Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at −100 to −195 °C (−150 to −320 °F). Temper immediately after part reaches room temperature

Tempering. To prevent cracking, temper within 10 min particularly if quenched in brine from 900 °C (1650 °F). Temper at 175 to 425 °C (345 to 795 °F). Approximate tempered hardness as it corresponds to tempering temperature, 60 to 50 HRC

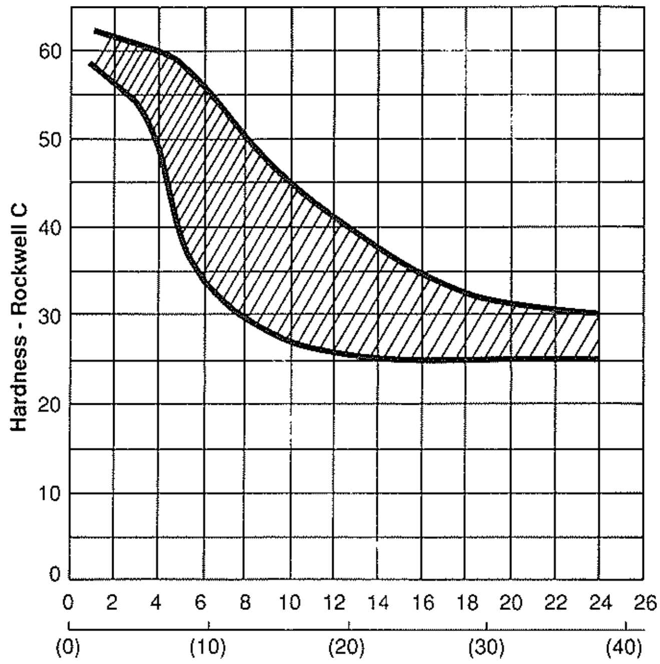
Recommended Processing Sequence

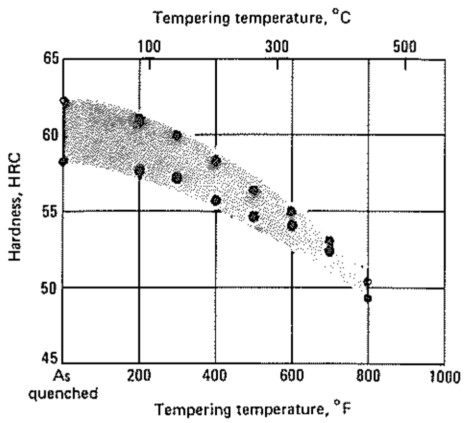
- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size

2: Isothermal Transformation Diagram. S2 containing 0.50 C, .35 Mn, 0.018 P, 0.013 S, 1.0 Si, 0.19 Ni, 0.11 Cr, 0.50 Mo. ustenitized at 845 °C (1555 °F). Grain size: 8. Source: Carpenter teel



S2: Jominy Hardenability. Distance from quenched end 1.5 mm (1/16 in.). Source: Carpenter Technology Corporation





S2: Hardness vs Tempering Temperature. O: S2 containing 0.50 C, 1.10 Si, 0.50 Mo, 0.20 V, quenched in water from 860 °C (1580 °F). ●: S2 containing 0.50 C, 1.10 Si, 0.50 Mo, 0.20 V, quenched in oil from 900 °C (1650 °F).

5

emical Composition. **AISI:** Nominal. 0.55 C, 0.80 Mn, 2.00 Si,) Mo. **AISI/UNS (T41905):** 0.40 to 0.50 C, 1.20 to 1.50 Mn, 2.00 to) Si, 1.20 to 1.50 Cr, 0.30 to 0.50 Mo, 0.20 to 0.40 V

nilar Steels (U.S. and/or Foreign). ASTM A681 (S-5); FED -T-570 (S-5); SAE J437(S5), J438(S5); (Ger.) DIN 1.2823; (U.K.) B.S. 9 BS5

aracteristics. Relatively high safety in hardening when quenched ›il, the recommended quenchant. Overheating or oversoaking during enitizing will lower durability and promote grain growth. Will decar-ze readily if not adequately protected. Readily available and among the expensive grades

Forging. Start forging at 1010 to 1120 °C (1850 to 2050 °F). Do not forge below 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat to 775 to 800 °C (1425 to 1475 °F). Use lower limit for small sections and upper limit for large sections. Holding time varies from approximately 1 h for light sections and small furnace charges, to approximately 4 h for heavy sections and large charges. Cool at a rate not to exceed 14 °C (25 °F) per h. Maximum rate not critical after cooling to approximately 510 °C (950 °F). Typical annealed hardness, 192 to 229 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Heat slowly. Preheat at 760 °C (1400 °F). Austenitize at 870 to 925 °C (1600 to 1695 °F), hold for 5 to 20 min, then quench in oil. As-quenched hardness, 58 to 61 HRC

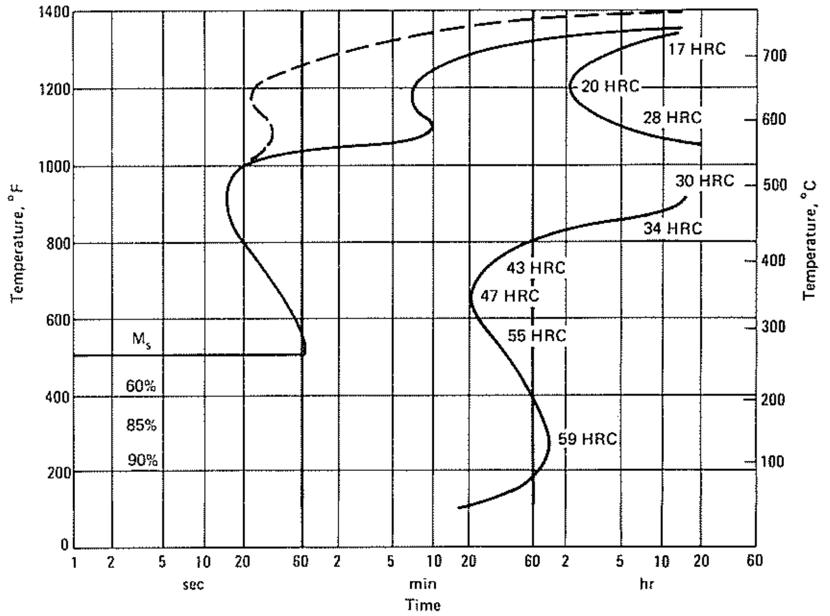
Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to –320 °F). Temper immediately after part reaches room temperature

Tempering. To prevent cracking, temper within 30 min if quenched from 870 °C (1600 °F), 15 min if quenched from 925 °C (1695 °F). Temper at 175 to 425 °C (345 to 795 °F). Approximate tempered hardness as it corresponds to tempering temperature, 60 to 50 HRC

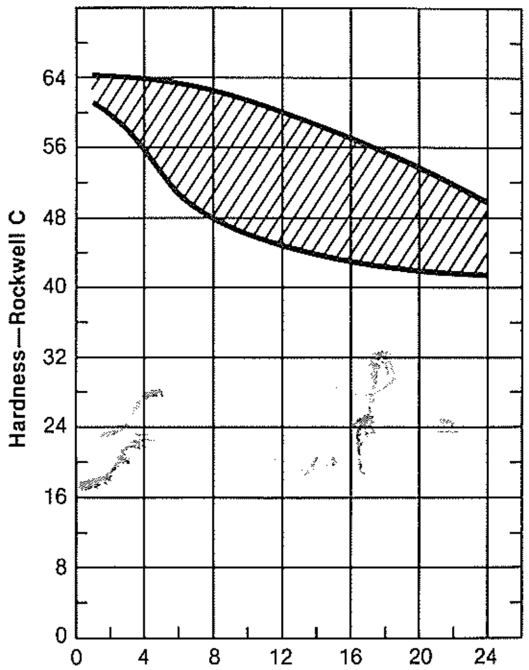
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size

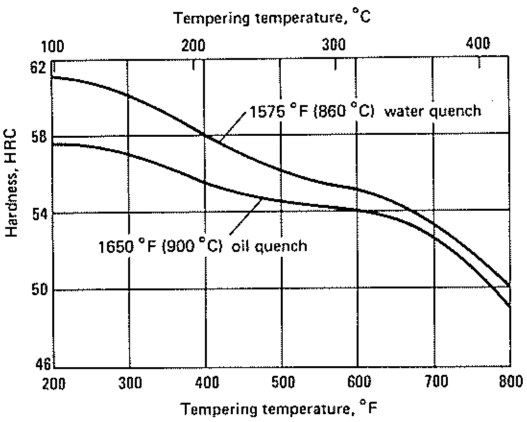
S5: Isothermal Transformation Diagram. S5 containing 0.60 C, 0.75 Mn, 1.90 Si, 0.25 Cr, 0.30 Mo. Austenitized at 900 °C (1650 °F). Source: Crucible Steel Co.



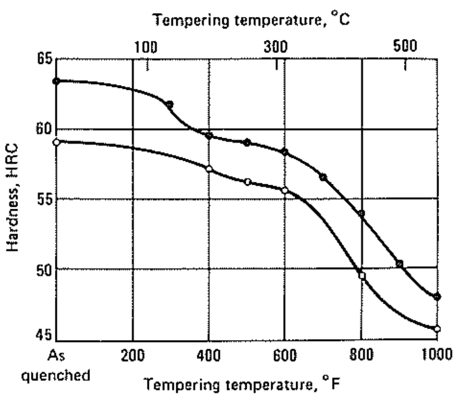
S5: Jominy Hardenability. Distance from quenched end 1.6 mm (1/16 in.) increments. Source: Carpenter Technology Corporation



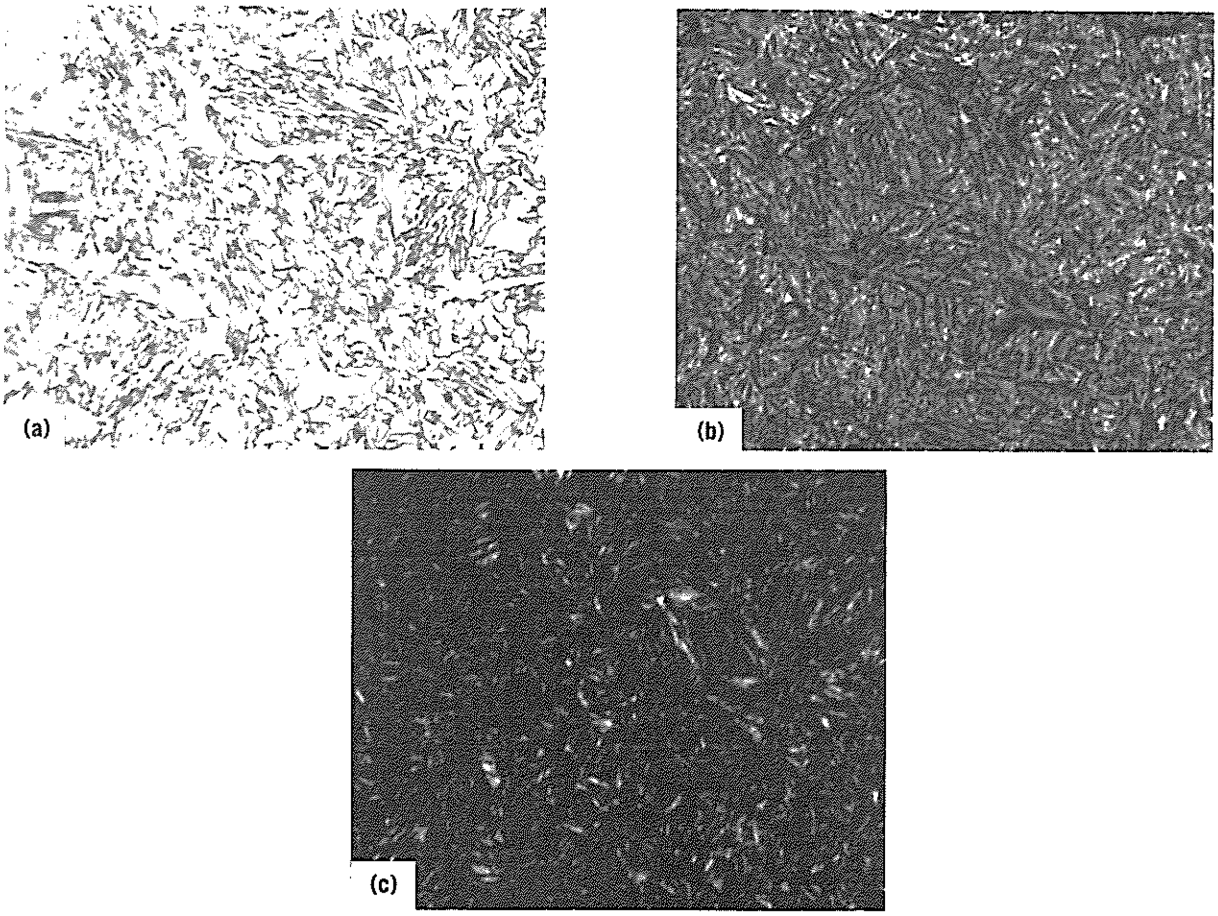
S5: Hardness vs Tempering Temperature. S5 water quenched from 860 °C (1580 °F). As-quenched hardness, 62 HRC. S5 oil quenched from 900 °C (1650 °F). As-quenched hardness, 58 HRC. Source: Universal-Cyclops



S5: Hardness vs Tempering Temperature. O: S5 containing 0.50 C, 0.70 Mn, 1.60 Si, 0.40 Mo, 0.12 V; quenched in oil from 870 °C (1600 °F). ●: S5 containing 0.60 C, 0.85 Mn, 2.00 Si, 0.25 Cr, 0.25 Mo, 0.20 V; quenched in oil from 885 °C (1625 °F). Source: Allegheny Ludlum Industries



;5: **Microstructures.** (a) Nital, 1000×. Normalized by austenitizing at 925 °C (1695 °F) for 1 h and air cooling. Mixture of martensite and ;oarse pearlite. (b) 2% nital, 1000×. Austenitized at 900 °C (1650 °F) and oil quenched. Steel not tempered. Fine untempered martensite. ;ee (c). (c) 2% nital, 1000×. Austenitized at 900 °C (1650 °F), oil quenched, and tempered at 400 °C (750 °F). Fine tempered martensite



;6

ıemical Composition. **AISI:** Nominal. 0.45 C, 1.40 Mn, 2.25 Si, ;0 Cr, 0.40 Mo. **AISI/UNS (T41906):** 0.40 to 0.50 C, 1.20 to 1.50 Mn, ı0 to 2.50 Si, 1.20 to 1.50 Cr, 0.30 to 0.50 Mo, 0.20 to 0.40 V

milar Steels (U.S. and/or Foreign). ASTM A681 (S-6); FED)-T-570 (S-6)

ıaracteristics. High safety in hardening. Will decarburize readily if : adequately protected. One of the more highly alloyed grades, making it ong the more expensive S series steels

ırging. Start forging at 1010 to 1120 °C (1850 to 2050 °F). Do not ge below 870 °C (1600 °F)

ɜcommended Heat Treating Practice

ırmalizing. Do not normalize

ınealing. Heat to 800 to 830 °C (1475 to 1525 °F). Use lower limit for all sections and upper limit for large sections. Holding time varies from approximately 1 h for light sections and small furnace charges, to approximately 4 h for heavy sections and large charges. Cool at a rate not to exceed 14 °C (25 °F) per h. Maximum rate not critical after cooling to approximately 510 °C (950 °F). Typical annealed hardness, 192 to 229 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Heat slowly. Preheat at 760 °C (1400 °F). Austenitize at 915 to 955 °C (1680 to 1750 °F), hold for 10 to 30 min, then quench in oil. As-quenched hardness, 56 to 60 HRC

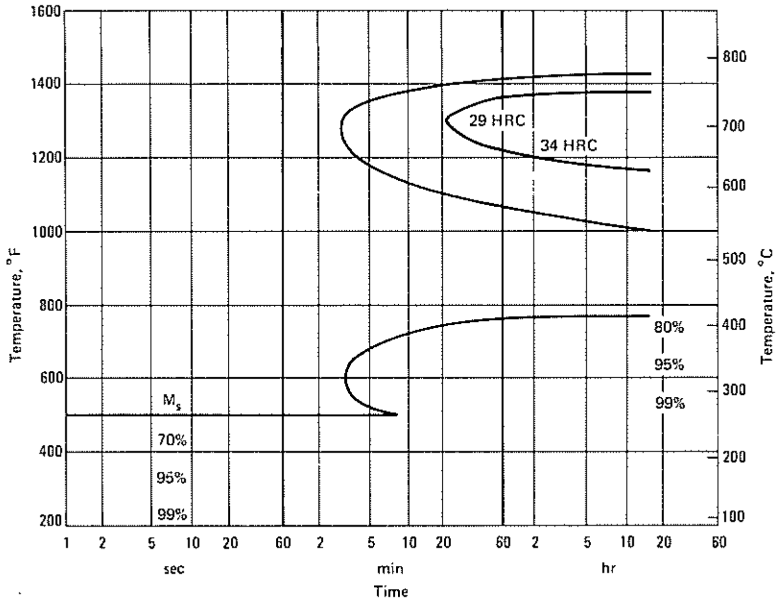
Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at −100 to −195 °C (−150 to −320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 205 to 315 °C (400 to 600 °F). Approximate tempered hardness as it corresponds to tempering temperature, 56 to 54 HRC

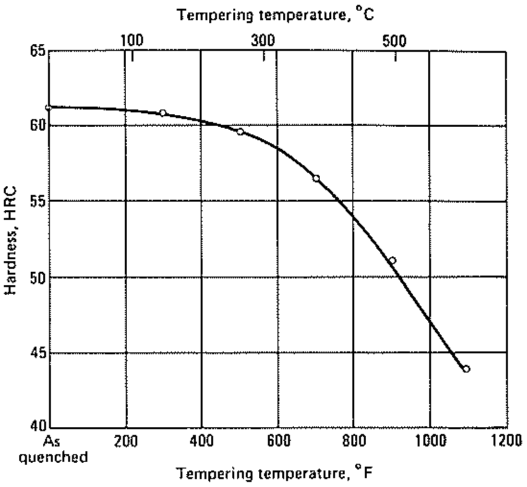
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size

S6: Isothermal Transformation Diagram. S6 containing 0.43 C, 1.35 Mn, 2.25 Si, 1.35 Cr, 0.40 Mo, 0.30 V. Austenitized at 925 °C (1695 °F) and oil quenched. As-quenched hardness, 60 HRC. Source: Crucible Steel



S6: Hardness vs Tempering Temperature. S6 containing 0.55 C, 0.97 Mn, 1.95 Si, 0.29 Cr, 1.07 Mo, 0.25 V. Austenitized at 870 °C (1600 °F) and quenched in oil. Source: Teledyne VASCO



S7

Chemical Composition. AISI: Nominal. 0.50 C, 1.40 Mo, 3.25 Cr. **AISI/UNS (T41907):** 0.45 to 0.55 C, 0.20 to 0.90 Mn, 0.20 to 1.00 Si, 3.00 to 3.50 Cr, 1.30 to 1.80 Mo, 0.20 to 0.30 V (optional)

Similar Steels (U.S. and/or Foreign). ASTM A681 (S-7)

Characteristics. Has highest hardenability of the S series steels and maximum softening resistance at elevated temperatures. Has moderate resistance to decarburization and grain growth

Forging. Start forging at 1065 to 1120 °C (1950 to 2050 °F). Do not forge below 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat to 815 to 845 °C (1500 to 1555 °F). Use lower limit for small sections and upper limit for large sections. Holding time varies from approximately 1 h for light sections and small furnace charges, to approximately 4 h for heavy sections and large charges. Cool at a rate not to exceed 14 °C (25 °F) per h. Maximum rate not critical after cooling to approximately 510 °C (950 °F). Typical annealed hardness, 187 to 223 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Heat slowly. Preheat at 650 to 705 °C (1200 to 1300 °F). When using an open furnace, austenitize at 925 to 955 °C (1695 to 1750 °F), hold for 15 to 45 min. For pack hardening, hold for ½ h per inch of pack cross section. Quench in oil or air cool. As-quenched hardness, 60 to 61 HRC

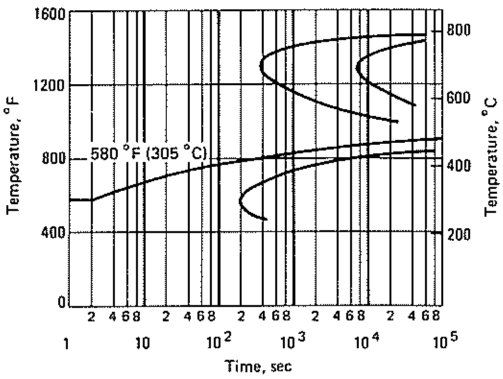
Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to –320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 205 to 620 °C (400 to 1150 °F). Approximate tempered hardness as it corresponds to tempering temperature, 57 to 45 HRC

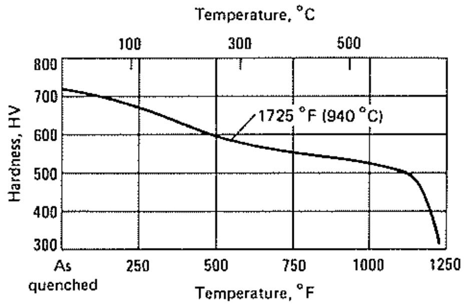
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size

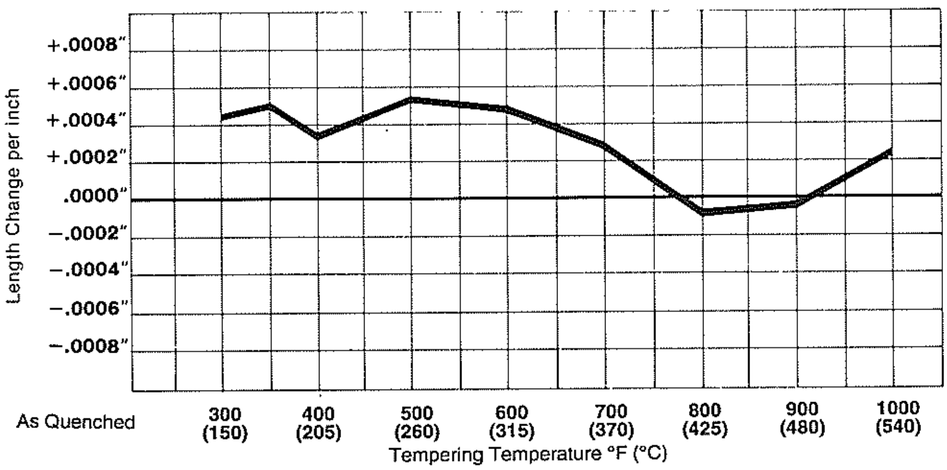
7: Isothermal Transformation Diagram. S7, austenitized at 00 °C (1650 °F)



S7: Hardness vs Tempering Temperature. S7, austenitized at 940 °C (1725 °F)



7: Size Change in Hardening. Air cooled from 940 °C (1725 °F); tempered 1 h at heat; 25 mm (1 in.) round. Source: Carpenter Technology orporation



Oil-Hardening Cold Work Tool Steels (O Series)

ntroduction

The standard oil-hardening cold work tool steels for which data are iven in this section are identified by the symbol "O", followed by the umbers 1, 2, 6, or 7. As a group, their hardenability is much higher than iat of the water-hardening tool steels (W series), and they can, therefore, e hardened by quenching in oil. Type O1 is by far the most widely used, id is produced by virtually all of the tool steel mills. Some minor vari-ions exist in the chemical composition of O1 steel; however, these ariations do not affect heat treating procedures significantly. Some of the irbon in O6 steel is in graphite form, which is sometimes a factor in the ibrication of intricate dies. The graphite particles in its microstructure also erve as a built-in lubricant that reportedly gives better die life in deep rawing operations. Type O7 sometimes is used in dies that require the tention of sharp cutting edges—a property enhanced by a tungsten addi-on and higher carbon content.

The O series steels generally are normalized to produce a more uni-ormly refined grain structure, especially after forging or previous heating temperatures much higher than the recommended austenitizing tempera-ıre. When finished or semifinished tools are annealed, they should be protected from decarburization or carburization during annealing. Type O1 steel can be cycle annealed. In most instances, stress relieving of tools prior to final hardening does not lessen distortion noticeably during hardening; however, preheating of the O steels will minimize distortion during subsequent hardening.

The optimum temperature range for quenching baths consisting of conventional oils is 50 to 70 °C (120 to 160 °F). Agitation is recommended. Although usually quenched in oil, type O7 steel sometimes is quenched in water or brine when maximum hardness is required and heavy sections are involved.

If control of distortion is particularly important, martempering sometimes is advantageous. A bath, oil, or molten salt, that is usually held approximately –14 to 28 °C (25 to 50 °F) above the M_s temperature is employed. The O steels should be tempered immediately after quenching, that is, before they reach room temperature. The most commonly used tempering range is 175 to 205 °C (345 to 400 °F). Time at temperature varies with section size.

)1

:hemical Composition. **AISI:** Nominal. 0.90 C, 1.00 Mn, 0.50 Cr, .50 W. **AISI/UNS (T31501):** 0.85 to 1.00 C, 1.00 to 1.40 Mn, 0.50 Si max, .30 Ni max, 0.40 to 0.60 Cr, 0.30 V max, 0.40 to 0.60 W

;imilar Steels (U.S. and/or Foreign). ASTM A681 (O-1); FED)Q-T-570 (O-1); SAE J437 (O1), J438 (O1); (Ger.) DIN 1.2510; (Fr.) \FNOR A35-590 2212 90 MWCV 5; (Jap.) JIS G4404 SKS 21, G4404 ;KS 3, G4404 SKS 94, G4404 SKS 95; (Swed.) SS 2140; (U.K.) B.S. 4659 3O1

:haracteristics. High dimensional stability during heat treating. Rela-ively shallow hardening. High resistance to decarburization. Very high afety in hardening

=orging. Start forging at 980 to 1065 °C (1795 to 1950 °F). Do not forge below 845 °C (1555 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). After uniform through heating, holding time varies from approximately 15 min for small sections to approximately 1 h for large sections. Work is cooled from temperature in still air

Annealing. Heat to 760 to 790 °C (1400 to 1455 °F). Use lower tem-perature for small sections and upper temperature for large sections. Hold-ing time is approximately 1 to 4 h. Use shorter time for light sections and small furnace charges, and longer time for heavy sections and large charges. For pack annealing, hold for 1 h per inch of cross section. Cool to 540 °C (1000 °F) at a rate not to exceed 22 °C (40 °F) per h, after which controlled cooling is not necessary. Typical annealed hardness, 183 to 212 HB

Cycle Annealing. Heat to 730 °C (1350 °F), hold for 4 h. Heat to 780 °C (1435 °F), hold for 2 h. Cool to 690 °C (1275 °F), hold for 6 h. Air cool

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

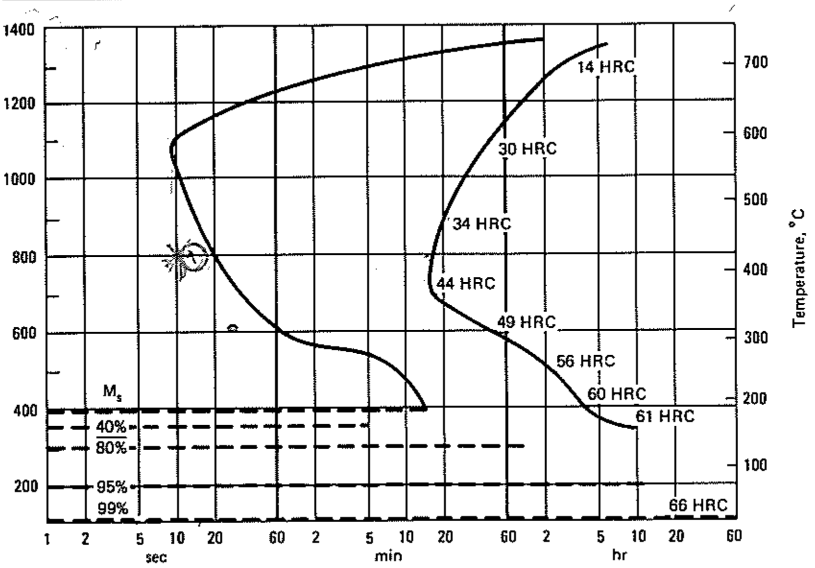
Hardening. Heat slowly. Preheat at 650 °C (1200 °F). Austenitize at 790 to 815 °C (1455 to 1500 °F) for 10 to 30 min, then quench in oil. Quenched hardness, 63 to 65 HRC

Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) for 20 to 30 min. Refrigerate at –100 to –195 °C (–150 to –320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 175 to 260 °C (345 to 500 °F) for a corresponding approximate tempered hardness of 62 to 57 HRC

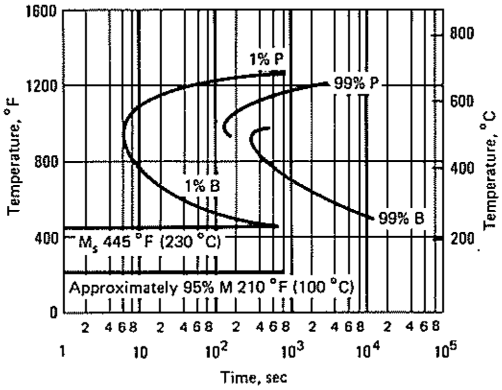
Recommended Processing Sequence

- Normalize
- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Temper
- Final grind to size

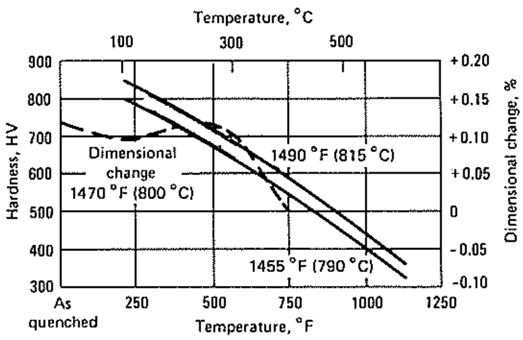


O1: Isothermal Transformation Diagram. Composition: 0.85 C, 1.18 Mn, 0.26 Si, 0.50 Cr, 0.44 W. Critical temperature (Ac_1): 745 °C (1370 °F). Prior condition: annealed

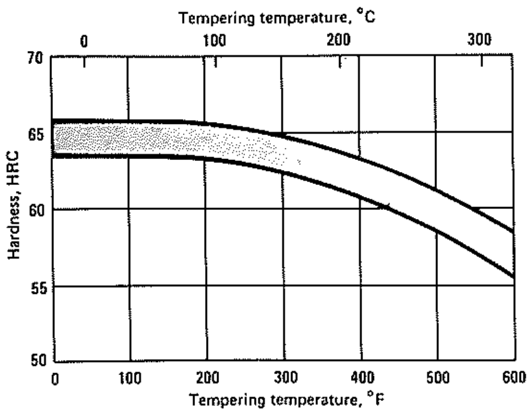
)1: **Isothermal Transformation Diagram.** Swedish grade ;howing percent pearlite and bainite as a function of time and ransformation temperature. Source: Uddeholm Steels



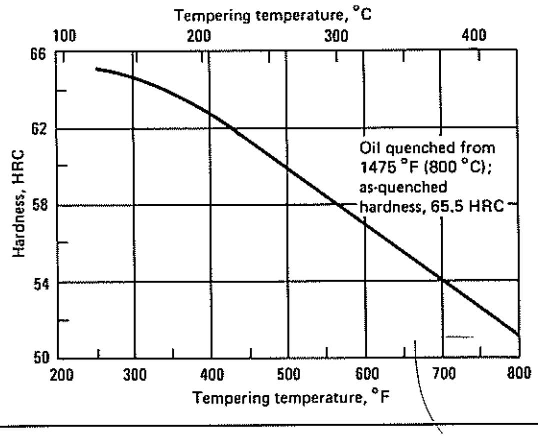
O1: Dimensional Changes and Hardness vs Tempering Temperature. Solid lines show approximate upper and lower limits of hardness after tempering. Broken line, dimensional change. Shaded area, optimum temperature range. Source: Uddeholm Steels



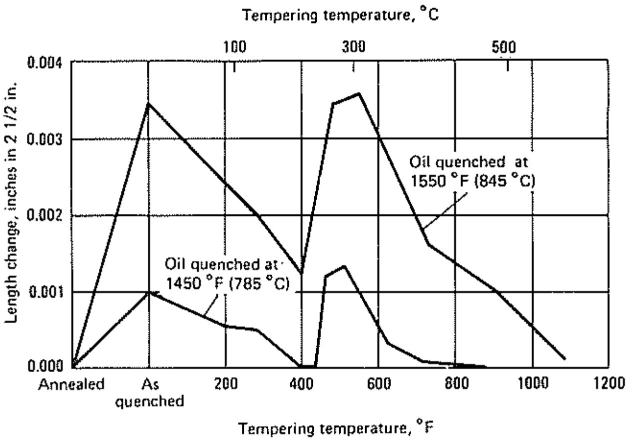
)1: **Hardness vs Tempering Temperature.** Austenitized at 790 :o 815 °C (1455 to 1500 °F). Band approximately 2 HRC points wide



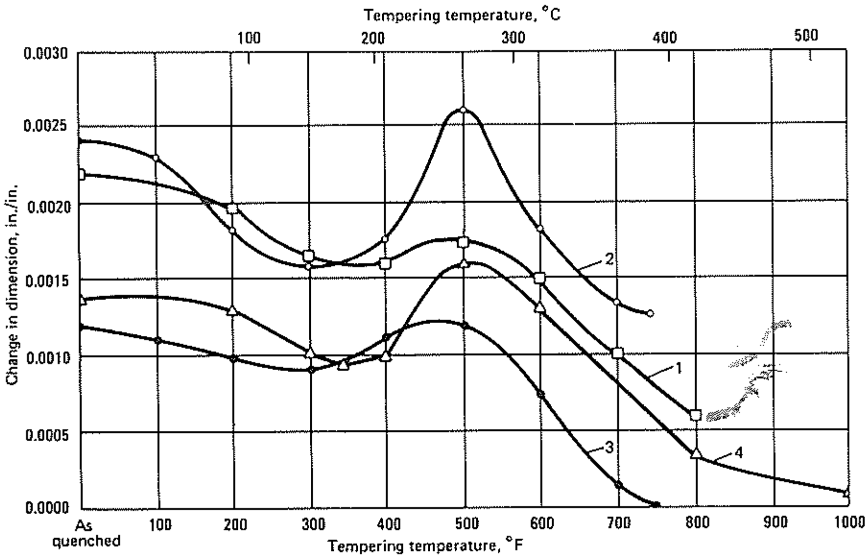
O1: Hardness vs Tempering Temperature. Austenitized at 800 °C (1475 °F). Source: Universal-Cyclops



O1: Length Changes vs Tempering Temperature

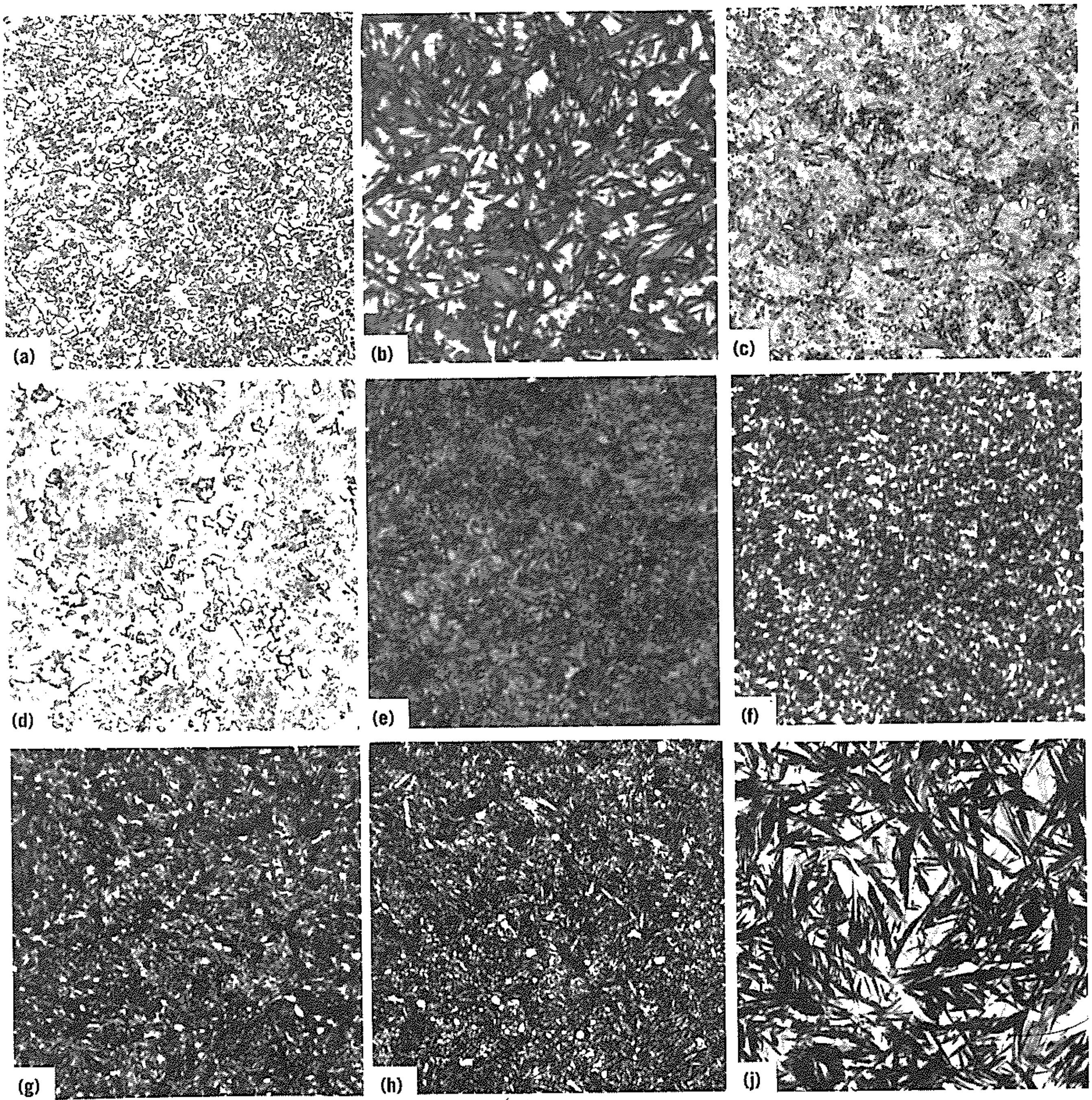


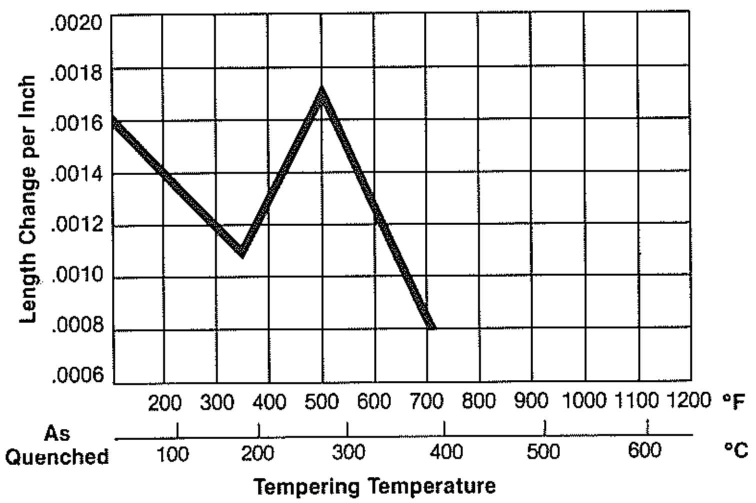
O1: Dimensional Changes vs Tempering Temperature. Source: Latrobe Steel Co., Uddeholm Steels, Allegheny Ludlum Industries



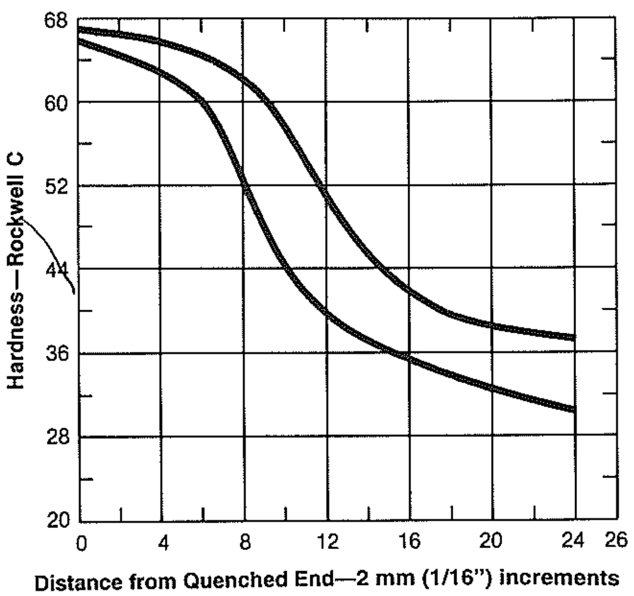
Curve	Hardening: Temperature °F	Hardening: Temperature °C	Hardening: Medium	Specimen size	Dimension measured
1	1500	815	Oil	1 by 2 by 6 in.	Average of three principal dimensions
2	1470	800	Oil	2 (diam) by 2 in.	Length
3	1470	800	Oil	3/8 (diam) by 2 in.	Length
4	1450	785	Oil	1 (diam) by 5 in.	Length

1: Microstructures. (a) 3% nital, 1000×. As received (mill annealed). Dispersion of spheroidal particles of carbide in a matrix of ferrite. haracteristic of the fully annealed condition. (b) Nital, 1000×. Normalized by austenitizing at 900 °C (1650 °F) for 1 h and air cooling. Unmpered martensite, some bainite, and retained austenite (white), from overheating. (c) 3% nital, 1000×. Austenitized at 815 °C (1500 °F), il quenched (not tempered). Hardness, 66 HRC. Spheroidal carbide particles in a matrix of untempered martensite. (d) 3% nital, 1000×. ustenitized at 775 °C (1425 °F), oil quenched. Untempered martensite, undissolved carbide particles, in a ferrite matrix, from underheatig. (e) Nital, 1000×. Austenitized 30 min at 800 °C (1475 °F), oil quenched briefly, then (before completely cool) tempered 2 h at 205 °C (400 F). Carbide particles in tempered martensite. (f) Austenitized at 800 °C (1475 °F) for 30 min, quenched briefly in oil, tempered at 205 °C 400 °F), for 2 h. Tempering was done too soon. Carbide particles in tempered martensite. (g) 3% nital, 1000×. Austenitized at 815 °C (1500 F), oil quenched, tempered at 220 °C (425 °F). Hardness, 58.5 HRC. Spheroidal carbide particles in a matrix of tempered martensite. (h) % nital, 1000×. Austenitized at 815 °C (1500 °F), oil quenched, tempered at 425 °C (795 °F). Spheroidal particles of carbide (white dots) in matrix of tempered martensite. (j) 3% nital, 1000×. Austenitized at 980 °C (1795 °F), oil quenched, tempered at 220 °C (425 °F). Coarse artensite (dark) and retained austenite (white), both resulting from overheating





O1: Size Change in Hardening. Specimens were 25 mm (1 in.) round by 100 mm (4 in.) long; austenitized 20 min at 800 °C (1475 °F), oil quenched, then tempered 1 h at indicated temperatures. Source: Carpenter Technology Corporation



O1: Jominy Hardenability. Parts were austenitized at 800 °C (1475 °F). Source: Carpenter Technology Corporation

O2

Chemical Composition. AISI: Nominal. 0.90 C, 1.60 Mn. **AISI/UNS (T31502):** 0.85 to 0.95 C, 1.40 to 1.80 Mn, 0.50 Si max, 0.30 Ni max, 0.50 Cr max, 0.30 V max, 0.30 Mo max

Similar Steels (U.S. and/or Foreign). ASTM A681 (O-2); FED QQ-T-570 (O-2); SAE J437 (O2), J438 (O2); (Ger.) DIN 1.2842; (Fr.) AFNOR 90 MV 8, A35-590 2211 90 MV 8; (U.K.) B.S. 4659 (USA 02), 4659 BO2; (Ital.) UNI 88 MnV 8 KU

Characteristics. Very good nondeforming properties. Medium depth of hardening. Very high safety in hardening. High resistance to decarburization

Forging. Start forging at 980 to 1050 °C (1795 to 1920 °F). Do not forge below 845 °C (1555 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 845 °C (1555 °F). After uniform through heating, holding time varies from approximately 15 min for small sections to approximately 1 h for large sections. Work is cooled from temperature in still air

Annealing. Heat to 745 to 775 °C (1370 to 1425 °F). Use lower temperature for small sections and upper temperature for large sections. Holding time is approximately 1 to 4 h. Use shorter time for light sections and small furnace charges, and longer time for heavy sections and large charges. For pack annealing, hold for 1 h per inch of cross section. Cool to 540 °C (1000 °F) at a rate not to exceed 22 °C (40 °F) per h, after which controlled cooling is not necessary. Typical annealed hardness, 183 to 217 HB

ess Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

dening. Heat slowly. Preheat at 650 °C (1200 °F). Austenitize at 760)0 °C (1400 to 1475 °F) for 5 to 20 min, then quench in oil. Quenched ness, 63 to 65 HRC

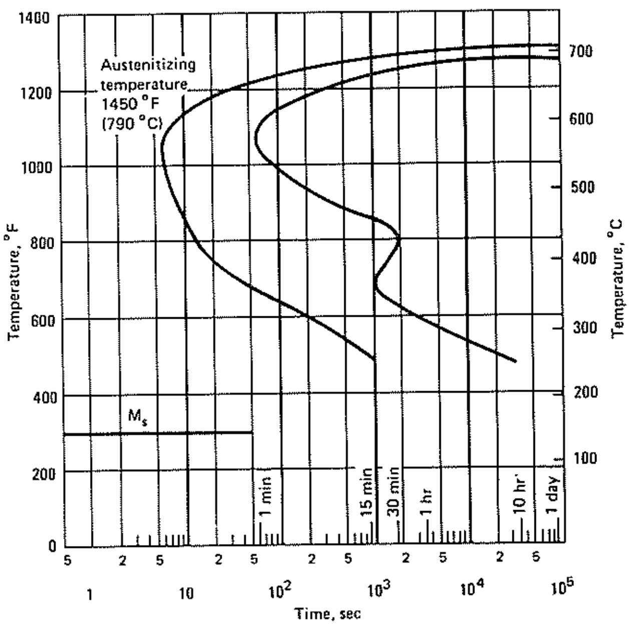
bilizing. Optional. For intricate shapes, stress relieve temper at 150 to °C (300 to 320 °F) for 20 to 30 min. Refrigerate at −100 to −195 °C (−150 320 °F). Temper immediately after part reaches room temperature

npering. Temper at 175 to 260 °C (345 to 500 °F) for a corresponding oximate tempered hardness of 62 to 57 HRC

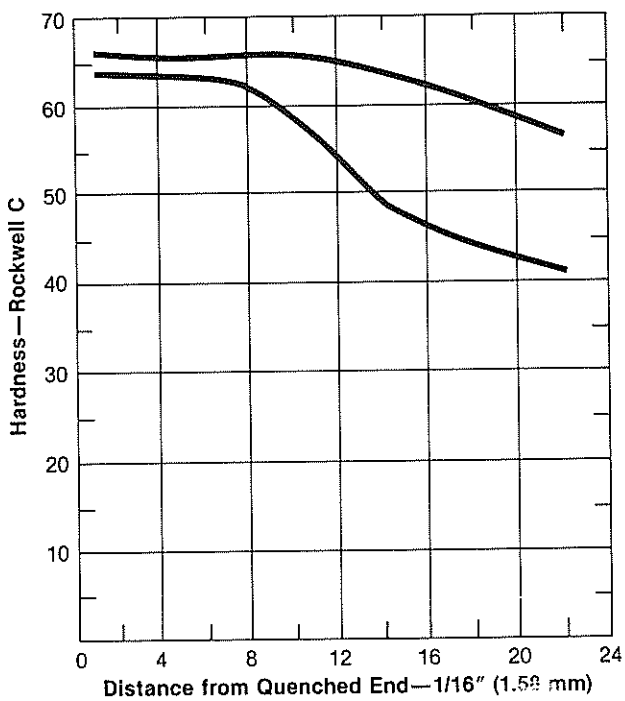
Recommended Processing Sequence

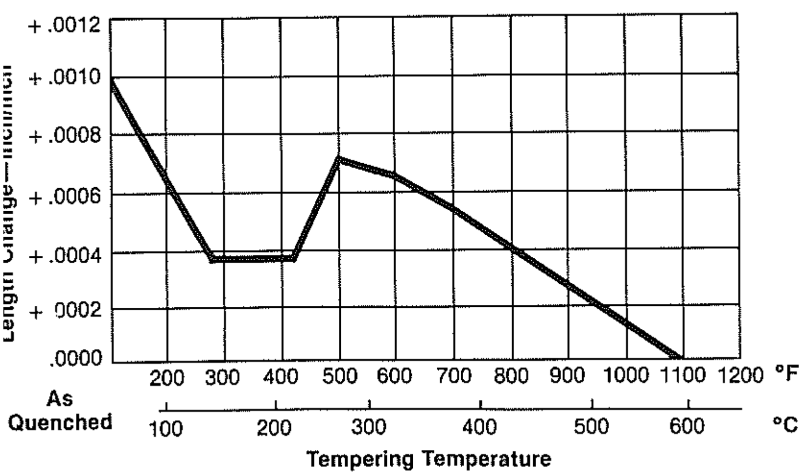
- Normalize
- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Temper
- Final grind to size

2: Isothermal Transformation Diagram. Composition: 0.87 C, 78 Mn, 0.027 P, 0.010 S, 0.29 Si, 0.15 Ni, 0.20 Cr, 0.03 Mo. Nose curve is at 6 sec for chemical composition. Source: Carpenter eel



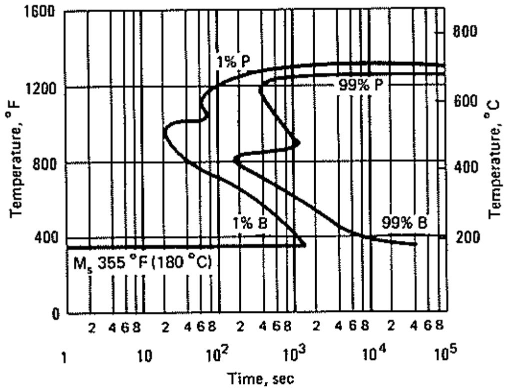
O2: Jominy Hardenability. Source: Carpenter Technology Corporation



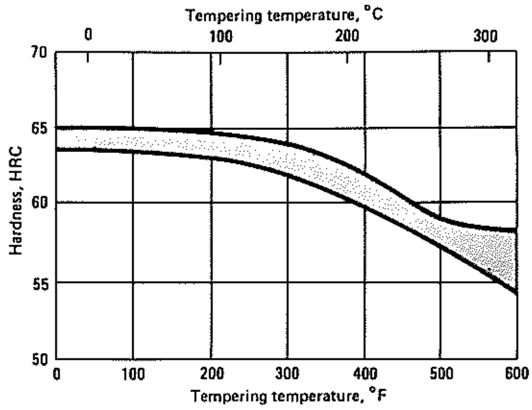


O2: Size Change in Hardening. Bar 25 mm (1 in.) in diam was oil quenched from 800 °C (1475 °F) and tempered 1 h at indicated temperatures. Source: Carpenter Technology Corporation

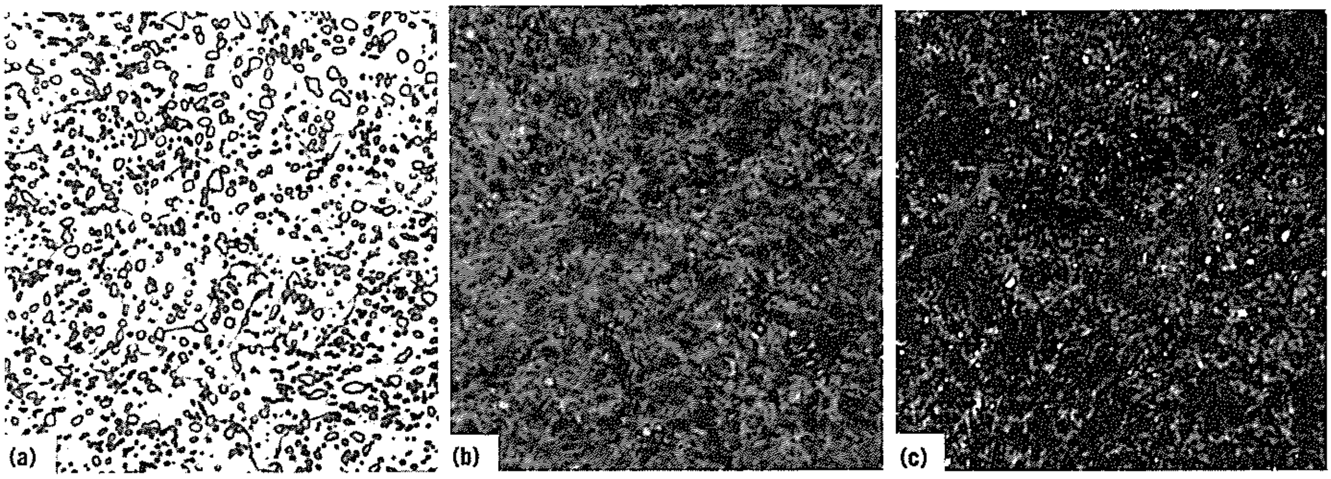
O2: Isothermal Transformation Diagram. British grade. Nose of curve is at 12 sec for chemical analysis. Percent pearlite and bainite, as a function of time and transformation temperature. Source: Jessop Saville



O2: Hardness vs Tempering Temperature. Austenitized at 775 to 800 °C (1425 to 1475 °F) and tempered for 1 h



O2: Microstructures. (a) Nital, 1000×. Annealed by heating to 725 °C (1335 °F), holding for 1 h per inch of section thickness and furnace cooling. Spheroidal carbide in a matrix of ferrite. (b) Nital, 1000×. Austenitized 15 min at 800 °C (1475 °F), quenched in oil. Some spheroidal carbide(white dots) in a matrix of untempered martensite. (c) Nital, 1000×. Austenitized and quenched same as (b), then tempered 1 h at 175 °C (345 °F). Some spheroidal carbide (white dots) in tempered martensite



O6

Chemical Composition. AISI: Nominal. 1.45 C, 0.80 Mn, 1.00 Si, 0.25 Mo. **AISI/UNS (T31506):** 1.25 to 1.55 C, 0.30 to 1.10 Mn, 0.55 to 1.55 Si, 0.30 Ni max, 0.30 Cr max, 0.20 to 0.30 Mo

Similar Steels (U.S. and/or Foreign). AISI O-6; ASTM A681 (O-6); FED QQ-T-570 (O-6); SAE J437 (O6), J438 (O6); (Ger.) DIN 1.2206; (Fr.) AFNOR A35-590 2132 130 C 3

Characteristics. Generally low distortion with high safety in hardening. Contains graphite and is relatively deep hardening with high abrasion resistance. Not readily obtainable in a variety of sizes

Forging. Start forging at 980 to 1065 °C (1795 to 1950 °F). Do not forge below 815 °C (1500 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). After uniform through heating, holding time varies from approximately 15 min for small sections to approximately 1 h for large sections. Work is cooled from temperature in still air

Annealing. Heat to 765 to 790 °C (1410 to 1455 °F). Use lower temperature for small sections and upper temperature for large sections. Holding time is approximately 1 to 4 h. Use shorter time for light sections and small furnace charges, and longer time for heavy sections and large charges. For pack annealing, hold for 1 h per inch of pack cross section. Cool at a rate not to exceed 6 °C (10 °F) per h. From 705 °C (1300 °F) to 540 °C (1000

:ool at a rate of 14 °C (25 °F) per h. Maximum rate not critical after ing below 540 °C (1000 °F). Typical annealed hardness, 183 to 217 HB

ɜss Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

'dening. Preheat slowly to 650 °C (1200 °F). Austenitize at 790 to 815 1455 to 1500 °F) for 10 to 30 min, then quench in oil. Quenched ness, 63 to 65 HRC

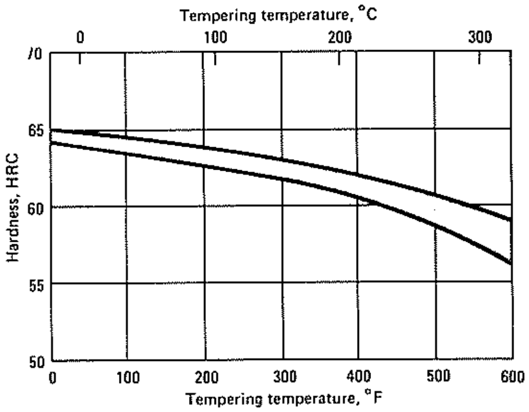
bilizing. Optional. For intricate shapes, stress relieve temper at 150 to °C (300 to 320 °F) for 20 to 30 min. Refrigerate at –100 to –195 °C 0 to –320 °F). Temper immediately after part reaches room tempera-

Tempering. Temper at 175 to 315 °C (345 to 600 °F) for a corresponding approximate tempered hardness of 63 to 58 HRC

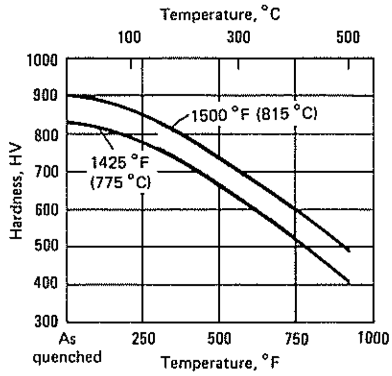
Recommended Processing Sequence

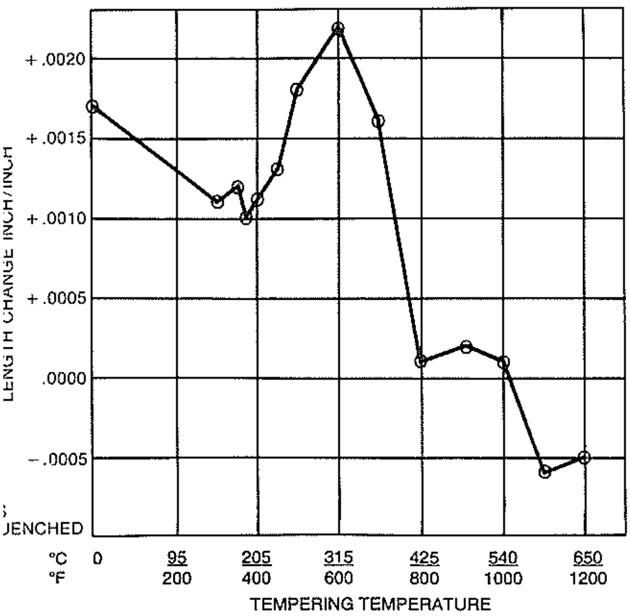
- Normalize
- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size

ɘ: Hardness vs Tempering Temperature. Austenitized at 790 815 °C (1455 to 1500 °F) and tempered 1 h



O6: Hardness vs Tempering Temperature. Hardness of a British grade of O6 tool steel as a function of austenitizing and tempering temperatures. The band represents upper and lower limits of hardness, and the shaded portion indicates the optimum tempering range. Source: British Steel





O6: Size Change in Hardening. Specimens were austenitized in salt at 800 °C (1475 °F) for 25 min, oil quenched, and tempered 1 h at temperature. Source: Carpenter Technology Corporation

O6: Microstructures. (a) 3% nital, 1000×. Austenitized at 800 °C (1475 °F), oil quenc ... nitized at 885 °C (1625
carburization (left), carbon-lean martensite (light gray), tempered martensite (dark ... 205 °C (400 °F). Struc-
at 790 °C (1455 °F) for 50 min, oil quenched, tempered at 205 °C (400 °F) for 2 h. ... ide (white) in a matrix
of graphite. (c) Nital, 1000×. Same steel, heat treatment and orientation as for (
particles of carbide in tempered martensite, with some particles of graphite. (d
quenched, tempered at 220 °C (425 °F). Spheroidal carbide and graphite in a matrix
heating). (e) 3% nital, 1000×. Austenitized at 815 °C (1500 °F), oil quenched, tempered
carbide particles (white) in a matrix of tempered martensite (gray). (f) 3% nital, 1000×. Aus
pered at 425 °C (795 °F). Graphite particles barely visible. Remaining structure is carbide
1000×. Austenitized at 815 °C (1500 °F) and quenched in oil. Microstructure consists of particles
of carbide (white dots) in untempered martensite

542 / Heat Treaters Gui
O7
Chemical Compo
AISI/UNS (T31507)
max, 0.35 to 0.85 C
Similar Steels
(O-7); FED QQ-
1.2519; (Fr.) AF
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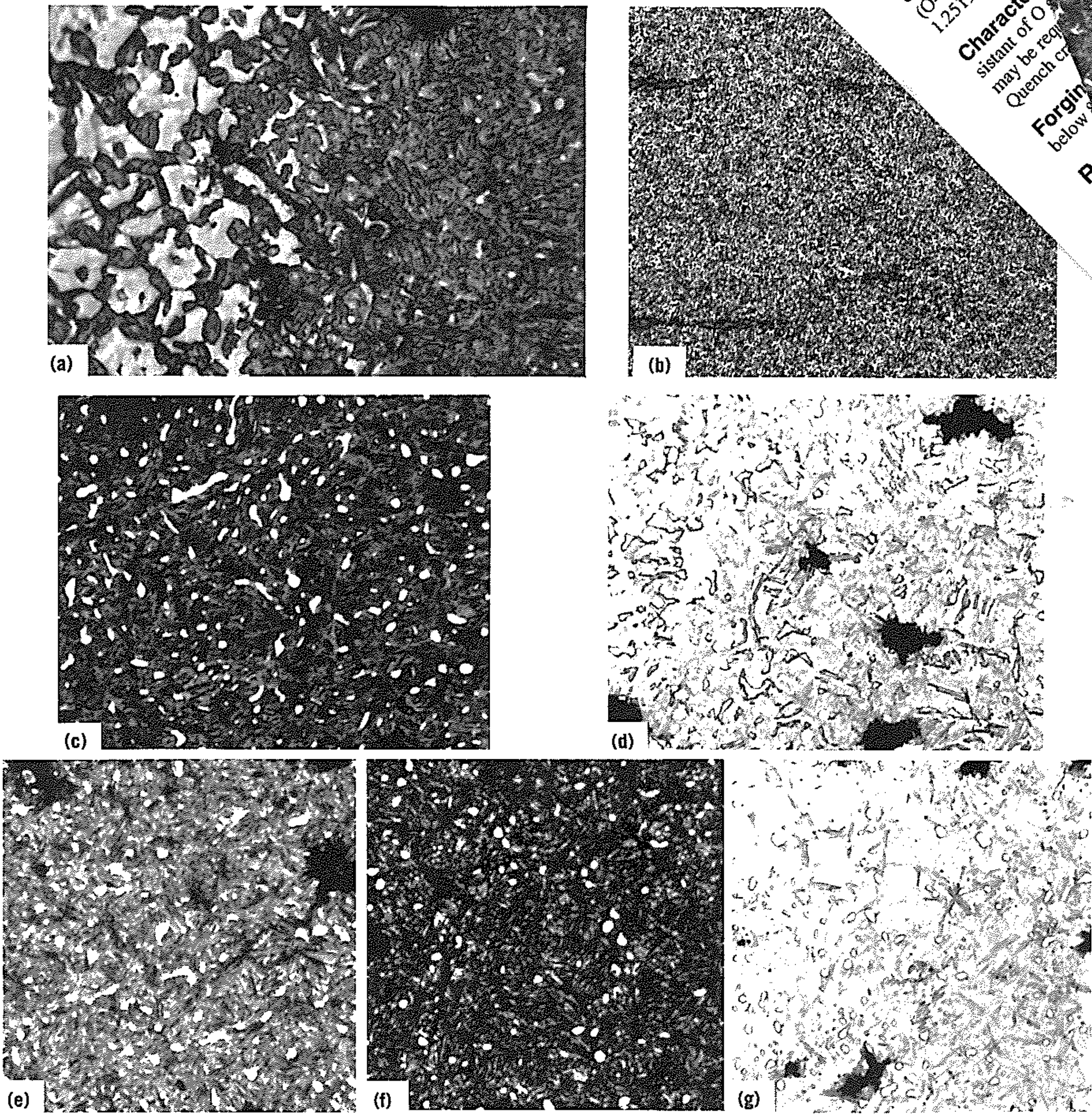


7

emical Composition. **AISI:** Nominal. 1.20 C, 0.75 Cr, 1.75 W. **I/UNS (T31507):** 1.10 to 1.30 C, 1.00 Mn max, 0.60 Si max, 0.30 Ni ., 0.35 to 0.85 Cr, 0.30 Mo max, 0.40 V max, 1.00 to 2.00 W

nilar Steels (U.S. and/or Foreign). AISI O-7; ASTM A681 7); FED QQ-T-570 (O-7); (Ger.) DIN 1.2414, 1.2419, 1.2442, 1.2516, 519; (Fr.) AFNOR A35-590 2141 105 WC 13; (Jap.) JIS G4404 SKS 2

aracteristics. Generally low hardenability although most wear re- ınt of O series steels. Hardenability is marginal, and water quenching / be required to obtain desired hardness, particularly in larger sections. ench cracking may be a problem with the more drastic quench

rging. Start forging at 980 to 1095 °C (1795 to 2005 °F). Do not forge ow 870 °C (1600 °F)

:commended Heat Treating Practice

rmalizing. Heat to 900 °C (1650 °F). After uniform through heating, ding time varies from approximately 15 min for small sections to roximately 1 h for large sections. Work is cooled from temperature in l air

nealing. Heat to 790 to 815 °C (1455 to 1500 °F). Use lower tem- ature for small sections and upper temperature for large sections. Hold- time is approximately 1 to 4 h. Use shorter time for light sections and all furnace charges, and longer time for heavy sections and large charges. pack annealing, hold for 1 h per inch of cross section. Cool to 540 °C 00 °F) at a rate not to exceed 22 °C (40 °F) per h, after which controlled oling is not necessary. Typical annealed hardness, 192 to 217 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Heat slowly. Preheat at 650 °C (1200 °F). If water quench is used, austenitize at 790 to 830 °C (1455 to 1525 °F) for 10 to 30 min and quench in water for a quenched hardness of 64 to 66 HRC. To prevent cracking, do not let tool cool below 60 °C (140 °F) and temper immediately. If oil quench is used, austenitize at 815 to 885 °C (1500 to 1625 °F) for 10 to 30 min and quench in oil for a quenched hardness of 64 to 66 HRC. Sections larger than 38 mm (1 ½ in.) will be softer

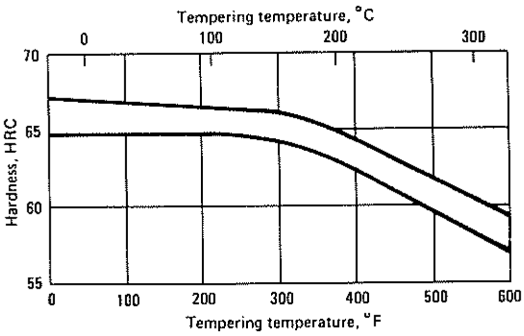
Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) for 20 to 30 min. Refrigerate at –100 to –195 °C (–150 to –320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 175 to 290 °C (345 to 555 °F) for a corresponding approximate tempered hardness of 64 to 58 HRC

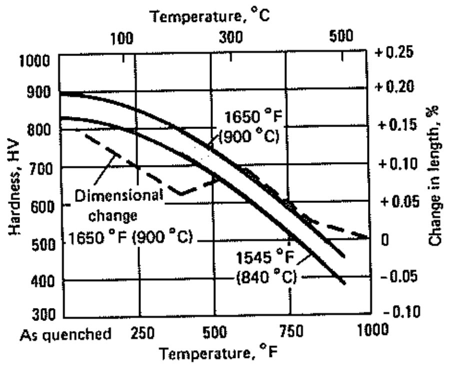
Recommended Processing Sequence

- Normalize
- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size

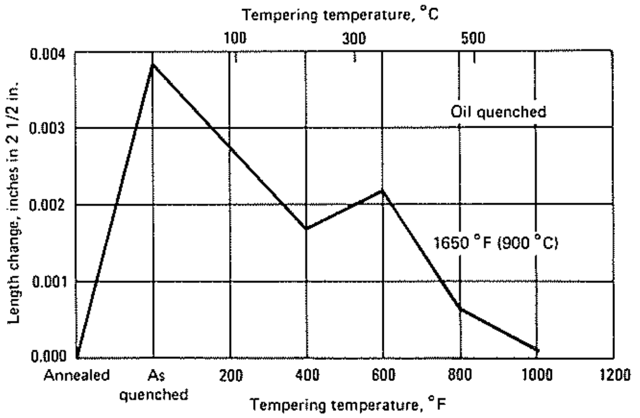
)7: Hardness vs Tempering Temperature. Hardness as a function of austenitizing and tempering temperatures. Large uniform ections were austenitized at 800 to 830 °C (1475 to 1525 °F) and vater quenched. Other sections were austenitized at 830 to 870 C (1525 to 1600 °F) and oil quenched. Duration of tempering was h



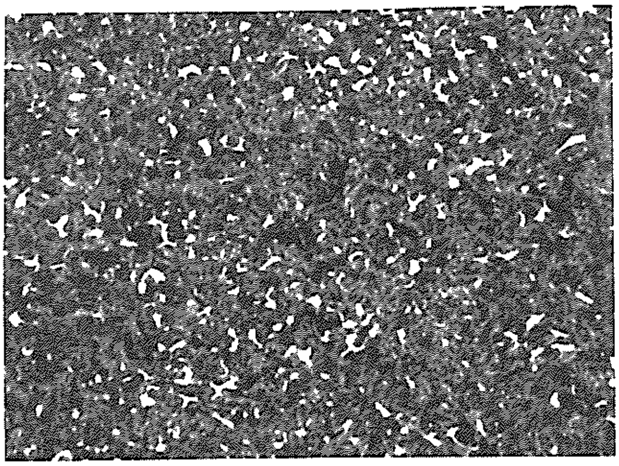
O7: Dimensional Change vs Tempering Temperature. Austenitized at 900 °C (1650 °F). Band shows approximate upper and lower hardness limits after tempering the steel when austenitized at 840 °C (1545 °F) and 900 °C (1650 °F). Shaded portion indicates optimum tempering range. Source: Bain and Grossman



O7: Length Changes vs Tempering Temperature. Quenched from the indicated temperature. Source: Bain and Grossman and Allegheny Ludlum Industries



O7: Microstructures. Nital, 1000×. Austenitized at 885 °C (1625 °F), quenched in oil, and then tempered at 205 °C (400 °F). Structure consists of undissolved particles of carbide (white) in a matrix of tempered martensite



Medium-Alloy, Air-Hardening Cold Work Tool Steels (A Series)

ıtroduction

The medium-alloy, air-hardening cold work tool steels considered in ; section are identified by the letter "A", followed by the numbers 2 ough 4, and 6 through 10. All have high hardenability and harden readily en cooled in air, the recommended quenching medium. Except for type 0, normalizing is not recommended for any of the A series steels.

All of these steels are usually supplied in the annealed condition by the nufacturer and, therefore, require annealing only after forging or weld-;, or prior to rehardening. Stress relieving is performed between rough 1 finish machining, or is generally limited to tools that cannot be ground ɜr hardening or to tools machined to final shape which can be straight-ːd after stress relieving and before final heat treatment.

To minimize distortion, these steels are almost always preheated before ng austenitized for hardening. They are austenitized in molten salt or in ·ious types of furnaces, using gaseous atmospheres for protection against ːdation and/or decarburization. The steels with the lowest austenitizing ıperatures, notably A4, A5, and A6, are often austenitized in molten lead in furnaces without protective atmospheres. The absence of protection of course, a calculated risk. Excessively high austenitizing temperatures ɔmote the retention of austenite upon cooling and should be avoided. All ;eries steels, as previously noted, are quenched in air.

The tempering practices for A series steels are essentially the same as ɔse employed for the D and O series steels. Tempering is usually begun en the steel reaches a temperature of approximately 50 to 66 °C (120 to 150 °F). Double, and even triple, tempering is used to maximize transformation of austenite to martensite. Stabilizing at subzero temperatures is also employed, always followed by tempering to avoid cracking newly transformed martensite.

The A series steels, notably A2 and A7, are often nitrided after hardening and tempering, when the presence of a nitrided layer is advantageous to the specific application.

The A tool steels cover a wide range of carbon and alloy contents, but all have high hardenability and harden readily by air cooling. All exhibit a high degree of dimensional stability in heat treatment. This property along with fairly good wear resistance and moderate price (compared to the cost of 12% chromium grades of the D series) make the A grades popular for a multitude of tooling applications.

The most readily available and widely used grade is A2. It does not possess the wear resistance of the D series, the toughness of the S series, or the resistance to softening at elevated temperature of the H series, but it rates higher in these properties than the manganese types of this series.

The low-carbon types A8 and A9 offer greater shock resistance than the other steels in this group, but are lower in wear resistance. Type A7, which has high carbon and vanadium content, exhibits maximum abrasion resistance, but should be restricted to applications where toughness is not a prime consideration. A10 is a graphitic steel, having properties similar to O6 except that A10 is higher in hardenability.

ı2

ıemical Composition. **AISI:** Nominal. 1.00 C, 5.00 Cr, 1.00 Mo. **SI/UNS (T30102):** 0.95 to 1.05 C, 1.00 Mn max, 0.50 Si max, 0.30 Ni ıx, 4.75 to 5.50 Cr, 0.90 to 1.40 Mo, 0.15 to 0.5 V

milar Steels (U.S. and/or Foreign). ASTM A681 (A-2); FED Ɔ-T-570 (A-2); SAE J437 (A2), J438 (A2); (Ger.) DIN 1.2363; (Fr.) ·NOR A35-590 2231 Z 100 CDV 5; (Jap.) JIS G4404 SKD 12; (Swed.) 2260; (U.K.) B.S. 4659 BA2

ıaracteristics. Deep hardening, with low distortion and very high ·ety in heat treating. High resistance to softening at elevated temperatures d medium resistance to decarburization. Has a tendency to retain stenite, which usually is eliminated or reduced to insignificant amounts ring tempering and double tempering

ɔrging. Heat slowly. Preheat at 650 to 675 °C (1200 to 1245 °F). Start rging at 1010 to 1095 °C (1850 to 2005 °F). Do not forge below 900 °C 550 °F). Cool slowly

ecommended Heat Treating Practice

ɔrmalizing. Do not normalize

nnealing. Heat slowly and uniformly to 845 to 870 °C (1555 to 1600). After soaking adequately for section size, restrict cooling to a maximum rate of 22 °C (40 °F) per h until 540 °C (1000 °F) is reached, after which a faster rate may be used. Typical annealed hardness, 201 to 229 HB. This grade can be isothermally annealed by cooling to 760 °C (1400 °F) from the annealing temperature, holding for 4 to 6 h and air cooling

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

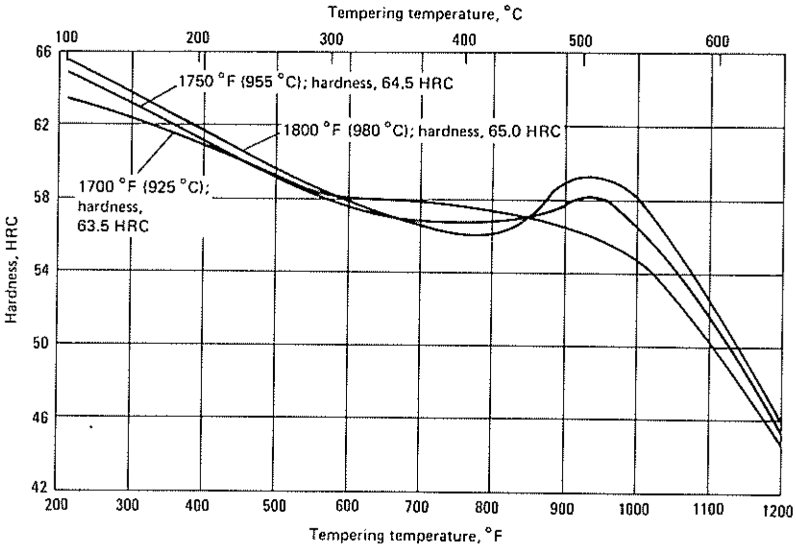
Hardening. Heat slowly. Preheat at 790 °C (1455 °F), austenitize at 925 to 980 °C (1695 to 1795 °F), and hold at temperature for 20 min for small tools to 45 min for large tools. Air cool as evenly as possible on all sides, particularly when cooling long flat dies. Typical quenched hardness, 62 to 65 HRC

Stabilizing. Optional. Low-temperature treatment may increase hardness and improve dimensional stability by reducing the amount of retained austenite, particularly when temperatures at the upper end of the austenitizing range are used. It is safer and definitely recommended to stress relieve temper at 150 to 160 °C (300 to 320 °F) for a short period before refrigerating to −85 °C (−120 °F), particularly for intricate shapes or tools having abrupt changes in section size. Temper immediately after tool reaches room temperature

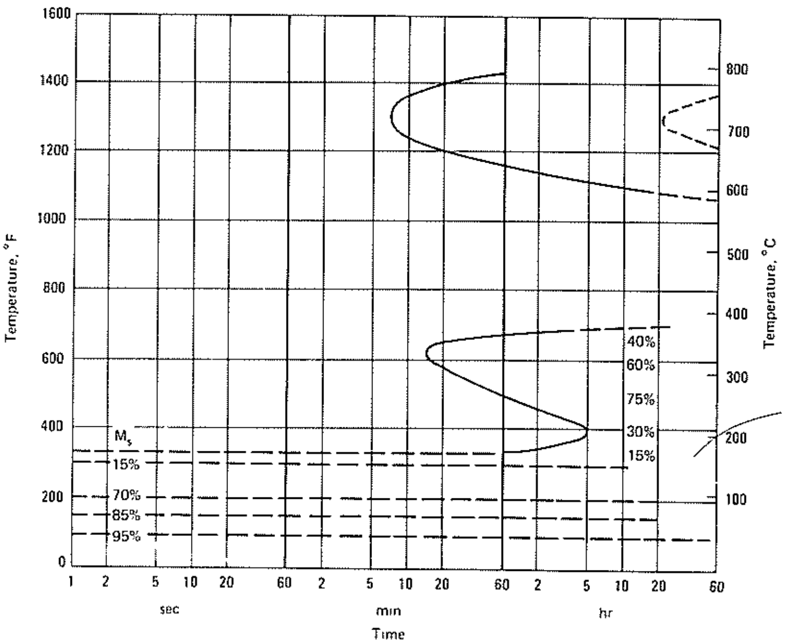
Tempering. Temper immediately at 175 to 540 °C (345 to 1000 °F) after tool has cooled to 50 to 66 °C (120 to 150 °F). Double temper, allowing tool to cool to room temperature before second temper. Range of hardness after tempering, 62 to 57 HRC. Tempering between 175 to 230 °C (345 to 445 °F) is recommended for maximum wear resistance, and between 370 to 400 °C (700 to 750 °F) for maximum shock resistance

Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/double temper
- Final grind

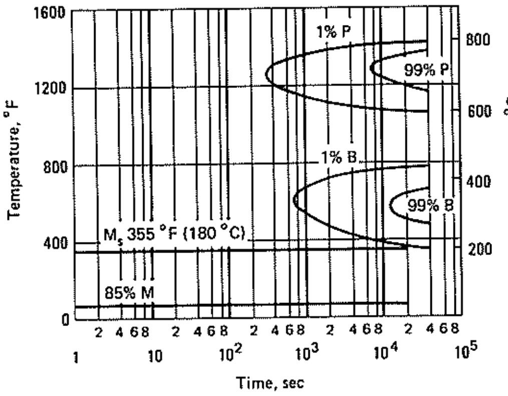


A2: Hardness vs Tempering Temperature. Austenitized at various temperatures and air cooled. Source: Universal-Cyclops

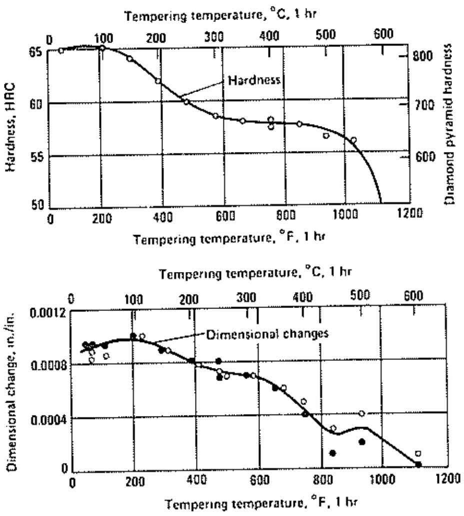


A2: Isothermal Transformation Diagram. 0.97 C, 0.48 Mn, 0.40 Si, 4.58 Cr, 1.04 Mo, 0.25 V. Prior condition, annealed. Austenitizing temperature, 1010 °C (1850 °F)

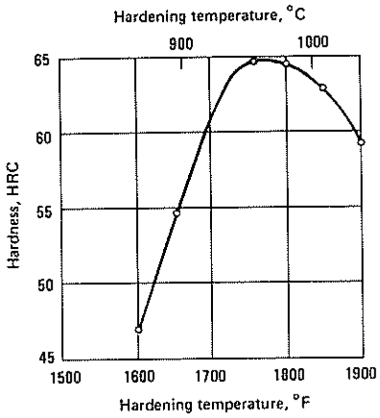
2: Isothermal Transformation Diagram. Swedish grade ustenitized at 950 °C (1740 °F). Source: Uddeholm



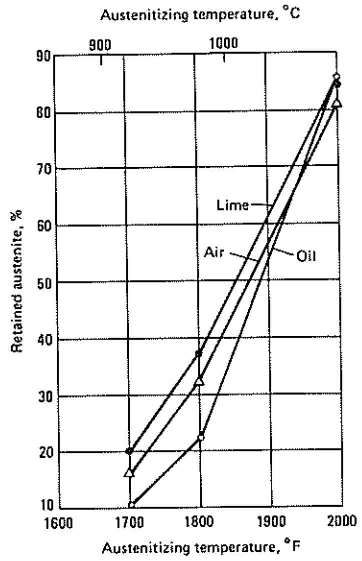
\2: Tempering Temperature vs Hardness and Dimensional Change. Cooled in 75% hydrogen and 25% nitrogen gas from)45 °C (1730 °F). Contains 1.00 C, 0.65 Mn, 0.30 Si, 5.20 Cr, 1.00 Mo, 0.25 V. Specimens, 25 mm (1 in.) diam, 50 mm (2 in.) long. O, diameter change; ●, length change

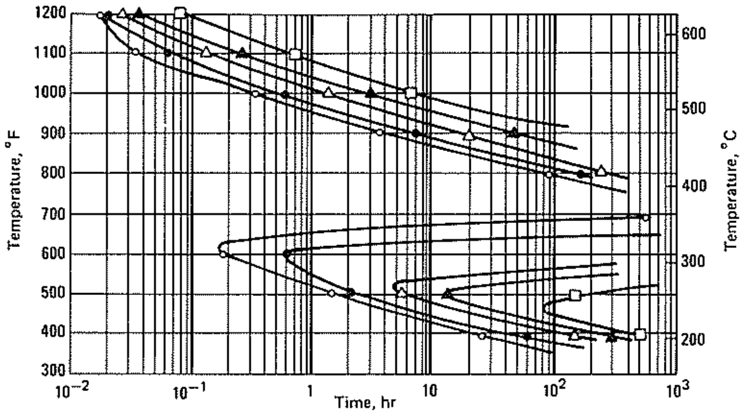


A2: Austenitizing Temperature vs Surface Hardness. Composition: 1.00 C, 0.50 Mn, 5.00 Cr, 1.00 Mo, 0.20 V, air cooled from the austenitizing temperature. Specimen size was 25 mm (1 in.) diam by 50 mm (2 in.) long. Source: Allegheny Ludlum Industries

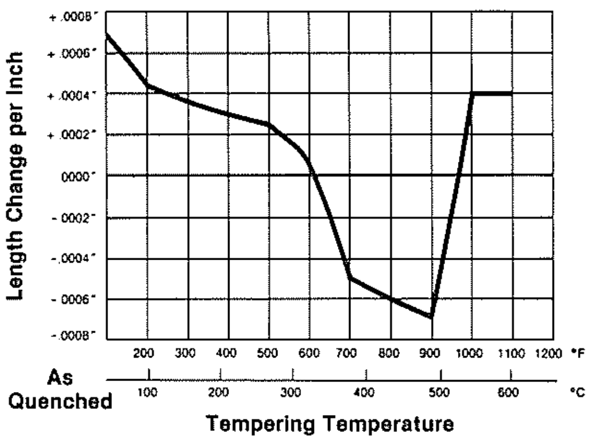


A2: Austenitizing Temperature vs Retained Austenite. Composition: 1.00 C, 0.61 Mn, 0.17 Si, 5.31 Cr, 1.13 Mo, 0.27 V, cooled at different rates

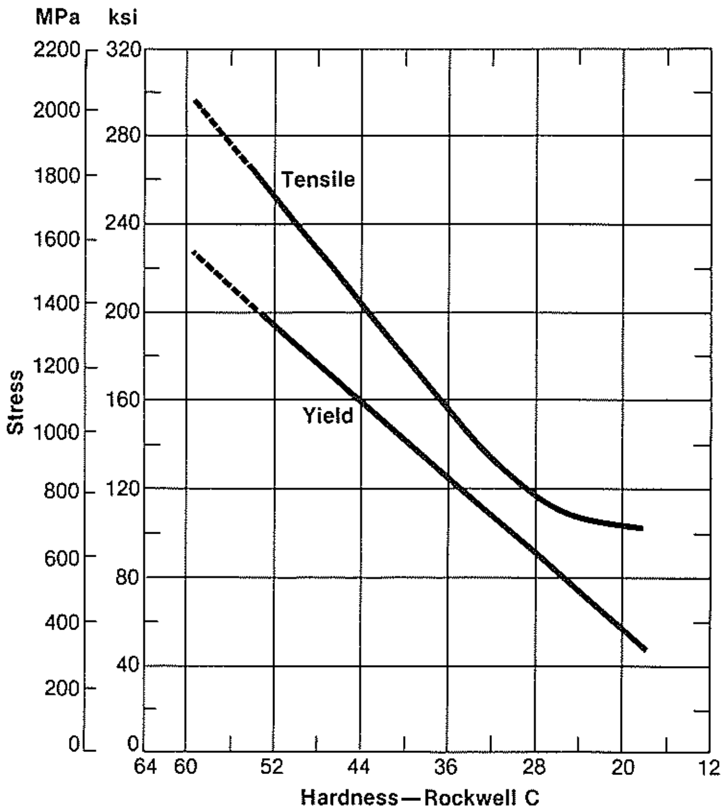




A2: Transformation of Retained Austenite. Transformation curves apply to structure at room temperature after tempering. O 30% transformed ● 50% transformed, Δ 75% transformed, ▲ 90% transformed, □ 100% transformed for A2 tool steel containing 1.00 C, 0.61 Mn, 0.014 P, 0.013 S, 0.17 Si, 5.31 Cr, 1.13 Mo, 0.27 V, air cooled from 980 °C (1795 °F)

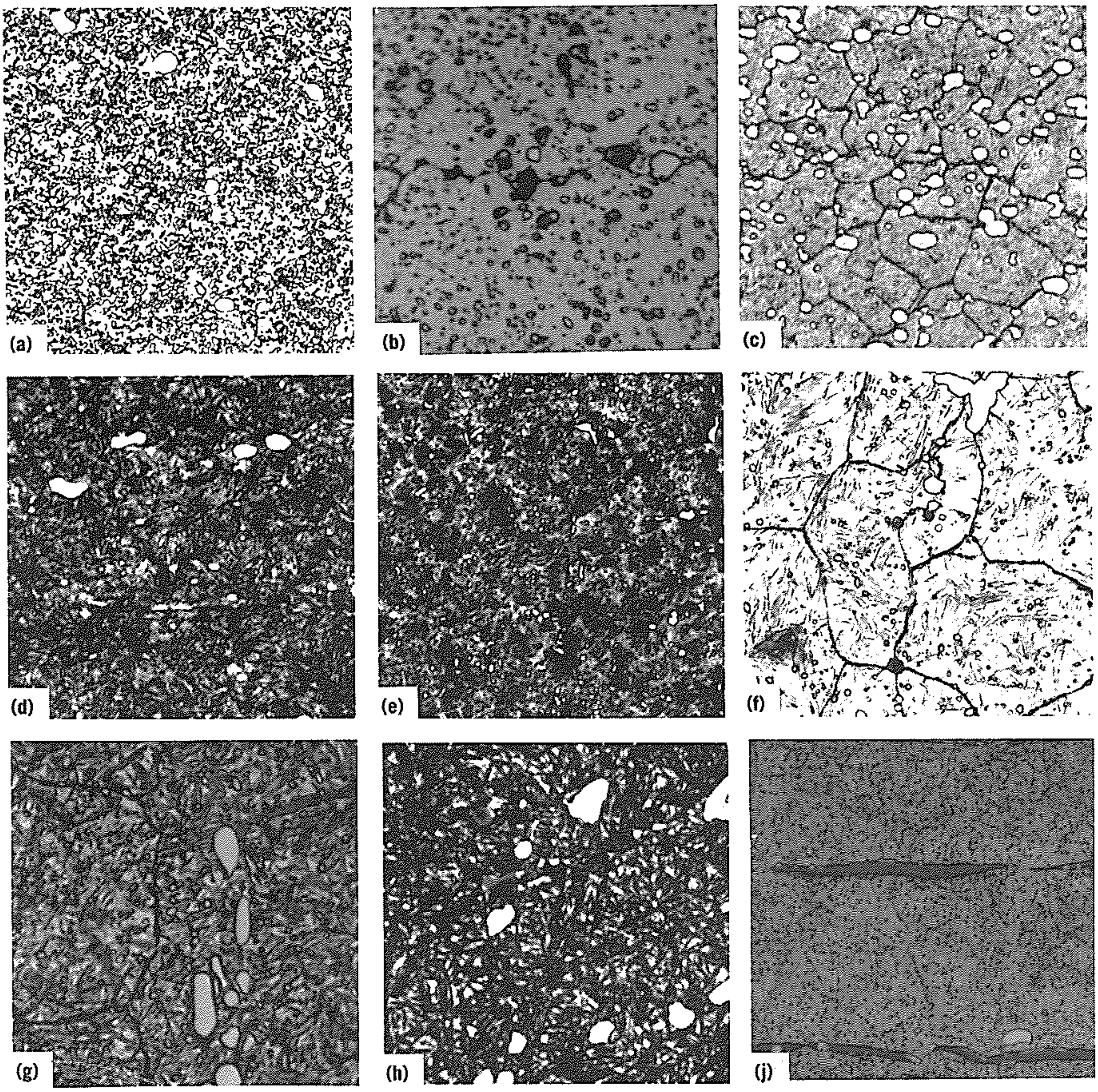


A2: Size Change in Hardening. Bar 25 mm (1 in.) in diam was air quenched from 955 °C (1750 °F); tempered 1 h at temperature. Source: Carpenter Technology Corporation



A2: Typical Tensile and Yield Strengths. Source: Carpenter Technology Corporation

2: Microstructures. (a)4% nital, 1000×. Annealed by austenitizing at 845 °C (1555 °F) and furnace cooling. Massive carbide and fine spheroidal carbide particles in matrix of ferrite. (b) 3% nital, 1000×. Austenitized at 980 °C (1795 °F) and air cooled (not tempered). 64 HRC. Spheroidal carbide particles in matrix of untempered martensite. (c) 4% nital, 1000×. Austenitized at 955 °C (1750 °F), air cooled, tempered at 150 °C (300 °F). Spheroidal carbide particles in matrix of tempered martensite. See (f). (d) 4% nital, 1000×. Austenitized at 955 °C (1750 °F), air cooled to room temperature, tempered at 540 °C (1000 °F). Particles of carbide (both massive alloy carbide and spheroidal carbide in matrix of tempered martensite. See (e). (e) 4% nital, 1000×. Austenitized at 925 °C (1695 °F), air cooled, tempered at 540 °C (1000 °F). Structure similar to (d), except considered underheated in austenitizing because more undissolved small carbide particles are present. (f) 4% nital, 1000×. Austenitized at 980 °C (1795 °F), air cooled to room temperature, Tempered at 150 °C (300 °F). Structure same as (c), except grains are coarser because austenitizing temperature was higher. (g) 3% nital, 1000×. Austenitized at 980 °C (1795 °F), air cooled, tempered at 175 °C (345 °F). 63 HRC. Large alloy carbide particles and small spheroidal carbide particles in matrix of tempered martensite. Grain boundaries (black lines) barely visible. (h) 3% nital, 1000×. Austenitized at 980 °C (1795 °F), air cooled, tempered at 540 °C (1000 °F). Hardness, 53 HRC. Particles of carbide (both massive alloy carbide and spheroidal carbide) in matrix of tempered martensite. (j) 3% nital, 500×. Austenitized at 980 °C (1800 °F), air cooled, tempered at 175 °C (345 °F). Longitudinal section. Large and small spheroidal carbide particles in tempered martensite. Streaks are sulfide stringers



A3

Chemical Composition. **AISI:** Nominal. 1.25 C, 5.00 Cr, 1.00 Mo, 1.00 V. **AISI/UNS (T30103):** 1.20 to 1.30 C, 0.40 to 0.60 Mn, 0.50 Si max, 0.30 Ni max, 4.75 to 5.50 Cr, 0.90 to 1.40 Mo, 0.80 to 1.40 V

Similar Steels (U.S. and/or Foreign). ASTM A681 (A-3); QQ-T-570 (A-3), FED QQ-T-570 (A-4)

Characteristics. Essentially similar to an A2 steel, with 0.25 carbon and 0.75 vanadium added for increased wear resistance. Austenitizing temperature is 10 °C (18 °F) higher, and soak time is longer than for A2. A deep air-hardening steel having low distortion and very high safety in heat treating. High resistance to softening at elevated temperatures, and medium to high resistance to decarburization. Has a tendency to retain austenite, which is usually eliminated or reduced to insignificant amounts during tempering and double tempering

Forging. Heat slowly. Preheat at 650 to 675 °C (1200 to 1245 °F). Start forging at 1010 to 1065 °C (1850 to 1950 °F). Do not forge below 900 °C (1650 °F). Cool slowly

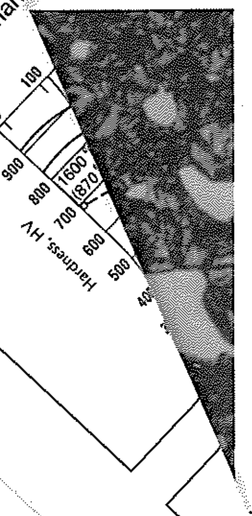
Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat slowly and uniformly to 845 to 870 °C (1555 to 1600 °F). After soaking adequately for section size, restrict cooling to a maximum rate of 22 °C (40 °F) per h until 540 °C (1000 °F) is reached, after which a faster rate may be used. Typical annealed hardness, 207 to 229 HB. This grade can be isothermally annealed by cooling to 760 °C (1400 °F) from the annealing temperature, holding for 4 to 6 h and air cooling

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

1795 °F), air cooled, tempered at ... ent as (d), except at higher mag- ... nite. (f), 1000×. Same steel and ... de particles increase wear re-



h... temp... ating t... abrupt cha... temperature

Tempering. Te... tool has cooled to 50 ... tool to cool to room temp... after tempering, 65 to 57 H...

Recommended Proce...

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/double temper
- Final grind

Note: Transformation and tempering data for A2 tool steel are ... applicable to A3

A4

Chemical Composition. **AISI:** Nominal. 1.00 C, 2.00 Mn, 5.00 Cr, 1.00 Mo. **AISI/UNS (T30104):** 0.95 to 1.05 C, 1.80 to 2.20 Mn, 0.50 Si max, 0.30 Ni max, 0.90 to 2.20 Cr, 0.90 to 1.40 Mo

Similar Steels (U.S. and/or Foreign). ASTM A681 (A-4); FED QQ-T-570 (A-4)

Characteristics. A manganese-alloyed air-hardening tool steel. Compared to A2, the chromium content has been reduced from 5 to 1%, and manganese has been increased from 1 to 2%. Has the advantage of a low austenitizing temperature. Isothermal characteristics similar to A2 steel. Classified as deep hardening. Among tool steels having lowest distortion in heat treating. Medium to high resistance to decarburization

Forging. Heat slowly. Preheat at 650 to 675 °C (1200 to 1245 °F). Start forging at 1010 to 1095 °C (1850 to 2005 °F). Do not forge below 900 °C (1650 °F). Cool slowly

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat slowly and uniformly to 740 to 760 °C (1365 to 1400 °F). After soaking adequately for section size, restrict cooling to a maximum rate of 15 °C (25 °F) per h until 540 °C (1000 °F) is reached, after which a faster rate may be used. Typical annealed hardness, 200 to 241 HB. For minimum hardness, a second anneal can be used. Repeat the cycle using 730 °C (1350 °F) as the annealing temperature

Stress Relieving. Optional. Heat to 675 to 705 °C (1245 to 1300 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Heat slowly. Preheat at 675 °C (1245 °F), austenitize at 815 to 870 °C (1500 to 1600 °F), and hold at temperature for 15 min for small tools to 90 min for large tools. Quench by air cooling as evenly as possible on all sides, particularly when cooling long flat dies. As quenched hardness, 61 to 64 HRC

Stabilizing. Optional. Low-temperature treatment may increase hardness and improve dimensional stability by reducing the amount of retained austenite, particularly when temperatures at the upper end of the austenitizing range are used. It is safer and definitely recommended to stress relieve temper at 150 to 160 °C (300 to 320 °F) for a short period before refrigerating to −85 °C (−120 °F), particularly for intricate shapes or tools having abrupt changes in section size. Temper immediately after tool reaches room temperature

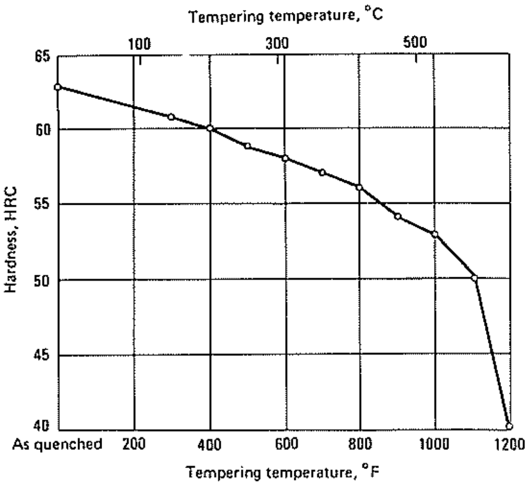
Tempering. Temper immediately at 175 to 425 °C (345 to 795 °F) after tool has cooled to 50 to 66 °C (120 to 150 °F). Double temper, allowing

l to cool to room temperature before second temper. Range of hardness
:r tempering, 62 to 54 HRC

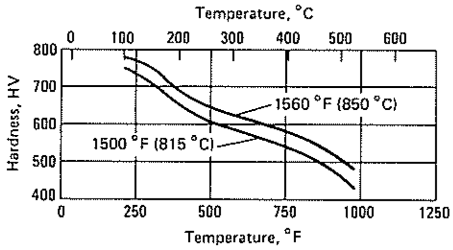
:commended Processing Sequence

- ʀough machine
- ;tress relieve (optional)
- ᵎinish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/double temper
- Final grind

.4: Hardness vs Tempering Temperature. Austenitized at 845 C (1555 °F) and cooled in air



A4: Hardness vs Tempering Temperature. Austenitized at 815 °C (1500 °F) and at 850 °C (1560 °F) and cooled in air. Data represent upper and lower limits of hardness



.6

ıemical Composition. **AISI:** Nominal. 0.70 C, 2.00 Mn, 1.00 Cr, .5 Mo. **AISI/UNS (T30106):** 1.25 to 1.55 C, 0.30 to 1.10 Mn, 0.55 to 0 Si, 0.30 Ni max, 0.30 Cr max, 0.20 to 0.30 Mo

milar Steels (U.S. and/or Foreign). ASTM A681 (A-6); FED)-T-570 (A-6); (U.K.) B.S. 4659 BA6

ıaracteristics. Has properties roughly similar to A4 except with ver carbon content. Among the lowest in distortion in heat treating. Deep ·dening, with high safety in hardening. Medium resistance to softening :levated temperature, and medium to high resistance to decarburization

ırging. Heat slowly. Start forging at 1040 to 1120 °C (1905 to 2050 °F). ı not forge below 870 °C (1600 °F)

:commended Heat Treating Practice

ɔrmalizing. Do not normalize

ınealing. Heat slowly and uniformly to 730 to 745 °C (1350 to 1370). After soaking adequately for section size, restrict cooling to a maxiım rate of 15 °C (25 °F) per h until 540 °C (1000 °F) is reached, after ıich a faster rate may be used. Typical annealed hardness, 217 to 248 HB.

ress Relieving. Optional. Heat to 675 to 705 °C (1245 to 1300 °F) ɪ hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

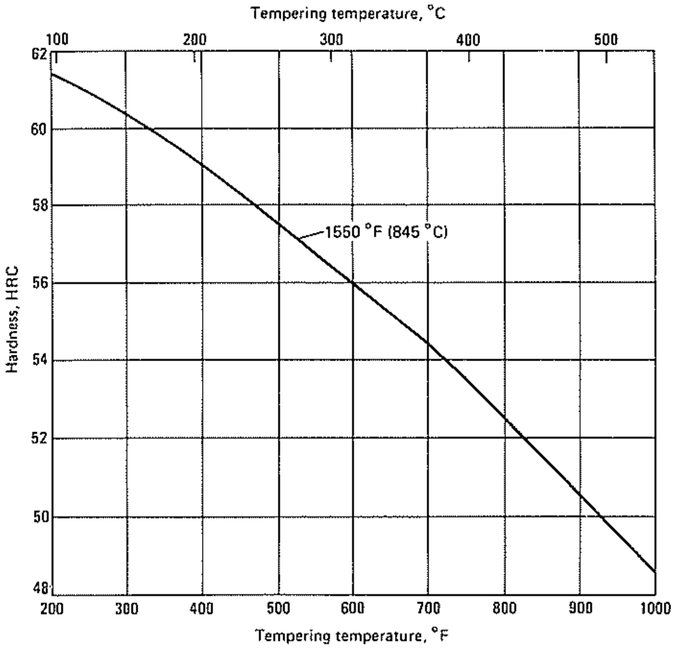
ırdening. Heat slowly. Preheat at 650 °C (1200 °F), austenitize at 830 870 °C (1525 to 1600 °F), and hold at temperature for 20 min for small tools to 45 min for large tools. Air quench. Typical quenched hardness, 59 to 63 HRC

Stabilizing. Optional. Low-temperature treatment may increase hardness and improve dimensional stability by reducing the amount of retained austenite, particularly when temperatures at the upper end of the austenitizing range are used. It is safer and definitely recommended to stress relieve temper at 150 to 160 °C (300 to 320 °F) for a short period before refrigerating to –85 °C (–120 °F), particularly for intricate shapes or tools having abrupt changes in section size. Temper immediately after tool reaches room temperature

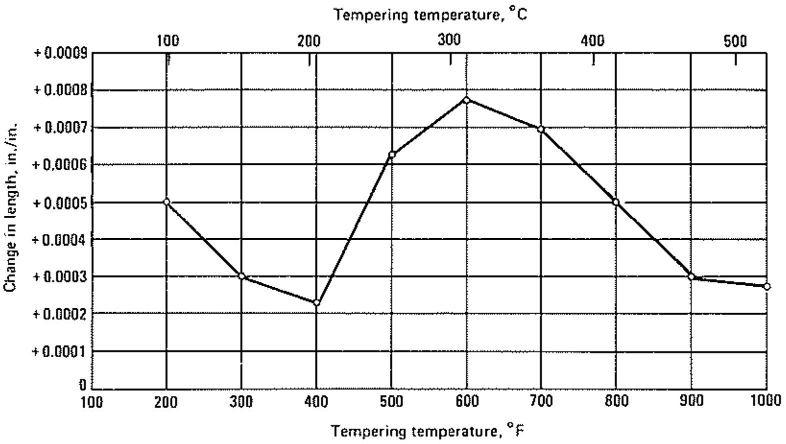
Tempering. Temper immediately at 150 to 425 °C (300 to 795 °F) after tool has cooled to 50 to 66 °C (120 to 150 °F). Double temper, allowing tool to cool to room temperature before second temper. Range of hardness after tempering, 60 to 54 HRC

Recommended Processing Sequence

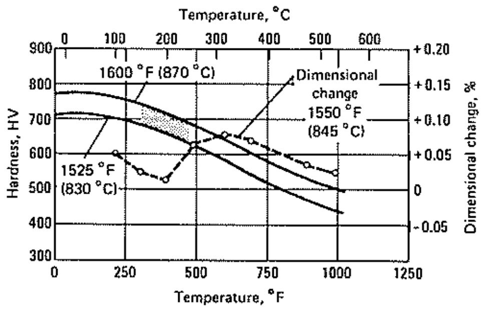
- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/double temper
- Final grind



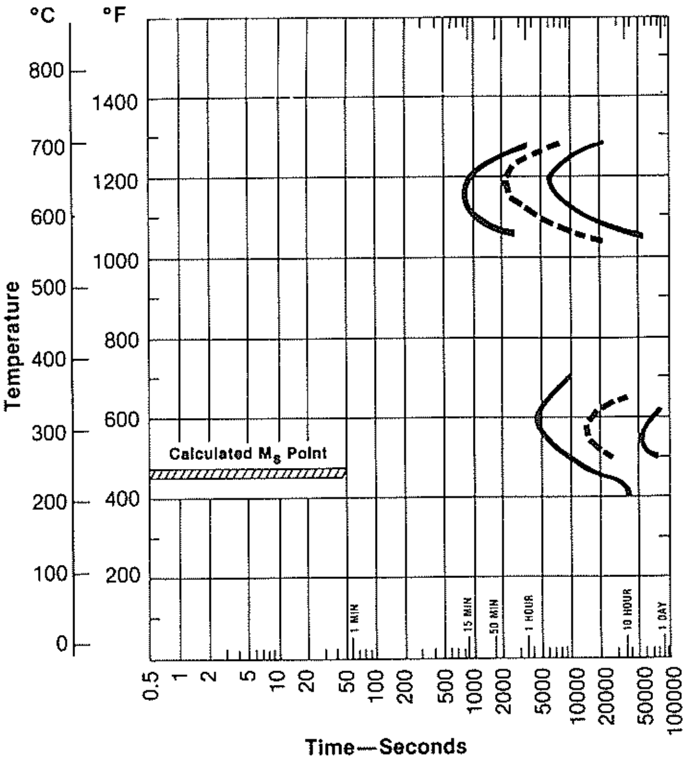
A6: Hardness vs Tempering Temperature. Austenitized at 845 °C (1555 °F) and air cooled. Hardness, 62 HRC. Source: Universal-Cyclops



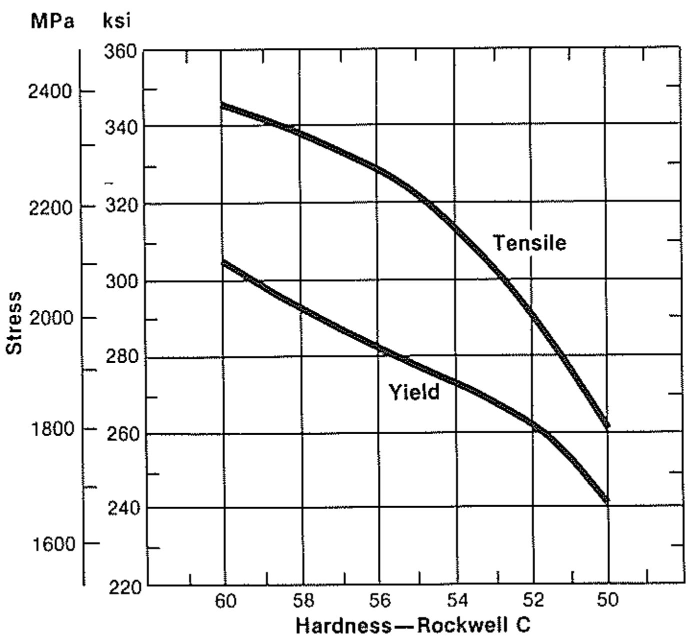
A6: Length Changes vs Tempering Temperature. Austenitized at 845 °C (1555 °F) and air cooled. Hardness, 62 HRC. Source: Allegheny Ludlum Industries and Carpenter Steel



A6: Tempering Characteristics vs Dimensional Change. Austenitized at 830 °C (1525 °F) and 870 °C (1600 °F) and air cooled, showing upper and lower limits of hardness. Dimensional changes, austenitized at 845 °C (1555 °F) and air cooled. Shaded portion indicates optimum tempering range which coincides with lowest dimensional change. Source: Carpenter Steel

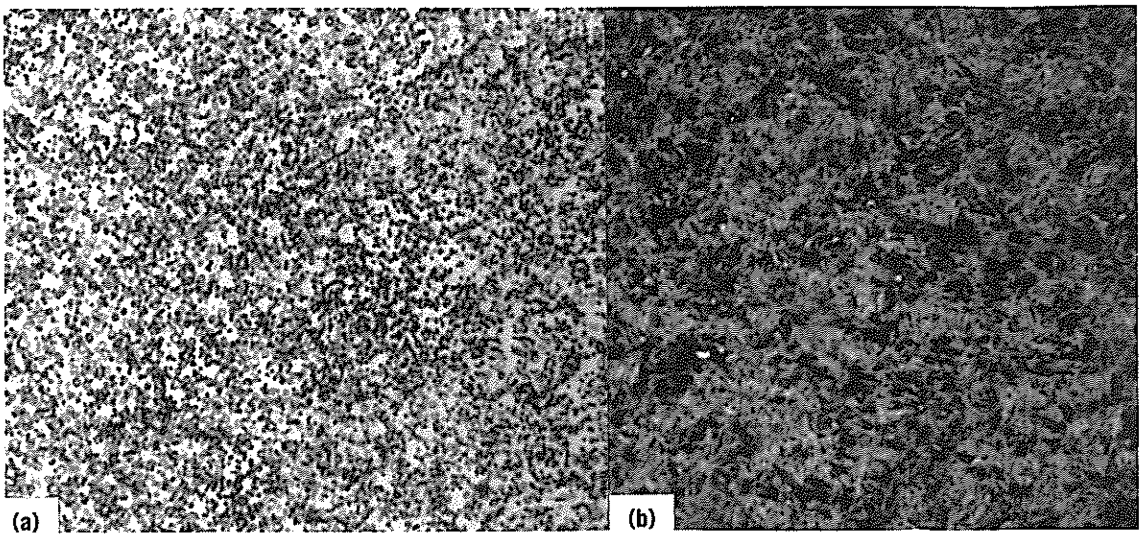


A6: Isothermal Transformation Diagram. Austenitized at 840 °C (1545 °F). Source: Carpenter Technology Corporation



A6: Typical Tensile and Yield Strengths. Source: Carpenter Technology Corporation

A6: Microstructures. (a) Nital, 1000×. Annealed by heating to 730 °C (1350 °F), holding 1 h per inch of section thickness and furnace cooling. Structure fine spheroidal carbide in matrix of ferrite. (b) Nital, 1000×. Austenitized ½ h at 845 °C (1555 °F), air cooled, and tempered 1 h at 175 °C (345 °F). Fine martensite matrix with a few undissolved carbide particles (white specks)



A7

Chemical Composition. **AISI:** Nominal. 2.25 C, 5.25 Cr, 1.00 Mo, 4.75 V, 1.00 W (optional). **AISI/UNS (T30107):** 2.00 to 2.85 C, 0.80 Mn max, 0.50 Si max, 0.30 Ni max, 5.00 to 5.75 Cr, 0.90 to 1.40 Mo, 3.90 to 5.15 V, 0.50 to 1.40 W

Similar Steels (U.S. and/or Foreign). ASTM A681 (A-7); FED QQ-T-570 (A-7)

Characteristics. Contains the highest carbon content of the A series steels, along with 4.75% vanadium and 5% chromium. Deep hardening with a relatively low austenitizing temperature. Low in distortion, with high resistance to softening at elevated temperatures, and medium resistance to decarburization

Forging. Heat slowly. Preheat at 650 to 675 °C (1200 to 1245 °F). Start forging at 1050 to 1150 °C (1920 to 2100 °F). Do not forge below 980 °C (1795 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat slowly and uniformly to 870 to 900 °C (1600 to 1650 °F). After soaking adequately for section size, restrict cooling to a maximum rate of 30 °C (55 °F) per h until 540 °C (1000 °F) is reached, after which a faster rate may be used. Typical annealed hardness, 235 to 262 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Heat slowly. Preheat at 815 °C (1500 °F), austenitize at 955 to 980 °C (1750 to 1795 °F), and hold at temperature for 30 min for small tools to 60 min for large tools. Air cool as evenly as possible on all sides, particularly when cooling long flat dies. Typical quenched hardness, 64 to 67 HRC

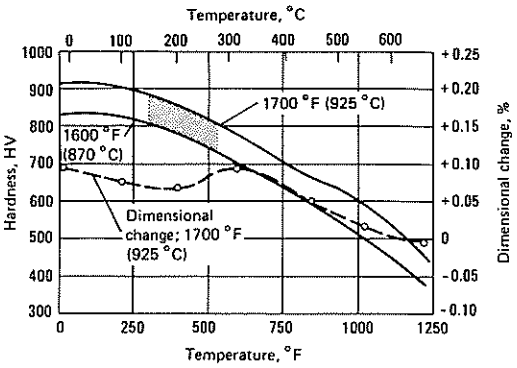
Stabilizing. Optional. Low-temperature treatment may increase hardness and improve dimensional stability by reducing the amount of retained austenite, particularly when temperatures at the upper end of the austenitizing range are used. It is safer and definitely recommended to stress relieve temper at 150 to 160 °C (300 to 320 °F) for a short period before refrigerating to −85 °C (−120 °F), particularly for intricate shapes or tools having abrupt changes in section size. Temper immediately after tool reaches room temperature

Tempering. Temper immediately at 150 to 540 °C (300 to 1000 °F) after tool has cooled to 50 to 66 °C (120 to 150 °F). Double temper, allowing tool to cool to room temperature before second temper. Range of hardness after tempering, 67 to 57 HRC

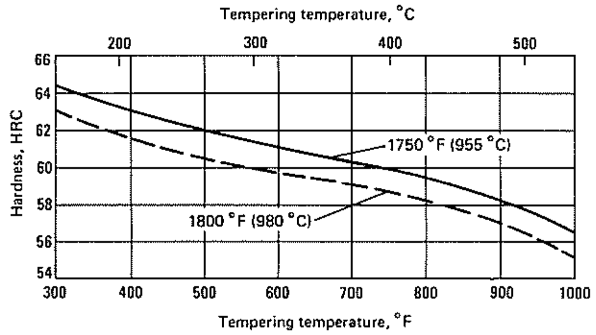
Recommended Processing Sequence

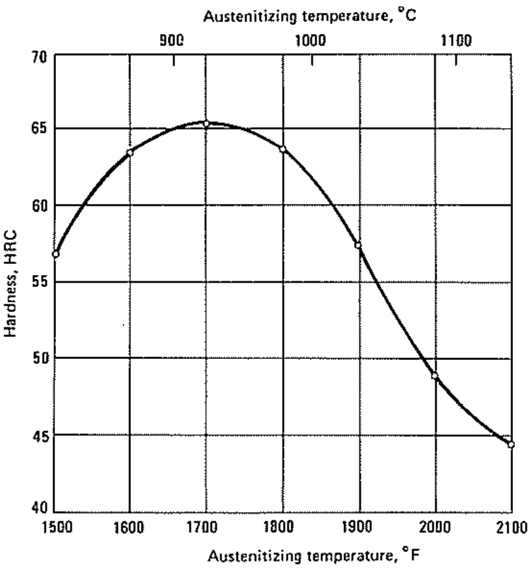
- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/double temper
- Final grind

A7: Tempering Characteristics vs Dimensional Change. Austenitized at 870 °C (1600 °F) and 925 °C (1695 °F) and air cooled, showing upper and lower limits of hardness. Dimensional changes for A7 tool steel, austenitized at 925 °C (1695 °F) and air cooled. Shaded portion shows optimum range which coincides with lowest dimensional change



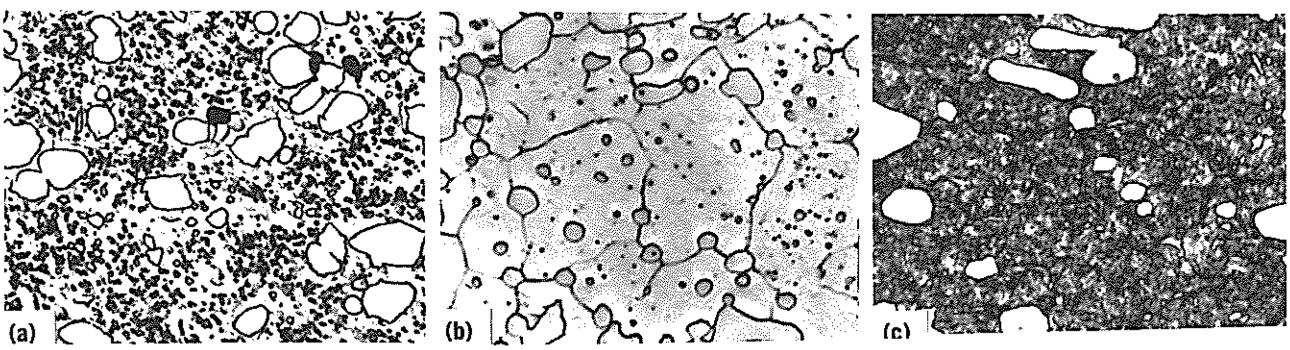
A7: Hardness vs Tempering Temperature. 13.5 mm (½ in.) plate austenitized at 955 °C (1750 °F) and air cooled. Hardness, 67 HRC. 76.2 mm (3 in.) cubes austenitized at 980 °C (1795 °F) and oil quenched. Hardness, 66 HRC. Source: Universal-Cyclops





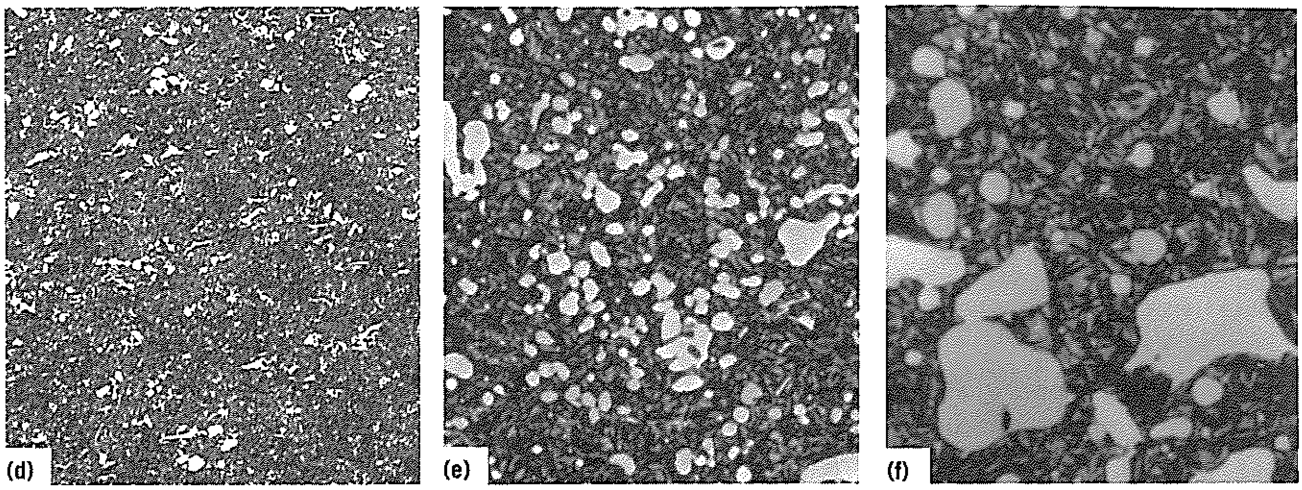
A7: Austenitizing Temperature vs As-Quenched Hardness. Composition: 2.30 C, 0.70 Mn, 0.40 Si, 5.25 Cr, 1.10 Mo, 4.75 V, 1.10 W, air quenched

A7: Microstructures. (a) 4% nital, 1000×. Box annealed at 900 °C (1650 °F) for 1 h per inch of container thickness and cooled at no higher than 25 °C (50 °F) per h. Structure massive alloy carbide and spheroidal carbide in a ferrite matrix. (b) 4% nital, 1000×. Austenitized at 955 °C (1750 °F), air cooled, tempered at 150 °C (300 °F). Structure massive alloy carbide (white areas) and a few spheroidal carbide particles in matrix of tempered martensite. (c) 4% nital, 1000×. Austenitized at 955 °C (1750 °F), air cooled, tempered at 315 °C (600 °F). Structure massive alloy carbide and a few spheroidal carbide particles in matrix of tempered martensite.



(continued)

A7: Microstructures. (continued) (d) Nital, 100×. Preheated at 675 °C (1245 °F), austenitized at 980 °C (1795 °F), air cooled, tempered at 175 °C (345 °F). See (e) and (f) for clear resolution of particles. (e) Nital, 500×. Same steel and heat treatment as (d), except at higher magnification. Structure large and small carbide particles in matrix of tempered martensite. Some retained austenite. (f), 1000×. Same steel and heat treatment as (d), except higher magnification. Evidence of retained austenite (light gray). Massive carbide particles increase wear resistance of steel surface



A8

Chemical Composition. **AISI:** Nominal. 0.55 C, 5.00 Cr, 1.25 Mo, 1.25 W. **AISI/UNS (T30108):** 0.50 to 0.60 C, 0.50 Mn max, 0.75 to 1.10 Si, 0.30 Ni max, 4.75 to 5.50 Cr, 1.15 to 1.65 Mo, 1.00 to 1.50 W

Similar Steels (U.S. and/or Foreign). ASTM A681 (A-8); FED QQ-T-570 (A-8); (Ger.) DIN 1.2606; (Fr.) AFNOR 3432 Z 38 CDW 5; (Jap.) JIS G4404 SKD 62

Characteristics. One of the toughest of the 5% Cr steels in the A series, containing a relatively low 0.55% C. Except for the lower carbon content and the addition of 1.25% W, it is similar to the widely used A2 grade. High resistance to softening at elevated temperature. Deep hardening, and among the lowest in distortion and the highest in safety in hardening of the tool steels, with medium resistance to decarburization

Forging. Heat slowly. Preheat at 650 to 675 °C (1200 to 1245 °F). Start forging at 1065 to 1150 °C (1950 to 2100 °F). Do not forge below 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat slowly and uniformly to 845 to 870 °C (1555 to 1600 °F). After soaking adequately for section size, restrict cooling to a maximum rate of 22 °C (40 °F) per h until 540 °C (1000 °F) is reached, after which a faster rate may be used. Typical annealed hardness, 192 to 223 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Heat slowly. Preheat at 790 °C (1455 °F), austenitize at 980 to 1010 °C (1795 to 1850 °F), and hold at temperature for 20 min for small tools to 45 min for large tools. Air cool. As-quenched hardness, 60 to 62 HRC

Stabilizing. Optional. Low-temperature treatment may increase hardness and improve dimensional stability by reducing the amount of retained austenite, particularly when temperatures at the upper end of the austenitizing range are used. It is safer and definitely recommended to stress relieve temper at 150 to 160 °C (300 to 320 °F) for a short period before refrigerating to −85 °C (−120 °F), particularly for intricate shapes or tools having abrupt changes in section size. Temper immediately after tool reaches room temperature

Tempering. Temper immediately at 175 to 595 °C (345 to 1105 °F) after tool has cooled to 50 to 66 °C (120 to 150 °F). Double temper, allowing tool to cool to room temperature before second temper. Range of hardness after tempering, 60 to 50 HRC

Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/double temper
- Final grind

\9

hemical Composition. **AISI:** Nominal. 0.50 C, 1.50 Ni, 5.00 Cr, 40 Mo, 1.00 V. **AISI/UNS (T30109):** 0.45 to .55 C, 0.50 Mn max, 0.95 1.15 Si, 1.25 to 1.75 Ni, 4.75 to 5.50 Cr, 1.30 to 1.80 Mo, 0.80 to 1.40 V

imilar Steels (U.S. and/or Foreign). ASTM A681 (A-9); FED Q-T-570 (A-9)

haracteristics. Similar to A8 in low carbon content, except with ghtly higher alloy content. Marked secondary hardening characteristics d usually tempered in the 510 to 620 °C (950 to 1150 °F) range. High in sistance to softening at elevated temperatures, deep hardening, and very w in distortion. Among the highest in safety in hardening, with medium sistance to decarburization

orging. Heat slowly. Preheat at 650 to 675 °C (1200 to 1245 °F). Start rging at 1065 to 1150 °C (1950 to 2100 °F). Do not forge below 925 °C 700 °F)

ecommended Heat Treating Practice

ormalizing. Do not normalize

nnealing. Heat slowly and uniformly to 845 to 870 °C (1555 to 1600 '). After soaking adequately for section size, restrict cooling to a maxi- um rate of 15 °C (25 °F) per h until 540 °C (1000 °F) is reached, after hich a faster rate may be used. Typical annealed hardness, 212 to 248 HB

tress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) d hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

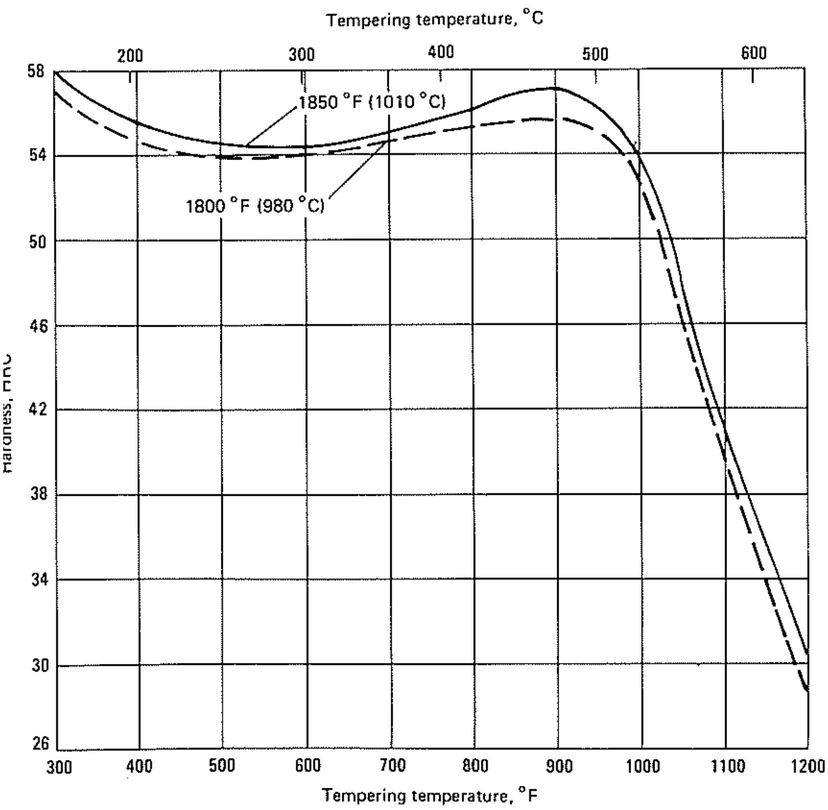
Hardening. Heat slowly. Preheat at 790 °C (1455 °F), austenitize at 980 to 1025 °C (1795 to 1875 °F), and hold at temperature for 20 min for small tools to 45 min for large tools. Air quench. Typical hardness, 56 to 58 HRC

Stabilizing. Optional. Low-temperature treatment may increase hardness and improve dimensional stability by reducing the amount of retained austenite, particularly when temperatures at the upper end of the austenitizing range are used. It is safer and definitely recommended to stress relieve temper at 150 to 160 °C (300 to 320 °F) for a short period before refrigerating to −85 °C (−120 °F), particularly for intricate shapes or tools having abrupt changes in section size. Temper immediately after tool reaches room temperature

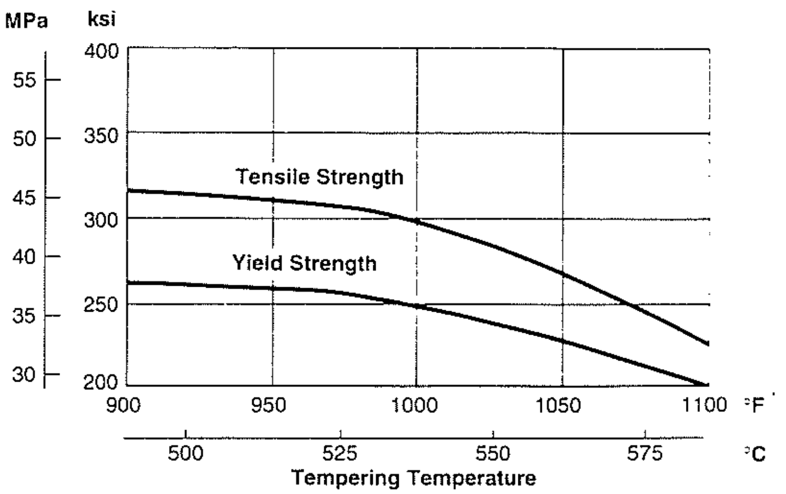
Tempering. Temper immediately at 510 to 620 °C (950 to 1150 °F) after tool has cooled to 50 to 66 °C (120 to 150 °F). Double temper, allowing tool to cool to room temperature before second temper. Range of hardness after tempering, 56 to 35 HRC

Recommended Processing Sequence

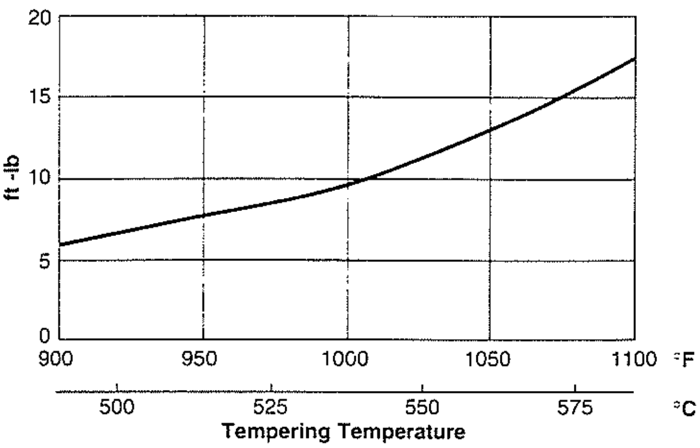
- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/double temper
- Final grind



A9: Hardness vs Tempering Temperature. Austenitized at 980 °C (1795 °F) and 1010 °C (1850 °F) and cooled in air. Source: Universal-Cyclops



A9: Typical Room-Temperature Tensile and Yield Strengths. Source: Carpenter Technology Corporation



A9: Typical Room-Temperature Charpy V-Notch Impact Data. Source: Carpenter Technology Corporation

A10

Chemical Composition. AISI: Nominal. 1.35 C, 1.80 Mn, 1.25 Si, 1.80 Ni, 1.50 Mo. **AISI/UNS (T30110):** 1.25 to 1.50 C, 1.60 to 2.10 Mn, 1.00 to 1.50 Si, 1.55 to 2.05 Ni, 1.25 to 1.75 Mo

Similar Steels (U.S. and/or Foreign). ASTM A681 (A-10); FED QQ-T-570 (A-10)

Characteristics. Manganese air hardening steel. Carbon and silicon high enough to precipitate out some carbon in the graphitic form, usually approximately 0.35% carbon. Medium to high in machinability. Deep hardening and among the lowest of tool steels in distortion in heat treating. Medium in toughness and resistance to softening at elevated temperature, high in wear resistance, and medium to high in resistance to decarburization

Forging. Heat slowly. Preheat at 650 to 675 °C (1200 to 1245 °F). Start forging at 980 to 1050 °C (1795 to 1920 °F). Do not forge below 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 790 °C (1455 °F). Holding time, after uniform through heating, varies from approximately 15 min, for small sections, to approximately 1 h, for large sections. Cool from temperature in still air

Annealing. Heat slowly and uniformly to 765 to 795 °C (1410 to 1460 °F). After soaking adequately for section size, restrict cooling to a maximum rate of 10 °C (15 °F) per h until 510 °C (950 °F) is reached, after which a faster rate may be used. Typical annealed hardness, 235 to 269 HB. For minimum hardness a second anneal can be used. Repeat the cycle using 730 °C (1350 °F) as the austenitizing temperature. An eight-step annealing cycle has been recommended, as follows:

1. Heat to 780 °C (1435 °F) and hold for 2 h
2. Cool to 540 °C (1000 °F) at 22 °C (40 °F) per h
3. Air cool to room temperature
4. Reheat to 780 °C (1435 °F) and hold 1 h per inch of section
5. Cool to 680 °C (1255 °F) at any convenient rate
6. Equalize at 680 °C (1255 °F) for 2 h
7. Cool to 510 °C (950 °F) at a rate not to exceed 8 °C (15 °F) per h
8. Air cool to room temperature

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

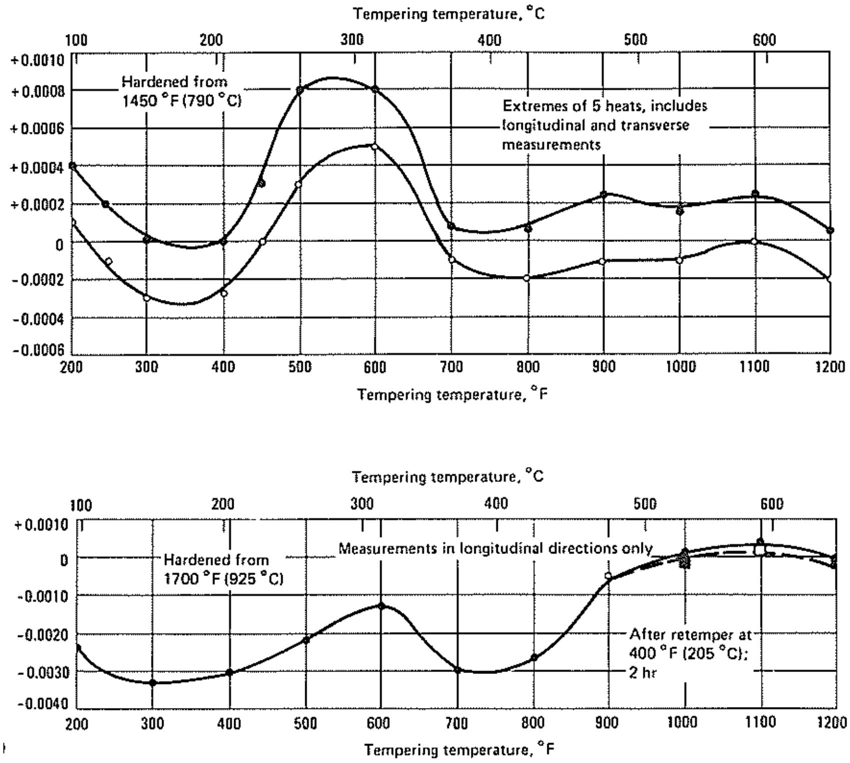
Hardening. Heat slowly. Preheat at 650 °C (1200 °F), austenitize at 790 to 815 °C (1455 to 1500 °F), and hold at temperature for 30 min for small s to 60 min for large tools. Air cool as evenly as possible on all sides, icularly when cooling long flat dies. Typical quenched hardness, 62 to IRC

ıbilizing. Optional. Low-temperature treatment may increase hard- ; and improve dimensional stability by reducing the amount of retained enite, particularly when temperatures at the upper end of the austenitiz- range are used. It is safer and definitely recommended to stress relieve per at 150 to 160 °C (300 to 320 °F) for a short period before refriger- g to –85 °C (–120 °F), particularly for intricate shapes or tools having ıpt changes in section size. Temper immediately after tool reaches room perature

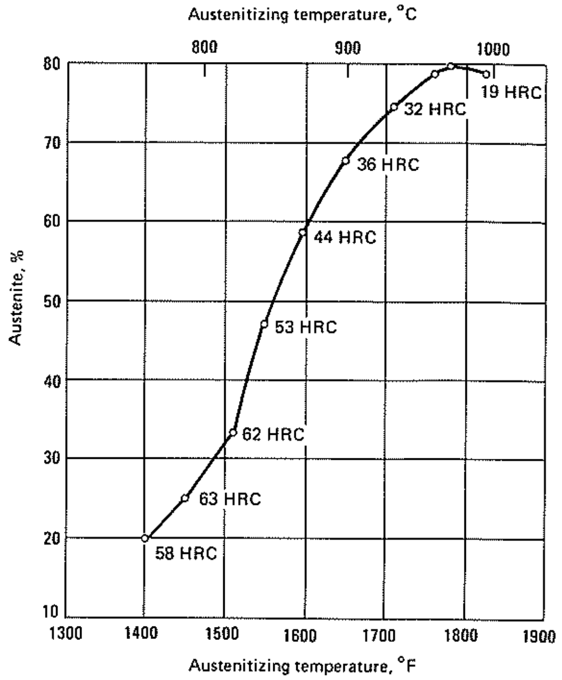
npering. Temper immediately at 175 to 425 °C (345 to 795 °F) after has cooled to 50 to 66 °C (120 to 150 °F). Double temper, allowing tool to cool to room temperature before second temper. Range of hardness after tempering, 62 to 55 HRC

Recommended Processing Sequence

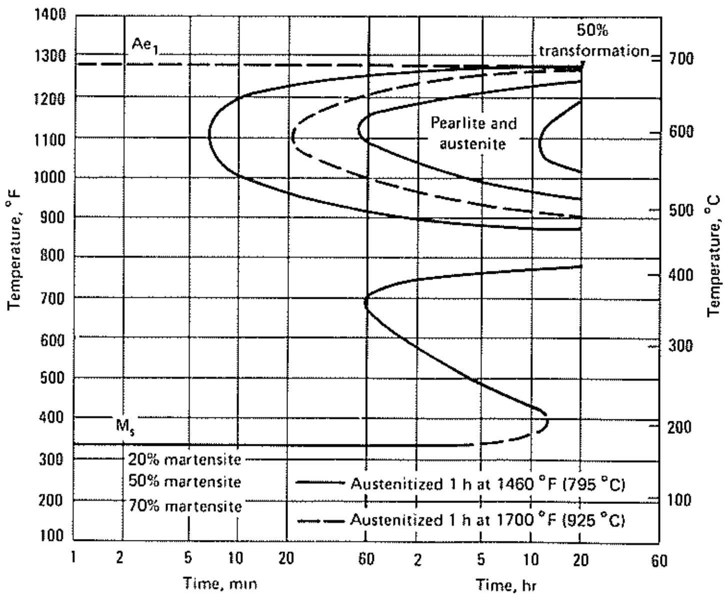
- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/double temper
- Final grind



A10: Tempering Temperature vs Dimensional Change. Dimensional changes by tempering A10 (a) after air cooling from 790 °C (1455 °F) and (b) 925 °C (1695 °F). Changes greater after quenching from 925 °C (1695 °F) due to large amounts of retained austenite. Specimen: 19.05 mm (0.750 in.) diam, 102 mm (4 in.) long



A10: Hardness and Retained Austenite vs Austenitizing Temperature



A10: Isothermal Transformation Diagram. Composition: 1.36 C, 1.84 Mn, 1.14 Si, 1.81 Ni, 0.15 Cr, 1.41 Mo, 0.38 graphite. Austenitized at temperatures listed

High-Carbon, High-Chromium Cold Work Tool Steels (D Series)

ıtroduction

The high-carbon, high-chromium cold work tool steels, identified by letter "D", are characterized by carbon contents ranging from 1.5 to ;% carbon and a nominal chromium content of 12%. The steels contain- molybdenum can be air hardened, while the molybdenum-free grade) is hardened by quenching in oil.

It is not recommended that D series steels be normalized. Generally e steels are supplied in the annealed condition, but they should be ealed after forging and prior to rehardening. Tools that cannot be ground r hardening are sometimes stress relieved after rough machining, espe- ly those that have delicate designs or that vary markedly in cross ion. In many instances, preheating prior to austenitizing relieves ma- ing stresses adequately.

Preheating prior to austenitizing reduces subsequent distortion in the lened parts by minimizing non-uniform dimensional changes during enitizing. The steels may be austenitized in nonoxidizing molten salt is, in vacuum, or in various types of furnaces using gaseous atmos- res to avoid decarburization, notably endothermic atmospheres, dry ociated ammonia, or dry hydrogen. Excessively high temperatures during austenitizing will promote retained austenite and should be avoided. To obtain required carbide solution for maximum hardness, these steels must be held at the austenitizing temperature for at least the recommended period of time.

The D series tool steels, except D3, are quenched in salt or air. Depending on section size and other physical variables, different methods may be employed to obtain accelerated cooling. These methods include cooling by quenching in salt at 540 °C (1000 °F) and holding only long enough to equalize temperature throughout all sections of the tool, by fan or air blast, or oil quenching to black—quenching in oil until the steel is below the temperature at which it glows dull red, then cooling to room temperature in air. Tempering is usually begun when the steel reaches a temperature of approximately 50 to 65 °C (120 to 150 °F). Double or even triple tempering is commonly employed to transform retained austenite.

Low-temperature stabilizing treatment is optional and may increase hardness and improve dimensional stability by reducing the amount of retained austenite, particularly when temperatures at the upper end of the austenitizing range are used.

2

emical Composition. **AISI:** Nominal. 1.50 C, 12.00 Cr, 1.00 Mo,) V. **AISI/UNS:** Composition: 1.40 to 1.60 C, 0.60 Mn max, 0.60 Si ;, 0.30 Ni max, 11.00 to 13.00 Cr, 0.70 to 1.20 Mo, 1.10 V max

nilar Steels (U.S. and/or Foreign). ASTM A681 (D-2); FED -T-570 (D-2); SAE J437 (D2), J438 (D2); (Ger.) DIN 1.2201, 1.2379, ;01; (Fr.) AFNOR A35-590 2235 Z 160 CDV 12; (Ital.) UNI X 150 Λo 12 KU; (Swed.) SS 2310; (U.K.) B.S. 4659 (USA D2), 4659 BD2, 9 BD2A

aracteristics. Most available and most popular of the D series tool :ls. Deep hardening, with low distortion and high safety in hardening. h resistance to softening and medium resistance to decarburizing. .dily nitrided

rging. Preheat to 650 to 705 °C (1200 to 1300 °F). Start forging at 0 to 1095 °C (1850 to 2005 °F). Do not forge after temperature of ;ing stock drops below 925 °C (1695 °F). Cool slowly after forging. ›id cooling in air from elevated temperatures, such as 925 °C (1695 °F), ot recommended

ːcommended Heat Treating Practice

rmalizing. Do not normalize

nealing. Surface protection in the form of atmospheric gas with per dew point, nonoxidizing salt bath, or an inert pack material, such as nt pitch coke, is required to avoid decarburization. Heat slowly and formly to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Holding time varies from 1 ¼ h for light sections to 6 h for heavy sections and large charges; about 1 ½ h per inch of thickness is an adequate approximation to follow. For pack annealing, hold for about 1 ½ h per inch of cross section of the pack. Cool slowly to 540 °C (1000 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 217 to 255 HB

Cycle Annealing. Heat to 900 °C (1650 °F) for 2 h. Slow cool to 775 °C (1425 °F) and hold at temperature for 4 to 6 h. Cool in air

Stress Relieving. Optional. Heat to 675 to 705 °C (1245 to 1300 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Heat very slowly. Preheat at 815 °C (1500 °F), and austenitize at 980 to 1025 °C (1795 to 1875 °F). Hold at temperature 15 min for small tools to 45 min for large tools. Quench in air and cool as evenly as possible on all sides. A block 76.2 by 152.4 by 254.0 mm (3 by 6 by 10 in.) will harden throughout to 62 to 64 HRC. When salt quenching, quench in salt bath at 540 °C (1000 °F), hold only long enough to equalize temperature, cool in air

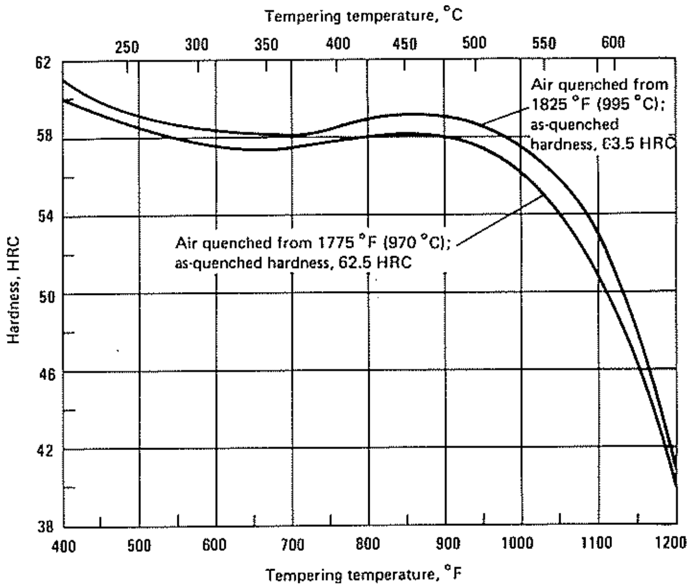
Stabilizing. Optional. For intricate shapes having abrupt changes in section size, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly before refrigerating at –85 °C (–120 °F). Temper immediately after part reaches room temperature

Tempering. Temper immediately at 205 to 540 °C (400 to 1000 °F) after tool has cooled to about 50 to 66 °C (120 to 150 °F). Double temper, allowing tool to cool to room temperature before second temper. Approximate tempered hardness, 61 to 54 HRC

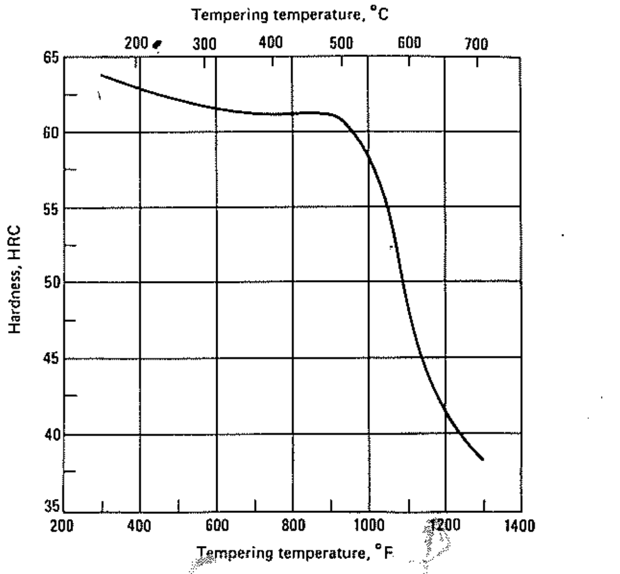
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/double temper
- Final grind to size

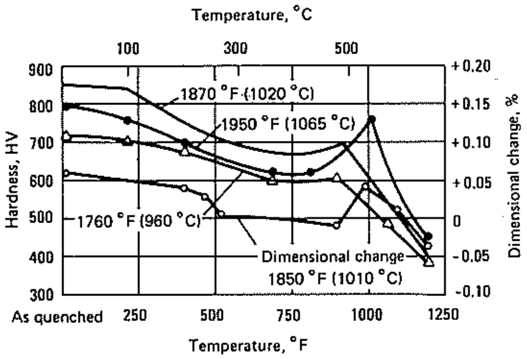
D2: Hardness vs Tempering Temperature. Austenitized at 970 °C (1775 °F) and 995 °C (1825 °F) then air quenched. Source: Universal-Cyclops



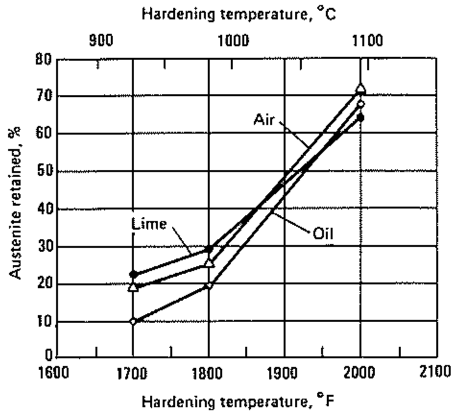
D2: Hardness vs Tempering Temperature. Composition: 1.50 C and 12.00 Cr; pack hardened at 1010 °C (1850 °F) and cooled in air. Source: Bethlehem Steel



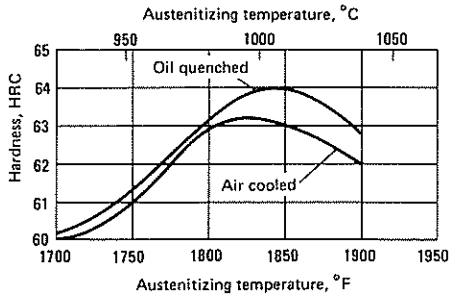
D2: Tempering Temperature vs Dimensional Change. Swedish grade austenitized at two different temperatures. Dimensional change for a similar steel austenitized at a slightly lower temperature. Source: Uddeholm and Carpenter Steel



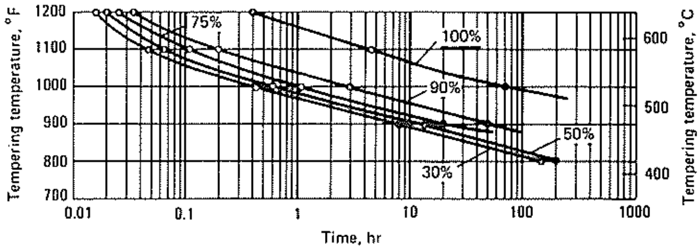
D2: Austenitizing Temperature vs Retained Austenite. Composition: 1.60 C, 0.33 Mn, 0.018 P, 0.010 S, 0.32 Si, 11.95 Cr, 0.79 Mo, 0.25 V, when quenched in lime, air and oil

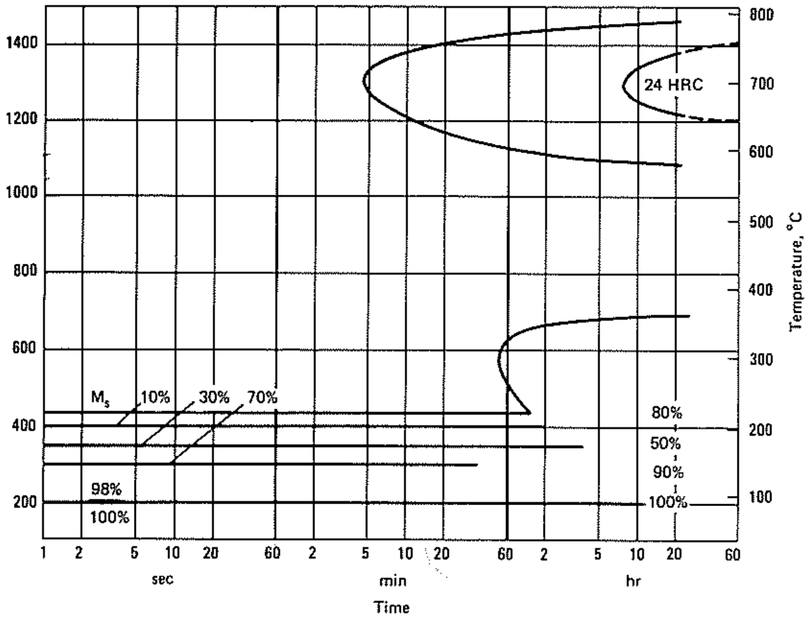


2: As-Quenched Hardness. Effect of quenching medium and ustenitizing temperature on as-quenched hardness of a D2 tool :eel containing 1.50 C

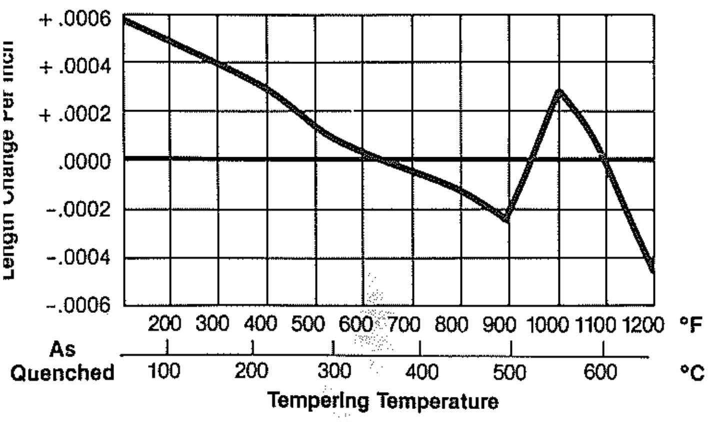


D2: Tempering Transformation Curves for Retained Austenite. Composition: 1.60 C, 0.33 Mn, 0.018 P, 0.010 S, 0.32 Si, 11.95 Cr, 0.79 Mo, 0.25 V, air cooled from 980 °C (1795 °F)

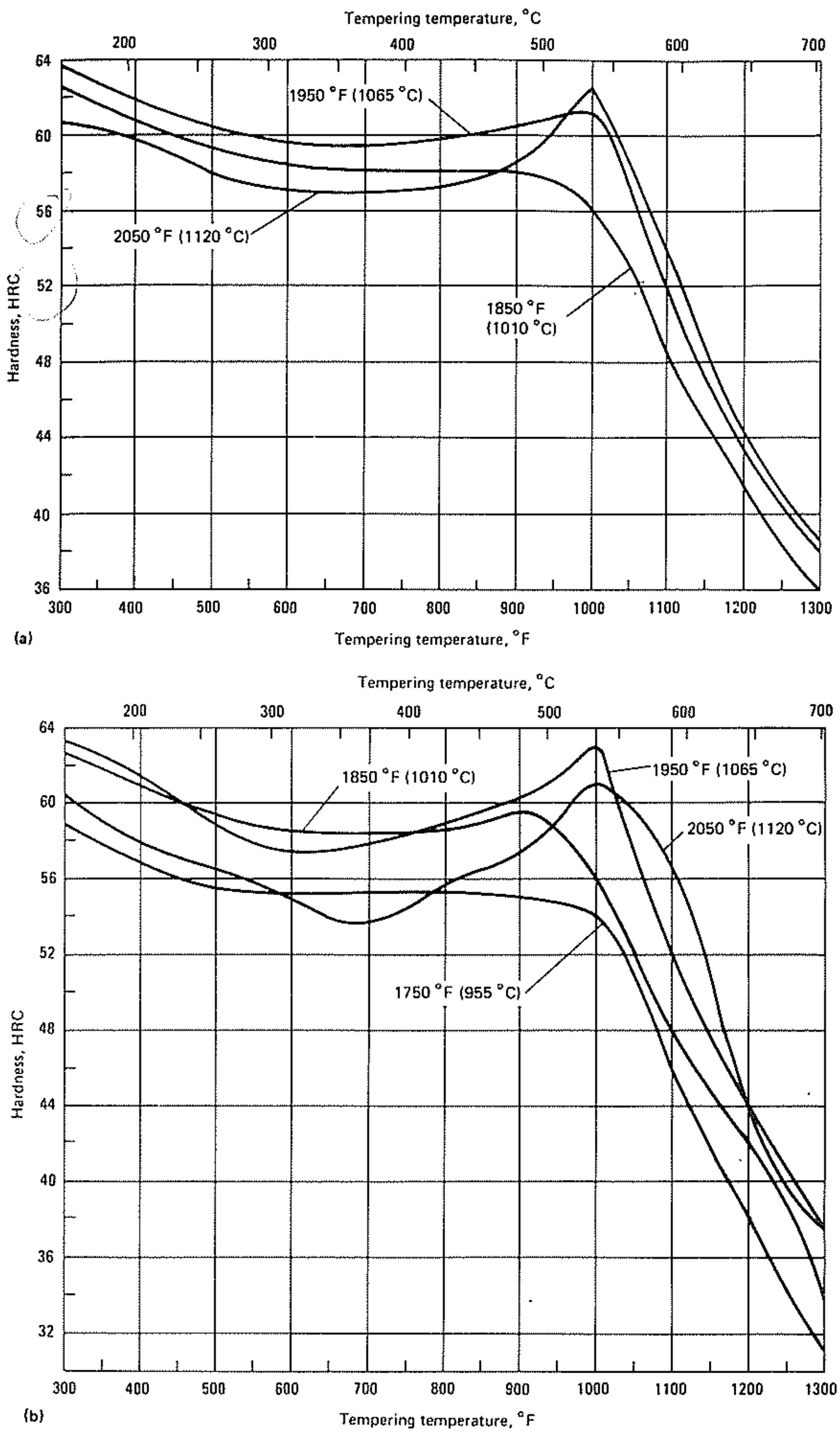




D2: Isothermal Transformation Diagram. Composition: 1.50 C, 11.50 Cr, 0.80 Mo, 0.20 V. Austenitized at 980 °C (1795 °F). Source: Crucible Steel

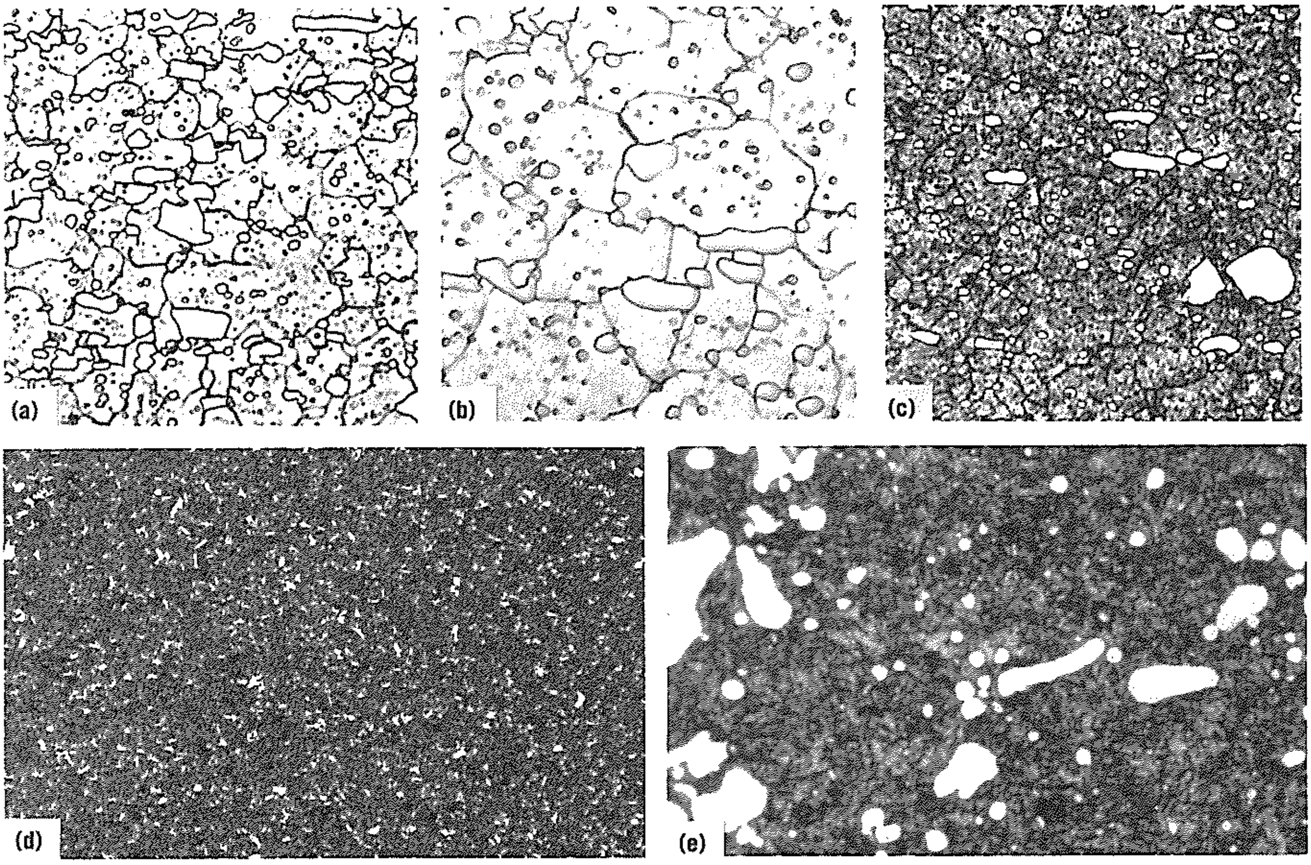


D2: Typical Size Changes in Hardening. Changes in length (in inches per inch of original length) of properly hardened and tempered 25 mm (1 in.) round, air quenched from 1010 °C (1850 °F), tempered 1 h at indicated temperature. Source: Carpenter Technology Corporation

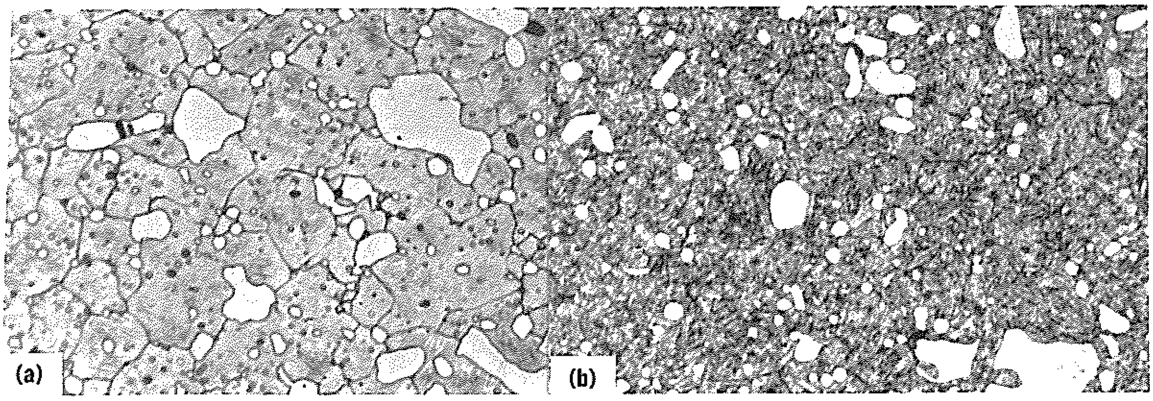


D2: Hardness vs Tempering Temperature. (a) Air cooled. (b) Oil quenched at austenitizing temperatures shown. Specimen size, 25.4 mm (1 in.) cube

2: **Microstructures.** (a) 2% nital, 500×. Austenitized at 1010 °C (1850 °F). Air cooled (not tempered). Massive alloy carbide and small ›heroidal carbide particles within grains in a matrix of untempered martensite. Hardness, 64 HRC. (b) 2% nital, 1000×. Same steel and heat ɜatment as (a), except shown at a higher magnification. Hardness, 64 HRC. Some retained austenite is present, but it is not resolved with e etch and magnification used. (c) 2% nital, 500×. Austenitized at 1010 °C (1850 °F), air cooled, tempered at 480 °C (895 °F) for 1 h. Note ıromium carbide particles (white) in a matrix of tempered martensite. Grain boundaries are evident. (d) Nital, 100×. Preheated at 790 °C 455 °F), austenitized at 1010 °C (1850 °F), air cooled, double tempered (2 h plus 2 h) at 540 °C (1000 °F). Magnification too low for good solution of microconstituents. (e) Nital, 1000×. Same steel and heat treatment as (d), except shown at a higher magnification. Carbide par- :les in a matrix of tempered martensite. Martensite appears dark because of high tempering temperature of 540 °C (1000 °F)

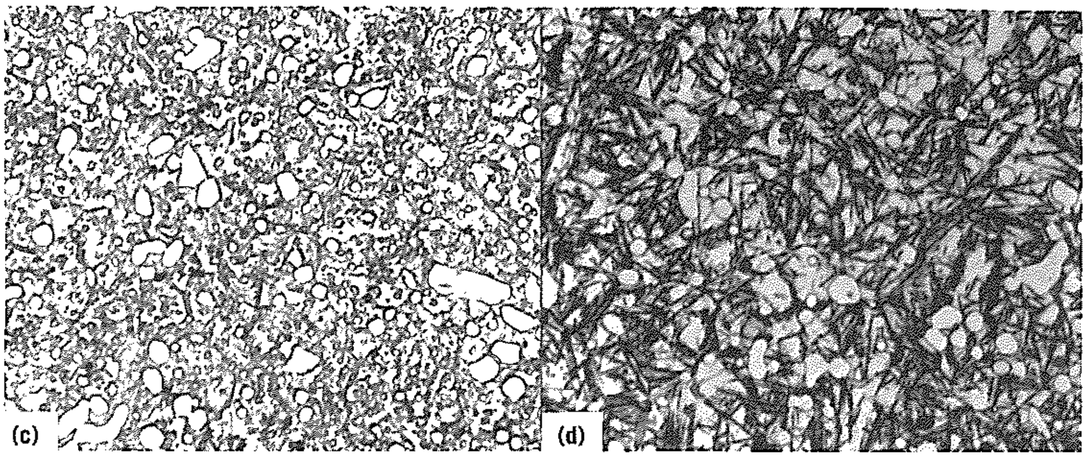


2: **Resulfurized and Cast Tool Steel Microstructures.** (a) 3% nital, 1000×. Resulfurized (0.100 S), austenitized at 1010 °C (1850 °F), air ɔoled, tempered at 205 °C (400 °F). Hardness, 59.5 HRC. Carbide particles in a matrix of tempered martensite. Black dots are sulfide in- usions. (b) 3% nital, 1000×. Same steel as (a), austenitized at 1010 °C (1850 °F), air cooled, double tempered (2 h plus 2 h) at 510 °C (950 ꟳ). Hardness, 57.5 HRC. Carbide and sulfide particles in a matrix of tempered martensite

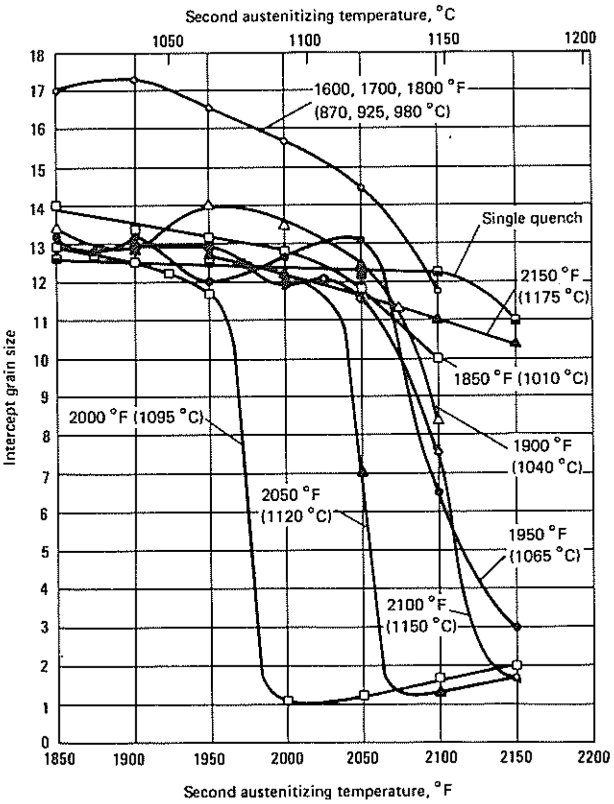


(continued)

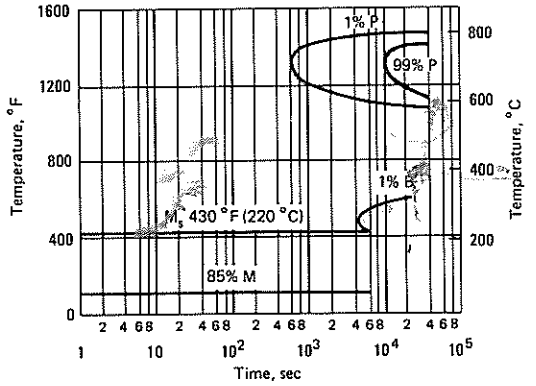
D2: Resulfurized and Cast Tool Steel Microstructures (continued). (c) 3% nital, 1000×. Same steel as (a), austenitized at 870 °C (1600 °F), air cooled, double tempered (2 h plus 2 h) at 510 °C (950 °F). Hardness, 47 HRC. Greater number of undissolved carbide particles indicate underheating. (d) 3% nital, 1000×. Same steel as (a), austenitized at 1120 °C (2050 °F), air cooled, double tempered (2 h plus 2 h) at 510 °C (950 °F). Hardness, 50 HRC. Excessive amount of retained austenite caused by high austenitizing temperature



D2: Grain Size vs Prequenching. Effect of austenitizing temperature on grain size after prequenching from indicated temperatures. Prequenching from 980 °C (1795 °F) and below results in significant grain refinement on subsequent hardening. Source: Teledyne VASCO



D2: Isothermal Transformation Diagram. Swedish grade austenitized at 1050 °C (1920 °F). Source: Stora Steels



3

ıemical Composition. AISI: Nominal. 2.25 C,12.00 Cr. **ƷI/UNS:** Composition: 2.00 to 2.35 C, 0.60 Mn max, 0.60 Si max, 0.30 max, 11.00 to 13.50 Cr, 1.00 V max, 1.00 W max

nilar Steels (U.S. and/or Foreign). ASTM A681 (D-3); FED)-T-570 (D-3); SAE J437 (D3), J438 (D3); (Ger.) DIN 1.2080, 1.2436, 884; (Fr.) AFNOR A35-590 2233 Z 200 C 12; (Ital.) UNI X 210 Cr 13 l; (Jap.) JIS G4404 SKD 1, G4404 SKD 2; (U.K.) B.S. 4659 BD3

ıaracteristics. Oil quenched. Not as deep hardening as D2, and large tions display greater dimensional change. Nevertheless, is rated as deep dening, relatively low in distortion, with high resistance to softening at vated temperatures and medium resistance to decarburization

ırging. Preheat to 650 to 705 °C (1200 to 1300 °F). Start forging at l0 to 1095 °C (1850 to 2005 °F). Do not forge after temperature of ging stock drops below 925 °C (1695 °F)

ɜcommended Heat Treating Practice

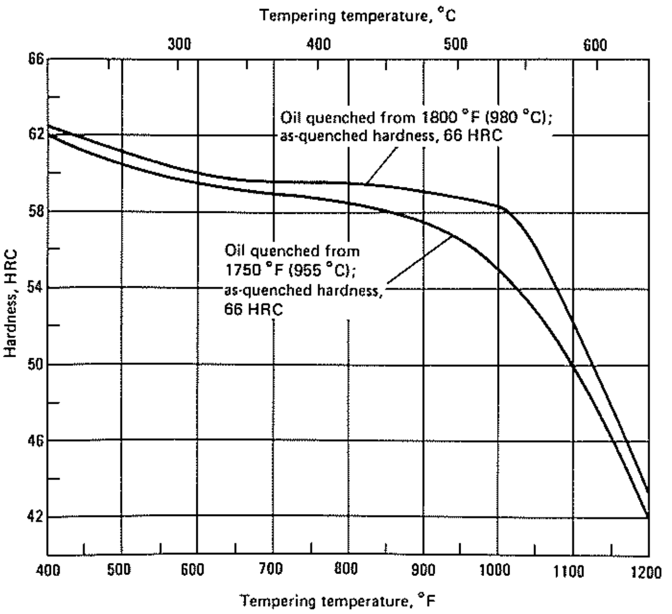
ırmalizing. Do not normalize

ınealing. Protection against decarburization. Heat slowly and uni- mly to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small tions and upper limit for large sections. Holding time varies from 1 ¼ h light sections to 6 h for heavy sections and large charges; about 1 ½ h inch of thickness is an adequate approximation to follow. For pack ıealing, hold for about 1 ½ h per inch of cross section of the pack. Cool wly to 540 °C (1000 °F) at a rate not to exceed 22 °C (40 °F) per h, after ich a faster cooling rate will not affect final hardness. Typical annealed dness, 217 to 255 HB

ɾcle Annealing. Heat to 900 °C (1650 °F) for 2 h. Slow cool to 775 (1425 °F) and hold at temperature for 4 to 6 h. Cool in air

ress Relieving. Optional. Heat to 675 to 705 °C (1245 to 1300 °F) l hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

)3: Hardness vs Tempering Temperature. Austenitized at 980 C (1795 °F) and 955 °C (1750 °F), quenched in oil. Source: Uni- ersal-Cyclops



Hardening. Heat very slowly. Preheat at 815 °C (1500 °F), and austenitize at 925 to 980 °C (1700 to 1795 °F). Hold at temperature 15 min for small tools to 45 min for large tools. Quench in warm oil. Approximate quenched hardness, 64 to 66 HRC

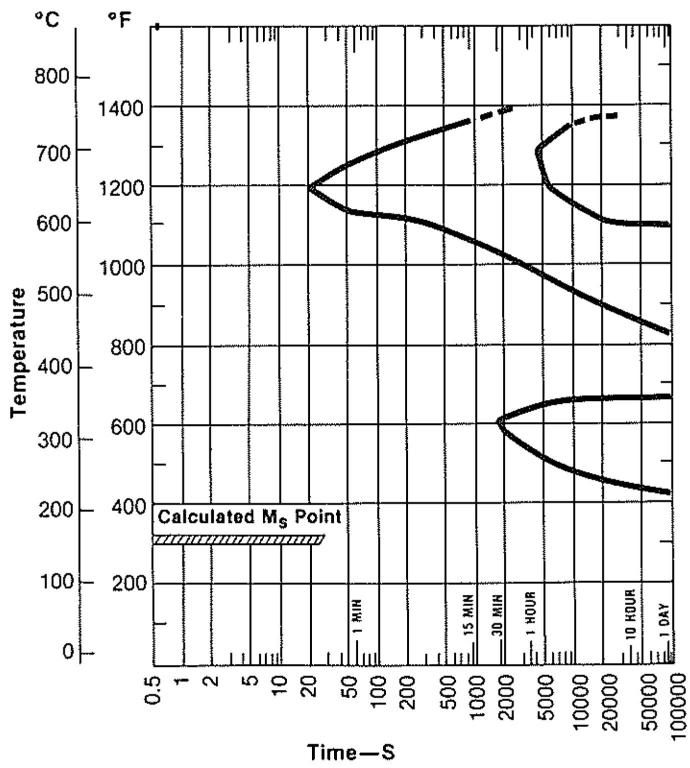
Stabilizing. Optional. Low-temperature treatment may increase hardness and improve dimensional stability by reducing the amount of retained austenite, particularly when temperatures at the upper end of the austenitizing range are used. For intricate shapes having abrupt changes in section size, it is safer and definitely recommended to stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at −85 °C (−120 °F). Temper immediately after part reaches room temperature

Tempering. Temper immediately at 205 to 540 °C (400 to 1000 °F) after tool has cooled to approximately 50 to 66 °C (120 to 150 °F). Double temper allowing tool to cool to room temperature before second temper. Approximate tempered hardness, 61 to 54 HRC

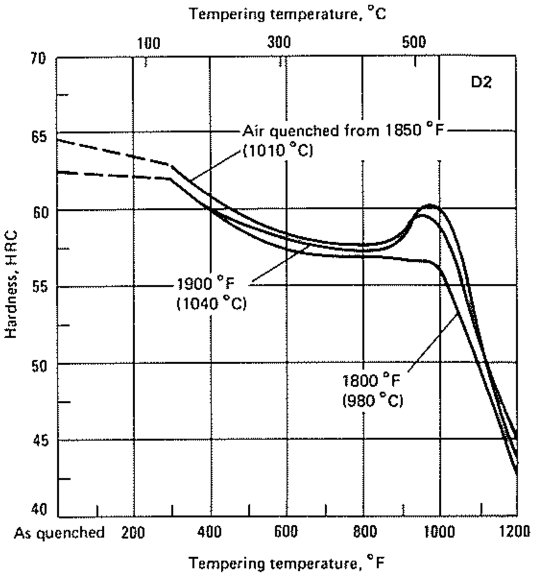
Recommended Processing Sequence

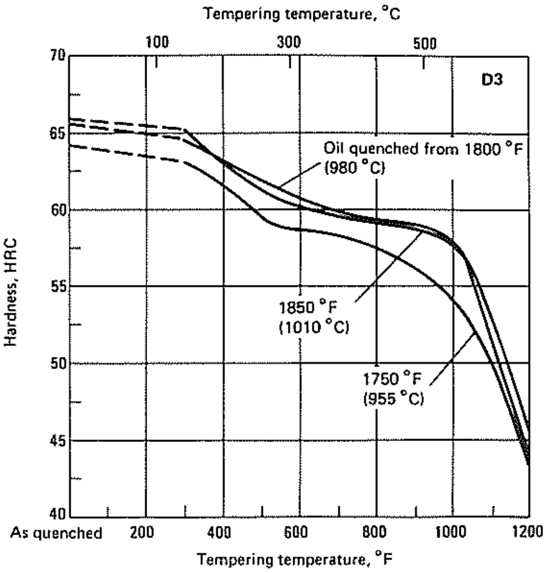
- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/double temper
- Final grind to size

D3: Isothermal Transformation Diagram. Austenitized at 970 °C (1775 °F). Source: Carpenter Technology Corporation

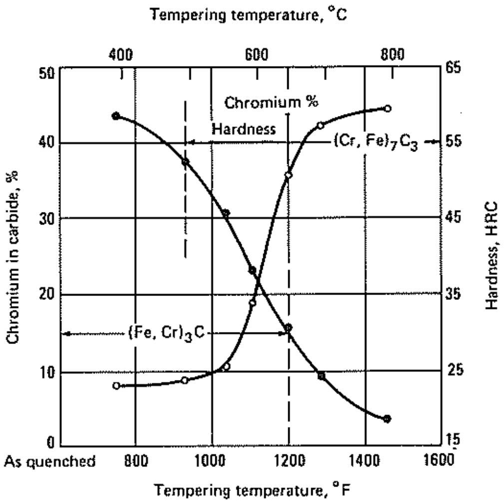


D3: Comparison of Tempering Characteristics. D2 and D3 tool steels quenched from several austenitizing temperatures. Steels were austenitized in an air furnace. A recirculating pit-type furnace was used for tempering. Curves represent steel from three suppliers; an average of five hardness measurements made on each specimen from each supplier. Specimens were 25.4 mm (1 in.) diam, and 38.1 mm (1 ½ in.) long

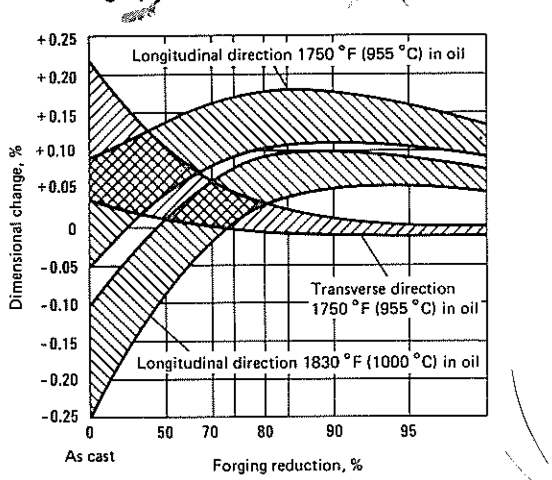


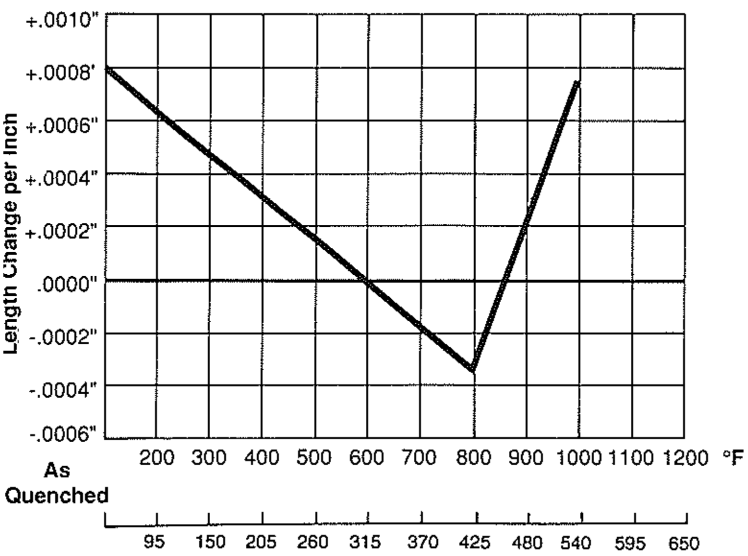


D3: Chromium Content of Precipitated Carbide vs Hardness. D3 matrix and composition after austenitizing at 950 °C (1740 °F). Steel contained 0.59 C, 0.56 Mn, 0.47 Si, 4.73 Cr. Tempering time, 1 h



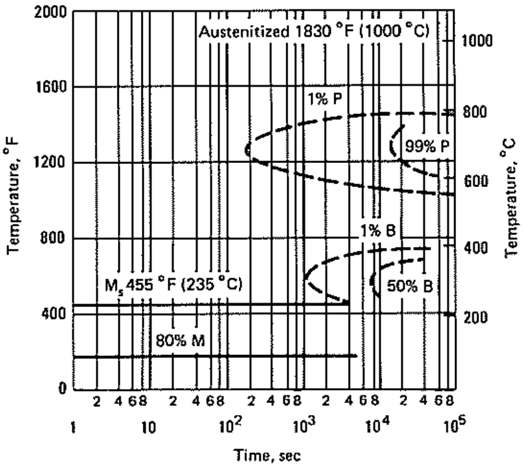
D3: Forging Reduction vs Dimensional Change After Hardening. Composition: 2.0 C, 0.30 Mn, 0.40 Si, 12.0 Cr. Cylindrical specimens, 20 mm (.8 in.) diam by 100 mm (4 in.) long. Bands represent the range of values obtained in specimens cut from square and round bars that had been given various amounts of forging reduction. Orientation of specimens with respect to the forged bars is indicated on the graph.



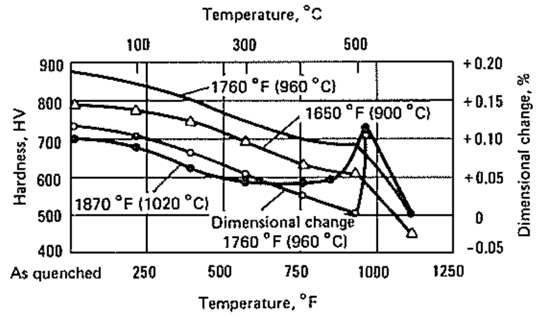


D3: Size Changes in Hardening. Specimens 25.4 mm (1 in.) diam, oil quenched from 970 °C (1775 °F) and tempered 1 h at temperature. Note: tool steels hold size best when quenched from proper hardening temperature. If overheated, they tend to shrink after tempering. Source: Carpenter Technology Corporation

3: Isothermal Transformation Diagram. Swedish grade ustenitized at 1000 °C (1830 °F). Source: Stora Steels



D3: Tempering Characteristics vs Dimensional Change. Swedish grade austenitized at temperatures shown. Source: Uddeholm Steels



4

iemical Composition. **AISI:** Nominal. 2.25 C,12.00 Cr, 1.00 Mo. **SI/UNS:** Composition: 2.05 to 2.40 C, 0.60 Mn max, 0.60 Si max, 0.30 max, 11.00 to 13.00 Cr, 0.70 to 1.20 Mo, 1.00 V max

milar Steels (U.S. and/or Foreign). ASTM A681 (D-4); FED)-T-570 (D-4); (Ger.) DIN 1.2436, 1.2884; (Fr.) AFNOR A35-590 2234 !00 CD 12; (Jap.) JIS G4404 SKD 2; (Swed.) SS 2312; (U.K.) B.S. 4659 SA D4)

iaracteristics. Very similar to D3, except has a 1% molybdenum lition giving it deeper hardening characteristics and enabling it to be ·dened in air. Distortion in heat treating as low as that of any of the air-hardening D series. High safety in hardening with high resistance to softening at elevated temperatures. Medium resistance to decarburization

Forging. Preheat to 650 to 705 °C (1200 to 1300 °F). Start forging at 1010 to 1095 °C (1850 to 2005 °F). Do not forge after temperature of forging stock drops below 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Surface protection in the form of endothermic atmospheric gas with proper dew point, nonoxidizing molten salt bath, or an inert pack material, such as spent pitch coke, is required to avoid decarburization.

Heat slowly and uniformly to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Holding time varies from 1¼ h for light sections to 6 h for heavy sections and large charges; about 1½ h per inch of thickness is an adequate approximation to follow. For pack annealing, hold for about 1½ h per inch of cross section of the pack. Cool slowly to 540 °C (1000 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 217 to 255 HB

Cycle Annealing. Heat to 900 °C (1650 °F) for 2 h. Slow cool to 775 °C (1425 °F) and hold at temperature for 4 to 6 h. Cool in air

Stress Relieving. Optional. Heat to 675 to 705 °C (1245 to 1300 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

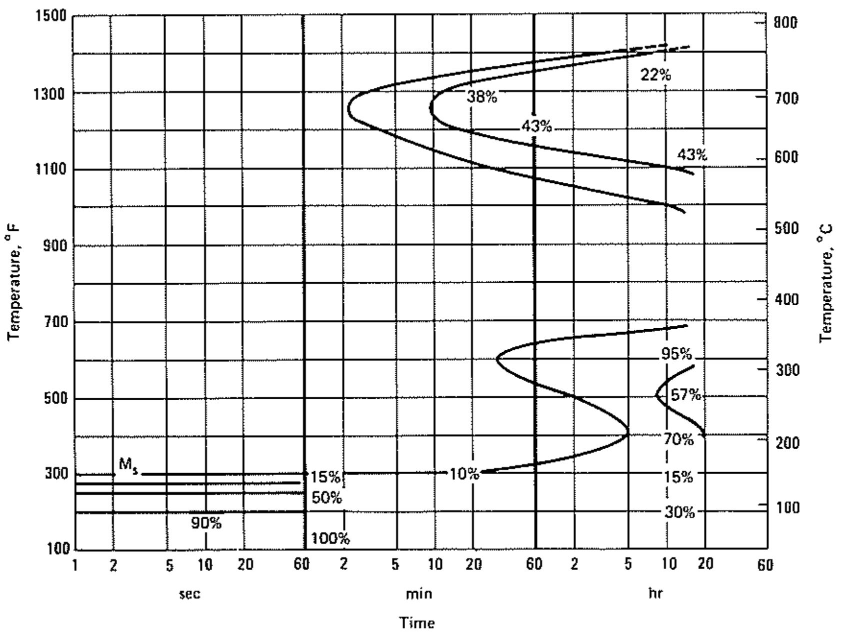
Hardening. Heat very slowly. Preheat at 815 °C (1500 °F), and austenitize at 970 to 1010 °C (1775 to 1850 °F). Hold at temperature 15 min for small tools to 45 min for large tools. Quench in air and cool as evenly as possible on all sides, particularly on long flat dies. Approximate quenched hardness, 64 to 66 HRC.

Stabilizing. Optional. Low-temperature treatment may increase hardness and improve dimensional stability by reducing the amount of retained austenite, particularly when temperatures at the upper end of the austenitizing range are used. For intricate shapes having abrupt changes in section size, it is safer and definitely recommended to stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at −85 °C (−120 °F). Temper immediately after part reaches room temperature

Tempering. Temper immediately at 205 to 540 °C (400 to 1000 °F) after tool has cooled to approximately 50 to 66 °C (120 to 150 °F). Double temper, allowing tool to cool to room temperature before second temper. Approximate tempered hardness, 54 to 61 HRC

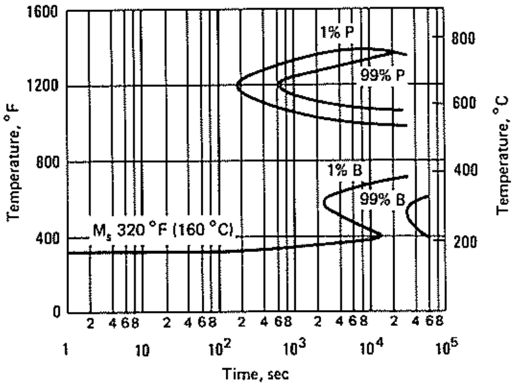
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/double temper
- Final grind to size

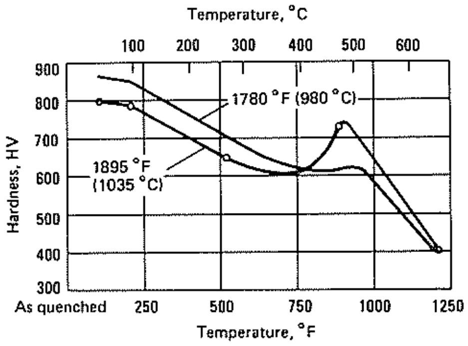


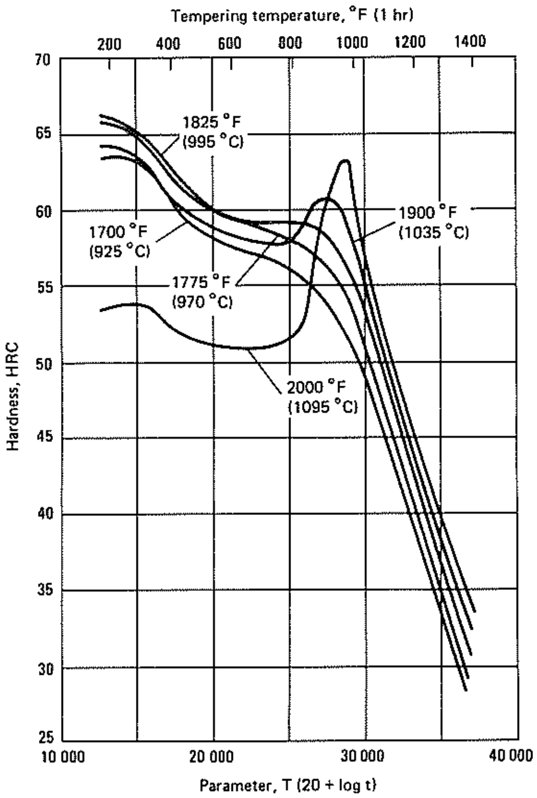
D4: Isothermal Transformation Diagram. Composition: 2.25 C, 11.50 Cr, 0.80 Mo, 0.20 V. Austenitized at 980 °C (1795 °F). Source: Crucible Steel

4: Isothermal Transformation Diagram. Austenitized at 980 ; (1795 °F)



D4: Hardness vs Tempering Temperature. Austenitized at 970 °C (1775 °F) and 1035 °C (1895 °F), and cooled in air





D4: Hardness vs Tempering Temperature. Tempering curves for D4 tool steel containing 2.17 C, 11.68 Cr, 0.78 V, 0.51 Co. Austenitized at the five temperatures shown, cooled in air, and tempered for 1 h at the tempering temperature. Source: Teledyne VASCO

)5

iemical Composition. **AISI:** Nominal. 1.50 C,12.00 Cr, 1.00 Mo,)0 Co. **AISI/UNS:** Composition: 1.40 to 1.60 C, 0.60 Mn max, 0.60 Si ıx, 0.30 Ni max, 11.00 to 13.00 Cr, 0.70 to 1.20 Mo, 1.00 V max, 2.50 to ;0 Co

milar Steels (U.S. and/or Foreign). ASTM A681 (D-5); FED Q-T-570 (D-5); SAE J437 (D5), J438 (D5); (Ger.) DIN 1.2880; (Fr.) ·NOR A35-590 2236 Z 160 CKDV 12.03

Characteristics. Very similar to D2, except it does not contain vanadium and 3% cobalt is added to impart resistance to softening at elevated temperature. As with other grades of the D series, it is deep hardening and very low in distortion, having very high wear resistance and medium decarburization resistance

Forging. Preheat to 650 to 705 °C (1200 to 1300 °F). Start forging at 1010 to 1095 °C (1850 to 2005 °F). Do not forge after temperature of forging stock drops below 925 °C (1695 °F). Slow cool after forging

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Surface protection in the form of endothermic atmospheric gas with proper dew point, nonoxidizing molten salt bath, or an inert pack material, such as spent pitch coke, is required to avoid decarburization. Heat slowly and uniformly to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Holding time varies from 1 ¼ h for light sections to 6 h for heavy sections and large charges; about 1 ½ h per inch of thickness is an adequate approximation to follow. For pack annealing, hold for about 1 ½ h per inch of cross section of the pack. Cool slowly to 540 °C (1000 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 217 to 255 HB

Cycle Annealing. Heat to 900 °C (1650 °F) for 2 h. Slow cool to 775 °C (1425 °F) and hold at temperature for 4 to 6 h. Cool in air

Stress Relieving. Optional. Heat to 675 to 705 °C (1245 to 1300 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Heat slowly. Preheat at 815 °C (1500 °F), and austenitize at 980 to 1025 °C (1795 to 1875 °F). Hold at temperature 15 min for small tools to 45 min for large tools. Quench in air and cool as evenly as possible on all sides. Approximate quenched hardness, 61 to 64 HRC

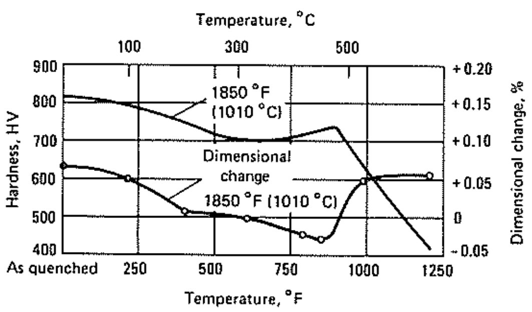
Stabilizing. Optional. Low-temperature treatment may increase hardness and improve dimensional stability by reducing the amount of retained austenite, particularly when temperatures at the upper end of the austenitizing range are used. For intricate shapes having abrupt changes in section size, it is safer and definitely recommended to stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at –85 °C (–120 °F). Temper immediately after part reaches room temperature

Tempering. Temper immediately at 205 to 540 °C (400 to 1000 °F) after tool has cooled to approximately 50 to 66 °C (120 to 150 °F). Double temper, allowing tool to cool to room temperature before second temper. Approximate tempered hardness, 54 to 61 HRC

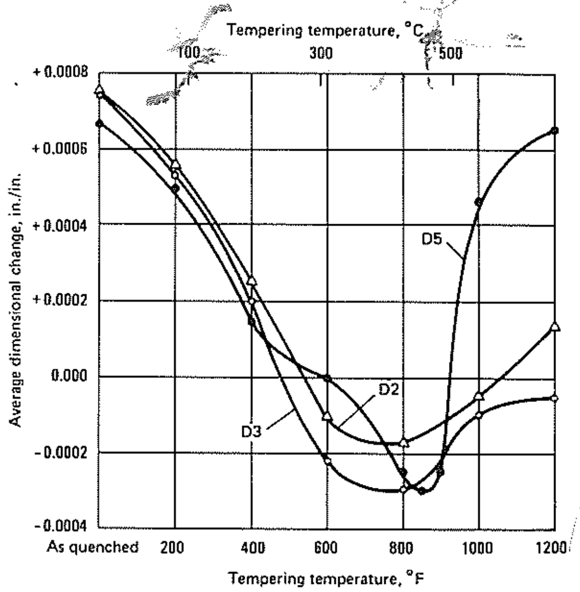
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/double temper
- Final grind to size

D5: Tempering Characteristics vs Dimensional Change. Austenitized at 1010 °C (1850 °F) and quenched in air



D5: Effect of Tempering Temperature on Dimensional Change. O, D3 austenitized at 955 °C (1750 °F) and quenched in oil. ●, D5 austenitized at 1010 °C (1850 °F) and cooled in air. Δ, D2 cooled in air. Specimen, 25.4 by 50.8 by 152.4 mm (1 by 2 by 6 in.). Source: Latrobe Steel



7

emical Composition. **AISI:** Nominal. 2.35 C,12.00 Cr, 1.00 Mo, V. **AISI/UNS:** Composition: 1.10 to 1.30 C, 1.00 Mn max, 0.60 Si max, Ni max, 0.35 to 0.85 Cr, 0.30 Mo max, 0.40 V max, 1.00 to 2.00 W

nilar Steels (U.S. and/or Foreign). ASTM A681 (D-7); FED -T-570 (D-7); SAE J437 (D7), J438 (D7); (Ger.) DIN 1.2378; (Fr.) NOR 2237 Z 230 CVA 12.04

aracteristics. Requires slightly higher temperature and longer time lissolve carbides when austenitizing than others in D series. Deep lening and relatively low distortion. Has high resistance to softening at ated temperatures, and medium decarburization resistance

rging. Preheat to 650 to 705 °C (1200 to 1300 °F). Start forging at 0 to 1165 °C (2050 to 2125 °F). Do not forge after temperature of ing stock drops below 980 °C (1795 °F)

commended Heat Treating Practice

rmalizing. Do not normalize

nealing. Surface protection in the form of atmospheric gas with per dew point, nonoxidizing molten salt bath, or an inert pack material, h as spent pitch coke, is required. Heat slowly and uniformly to 870 to °C (1600 to 1650 °F). Use lower limit for small sections and upper limit large sections. Holding time varies from 1 ¼ h for light sections to 6 h heavy sections and large charges; about 1 ½ h per inch of thickness is adequate approximation to follow. For pack annealing, hold for about 1 per inch of cross section of the pack. Cool slowly to 540 °C (1000 °F) rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate not affect final hardness. Typical annealed hardness, 217 to 255 HB

cle Annealing. Heat to 900 °C (1650 °F) for 2 h. Slow cool to 775 (1425 °F) and hold at temperature for 4 to 6 h. Cool in air

Stress Relieving. Optional. Heat to 675 to 705 °C (1245 to 1300 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Heat slowly. Preheat at 815 °C (1500 °F), and austenitize at 1010 to 1065 °C (1850 to 1950 °F). Hold at temperature 30 min for small tools to 1 h for large tools. Quench in air and cool as evenly as possible on all sides. Approximate quenched hardness 63 to 66 HRC

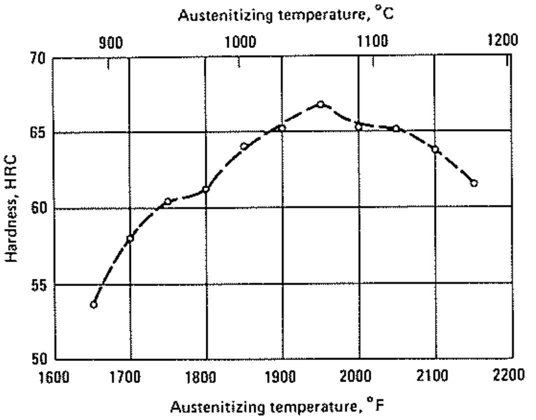
Stabilizing. Optional. Low-temperature treatment may increase hardness and improve dimensional stability by reducing the amount of retained austenite, particularly when temperatures at the upper end of the austenitizing range are used. For intricate shapes having abrupt changes in section size, it is safer and definitely recommended to stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at −85 °C (−120 °F). Temper immediately after part reaches room temperature

Tempering. Temper immediately at 150 to 540 °C (300 to 1000 °F) after tool has cooled to approximately 50 to 66 °C (120 to 150 °F). Double temper, allowing tool to cool to room temperature before second temper. Approximate tempered hardness, 58 to 65 HRC

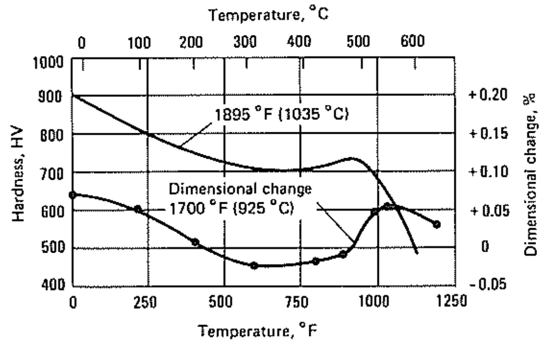
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/double temper
- Final grind to size

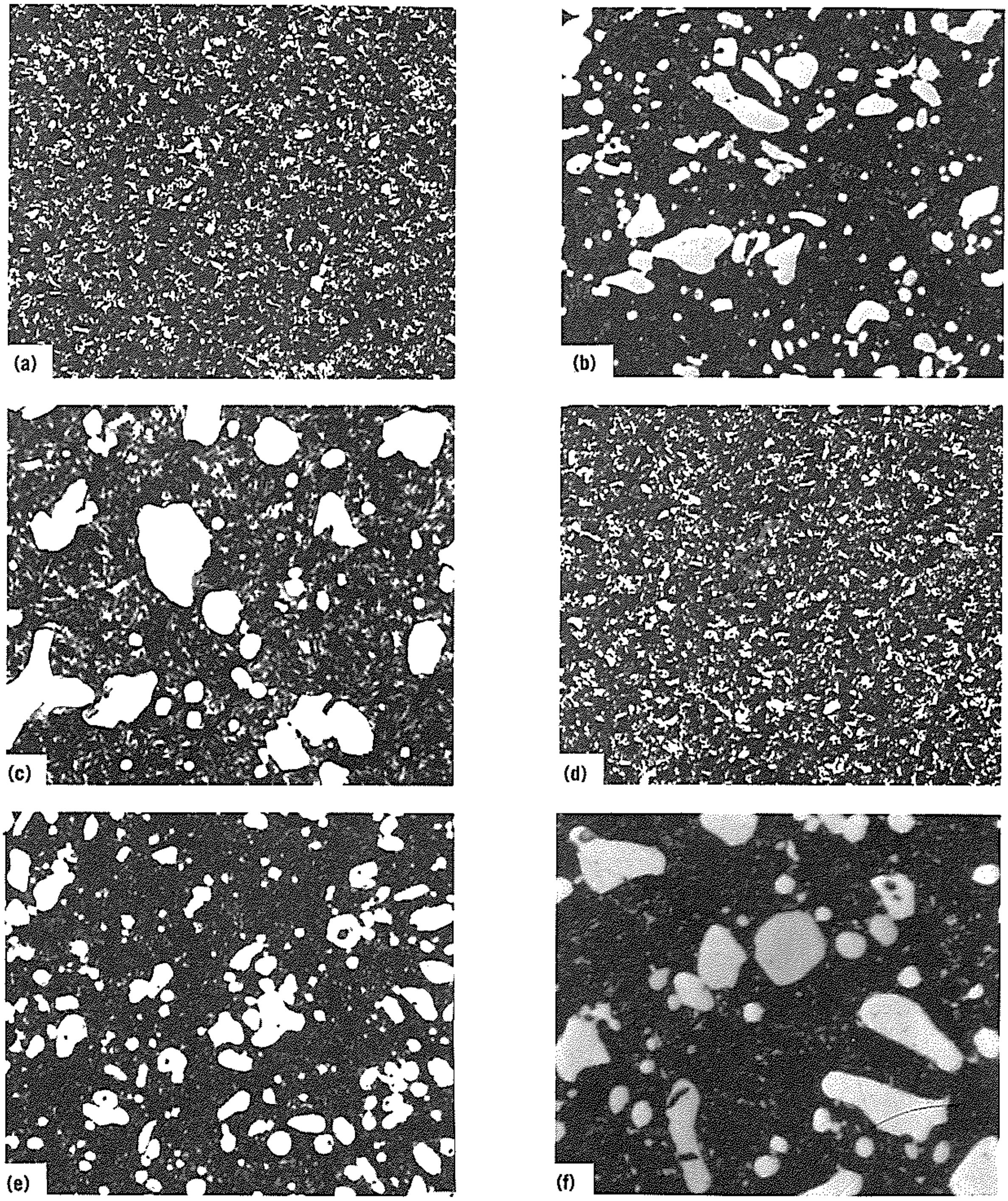
7: Austenitizing Temperature vs As-Quenched Hardness. omposition: 2.30 C, 0.40 Mn, 0.40 Si, 12.50 Cr, 1.10 Mo, 4.00 V nd air quenched



D7: Tempering Characteristics and Dimensional Change. Austenitized at 1035 °C (1895 °F) and air quenched. Dimensional change for the same steel austenitized at 925 °C (1695 °F) and air quenched



D7: Microstructures. (a) Nital, 100×. Preheated ½ h at 815 °C (1500 °F), austenitized at 1080 °C (1975 °F), and air cooled. Not tempered. See (b) for better resolution of structure. (b) Nital, 500×. Same steel and heat treatment as (a), except higher magnification. Small spheroidal particles of carbide resolved. Massive complex alloy carbide provides abrasion resistance. Matrix is martensite. (c) 4% nital, 1000×. Austenitized at 1040 °C (1905 °F), air cooled, and tempered at 540 °C (1000 °F). 61 HRC. Structure of small and massive carbide particles (white) in a matrix of tempered martensite. (d) Nital, 100×. Preheated at 815 °C (1500 °F), austenitized at 1080 °C (1975 °F), air cooled, and tempered at 175 °C (345 °F) for 2 h. Structure carbide particles in tempered martensite. See (e) and (f) for better resolutions. (e) Nital, 500×. Same steel and heat treatment as (d), except shown at higher magnification. Austenitizing temperature high. Matrix contains considerable unetched retained austenite. (f) Nital, 1000×. Same steel and heat treatment as (d), except shown at still higher magnification. Most of the small carbide particles have dissolved because of high austenitizing temperature, but massive carbide remains



Low-Alloy Special-Purpose Tool Steels (L Series)

ntroduction

The L series tool steels are essentially similar in composition to the ıter-hardening tool steels, except that the addition of chromium and other :ments provides these steels with greater wear resistance and hardenabil-. Type L2, for example, is similar to the bearing steel 52100 except for ·bon content. Because of their relatively low austenitizing temperatures, ;teels are easily heat treated.

The L steels should be normalized following forging or when other-se subjected to temperatures above their austenitizing temperatures. For :se steels, normalizing consists of through heating to 870 to 900 °C (1600 1650 °F) and cooling in still air. Using a protective atmosphere is :ommended if all surfaces will not be removed by machining.

Annealing must follow normalizing and precede any rehardening eration. The recommended annealing temperature, cooling rates, and pected as-annealed hardness values are given below for the individual :els covered in this section.

To minimize distortion during hardening, stress relieving prior to rdening may be advantageous for complex tools. One common practice for complex tools is to rough machine, heat to 620 to 650 °C (1150 to 1200 °F) for 1 h per inch of cross section, cool in air, and finish machine prior to hardening.

The L steels seldom require preheating prior to austenitizing. Salt baths and atmosphere furnaces are satisfactory for austenitizing these steels. A neutral salt bath, such as a mixture containing 70% barium chloride and 30% sodium chloride, is recommended. This salt may be deoxidized by means of rectification for control of decarburization.

Oil is the quenching medium most commonly used for L steels. Water or brine may be used for simple shapes or for large sections that do not attain full hardness by oil quenching. Rolling-mill rolls are parts for which water or brine quenching is used. L steels respond well to martempering.

The L steels should be withdrawn from the quenching medium at approximately 52 to 82 °C (125 to 180 °F) and should be tempered immediately thereafter, or cracking may occur. Tempering these low-alloy steels at a minimum of 120 °C (250 °F) is recommended, even if maximum hardness is desired. Double tempering is also recommended.

.2

ıemical Composition. **AISI:** Nominal. 0.50 to 1.10 C (various rbon contents are available), 1.00 Cr, 0.20 V. **AISI/UNS (T61202):** ımposition: 0.45 to 1.00 C, 0.10 to 0.90 Mn, 0.50 Si max, 0.70 to 1.20 , 0.25 Mo max, 0.10 to 30 V

milar Steels (U.S. and/or Foreign). ASTM A681 (L-2); FED Q-T-570 (L-2); (Ger.) DIN 1.2235, 1.2241, 1.2242, 1.2243; (Fr.) AFNOR 35-590 3335 55 CNDV 4; (Jap.) JIS G4404 SKT 3

haracteristics. A general-purpose steel containing 1% chromium for rdenability and wear resistance, and 0.20% vanadium for grain refine-ɜnt. Available in a range of carbon contents from 0.50 to 1.10%. Is nsidered to be similar to several alloy constructional steels, depending on rbon content. Has high safety in hardening, medium depth of hardening d distortion in heat treating, low to medium wear resistance, high ma-inability and resistance to decarburization

ɔrging. Start forging at 980 to 1095 °C (1795 to 2005 °F). Do not forge low 845 °C (1555 °F)

ecommended Heat Treating Practice

ormalizing. Heat to 870 to 900 °C (1600 to 1650 °F). Holding time, :er uniform through heating, varies from approximately 15 min for small ctions to approximately 1 h for large sections. Work is cooled from nperature in still air

Annealing. Atmosphere protection against decarburization or carburization is required unless all surfaces are to be removed by machining before final heat treatment and use. Heat to 760 to 790 °C (1400 to 1455 °F). Use lower limit for small sections and upper limit for large sections. Holding time varies from approximately 1 h for light sections and small furnace charges, to approximately 4 h for heavy sections and large charges. For pack annealing, hold for 1 h per inch of cross section. Cool slowly to 540 °C (1000 °F) at a rate not to exceed 22 °C (40 °F) per h, after which faster cooling will not affect final hardness. Typical annealed hardness, 163 to 197 HB

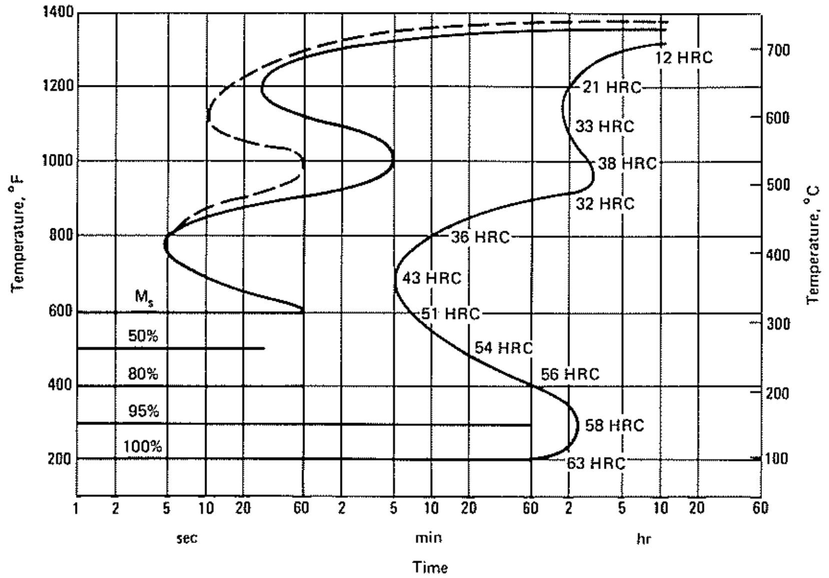
Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section. Cool in air

Hardening. Use protective media such as endothermic gas (use dew point of 10 to 13 °C, or 50 to 55 °F, for 0.50% carbon and 2 to 4 °C, or 35 to 40 °F, for 1.00% carbon), molten salt, pack, or vacuum to prevent decarburization or carburization. Heat slowly (particularly intricate tools). Austenitize at 845 to 925 °C (1555 to 1695 °F) for oil quenching, and 790 to 845 °C (1455 to 1555 °F) for water quenching. The latter may be used for large sections that are symmetrical, uncomplicated, and have no sharp stress raisers. However, cool no lower than 60 °C (140 °F) and temper immediately. Time at austenitizing temperature varies from approximately 10 min for small sections to approximately 30 min for large sections. Quench in warm, agitated oil to approximately 52 °C (125 °F), and place immediately in tempering furnace. As-quenched hardness, 54 to 61 HRC

Tempering. Temper at 175 to 540 °C (345 to 1000 °F) for a corresponding approximate tempered hardness of 63 to 45 HRC

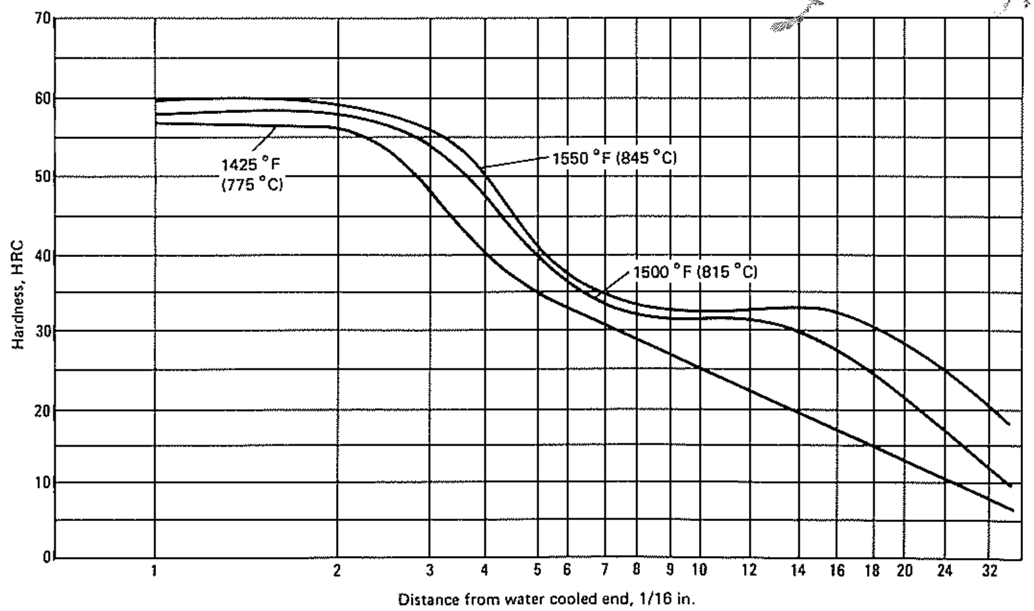
Recommended Processing Sequence

- Normalize
- Rough machine
- Stress relieve (optional)
- Finish machine
- Austenitize
- Quench
- Temper
- Final grind to size

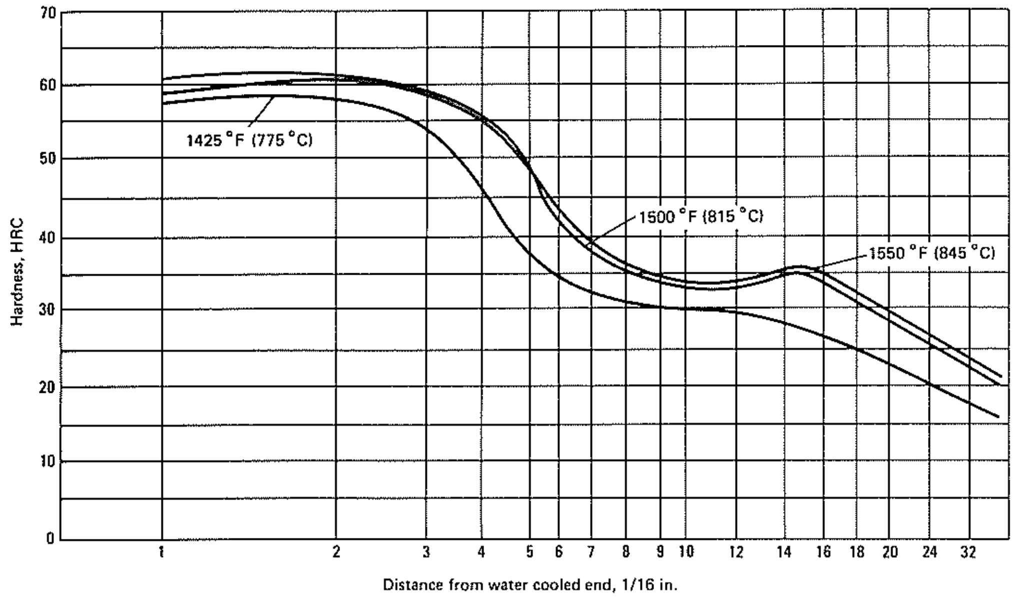


L2: Isothermal Transformation Diagram. Special-purpose tool steel containing 0.45 C, 0.70 Mn, 1.00 Cr, 0.20 V. Austenitizing temperature: 900 °C (1650 °F). Source: Crucible Steel

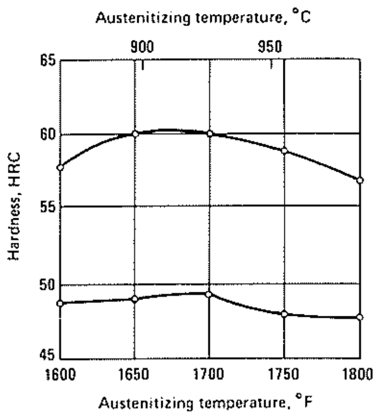
L2: Jominy End-Quench Hardenability. Special-purpose tool steel containing 0.50 C, 0.80 Cr, 0.20 V, after austenitizing. Source: Teledyne VASCO



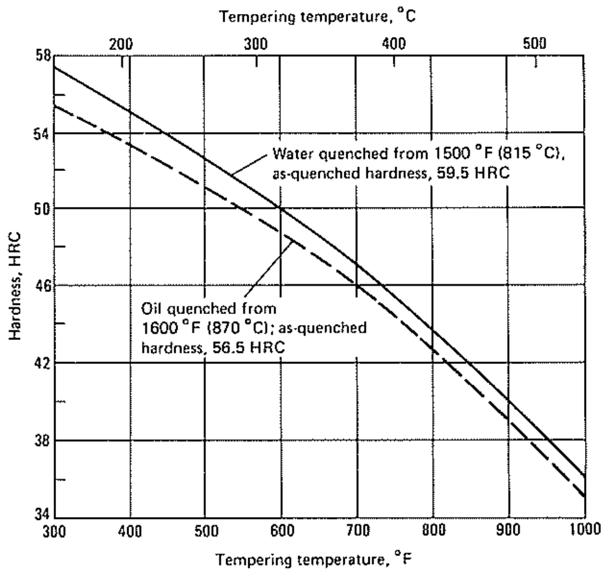
.2: **Jominy End-Quench Hardenability.** Composition: 0.60 C, 0.80 Cr, 0.20 V after austenitizing. Source: Teledyne VASCO



.2: **Austenitizing Temperature vs As-Quenched Hardness.** ;pecial-purpose tool steel containing 0.45 C, 0.55 Mn, 0.95 Cr,).20 V. Source: Bethlehem Steel



L2: Tempering Temperature vs Hardness. Effect of tempering and austenitizing temperature, and quenching medium on hardness of special-purpose tool steel. Source: Universal-Cyclops



.6

hemical Composition. **AISI:** Nominal. 0.70 C, 1.50 Ni, 0.75 Cr, 25 Mo (optional). **AISI/UNS (T61206):** Composition: 0.65 to 0.75 C, 25 to 0.80 Mn, 0.50 Si max, 1.25 to 2.00 Ni, 0.60 to 1.20 Cr, 0.50 Mo ax, 0.20 to 30 V (optional)

imilar Steels (U.S. and/or Foreign). ASTM A681 (L-6); FED Q-T-570 (L-6); SAE J437 (L6), J438 (L6); (Ger.) DIN 1.2713, 1.2714; (Fr.) AFNOR A35-590 3381 55 NCDV 7; (Jap.) JIS G4404 SKS 51, G4404 SKT 41

Characteristics. A general-purpose steel capable of hardening to as high as 62 HRC. Composition similar to that of the popular 4340 alloy grade, but contains 0.70% carbon. Available with several molybdenum contents; additional amounts of molybdenum increase the depth of hardness, which is generally classified as medium. Has low distortion in heat treating, high safety in hardening, and high resistance to decarburization

Forging. Start forging at 980 to 1095 °C (1795 to 2000 °F). Stop forging at 845 °C (1555 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 °C (1600 °F). Holding time, after uniform through heating, varies from approximately 15 min for small sections to approximately 1 h for large sections. Work is cooled from temperature in still air

Annealing. Atmosphere protection against decarburization or carburization is required unless all surfaces are to be removed by machining before final heat treatment and use. Heat to 760 to 790 °C (1400 to 1455 °F). Use lower limit for small sections and upper limit for large sections. Holding time varies from approximately 1 h for light sections and small furnace charges, to approximately 4 h for heavy sections and large charges. For pack annealing, hold for 1 h per inch of cross section of container. Cool slowly to 540 °C (1000 °F) at a rate not to exceed 22 °C (40 °F) per h, after which faster cooling will not affect final hardness. Typical annealed hardness, 183 to 255 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section. Cool in air

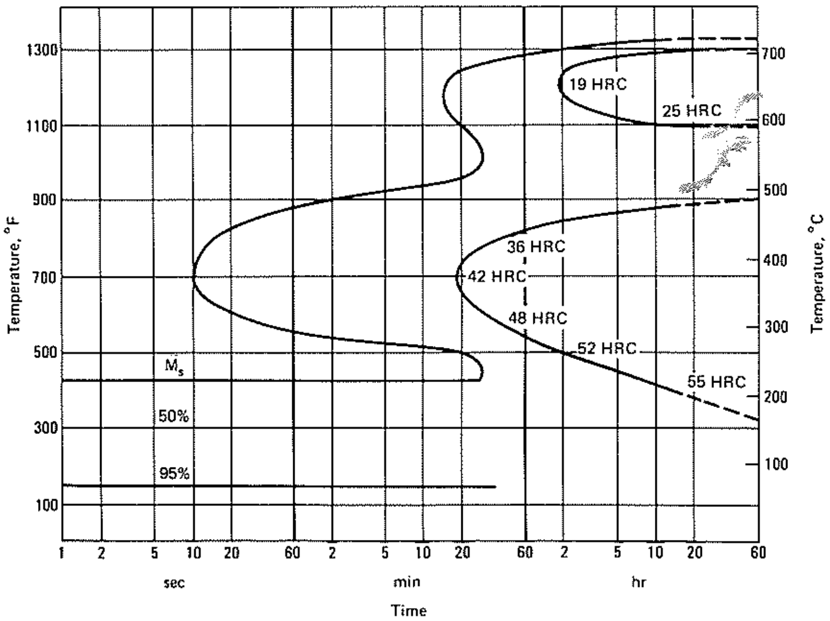
Hardening. Use protective media such as endothermic gas (use dew point of 13 to 18 °C, or 55 to 65 °F), molten salt, pack, or vacuum to prevent decarburization or carburization. Heat slowly (particularly intricate tools). Austenitize at 790 to 845 °C (1455 to 1555 °F) for 10 to 30 min and quench in warm, agitated oil. Thin intricate sections can be quenched in an agitated salt bath at approximately 175 °C (345 °F) until tools reach bath temperature. Then cool in air. This may decrease quenched hardness by an HRC point or two, but will hold distortion to a minimum. Place in tempering furnace immediately. Quenched hardness, 58 to 63 HRC

Tempering. Temper at 175 to 540 °C (345 to 1000 °F) for a corresponding approximate tempered hardness of 62 to 45 HRC

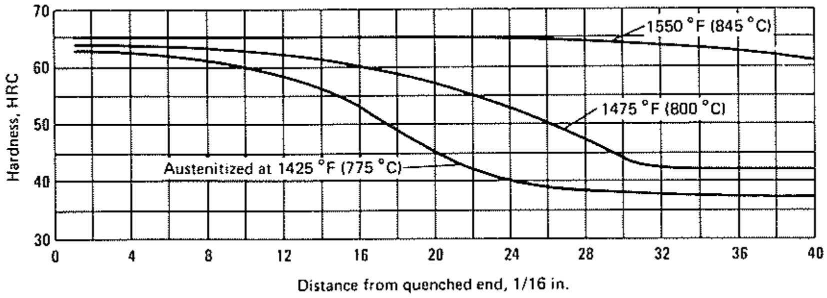
Recommended Processing Sequence

- Normalize
- Rough machine
- Stress relieve (optional)
- Finish machine
- Austenitize
- Quench
- Temper
- Final grind to size

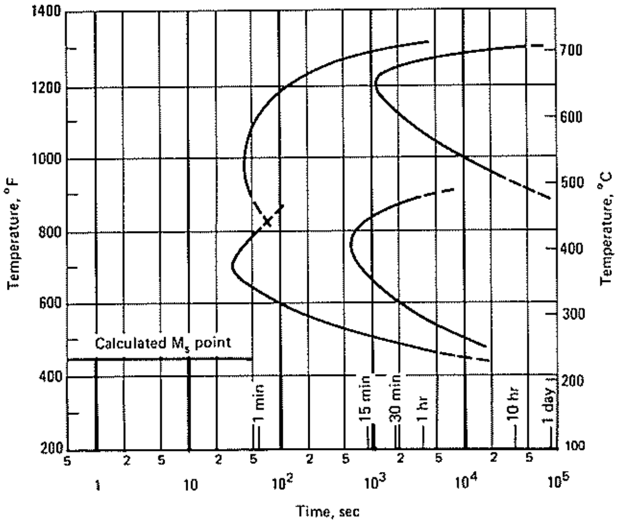
L6: Isothermal Transformation Diagram. Special-purpose tool steel, containing 0.75 C, 0.70 Mn, 1.50 Ni, 0.75 Cr, 0.30 Mo. Austenitizing temperature: 845 °C (1555 °F). Source: Crucible Steel



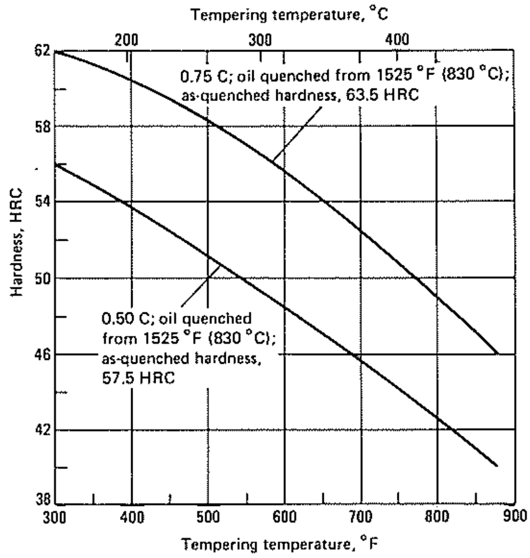
L6: Jominy End-Quench Hardenability. Hardenability curves for an L6 special-purpose tool steel containing 0.70 C, 0.55 Mn, 1.40 Ni, 0.85 Cr, 0.25 Mo. Source: Teledyne VASCO



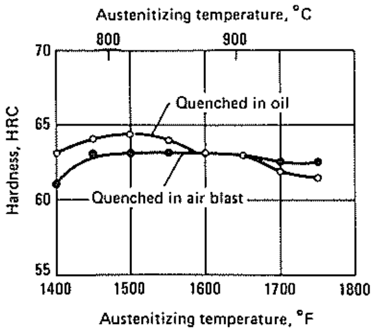
L6: Isothermal Transformation Diagram. Special-purpose tool steel, containing 0.72 C, 0.35 Mn, 0.018 P, 0.010 S, 0.23 Si, 1.75 Ni, 0.94 Cr. Austenitizing temperature: 830 °C (1525 °F). Source: Carpenter Steel



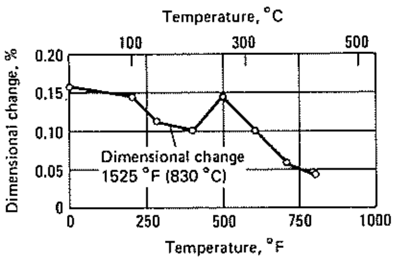
L6: Tempering Temperature vs Hardness. Effect of tempering temperature and carbon content on the hardness. Source: Universal-Cyclops

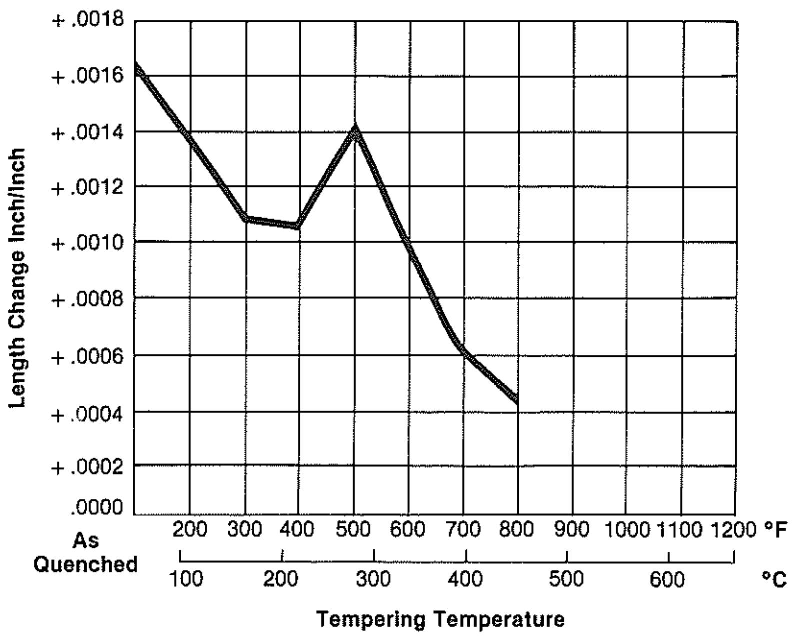


L6: Austenitizing Temperature and Quenchant vs As-Quenched Hardness. Effect of austenitizing temperature and quenching medium on the as-quenched hardness of a 25 mm (1 in.) diam by 125 mm (5 in.) specimen containing 0.75 C, 0.75 Mn, 1.75 Ni, 0.90 Cr, 0.35 Mo. Source: Bethlehem Steel



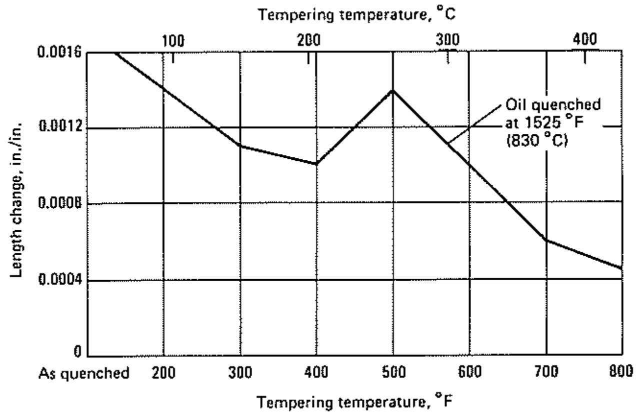
L6: Dimensional Change vs Tempering Temperature. Effect of tempering temperature on dimensional change of special-purpose tool steel. Source: Carpenter Steel



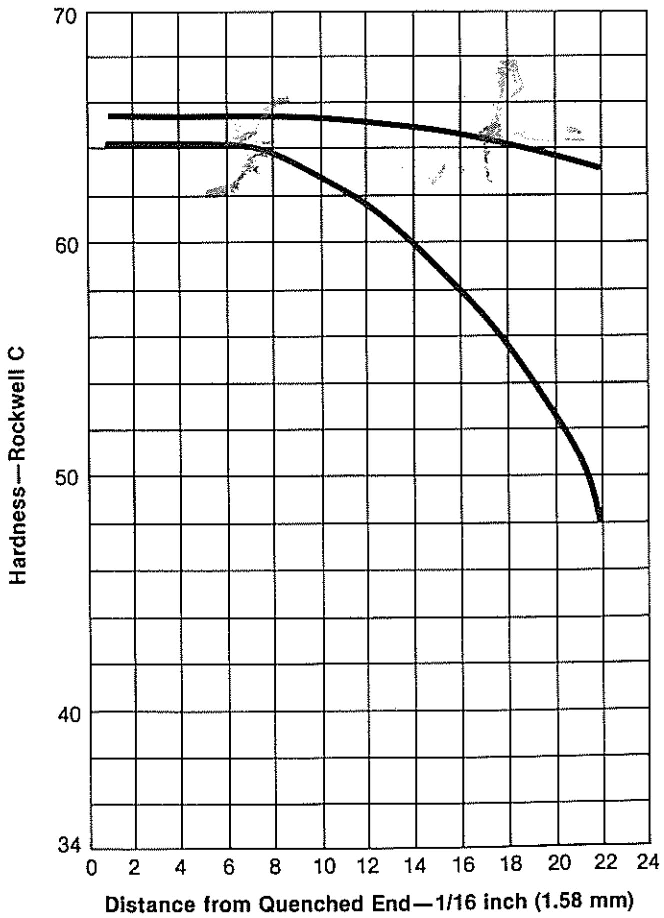


L6: Size Change in Hardening. Bar 25 mm (1 in.) in diam was oil quenched from 830 °C (1525 °F) and tempered 1 h at indicated temperatures. Source: Carpenter Technology Corporation

L6: Length Change as a Function of Tempering Temperature. A 19 mm (¾ in.) round specimen of an L6 special-purpose tool steel containing 0.75 C, 0.35 Mn, 1.75 Ni, 1.00 Cr



L6: Jominy Hardenability. Austenitized at 845 °C (1555 °F). Source: Carpenter Technology Corporation



Mold Steels (P Series)

ntroduction

The P series steels are unique in that their carbon content ranges ›m very low to medium and their alloy content from about 0.5% to a ıximum of about 5%. Depending on composition, P steels can be used · plastic molds, and, to a lesser extent, for die-casting dies. The rdening process is explained in detail in the paragraphs describing :h P steel. P21 is an exception, hardened by solution treating and ing. The low-carbon grades may be carburized, and the medium-car- n grades are sometimes nitrided.

The annealing of these steels often is neither necessary nor desirable, because a fully annealed structure is more difficult to machine. The carburizing and nitriding processes used follow the standard practices for other carbon or low-alloy steels. The heat treatment or P series steels closely resembles the practices applied to many carbon and low-alloy steels and has little similarity to the methods used with the higher alloyed tool steels, especially those with high carbon contents. Details of heat treating the various P steels are covered in the following paragraphs.

'2

hemical Composition. **AISI:** Nominal. 0.07 C, 2.00 Cr, 0.50 Ni, ?0 Mo. **AISI/UNS (T51602):** Composition: 0.10 C max, 0.10 to 0.40 n, 0.10 to 0.40 Si, 0.10 to 0.50 Ni, 0.75 to 1.25 Cr, 0.15 to 0.40 Mo

milar Steels (U.S. and/or Foreign). ASTM A681(P-2)

haracteristics. A low-carbon grade with good hobbing charac- istics. Contains chromium and molybdenum for hardenability after car- rizing, and nickel to improve core strength. Full hardness is usually tained by oil quenching, which minimizes distortion. Rated medium in pth of hardening, low in distortion in heat treating, low in resistance to ftening at elevated temperature, and high in resistance to decarburization

orging. Start forging at 1010 to 1120 °C (1850 to 2050 °F). Do not rge below 845 °C (1555 °F)

ecommended Heat Treating Practice

ormalizing. Not necessary to normalize

nnealing. Heat to 730 to 815 °C (1350 to 1500 °F). Use lower limit for ıall sections and upper limit for large sections. Holding time varies from proximately 1 h for light sections and small furnace charges, to approxi- ately 4 h for heavy sections and large charges. For pack annealing, hold r 1 h per inch of cross section. Avoid surface carburization, which astically impairs metal flow when hobbing. Cool at a maximum rate of 22 °C (40 °F) per h. The maximum rate is not critical after cooling to below 540 °C (1000 °F). Typical annealed hardness, 103 to 123 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

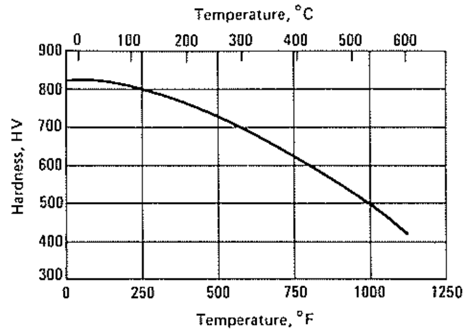
Hardening. Carburize at 900 to 925 °C (1650 to 1695 °F) to desired case depth. Austenitize at 830 to 845 °C (1525 to 1555 °F). Hold at austenitizing temperature for 15 min once the temperature is uniform throughout the tool. Quench in warm, agitated oil or in brine. Approximate quenched hardness, 62 to 65 HRC

Tempering. Temper at 175 to 260 °C (345 to 500 °F). Approximate hardness of the case as it corresponds to tempering temperature, 64 to 58 HRC

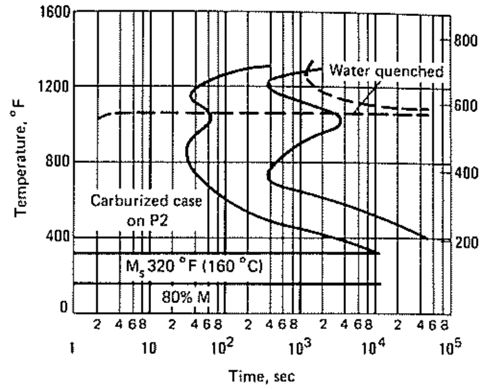
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional, between and after final hobbing)
- Finish machine
- Carburize
- Harden
- Quench
- Temper
- Final grind and polish

P2: Hardness vs Tempering Temperature. Tempered surface hardness of a P2 tool steel (carburized case) carburized at 925 °C (1695 °F) for 8 h and quenched in oil. Source: Crucible Steel



P2: Isothermal Transformation Diagram. P2 tool steel with a carburized case, indicating depth hardening characteristics after carburizing. Composition of the steel, which was austenitized at 845 °C (1555 °F), was 0.07 C max, 0.55 Ni, 1.35 Cr, and 0.20 Mo. Source: Crucible Steel



P3

Chemical Composition. **AISI:** Nominal. 0.10 C, 0.60 Cr, 1.25 Ni. **AISI/UNS (T51603):** Composition: 0.10 C max, 0.20 to 0.60 Mn, 0.40 Si max, 1.00 to 1.50 Ni, 0.40 to 0.75 Cr

Similar Steels (U.S. and/or Foreign). ASTM A681(P-3); (Ger.) DIN 1.5713; (Fr.) AFNOR 2881 Y 10 NC 6

Characteristics. Another hobbing grade, alloyed to provide medium hardenability, a high case hardness, and good surface polishing characteristics. Usually oil quenched, but the carburizing and hardening practice is essentially the same as that for P2. Rates low in distortion in heat treating, high in toughness, low in resistance to softening at elevated temperature, and high in resistance to decarburization. Range of core hardness, 15 to 25 HRC

Forging. Start forging at 1010 to 1120 °C (1850 to 2050 °F). Do not forge below 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Not necessary to normalize

Annealing. Heat to 730 to 815 °C (1350 to 1500 °F). Use lower limit for small sections and upper limit for large sections. Holding time varies from approximately 1 h for light sections and small furnace charges, to approximately 4 h for heavy sections and large charges. For pack annealing, hold for 1 h per inch of cross section. Avoid surface carburization, which drastically impairs metal flow when hobbing. Cool at a maximum rate of 22 °C (40 °F) per h. The maximum rate is not critical after cooling to below 540 °C (1000 °F). Typical annealed hardness, 109 to 137 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Carburize at 900 to 925 °C (1650 to 1695 °F) to desired case depth. Harden at 800 to 830 °C (1475 to 1525 °F). Hold at austenitizing temperature for 15 min once the temperature is uniform throughout the tool. Quench in warm, vigorously agitated oil. This grade has the lowest hardenability of the P series mold steels. Approximate quenched hardness, 62 to 64 HRC

Tempering. Temper at 175 to 260 °C (345 to 500 °F). Approximate tempered case hardness as it corresponds to tempering temperature, 64 to 58 HRC

Recommended Processing Sequence

- Rough machine
- Stress relieve (optional, between and after final hobbing)
- Finish machine
- Carburize
- Harden
- Quench
- Temper
- Final grind and polish

P4

Chemical Composition. **AISI:** Nominal. 0.07 C, 5.00 Cr, 0.75 Mo. **AISI/UNS (T51604):** Composition: 0.12 C max, 0.20 to 0.60 Mn, 0.10 to 0.40 Si, 4.00 to 5.25 Cr, 0.40 to 1.00 Mo

Similar Steels (U.S. and/or Foreign). ASTM A681(P-4); (Ger.) DIN 1.2341; (Swed.) SS (USA P4)

Characteristics. Has the highest hardenability of the hobbing grades of P tool steels and can be considered the mold steel equivalent to the medium-alloy cold work die steel A2. Can be air hardened for minimum distortion or oil quenched to avoid surface scaling. Has the highest wear resistance and softening resistance at elevated temperatures of any of the ld steels. Rates high in depth of hardening, very low in distortion in heat ıting, with high resistance to decarburization

·rging. Start forging at 1010 to 1120 °C (1850 to 2050 °F). Do not ge below 870 °C (1600 °F)

ːcommended Heat Treating Practice

ırmalizing. Do not normalize

ınealing. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for all sections and upper limit for large sections. Holding time varies from ıroximately 1 h for light sections and small furnace charges, to approxitely 4 h for heavy sections and large charges. For pack annealing, hold 1 h per inch of cross section. Avoid surface carburization, which stically impairs metal flow when hobbing. Cool at a maximum rate of °C (25 °F) per h. The maximum rate is not critical after cooling to below) °C (1000 °F). Typical annealed hardness, 116 to 128 HB

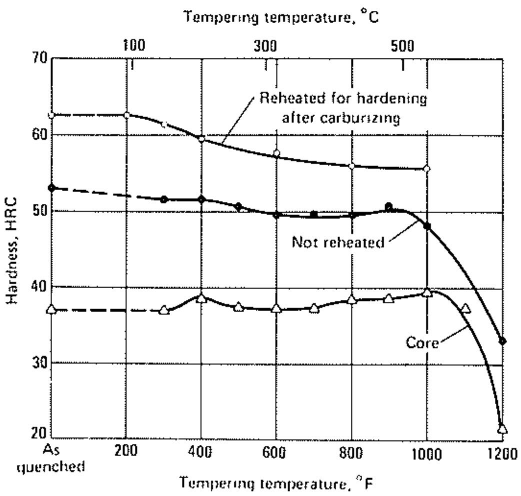
·ess Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) l hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

rdening. Carburize at 970 to 995 °C (1775 to 1825 °F) to desired case ıth. Harden at 970 to 995 °C (1775 to 1825 °F) by holding at temperature 15 min once the temperature is uniform throughout the tool. Quench in or oil. This grade may also be quenched in hot salt at 540 to 650 °C (1000 200 °F) to prevent scaling of cavity. Cool in air as soon as temperature niform throughout the tool. Approximate quenched hardness, 62 to 65 C

ıbilizing. Optional. Low-temperature treatment may increase surface dness. It is safer to stress relieve temper at 150 to 160 °C (300 to 320 for a short period after refrigerating at −85 °C (−120 °F)

mpering. Temper at 175 to 480 °C (345 to 895 °F). Approximate face hardness as it corresponds to tempering temperature, 64 to 58 HRC

4: Tempering Characteristics—Carburized Case and Core. ·: P4 carburized in hardwood charcoal at 910 to 925 °C (1675 to 700 °F) for 8 h, air cooled in pack, reheated at 940 to 955 °C 725 to 1750 °F), cooled in air, and tempered. ●: P4 carburized cast iron chips at 940 to 955 °C (1725 to 1750 °F), removed from ack, cooled in air and tempered



Recommended Processing Sequence

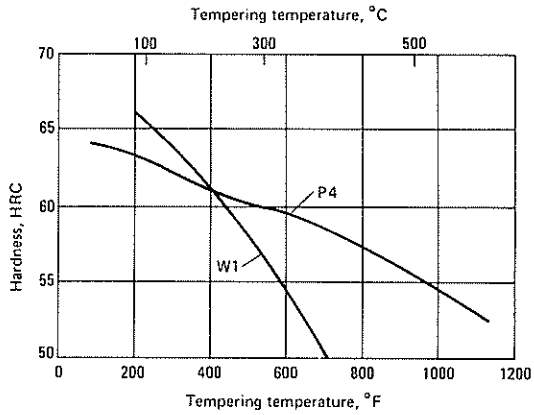
- Rough machine
- Stress relieve (optional, between and after final hobbing operation)
- Hob
- Carburize
- Harden
- Quench
- Stabilize (optional)
- Temper
- Final grind and polish

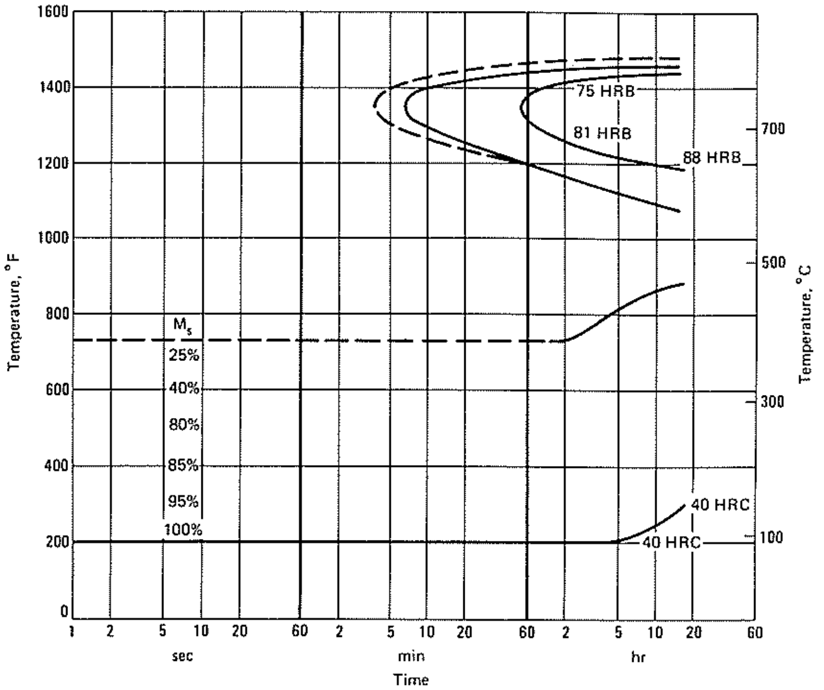
P4: Effect of Tempering Temperatures on Hardness

Tempering temperature °C	Tempering temperature °F	Case hardness HRC	Core hardness HRC
As treated		52/54	36/38
150	300	50/53	36/38
205	400	50/53	38/39
260	500	50/51	37/38
315	600	49/50	37/38
370	700	49/50	37/38
425	800	49/50	38/39
480	900	50/51	38/39
540	1000	48/49	39/40
595	1100	42/44	37/38
650	1200	32/34	21/22

40 mm (1.5 in.) round packed in new gray cast iron chips, cooled in air from 955 °C (1750 °F). Source: Carpenter Technology Corporation

P4: Tempering Temperature vs Carburized Surface Hardness. P4 compared to W1. Both carburized at 925 °C (1695 °F) for 8 h in charcoal powder, and quenched in oil. Source: Uddeholm Steel





P4: Isothermal Transformation Diagram. P4 containing 0.14 C, 0.41 Mn, 0.21 Si, 0.19 Ni, 5.12 Cr, and 0.51 Mo. Austenitized at 900 °C (1650 °F) and quenched in water. As-quenched hardness, 41 HRC

P5

Chemical Composition. **AISI:** Nominal. 0.10 C, 2.25 Cr. **AISI/UNS (T51605):** Composition: 0.10 C max, 0.20 to 0.60 Mn, 0.40 Si max, 0.35 Ni max, 2.00 to 2.50 Cr

Similar Steels (U.S. and/or Foreign). ASTM A681(P-5)

Characteristics. Low carbon hobbing grade with enough alloy to impart medium hardenability. Has low distortion in heat treating when oil quenched, low resistance to softening at elevated temperatures, and high resistance to decarburization

Forging. Start forging at 1010 to 1120 °C (1850 to 2050 °F). Do not forge below 845 °C (1555 °F)

Recommended Heat Treating Practice

Normalizing. Not necessary to normalize

Annealing. Heat to 845 to 870 °C (1555 to 1600 °F). Use lower limit for small sections and upper limit for large sections. Holding time varies from approximately 1 h for light sections and small furnace charges, to approximately 4 h for heavy sections and large charges. For pack annealing, hold for 1 h per inch of cross section. Avoid surface carburization, which drastically impairs metal flow when hobbing. Cool at a maximum rate of 22 °C (40 °F) per h. The maximum rate is not critical after cooling to below 540 °C (1000 °F). Typical annealed hardness, 105 to 131 HB

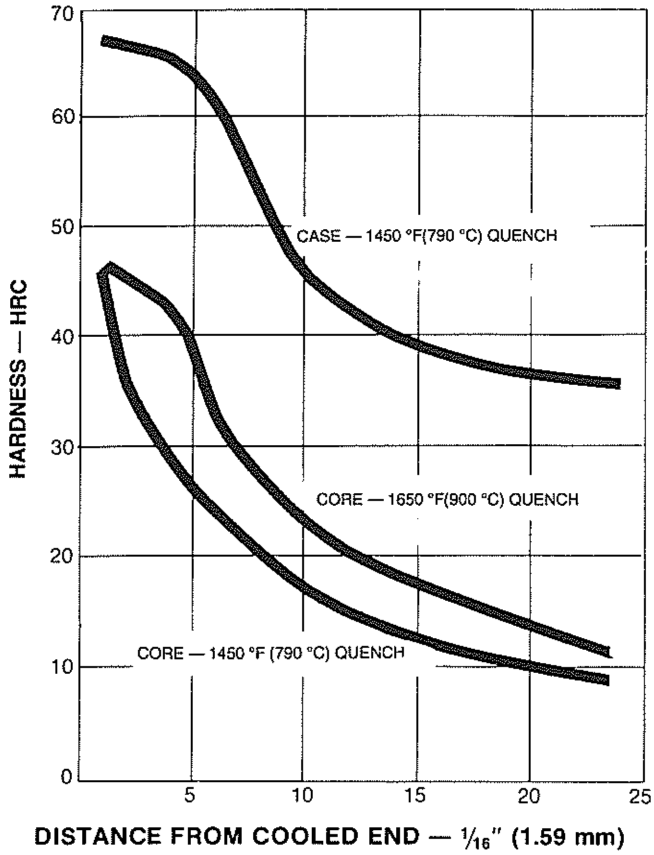
Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Carburize at 900 to 925 °C (1650 to 1695 °F) to desired case depth. Harden at 845 to 870 °C (1555 to 1600 °F). Hold at austenitizing temperature for 15 min once the temperature is uniform throughout the tool. Quench in warm, agitated oil. Large sections without severe stress raisers can be water quenched with caution if maximum hardness is desired

Tempering. Temper at 175 to 260 °C (345 to 500 °F). Approximate case hardness as it corresponds to tempering temperature, 64 to 58 HRC

Recommended Processing Sequence

- Rough machine
- Stress relieve (optional, between and after final hobbing)
- Finish machine
- Carburize
- Harden
- Quench
- Temper
- Final grind and polish



P5: Jominy Hardenability. Carburized at 925 °C (1695 °F). Source: Carpenter Technology Corporation

›6

:hemical Composition. **AISI:** Nominal. 0.10 C, 1.50 Cr, 3.50 Ni. **ISI/UNS (T51606):** Composition: 0.05 to 0.15 C, 0.35 to 0.70 Mn, 0.10 ı 0.40 Si, 3.25 to 3.75 Ni, 1.25 to 1.75 Cr

imilar Steels (U.S. and/or Foreign). ASTM A681(P-6); (Ger.) ·IN 1.2330, 1.2735, 1.2745; (Fr.) AFNOR 2882 10 NC 12; (Jap.) JIS 4410 SKC 31; (U.K.) B.S. 4659 (USA P20)

:haracteristics. A hobbing grade with fairly high hardenability. Can- ɔt be annealed to a hardness much lower than 183 HB, because the high ickel content strengthens the ferrite. Consequently, the mold cavity is ften machined rather than hobbed. Has high core strength, and small :ctions can be air quenched. Low resistance to softening at elevated :mperature, medium resistance to wear, and high resistance to decarburi- ation

'orging. Start forging at 1065 to 1175 °C (1950 to 2150 °F). Do not ɔrge below 925 °C (1695 °F)

lecommended Heat Treating Practice

lormalizing. Not necessary to normalize

ınnealing. Heat to 845 to 870 °C (1555 to 1600 °F). Use lower limit for nall sections and upper limit for large sections. Holding time varies from ɔproximately 1 h for light sections and small furnace charges, to approxi- ıately 4 h for heavy sections and large charges. For pack annealing, hold ɔr 1 h per inch of cross section. Avoid surface carburization, which rastically impairs metal flow when hobbing. Cool at a maximum rate of 8 °C (15 °F) per h. The maximum rate is not critical after cooling to below 540 °C (1000 °F). Typical annealed hardness, 183 to 217 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

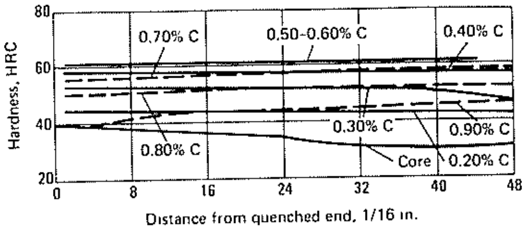
Hardening. Carburize at 900 to 925 °C (1650 to 1695 °F) to desired case depth. Harden at 790 to 815 °C (1450 to 1500 °F). Hold at austenitizing temperature for 15 min once the temperature is uniform throughout the tool. Quench small sections in air and larger sections in oil. Approximate quenched hardness, 60 to 62 HRC

Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to –320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 175 to 230 °C (345 to 445 °F). Approximate tempered hardness as it corresponds to tempering temperature, 61 to 58 HRC

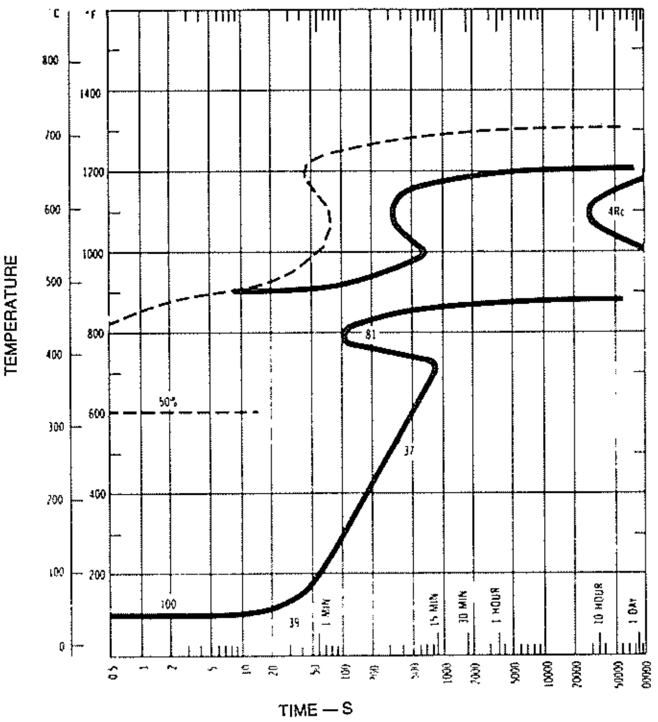
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional, between and after final hobbing)
- Finish machine
- Carburize
- Harden
- Quench
- Stabilize (optional)
- Temper
- Final grind and polish

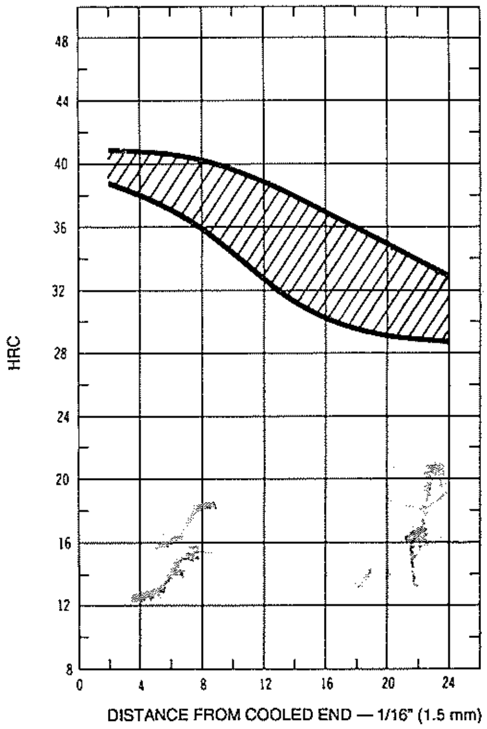


P6: End-Quench Hardenability. Hardness of P6 carburized bars containing 3.5% Ni and 1.5% Cr, along end-quench hardenability bar at various case-depth levels. Note decrease in hardness with increasing carbon content because of retained austenite. ASTM grain size: 7 to 8

P6: Isothermal Transformation Diagram. Composition of alloy: 0.10 C, 0.34 Mn, 0.20 Si, 3.51 Ni, 1.66 Cr, 0.06 Mo. Austenitizing temperature was 790 °C (1455 °F). Source: Carpenter Technology Corporation



P6: Jominy Core Hardenability. Source: Carpenter Technology Corporation



P20

Chemical Composition. **AISI:** Nominal. 0.35 C, 1.70 Cr, 0.40 Mo. **AISI/UNS (T51620):** Composition: 0.28 to 0.40 C, 0.60 to 1.00 Mn, 0.20 to 0.80 Si, 1.40 to 2.00 Cr, 0.30 to 0.55 Mo

Similar Steels (U.S. and/or Foreign). ASTM A681(P-20); (Ger.) DIN 1.2311, 1.2328, 1.2330; (Fr.) AFNOR A35-590 Z 333 35 CHD 7; (Swed.) SS (USA P20); (U.K.) B.S. 4659 (USA P20)

Characteristics. Medium hardening grade with high core toughness, low softening resistance at elevated temperature, and high decarburization resistance. Usually purchased in preheat treated condition with a hardness of approximately 300 HB. Cavity is machined and may be used at this hardness. For maximum wear resistance, molds may be carburized or nitrided

Forging. Start forging at 1010 to 1120 °C (1850 to 2050 °F). Do not forge below 870 °C (1600 °F)

Recommended Heat Treating Practice

Normalizing. Normalize at 900 °C (1650 °F)

Annealing. Heat to 760 to 790 °C (1400 to 1455 °F). Use lower limit for small sections and upper limit for large sections. Holding time varies from approximately 1 h for light sections and small furnace charges, to approximately 4 h for heavy sections and large charges. For pack annealing, hold for 1 h per inch of cross section. Avoid surface carburization, which drastically impairs metal flow when hobbing. Cool at a maximum rate of 22 °C (40 °F) per h. The maximum rate is not critical after cooling to below 540 °C (1000 °F). Typical annealed hardness, 149 to 212 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

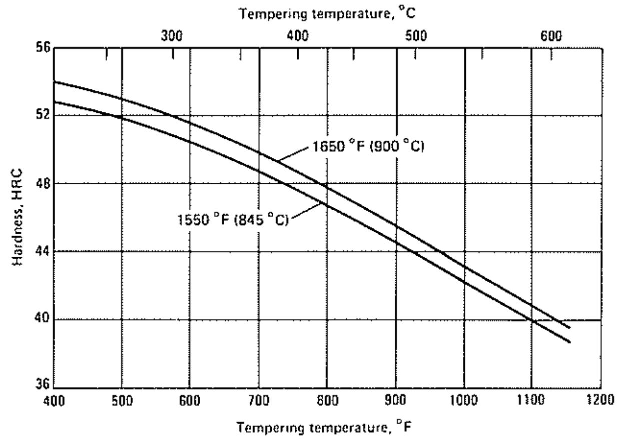
Hardening. Carburize at 870 to 900 °C (1600 to 1650 °F) to desired case depth. Harden at 815 to 870 °C (1500 to 1600 °F). Hold at austenitizing temperature for 15 min once the temperature is uniform throughout the tool. Quench in warm, agitated oil. Nitriding is a suitable alternative for dies used in die casting

Tempering. If not carburized and a hardness of 37 to 28 HRC is desired, temper at 480 to 595 °C (895 to 1105 °F). If carburized, temper at 175 to 230 °C (345 to 445 °F) for an approximate hardness of 62 to 58 HRC. This grade can be nitrided using conventional nitriding practice. The die should be quenched and tempered to approximately 300 HB, the cavity machined, and then nitrided

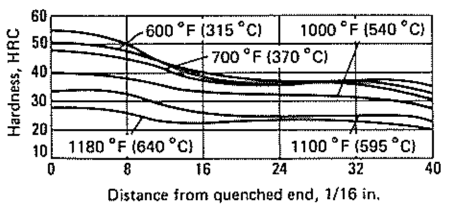
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat (large or intricately shaped tools)
- Carburize
- Harden
- Quench
- Temper
- Final grind and polish

P20: Hardness vs Austenitizing and Tempering Temperatures. P20 austenitized at 845 °C (1555 °F) and oil quenched. As-quenched hardness, 53.5 HRC. When austenitized at 900 °C (1650 °F) and oil quenched, the as-quenched hardness is 54.5 HRC. Source: Universal-Cyclops



P20: End-Quench Hardenability. P20 tool steel after quenching and tempering at indicated temperatures for 2 h. Steel austenitized at 855 °C (1570 °F). Source: Teledyne VASCO



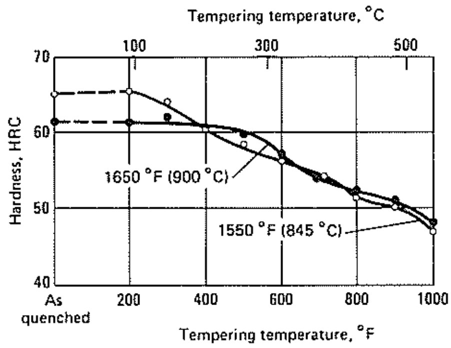
Effect of Carburizing Temperature on Case Depth and Surface Hardness for P20

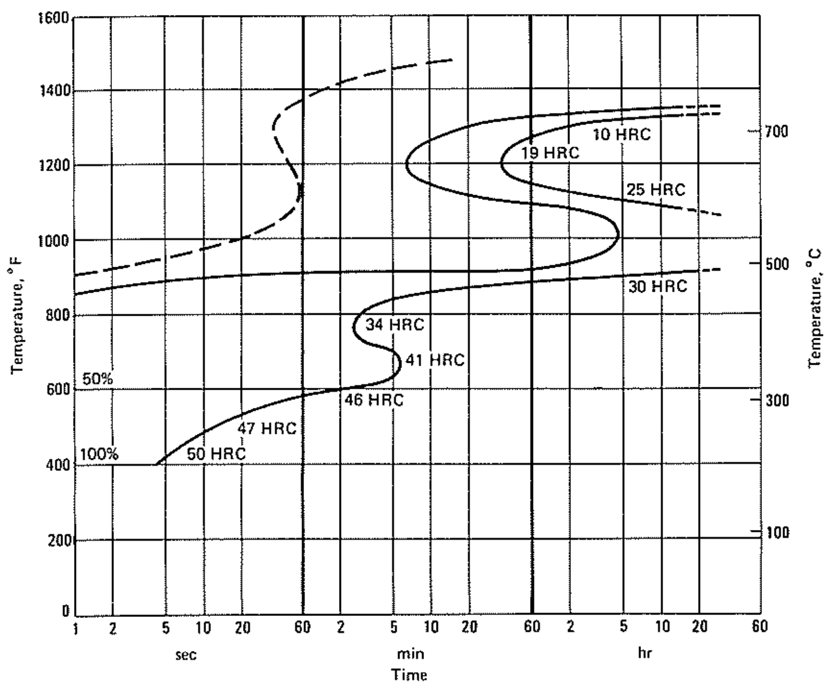
Specimens were 25-mm (1-in.) cubes, held 2 h at temperature in carburizing compound and quenched in oil

Carburizing temperature		Surface hardness,	Case depth	
°C	°F	HRC	in.	mm
845	1555	65.6	0.014	0.356
870	1600	64.2	0.017	0.432
900	1650	62.5	0.016	0.406
925	1700	59.2	0.020	0.508
955	1750	58.6	0.022	0.559
980	1800	58.6	0.028	0.711

Source: Teledyne VASCO

P20: Tempering Characteristics (Carburized). Surface hardness of P20 after heating at 900 °C (1650 °F) and 845 °C (1555 °F) for 2 h in carburizing compound, oil quenching, and tempering





P20: Isothermal Transformation Diagram. P20 containing 0.30 C, 0.75 Mn, 0.50 Si, 0.80 Cr, and 0.25 Mo and austenitized at 845 °C (1555 °F). Source: Crucible Steel

P21

Chemical Composition. **AISI:** Nominal. 0.20 C, 4.00 Ni, 1.20 Al. **AISI/UNS (T51621):** Composition: 0.18 to 0.22 C, 0.20 to 0.40 Mn, 0.20 to 0.40 Si, 3.90 to 4.25 Ni, 0.50 Cr max, 0.15 to 0.25 Mo, 1.05 to 1.25 Al

Similar Steels (U.S. and/or Foreign). ASTM A681(P-21)

Characteristics. An age-hardening tool steel. When heat treating, a high-temperature tempering treatment is used to lower hardness and enable the cavity to be machined. Final hardening occurs during aging. This grade can be nitrided, but should not be carburized. Is deep hardening, with medium softening resistance at elevated temperatures, and high decarburization resistance

Forging. Start forging at 1095 to 1150 °C (2005 to 2100 °F). Do not forge below 955 °C (1750 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 900 °C (1650 °F). After uniform through heating, holding time varies from approximately 15 min for small sections to about 1 h for large sections. Work is cooled from temperature in still air

Annealing. Do not anneal

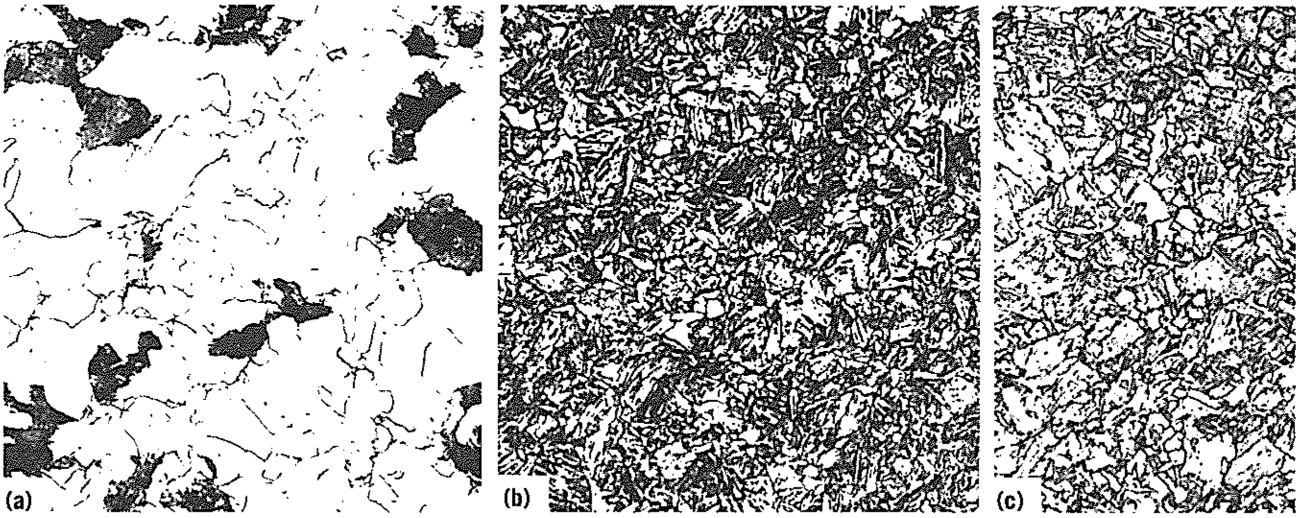
Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Solution treat by heating slowly to 705 to 730 °C (1300 to 1350 °F) and holding for 60 min for small sections to 180 min for large sections. Do not preheat. Cool in air or quench in oil to accelerate cooling. Approximate hardness range, 24 to 28 HRC. After machining, age harden at 510 to 550 °C (950 to 1020 °F), holding at temperature for 20 h for small sections and up to 24 h for large sections. Approximate aged hardness, 40 to 30 HRC. This grade cannot be carburized, but may be nitrided by holding in a gas nitriding furnace containing ammonia for 20 to 24 h at 510 to 525 °C (950 to 975 °F). Case depth will be approximately 0.152 to 0.203 mm (0.006 to 0.008 in.) with a hardness of 94 HR15N

Recommended Processing Sequence

- Normalize (if not purchased ready for solution treating)
- Solution treat
- Quench
- Rough machine
- Stress relieve (optional, below aging temperature such as 400 to 425 °C or 750 to 800 °F))
- Finish machine
- Age

P21: Microstructures. (a) 4% nital, 500×. Annealed by slow cooling from hot working. Principally pearlite (dark) and ferrite (white). Some austenite is probably present. (b) 4% nital, 500×. Solution treated by holding 1 h at 900 °C (1650 °F), water quenching, reheating to 730 °C (1350 °F), holding 1 h, water quenching. Structure: martensite. (c) 4% nital, 500×. Solution treated as in (b), then aged by holding 20 h at 510 °C (950 °F). Precipitate at grain boundaries and within grains has not been identified



Hot Work Tool Steels (H Series)

Introduction

The hot work tool steels are divided into three major groups: chromium, tungsten, and molybdenum. The distinction is intended to indicate the *principal* alloying addition, although all steels contain chromium in amounts varying from 2 to 12%. All are used extensively for hot work applications.

Because these steels are either partially or completely air hardening, normalizing is not recommended. Recommended annealing temperatures, cooling practice, and expected hardness values are given in the sections that follow. Heating for annealing should be slow and uniform to prevent cracking, especially when annealing hardened tools. Heat losses from the furnace usually determine the rate of cooling; large furnace loads will cool at a slower rate than light loads. The H steels are extremely susceptible to both carburizing and decarburizing and must be carefully protected against both. Use packing, controlled atmosphere, or a vacuum.

Stress relieving tools of hot work steel can be beneficial if done after rough machining but before final machining. Heat tools to 650 to 730 °C (1200 to 1350 °F). This treatment minimizes distortion during hardening, particularly for dies or tools having major changes in configuration or deep cavities. Closer dimensional control may be obtained by hardening and tempering after rough machining and prior to final machining. However, final hardness obtained by this method should be within machinable range. With few exceptions, preheating is recommended prior to austenitizing hot work steels.

Rapid heating from the preheating temperatures to the austenitizing temperature is preferred for types H19 through H43. With the exception of steels H10 through H14, time at the austenitizing temperature should only be sufficient to heat the work completely through. Prolonged soaking is not recommended. Tools or dies made of hot work steel must be protected against carburization and decarburization when being heated for austenitizing. An endothermic atmosphere produced by a gas generator is probably the most widely used medium. The dew point is normally held from 3 to 8 °C (5.5 to 15 °F) *in the furnace*, depending on the carbon content of the steel and the operating temperature. A dew point of 3 to 4 °C (5 to 7 °F) is ideal for types H11 and H13 when austenitized at 1010 °C (1850 °F). Molten salt baths are also widely used. In small shops where the use of a protective atmosphere is not feasible because of equipment costs, the work is packed in spent pitch coke before heating it for austenitizing as a common practice.

Hot work steels range from high to extremely high in hardenability. Most will achieve full hardness by cooling in still air. However, even with the steels having the highest hardenability, sections of die blocks may be so large that insufficient hardening results. In such instances, an air blast or an oil quench (*never* a water quench) is required to achieve full hardness. Some of the H steels, especially the tungsten and molybdenum types, will scale considerably during cooling to room temperature in air. An interrupted quench reduces this scaling by eliminating the long period of contact with air at elevated temperature, but it also increases distortion.

Hot work tool steels should be tempered immediately after quenching, although sensitivity to cracking at this stage varies considerably. Multiple tempering serves to transform retained austenite and to minimize cracking due to hardening stresses. The H steels containing 0.35% or less carbon are occasionally carburized to achieve a very high surface hardness (HRC 60 to 62). For some applications, the steels are nitrided after hardening and tempering.

H10

Chemical Composition. **AISI:** Nominal. 0.40 C, 2.50 Mn, 3.25 Cr, 0.40 V. **AISI/UNS (T20810):** Composition: 0.35 to 0.45 C, 0.25 to 0.70 Mn, 0.80 to 1.20 Si, 0.30 Ni max, 3.00 to 3.75 Cr, 2.00 to 3.00 Mo, 0.25 to 0.75 V

Similar Steels (U.S. and/or Foreign). ASTM A681 (H-10); FED QQ-T-570 (H-10); (Ger.) DIN 1.2365, 1.2367; (Fr.) AFNOR A35-590 3431 FZ 38 CDV 5; (Jap.) JIS G4404 SKD 7; (U.K.) B.S. 4659 BH10

Characteristics. Lowest in alloy content of the hot work steels, but offers deep-hardening properties at relatively low cost. Has high toughness and can be water cooled in service. Can be carburized or nitrided to increase surface hardness with some loss in resistance to heat checking. Has very low distortion in heat treating, high resistance to softening at elevated temperature and medium wear resistance. Has medium to high machinability and medium resistance to decarburization

Forging. Heat slowly. Preheat at 705 to 815 °C (1300 to 1500 °F), start forging at 1065 to 1150 °C (1950 to 2100 °F). Do not forge after temperature of forging stock drops below 900 °C (1650 °F). Cool slowly

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Surface protection against decarburization by use of pack, controlled atmosphere, or vacuum is required. Heat to 845 to 900 °C (1555 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Heat slowly and uniformly, especially for hardened tools. Holding time varies from about 1 h for light sections and small furnace charges to about 4 h for heavy sections and large charges. For pack annealing, hold 1 h per inch of cross section. Cool slowly in furnace to 540 °C (1000 °F) at a rate not to exceed 30 °C (55 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 192 to 229 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

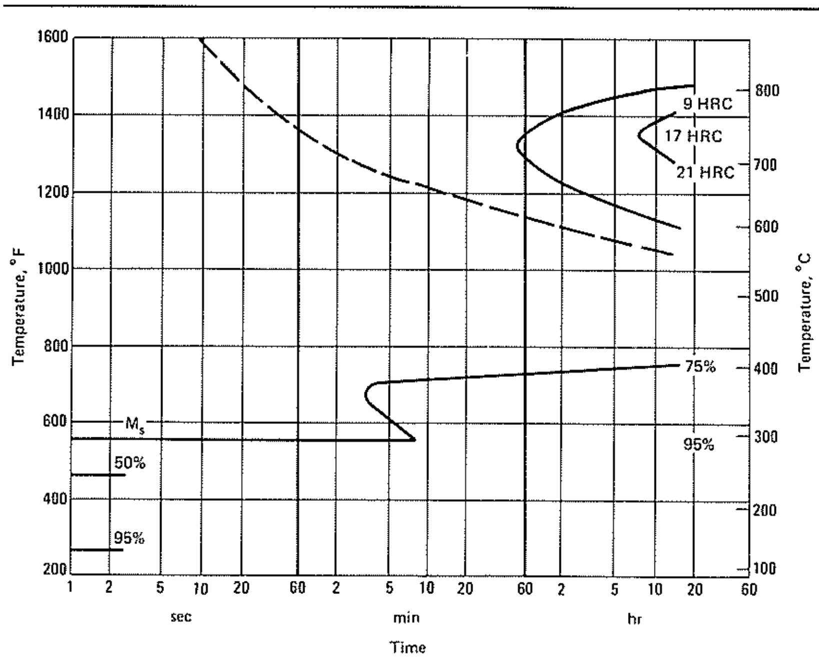
Hardening. Surface protection against decarburization or carburization is required by utilizing molten salt bath, pack, controlled atmosphere, or vacuum. For preheating, die blocks or other tools for open furnace treat-nent should be placed in a furnace at a temperature that does not exceed 260 °C (500 °F). Work packed in containers may be safely placed in a urnace at 370 to 540 °C (700 to 1000 °F). Once the workpieces (or container) have attained temperature, heat slowly to 815 °C (1500 °F), at a ate not to exceed 110 °C (200 °F) per h. Hold for 1 h per inch of thickness or per inch of container thickness if packed). If double preheat facilities are available, such as salt baths, thermal shock can be reduced by preheating at 540 to 650 °C (1000 to 1200 °F) and then preheating at 845 to 870 °C 1555 to 1600 °F). Austenitize at 1010 to 1040 °C (1850 to 1905 °F) for 15 o 40 min. Use shorter time for small sections and longer time for large ections. Quench in air. If air blast cooled, air should be dry and blasted uniformly on the surface to be hardened. To minimize scale, tools can be lash quenched in oil to cool the surface to below scaling temperature approximately 540 °C (1000 °F)], then cooled in air, but this increases listortion. The safer procedure is to quench from the austenitizing temperature into a salt bath held at 595 to 650 °C (1105 to 1200 °F), and hold in the quench until the workpiece reaches the temperature of the bath. Then withdraw the workpiece and allow it to cool in air. Quench hardness, 52 to 59 HRC

Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 o 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to -320 °F). Temper immediately after part reaches room temperature

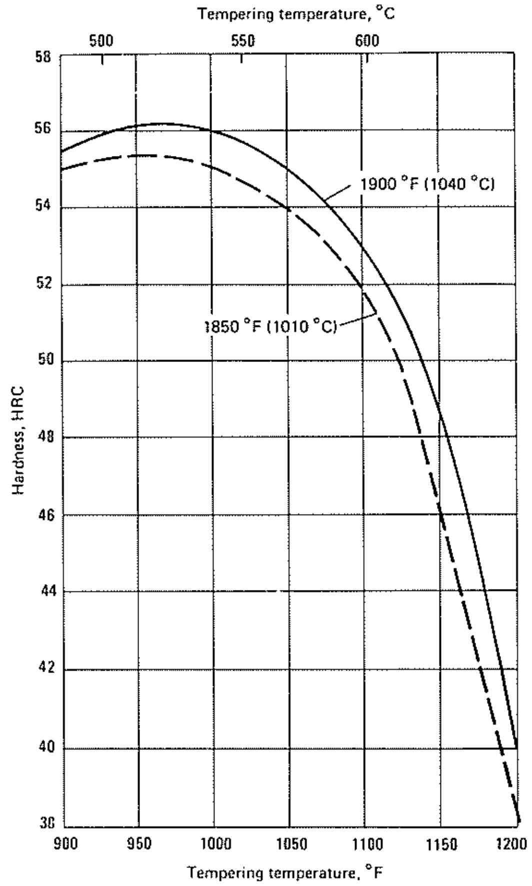
Tempering. Temper immediately after tool reaches about 50 °C (120 °F) at 540 to 650 °C (1000 to 1200 °F). Forced-convection air tempering furnaces heat tools at a moderately safe rate. Salt baths are acceptable for small parts but may cause large or intricate shaped dies to crack due to thermal shock. Temper for 1 h per inch of thickness, cool to room temperature, and retemper using the same time at temperature. The second temper is essential and a third temper is beneficial. Approximate tempered hardness, 56 to 39 HRC

Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size



H10: Isothermal Transformation Diagram. H10 tool steel: 0.40 C, 0.55 Mn, 1.00 Si, 3.25 Cr, 2.50 Mo, 0.33 V. Austenitized at 1035 °C (1895 °F). Source: Crucible Steel



H10: Hardness vs Tempering Temperature. H10, air cooled from 1040 °C (1905 °F) and 1010 °C (1850 °F). Double tempered. Source: Universal-Cyclops

H11

Chemical Composition. **AISI:** Nominal. 0.35 C, 1.50 Mn, 5.00 Cr, 0.40 V. **AISI/UNS (T20811):** Composition: 0.33 to 0.43 C, 0.20 to 0.50 Mn, 0.80 to 1.20 Si, 0.30 Ni max, 4.75 to 5.50 Cr, 1.10 to 1.60 Mo, 0.30 to 0.60 V

Similar Steels (U.S. and/or Foreign). AMS 6437, 6485, 6487, 6488; ASTM A681 (H-11); FED QQ-T-570 (H-11); SAE J437 (H11), J438 (H11), J467 (H11); (Ger.) DIN 1.2343, 1.7783, 1.7784; (Fr.) AFNOR A35-590 3431 FZ 38 CDV 5; (Ital.) UNI X 35 CrMo 05 KU; (Jap.) JIS G4404 SKD 6; (U.K.) B.S. BH11

Characteristics. A popular and relatively economical grade of hot work steel suitable for many applications. Is deep hardening, has excellent resistance to heat checking, and can be water cooled in service. Can be carburized or nitrided with some loss in resistance to heat checking. Has high resistance to softening at elevated temperature. Hardness does not vary up to 595 °C (1105 °F), and tools can withstand working temperature up to 595 °C (1105 °F). Does not exhibit notable secondary hardening effect during tempering because of low carbon content. Hardness begins to drop off rapidly when tempering above 565 °C (1050 °F). Has high toughness, very low distortion in heat treating, and medium wear resistance. Has medium-to-high machinability and medium resistance to decarburization

Forging. Heat slowly. Preheat at 705 to 815 °C (1300 to 1500 °F), start forging at 1065 to 1150 °C (1950 to 2100 °F). Do not forge after temperature of forging stock drops below 900 °C (1650 °F). Cool slowly

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Surface protection against decarburization by use of pack, controlled atmosphere, or vacuum is required. Heat to 845 to 900 °C (1555 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Heat slowly and uniformly, especially for hardened tools. Holding time varies from about 1 h for light sections and small furnace charges to about 4 h for heavy sections and large charges. For pack annealing, hold 1 h per inch of cross section. Cool slowly in furnace to 540 °C (1000 °F) at a rate not to exceed 30 °C (55 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 192 to 235 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

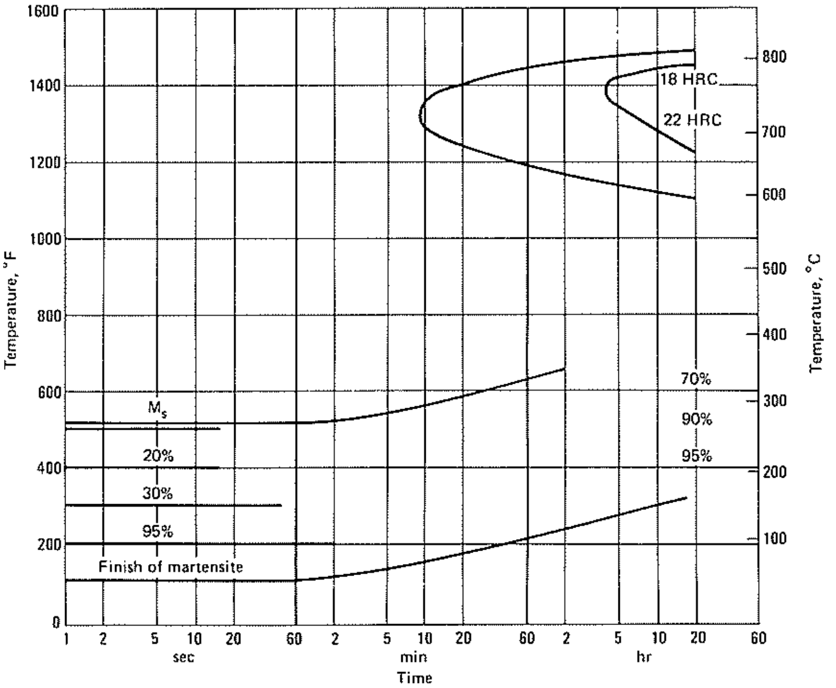
Hardening. Surface protection against decarburization or carburization is required by utilizing salt, pack, controlled atmosphere, or vacuum. For preheating, die blocks or other tools for open furnace treatment should be placed in a furnace at a temperature that does not exceed 260 °C (500 °F). Work packed in containers may be safely placed in a furnace at 370 to 540 °C (700 to 1000 °F). Once the workpieces (or container) have attained temperature, heat slowly to 815 °C (1500 °F), at a rate not to exceed 110 °C (200 °F) per h. Hold for 1 h per inch of thickness (or per inch of container thickness if packed). If double preheat facilities are available, such as salt baths, thermal shock can be reduced by preheating at 540 to 650 °C (1000 to 1200 °F) and then preheating at 845 to 870 °C (1555 to 1600 °F). Austenitize at 995 to 1025 °C (1825 to 1875 °F) for 15 to 40 min. Use shorter time for small sections and longer time for large sections. Quench in air. If air blast cooled, air should be dry and blasted uniformly on the surface to be hardened. To minimize scale, tools can be flash quenched in oil to cool the surface to below scaling temperature [approximately 540 °C (1000 °F)], then cooled in air, but this increases distortion. The safer procedure is to quench from the austenitizing temperature into a salt bath held at 595 to 650 °C (1105 to 1200 °F), and hold in the quench until the workpiece reaches the temperature of the bath. Then withdraw the workpiece and allow it to cool in air. Quench hardness, 53 to 55 HRC

Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to –320 °F). Temper immediately after part reaches room temperature

Tempering. Temper immediately after tool reaches about 50 °C (120 °F) at 540 to 650 °C (1000 to 1200 °F). Forced-convection air tempering furnaces heat tools at a moderately safe rate. Salt baths are acceptable for small parts but may cause large or intricate shaped dies to crack due to thermal shock. Temper for 1 h per inch of thickness, cool to room temperature, and retemper using the same time at temperature. The second temper is essential and a third temper is beneficial. Approximate tempered hardness, 54 to 38 HRC

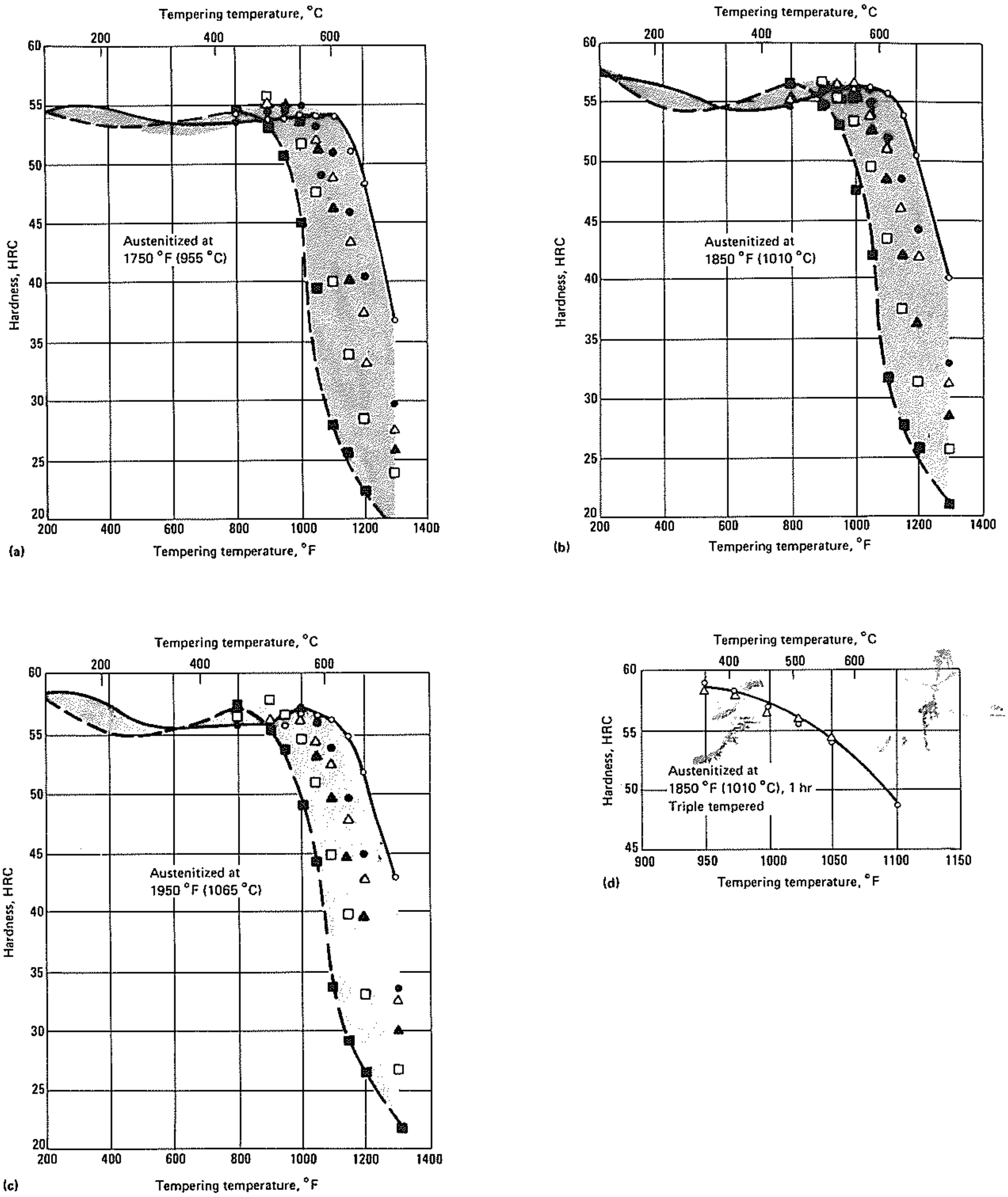
Recommended Processing Sequence

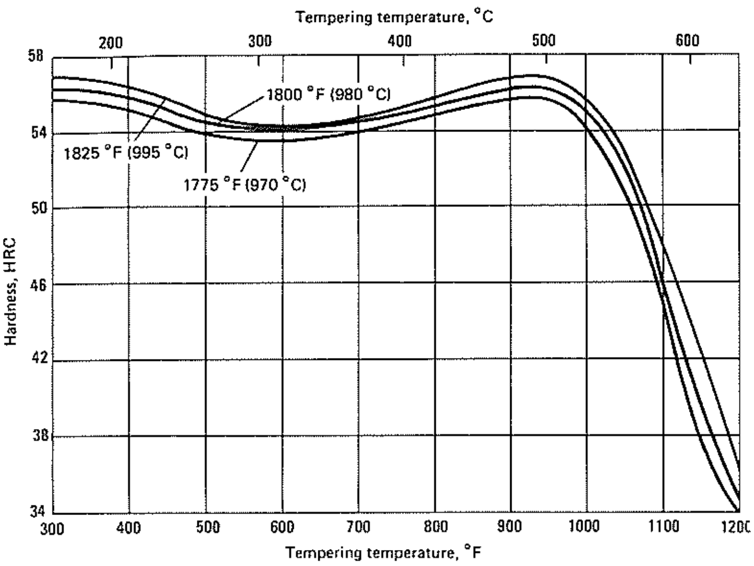
- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size



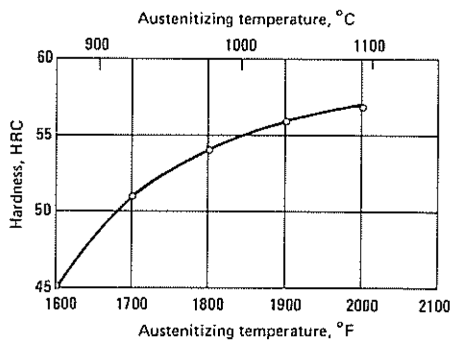
H11: Isothermal Transformation Diagram. H11 tool steel: 0.40 C, 1.05 Si, 5.00 Cr, 1.35 Mo, 0.35 V. Austenitized at 1010 °C (1850 °F). Source: Crucible Steel

H11: Hardness vs Austenitizing and Tempering Conditions. (a, b, c) tempered: ○, 0.1 h; ●, 0.5 h; △, 1.0 h; ▲, 2.5 h; □, 10.0 h; ■, 100.0 h. (d) ○, consumable-electrode vacuum melted. △, air melted

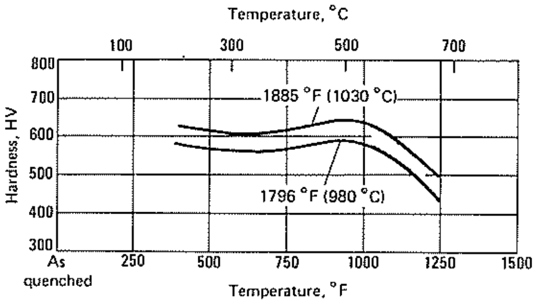




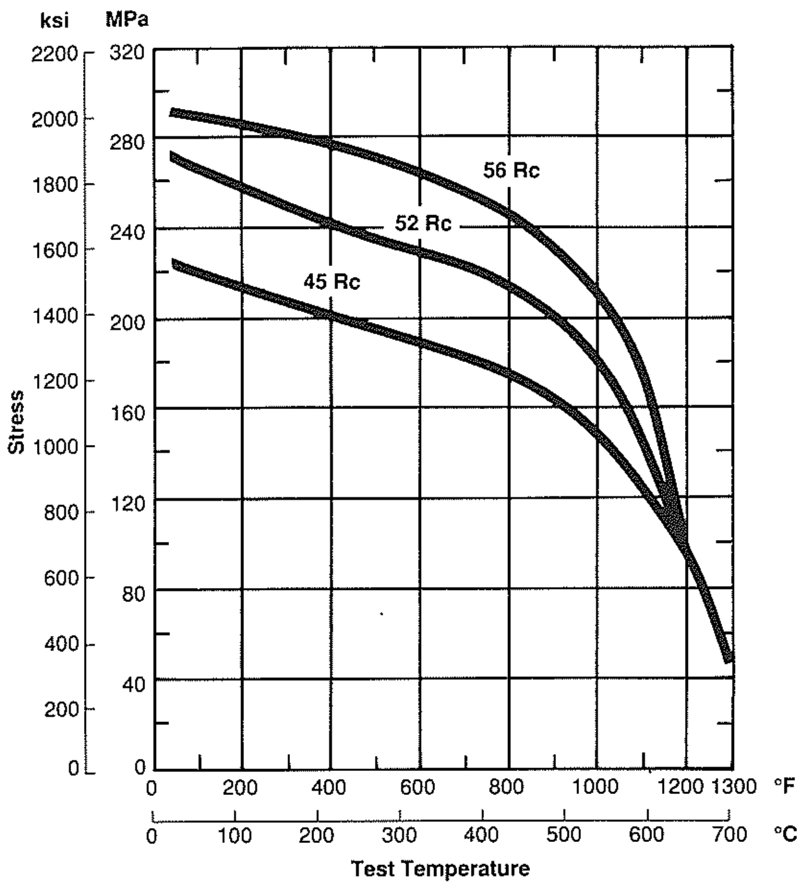
H11: As-Quenched Hardness vs Austenitizing Temperature. H11 tool steel: 0.38 C, 1.00 Si, 5.25 Cr, 1.35 Mo, 0.50 V. Test specimens: 25.4 mm (1 in.) diam, 76.2 mm (3 in.) long. Cooled in air. Source: Columbia Tool Steel and Latrobe Steel



H11: Hardness vs Austenitizing and Tempering Temperature. H11 air cooled from 995 °C (1825 °F), 980 °C (1795 °F), 970 °C (1775 °F). Source: Universal-Cyclops

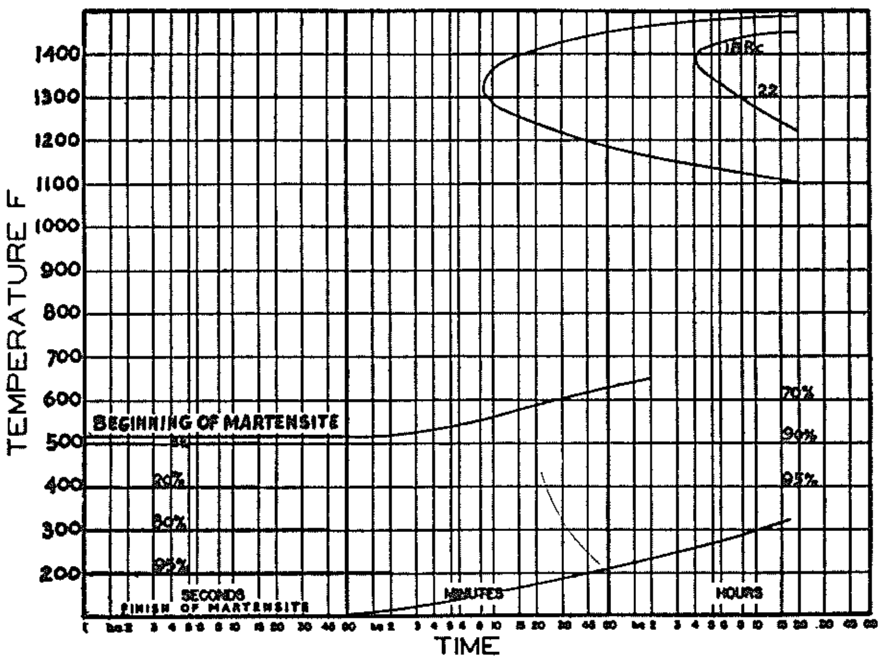


H11: Hardness vs Austenitizing and Tempering Temperature. English grade of H11 tool steel. Source: British Steel

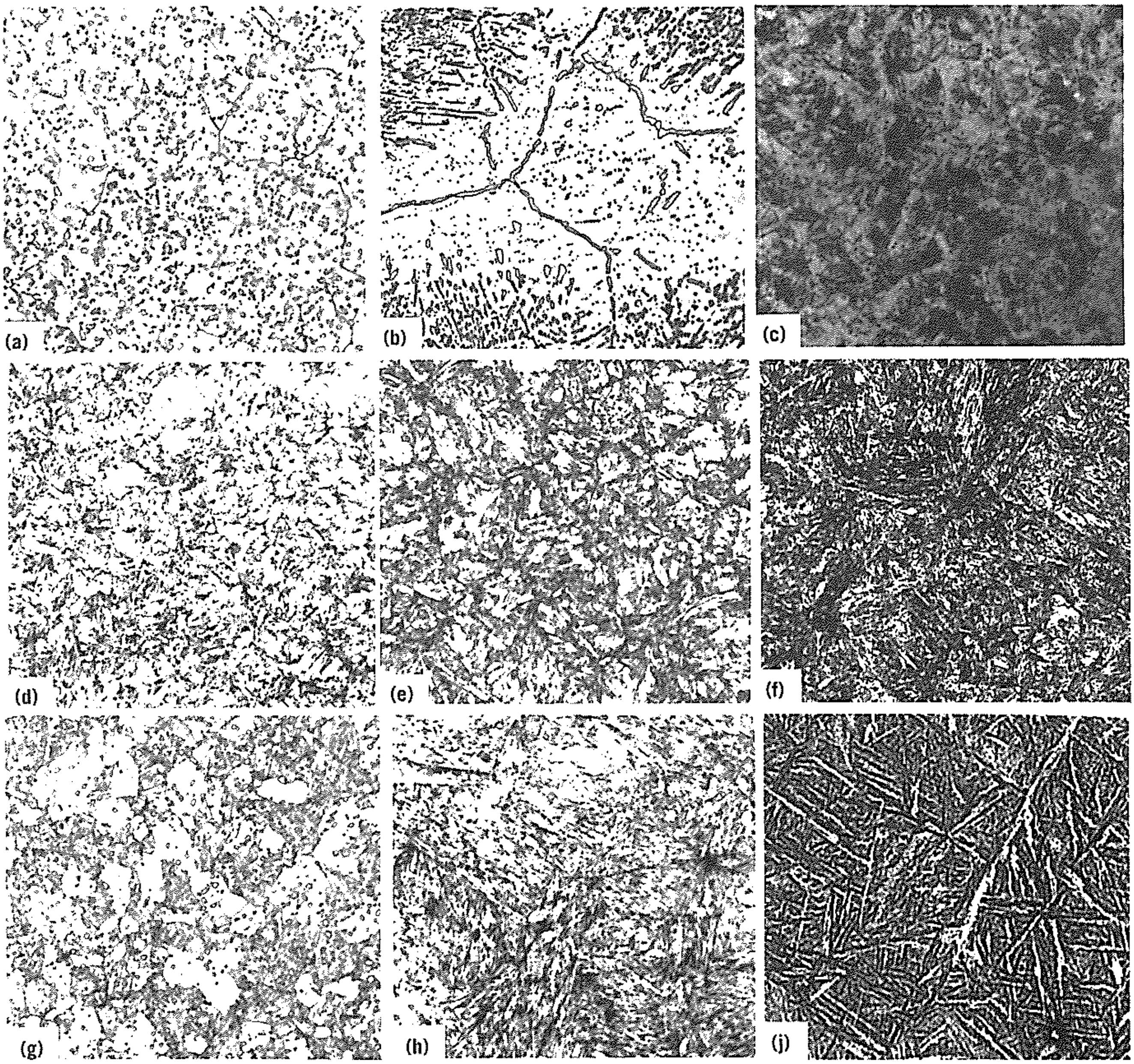


H11: Elevated-Temperature Tensile Strength. Source: Carpenter Technology Corporation

H11: Isothermal Transformation Diagram. Composition: 0.40 C, 1.05 Si, 5.00 Cr, 1.35 Mo, 0.35 V. Austenitized at 1010 °C (1850 °F)



H11: Microstructures. (a) 3% nital, 1000×. As received (mill annealed). Fine dispersion of small spheroidal carbide particles in a matrix of ferrite (white). Grain boundaries (black lines) revealed by the etch in several areas. (b) Picral with HCl, for 10 sec, 500×. Annealed by austenitizing at 870 °C (1600 °F), holding for 20 h, cooling to 650 °C (1200 °F) at 8 °C (15 °F) per h, then air cooling. Spheroidal, lamellar and grain-boundary alloy carbide (primarily, chromium carbide) in ferrite. (c) 3% nital, 1000×. Austenitized at 1010 °C (1850 °F), cooled in still air. Mainly untempered martensite with some very small spheroidal particles of carbide and some retained austenite (the latter two constituents are not well resolved at 1000×). (d) 3% nital, 1000×. Austenitized at 1010 °C (1850 °F), air cooled, double tempered (2 h plus 2 h) at 565 °C (1050 °F), a common heat treatment for this steel. Hardness, 54 HRC. Very fine spheroidal particles of carbide (small black or white dots) in a matrix of tempered martensite (grayish). (e) 3% nital, 1000×. Austenitized at 1010 °C (1850 °F), air cooled, double tempered (2 h plus 2 h) at 620 °C (1150 °F). Hardness, 42 HRC. Fine spheroidal alloy carbide in a matrix of tempered martensite. Change in matrix from (d) due to higher tempering temperature. (f) 2% nital, for 90 sec, 500×. Austenitized at 1120 °C (2050 °F), oil quenched, double tempered (2 h plus 2 h) at 595 °C (1105 °F). Hardness, 46 to 48 HRC. Coarse tempered martensite with a few spheroidal particles of alloy carbide. Most carbide dissolved because of the high austenitizing temperature. (g) 3% nital, 1000×. Austenitized at 925 °C (1695 °F), air cooled, double tempered (2 h plus 2 h) at 565 °C (1050 °F). Hardness, 37 HRC. Ferrite (white), spheroidal carbide, and tempered martensite, showing underheating. (h) Nital, 1000×. Austenitized at 1150 °C (2100 °F), air cooled, double tempered (2 h plus 2 h) at 565 °C (1050 °F). Hardness, 55 HRC. Fine spheroidal carbide in coarse tempered martensite and retained austenite, showing overheating. (j) Austenitized 1 h at 1230 °C (2245 °F), air cooled, tempered 2 h at 565 °C (1050 °F). Very coarse tempered martensite, due to high austenitizing temperature. (ASTM grain size of prior austenite is larger than 1). Retained austenite also present



H12

Chemical Composition. **AISI:** Nominal. 0.35 C, 1.50 W, 5.00 Cr, 1.50 Mo, 0.40 V. **AISI/UNS (T20812):** Composition: 0.30 to 0.40 C, 0.20 to 0.50 Mn, 0.80 to 1.20 Si, 0.30 Ni max, 4.75 to 5.50 Cr, 1.25 to 1.75 Mo, 1.00 to 1.70 W, 0.50 V max

Similar Steels (U.S. and/or Foreign). ASTM A681 (H-12); FED QQ-T-570 (H-12); SAE J437 (H12), J438 (H12), J467 (H12); (Ger.) DIN 1.2606; (Fr.) AFNOR A35-590 3432 Z 35 CWDV 5; (Ital.) UNI X 35 CrMoW 05 KU; (Jap.) JIS G4404 SKD 62; (U.K.) B.S. 4659 BH12

Characteristics. A popular grade having very high toughness. Has excellent resistance to heat checking and can be water cooled in service. Can be carburized or nitrided to increase surface hardness with some loss in resistance to heat checking. A special die casting grade is available. Is suitable for extrusion dies, die casting dies, mandrels, hot shears, and hot forging dies and punches. Has high resistance to softening at elevated temperature. Hardness does not vary up to 425 °C (800 °F) and tools can withstand working temperatures up to 540 °C (1000 °F). Does not exhibit notable secondary hardening effect during tempering because of low carbon content. Hardness begins to drop off rapidly when tempering above 595 °C (1100 °F). Is deep hardening and has low distortion in heating treating. Has medium wear resistance, medium to high machinability and medium resistance to decarburization

Forging. Heat slowly. Preheat at 705 to 815 °C (1300 to 1500 °F), start forging at 1065 to 1150 °C (1950 to 2100 °F). Do not forge after temperature of forging stock drops below 900 °C (1650 °F). Cool slowly

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Surface protection against decarburization by use of pack, controlled atmosphere, or vacuum is required. Heat to 845 to 900 °C (1555 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Heat slowly and uniformly, especially for hardened tools. Holding time varies from about 1 h for light sections and small furnace charges to about 4 h for heavy sections and large charges. For pack annealing, hold 1 h per inch of cross section. Cool slowly in furnace to 540 °C (1000 °F) at a rate not to exceed 30 °C (55 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 192 to 235 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Surface protection against decarburization or carburization is required by utilizing salt, pack, controlled atmosphere, or vacuum. For preheating, die blocks or other tools for open furnace treatment should be placed in a furnace at a temperature that does not exceed 260 °C (500 °F). Work packed in containers may be safely placed in a furnace at 370 to 540 °C (700 to 1000 °F). Once the workpieces (or container) have attained temperature, heat slowly to 815 °C (1500 °F), at a rate not to exceed 110 °C (200 °F) per h. Hold for 1 h per inch of thickness (or per inch of container thickness if packed). If double preheat facilities are available, such as salt baths, thermal shock can be reduced by preheating at 540 to 650 °C (1000 to 1200 °F) and then preheating at 845 to 870 °C (1555 to 1600 °F). Austenitize at 995 to 1025 °C (1825 to 1875 °F) for 15 to 40 min. Use shorter time for small sections and longer time for large sections. Quench in air. If air blast cooled, air should be dry and blasted uniformly on the surface to be hardened. To minimize scale, tools can be flash quenched in oil to cool the surface to below scaling temperature [approximately 540 °C (1000 °F)], but this increases distortion. The safer procedure is to quench from the austenitizing temperature into a salt bath held at 595 to 650 °C (1105 to 1200 °F), and hold in the quench until the workpiece reaches the temperature of the bath. Then withdraw the workpiece and allow it to cool in air. Quench hardness, 53 to 55 HRC

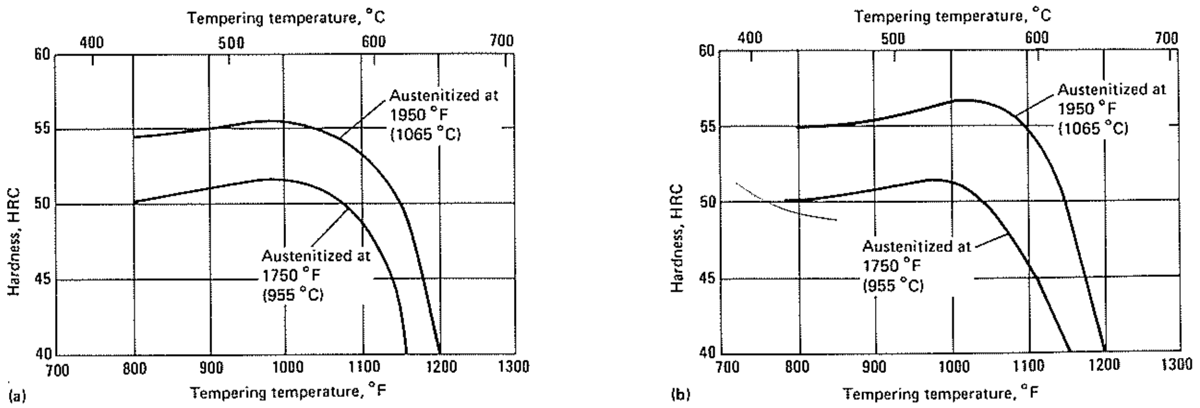
Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to –320 °F). Temper immediately after part reaches room temperature

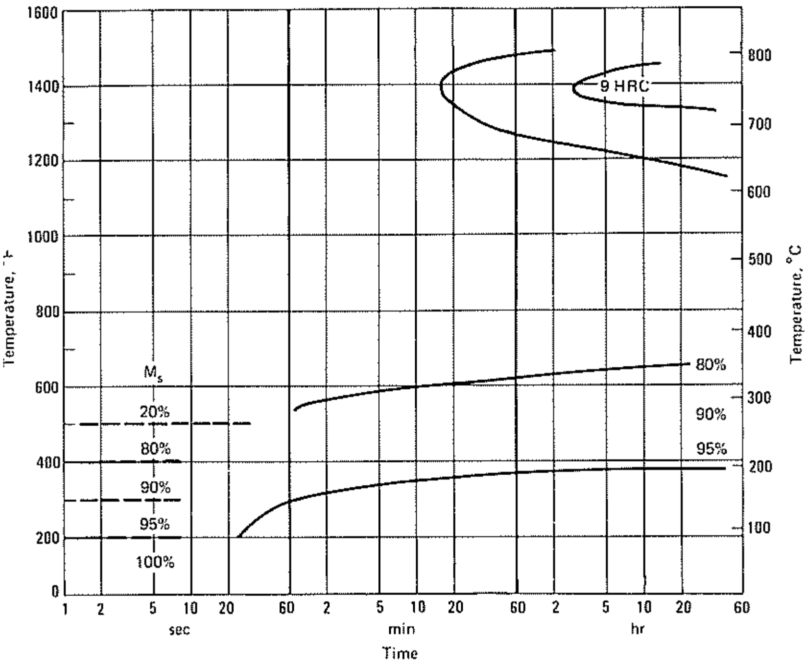
Tempering. Temper immediately after tool reaches about 50 °C (120 °F) at 540 to 650 °C (1000 to 1200 °F). Forced-convection air tempering furnaces heat tools at a moderately safe rate. Salt baths are acceptable for small parts but may cause large or intricate shaped dies to crack due to thermal shock. Temper for 1 h per inch of thickness, cool to room temperature, and retemper using the same time at temperature. The second temper is essential and a third temper is beneficial. Approximate tempered hardness, 55 to 38 HRC

Recommended Processing Sequence

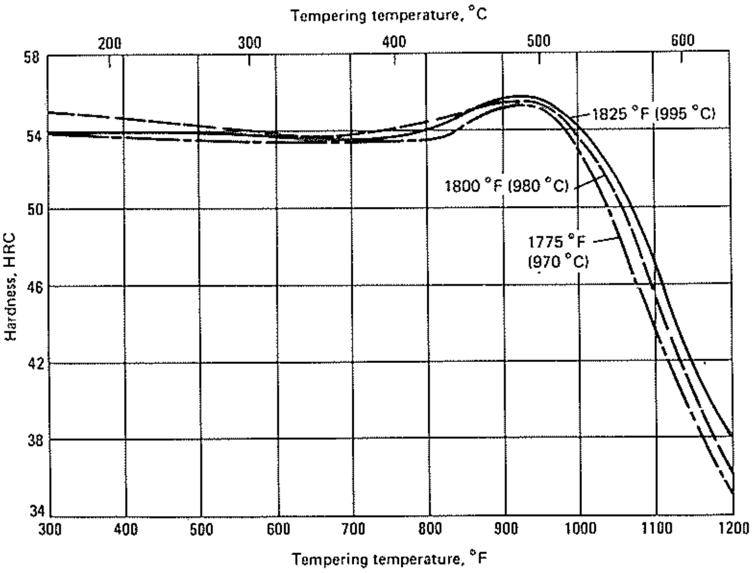
- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size

H12: Hardness vs Austenitizing and Tempering Conditions. (a) H12, oil quenched. Single temper, 2 h. (b) H12, air quenched. Single temper, 2 h

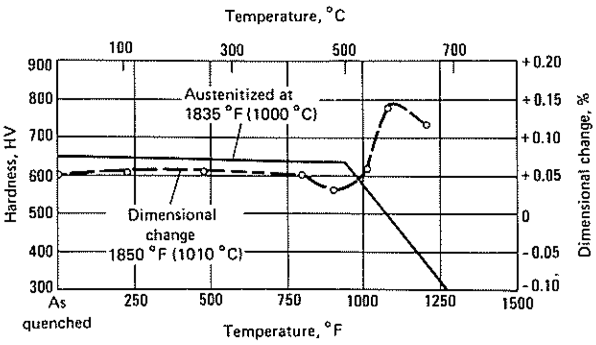




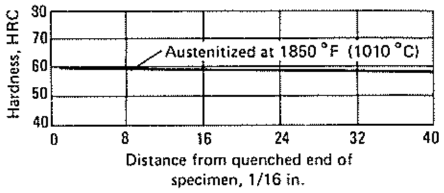
H12: Isothermal Transformation Diagram. Annealed H12 tool steel: 0.32 C, 0.35 Mn, 0.95 Si, 4.86 Cr, 1.45 Mo, 1.29 W. Austenitized at 1010 °C (1850 °F). Critical points: Ac_1, 835 °C (1535 °F)



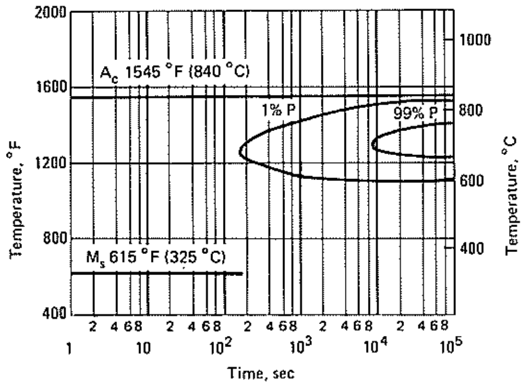
H12: Hardness vs Austenitizing and Tempering Temperature. H12 air cooled from 995 °C (1825 °F), 980 °C (1795 °F), 970 °C (1775 °F), and tempered. Source: Universal-Cyclops



H12: Tempering Temperature vs Hardness and Dimensional Change. H12: hardness and dimensional change at 2 austenitizing temperatures

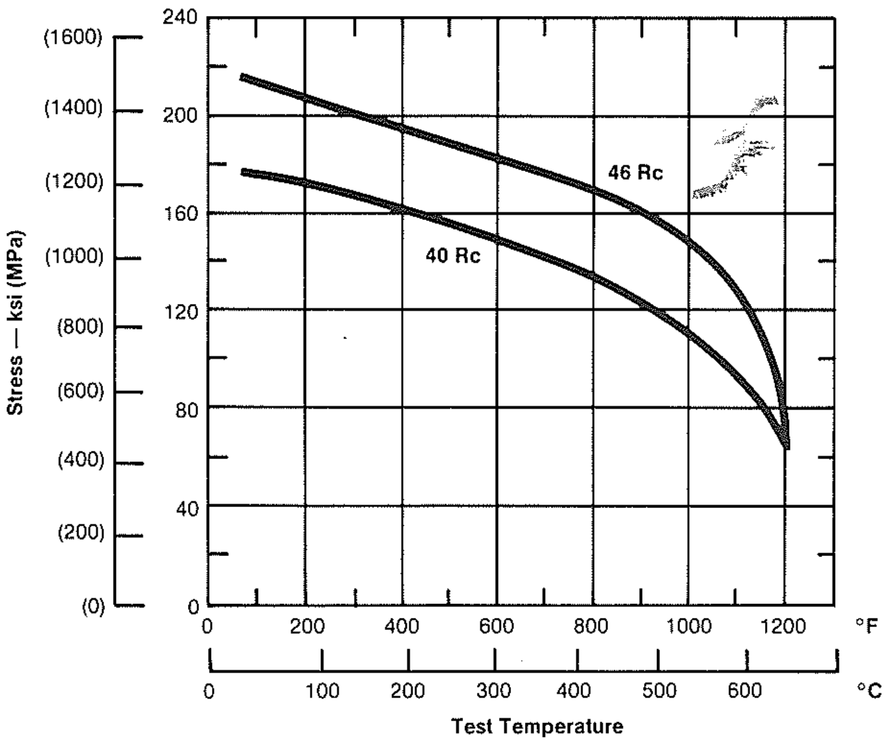


H12: Jominy End-Quench Hardenability. H12 tool steel: 0.35 C, 0.92 Si, 4.76 Cr, 1.49 Mo, 1.42 W. Source: Teledyne VASCO

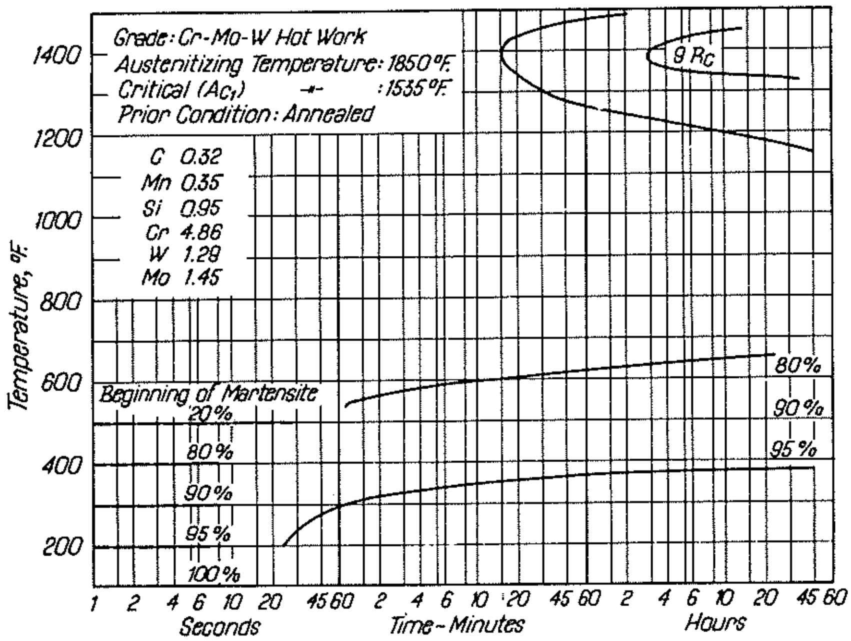


H12: Isothermal Transformation Diagram. Source: Jessop-Saville

H12: Typical Elevated-Temperature Tensile Strength. Source: Carpenter Technology Corporation



H12: Isothermal Transformation Diagram. Composition: 0.32 C, 0.35 Mn, 0.95 Si, 4.86 Cr, 1.45 Mo, 1.29 W. Austenitized at 1010 °C (1850 °F)



H13

Chemical Composition. AISI: Nominal. 0.35 C, 5.00 Cr, 1.50 Mo, 1.00 V. **AISI/UNS (T20813):** Composition: 0.32 to 0.45 C, 0.20 to 0.50 Mn, 0.80 to 1.20 Si, 0.30 Ni max, 4.75 to 5.50 Cr, 1.10 to 1.75 Mo, 0.80 to 1.20 V

Similar Steels (U.S. and/or Foreign). ASTM A681 (H-13); FED QQ-T-570 (H-13); SAE J437 (H13), J438 (H13), J467 (H13); (Ger.) DIN 1.2344; (Fr.) AFNOR A35-590 3433 Z 40 CDV 5; (Ital.) UNI X 35 CrMoV 05 KU; (Jap.) JIS SKD 61; (Swed.) SS 2242; (U.K.) B.S. 4659 BH13, 4659 H13

Characteristics. A very popular and available grade. Is deep hardening and has very high toughness. Has excellent resistance to heat checking and can be water cooled in service. Is suitable for a wide range of applications including extrusion dies, die casting dies, mandrels, hot shears, and hot forging dies and punches. Has medium wear resistance, but can be carburized or nitrided to impart higher surface hardness with some loss in resistance to heat checking. Because of low carbon content, does not exhibit notable secondary hardening during tempering. Hardness begins to drop off rapidly when tempering above 425 °C (800 °F), and tools can withstand working temperatures of 540 °C (1000 °F). Has medium to high machinability and medium resistance to decarburization

Forging. Heat slowly. Preheat at 705 to 815 °C (1300 to 1500 °F), start forging at 1065 to 1150 °C (1950 to 2100 °F). Do not forge after temperature of forging stock drops below 900 °C (1650 °F). Cool slowly

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Surface protection against decarburization by use of pack, controlled atmosphere, or vacuum is required. Heat to 845 to 900 °C (1555 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Heat slowly and uniformly, especially for hardened tools. Holding time varies from about 1 h for light sections and small furnace charges to about 4 h for heavy sections and large charges. For pack annealing, hold 1 h per inch of cross section. Cool slowly in furnace to 540 °C (1000 °F) at a rate not to exceed 30 °C (55 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 192 to 229 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

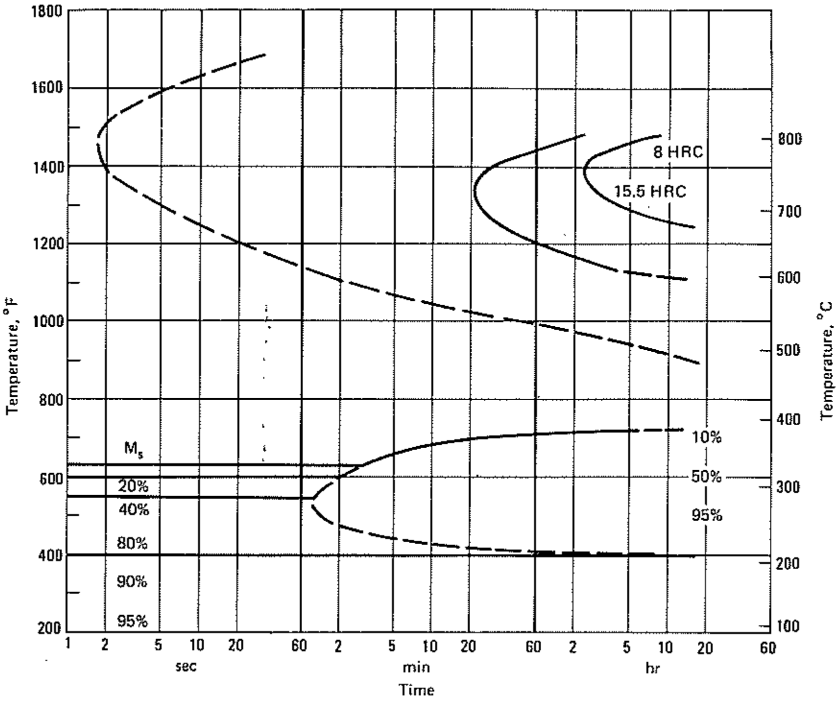
Hardening. Surface protection against decarburization or carburization is required by utilizing salt, pack, controlled atmosphere, or vacuum. For preheating, die blocks or other tools for open furnace treatment should be placed in a furnace at a temperature that does not exceed 260 °C (500 °F). Work packed in containers may be safely placed in a furnace at 370 to 540 °C (700 to 1000 °F). Once the workpieces (or container) have attained temperature, heat slowly to 815 °C (1500 °F), at a rate not to exceed 110 °C (200 °F) per h. Hold for 1 h per inch of thickness (or per inch of container thickness if packed). If double preheat facilities are available, such as salt baths, thermal shock can be reduced by preheating at 540 to 650 °C (1000 to 1200 °F) and then preheating at 845 to 870 °C (1555 to 1600 °F). Austenitize at 995 to 1040 °C (1825 to 1905 °F) for 15 to 40 min. Use shorter time for small sections and longer time for large sections. Quench in air. If air blast cooled, air should be dry and blasted uniformly on the surface to be hardened. To minimize scale, tools can be flash quenched in oil to cool the surface to below scaling temperature [approximately 540 °C (1000 °F)], but this increases distortion. The safer procedure is to quench from the austenitizing temperature into a salt bath held at 595 to 650 °C (1105 to 1200 °F), and hold in the quench until the workpiece reaches the temperature of the bath. Then withdraw the workpiece and allow it to cool in air. Quench hardness, 51 to 54 HRC

Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to –320 °F). Temper immediately after part reaches room temperature

Tempering. Temper immediately after tool reaches about 50 °C (120 °F) at 540 to 650 °C (1000 to 1200 °F). Forced-convection air tempering furnaces heat tools at a moderately safe rate. Salt baths are acceptable for small parts but may cause large or intricate shaped dies to crack due to thermal shock. Temper for 1 h per inch of thickness, cool to room temperature, and retemper using the same time at temperature. The second temper is essential and a third temper is beneficial. Approximate tempered hardness, 53 to 38 HRC

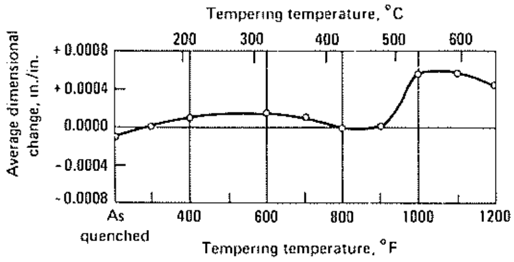
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size

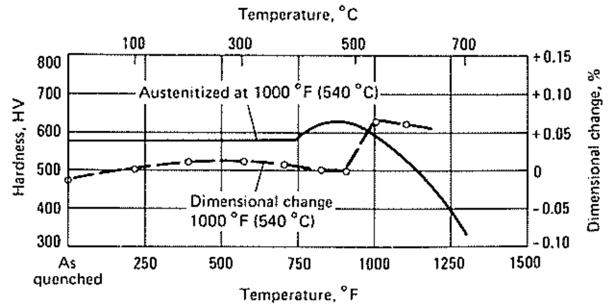


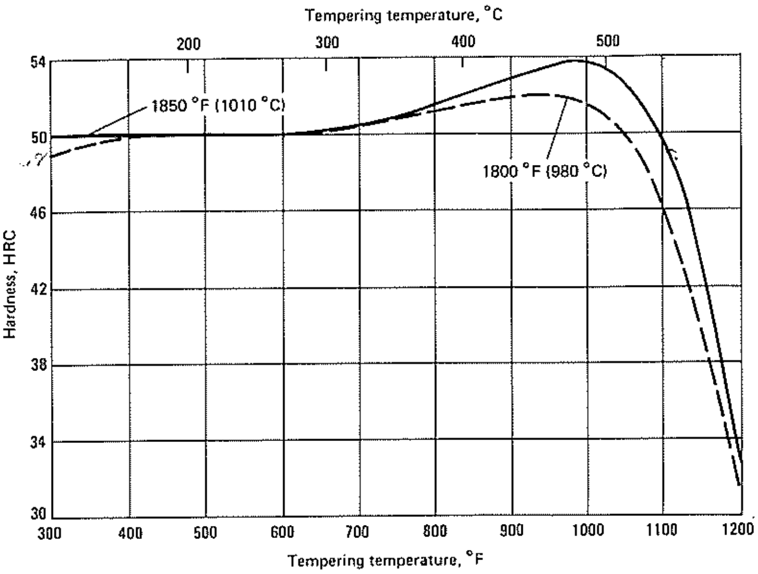
H13: Isothermal Transformation Diagram. Diagram for H13 tool steel, containing 0.40 C, 1.05 Si, 5.00 Cr, 1.35 Mo, 1.10 V. Austenitized at 1010 °C (1850 °F). Source: Crucible Steel

H13: Dimensional Change vs Tempering Temperature. H13 containing 0.40 C, 1.00 Si, 5.00 Cr, 1.20 Mo, 1.00 V. Change in a block 25 by 51 by 152 mm (1 by 2 by 6 in.). Source: Latrobe Steel



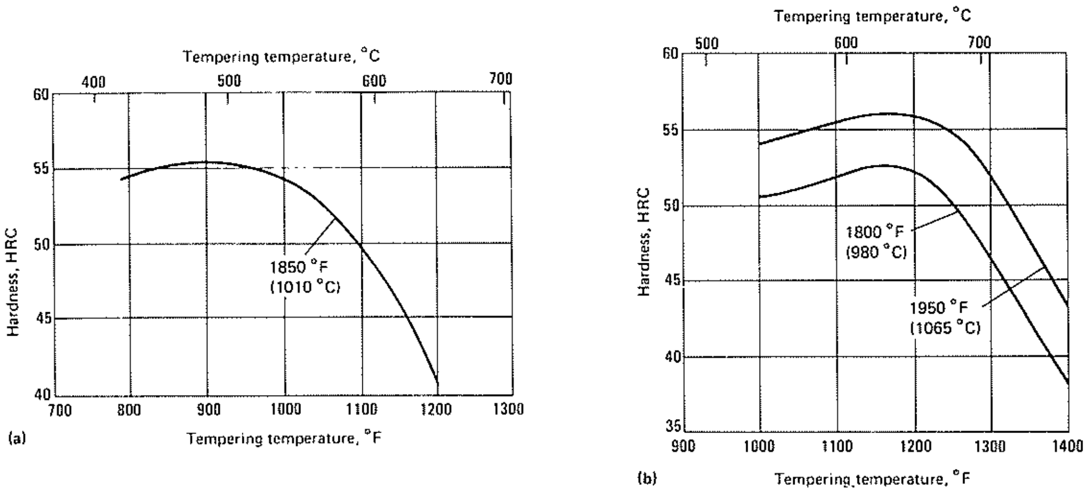
H13: Hardness vs Tempering Temperature. Hardness and dimensional change for H13 steel, austenitized at 540 °C (1000 °F). Source: Jessop-Saville

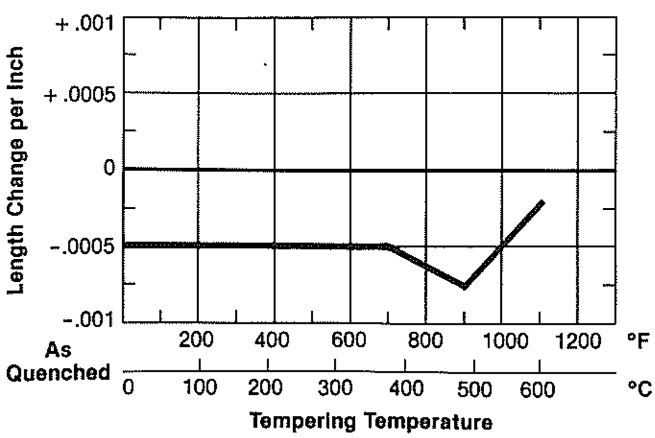




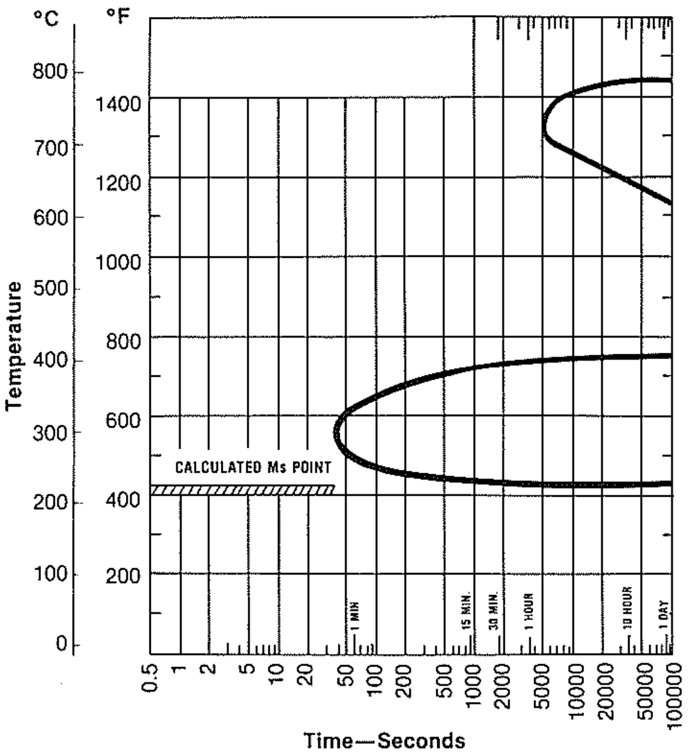
H13: Hardness vs Tempering Temperature . H13, air cooled from 1010 °C (1850 °F) and 980 °C (1795 °F) and double tempered. Source: Universal-Cyclops

H13: Hardness vs Tempering Temperature. (a) H13: Austenitized at 1010 °C (1850 °F), oil quenched, and tempered for 2 h. (b) H13: Austenitized at the indicated temperatures, air quenched, and tempered for 2 h

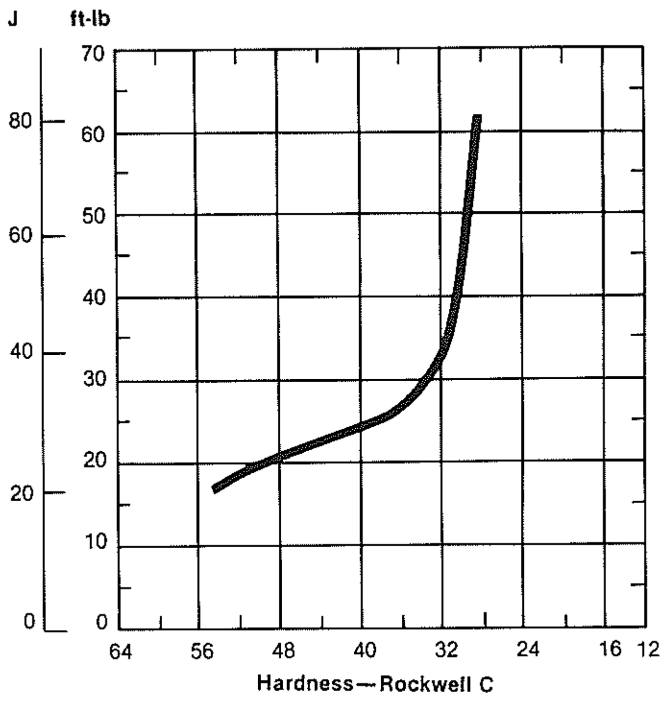




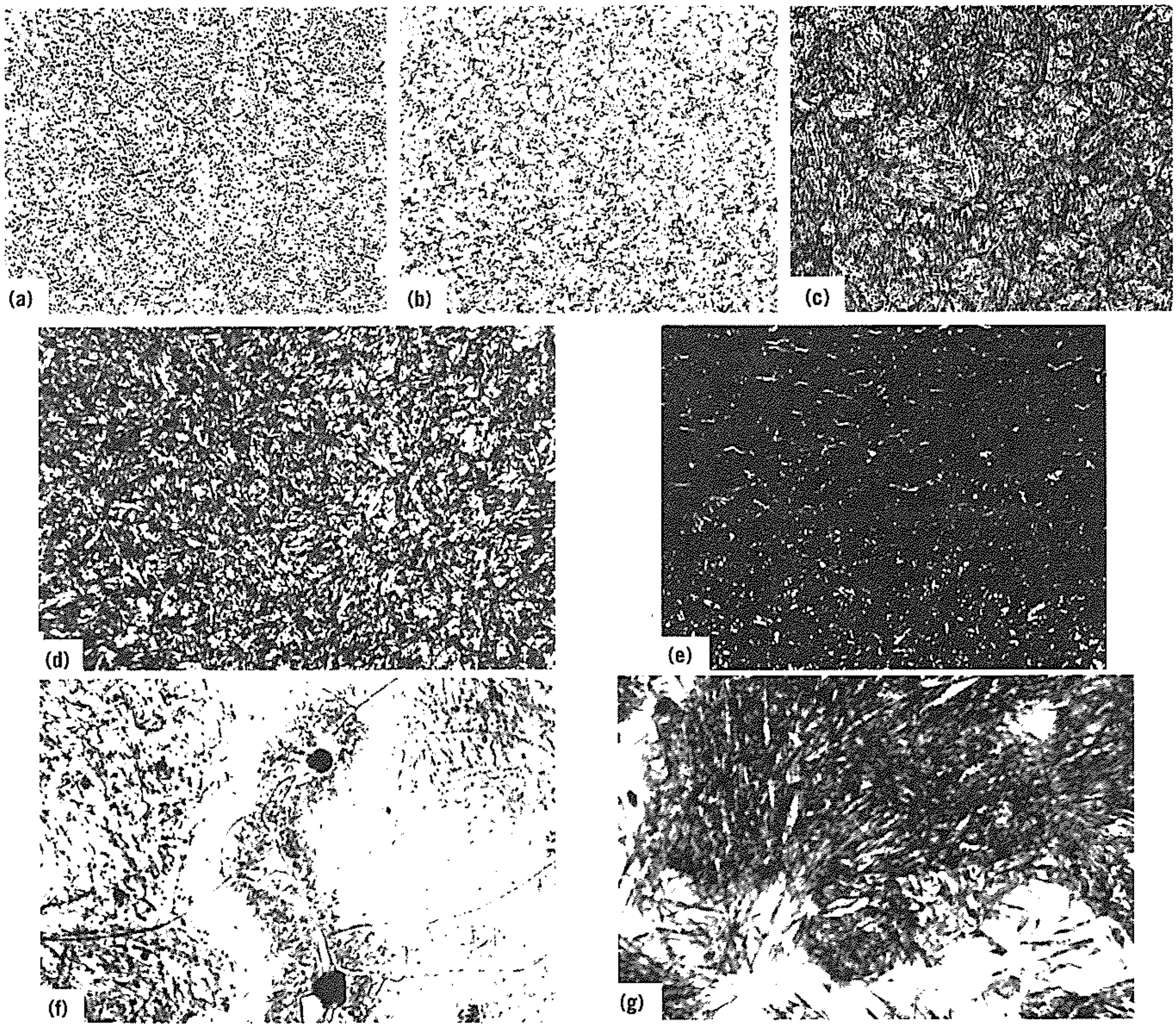
H13: Size Change in Hardening. Chart shows typical length changes when H13 is properly hardened and tempered. Alloy was austenitized at 1025 °C (1875 °F), oil quenched and tempered 1 h at indicated temperatures. Source: Carpenter Technology Corporation



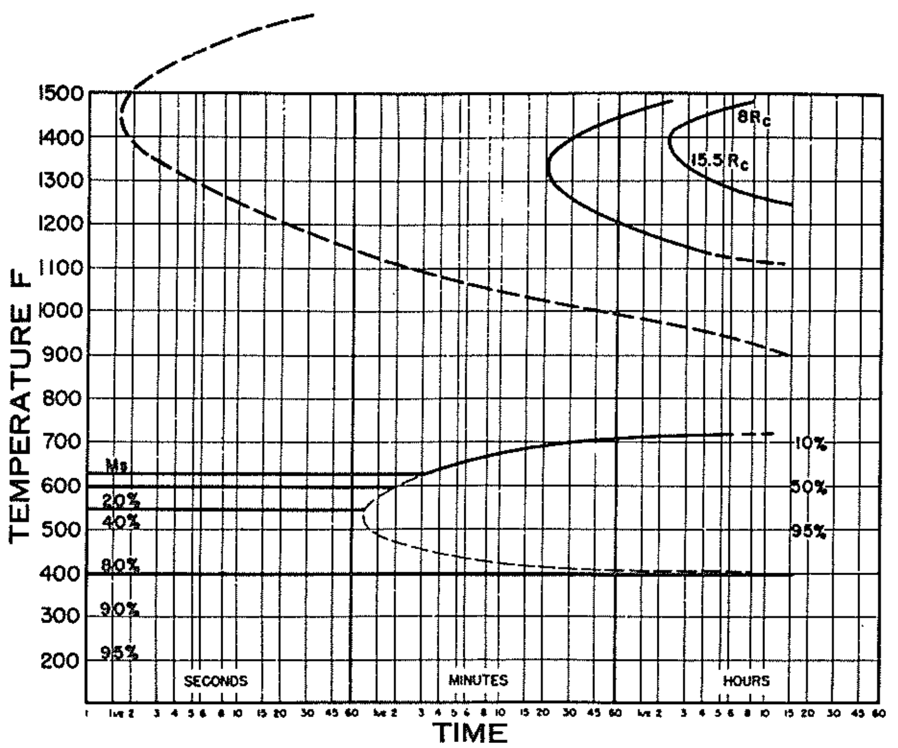
H13: Isothermal Phase Diagram. Austenitizing temperature was 1010 °C (1850 °F). Source: Carpenter Technology Corporation



H13: Charpy V-Notch Impact Strength. Source: Carpenter Technology Corporation ı13: **Microstructures.** (a) 4% nital, 500×. As received (mill annealed). Held at 830 °C (1525 °F) for 2 h, cooled to 540 °C (1000 °F) at 28 °C ɜ0 °F) per h, then air cooled. 94 HRB. Fine spheroidal particles of carbide in matrix of ferrite. (b) Picral with HCl, for 10 sec, 500×. Annealed ıy austenitizing at 845 °C (1555 °F), cooling to 650 °C (1200 °F) at 8 °C (15 °F) per h, then cooling in air. 11 to 12 HRC. Fine spheroidal ıarticles of carbide (primarily chromium carbide) in matrix of ferrite. (c) 4% nital, 500×. Austenitized at 1010 °C (1850 °F), air cooled, triple ɜmpered (2 h plus 2 h plus 2 h) at 540 °C (1000 °F). Hardness, 53 HRC. A few spheroidal particles of alloy carbide in a matrix of tempered nartensite. (d) 2% nital, for 90 sec, 500×. Austenitized at 1010 °C (1850 °F), oil quenched, double tempered (2 h plus 2 h) at 595 °C (1105 F). Hardness, 47 to 48 HRC. Matrix of tempered martensite with a few spheroidal particles of alloy carbide. (e) 2% nital, for 60 sec, 500×. ıustenitized at 1010 °C (1850 °F), oil quenched, double tempered (2 h plus 2 h) at 565 °C (1050 °F), gas nitrided 15 h at 510 °C (950 °F). ;ase (beginning at top) 0.152 mm (0.006 in.) deep, contains carbide and elongated nitride (white streaks). (f) 3% nital, 1000×. As cast. 57 ıRC. Some carbide particles in matrix of untempered martensite (dark areas) and retained austenite (light areas). White spots grain boundıry carbide. Black spots nonmetallic inclusions. (g) 2% nital, 500×. Cast H13, double tempered (2 h plus 2 h) at 565 °C (1050 °F). 53 HRC. /ery fine alloy carbide particles in matrix of tempered martensite (coarse, needlelike constituent). Large light gray areas retained austenite



H13: Isothermal Transformation Diagram. Composition: 0.40 C, 1.05 Si, 5.00 Cr, 1.35 Mo, 1.10V. Austenitized at 1010 °C (1850 °F)



H14

Chemical Composition. **AISI:** Nominal. 0.40 C, 5.00 Cr, 5.00 W. **AISI/UNS (T20814):** Composition: 0.35 to 0.45 C, 0.20 to 0.50 Mn, 0.80 to 1.20 Si, 0.30 Ni max, 4.75 to 5.50 Cr, 4.00 to 5.25 W

Similar Steels (U.S. and/or Foreign). ASTM A681 (H-14); FED QQ-T-570 (H-14); (Ger.) DIN 1.2567; (Fr.) AFNOR 3541 Z 40 WCV 5; (Jap.) JIS G4404 SKD 4; (U.K.) B.S. BH11

Characteristics. Contains 5% chromium and 5% tungsten. Is also available with small additions of vanadium (0.25%), molybdenum (0.25%), and cobalt (0.50%). Has greater hot hardness and wear resistance than H11, 12, or 13, but is not as shock resistant. Can be hardened from a relatively low temperature. The isothermal transformation diagram shows the high hardenability of this grade. Does not exhibit notable secondary hardening during tempering, and hardness begins to drop off rapidly when tempering above 540 °C (1000 °F). Has medium machinability and resistance to decarburization

Forging. Heat slowly. Preheat at 705 to 815 °C (1300 to 1500 °F), start forging at 1065 to 1175 °C (1950 to 2150 °F). Do not forge after temperature of forging stock drops below 925 °C (1695 °F). Cool slowly

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Surface protection against decarburization by use of pack, controlled atmosphere, or vacuum is required. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Heat slowly and uniformly, especially for hardened tools. Holding time varies from about 1 h for light sections and small furnace charges to about 4 h for heavy sections and large charges. For pack annealing, hold 1 h per inch of cross section. Cool slowly in furnace to 595 °C (1105 °F) at a rate not to exceed 30 °C (55 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 207 to 235 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Surface protection against decarburization or carburization is required by utilizing salt, pack, controlled atmosphere, or vacuum. For preheating, die blocks or other tools for open furnace treatment should be placed in a furnace at a temperature that does not exceed 260 °C (500 °F). Work packed in containers may be safely placed in a furnace at 370 to 540 °C (700 to 1000 °F). Once the workpieces (or container) have attained temperature, heat slowly and uniformly to 815 °C (1500 °F), at a rate not to exceed 110 °C (200 °F) per h. Hold for 1 h per inch of thickness (or per inch of container thickness if packed). If double preheat facilities are available, such as salt baths, thermal shock can be reduced by preheating at 540 to 650 °C (1000 to 1200 °F) and then preheating at 845 to 870 °C (1555 to 1600 °F). Austenitize at 1010 to 1065 °C (1850 to 1950 °F) for 15 to 40 min. Use shorter time for small sections and longer time for large sections. Quench in air. If air blast cooled, air should be dry and blasted uniformly on the surface to be hardened. To minimize scale, tools can be flash quenched in oil to cool the surface to below scaling temperature [approximately 540 °C (1000 °F)], but this increases distortion. The safer procedure is to quench from the austenitizing temperature into a salt bath held at 595 to 650 °C (1105 to 1200 °F), and hold in the quench until the workpiece reaches the temperature of the bath. Then withdraw the workpiece and allow it to cool in air. Quench hardness, 53 to 57 HRC

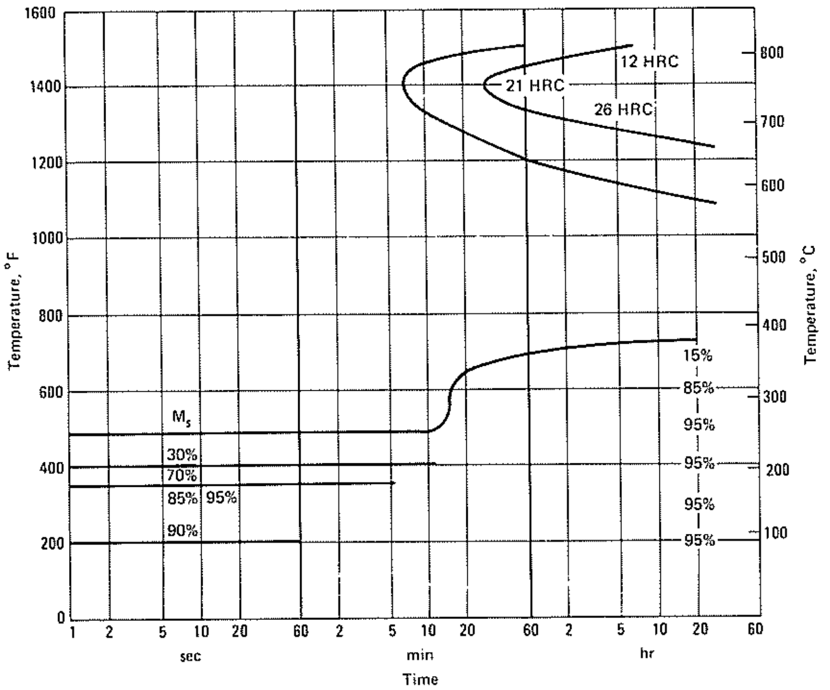
abilizing. Optional. For intricate shapes, stress relieve temper at 150 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to 20 °F). Temper immediately after part reaches room temperature

:mpering. Temper immediately after tool reaches about 50 °C (120 °F) 595 to 650 °C (1105 to 1200 °F). Forced-convection air tempering naces heat tools at a moderately safe rate. Salt baths are acceptable for iall parts but may cause large or intricate shaped dies to crack due to ermal shock. Temper for 1 h per inch of thickness, cool to room tempera- e, and retemper using the same time at temperature. The second temper essential and a third temper is beneficial. Approximate tempered hard- ss, 47 to 40 HRC

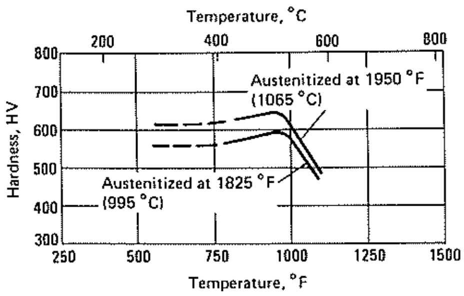
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size

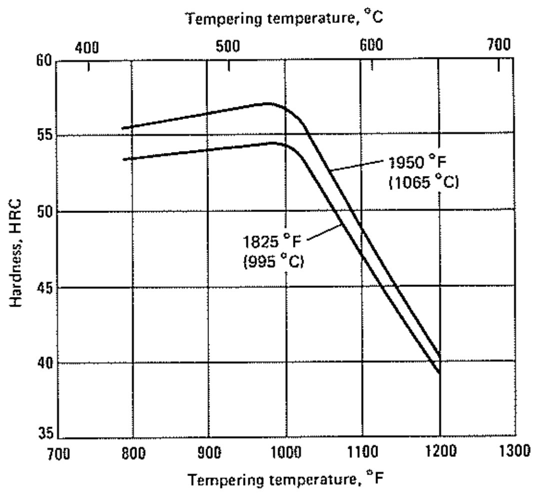
-I14: Isothermal Transformation Diagram. H14 tool steel containing: 0.40 C, 1.15 Si, 5.25 Cr, 4.25 W. Austenitized at 1065 °C (1950 °F). Source: Crucible Steel



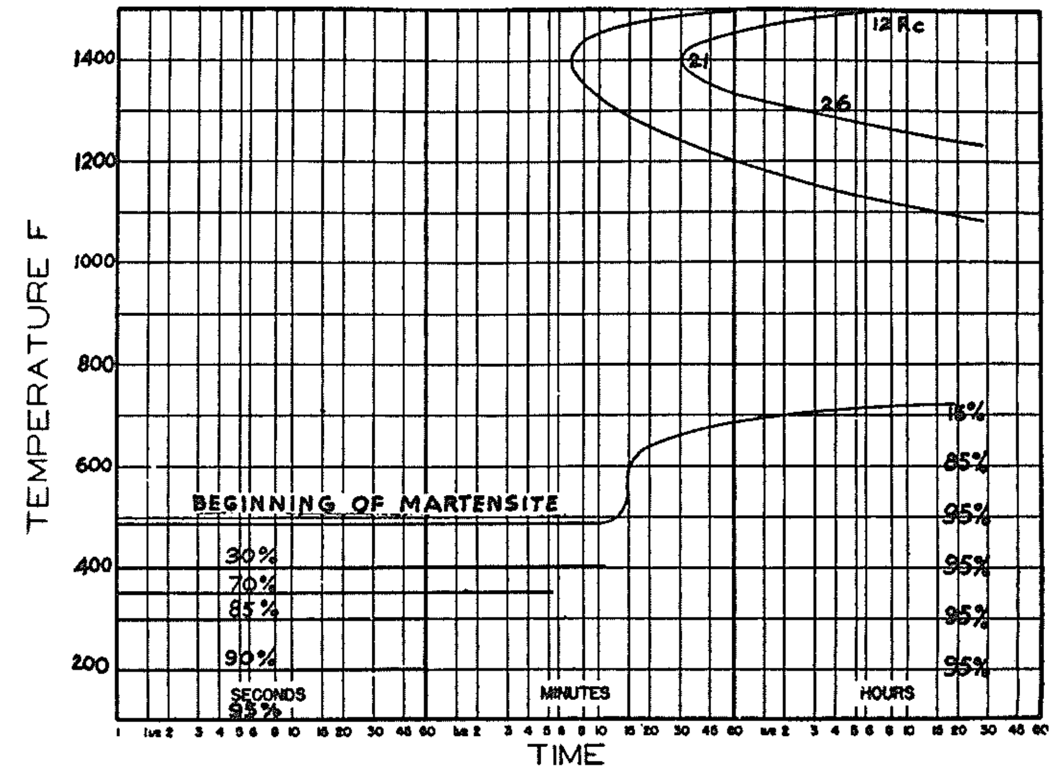
H14: Hardness vs Tempering Temperature. H14 austenitized at the temperatures shown



H14: Hardness vs Tempering Temperature. H14 austenitized at the temperatures shown, air quenched, receiving single temper for 4 h



H14: Isothermal Transformation Diagram. Composition: 0.40 C, 1.15 Si, 5.25 Cr, 4.25 W. Austenitized at 1040 °C (1950 °F)



H19

Chemical Composition. **AISI:** Nominal. 0.40 C, 4.25 Cr, 2.00 V, 4.25 W, 4.25 Co. **AISI/UNS (T20819):** Composition: 0.32 to 0.45 C, 0.20 to 0.50 Mn, 0.20 to 0.50 Si, 0.30 Ni max, 4.00 to 4.75 Cr, 0.30 to 0.55 Mo, 1.75 to 2.20 V, 3.75 to 4.50 W

Similar Steels (U.S. and/or Foreign). ASTM A681 (H-19); FED QQ-T-570 (H-19); (Ger.) DIN 1.2678; (Jap.) JIS G4404 SKD 8; (U.K.) B.S. 4659 BH19

Characteristics. A chromium-tungsten grade with 2% vanadium and 4.25% cobalt added. Requires high austenitizing temperature and short time at heat. Can be air cooled or oil quenched from hardening temperature. Exhibits greater secondary hardness than any of the H steels with identification numbers less than H19 (H14, H13 etc.). Hardness begins to drop off rapidly when tempering above 550 °C (1020 °F). Has high toughness and resistance to softening at elevated temperature. Has medium to high wear resistance, medium machinability, and resistance to decarburization

Forging. Heat slowly. Preheat at 705 to 815 °C (1300 to 1500 °F), start forging at 1040 to 1150 °C (1905 to 2100 °F). Do not forge after temperature of forging stock drops below 900 °C (1650 °F). Cool slowly

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Surface protection against decarburization by use of pack, controlled atmosphere, or vacuum is required. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Heat slowly and uniformly, especially for hardened tools. Holding time varies from about 1 h for light sections and small furnace charges to about 4 h for heavy sections and large charges. For pack annealing, hold 1 h per inch of cross section. Cool slowly in furnace to 595 °C (1105 °F) at a rate not to exceed 30 °C (55 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 207 to 241 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

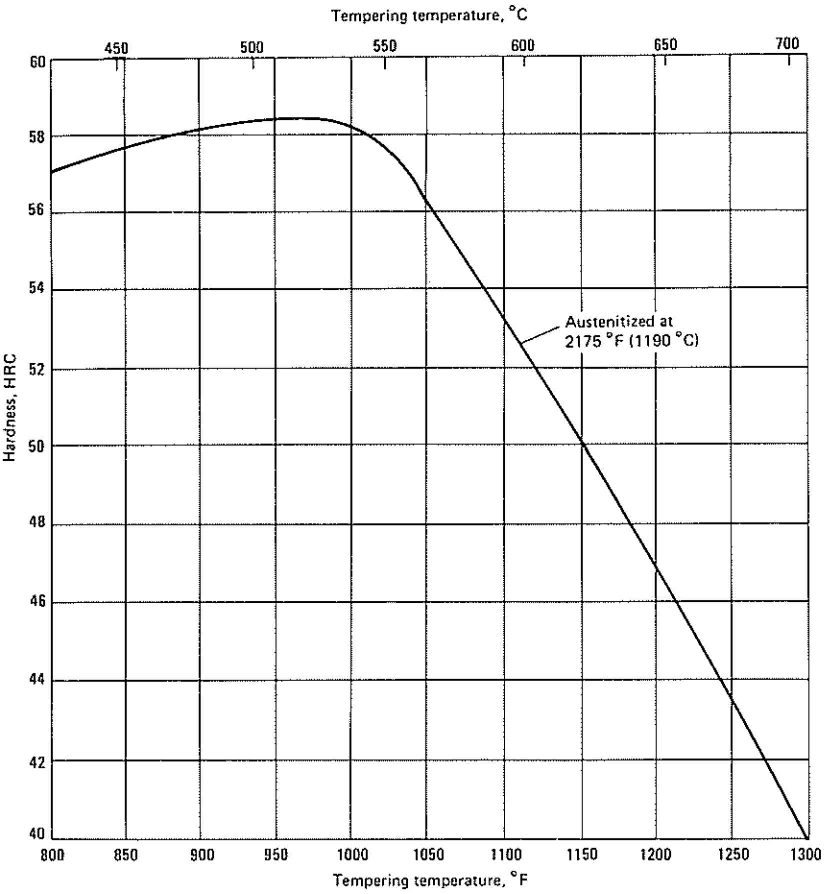
Hardening. Surface protection against decarburization or carburization is required by utilizing salt, pack, controlled atmosphere, or vacuum. For preheating, die blocks or other tools for open furnace treatment should be placed in a furnace at a temperature that does not exceed 260 °C (500 °F). Work packed in containers may be safely placed in a furnace at 370 to 540 °C (700 to 1000 °F). Once the workpieces (or container) have attained temperature, heat slowly to 815 °C (1500 °F), at a rate not to exceed 110 °C (200 °F) per h. Hold for 1 h per inch of thickness (or per inch of container thickness if packed). If double preheat facilities are available, such as salt baths, thermal shock can be reduced by preheating at 540 to 650 °C (1000 to 1200 °F) and then preheating at 845 to 870 °C (1555 to 1600 °F). Heat rapidly to austenitizing temperature or 1095 to 1205 °C (2005 to 2200 °F) and hold for 2 to 5 min. Do not over soak. When using salt baths, reduce temperature by 14 °C (25 °F). Use shorter time for small sections and longer time for large sections. Quench in air. If air blast cooled, air should be dry and blasted uniformly on the surface to be hardened. To minimize scale, tools can be flash quenched in oil to cool the surface to below scaling temperature [approximately 540 °C (1000 °F)], but this increases distortion. The safer procedure is to quench from the austenitizing temperature into a salt bath held at 595 to 650 °C (1105 to 1200 °F), and ıld in the quench until the workpiece reaches the temperature of the bath. ıen withdraw the workpiece and allow it to cool in air. Quench hardness, ; to 57 HRC

tabilizing. Optional. For intricate shapes, stress relieve temper at 150 160 °C (300 to 320 °F) briefly. Refrigerate at −100 to −195 °C (−150 to ;20 °F). Temper immediately after part reaches room temperature

ɜmpering. Temper immediately after tool reaches about 50 °C (120 °F) 540 to 705 °C (1000 to 1300 °F). Forced-convection air tempering rnaces heat tools at a moderately safe rate. Salt baths are acceptable for nall parts but may cause large or intricate shaped dies to crack due to ermal shock. Temper for 1 h per inch of thickness, cool to room tempera-re, and retemper using the same time at temperature. The second temper is essential and a third temper is beneficial. Approximate tempered hardness, 57 to 40 HRC

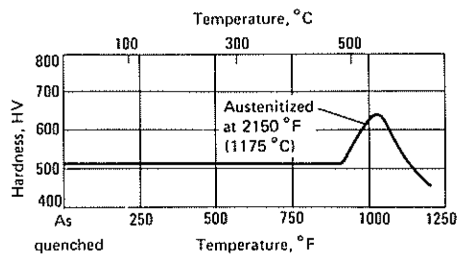
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size

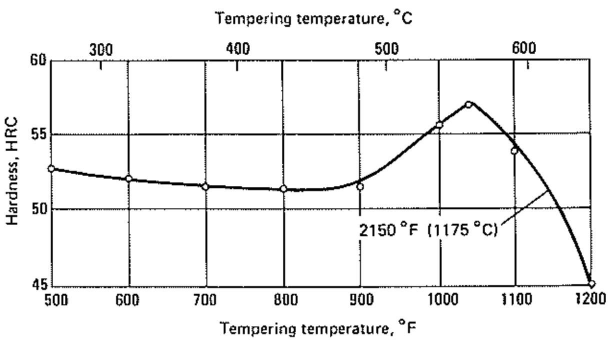


H19: Hardness vs Tempering Temperature. H19 oil quenched from 1190 °C (2175 °F) and double tempered. Source: Universal-Cyclops

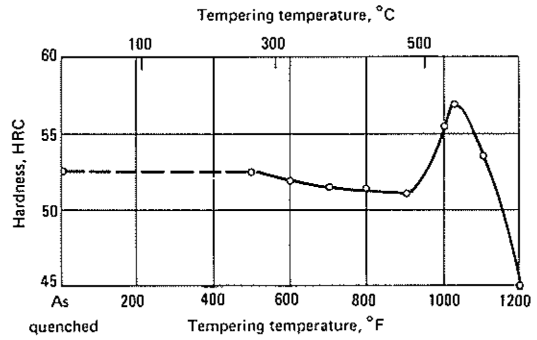
H19: Hardness vs Tempering Temperature. H19 austenitized at 1175 °C (2150 °F). Source: Jessop-Saville



H19: Hardness vs Tempering Temperature. H19 austenitized at 1175 °C (2150 °F), and oil quenched



H19: Hardness vs Tempering Temperature. H19 containing 0.42 C, 0.31 Mn, 0.21 Si, 4.12 Cr, 0.46 Mo, 2.19 V, 4.26 W, 4.16 Co. Austenitized at 1175 °C (2150 °F), quenched in oil. Source: Teledyne VASCO



H19: Elevated-Temperature Impact Data

Testing Temperature °C	Testing Temperature °F	Charpy Impact (V-Notch) J	Charpy Impact (V-Notch) ft-lb	Rockwell C Hardness
20	70	7	5	54
205	400	11	8	53
315	600	8	6	53
425	800	16	12	54
540	1000	12	9	53
650	1200	12	9	50

H21

Chemical Composition. **AISI:** Nominal. 0.35 C, 3.50 Cr, 0.50 V, 9.00 W. **AISI/UNS (T20821):** Composition: 0.26 to 0.36 C, 0.15 to 0.40 Mn, 0.15 to 0.50 Si, 0.30 Ni max, 3.00 to 3.75 Cr, 0.30 to 0.60 V, 8.50 to 10.00 W

Similar Steels (U.S. and/or Foreign). ASTM A681 (H-21); FED QQ-T-570 (H-21); SAE J437 (H21), J438 (H21); (Ger.) DIN 1.2581; (Fr.) AFNOR A35-590 3543 Z 30 WCV 9; (Ital.) UNI X 28 W 09 KU; (Jap.) JIS G4404 SKD 5; (Swed.) SS 2730; (U.K.) B.S. 4659 BH21 A, 4659 H21

Characteristics. Has the lowest tungsten content and is the most available of the tungsten hot work steels. Used where resistance to softening is of greatest concern and resistance to shock is secondary. Can water cool tool in service, only if done with caution and if the design of die permits this degree of thermal shock. Requires high austenitizing temperature and short heating time. Has appreciable secondary hardness characteristics. Hardness in tempering begins to drop off at about 565 °C (1050 °F). High in toughness, medium to high in wear resistance, medium in machinability and resistance to decarburization

Forging. Heat slowly. Preheat at 790 to 845 °C (1455 to 1555 °F), start forging at 1065 to 1175 °C (1950 to 2150 °F). Do not forge after temperature of forging stock drops below 900 °C (1650 °F). Cool slowly

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Surface protection against decarburization by use of pack, controlled atmosphere, or vacuum is required. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Heat slowly and uniformly, especially for hardened tools. Holding time varies from about 1 h for light sections and small furnace charges to about 4 h for heavy sections and large charges. For pack annealing, hold 1 h per inch of cross section. Cool slowly in furnace to 595 °C (1105 °F) at a rate not to exceed 30 °C (55 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 207 to 235 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Surface protection against decarburization or carburization is required by utilizing molten salt bath, pack, controlled atmosphere, or vacuum. For preheating, die blocks or other tools for open furnace treatment should be placed in a furnace at a temperature that does not exceed 260 °C (500 °F). Work packed in containers may be safely placed in a furnace at 370 to 540 °C (700 to 1000 °F). Once the workpieces (or container) have attained temperature, heat slowly to 815 °C (1500 °F), at a rate not to exceed 110 °C (200 °F) per h. Hold for 1 h per inch of thickness (or per inch of container thickness if packed). If double preheat facilities are available, such as salt baths, thermal shock can be reduced by preheating at 540 to 650 °C (1000 to 1200 °F) and then preheating at 845 to 870 °C (1555 to 1600 °F). Heat rapidly to austenitizing temperature of 1095 to 1205 °C (2005 to 2200 °F) and hold for 2 to 5 min. Do not over soak. When salt baths are used, reduce temperature by 14 °C (25 °F). Use shorter time for small sections and longer time for large sections. Quench in air. If air blast cooled, air should be dry and blasted uniformly on the surface to be hardened. To minimize scale, tools can be flash quenched in oil to cool the surface to below scaling temperature [approximately 540 °C (1000 °F)], but this increases distortion. The safer procedure is to quench from the austenitizing temperature into a salt bath held at 595 to 650 °C (1105 to 1200 °F), and hold in the quench until the workpiece reaches the temperature of the bath. Then withdraw the workpiece and allow it to cool in air. Quench hardness, 45 to 53 HRC

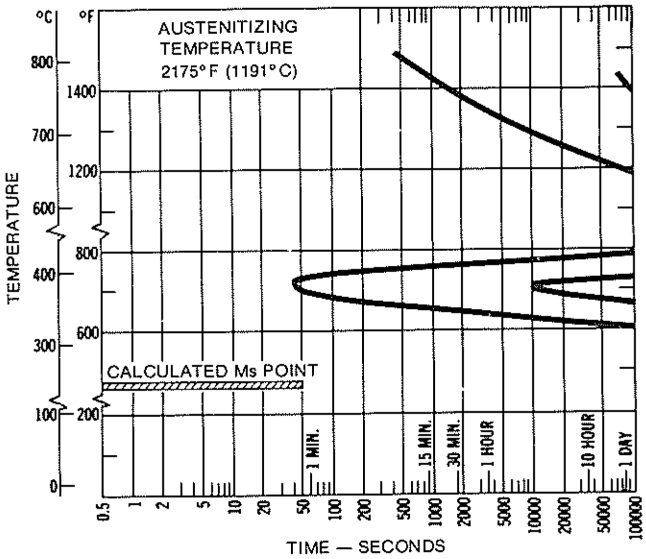
Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to –320 °F). Temper immediately after part reaches room temperature

Tempering. Temper immediately after tool reaches about 50 °C (120 °F) at 595 to 675 °C (1105 to 1245 °F). Forced-convection air tempering furnaces heat tools at a moderately safe rate. Salt baths are acceptable for small parts but may cause large or intricate shaped dies to crack due to thermal shock. Temper for 1 h per inch of thickness, cool to room temperature, and retemper using the same time at temperature. The second temper is essential and a third temper is beneficial. Approximate tempered hardness, 55 to 36 HRC

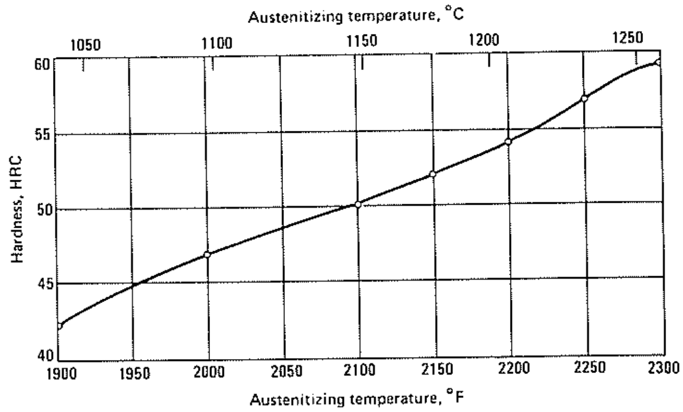
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/double temper
- Final grind to size

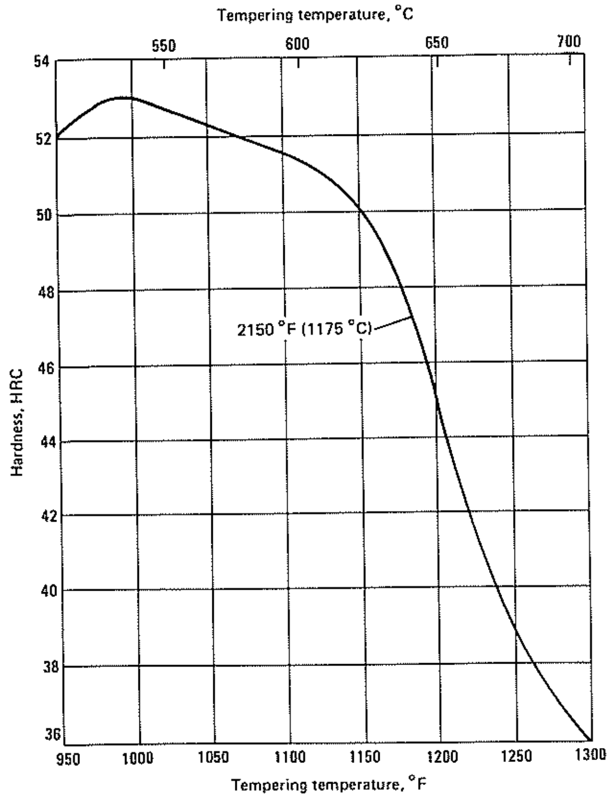
H21: Isothermal Transformation Diagram. Source: Carpenter Technology Corporation



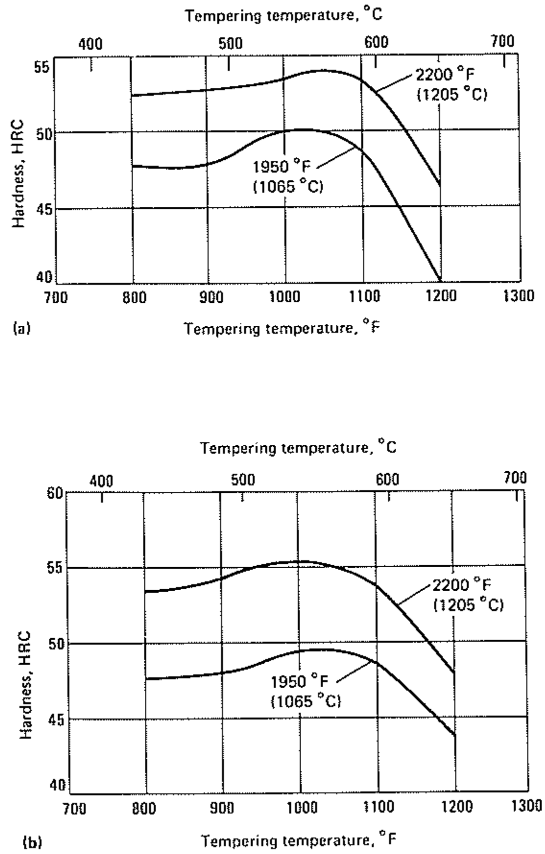
H21: Hardness vs Austenitizing Temperature. H21 containing 0.35 C, 3.25 Cr, 0.50 V, 9.35 W. Quenched in air. Specimen size: 25 mm (1 in.) diam by 127 mm (5 in.). Source: Bethlehem Steel, Vulcan-Kidd, Allegheny Ludlum



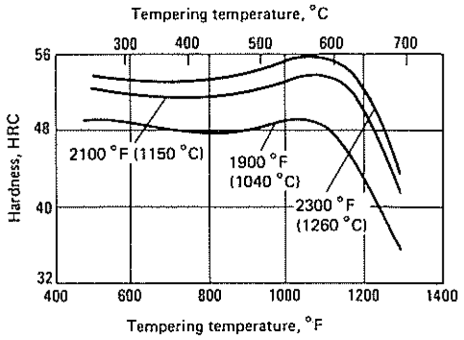
H21: Hardness vs Tempering Temperature. H21 oil quenched at 1175 °C (2150 °F) and double tempered. Source: Universal-Cyclops



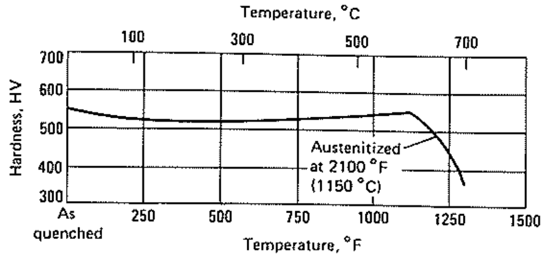
H21: Hardness vs Tempering Temperature. (a) H21 austenitized at the temperatures shown, oil quenched, receiving single temper for 2 h. (b) H21, austenitized at the temperature shown, air quenched, receiving single temper for 2 h



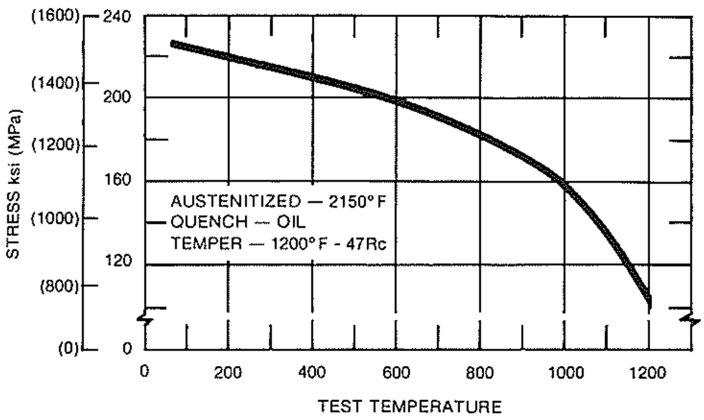
H21: Hardness vs Tempering Temperature. H21 oil quenched from the indicated temperatures. Source: Teledyne VASCO



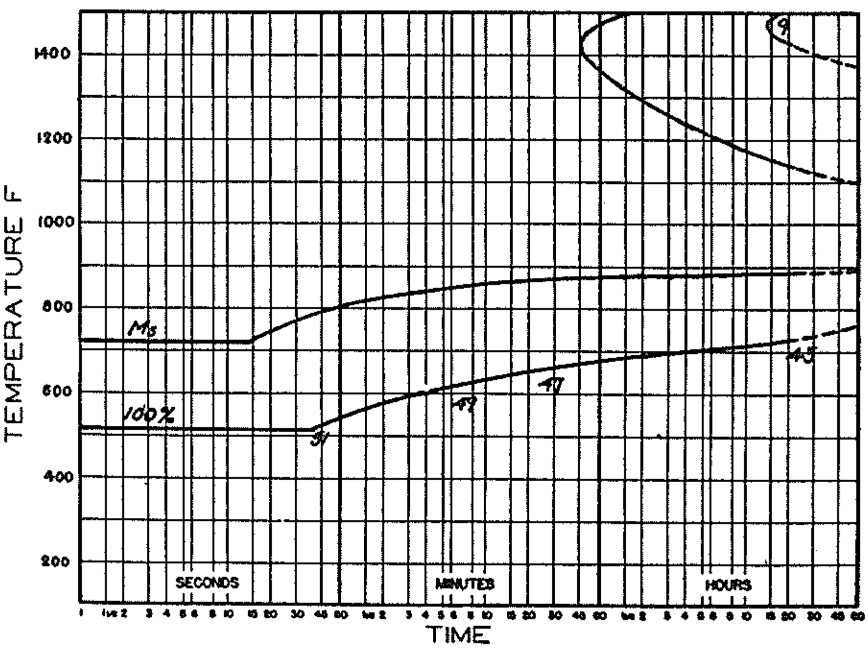
H21: Hardness vs Tempering Temperature. H21 austenitized at the temperature shown. Source: Jessop-Saville



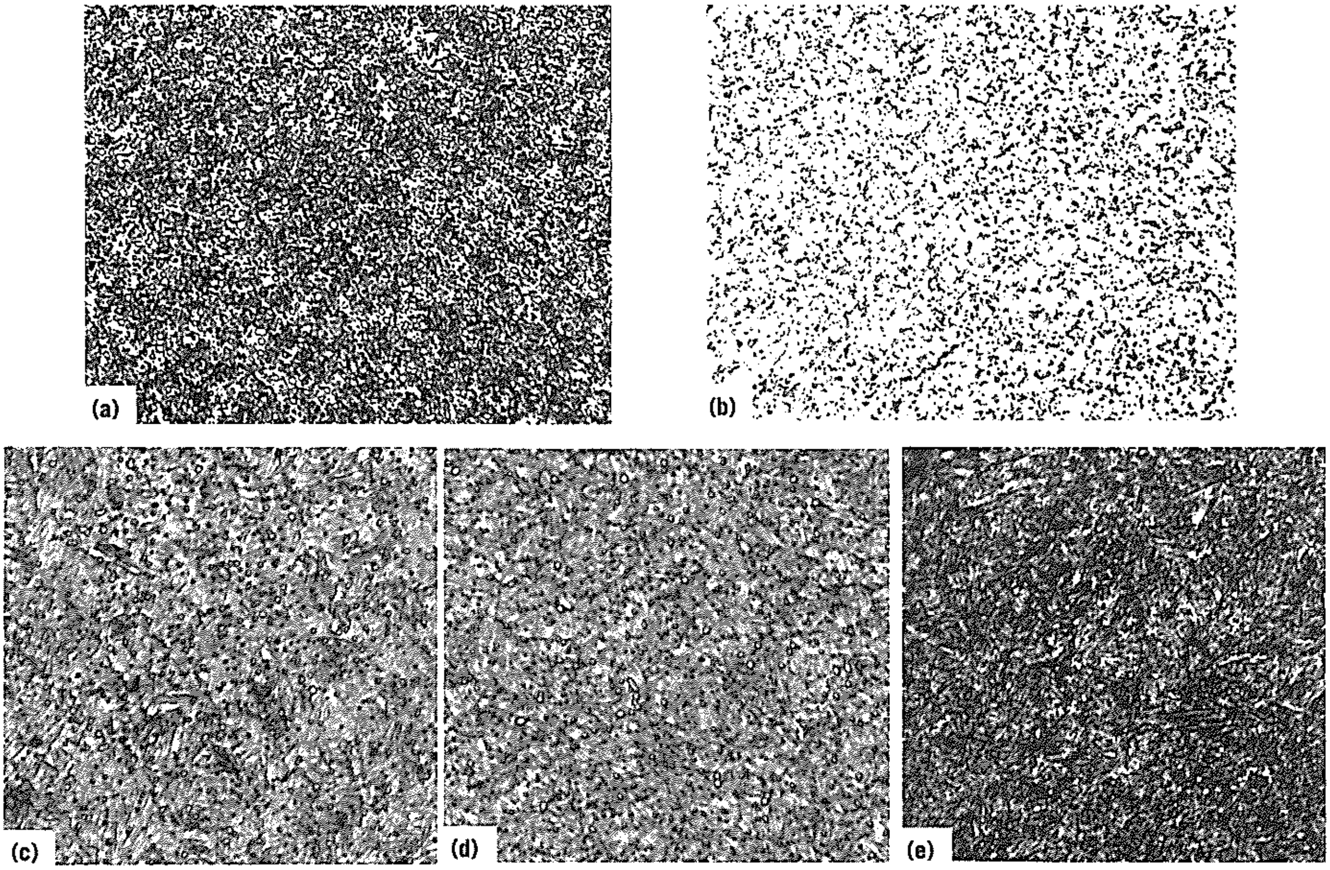
H21: Elevated-Temperature Tensile Strength



H21: Isothermal Transformation Diagram. Composition: 0.28 C, 3.25 Cr, 0.25 V, 9.00 W. Austenitized at 1175 °C (2150 °F), quenched in oil, tempered at 650 °C (1200 °F) to 47 HRC. Source: Carpenter Technology Corporation



H21: Microstructures. (a) 3% nital, 1000×. Annealed by holding at 870 °C (1600 °F) for 2 h and cooling to 540 °C (1000 °F) at 28 °C (50 °F) per h, then air cooling. Hardness, 98 HRB. Dispersion of very fine alloy carbide particles in matrix of ferrite. (b) Picral with HCl, for 10 sec, 500×. Annealed by austenitizing at 900 °C (1650 °F), cooling to 650 °C (1200 °F) at 8 °C (15 °F) per h, then air cooling to room temperature. Fine particles of carbide (mainly tungsten and chromium carbides) in matrix of ferrite. (c) 4% nital, 500×. Austenitized at 1150 °C (2100 °F) and cooled in air. Hardness, 55 HRC. Fine spheroidal alloy carbide particles (mainly tungsten carbide and chromium carbide) in matrix of untempered martensite. (d) 4% nital, 500×. Austenitized at 1150 °C (2100 °F), air cooled, double tempered (2 h plus 2 h) at 555 °C (1030 °F). Hardness, 53 HRC. Fine dispersion of spheroidal alloy carbide particles in matrix of tempered martensite. (e) 2% nital, for 90 sec, 500×. Austenitized at 1150 °C (2100 °F), air cooled, double tempered (2 h plus 2 h) at 595 °C (1105 °F). Hardness, 50 to 51 HRC. Fine dispersion of spheroidal alloy carbide particles in matrix of tempered martensite



H22

Chemical Composition. AISI: Nominal. 0.35 C, 2.00 Cr, 0.40 V, 11.00 W. **AISI/UNS (T20822):** Composition: 0.30 to 0.40 C, 0.15 to 0.40 Mn, 0.15 to 0.40 Si, 0.30 Ni max, 1.75 to 3.75 Cr, 0.25 to 0.50 V, 10.00 to 11.75 W

Similar Steels (U.S. and/or Foreign). ASTM A681 (H-22); FED QQ-T-570 (H-22); (Ger.) DIN 1.2581; (Jap.) JIS G4404 SKD 5

Characteristics. An 11% tungsten hot work steel. Water cooling not advised. Requires high austenitizing temperature and short time at heat. Hardness during tempering begins to drop off about 595 °C (1105 °F). Has high toughness and resistance to softening at elevated temperature. Has medium to high wear resistance and medium machinability and resistance to decarburization

Forging. Heat slowly. Preheat at 790 to 845 °C (1455 to 1555 °F), start forging at 1065 to 1175 °C (1950 to 2150 °F). Do not forge after temperature of forging stock drops below 900 °C (1650 °F). Cool slowly

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Surface protection against decarburization by use of pack, controlled atmosphere, or vacuum is required. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Heat slowly and uniformly, especially for hardened tools. Holding time varies from about 1 h for light sections and small furnace charges to about 4 h for heavy sections and large charges. For pack annealing, hold 1 h per inch of cross section. Cool slowly in furnace to 595 °C (1105 °F) at a rate not to exceed 30 °C (55 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 207 to 235 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Surface protection against decarburization or carburization is required by utilizing molten salt bath, pack, controlled atmosphere, or vacuum. For preheating, die blocks or other tools for open furnace treatment should be placed in a furnace at a temperature that does not exceed 260 °C (500 °F). Work packed in containers may be safely placed in a furnace at 370 to 540 °C (700 to 1000 °F). Once the workpieces (or container) have attained temperature, heat slowly to 815 °C (1500 °F), at a rate not to exceed 110 °C (200 °F) per h. Hold for 1 h per inch of thickness (or per inch of container thickness if packed). If double preheat facilities are available, such as salt baths, thermal shock can be reduced by preheating at 540 to 650 °C (1000 to 1200 °F) and then preheating at 845 to 870 °C (1555 to 1600 °F). Heat rapidly to austenitizing temperature of 1095 to 1205 °C (2005 to 2200 °F) and hold for 2 to 5 min. Do not over soak. When salt baths are used, reduce temperature by 14 °C (25 °F). Use shorter time for small sections and longer time for large sections. Quench in air. If air blast cooled, air should be dry and blasted uniformly on the surface to be hardened. To minimize scale, tools can be flash quenched in oil to cool the surface to below scaling temperature [approximately 540 °C (1000 °F)], but this increases distortion. The safer procedure is to quench from the austenitizing temperature into a salt bath held at 595 to 650 °C (1105 to 1200 °F), and hold in the quench. Then withdraw the workpiece and allow it to cool in air. Quench hardness, 48 to 56 HRC

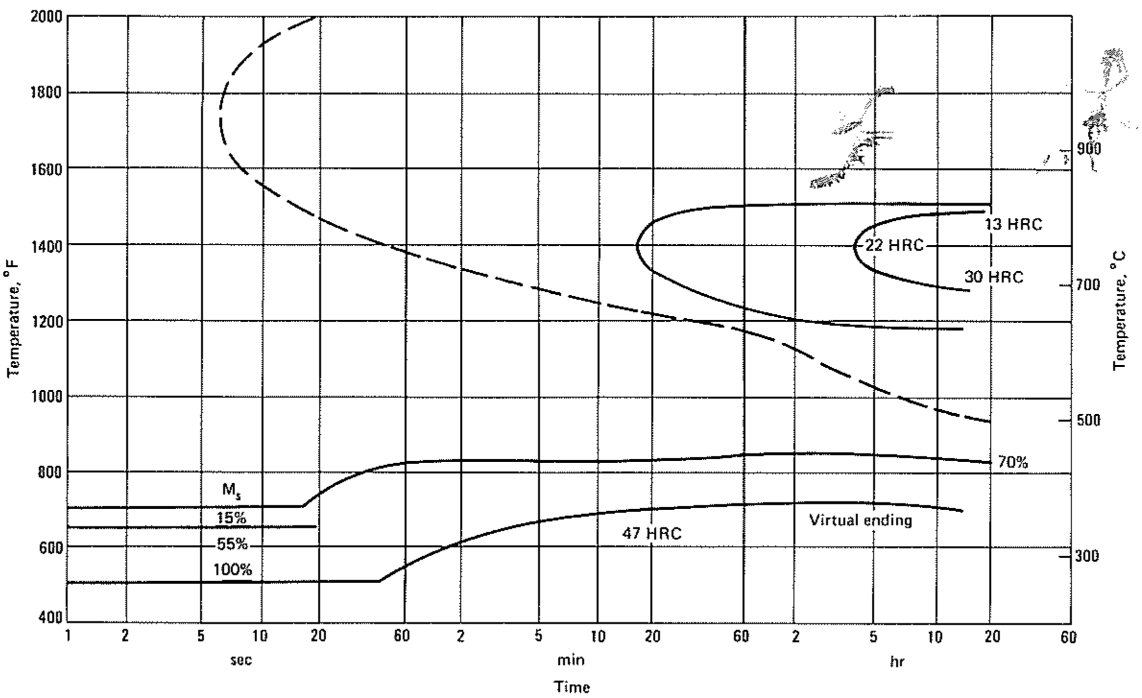
Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to –320 °F). Temper immediately after part reaches room temperature

Tempering. Temper immediately after tool reaches about 50 °C (120 °F) at 595 to 675 °C (1105 to 1245 °F). Forced-convection air tempering furnaces heat tools at a moderately safe rate. Salt baths are acceptable for small parts but may cause large or intricate shaped dies to crack due to thermal shock. Temper for 1 h per inch of thickness, cool to room temperature, and retemper using the same time at temperature. The second temper is essential and a third temper is beneficial. Approximate tempered hardness, 52 to 39 HRC

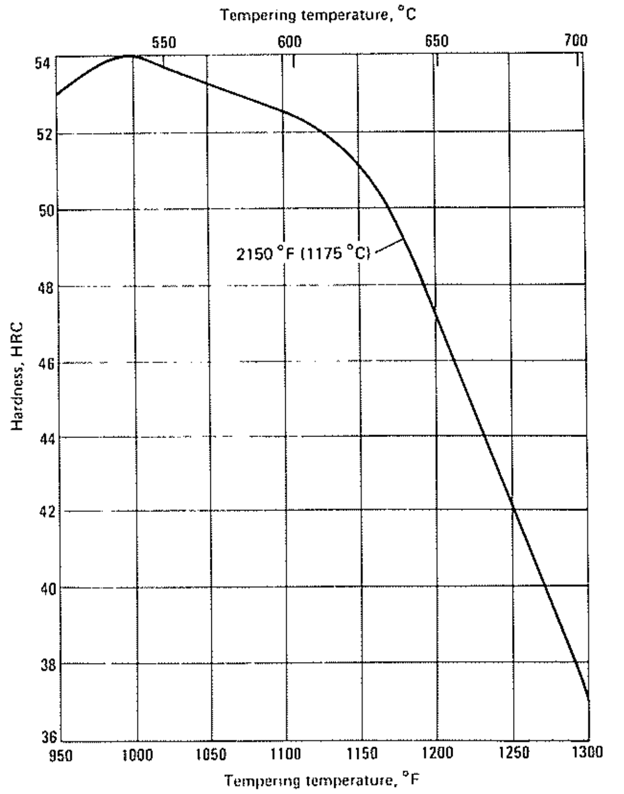
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size

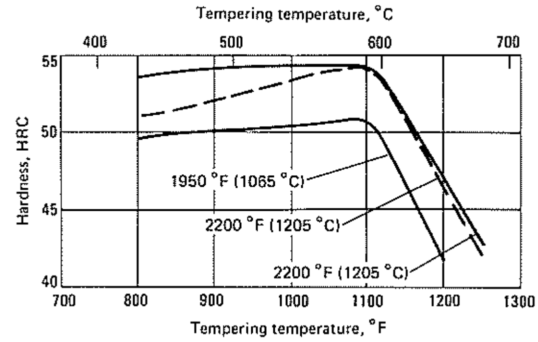
H22: Isothermal Transformation Diagram. H22 containing 0.40 C, 2.00 Cr, 0.35 V, 11.50 W. Austenitized at 1175 °C (2150 °F)



H22: Hardness vs Tempering Temperature. H22 oil quenched from 1175 °C (2150 °F), and double tempered. Source: Universal-Cyclops



H22: Hardness vs Tempering Temperature. H22 austenitized at 1065 °C (1950 °F) and oil quenched, austenitized at 1205 °C (2200 °F) and air quenched, and austenitized at 1205 °C (2200 °F) and oil quenched. Each received single temper for 2 h



H23

Chemical Composition. AISI: Nominal. 0.30 C, 12.00 Cr, 1.00 V, 12.00 W. **AISI/UNS (T20823):** Composition: 0.25 to 0.35 C, 0.15 to 0.40 Mn, 0.15 to 0.60 Si, 0.30 Ni max, 11.00 to 12.75 Cr, 0.75 to 1.25 V, 11.00 to 12.75 W

Similar Steels (U.S. and/or Foreign). ASTM A681 (H-23); FED QQ-T-570 (H-23); (Ger.) DIN 1.2625

Characteristics. A relatively low carbon grade containing 12% tungsten and 12% chromium. Has very high resistance to softening at elevated temperature and high resistance to hardness drop during tempering. Is deep hardening and exhibits unusually high secondary hardening during tempering. Requires high austenitizing temperature and short time at heat. At an austenitizing temperature of 1260 °C (2300 °F), has duplex structure of austenite and ferrite. On isothermal transformation, precipitation from the ferrite (of iron tungsten) begins within a few seconds which is not detrimental to as-quenched or final hardness. More important, the nose of the transformation curve is encountered in only 60 sec at 980 °C (1795 °F). Therefore, oil quenching or a strongly agitated hot salt bath (preferably cascade type) at approximately 175 °C (345 °F) is used. The M_s temperature is approximately –45 °C (–50 °F). As-quenched structure consists of undissolved carbide, austenite, and ferrite. (Absence of martensite explains resistance to tempering). As-quenched hardness, 34 to 40 HRC. During tempering, it will increase to the usual working hardness of 34 to 48 HRC. Hardness begins to drop off gradually at 540 to 595 °C (1000 to 1105 °F) and very rapidly in the 650 to 705 °C (1200 to 1300 °F) range. Has medium toughness, medium to high wear resistance, and medium machinability and resistance to decarburization

Forging. Heat slowly. Preheat at 790 to 845 °C (1455 to 1555 °F), start forging at 1065 to 1175 °C (1950 to 2150 °F). Do not forge after temperature of forging stock drops below 980 °C (1795 °F). Cool slowly

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Surface protection against decarburization by use of pack, controlled atmosphere, or vacuum is required. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Heat slowly and uniformly, especially for hardened tools. Holding time varies from about 1 h for light sections and small furnace charges to about 4 h for heavy sections and large charges. For pack annealing, hold 1 h per inch of cross section. Cool slowly in furnace to 595 °C (1105 °F) at a rate not to exceed 30 °C (55 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 212 to 255 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

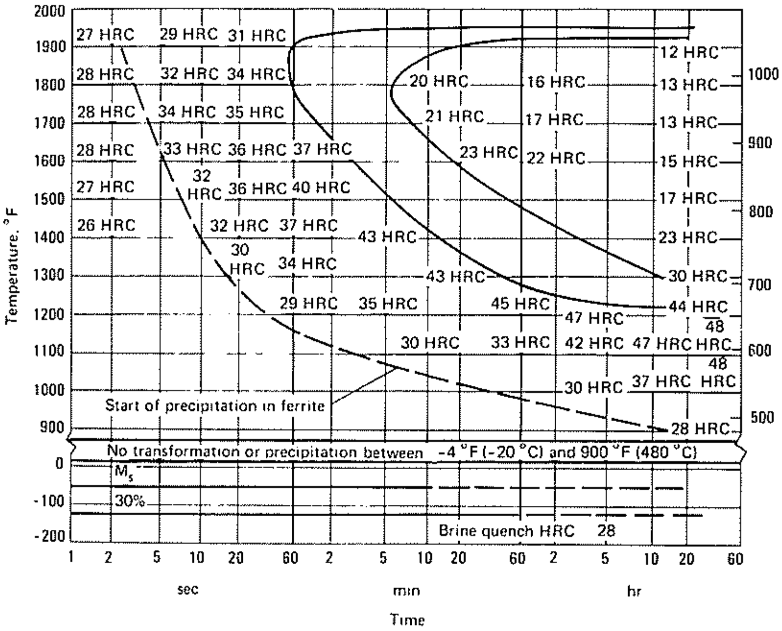
Hardening. Surface protection against decarburization or carburization is required by utilizing molten salt bath, pack, controlled atmosphere, or vacuum. For preheating, die blocks or other tools for open furnace treatment should be placed in a furnace at a temperature that does not exceed 260 °C (500 °F). Work packed in containers may be safely placed in a furnace at 370 to 540 °C (700 to 1000 °F). Once the workpieces (or container) have attained temperature, heat slowly to 845 °C (1555 °F), at a rate not to exceed 110 °C (200 °F) per h. Hold for 1 h per inch of thickness (or per inch of container thickness if packed). If double preheat facilities are available, such as salt baths, thermal shock can be reduced by preheating at 540 to 650 °C (1000 to 1200 °F) and then preheating at 845 to 870 °C (1555 to 1600 °F). Heat rapidly to austenitizing temperature of 1205 to 1260 °C (2200 to 2300 °F) and hold for 2 to 5 min. Do not over soak. When salt baths are used, reduce temperature by 14 °C (25 °F). Use shorter time for small sections and longer time for large sections. Quench from the austenitizing temperature in warm oil or an agitated salt bath held at 165 to 190 °C (330 to 375 °F), and hold in the quench until the workpiece reaches the temperature of the bath. Then withdraw the workpiece and allow it to cool in air. Quench hardness, 34 to 40 HRC

Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to –320 °F). Temper immediately after part reaches room temperature

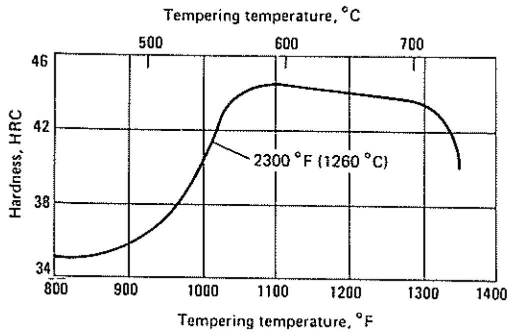
Tempering. Temper immediately after tool reaches about 50 °C (120 °F) at 650 to 730 °C (1200 to 1350 °F). Forced-convection air tempering furnaces heat tools at a moderately safe rate. Salt baths are acceptable for small parts but may cause large or intricate shaped dies to crack due to thermal shock. Temper for 1 h per inch of thickness, cool to room temperature, and retemper using the same time at temperature. The second temper is essential and a third temper is beneficial. Approximate tempered hardness, 48 to 34 HRC

Recommended Processing Sequence

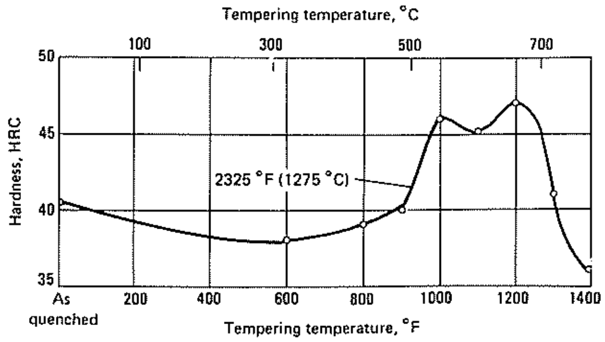
- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size



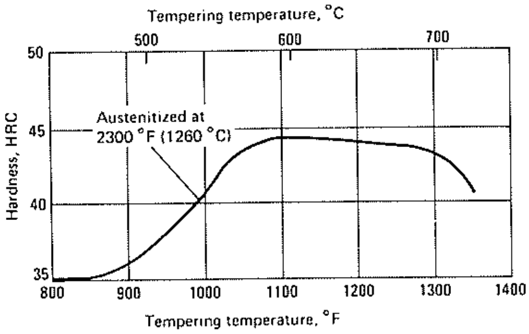
H23: Isothermal Transformation Diagram. Note that M_s is below room temperature. Source: Crucible Steel



H23: Hardness vs Tempering Temperature. H23 oil quenched from 1260 °C (2300 °F) and triple tempered (2 plus 2 plus 2 h). Source: Universal-Cyclops

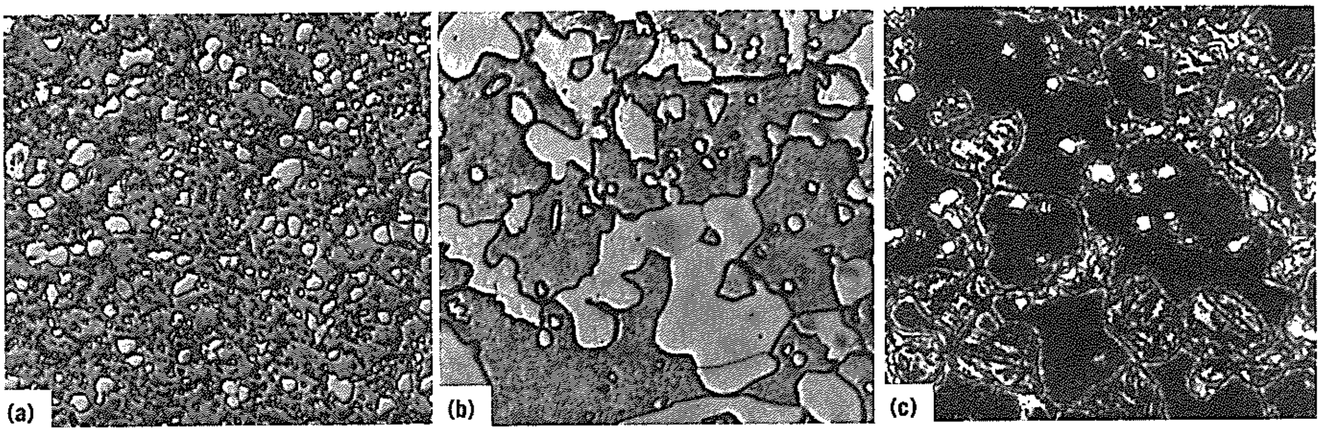


H23: Hardness vs Tempering Temperature. H23 containing 0.35 C, 0.33 Mn, 0.45 Si, 11.87 Cr, 1.08 V, 12.07 W. Austenitized at 1275 °C (2325 °F) and quenched in oil. Source: Teledyne VASCO



H23: Hardness vs Tempering Temperature. H23 austenitized at temperature indicated, oil quenched, triple tempered (2 plus 2 plus 2 h)

H23: Microstructures. (a) Kalling's reagent, 500×. Annealed by austenitizing at 870 °C (1600 °F) for 2 h, cooling to 540 °C (1000 °F) at 28 °C (50 °F) per h, and air cooling. 98 HRB. Tiny spheroidal and some larger alloy carbide particles in matrix of ferrite. (b) Kalling's reagent, 500×. Austenitized at 1270 °C (2320 °F) and quenched in molten salt at 175 °C (345 °F). Hardness, 40 HRC. Retained austenite (large light gray areas), ferrite (dark gray areas), and spheroidal particles of carbide. (c) Kalling's reagent, 500×. Austenitized at 1270 °C (2320 °F), quenched in molten salt at 175 °C (345 °F), tempered at 555 °C (1030 °F), then at 790 °C (1455 °F). Ferrite (black), austenite transformed during tempering (mottled), and spheroidal carbide particles



H24

Chemical Composition. **AISI:** Nominal. 0.45 C, 3.00 Cr, 0.50 V, 15.00 W. **AISI/UNS (T20824):** Composition: 0.42 to 0.53 C, 0.15 to 0.40 Mn, 0.15 to 0.40 Si, 0.30 Ni max, 2.50 to 3.50 Cr, 0.40 to 0.60 V, 14.00 to 16.00 W

Similar Steels (U.S. and/or Foreign). ASTM A681 (H-24); FED QQ-T-570 (H-24)

Characteristics. A tungsten hot work grade containing 15% tungsten, 0.45% carbon, plus chromium and vanadium. Requires high austenitizing temperature and short time at heat. Oil quenching is recommended rather than air. Tools should not be water cooled during hot work service. Tungsten steels are sensitive to rapid heating and cooling cycles. For this reason, they are usually finish ground with free cutting coarse grain wheels, which tend to reduce localized heating during grinding. Has mild secondary hardening characteristics, and hardness will peak out at approximately 540 °C (1000 °F) when austenitized at 1205 °C (2200 °F). Is deep hardening, has very high resistance to softening at elevated temperature, and has medium toughness. Wear resistance is high. Has medium machinability and resistance to decarburization

Forging. Heat slowly. Preheat at 790 to 845 °C (1455 to 1555 °F), start forging at 1065 to 1175 °C (1950 to 2150 °F). Do not forge after temperature of forging stock drops below 955 °C (1750 °F). Cool slowly

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Surface protection against decarburization by use of pack, controlled atmosphere, or vacuum is required. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Heat slowly and uniformly, especially for hardened tools. Holding time varies from about 1 h for light sections and small furnace charges to about 4 h for heavy sections and large charges. For pack annealing, hold 1 h per inch of cross section. Cool slowly in furnace to 595 °C (1105 °F) at a rate not to exceed 30 °C (55 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 217 to 241 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Surface protection against decarburization or carburization is required by utilizing molten salt bath, pack, controlled atmosphere, or vacuum. For preheating, die blocks or other tools for open furnace treatment should be placed in a furnace at a temperature that does not exceed 260 °C (500 °F). Work packed in containers may be safely placed in a furnace at 370 to 540 °C (700 to 1000 °F). Once the workpieces (or container) have attained temperature, heat slowly to 815 °C (1500 °F), at a rate not to exceed 110 °C (200 °F) per h. Hold for 1 h per inch of thickness (or per inch of container thickness if packed). If double preheat facilities are available, such as salt baths, thermal shock can be reduced by preheating at 540 to 650 °C (1000 to 1200 °F) and then preheating at 845 to 870 °C (1555 to 1600 °F). Heat rapidly to austenitizing temperature of 1095 to 1230 °C (2005 to 2245 °F) and hold for 2 to 5 min. Do not over soak. When salt baths are used, reduce temperature by 14 °C (25 °F). Use shorter time for small sections and longer time for large sections. Quench in warm oil or agitated salt bath held at approximately 175 °C (345 °F), and hold in the quench until the workpiece reaches the temperature of the bath. Then withdraw the workpiece and allow it to cool in air. Quench hardness, 52 to 56 HRC

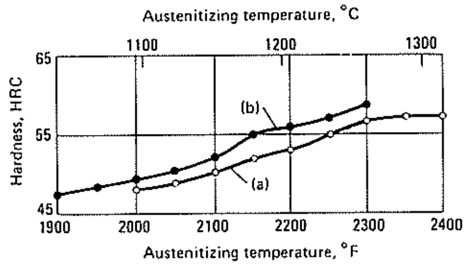
Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to –320 °F). Temper immediately after part reaches room temperature

Tempering. Temper immediately after tool reaches about 50 °C (120 °F) at 565 to 650 °C (1050 to 1200 °F). Forced-convection air tempering furnaces heat tools at a moderately safe rate. Salt baths are acceptable for small parts but may cause large or intricate shaped dies to crack due to thermal shock. Temper for 1 h per inch of thickness, cool to room temperature, and retemper using the same time at temperature. The second temper is essential and a third temper is beneficial. Approximate tempered hardness, 55 to 45 HRC

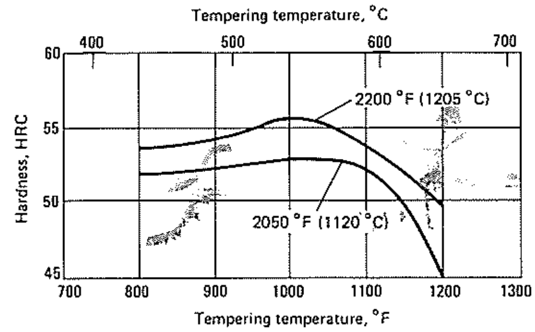
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size

H24: Hardness vs Austenitizing Temperature. (a) H24 containing 0.42 C, 3.50 Cr, 0.30 V, 14.00 W, quenched in air. Specimen 25 mm (1 in.) diam by 127 mm (5 in.). (b) H24 containing 0.47 C, 3.50 Cr, 0.70 V, 14.00 W, quenched in air. Specimen 25 mm (1 in.) diam by 127 mm (5 in.). Source: Bethlehem Steel and Allegheny Ludlum



H24: Hardness vs Tempering Temperature. H24 austenitized at the temperatures shown, oil quenched, and receiving single temper for 2 h



H25

Chemical Composition. **AISI:** Nominal. 0.25 C, 4.00 Cr, 0.50 V, 15.00 W. **AISI/UNS (T20825):** Composition: 0.22 to 0.32 C, 0.15 to 0.40 Mn, 0.15 to 0.40 Si, 0.30 Ni max, 3.75 to 4.50 Cr, 0.40 to 0.60 V, 14.00 to 16.00 W

Similar Steels (U.S. and/or Foreign). ASTM A681 (H-25); FED QQ-T-570 (H-25)

Characteristics. Very similar to H24, except has lower carbon content and 1% more chromium. A 15% tungsten hot work grade. Its relatively low level of carbon gives it a toughness rating equal to the popular 9% tungsten grades which have higher levels of carbon. The high tungsten imparts very high resistance to softening at elevated temperature. Requires high austenitizing temperature and short time at heat. Cannot be water cooled in service and should be ground with coarse open wheel. Hardness in tempering begins to drop after 540 °C (1000 °F) when the high end of the austenitizing range is used. Has high toughness, and medium wear resistance, machinability, and resistance to decarburization

Forging. Heat slowly. Preheat at 790 to 845 °C (1455 to 1555 °F), start forging at 1065 to 1175 °C (1950 to 2150 °F). Do not forge after temperature of forging stock drops below 925 °C (1695 °F). Cool slowly

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Surface protection against decarburization by use of pack, controlled atmosphere, or vacuum is required. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Heat slowly and uniformly, especially for hardened tools. Holding time varies from about 1 h for light sections and small furnace charges to about 4 h for heavy sections and large charges. For pack annealing, hold 1 h per inch of cross section. Cool slowly in furnace to 595 °C (1105 °F) at a rate not to exceed 30 °C (55 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 207 to 235 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245°F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

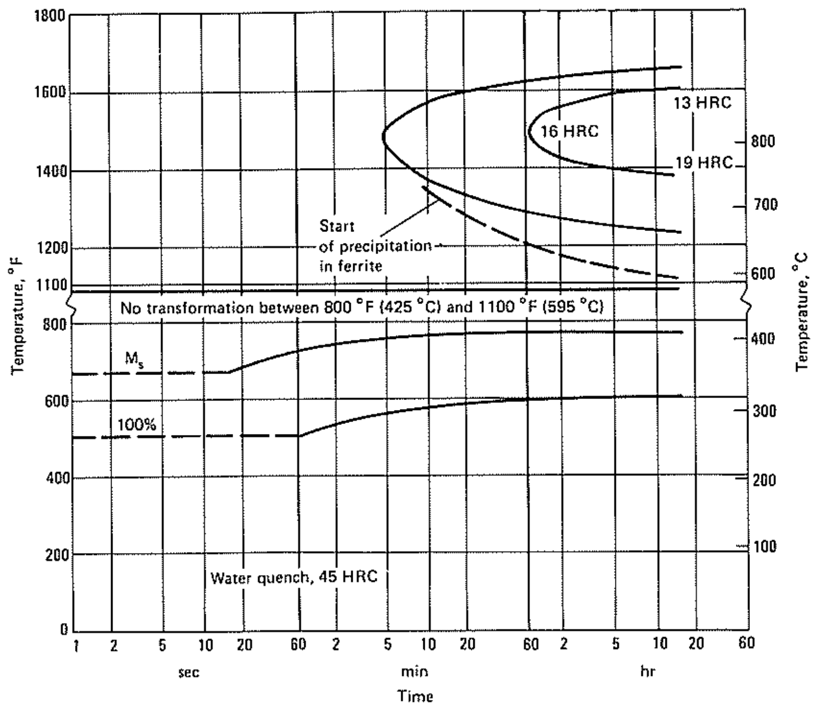
Hardening. Surface protection against decarburization or carburization is required by utilizing molten salt bath, pack, controlled atmosphere, or vacuum. For preheating, die blocks or other tools for open furnace treatment should be placed in a furnace at a temperature that does not exceed 260 °C (500 °F). Work packed in containers may be safely placed in a furnace at 370 to 540 °C (700 to 1000 °F). Once the workpieces (or container) have attained temperature, heat slowly to 815 °C (1500 °F), at a rate not to exceed 110 °C (200 °F) per h. Hold for 1 h per inch of thickness (or per inch of container thickness if packed). If double preheat facilities are available, such as salt baths, thermal shock can be reduced by preheating at 540 to 650 °C (1000 to 1200 °F) and then preheating at 845 to 870 °C (1555 to 1600 °F). Heat rapidly to austenitizing temperature of 1150 to 1260 °C (2100 to 2300 °F) and hold for 2 to 5 min. Do not over soak. When salt baths are used, reduce temperature by 14 °C (25 °F). Use shorter time for small sections and longer time for large sections. Quench in air. If air blast cooled, air should be dry and blasted uniformly on the surface to be hardened. To minimize scale, tools can be flash quenched in oil to cool the surface to below scaling temperature [approximately 540 °C (1000 °F)], but this increases distortion. The safer procedure is to quench from the austenitizing temperature into a salt bath held at 595 to 650 °C (1105 to 1200 °F), and hold in the quench until the workpiece reaches the temperature of the bath. Then withdraw the workpiece and allow it to cool in air. Quench hardness, 33 to 46 HRC

Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at −100 to −195 °C (−150 to −320 °F). Temper immediately after part reaches room temperature

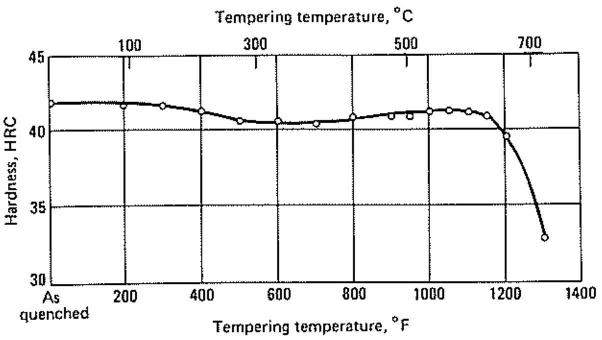
Tempering. Temper immediately after tool reaches about 50 °C (120 °F) at 565 to 675 °C (1050 to 1245 °F). Forced-convection air tempering furnaces heat tools at a moderately safe rate. Salt baths are acceptable for small parts but may cause large or intricate shaped dies to crack due to thermal shock. Temper for 1 h per inch of thickness, cool to room temperature, and retemper using the same time at temperature. The second temper is essential and a third temper is beneficial. Approximate tempered hardness, 44 to 35 HRC

Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size



H25: Isothermal Transformation Diagram. H25 containing 0.25 C, 4.00 Cr, 0.50 V, 15.00 W. Austenitized at 1175 °C (2150 °F). Source: Crucible Steel



H25: Hardness vs Tempering Temperature. H25 containing 0.26 C, 3.60 Cr, 0.40 V, 14.30 W. Austenitized at 1175 °C (2150 °F) and quenched in oil. Specimen: 13 mm (0.50 in.) diam by 15.8 mm (0.625 in.)

H26

Chemical Composition. **AISI:** Nominal. 0.50 C, 4.00 Cr, 1.00 V, 18.00 W. **AISI/UNS (T20826):** Composition: 0.45 to 0.55 C, 0.15 to 0.40 Mn, 0.15 to 0.40 Si, 0.30 Ni max, 3.75 to 4.50 Cr, 0.75 to 1.25 V, 17.25 to 19.00 W

Similar Steels (U.S. and/or Foreign). ASTM A681 (H-26); FED QQ-T-570 (H-26); (U.K.) B.S. 4659 BH26

Characteristics. Hot work version of 18-4-1 or T1 high speed steel except with lower carbon to increase toughness to a medium rating. The most erosion resistant and lowest shock resistant of the tungsten hot work steels. Heated in a similar manner to high speed steel, with a high austenitizing temperature and a short time at heat. Will not withstand water cooling in service. Can be quenched in salt, oil, or air. Hardness begins to drop off rapidly during tempering above approximately 525 °C (975 °F). Has medium machinability and resistance to decarburization. Available in several carbon ranges

Forging. Heat slowly. Preheat at 790 to 845 °C (1455 to 1555 °F), start forging at 1065 to 1175 °C (1950 to 2150 °F). Do not forge after temperature of forging stock drops below 955 °C (1750 °F). Cool slowly

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Surface protection against decarburization by use of pack, controlled atmosphere, or vacuum is required. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Heat slowly and uniformly, especially for hardened tools. Holding time varies from about 1 h for light sections and small furnace charges to about 4 h for heavy sections and large charges. For pack annealing, hold 1 h per inch of cross section. Cool slowly in furnace to 540 °C (1000 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 217 to 241 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

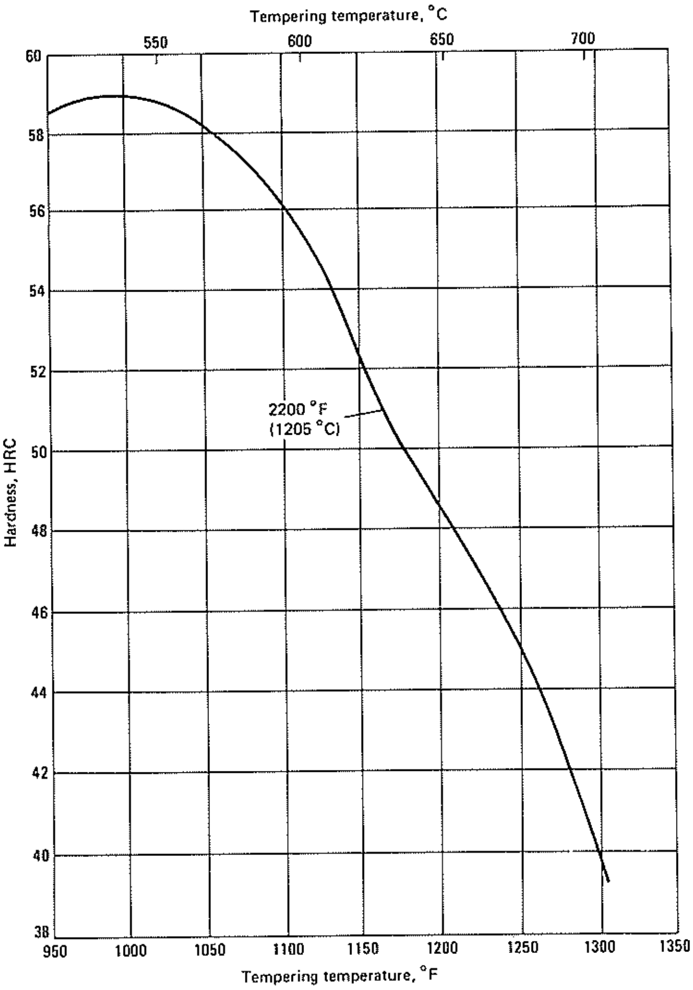
Hardening. Surface protection against decarburization or carburization is required by utilizing molten salt bath, pack, controlled atmosphere, or vacuum. For preheating, die blocks or other tools for open furnace treatment should be placed in a furnace at a temperature that does not exceed 260 °C (500 °F). Work packed in containers may be safely placed in a furnace at 370 to 540 °C (700 to 1000 °F). Once the workpieces (or container) have attained temperature, heat slowly to 870 °C (1600 °F), at a rate not to exceed 110 °C (200 °F) per h. Hold for 1 h per inch of thickness (or per inch of container thickness if packed). If double preheat facilities are available, such as salt baths, thermal shock can be reduced by preheating at 540 to 650 °C (1000 to 1200 °F) and then preheating at 845 to 870 °C (1555 to 1600 °F). Heat rapidly to austenitizing temperature of 1175 to 1260 °C (2150 to 2300 °F) and hold for 2 to 5 min. Do not over soak. When salt baths are used, reduce temperature by 14 °C (25 °F). Use shorter time for small sections and longer time for large sections. Quench in salt, oil, or air. If air blast cooled, air should be dry and blasted uniformly on the surface to be hardened. To minimize scale, tools can be flash quenched in oil to cool the surface to below scaling temperature [approximately 540 °C (1000 °F)], but this increases distortion. The safer procedure is to quench from the austenitizing temperature into a salt bath held at 595 to 650 °C (1105 to 1200 °F), and hold in the quench until the workpiece reaches the temperature of the bath. Then withdraw the workpiece and allow it to cool in air. Quench hardness, 51 to 59 HRC

Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to –320 °F). Temper immediately after part reaches room temperature

Tempering. Temper immediately after tool reaches about 50 °C (120 °F) at 565 to 675 °C (1050 to 1245 °F). Forced-convection air tempering furnaces heat tools at a moderately safe rate. Salt baths are acceptable for small parts but may cause large or intricate shaped dies to crack due to thermal shock. Temper for 1 h per inch of thickness, cool to room temperature, and retemper using the same time at temperature. The second temper is essential and a third temper is beneficial. Approximate tempered hardness as it corresponds to tempering temperature is 58 to 43 HRC

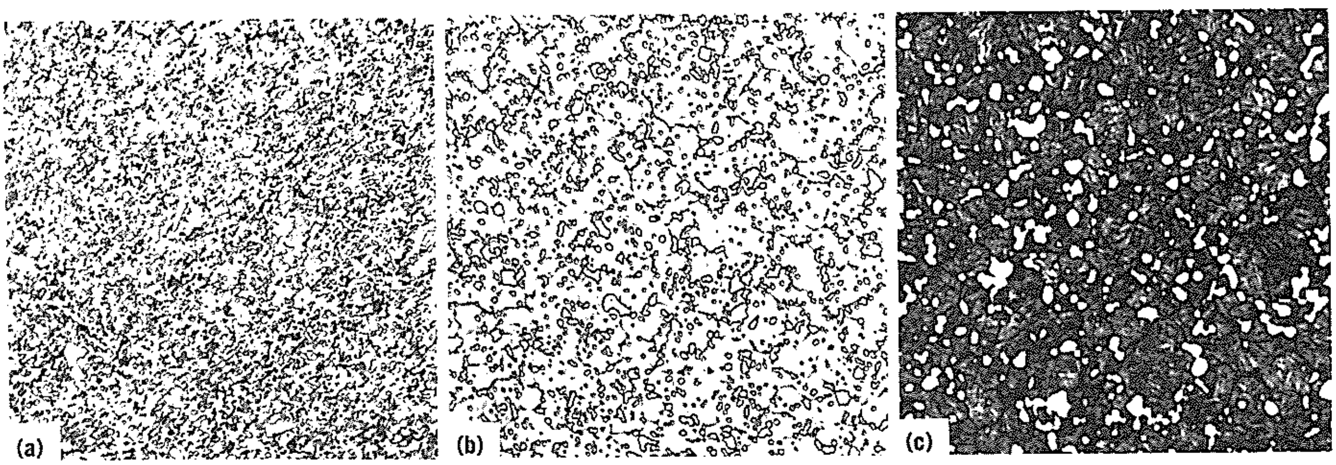
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size



H26: Hardness vs Tempering Temperature. H26 oil quenched from 1205 °C (2200 °F) and double tempered. Source: Universal-Cyclops

H26: Microstructures. (a) Picral with HCl, for 10 sec, 500×. Annealed by austenitizing at 900 °C (1650 °F), cooling to 650 °C (1200 °F) at 8 °C (15 °F) per h, and air cooling. Hardness, 22 to 23 HRC. Dispersion of fine particles of alloy carbide in matrix of ferrite. (b) 4% nital, 500×. Austenitized at 1260 °C (2300 °F) and oil quenched. Hardness, 58 HRC. Small spheroidal carbide particles and some larger alloy carbide (principally tungsten carbide) in matrix of untempered martensite. (**c**) 4% nital, 500×. Austenitized at 1260 °C (2300 °F), oil quenched (2 h plus 2 h) at 550 °C (1020 °F). Hardness, 59 HRC. Particles of alloy carbide more clearly resolved in (b). Matrix tempered martensite



H42

Chemical Composition. **AISI:** Nominal. 0.60 C, 4.00 Cr, 5.00 Mo, 2.00 V, 6.00 W. **AISI/UNS (T20842):** Composition: 0.55 to 0.70 C, 0.15 to 0.40 Mn, 3.75 to 4.50 Cr, 1.75 to 2.20 V, 5.50 to 6.75 W

Similar Steels (U.S. and/or Foreign). ASTM A681 (H-42); FED QQ-T-570 (H-42); (Fr.) AFNOR 3548 Z 65 WDCV 6.05

Characteristics. Hot work version of the popular M2 high speed steel with lower carbon content to increase toughness to a medium rating. Has very high resistance to softening at elevated temperature. Treated much like a high speed steel, requiring high austenitizing temperature and a short time at heat. Will not withstand water cooling in service. Hardness begins to drop off fairly rapidly during tempering in the 510 to 540 °C (950 to 1000 °F) range. Has medium machinability and resistance to decarburization. Available in several carbon ranges

Forging. Heat slowly. Preheat at 760 to 815 °C (1400 to 1500 °F), start forging at 1040 to 1150 °C (1905 to 2100 °F). Do not forge after temperature of forging stock drops below 925 °C (1695 °F). Cool slowly

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Surface protection against decarburization by use of pack, controlled atmosphere, or vacuum is required. Heat to 845 to 900 °C (1555 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Heat slowly and uniformly, especially for hardened tools. Holding time varies from about 1 h for light sections and small furnace charges to about 4 h for heavy sections and large charges. For pack annealing, hold 1 h per inch of cross section. Cool slowly in furnace to 540 °C (1000 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 207 to 235 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Surface protection against decarburization or carburization is required by utilizing molten salt bath, pack, controlled atmosphere, or vacuum. For preheating, die blocks or other tools for open furnace treatment should be placed in a furnace at a temperature that does not exceed 260 °C (500 °F). Work packed in containers may be safely placed in a furnace at 370 to 540 °C (700 to 1000 °F). Once the workpieces (or container) have attained temperature, heat slowly to 730 to 845 °C (1350 to 1555 °F), at a rate not to exceed 110 °C (200 °F) per h. Hold for 1 h per inch of thickness (or per inch of container thickness if packed). If double preheat facilities are available, such as salt baths, thermal shock can be reduced by preheating at 540 to 650 °C (1000 to 1200 °F) and then preheating at 845 to 870 °C (1555 to 1600 °F). Heat rapidly to austenitizing temperature of 1120 to 1220 °C (2050 to 2225 °F) and hold for 2 to 5 min. Do not over soak. When salt baths are used, reduce temperature by 14 °C (25 °F). Use shorter time for small sections and longer time for large sections. Quench in salt, oil, or air. If air blast cooled, air should be dry and blasted uniformly on the surface to be hardened. To minimize scale, tools can be flash quenched in oil to cool the surface to below scaling temperature [approximately 540 °C (1000 °F)], but this increases distortion. The safer procedure is to quench from the austenitizing temperature into a salt bath held at 595 to 650 °C (1105 to 1200 °F), and hold in the quench until the workpiece reaches the temperature of the bath. Then withdraw the workpiece and allow it to cool in air. Quench hardness, 54 to 62 HRC

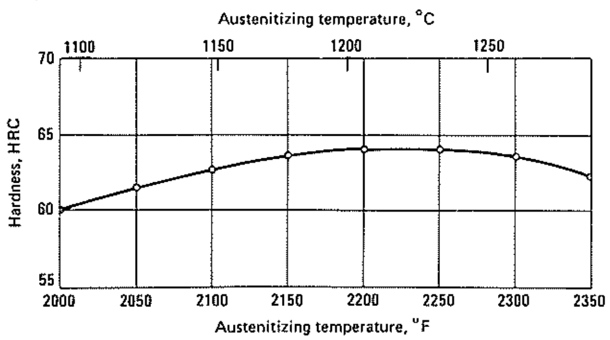
Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to –320 °F). Temper immediately after part reaches room temperature

Tempering. Temper immediately after tool reaches about 50 °C (120 °F) at 565 to 650 °C (1050 to 1200 °F). Forced-convection air tempering furnaces heat tools at a moderately safe rate. Salt baths are acceptable for small parts but may cause large or intricate shaped dies to crack due to thermal shock. Temper for 1 h per inch of thickness, cool to room temperature, and retemper using the same time at temperature. The second temper is essential and a third temper is beneficial. Approximate tempered hardness as it corresponds to tempering temperature is 60 to 50 HRC

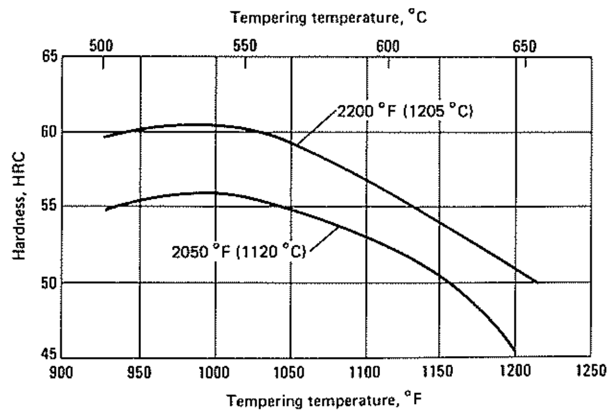
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size

H42: Hardness vs Austenitizing Temperature. H42 containing 0.68 C, 0.30 Si, 4.25 Cr, 5.00 Mo, 1.90 V, 6.40 W. Specimen oil quenched from indicated temperatures. Source: Latrobe Steel and Bethlehem Steel



H42: Hardness vs Tempering Temperature. H42 austenitized at 1205 °C (2200 °F) and 1120 °C (2050 °F) and oil quenched



Tungsten High-Speed Tool Steels (T Series)

Introduction

Tungsten high-speed tool steels are primarily used for cutting tools such as broaches, chasers, cutters, drills, hobs, reamers, and taps. The T steels need not be normalized, but they must be fully annealed after forging or when rehardening is required.

The T-series steels are always preheated prior to austenitizing to minimize the stresses that might develop because of the transformation to austenite at approximately 760 °C (1400 °F). Double preheating is often recommended to minimize thermal shock. Only small tools and those that do not incorporate sharp notches or abrupt changes in section may be placed directly into the austenitizing furnace with reasonable safety.

All high-speed tool steels depend on the solution of various complex alloy carbides during austenitizing to develop both their heat-resisting qualities and cutting ability. These carbides do not dissolve to any appreciable extent unless the steel is heated to temperatures approaching the melting point of the steel. Therefore, exceedingly accurate temperature control is required in austenitizing high-speed steel. A steel such as T15, which contains more than 3% vanadium, may be held at the austenitizing temperature about 50% longer than those containing lesser amounts. The relatively pure vanadium carbide phase inherent in the microstructure of this steel is virtually insoluble at temperatures below the melting point and restricts grain growth, permitting longer soaking times without detriment. However, the recommended austenitizing temperature for this steel should not be exceeded.

Single point tools intended for heavy-duty cutting can often be effectively austenitized at 8 to 17 °C (15 to 30 °F) above the nominal austenitizing temperature to improve hot hardness and temper resistance. The higher temperature increases alloy solution, temper resistance, and hot hardness, but it also results in some sacrifice in toughness. Fine-edged tools, such as taps and chasers, may be hardened at temperatures 14 to 28 °C (25 to 50 °F) below the nominal austenitizing temperature to impart added toughness. Other adjustments in austenitizing temperature depend on the type of heating equipment employed.

The T-series steels can be quenched in air, oil, or molten salt. The steels are normally subjected to two separate tempering treatments. Refrigeration may be used to transform retained austenite. The hardened or hardened and tempered tool is cooled to at least −85 °C (−120 °F) and tempered or retempered at normal tempering temperatures. The steels may also be nitrided. Liquid nitriding baths, capable of producing a more ductile case with a lower nitrogen content than that normally obtained in gaseous nitriding atmospheres, are preferred. Nitriding provides high hardness and wear resistance and a low friction coefficient.

T1

Chemical Composition. **AISI:** Nominal. 0.75 C (other carbon contents may be available), 4.00 Cr, 1.00 V, 18.00 W. **AISI/UNS (T12001):** Composition: 0.45 to 0.55 C, 0.15 to 0.40 Mn, 0.30 Ni max, 3.75 to 4.50 Cr, 4.50 to 5.50 Mo, 0.75 to 1.25 V, 5.50 to 6.75 W

Similar Steels (U.S. and/or Foreign). AMS 5626; ASTM A600; FED QQ-T-590; SAE J437, J438; (Ger.) DIN 1.3355; (Fr.) AFNOR Z 80 WCV 18-04-01, 3548 Z 65 WDCV 6.05; (Ital.) UNI X 75 W 18 KU; (Jap.) JIS SKH 2; (U.K.) B.S. BT1

Characteristics. Has been the standard 18-4-1 high-speed steel over the years. Available with several carbon content levels and has the advantage of high resistance to decarburization. Rates very high in wear resistance and in softening resistance at elevated temperature. Is similar to other high-speed steels in that it has low toughness when rated with tool steels in general. Using lower austenitizing temperatures, however, results in lower hardness and improved impact resistance

Forging. Start forging at 1065 to 1175 °C (1950 to 2150 °F). Do not forge after temperature of forging stock drops below 955 °C (1750 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Pack annealing in tightly closed containers or using a controlled atmosphere or vacuum is recommended to minimize decarburization. The packing material can be dry sand or lime to which a small amount of charcoal has been added. Burned cast iron chips are also satisfactory. Use a container that is only slightly larger than the load to minimize the amount of packing material required. This allows the pack to heat rapidly. After the steel has reached the annealing temperature, it should be held at temperature for 1 h per inch of thickness of the container. Cool slowly in furnace to 650 °C (1200 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 217 to 255 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

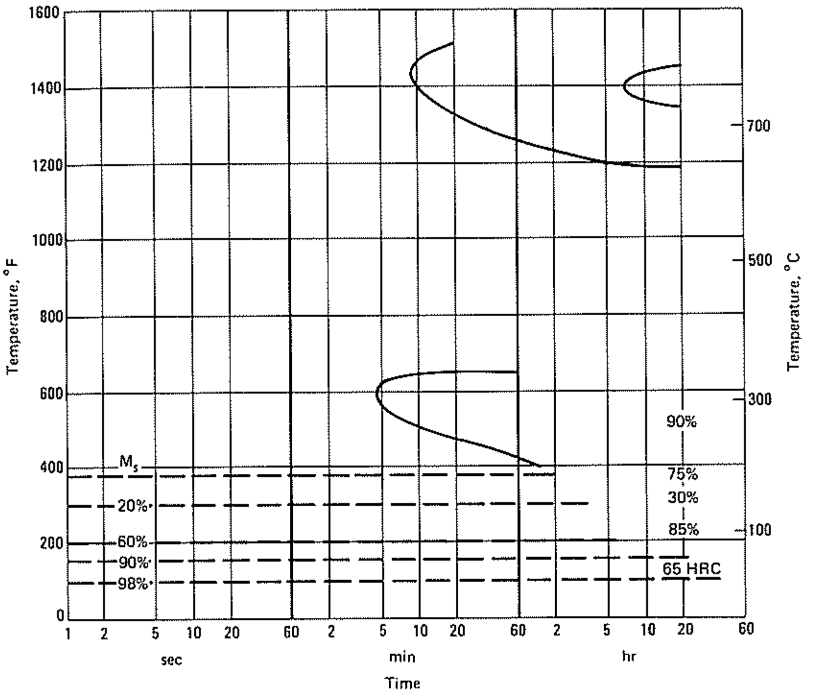
Hardening. Preheat at 815 to 870 °C (1500 to 1600 °F). Double preheating in one furnace at 540 to 650 °C (1000 to 1200 °F) and in another at 845 to 870 °C (1555 to 1600 °F) will minimize thermal shock. Preheating time, after all sections of the tool have reached equal temperature, should be twice the length of time required at the austenitizing temperature. Heat rapidly from preheating to austenitizing temperature. Heat rapidly from preheating to austenitizing temperature. Austenitize at 1260 to 1300 °C (2300 to 2375 °F) for 2 to 5 min. Use 14 °C (25 °F) lower when hardening from salt. When high carbon material is involved, lower the austenitizing temperature 14 °C (25 °F) in addition to the reduction when hardening from salt bath. Use shorter time for small sections and longer time for large sections. Quench in oil, air, or salt. As-quenched hardness, 64 to 66 HRC

Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at −100 to −195 °C (−150 to −320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 540 to 595 °C (1000 to 1105 °F) for at least 2 h, cool to room temperature, and retemper for two more hours. Approximate tempered hardness as it corresponds to tempering temperature, 65 to 60 HRC

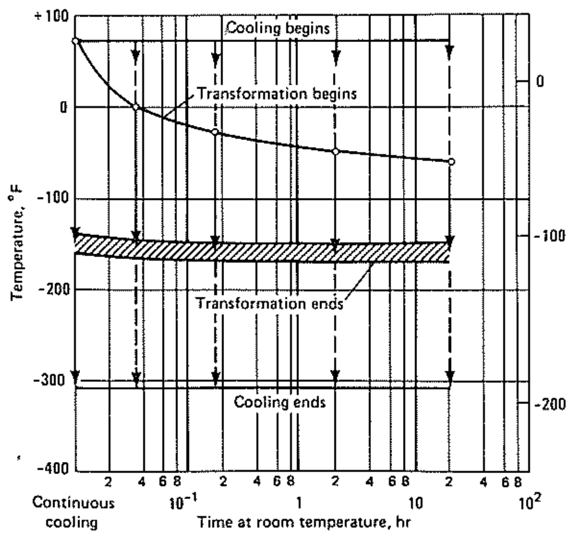
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size

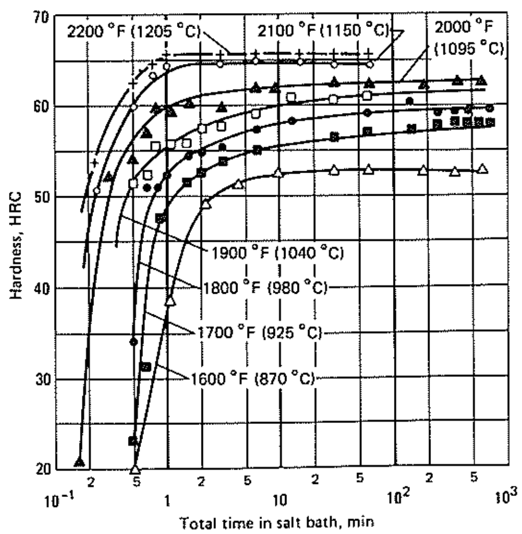


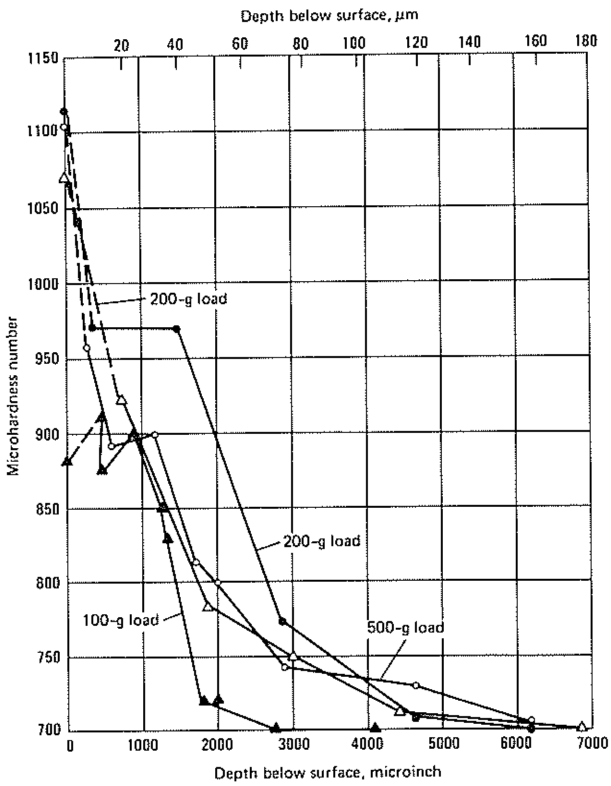
T1: Isothermal Transformation Diagram. T1 containing 0.72 C, 0.27 Mn, 0.39 Si, 4.09 Cr, 1.25 V, 18.59 W. Austenitized at 1290 °C (2355 °F)

T1: Transformation of Retained Austenite. Effect of room-temperature aging on the transformation range of retained austenite in hardened T1 during cooling to −190 °C (−310 °F)



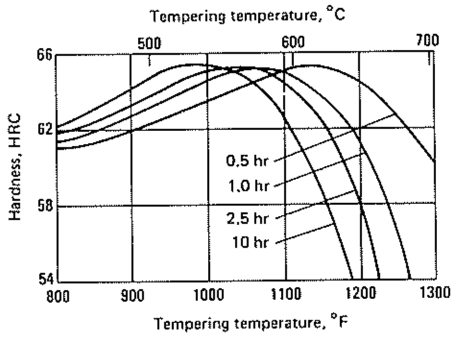
T1: Hardness vs Austenitizing Time and Temperature. Sample was 9.525 mm (⅜ in.) round by 9.525 mm (⅜ in.), brine quenched, and austenitized in a salt bath. Source: Teledyne VASCO



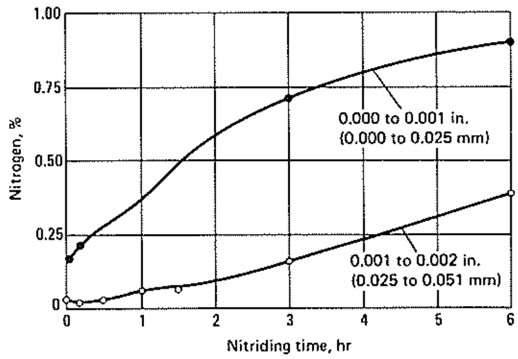


T1: Nitrided Microhardness Gradients. O: nitrided in aged bath 90 min, ●: nitrided in aged bath 180 min, Δ: nitrided in aged bath 360 min, ▲: nitrided in new bath 90 min. Specimens nitrided at 565 °C (1050 °F). Dotted lines are projected to surface hardness of other samples given same time in bath. Δ has surface sample nitrided 300 min

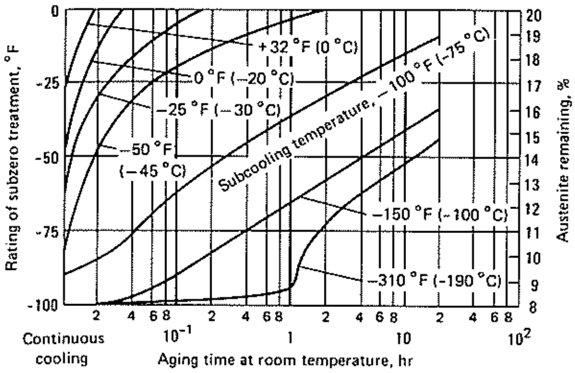
T1: Hardness vs Time and Tempering Temperature. Austenitized at 1290 °C (2355 °F) and tempered at the temperatures indicated



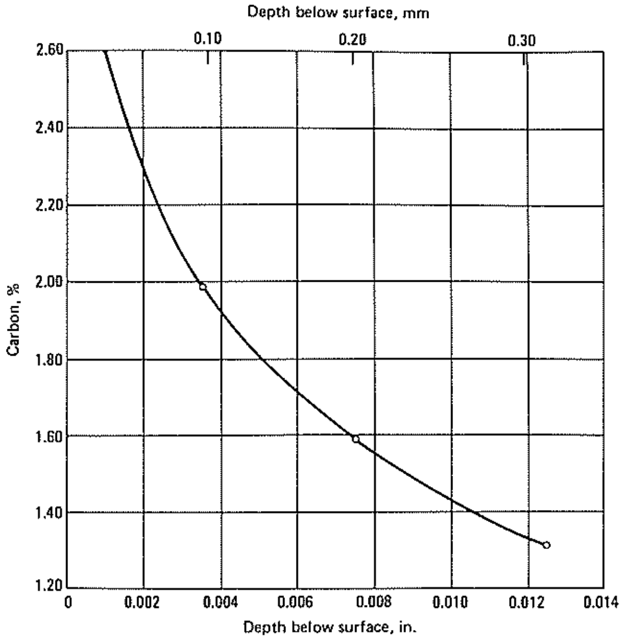
T1: Nitriding Time vs Nitrogen Content. Nitrided at 565 °C (1050 °F)



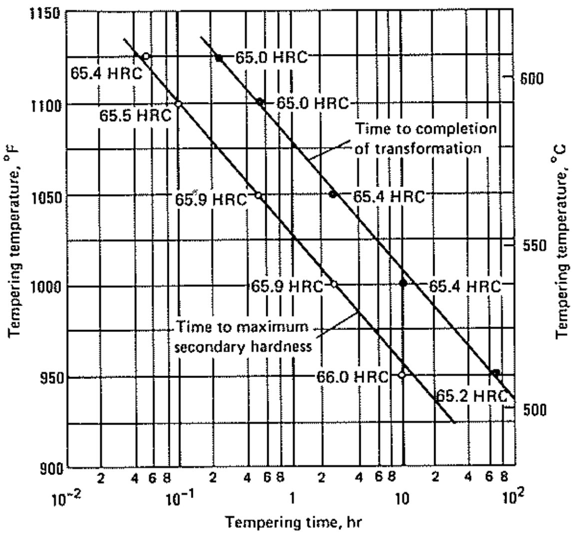
T1: Retained Austenite Transformation vs Subcooling Temperatures. Effect of room-temperature aging stabilization on the transformation of retained austenite on hardened T1 when subcooled to different temperatures. Note that the longer the holding time at room temperature, the less austenite decomposition is accomplished by a given cold treatment. Austenitized at 1290 °C (2355 °F)



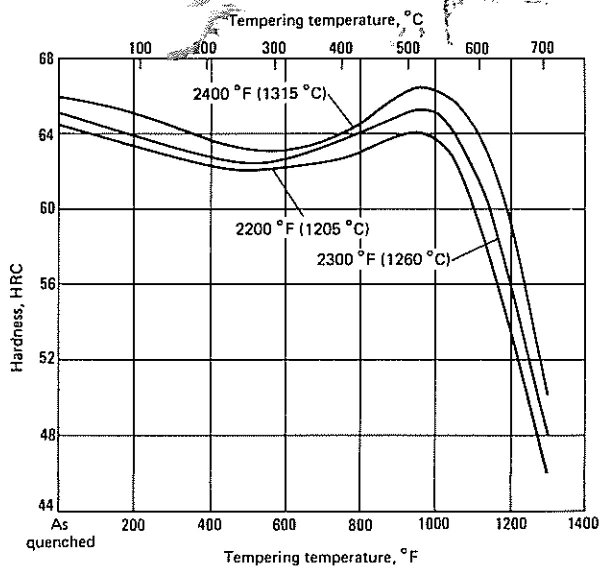
T1: Carbon Penetration in Carburizing. Carburized at 925 °C (1695 °F) for 8 h



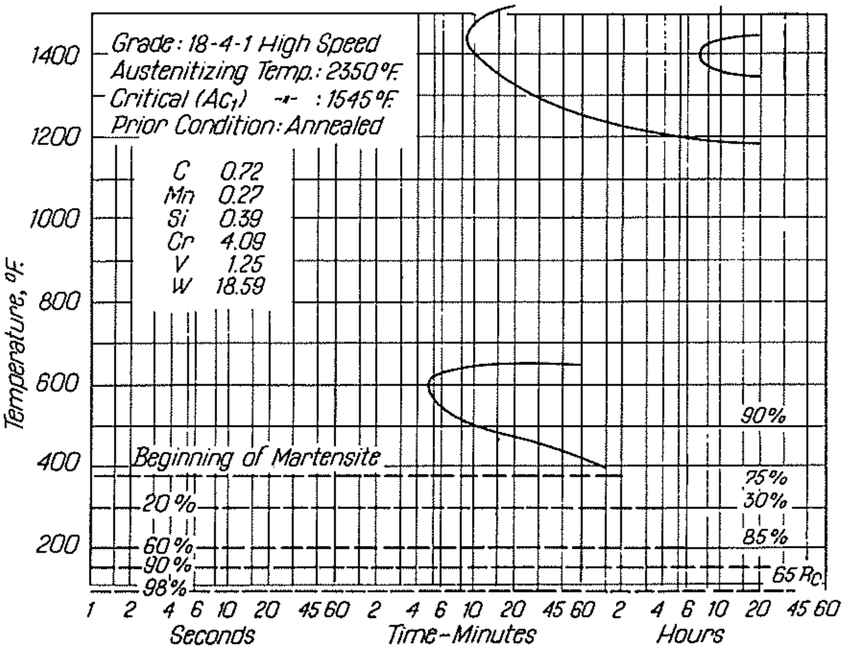
T1: Hardness vs Time and Tempering Temperature. Oil quenched from 1290 °C (2355 °F). Time and tempering temperature needed to produce maximum secondary hardness and complete transformation of austenite. Specimen size, 12.7 by 12.7 by 15.875 mm (0.50 by 0.50 by 0.625 in.)



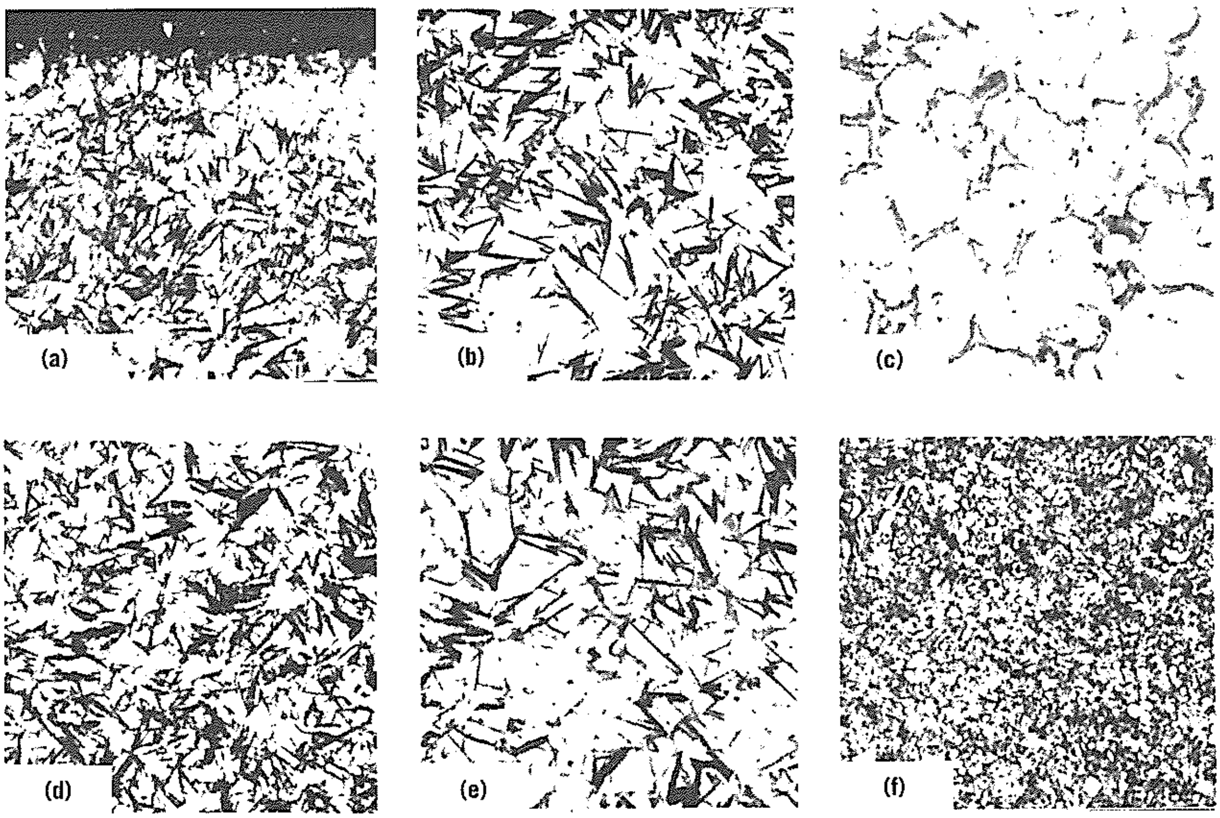
T1: Hardness vs Tempering Temperature. T1 containing 0.70 C and quenched from 1205 °C (2200 °F), 1260 °C (2300 °F), and 1315 °C (2400 °F). Tempering time, 2 ½ h. Specimen size, 44.45 by 25.4 by 19.05 mm (1.75 by 1 by 0.75 in.). Source: Vanadium-Alloys Steel



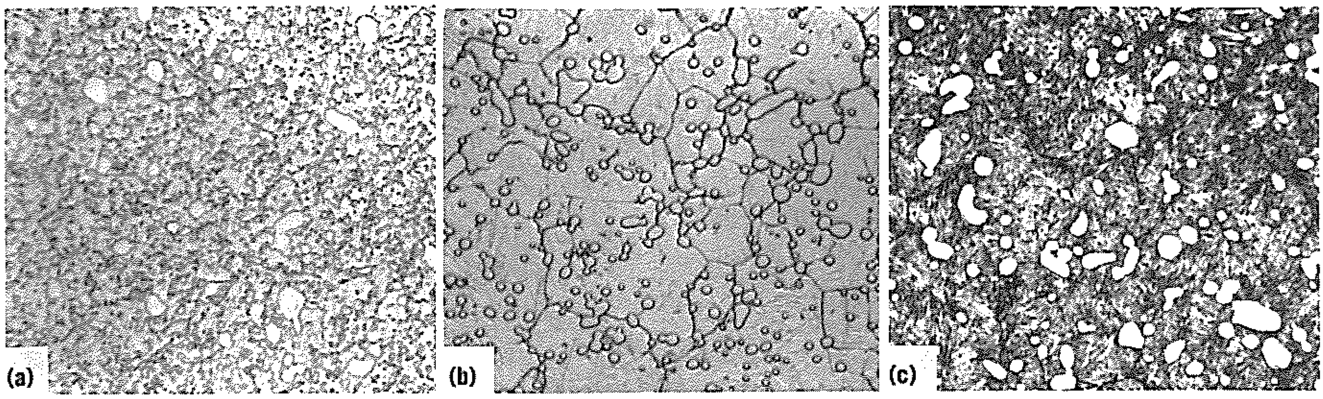
T1: Isothermal Transformation Diagram



T1: Carburized Microstructures. T1 microstructure across the carburized zone. Carburized 8 h at 955 °C (1750 °F), oil quenched from 1205 °C (2200 °F), and tempered 2 ½ h at 565 °C (1050 °F). (a) 0.00 mm (0.00 in.). (b) 0.914 mm (0.036 in.). (c) 0.305 mm (0.012 in.). (d) 1.168 mm (0.046 in.). (e) 0.559 mm (0.022 in.). (f) 1.829 mm (0.072 in.). Source: Teledyne VASCO



T1: Microstructures. (a) 2% nital, 1000×. As received (mill annealed). Large and small spheroidal carbide particles in matrix of ferrite. See (b) and (c). (b) 10% nital, 1000×. Austenitized 3 to 4 min at 1280 °C (2335 °F), salt quenched to 605 °C (1125 °F), air cooled. Undissolved carbide particles in untempered martensite. See (c). (c) 4% nital, 1000×. Austenitized and salt quenched same as (b), then double tempered at 540 °C (1000 °F). Undissolved carbide particles in matrix of tempered martensite



T2

Chemical Composition. **AISI:** Nominal. 0.80 C, 4.00 Cr, 2.00 V, 18.00 W. **AISI/UNS (T12002):** Composition: 0.80 to 0.90 C, 0.20 to 0.40 Mn, 0.20 to 0.40 Si, 0.030 Ni max, 3.75 to 4.50 Cr, 1.00 Mo max, 1.80 to 2.40 V, 17.50 to 19.00 W

Similar Steels (U.S. and/or Foreign). ASTM A600; FED QQ-T-590; SAE J437, J438; (Fr.) AFNOR A35-590 4201 CV 18-04-01, 4203 18-0-2; (U.K.) B.S. 4659 BT1, 4659 BT2, 4659 BT20

Characteristics. This 18-4-2 grade has slightly better wear resistance and hot hardness than the T1 grade and rates very high in both categories. It is suitable for chip removal and many other applications. Is similar to other high-speed steels, having low toughness when rated against other tool steels in general. Using a lower austenitizing temperature, however, results in lower hardness and improved impact resistance. Has medium machinability

Forging. Start forging at 1065 to 1175 °C (1950 to 2150 °F). Do not forge after temperature of forging stock drops below 955 °C (1750 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Pack annealing in tightly closed containers or using a controlled atmosphere or vacuum is recommended to minimize decarburization. The packing material can be dry sand or lime to which a small amount of charcoal has been added. Burned cast iron chips are also satisfactory. Use a container that is only slightly larger than the load to minimize the amount of packing material required. This allows the pack to heat rapidly. After the steel has reached the annealing temperature, it should be held at temperature for 1 h per inch of thickness of the container. Cool slowly in furnace to 650 °C (1200 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 223 to 255 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

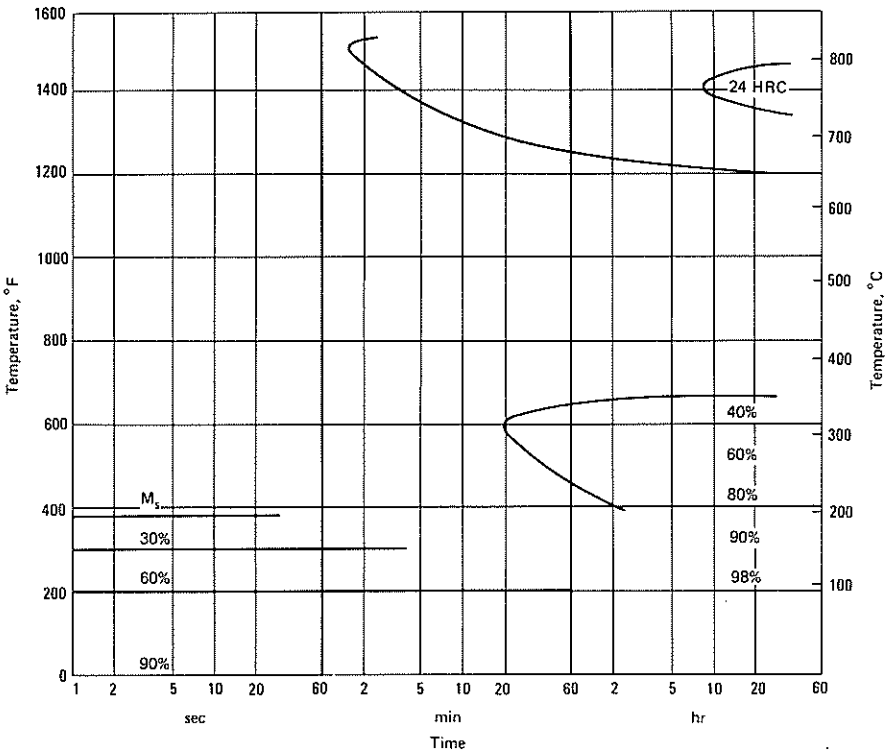
Hardening. Preheat at 815 to 870 °C (1500 to 1600 °F). Double preheating in one furnace at 540 to 650 °C (1000 to 1200 °F) and in another at 845 to 870 °C (1555 to 1600 °F) will minimize thermal shock. Preheating time, after all sections of the tool have reached equal temperature, should be twice the length of time required at the austenitizing temperature. Heat rapidly from the preheating to the austenitizing temperature. Austenitize at 1260 to 1300 °C (2300 to 2375 °F) for 2 to 5 min. Use 14 °C (25 °F) lower when hardening from salt. Use shorter time for small sections and longer time for large sections. Tools austenitized at the lower end of the temperature range will have greater toughness, when compared to tools austenitized at the upper end of the range where greater alloy solution serves to impart higher hardness and hot hardness in service. Quench in oil, air, or salt. As-quenched hardness, 65 to 67 HRC

Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at −100 to −195 °C (−150 to −320 °F). Temper immediately after part reaches room temperature

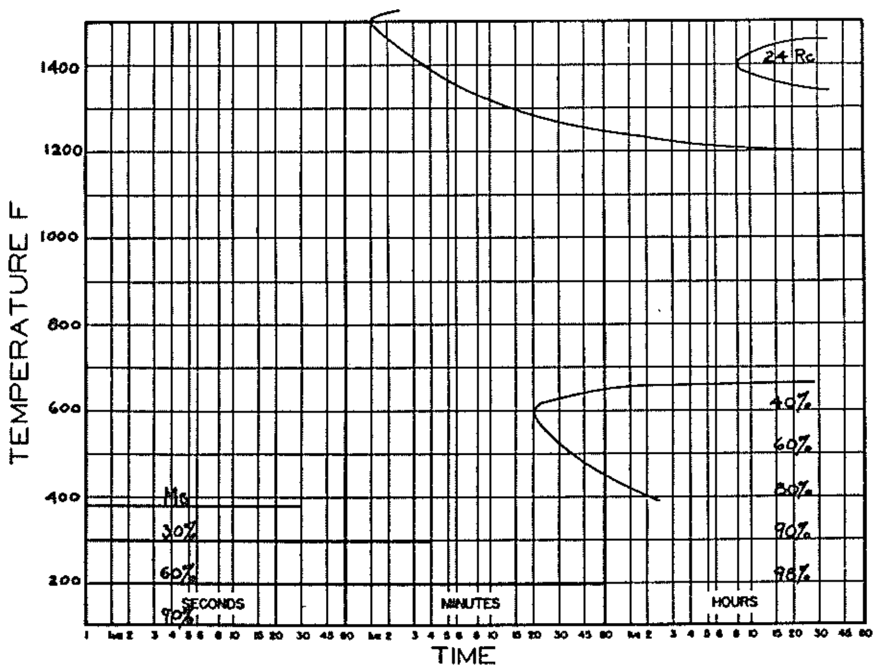
Tempering. Temper at 540 to 595 °C (1000 to 1105 °F) for at least 2 h, cool to room temperature, and retemper for two more hours. Approximate tempered hardness as it corresponds to tempering temperature, 66 to 61 HRC

Recommended Processing Sequence

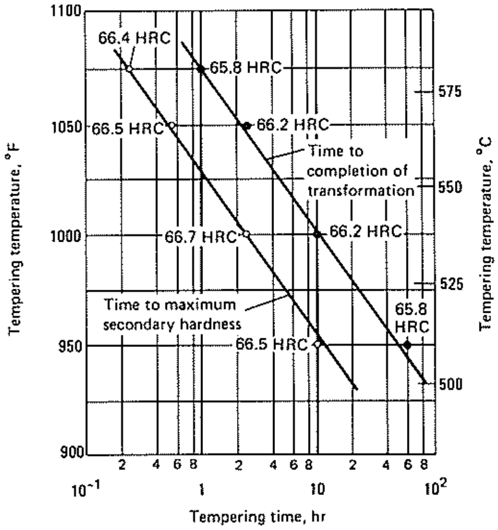
- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size



T2: Isothermal Transformation Diagram. Containing 0.85 C, 4.00 Cr, 0.75 Mo, 2.10 V, 18.50 W. Austenitized at 1290 °C (2355 °F). Source: Crucible Steel



T2: Isothermal Transformation Diagram. Composition: 0.85 C, 4.00 Cr, 0.75 Mo, 2.10 V, 18.50 W. Austenitized at 1285 °C (2350 °F)



T2: Hardness vs Time and Tempering Temperature. Relationship between time and tempering temperature required to produce maximum secondary hardness and complete the transformation of austenite. T2 containing 4 Cr, 2 V, 18 W was oil quenched from 1290 °C (2355 °F). Source: Teledyne VASCO

T4

Chemical Composition. **AISI:** Nominal. 0.75 C, 4.00 Cr, 1.00 V, 18.00 W, 5.00 Co. **AISI/UNS (T12004):** Composition: 0.70 to 0.80 C, 0.10 to 0.40 Mn, 0.20 to 0.40 Si, 0.30 Ni max, 3.75 to 4.50 Cr, 0.40 to 1.00 Mo, 0.80 to 1.20 V, 17.50 to 19.00 W, 4.25 to 5.75 Co

Similar Steels (U.S. and/or Foreign). ASTM A600; FED QQ-T-590; SAE J437, J438; (Ger.) DIN 1.3255; (Fr.) AFNOR A35-590 4271 Z 80 WKC 18-05-04-0.1, A35-590 4275 Z 80 WKCV 18-10-04-02; (Ital.) UNI X 78 WCo 1805 KU; (Jap.) JIS G4403 SKH 3; (U.K.) B.S. 4659 BT4

Characteristics. Essentially a T1 grade with 5% cobalt added. Joins the other cobalt-bearing high-speed grades in having the highest rating among tool steels in resistance to softening at elevated temperature. Is particularly suited for heavy cutting difficult-machining alloys. Similar to other high-speed steels in having relatively low toughness when compared to tool steels in general. Use of lower austenitizing temperature, however, results in lower hardness and improved impact resistance. Has very high wear resistance, medium machinability, and medium decarburization resistance

Forging. Start forging at 1065 to 1175 °C (1950 to 2150 °F). Do not forge after temperature of forging stock drops below 955 °C (1750 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Pack annealing in tightly closed containers or using a controlled atmosphere or vacuum is recommended to minimize decarburization. The packing material can be dry sand or lime to which a small amount of charcoal has been added. Burned cast iron chips are also satisfactory. Use a container that is only slightly larger than the load to minimize the amount of packing material required. This allows the pack to heat rapidly. After the steel has reached the annealing temperature, it should be held at temperature for 1 h per inch of thickness of the container. Cool slowly in furnace to 650 °C (1200 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 229 to 269 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

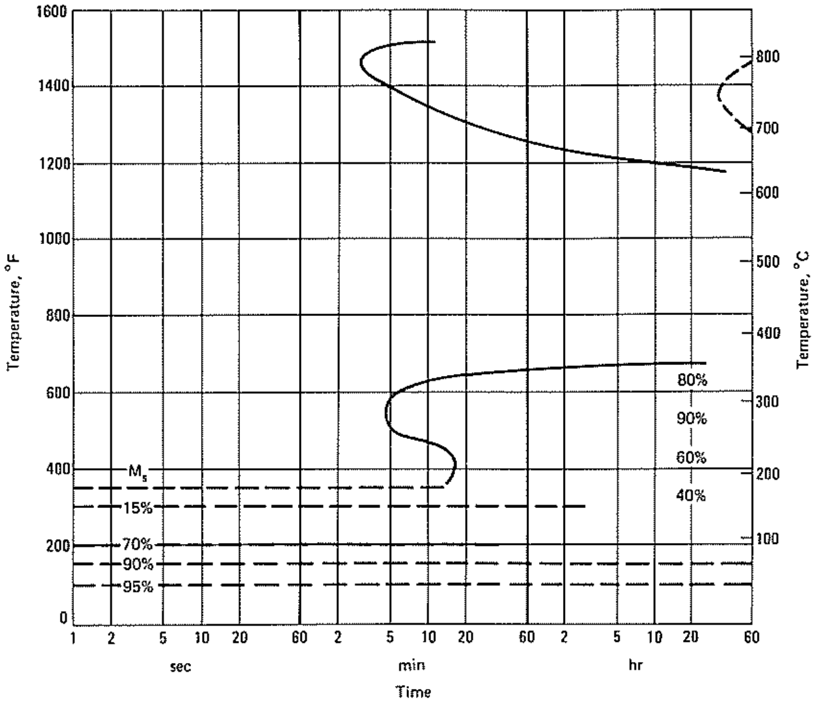
Hardening. Preheat at 815 to 870 °C (1500 to 1600 °F). Double preheating in one furnace at 540 to 650 °C (1000 to 1200 °F) and in another at 845 to 870 °C (1555 to 1600 °F) will minimize thermal shock. Preheating time, after all sections of the tool have reached equal temperature, should be twice the length of time required at the austenitizing temperature. Heat rapidly from the preheating to the austenitizing temperature. Austenitize at 1260 to 1300 °C (2300 to 2375 °F) for 2 to 5 min. Use 14 °C (25 °F) lower when hardening from salt. Use shorter time for small sections and longer time for large sections. Tools austenitized at the lower end of the temperature range will have greater toughness, when compared to tools austenitized at the upper end of the range where greater alloy solution serves to impart higher hardness and hot hardness in service. Quench in oil, air, or salt. As-quenched hardness, 63 to 66 HRC

Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at −100 to −195 °C (−150 to −320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 540 to 595 °C (1000 to 1105 °F) for at least 2 h, cool slowly in furnace to room temperature to prevent the freshly transformed martensite from causing cracking of intricate tools. Retemper for two more hours. Furnace cooling not necessary; tools can cool in air. A third temper is beneficial. Approximate tempered hardness as it corresponds to tempering temperature, 66 to 62 HRC

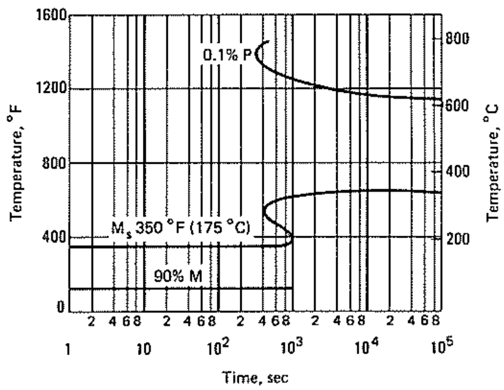
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size

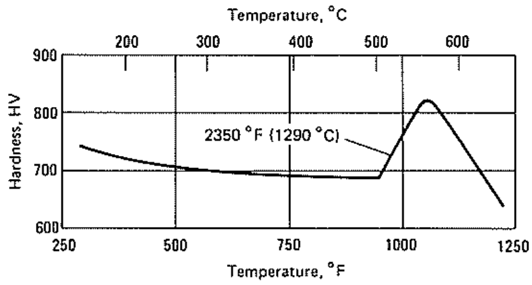


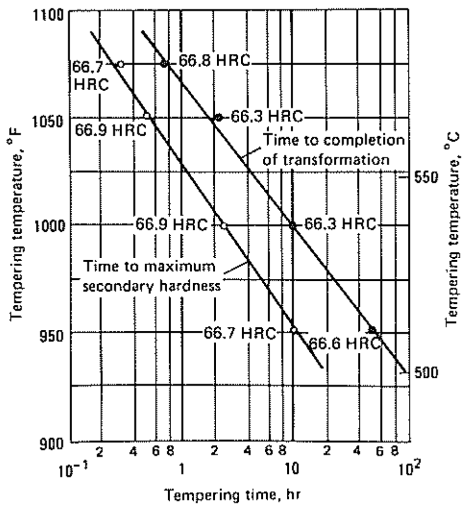
T4: Isothermal Transformation Diagram. T4 containing 0.72 C, 0.23 Mn, 0.43 Si, 4.04 Cr, 1.24 V, 18.38 W, 4.72 Co. Austenitized at 1290 °C (2355 °F)

T4: Isothermal Transformation Diagram. A British grade of T4, austenitized at 1290 °C (2355 °F)

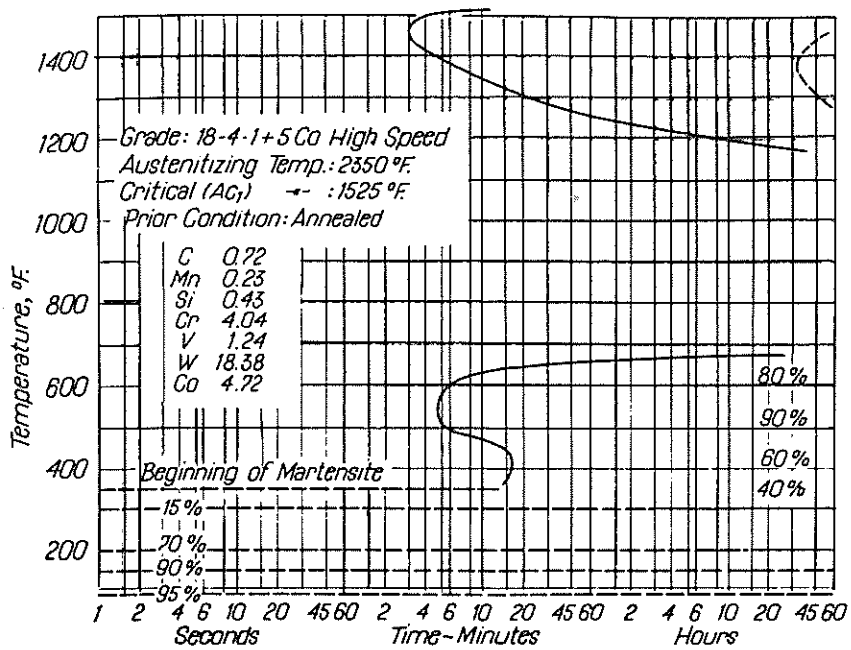


T4: Hardness vs Tempering Temperature. Austenitized at 1290 °C (2355 °F)



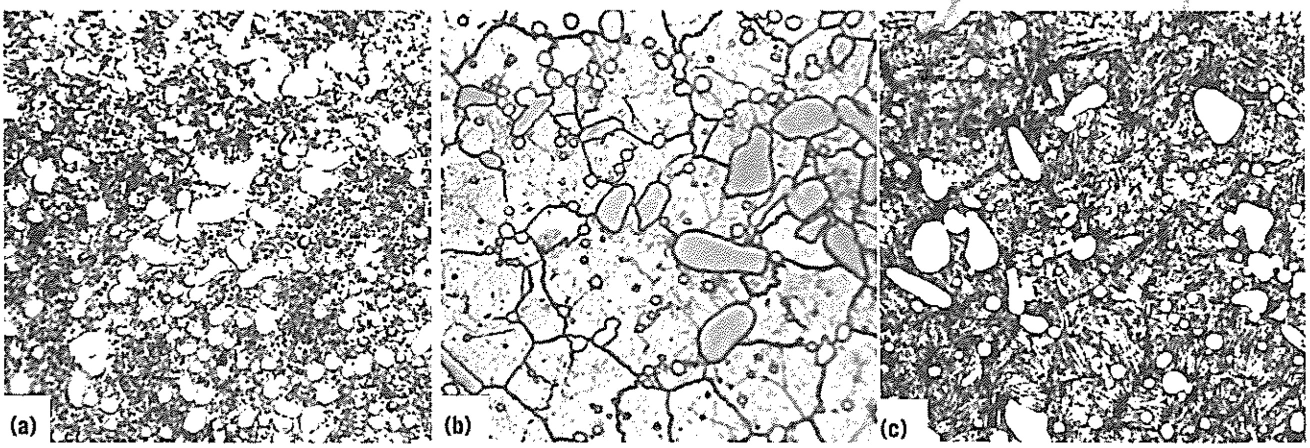


T4: Hardness vs Time and Tempering Temperature. Relationship between the tempering time and tempering temperature required to produce maximum secondary hardness and complete the transformation of retained austenite. Containing 4.00 Cr, 1.00 V, 18.00 W, 5.00 Co and oil quenched from 1295 °C (2360 °F). Specimen size, 12.7 by 12.7 by 15.875 mm (0.50 by 0.50 by 0.625 in.)



T4: Isothermal Transformation Diagram

T4: Microstructures. (a) 2% nital, 1000×. As received (mill annealed). Large and small particles of carbide (white and gray pools) in a matrix of ferrite. See (b) and (c). (b) 10% nital, 1000×. Austenitized at 1290 °C (2355 °F) for 3 to 4 min, quenched in salt to 605 °C (1125 °F), and air cooled. Undissolved carbide particles (large and small pools) in a matrix of untempered martensite. See (c). (c) 4% nital, 1000×. Austenitized and salt quenched as for (b), then double tempered at 540 °C (1000 °F). Undissolved particles of carbide (white) in a matrix of tempered martensite



T5

Chemical Composition. **AISI:** Nominal. 0.80 C, 4.00 Cr, 2.00 V, 18.00 W, 8.00 Co. **AISI/UNS (T12005):** Composition: 0.75 to 0.85 C, 0.20 to 0.40 Mn, 0.20 to 0.40 Si, 0.30 Ni max, 3.75 to 5.00 Cr, 0.50 to 1.25 Mo, 1.80 to 2.40 V, 17.50 to 19.00 W, 7.00 to 9.50 Co

Similar Steels (U.S. and/or Foreign). ASTM A600; FED QQ-T-590; SAE J437, J438; (Ger.) DIN 1.3265; (Fr.) AFNOR A35-590 4275 Z 80 WKCV 18-10-04-02; (Ital.) UNI X 80 WCo 1810 KU; (Jap.) JIS G4403 SKH 4; (Swed.) SS (USA T5); (U.K.) B.S. 4659 BT5

Characteristics. An 18-4-2 grade with an 8% cobalt addition that imparts extreme resistance to softening at elevated temperatures. Rates among the highest in softening resistance and, in common with other cobalt-bearing high-speed grades, is very suitable for heavy chip removal and difficult machining tasks. Has very high wear resistance, low to medium machinability, and low decarburization resistance

Forging. Start forging at 1065 to 1175 °C (1950 to 2150 °F). Do not forge after temperature of forging stock drops below 980 °C (1795 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Pack annealing in tightly closed containers or using a controlled atmosphere or vacuum is recommended to minimize decarburization. The packing material can be dry sand or lime to which a small amount of charcoal has been added. Burned cast iron chips are also satisfactory. Use a container that is only slightly larger than the load to minimize the amount of packing material required. This allows the pack to heat rapidly. After the steel has reached the annealing temperature, it should be held at temperature for 1 h per inch of thickness of the container. Cool slowly in furnace to 650 °C (1200 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 235 to 285 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Preheat at 815 to 870 °C (1500 to 1600 °F). Double preheating in one furnace at 540 to 650 °C (1000 to 1200 °F) and in another at 845 to 870 °C (1555 to 1600 °F) will minimize thermal shock. Preheating time, after all sections of the tool have reached equal temperature, should be twice the length of time required at the austenitizing temperature. Heat rapidly from the preheating to the austenitizing temperature. Austenitize at 1275 to 1300 °C (2325 to 2375 °F) for 2 to 5 min. Use 14 °C (25 °F) lower when hardening from salt. Use shorter time for small sections and longer time for large sections. Tools austenitized at the lower end of the temperature range will have greater toughness, when compared to tools austenitized at the upper end of the range where greater alloy solution serves to impart higher hardness and hot hardness in service. Quench in oil, air, or salt. As-quenched hardness, 64 to 66 HRC

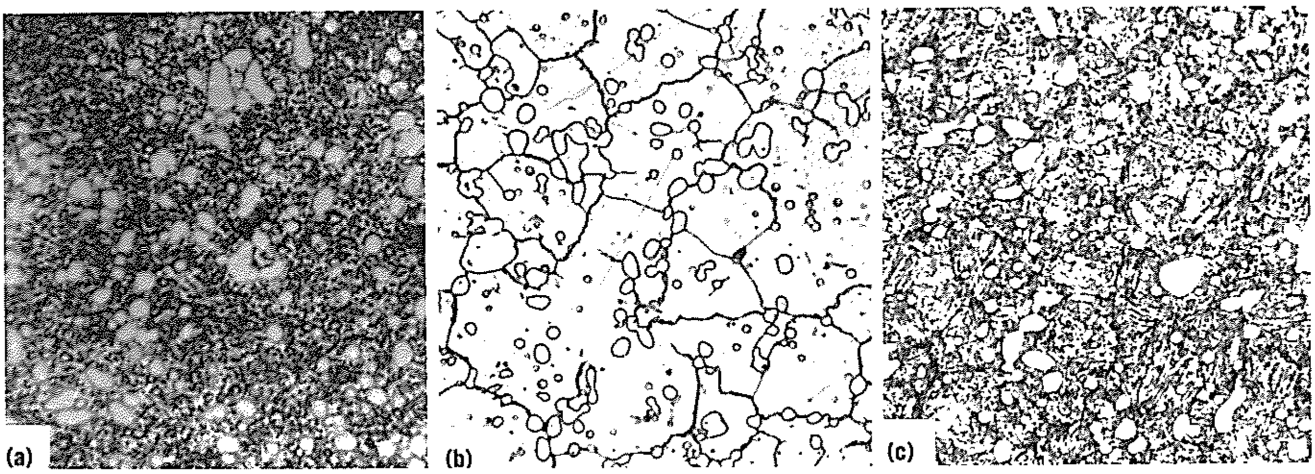
Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at −100 to −195 °C (−150 to −320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 540 to 595 °C (1000 to 1105 °F) for at least 2 h, cool slowly in furnace to room temperature to prevent the freshly transformed martensite from causing cracking of intricate tools. Retemper for two more hours. Furnace cooling not necessary; tools can be cooled in air. Approximate tempered hardness as it corresponds to tempering temperature, 65 to 60 HRC

Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size

T5: Microstructures. (a) 2% nital, 1000x. As received (mill annealed). Large and small spheroidal particles of carbide in a matrix of ferrite. Compare with structures in (b) and (c). (b) 10% nital, 1000x. Austenitized 3 to 4 min at 1280 °C (2335 °F), salt quenched to 605 °C (1125 °F), air cooled. Undissolved carbide particles (large and small pools) in a matrix of untempered martensite. See (c). (c)4% nital, 1000x. Austenitized and salt quenched same as (b), then double tempered at 540 °C (1000 °F). Undissolved particles in a matrix of tempered martensite



T6

Chemical Composition. AISI: Nominal. 0.80 C, 4.50 Cr, 1.50 V, 20.00 W, 12.00 Co. **AISI/UNS (T12005):** Composition: 0.75 to 0.85 C, 0.20 to 0.40 Mn, 0.20 to 0.40 Si, 0.30 Ni max, 4.00 to 4.75 Cr, 0.40 to 1.00 Mo 1.50 to 2.10 V, 18.50 to 21.00 W, 11.00 to 13.00 Co

Similar Steels (U.S. and/or Foreign). ASTM A600 (T-6); FED QQ-T-590 (T-6); (Ger.) DIN 1.3257; (Jap.) JIS G4403 SKH 4B; (U.K.) B.S. 4659 BT6

Characteristics. An ultrahigh-alloy high-speed steel, containing 20% tungsten and 12% cobalt. With other cobalt-containing high-speed steels, rated highest in resistance to softening at elevated temperature. Has very high wear resistance and is particularly suitable for heavy-feed chip removal on difficult machining materials, such as superalloys. Has a low toughness rating when compared to tool steels in general and falls below the median in toughness among high-speed steels. Use of lower austenitizing temperature reduces hardness and improves impact resistance. Has low to medium machinability and low decarburization resistance

Forging. Start forging at 1065 to 1175 °C (1950 to 2150 °F). Do not forge after temperature of forging stock drops below 980 °C (1795 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Pack annealing in tightly closed containers or using a controlled atmosphere or vacuum is recommended to minimize decarburization. The packing material can be dry sand or lime to which a small amount of charcoal has been added. Burned cast iron chips are also satisfactory. Use a container that is only slightly larger than the load to minimize the amount of packing material required. This allows the pack to heat rapidly. After the steel has reached the annealing temperature, it should be held at temperature for 1 h per inch of thickness of the container. Cool slowly in furnace to 650 °C (1200 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 248 to 302 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

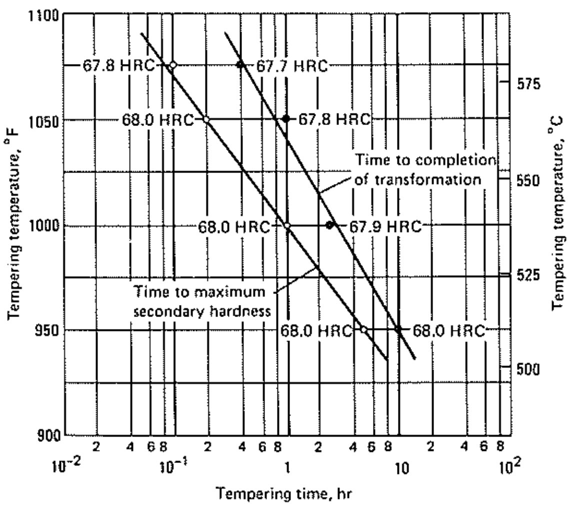
Hardening. Preheat at 815 to 870 °C (1500 to 1600 °F). Double preheating in one furnace at 540 to 650 °C (1000 to 1200 °F) and in another at 845 to 870 °C (1555 to 1600 °F) will minimize thermal shock. Preheating time, after all sections of the tool have reached equal temperature, should be twice the length of time required at the austenitizing temperature. Heat rapidly from the preheating to the austenitizing temperature. Austenitize at 1275 to 1300 °C (2325 to 2375 °F) for 2 to 5 min. Use 14 °C (25 °F) lower when hardening from salt. Use shorter time for small sections and longer time for large sections. Tools austenitized at the lower end of the temperature range will have greater toughness, when compared to tools austenitized at the upper end of the range where greater alloy solution serves to impart higher hardness and hot hardness in service. Quench in oil, air, or salt. As-quenched hardness, 64 to 66 HRC

Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to –320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 540 to 595 °C (1000 to 1105 °F) for at least 2 h, cool slowly in furnace to room temperature to prevent the freshly transformed martensite from causing cracking of intricate tools. Retemper for two more hours. Furnace cooling is not necessary; cool tools in air. A third temper is required. Approximate tempered hardness as it corresponds to tempering temperature, 65 to 60 HRC

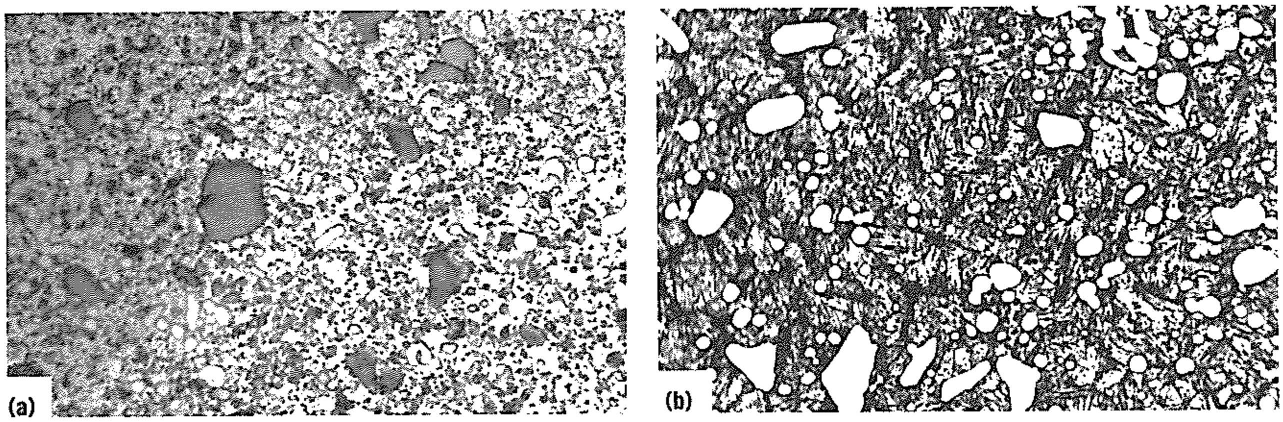
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size



T6: Hardness vs Time and Tempering Temperature. Relationship between the tempering time and the tempering temperature required to produce maximum secondary hardness and complete the transformation of retained austenite. T6 containing 4.00 Cr, 1.75 V, 20.00 W, 12.00 Co. Oil quenched from 1295 °C (2360 °F)

Γ6: **Microstructures.** (a) 2% nital, 1000×. As received (mill annealed). Particles of carbide (small white pools and large gray pools) in a ma-rix of ferrite. The quenched and tempered microstructure is shown in (b). (b) 4% nital, 1000×. Austenitized at 1290 °C (2355 °F) for 3 to 4 nin, quenched in salt to 605 °C (1125 °F), air cooled, and double tempered at 540 °C (1000 °F). Large and small particles of carbide (white) n a matrix of tempered martensite



Γ8

hemical Composition. **AISI:** Nominal. 0.75 C, 4.00 Cr, 2.00 V, 4.00 W, 5.00 Co. **AISI/UNS (T12008):** Composition: 0.75 to 0.85 C, 0.20 0.40 Mn, 0.20 to 0.40 Si, 0.30 Ni max, 3.75 to 4.50 Cr, 0.40 to 1.00 Mo, 80 to 2.40 V, 13.25 to 14.75 W, 4.25 to 5.75 Co

imilar Steels (U.S. and/or Foreign). ASTM A600; FED QQ-T-90; SAE J437, J438

haracteristics. Tungsten is the principal alloying element; 5% cobalt added for hot hardness. Along with the other cobalt-bearing high-speed eels, rates highest among tool steels in resistance to softening at elevated mperature. Has very high wear resistance and is suitable for heavy chip moval on difficult machining alloys. Rates low in toughness, as do other igh-speed steels. Use of lower austenitizing temperatures results in lower ardness and improved impact resistance. Has medium machinability and iedium decarburization resistance

orging. Start forging at 1065 to 1175 °C (1950 to 2150 °F). Do not orge after temperature of forging stock drops below 955 °C (1750 °F)

ecommended Heat Treating Practice

lormalizing. Do not normalize

nnealing. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for mall sections and upper limit for large sections. Pack annealing in tightly losed containers or using a controlled atmosphere or vacuum is recom-iended to minimize decarburization. The packing material can be dry sand r lime to which a small amount of charcoal has been added. Burned cast on chips are also satisfactory. Use a container that is only slightly larger ian the load to minimize the amount of packing material required. This llows the pack to heat rapidly. After the steel has reached the annealing emperature, it should be held at temperature for 1 h per inch of thickness f the container. Cool slowly in furnace to 650 °C (1200 °F) at a rate not to xceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect inal hardness. Typical annealed hardness, 229 to 255 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1250 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

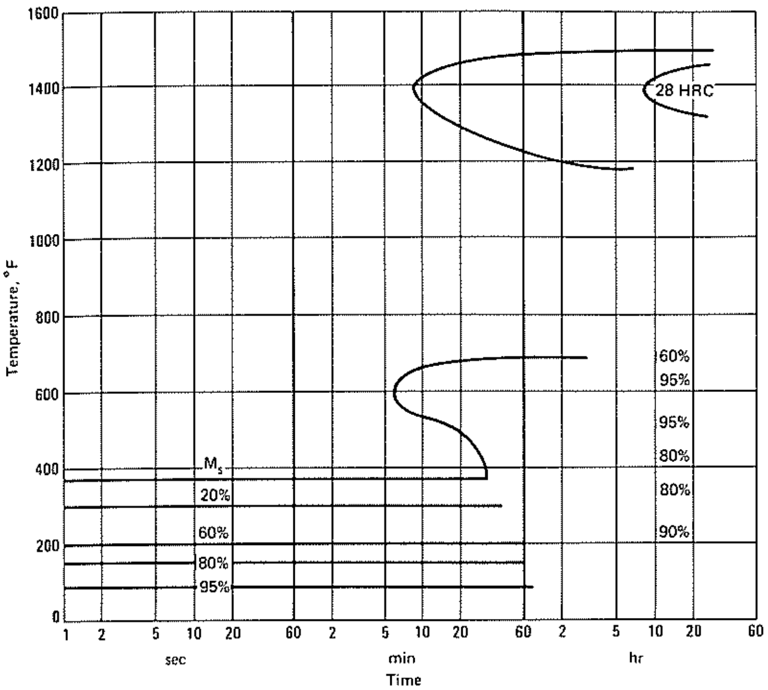
Hardening. Preheat at 815 to 870 °C (1500 to 1600 °F). Double preheating in one furnace at 540 to 650 °C (1000 to 1200 °F) and in another at 845 to 870 °C (1555 to 1600 °F) will minimize thermal shock. Preheating time, after all sections of the tool have reached equal temperature, should be twice the length of time required at the austenitizing temperature. Heat rapidly from the preheating to the austenitizing temperature. Austenitize at 1260 to 1300 °C (2300 to 2375 °F) for 2 to 5 min. Use 14 °C (25 °F) lower when hardening from salt. Use shorter time for small sections and longer time for large sections. Tools austenitized at the lower end of the temperature range will have greater toughness, when compared to tools austenitized at the upper end of the range where greater alloy solution serves to impart higher hardness and hot hardness in service. Quench in oil, air, or salt. As-quenched hardness, 64 to 66 HRC

Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at −100 to −195 °C (−150 to −320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 540 to 595 °C (1000 to 1105 °F) for at least 2 h, cool slowly in furnace to room temperature to prevent the freshly transformed martensite from causing cracking of intricate tools. Retemper for two more hours. Furnace cooling is not necessary; cool tools in air. Approximate hardness, 65 to 60 HRC

Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size



T8: Isothermal Transformation Diagram. T8 containing 0.80 C, 4.00 Cr, 0.75 Mo, 2.00 V, 14.00 W, 5.00 Co. Austenitized at 1290 °C (2355 °F). Source: Crucible Steel

T15

Chemical Composition. **AISI:** Nominal. 1.50 C, 4.00 Cr, 5.00 V, 12.00 W, 5.00 Co. **AISI/UNS (T12015):** Composition: 1.50 to 1.60 C, 0.15 to 0.40 Mn, 0.15 to 0.40 Si, 0.30 Ni max, 3.75 to 5.00 Cr, 1.00 Mo max, 4.50 to 5.25 V, 11.75 to 13.00 W, 4.75 to 5.25 Co

Similar Steels (U.S. and/or Foreign). ASTM A600; FED QQ-T-590; (Ger.) DIN 1.3202; (Fr.) AFNOR A35-590 4171 Z 160 WKCV 12-05-05-04; (Ital.) UNI X 150 WCoV 130505 KU; (Swed.) SS (USA T15); (U.K.) B.S. 4659 BT15

Characteristics. Has both the highest carbon (1.5%) and vanadium content (5%) of the high-speed steels. Similar to grade M4, is rated highest in wear resistance among tool steels, including erosion at service temperature. Is particularly suitable for heavy chip removal on difficult-machining alloys. Toughness is low. Using low austenitizing temperatures results in lower hardness and improved impact resistance. Has low to medium machinability and medium decarburization resistance

Forging. Start forging at 1065 to 1175 °C (1950 to 2150 °F). Do not forge after temperature of forging stock drops below 980 °C (1795 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Pack annealing in tightly closed containers or using a controlled atmosphere or vacuum is recommended to minimize decarburization. The packing material can be dry sand or lime to which a small amount of charcoal has been added. Burned cast iron chips are also satisfactory. Use a container that is only slightly larger than the load to minimize the amount of packing material required. This allows the pack to heat rapidly. After the steel has reached the annealing temperature, it should be held at temperature for 1 h per inch of thickness of the container. Cool slowly in furnace to 650 °C (1200 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 241 to 277 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Preheat at 815 to 870 °C (1500 to 1600 °F). Double preheating in one furnace at 540 to 650 °C (1000 to 1200 °F) and in another at 845 to 870 °C (1555 to 1600 °F) will minimize thermal shock. Preheating time, after all sections of the tool have reached equal temperature, should be twice the length of time required at the austenitizing temperature. Heat rapidly from the preheating to the austenitizing temperature. Austenitize at 1205 to 1260 °C (2200 to 2300 °F) for 2 to 5 min. Use 14 °C (25 °F) lower when hardening from salt. Use shorter time for small sections and longer time for large sections. Tools austenitized at the lower end of the temperature range will have greater toughness, when compared to tools austenitized at the upper end of the range where greater alloy solution serves to impart higher hardness and hot hardness in service. Quench in oil, air, or salt. As-quenched hardness, 65 to 68 HRC

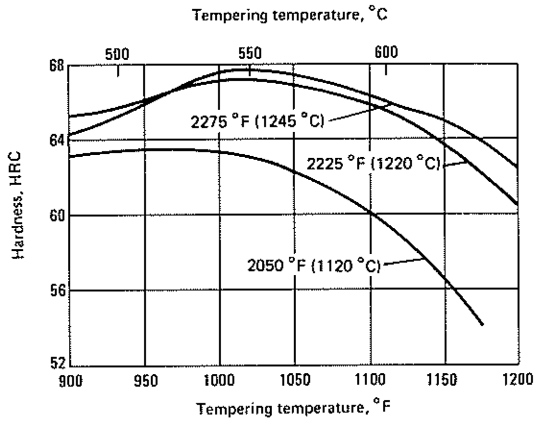
Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at −100 to −195 °C (−150 to −320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 540 to 650 °C (1000 to 1200 °F) for at least 2 h, cool slowly in furnace to room temperature to prevent the freshly formed martensite from causing cracking of intricate tools. Retemper for two more hours. Furnace cooling is not necessary; cool tools in air. A third temper is required. Approximate tempered hardness as it corresponds to tempering temperature, 68 to 63 HRC

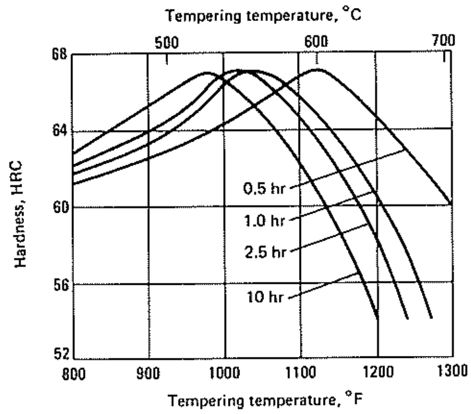
Recommended Processing Sequence

- Rough machine
- Stress relieve
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size

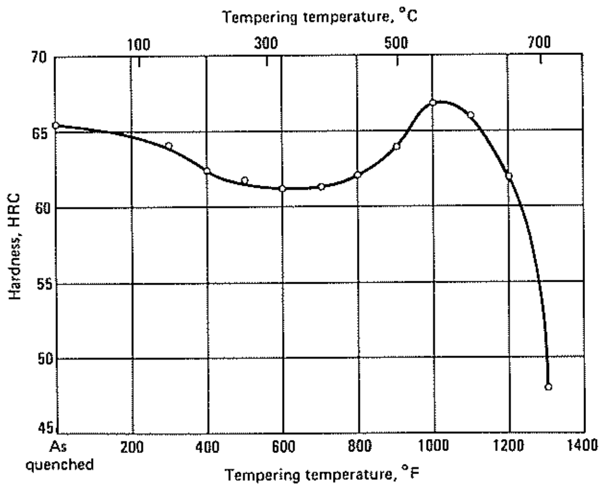
T15: Hardness vs Austenitizing and Tempering Temperature. Austenitized at 1245 °C (2275 °F), 1220 °C (2225 °F) and 1120 °C (2050 °F) and double tempered (2 h plus 2 h)



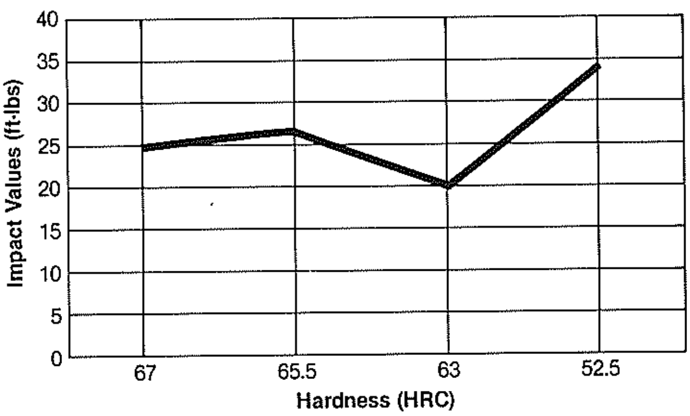
T15: Hardness vs Time and Tempering Temperature. Austenitized at 1245 °C (2275 °F) and tempered at times and temperatures indicated



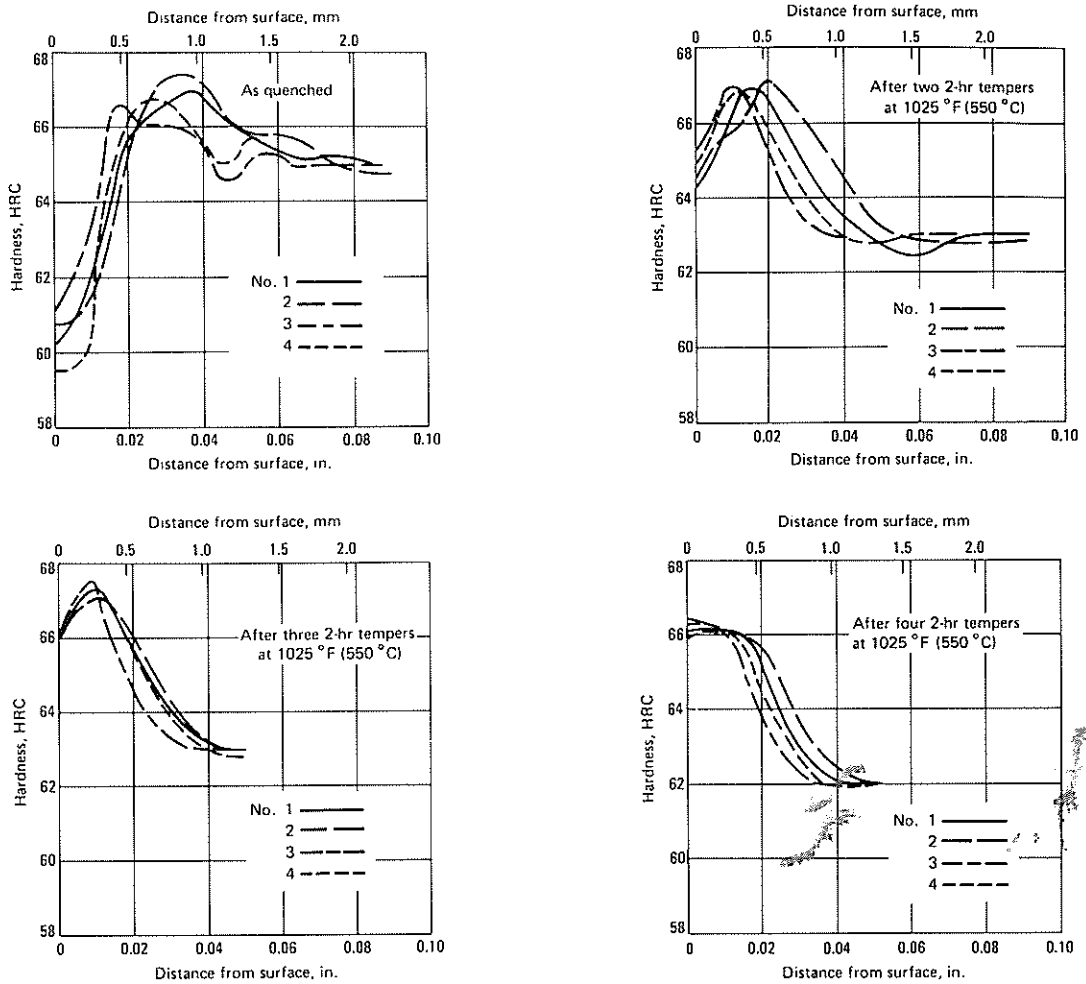
T15: Hardness vs Tempering Temperature. Austenitized at 1245 °C (2275 °F). Source: Teledyne VASCO



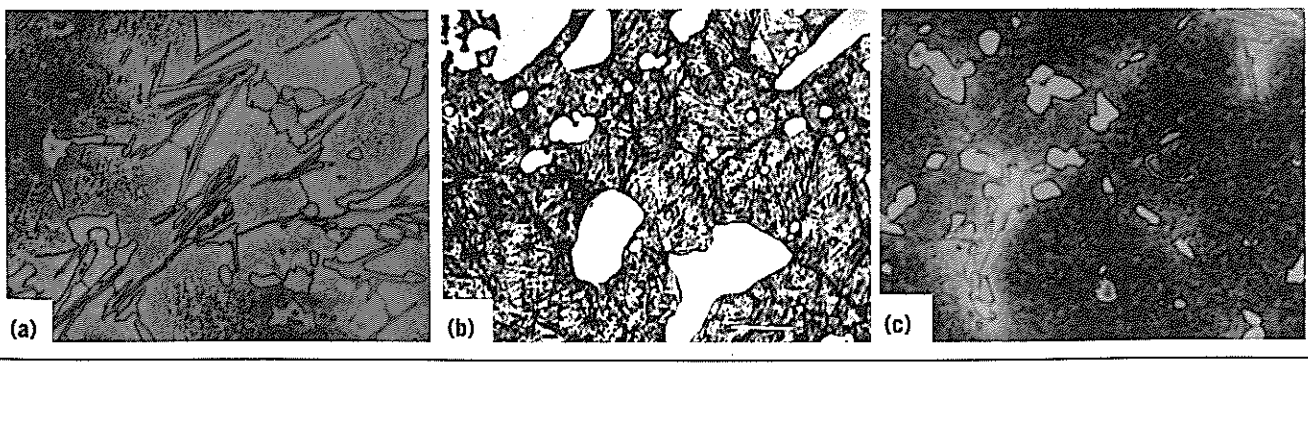
T15: Unnotched IZOD Impact Values. All specimens were austenitized at 1245 °C (2275 °F) in salt for 5 min at heat, oil quenched, triple tempered to hardness for 2 h plus 2 h plus 2 h and air cooled. Source: Carpenter Technology Corporation

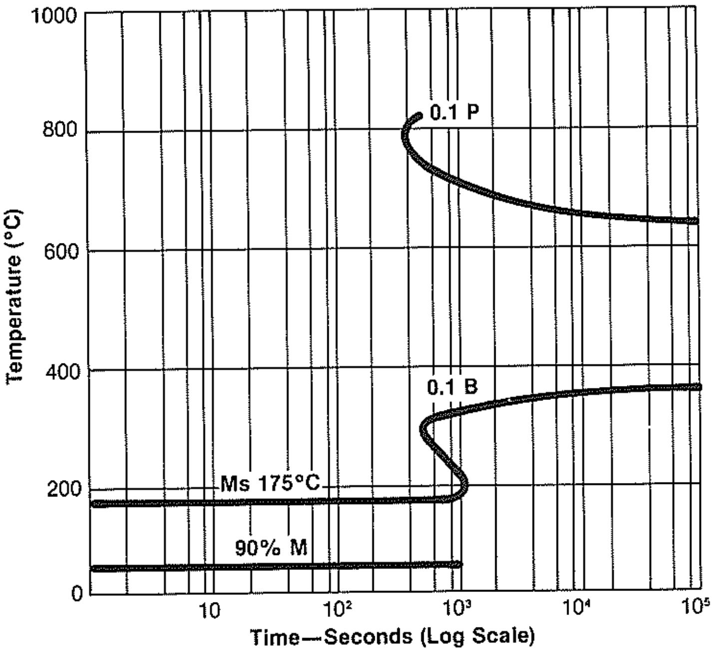


T15: Carburized Case Hardness. After four different carburizing treatments: (a) 3 h at 900 °C (1650 °F), plus 20 min at 1065 °C (1950 °F) and oil quenched; (b) 3 h at 900 °C (1650 °F), plus 40 min at 1065 °C (1950 °F) and oil quenched; (c) 30 min at 815 to 845 °C (1500 to 1555 °F), plus 20 min at 1065 °C (1950 °F) and oil quenched; (d) 30 min at 815 to 845 °C (1500 to 1555 °F), plus 40 min at 1065 °C (1950 °F) and oil quenched. Source: Teledyne VASCO



T15: Microstructures. (a) 6% nital, 500×. As cast. 76 mm (3 in.) diam disk, 13 mm (0.50 in.) thick. Dark areas are self-tempered martensite and chromium-rich $M_{23}C_6$; light areas are alloy-rich austenite-carbide eutectic. Fan-shape particles are primary M_6C; irregular globules are vanadium-rich MC. (b) 4% nital, 1000×. Austenitized at 1230 °C (2245 °F) for 3 to 4 min, quenched in salt to 605 °C (1125 °F), air cooled, and triple tempered at 540 °C (1000 °F). Undissolved particles of carbide in a matrix of tempered martensite. (c) 5% nital, 500×. Annealed at 900 °C (1650 °F), austenitized in salt at 1220 °C (2225 °F), salt quenched at 595 °C (1105 °F), triple tempered at 595 °C (1105 °F). Dark is tempered martensite, secondary M_6C. Light is remnants of austenite-carbide eutectic, primary M_6C. White globules are MC





T15: Isothermal Transformation Diagram. Specimens were austenitized at 1260 °C (2300 °F). Source: Carpenter Technology Corporation

Molybdenum High-Speed Tool Steels (M Series)

Introduction

Molybdenum high-speed tool steels are used primarily for cutting tools. Normalizing these steels is not recommended. However, the M series steels must be fully annealed after forging or when rehardening is required. The details of annealing are explained for each of the M steels on the following pages.

The M series steels, in common with the T series, are always preheated prior to austenitizing to enable equalization of expansion in various sections of the tool and to minimize stresses that might occur because of the transformation to austenite at approximately 760 °C (1400 °F). Double preheating, as described below, is often recommended to minimize thermal shock. If only a single preheat is used, preheat M6 at 790 °C (1455 °F) and M15 at 815 to 870 °C (1500 to 1600 °F). The remaining M steels should be preheated at 730 to 845 °C (1350 to 1555 °F). Preheating time, after all sections of the tool have reached equal temperature, should be twice the length of time required at the austenitizing temperature. When preheating in two stages, longer time can be utilized at the first stage, 540 to 650 °C (1000 to 1200 °F), without incurring harmful effect. Only small tools and those that do not incorporate sharp notches or abrupt changes in section may be placed directly into the austenitizing furnace with reasonable safety.

To dissolve the various complex alloy carbides in the M tool steels to any appreciable extent during austenitizing, the steels must be heated to temperatures approaching their melting point. For this reason, exceedingly accurate control is required in austenitizing these steels. Steels containing about 3% or more vanadium may be held at the austenitizing temperature about 50% longer than the lower vanadium types. The relatively pure vanadium carbide phase inherent in the microstructure is virtually insoluble at temperatures below the melting point and acts to restrict grain growth, permitting longer soaking times. However, the recommended austenitizing temperature for these steels should not be exceeded.

Single point tools intended for heavy-duty cutting can be effectively austenitized at 8 to 17 °C (15 to 30 °F) above the nominal austenitizing temperature to improve hot hardness and temper resistance. Fine-edged tools, such as taps and chasers, may be hardened at temperatures 14 to 28 °C (25 to 50 °F) *below* the nominal austenitizing temperature to impart added toughness. Other adjustments in austenitizing temperature depend on the type of heating equipment employed, as explained below.

Other variables are also noteworthy. Below 1175 °C (2150 °F), for example, M2 steel cannot develop full hardness on quenching, because of insufficient carbide solution. At temperatures above approximately 1230 °C (2245 °F), the as-quenched hardness of M2 decreases because of too much carbon and alloy solution as well as an excess of retained austenite in the as-quenched steel.

The M series steels can be quenched in air, oil, or molten salt. Stabilizing may be used to transform retained austenite. The hardened or hardened and tempered tool is cooled to at least −85 °C (−120 °F) and then tempered or retempered at normal tempering temperatures. As noted in the data below, the response to secondary hardening is also a factor in the selection of tempering temperature.

The steels may be nitrided, preferably in liquid nitriding baths, capable of producing a more ductile case with a lower nitrogen content than that normally obtained in gaseous nitriding atmospheres. Nitriding provides high hardness and wear resistance and a low friction coefficient.

M1

Chemical Composition. **AISI:** Nominal. 0.85 C (other carbon contents may be available), 4.00 Cr, 8.50 Mo, 1.00 V, 1.50 W. **AISI/UNS:** Composition: 0.78 to 0.88 C, 0.15 to 0.40 Mn, 0.20 to 0.50 Si, 0.30 Ni max, 3.50 to 4.00 Cr, 8.20 to 9.20 Mo, 1.00 to 1.35 V, 1.40 to 2.10 W

Similar Steels (U.S. and/or Foreign). ASTM A600 (M-1); FED QQ-T-590 (M-1); SAE J437 (M1), J438 (M1); (Ger.) DIN 1.3346; (Fr.) AFNOR A35-590 4441 Z 85 DCWV 08-04-02-01; (Ital.) UNI X 82 MoW 09 KU; (Swed.) SS 2715; (U.K.) B.S. 4659 BM1

Characteristics. Molybdenum is the principal alloying element in this, one of the leaner alloyed high-speed steels. It is as available as the popular M2 grade and costs less; the least expensive high-speed steel. Available in several carbon levels, and very suitable for chip forming tools. Rated very high in resistance to softening at elevated temperatures, and in resistance to wear. Low in toughness (as are other high-speed steels of comparable carbon content), and low in decarburization resistance

Forging. Start forging at 1040 to 1150 °C (1905 to 2100 °F). Do not forge after temperature of forging stock drops below 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat to 815 to 870 °C (1500 to 1600 °F). Use lower limit for small sections and upper limit for large sections. Pack annealing in tightly closed containers or using a controlled atmosphere or vacuum is required to minimize decarburization. The packing material can be dry sand or lime to which a small amount of charcoal has been added. Burned cast iron chips are also satisfactory. Use a container that is only slightly larger than the load to minimize the amount of packing material required. This allows the pack to heat rapidly. After the steel has reached the annealing temperature, it should be held at temperature for 1 h per inch of thickness of the container. Cool slowly in furnace to 650 °C (1200 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 207 to 235 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

lardening. Preheat at 730 to 815 °C (1350 to 1500 °F). Double preheat-ıg in one furnace at 540 to 650 °C (1000 to 1200 °F) and in another at 845 › 870 °C (1555 to 1600 °F) will minimize thermal shock. Preheating time, fter all sections of the tool have reached equal temperature, should be vice the length of time required at the austenitizing temperature. Heat ıpidly from the preheating to the austenitizing temperature. Austenitize at 175 to 1220 °C (2150 to 2225 °F) for 2 to 5 min. Use 14 °C (25 °F) lower /hen hardening from salt. When high carbon material is involved, lower ıe austenitizing temperature 14 °C (25 °F) in addition to the reduction /hen hardening from salt bath. Use shorter time for small sections and ɔnger time for large sections. Tools austenitized at the lower end of the ɜmperature range will have greater toughness, when compared to tools ustenitized at the upper end of the range where greater alloy solution erves to impart higher hardness and hot hardness. Quench in oil, air, or salt. ɩs-quenched hardness, 64 to 66 HRC

ʒtabilizing. Optional. For intricate shapes, stress relieve temper at 150 ɔ 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to ·320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 540 to 595 °C (1000 to 1105 °F) for at least 2 h, cool to room temperature, and retemper for 2 h. Approximate tempered hardness as it corresponds to tempering temperature, 65 to 60 HRC

Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/double
- Final grind to size

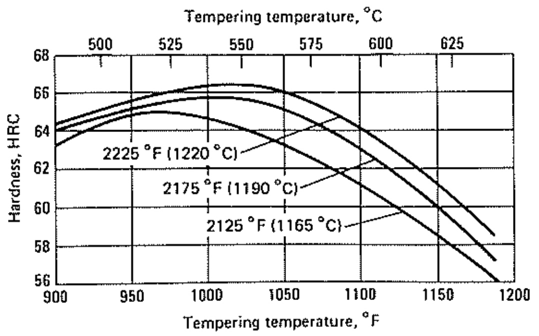
ʍ1: Effect of High-Carbon High-Alloy Surface Austenite in M1 High-Speed Steel on the Hardness After Liquid Nitriding

ʒpecimens 12.7 mm (½ in.) long were cut from a treated bar, 9.525 by 31.75 by 101.6 mm (⅜ by 1¼ by 4 in.); bar hardened at 1225 °C (2240 ·F) in 34 to 35% atmosphere and tempered for 1 h at 550 °C (1025 °F); before nitriding, 0.0152 mm (0.0006 in.) was removed from the treated ɜxterior surfaces

ʒurface condition	Nitriding time at 1050 °F (565 °C), h	Hardness, HRA	Hardness, HRC	Microhardness load, g 2000	1000	500	200	100
ɔarburized								
ɴitrided	1	85.1	66.0	885	853	889	886	...
ɜxterior surface	1	85.0	66.0	767	801	827	902	827
	2	85.0	66.0	767	801	827	902	827
ɴoncarburized								
ɴitrided	1	84.4	65.0	1020	1056	1058	1116	...
ʒectioned surface	1	84.5	65.0	1086	1104	1150	1156	1132
	2	84.5	65.0	1086	1104	1150	1156	1132

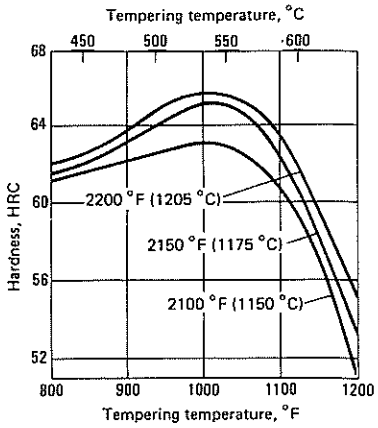
M1: Effect of Subzero Treatment on M1 High-Speed Steel After Hardening at 1205 °C (2200 °F) With No Subsequent Tempering

Continuously cooled to: °F	°C	Increase in volume, %	Hardness, HRC	Torsional properties: Proportional limit, ksi	Proportional limit, MPa	Modulus of rupture, ksi	Modulus of rupture, MPa	Plastic strain, in./in.	Plastic strain, mm/mm
+80 (regular)	+26	...	65.3	91	627	236	1627	0.017	0.432
–25	–32	0.25	67.2	130	896	252	1737	0.009	0.229
–50	–46	0.28	67.4	130	896	249	1717	0.007	0.178
–100	–73	0.31	67.3	160	1103	257	1772	0.007	0.178
–120	–84	0.39	67.9	170	1172	266	1834	0.007	0.178

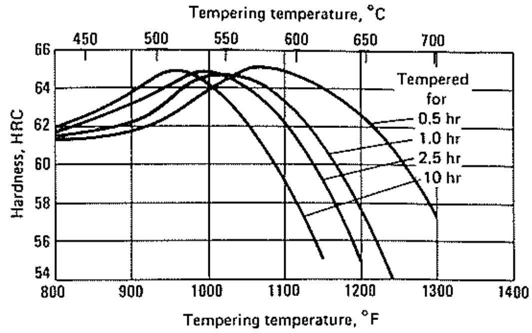


M1: Hardness vs Austenitizing and Tempering Temperatures. Austenitized at 1220 °C (2225 °F), 1190 °C (2175 °F), and 1165 °C (2125 °F) and double tempered (2 h plus 2 h)

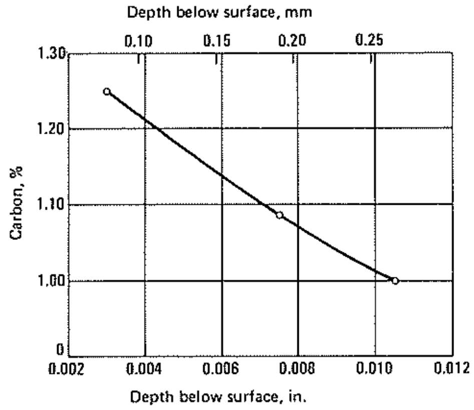
M1: Hardness vs Tempering Temperature. Austenitized at 1205 °C (2200 °F), 1175 °C (2150 °F), and 1150 °C (2100 °F) and double tempered. Source: Universal-Cyclops



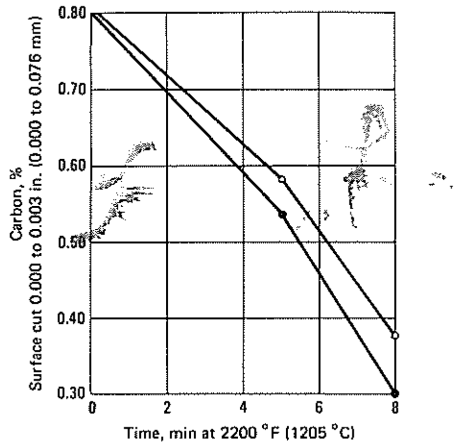
M1: Hardness vs Time and Tempering Temperature. The effect of time at tempering temperature on M1, austenitized at 1205 °C (2200 °F).



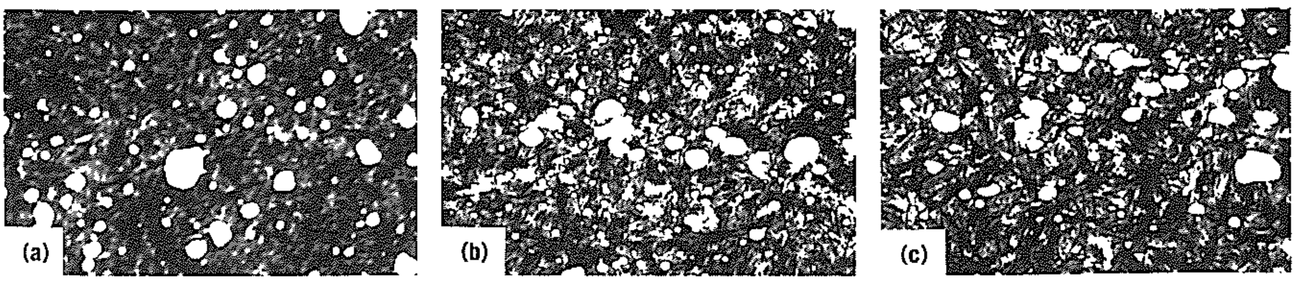
M1: Effect of Carbon Monoxide Atmosphere on Surface Carbon Content. Containing 0.80 C, 8.71 Mo, 0.99 V, 1.80 W in an atmosphere of 23% carbon monoxide. Austenitized at 1205 °C (2200 °F) for 8 min



M1: Effect of Time on Surface Carbon Content. Treated in an atmosphere of 11% carbon monoxide. O represents M1 containing 8.67 Mo, 1.19 V, 1.61 W. ● represents M1 containing 8.90 Mo, 1.04 V, 1.42 W



M1: Microstructures. (a) 2% nital, 1000×. Austenitized at 1150 °C (2100 °F), quenched in salt, double tempered (2 h plus 2 h) at 550 °C (1020 °F). Carbide particles in matrix of tempered martensite. See (b) and (c) for effects of lower and higher austenitizing temperatures. (b) 2% nital, 1000×. Given the same heat treatment as (a), except the austenitizing temperature was lower, 1120 °C (2050 °F). Carbide particles in matrix of tempered martensite. Excess of small particles caused by underheating. (c) 2% nital, 1000×. Given the same heat treatment as (a), except the austenitizing temperature was higher, 1220 °C (2225 °F). Some carbide is present in the matrix of tempered martensite. Higher austenitizing temperature dissolved most of the carbide



M2

Chemical Composition. **AISI:** Nominal. 0.85 to 1.00 C (other carbon contents may be available), 4.00 Cr, 5.00 Mo, 2.00 V, 6.00 W. **AISI/UNS:** Composition: 0.78 to 0.88 C, 0.95 to 1.05 C, 0.15 to 0.40 Mn, 0.20 to 0.45 Si, 0.30 Ni max, 3.75 to 4.50 Cr, 4.75 to 6.50 Mo, 2.25 to 2.75 V, 5.00 to 6.75 W

Similar Steels (U.S. and/or Foreign). **Regular Carbon Composition:** ASTM A600 (M-2); FED QQ-T-590 (M-2); SAE J437 (M2), J438 (M2); (Ger.) DIN 1.3341, 1.3343, 1.3345, 1.3553, 1.3554; (Fr.) AFNOR A35-590 4301 Z 85 WDCV 06-05-04-02; (Ital.) UNI X 82 WMo 0605 KU; (Jap.) JIS G4403 SKH 51, SKH 59; (Swed.) SS 2722; (U.K.) B.S. 4659 BM2. **High Carbon Composition:** (Ger.) DIN 1.3340, 1.3342; (Fr.) AFNOR A35-590 4302 Z 90 WDCV 06-05-04-02

Characteristics. The most widely used high-speed steel. A relatively low cost grade with the distinction of being a general all-purpose steel. Suitable for a multitude of applications and available with several carbon contents. Rates very high in resistance to wear and resistance to softening at elevated temperature. It rates low in toughness, but using a lower austenitizing temperature with the resulting slightly lower hardness improves its impact resistance. Has medium resistance to decarburization. Available in regular and high carbon compositions

Forging. Start forging at 1040 to 1150 °C (1905 to 2100 °F). Do not forge after temperature of forging stock drops below 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Pack annealing in tightly closed containers or using a controlled atmosphere or vacuum is required to minimize decarburization. The packing material can be dry sand or lime to which a small amount of charcoal has been added. Burned cast iron chips are also satisfactory. Use a container that is only slightly larger than the load to minimize the amount of packing material required. This allows the pack to heat rapidly. After the steel has reached the annealing temperature, it should be held at temperature for 1 h per inch of thickness of the container. Cool slowly in furnace to 650 °C (1200 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 212 to 241 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

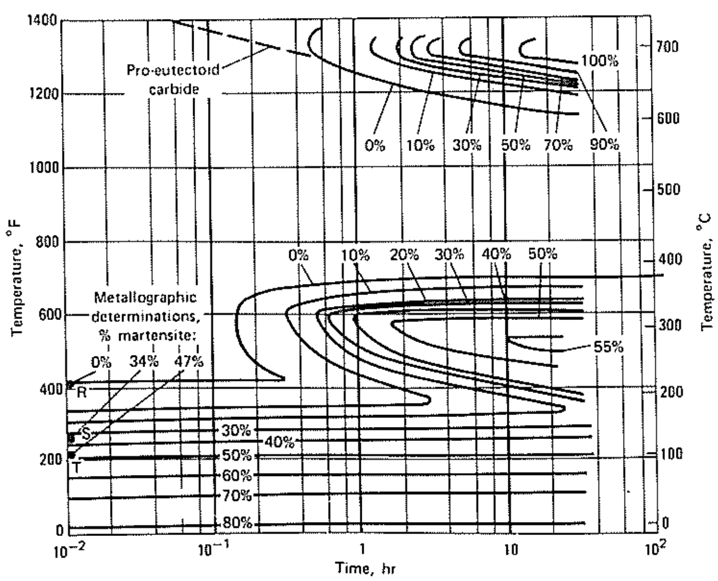
Hardening. Preheat at 730 to 845 °C (1350 to 1555 °F). Double preheating in one furnace at 540 to 650 °C (1000 to 1200 °F) and in another at 845 to 870 °C (1555 to 1600 °F) will minimize thermal shock. Preheating time, after all sections of the tool have reached equal temperature, should be twice the length of time required at the austenitizing temperature. Heat rapidly from the preheating to the austenitizing temperature. Austenitize at 1190 to 1230 °C (2175 to 2245 °F) for 2 to 5 min. Use 14 °C (25 °F) lower when hardening from salt. When high carbon material is involved, lower the austenitizing temperature 14 °C (25 °F) in addition to the reduction when hardening from salt bath. Use shorter time for small sections and longer time for large sections. Tools austenitized at the lower end of the temperature range will have greater toughness, when compared to tools austenitized at the upper end of the range where greater alloy solution serves to impart higher hardness and hot hardness. Quench in oil, air, or salt. As-quenched hardness, 64 to 66 HRC

Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at −100 to −195 °C (−150 to −320 °F). Temper immediately after part reaches room temperature

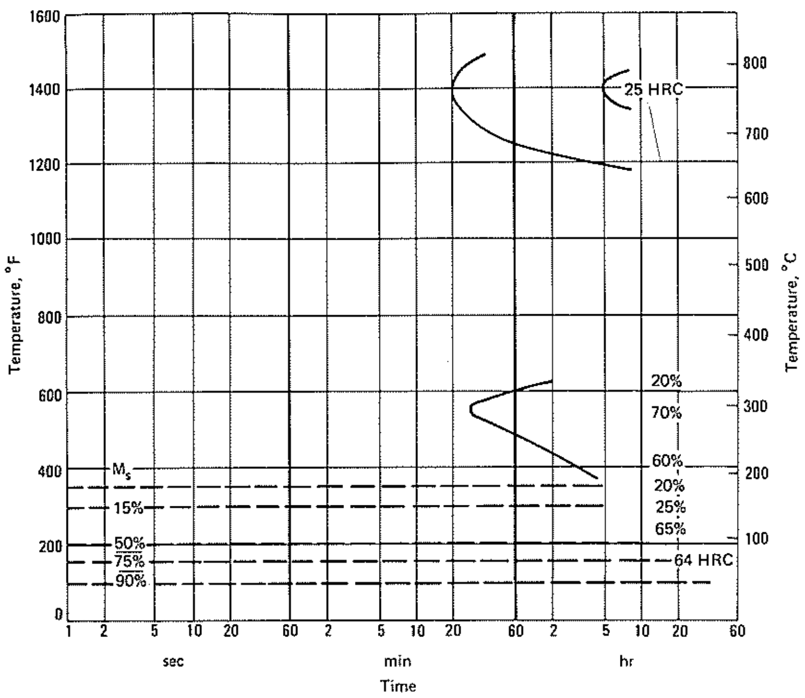
Tempering. Temper at 540 to 595 °C (1000 to 1105 °F) for at least 2 h, cool to room temperature, and retemper for 2 h. Approximate tempered hardness as it corresponds to tempering temperature, 65 to 60 HRC

Recommended Processing Sequence

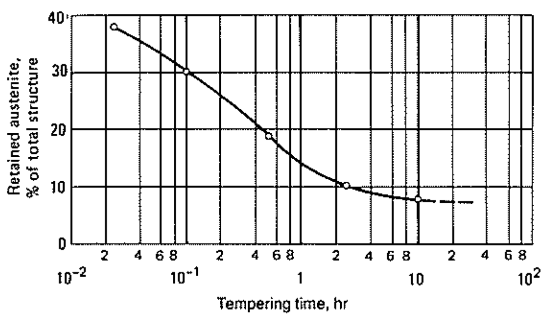
- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/double
- Final grind to size



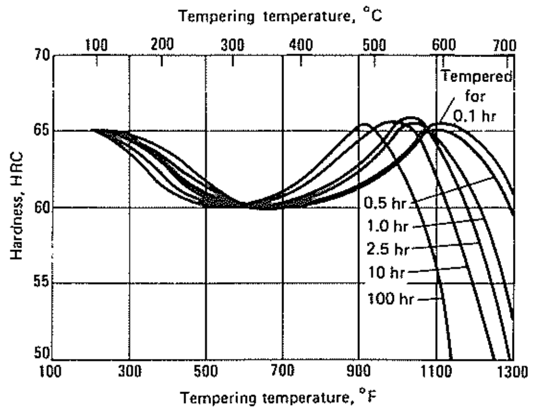
M2: Isothermal Transformation Diagram. Contains 0.81 C, 0.24 Mn, 0.016 P, 0.007 S, 0.26 Si, 4.10 Cr, 4.69 Mo, 1.64 V, 5.95 W



M2: Isothermal Transformation Diagram. Modified M2 containing 0.83 C, 0.32 Mn, 0.25 Si, 3.89 Cr, 4.30 Mo, 1.30 V, 5.79 W. Austenitized at 1220 °C (2225 °F). Prior condition, annealed

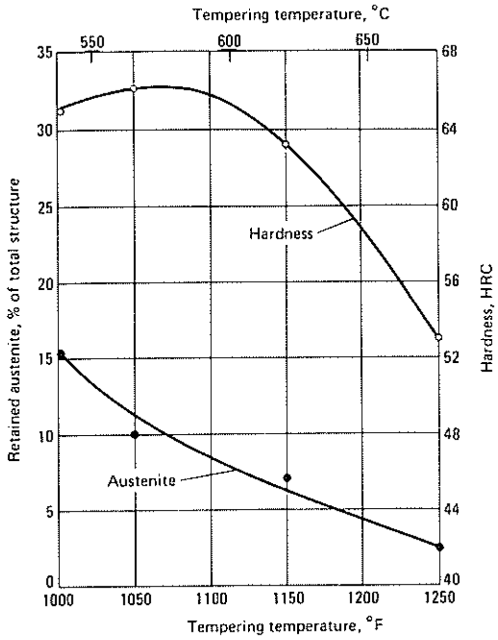


M2: Retained Austenite vs Tempering Time. Quenched from 1220 °C (2225 °F), to 105 °C (225 °F), and tempered at 565 °C (1050 °F)

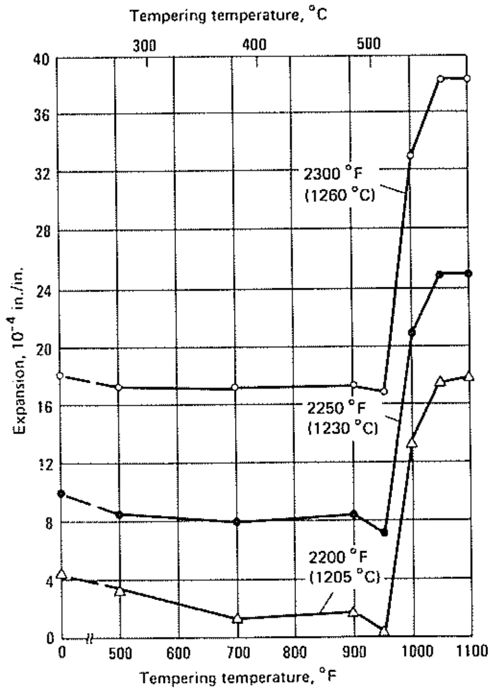


M2: Hardness vs Time at Tempering Temperature. Austenitized at 1220 °C (2225 °F) and tempered at the times indicated

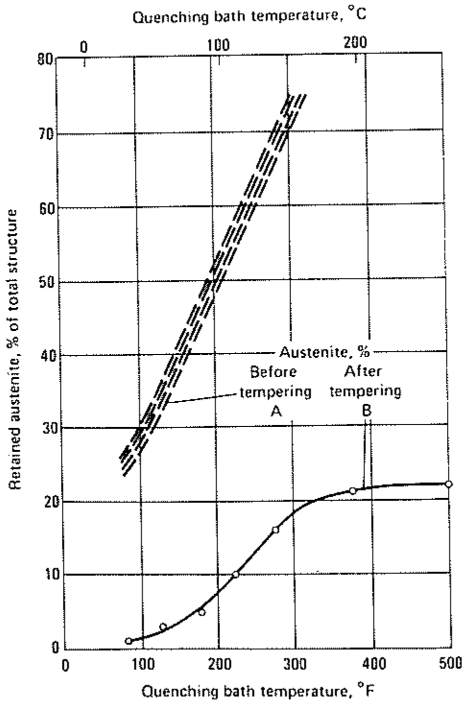
M2: Retained Austenite vs Hardness. Quenched from 1220 °C (2225 °F) to 105 °C (225 °F), and tempered at indicated temperatures for 2 ½ h



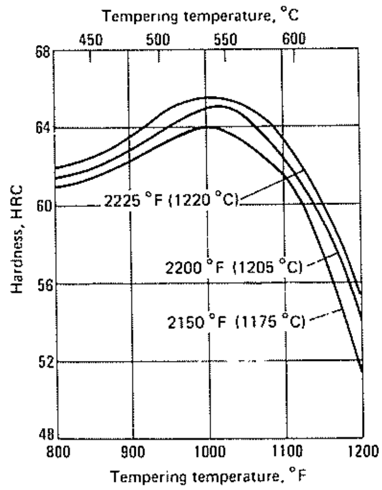
M2: Dimensional Change vs Tempering Temperature. A 19.05 mm (0.75 in.) round by 101.6 mm (4 in.) specimen of M2, quenched for 2 h from 1260 °C (2300 °F), 1230 °C (2245 °F), and 1205 °C (2200 °F)

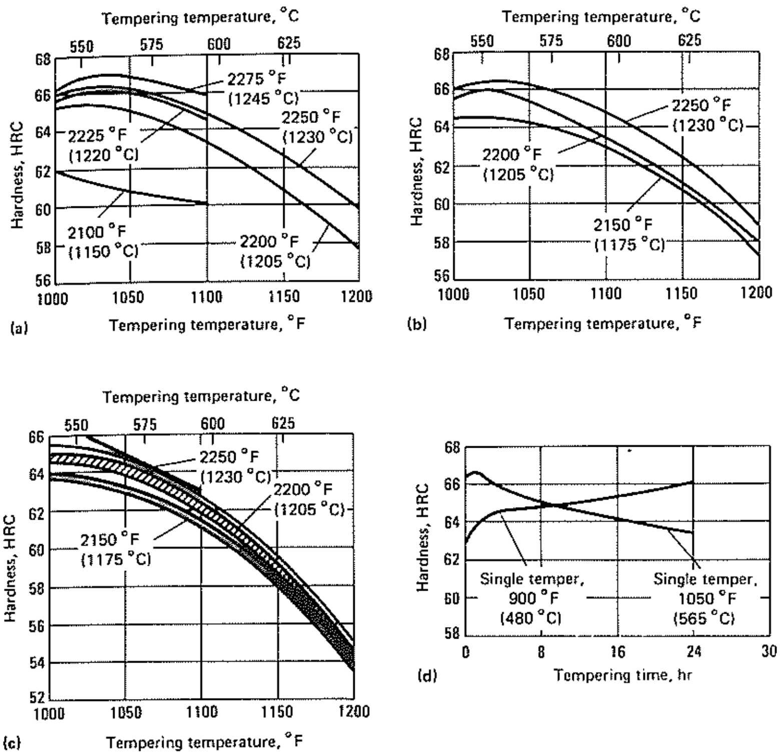


M2: Retained Austenite vs Quenching Bath Temperature. Quenched from 1220 °C (2225 °F) to indicated temperatures and single tempered at 565 °C (1050 °F) for 2 ½ h



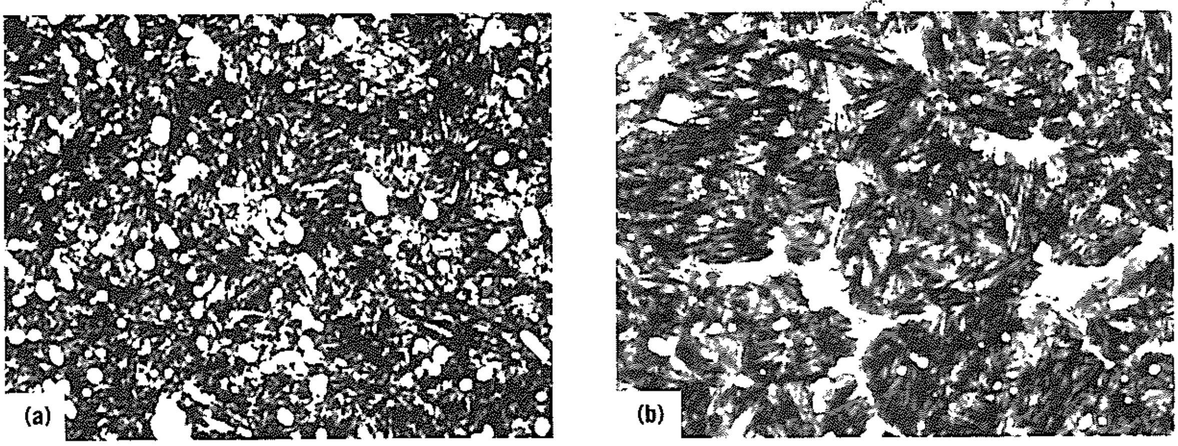
M2: Hardness vs Tempering Temperature. Source: Universal-Cyclops





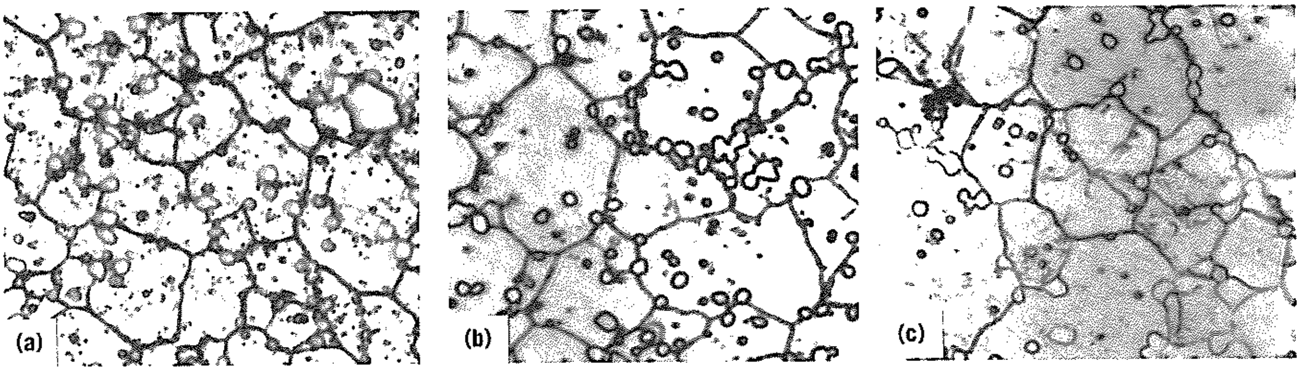
M2: Hardness vs Austenitizing and Tempering Conditions. (a) Austenitized at 1245 °C (2275 °F), 1230 °C (2245 °F), 1205 °C (2200 °F), and 1150 °C (2100 °F), and receiving single temper for 1 h. (b) Austenitized at 1230 °C (2245 °F), 1205 °C (2200 °F), and 1175 °C (2150 °F), and receiving single temper for 2 h. (c) Austenitized at 1230 °C (2245 °F), 1205 °C (2200 °F), and 1175 °C (2150 °F), and double temper (2 h plus 2 h). (d) Austenitized at 1225 °C (2240 °F), single temper at 480 °C (895 °F) and 565 °C (1050 °F)

M2: Microstructures. (a) 3% nital, 1000×. 50.8 mm (2 in.) diam bar austenitized at 1220 °C (2225 °F), oil quenched, tempered at 550 °C (1020 °F) for 1 h. Spheroidal carbide particles in matrix of tempered martensite. Some small areas of retained austenite evident. (b) 6% nital, 750×. 22.23 mm (0.875 in.) diam bar, austenitized at 1260 °C (2300 °F), oil quenched, double tempered at 565 °C (1050 °F). Tempered martensite with a few spheroidal carbide particles. Incipient melting at grain boundaries resulted from overheating

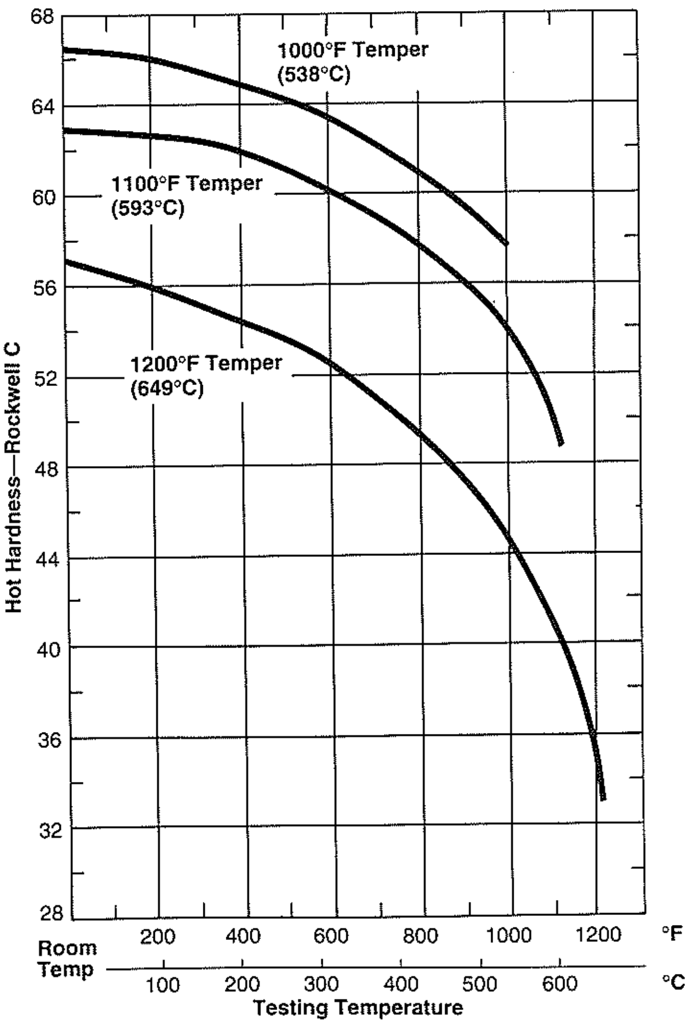


(continued)

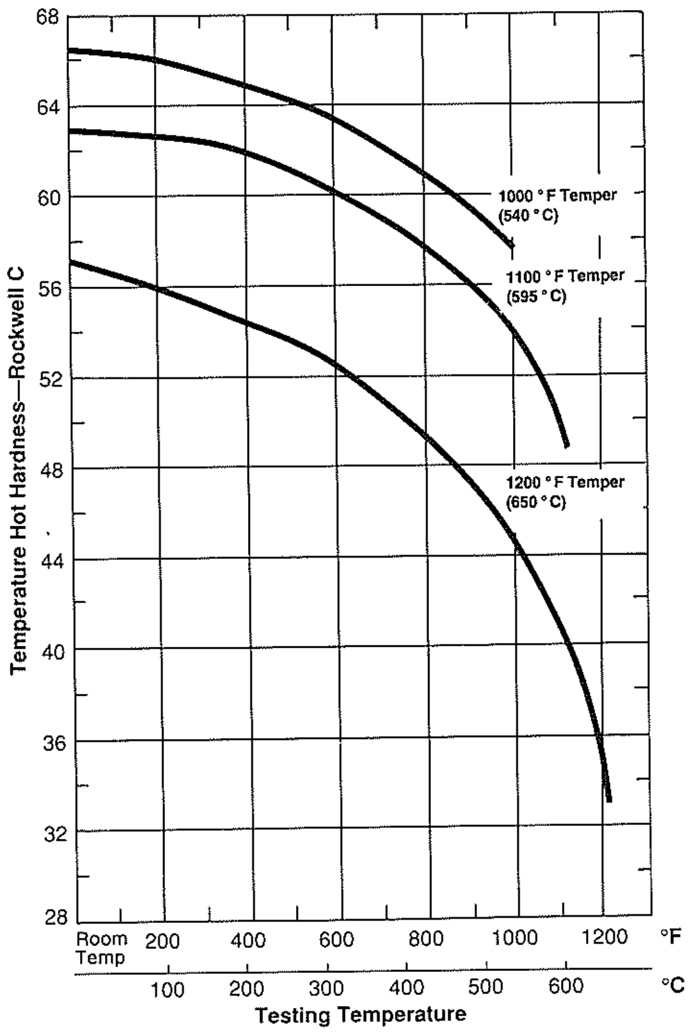
M2: Microstructures (continued). (a) 10% nital, 1000×. 22.23 mm (0.875 in.) diam bar, austenitized at 1165 °C (2125 °F) and oil quenched. Spheroidal carbide particles in untempered martensite. ASTM grain size, 17. (b) 10% nital, 1000×. Same steel as (a), except austenitized at 1210 °C (2210 °F). ASTM grain size had increased to 12 because of higher austenitizing temperature. (c) 10% nital, 1000×. Same steel as (a), except austenitized at 1240 °C (2260 °F), resulting in a further increase in ASTM grain size to 8

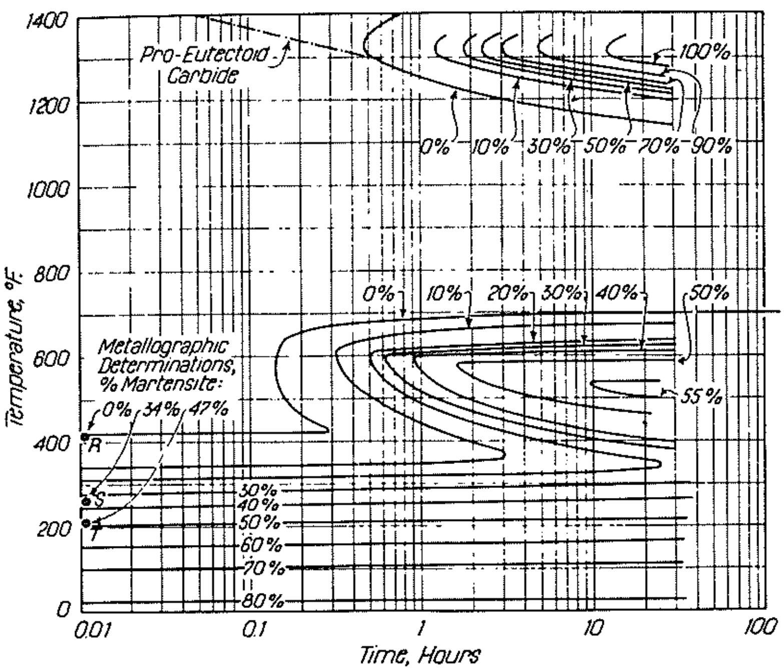


M2: Hot Hardness of Regular Carbon Grade. Source: Carpenter Technology Corporation

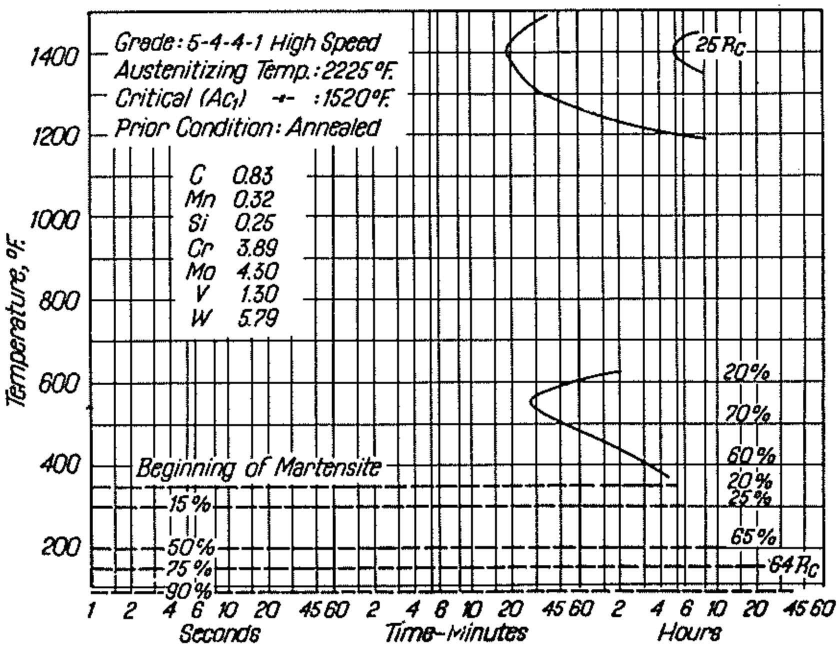


M2: Hot Hardness of High Carbon Grade. Source: Carpenter Technology Corporation





M2: Isothermal Transformation Diagram. Composition: 0.81 C, 0.24 Mn, 0.26 Si, 0.16 P, 0.007 S, 4.10 Cr, 4.69 Mo, 1.64 V, 5.95 W



M2 (Mod): Isothermal Transformation Diagram. Composition: 0.83 C, 0.32 Mn, 0.25 Si, 3.89 Cr, 4.30 Mo, 1.30 V, 5.79 W. Austenitized at 1220 °C (2225 °F)

M3 Class 1

Chemical Composition. **AISI:** Nominal. 1.05 C, 4.00 Cr, 5.00 Mo, 2.40 V, 6.00 W. **AISI/UNS:** Composition: 1.00 to 1.10 C, 0.15 to 0.40 Mn, 0.20 to 0.45 Si, 0.30 Ni max, 3.75 to 4.50 Cr, 4.75 to 6.50 Mo, 1.75 to 2.20 V, 5.50 to 6.75 W

Similar Steels (U.S. and/or Foreign). ASTM A600 (M-3, Cl.1); FED QQ-T-590 (M-3); SAE J437 (M3), J438 (M3); (Ger.) DIN 1.3342; (Fr.) AFNOR Z 90 WDCV 06-05-04-02; (Jap.) JIS G4403 SKH 52

Characteristics. Contains slightly higher vanadium and carbon content than M2 which gives it slightly higher resistance to wear and resistance to softening at elevated temperatures. Toughness rating is also slightly less than M2, but use of lower austenitizing temperature and the slightly lower hardness which results, improves its impact resistance. Has medium resistance to decarburization

Forging. Start forging at 1040 to 1150 °C (1905 to 2100 °F). Do not forge after temperature of forging stock drops below 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Pack annealing in tightly closed containers or using a controlled atmosphere or vacuum is required to minimize decarburization. The packing material can be dry sand or lime to which a small amount of charcoal has been added. Burned cast iron chips are also satisfactory. Use a container that is only slightly larger than the load to minimize the amount of packing material required. This allows the pack to heat rapidly. After the steel has reached the annealing temperature, it should be held at temperature for 1 h per inch of thickness of the container. Cool slowly in furnace to 650 °C (1200 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 223 to 255 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

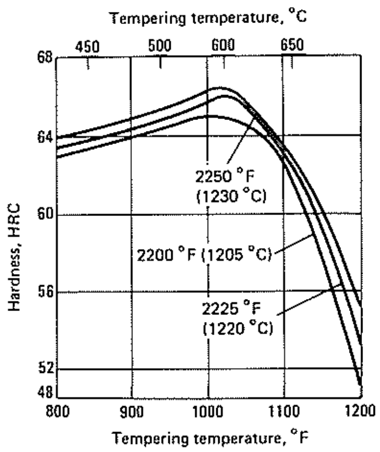
Hardening. Preheat at 730 to 845 °C (1350 to 1555 °F). Double preheating in one furnace at 540 to 650 °C (1000 to 1200 °F) and in another at 845 to 870 °C (1555 to 1600 °F) will minimize thermal shock. Preheating time, after all sections of the tool have reached equal temperature, should be twice the length of time required at the austenitizing temperature. Heat rapidly from the preheating to the austenitizing temperature. Austenitize at 1205 to 1230 °C (2200 to 2245 °F) for 2 to 5 min. Use 14 °C (25 °F) lower when hardening from salt. Use shorter time for small sections and longer time for large sections. Tools austenitized at the lower end of the temperature range will have greater toughness, when compared to tools austenitized at the upper end of the range where greater alloy solution serves to impart higher hardness and hot hardness. Quench in oil, air, or salt. As-quenched hardness, 64 to 66 HRC

Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at −100 to −195 °C (−150 to −320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 540 to 595 °C (1000 to 1105 °F) for at least 2 h, cool to room temperature, and retemper for 2 h. Approximate tempered hardness as it corresponds to tempering temperature, 66 to 61 HRC

Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/double
- Final grind to size



M3 Class 1: Hardness vs Tempering Temperature. Triple tempered after hardening at 1230 °C (2245 °F), 1220 °C (2225 °F), and 1205 °C (2200 °F). Source: Universal-Cyclops

M3 Class 2

Chemical Composition. **AISI:** Nominal. 1.20 C, 4.00 Cr, 5.00 Mo, 3.00 V, 6.00 W. **AISI/UNS:** Composition: 1.15 to 1.25 C, 0.15 to 0.40 Mn, 0.20 to 0.45 Si, 0.30 Ni max, 3.75 to 4.50 Cr, 4.75 to 6.50 Mo, 2.75 to 3.75 V, 5.00 to 6.75 W

Similar Steels (U.S. and/or Foreign). ASTM A600 (M-3, Cl.2); FED QQ-T-590 (M-3); SAE J437 (M3), J438 (M3); (Ger.) DIN 1.3344; (Fr.) AFNOR A35-590 4360 WDCV 06-05-04-03, A35-590 4361 Z130 WDCV 05-04-04, A35-590 4442 Z100 DCWV 09-04-02-02; (Jap.) JIS G4403 SKH 52, G4403 SKH 53; (Swed.) SS (USA M3, class 2)

Characteristics. Definitely a more wear-resistant grade than M2. Has greater amounts of carbon and vanadium than M3-class 1 grade. Its toughness will be correspondingly lower, but use of lower austenitizing temperature and the resulting slightly lower hardness improves its impact resistance. It is rated very high in resistance to softening at elevated temperature, medium in machinability, and medium in resistance to decarburization

Forging. Start forging at 1040 to 1150 °C (1905 to 2100 °F). Do not forge after temperature of forging stock drops below 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Pack annealing in tightly closed containers or using a controlled atmosphere or vacuum is required to minimize decarburization. The packing material can be dry sand or lime to which a small amount of charcoal has been added. Burned cast iron chips are also satisfactory. Use a container that is only slightly larger than the load to minimize the amount of packing material required. This allows the pack to heat rapidly. After the steel has reached the annealing temperature, it should be held at temperature for 1 h per inch of thickness of the container. Cool slowly in furnace to 650 °C (1200 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 223 to 255 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Preheat at 730 to 815 °C (1350 to 1500 °F). Double preheating in one furnace at 540 to 650 °C (1000 to 1200 °F) and in another at 845 to 870 °C (1555 to 1600 °F) will minimize thermal shock. Preheating time, after all sections of the tool have reached equal temperature, should be twice the length of time required at the austenitizing temperature. Heat rapidly from the preheating to the austenitizing temperature. Austenitize at 1205 to 1230 °C (2200 to 2245 °F) for 2 to 5 min. Use 14 °C (25 °F) lower when hardening from salt. Use shorter time for small sections and longer time for large sections. Tools austenitized at the lower end of the temperature range will have greater toughness, when compared to tools austenitized at the upper end of the range where greater alloy solution serves to impart higher hardness and hot hardness. Quench in oil, air, or salt. As-quenched hardness, 64 to 66 HRC

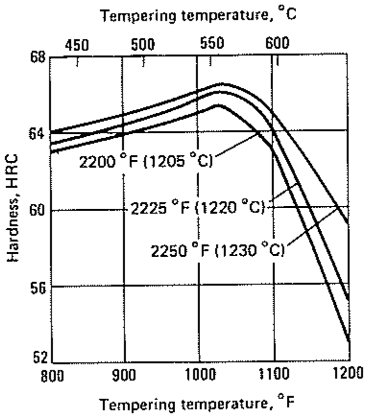
Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at −100 to −195 °C (−150 to −320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 540 to 595 °C (1000 to 1105 °F) for at least 2 h, cool to room temperature, and retemper for 2 h. Approximate tempered hardness as it corresponds to tempering temperature, 66 to 61 HRC

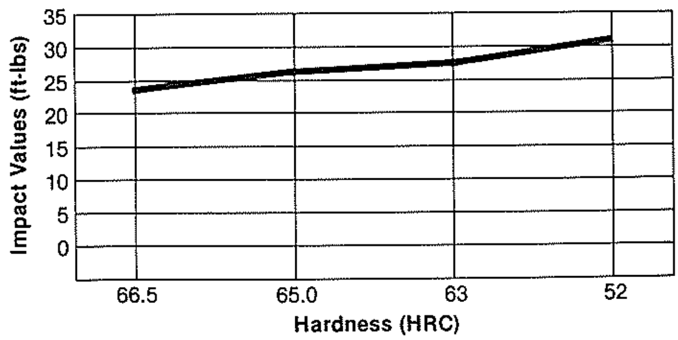
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/double
- Final grind to size

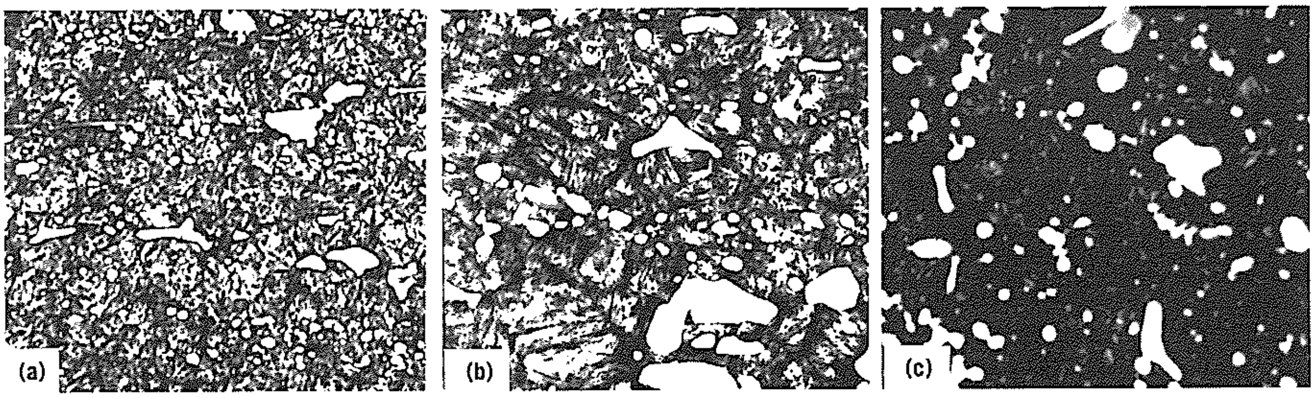
M3 Class 2: Hardness vs Tempering Temperature. Triple tempered after austenitizing at 1230 °C (2245 °F), 1220 °C (2225 °F), and 1205 °C (2200 °F). Source: Universal-Cyclops



M3 Class 2: Unnotched Impact Values of Class 2 Alloy. Specimens were austenitized 5 min at 1205 °C (2200 °F) in salt, oil quenched, then triple tempered (2 h each) to hardness, and air cooled. Source: Carpenter Technology Corporation



M3 Class 2: Microstructures. (a) 2% nital, 500×. Austenitized at 1205 °C (2200 °F), quenched in a salt bath, double tempered (2 h plus 2 h) at 550 °C (1020 °F). Large and small alloy carbide particles (white) in tempered martensite. See (b). (b) 2% nital, 1000×. Same steel and heat treatment as (a), but shown at higher magnification. Large white areas in structure are vanadium carbide, which characterized this grade of high-speed tool steel. (c) 10% nital, 1000×. Austenitized at 1220 °C (2225 °F), quenched in a salt bath, double tempered at 550 °C (1020 °F). Large and small particles of alloy carbide in matrix of tempered martensite.



M4

Chemical Composition. **AISI:** Nominal. 1.30 C, 4.00 Cr, 4.50 Mo, 4.00 V, 5.50 W. **AISI/UNS:** Composition: 1.25 to 1.40 C, 0.15 to 0.40 Mn, 0.20 to 0.45 Si, 0.30 Ni max, 3.75 to 4.75 Cr, 4.25 to 5.50 Mo, 3.75 to 4.50 V, 5.25 to 6.50 W

Similar Steels (U.S. and/or Foreign). ASTM A600 (M-4); FED QQ-T-590 (M-4); SAE J437 (M4), J438 (M4); (Fr.) AFNOR A35-590 4361 Z 130 WDCV 06-05-04-04; (Jap.) JIS G4403 SKH 54; (Swed.) SS 2782; (U.K.) B.S. 4659 BH4

Characteristics. This grade contains the same amount of carbon and vanadium as the highest modifications of the popular M2 grade. Its carbon content is greater than 1.25% and its vanadium content is greater than 3%, which qualifies it as a super high-speed steel. One of the most wear-resistant grades of high-speed steel. Its toughness is reduced correspondingly, but using lower austenitizing temperatures with lower resulting hardness helps to improve its impact resistance. Has high resistance to softening at elevated temperatures, low to medium machinability, and medium resistance to decarburization

Forging. Start forging at 1040 to 1150 °C (1905 to 2100 °F). Do not forge after temperature of forging stock drops below 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Pack annealing in tightly closed containers or using a controlled atmosphere or vacuum is required to minimize decarburization. The packing material can be dry sand or lime to which a small amount of charcoal has been added. Burned cast iron chips are also satisfactory. Use a container that is only slightly larger than the load to minimize the amount of packing material required. This allows the pack to heat rapidly. After the steel has reached the annealing temperature, it should be held at temperature for 1 h per inch of thickness of the container. Cool slowly in furnace to 650 °C (1200 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 223 to 255 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Preheat at 730 to 845 °C (1350 to 1555 °F). Double preheating in one furnace at 540 to 650 °C (1000 to 1200 °F) and in another at 845 to 870 °C (1555 to 1600 °F) will minimize thermal shock. Preheating time, after all sections of the tool have reached equal temperature, should be twice the length of time required at the austenitizing temperature. Heat rapidly from the preheating to the austenitizing temperature. Austenitize at 1205 to 1230 °C (2200 to 2245 °F) for 2 to 5 min. Use 14 °C (25 °F) lower when hardening from salt. Use shorter time for small sections and longer time for large sections. Tools austenitized at the lower end of the temperature range will have greater toughness, when compared to tools austenitized at the upper end of the range where greater alloy solution serves to impart higher hardness and hot hardness. Quench in oil, air, or salt. As-quenched hardness, 65 to 67 HRC

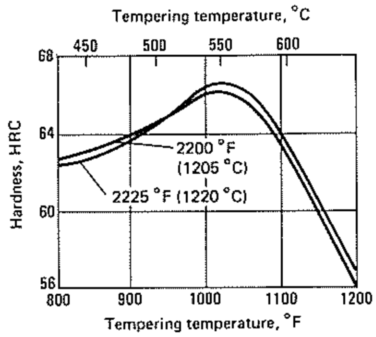
Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at −100 to −195 °C (−150 to −320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 540 to 595 °C (1000 to 1105 °F) for at least 2 h, cool to room temperature, and retemper for 2 h. Approximate tempered hardness, 66 to 61 HRC

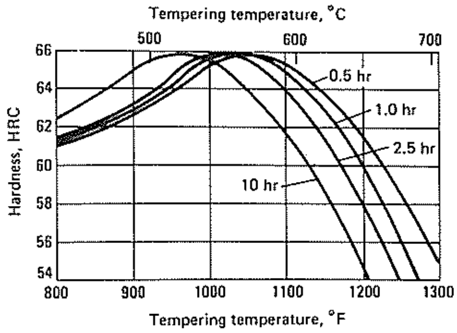
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/double
- Final grind to size

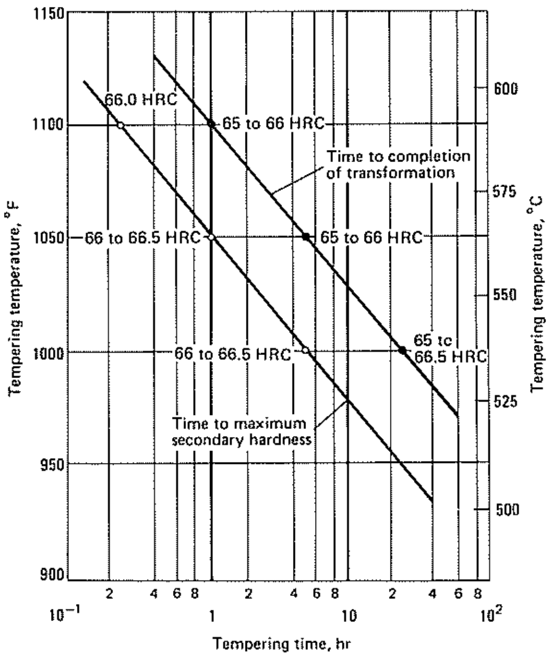
M4: Hardness vs Tempering Temperature. Triple tempered, after austenitizing at 1205 °C (2200 °F) and 1220 °C (2225 °F). Source: Universal-Cyclops



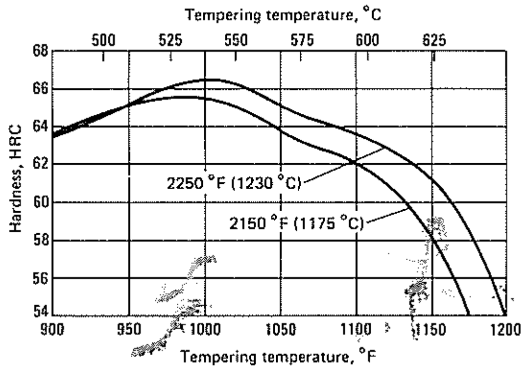
M4: Hardness vs Time at Tempering Temperatures. Austenitized at 1220 °C (2225 °F)

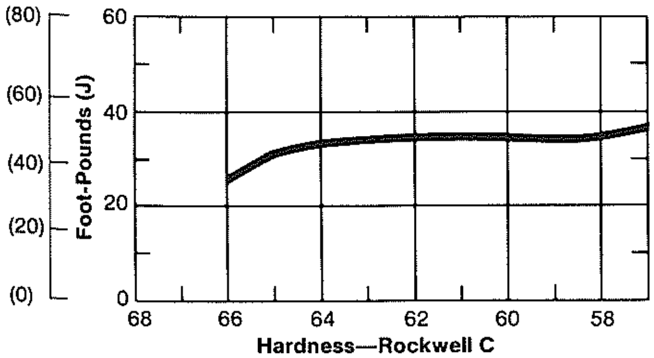


M4: Hardness vs Time and Tempering Temperature. Contains 1.25 C, 5.0 Mo, 4.0 V, 6.0 W. Quenched in oil from 1215 °C (2220 °F)



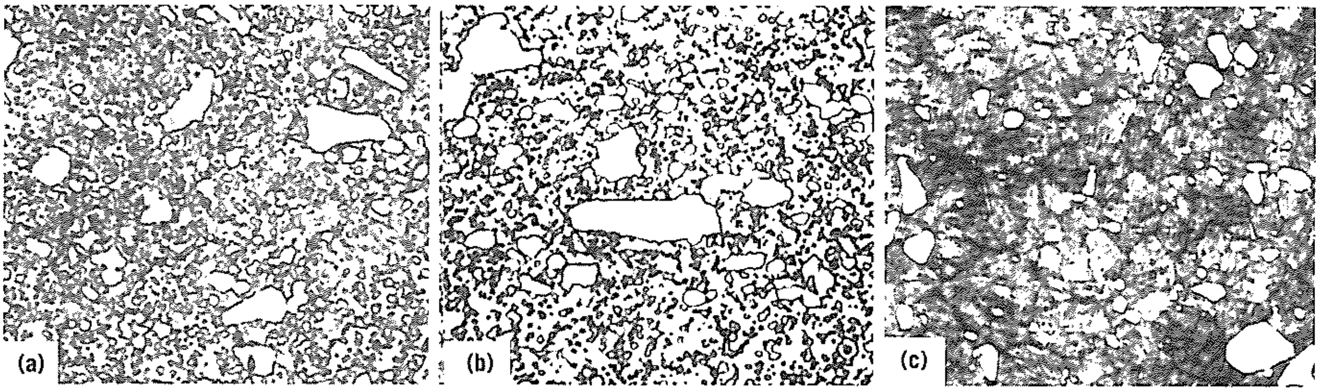
M4: Hardness vs Austenitizing and Tempering Temperatures. Austenitized at 1230 °C (2245 °F) and 1175 °C (2150 °F) and double tempered (2 h plus 2 h)





M4: Typical Unnotched IZOD Impact Properties. Source: Carpenter Technology Corporation

M4: Microstructures. (a) 4% picral, 1000×. 13.1 mm (0.515 in.) diam rod, as received (mill annealed). Particles of vanadium carbide (large, light), other alloy carbide (small spheroids) in ferrite. (b) 4% picral, 1000×. Same steel and condition as (a), except a longitudinal section. Some carbide particles are slightly elongated. Vanadium carbide impacts high abrasion resistance. (c) 6% nital, 750×. 12.7 mm (0.50 in.) diam bar, austenitized at 1210 °C (2210 °F), oil quenched, double tempered (2 h plus 2 h) at 545 °C (1015 °F), air cooled. Spheroidal and angular particles of carbide in matrix of tempered martensite



M7

Chemical Composition. **AISI:** Nominal. 1.00 C, 4.00 Cr, 8.75 Mo, 2.00 V, 1.75 W. **AISI/UNS:** Composition: 0.97 to 1.05 C, 0.15 to 0.40 Mn, 0.20 to 0.55 Si, 0.30 Ni max, 3.50 to 4.00 Cr, 8.20 to 9.20 Mo, 1.75 to 2.25 V, 1.40 to 2.10 W

Similar Steels (U.S. and/or Foreign). ASTM A600 (M-7); FED QQ-T-590 (M-7); (Ger.) DIN 1.3348; (Fr.) AFNOR A35-590 4442 Z 100 DCWV 09-04-02-02; (Jap.) JIS G4403 SKH 58

Characteristics. Molybdenum is the principal alloying element, which makes this an economical grade of high-speed steel. Very high resistance to wear and resistance to softening at elevated temperatures. Has a relatively low toughness rating, as do most high-speed steels, but using a lower austenitizing temperature results in lower hardness and improved impact resistance. Has medium machinability and low decarburization resistance

Forging. Start forging at 1040 to 1150 °C (1905 to 2100 °F). Do not forge after temperature of forging stock drops below 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat to 815 to 870 °C (1500 to 1600 °F). Use lower limit for small sections and upper limit for large sections. Pack annealing in tightly closed containers or using a controlled atmosphere or vacuum is required to minimize decarburization. The packing material can be dry sand or lime to which a small amount of charcoal has been added. Burned cast iron chips are also satisfactory. Use a container that is only slightly larger than the load to minimize the amount of packing material required. This allows the pack to heat rapidly. After the steel has reached the annealing temperature, it should be held at temperature for 1 h per inch of thickness of the container. Cool slowly in furnace to 650 °C (1200 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 217 to 255 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Preheat at 730 to 815 °C (1350 to 1500 °F). Double preheating in one furnace at 540 to 650 °C (1000 to 1200 °F) and in another at 845 to 870 °C (1555 to 1600 °F) will minimize thermal shock. Preheating time, after all sections of the tool have reached equal temperature, should be twice the length of time required at the austenitizing temperature. Heat rapidly from the preheating to the austenitizing temperature. Austenitize at 1175 to 1220 °C (2150 to 2225 °F) for 2 to 5 min. Use 14 °C (25 °F) lower when hardening from salt. Use shorter time for small sections and longer time for large sections. Tools austenitized at the lower end of the temperature range will have greater toughness, when compared to tools austenitized at the upper end of the range where greater alloy solution serves to impart higher hardness and hot hardness. Quench in oil, air, or salt. As-quenched hardness, 64 to 66 HRC

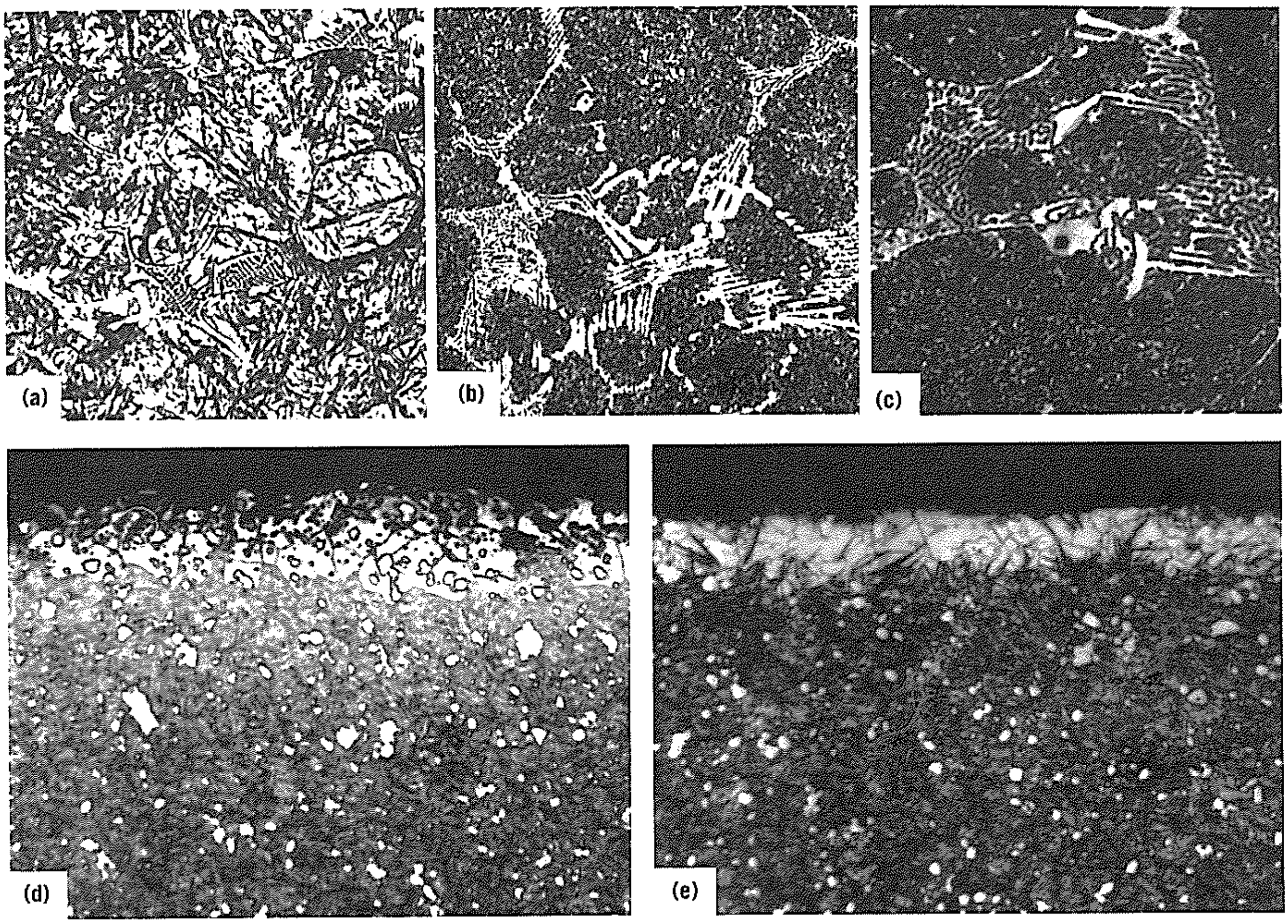
Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to –320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 540 to 595 °C (1000 to 1105 °F) for at least 2 h, cool to room temperature, and retemper for 2 h. Approximate tempered hardness as it corresponds to tempering temperature, 66 to 61 HRC

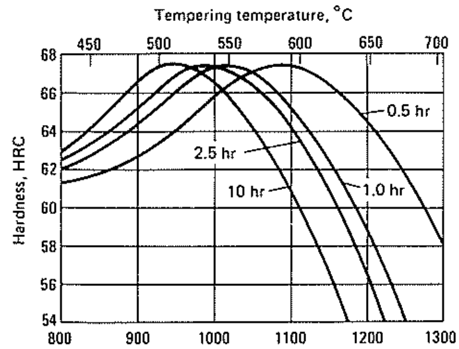
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/double
- Final grind to size

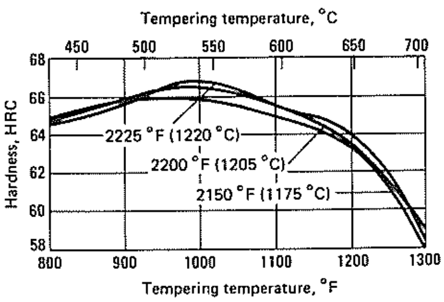
M7: Microstructures. (a) 2% nital, 500×. Austenitized at 1260 °C (2300 °F), salt quenched, double tempered at 550 °C (1020 °F). Severely overheated structure shows reprecipitated carbide eutectic and grain-boundary carbide in matrix of coarse martensite. See (d). (b) 3% nital, 500×. Cast M7, annealed by austenitizing at 870 °C (1600 °F) for 4 h and furnace cooling to 150 °C (300 °F). Spheroidal particles of carbide within prior austenite grains, and a eutectic structure (white, lamellar) at grain boundaries. See (c). (c) 3% nital, 1000×. Same steel and heat treatment as (b), except shown at higher magnification. Grain-boundary eutectic is now clearly resolved. Fully annealed structure suitable for subsequent hardening treatment. (d) 6% nital, 750×. Decarburized M7. White layer of ferrite at surface contains carbide particles (spheroids) and oxide (black). (e) 6% nital, 750×. Carburized M7. White layer consists mainly of tempered martensite and retained austenite

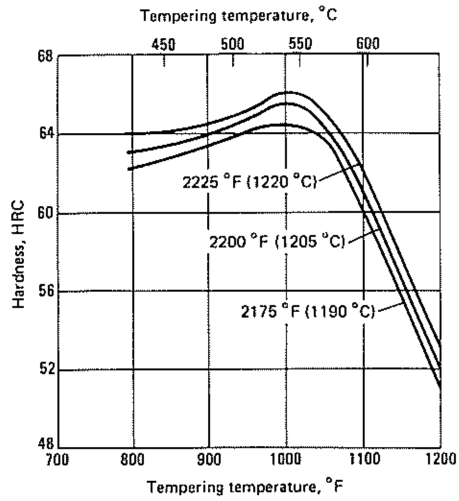


M7: Hardness vs Time at Tempering Temperature. Austenitized at 1220 °C (2225 °F) and tempered for times shown



M7: Hardness vs Austenitizing and Tempering Temperatures. Austenitized at 1220 °C (2225 °F), 1205 °C (2200 °F), and 1175 °C (2150 °F) and double tempered (2 h plus 2 h)





M7: Hardness vs Tempering Temperature. Austenitized at 1220 °C (2225 °F), 1205 °C (2200 °F), and 1190 °C (2175 °F) and double tempered. Source: Universal-Cyclops

M10

Chemical Composition. **AISI:** Nominal. 0.85 to 1.00 C (other carbon contents may be available), 4.00 Cr, 8.00 Mo, 2.00 V. **AISI/UNS:** Composition: 0.84 to 0.94 C, 0.95 to 1.05 C, 0.10 to 0.40 Mn, 0.20 to 0.45 Si, 0.30 Ni max, 3.75 to 4.50 Cr, 7.75 to 8.50 Mo, 1.80 to 2.20 V

Similar Steels (U.S. and/or Foreign). ASTM A600 (M-10); FED QQ-T-590 (M-10). No similar or foreign steels for regular or high carbon compositions

Characteristics. Molybdenum is the principal alloying element making this an economical grade of high-speed steel. Available in several levels of carbon content. Very high resistance to wear and softening at elevated temperature. Has a relatively low toughness rating as do most high-speed steels, but using a lower austenitizing temperature results in lower hardness and improved impact resistance. Medium machinability and low decarburization resistance. Available in regular and high carbon compositions

Forging. Start forging at 1040 to 1150 °C (1905 to 2100 °F). Do not forge after temperature of forging stock drops below 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat to 815 to 870 °C (1500 to 1600 °F). Use lower limit for small sections and upper limit for large sections. Pack annealing in tightly closed containers or using a controlled atmosphere or vacuum is required to minimize decarburization. The packing material can be dry sand or lime to which a small amount of charcoal has been added. Burned cast iron chips are also satisfactory. Use a container that is only slightly larger than the load to minimize the amount of packing material required. This allows the pack to heat rapidly. After the steel has reached the annealing temperature, it should be held at temperature for 1 h per inch of thickness of the container. Cool slowly in furnace to 650 °C (1200 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 207 to 255 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Preheat at 730 to 845 °C (1350 to 1555 °F). Double preheating in one furnace at 540 to 650 °C (1000 to 1200 °F) and in another at 845 to 870 °C (1555 to 1600 °F) will minimize thermal shock. Preheating time, after all sections of the tool have reached equal temperature, should be twice the length of time required at the austenitizing temperature. Heat rapidly from the preheating to the austenitizing temperature. Austenitize at 1175 to 1220 °C (2150 to 2225 °F) for 2 to 5 min. Use 14 °C (25 °F) lower when hardening from salt. When high carbon material is involved, lower the austenitizing temperature 14 °C (25 °F) in addition to the reduction when hardening from salt bath. Use shorter time for small sections and longer time for large sections. Tools austenitized at the lower end of the temperature range will have greater toughness, when compared to tools austenitized at the upper end of the range where greater alloy solution serves to impart higher hardness and hot hardness. Quench in oil, air, or salt. As-quenched hardness, 64 to 66 HRC

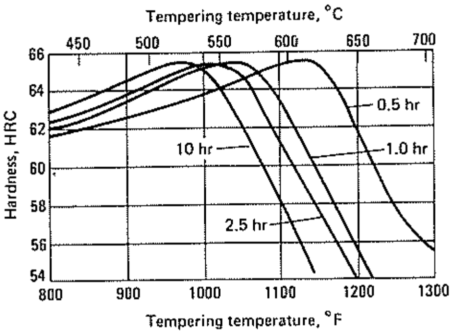
Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to –320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 540 to 595 °C (1000 to 1105 °F) for at least 2 h, cool to room temperature, and retemper for 2 h. Approximate tempered hardness as it corresponds to tempering temperature, 65 to 60 HRC

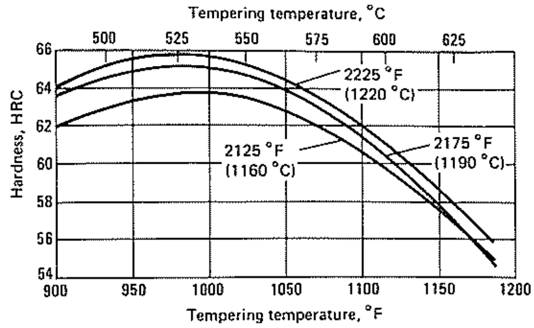
Recommended Processing Sequence

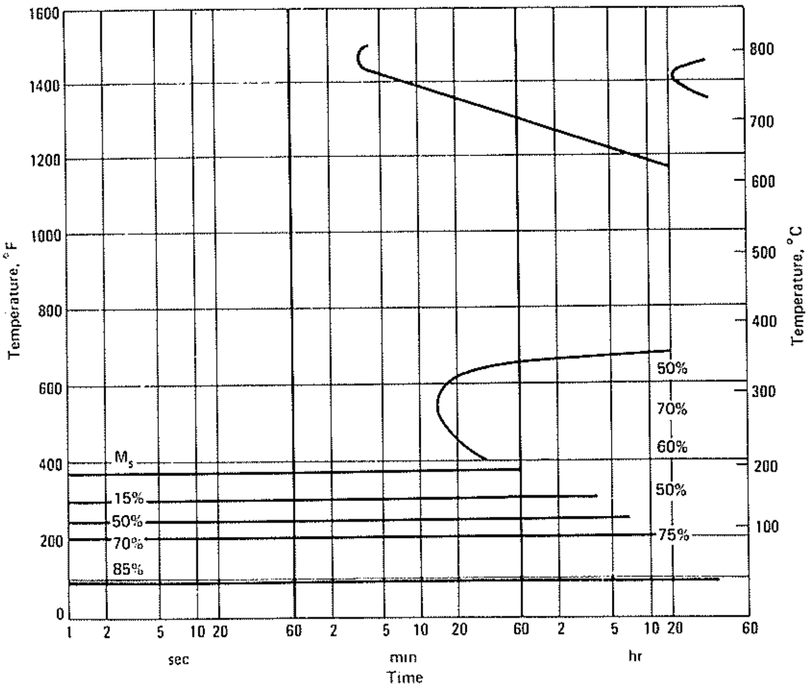
- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/double
- Final grind to size

M10: Hardness vs Time and Tempering Temperature. Austenitized at 1205 °C (2200 °F) and tempered for times indicated



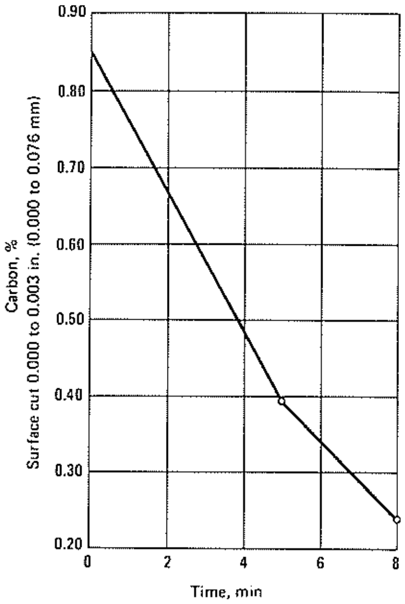
M10: Hardness vs Tempering Temperature. Austenitized at 1220 °C (2225 °F), 1190 °C (2175 °F), and 1165 °C (2125 °F) and double tempered (2 h plus 2 h)



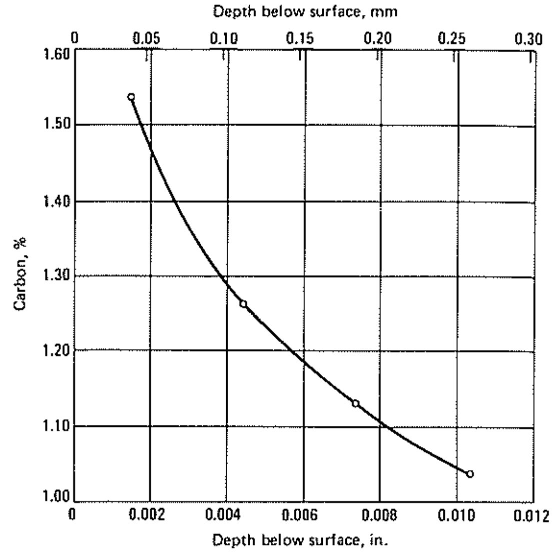


M10: Isothermal Transformation Diagram. Contains 0.85 C, 4.0 Cr, 8.0 Mo, 1.90 V. Austenitized at 1220 °C (2225 °F). Source: Crucible Steel

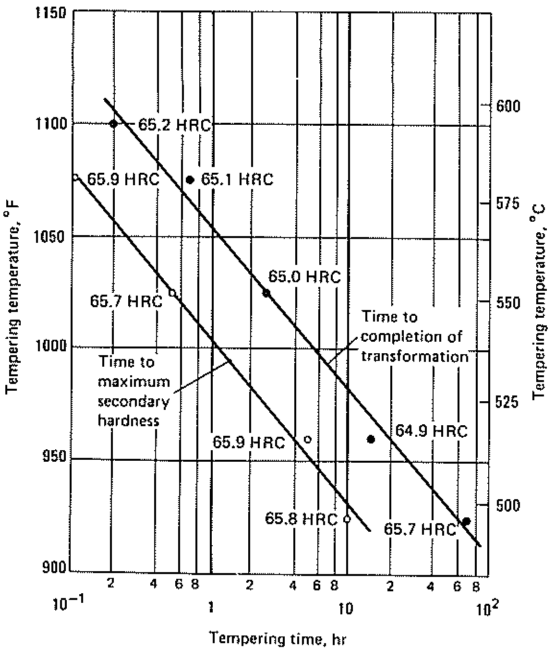
M10: Surface Carbon Content vs Time at Temperature. The effect of time at 1205 °C (2200 °F) on the surface carbon content of M10 containing 2.26 V and 8.28 Mo. Treated in 11% carbon monoxide atmosphere



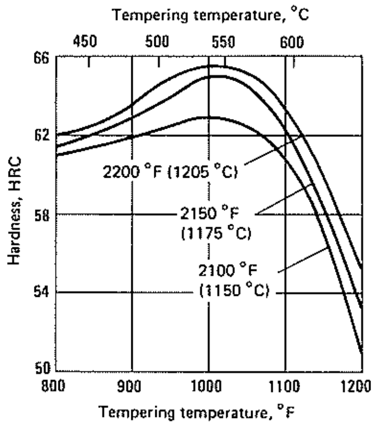
M10: Surface Carbon Content. M10 containing 0.87 C, 2.13 V, 8.20 Mo. Held at 1205 °C (2200 °F) for 6 min in an atmosphere of 23% carbon monoxide

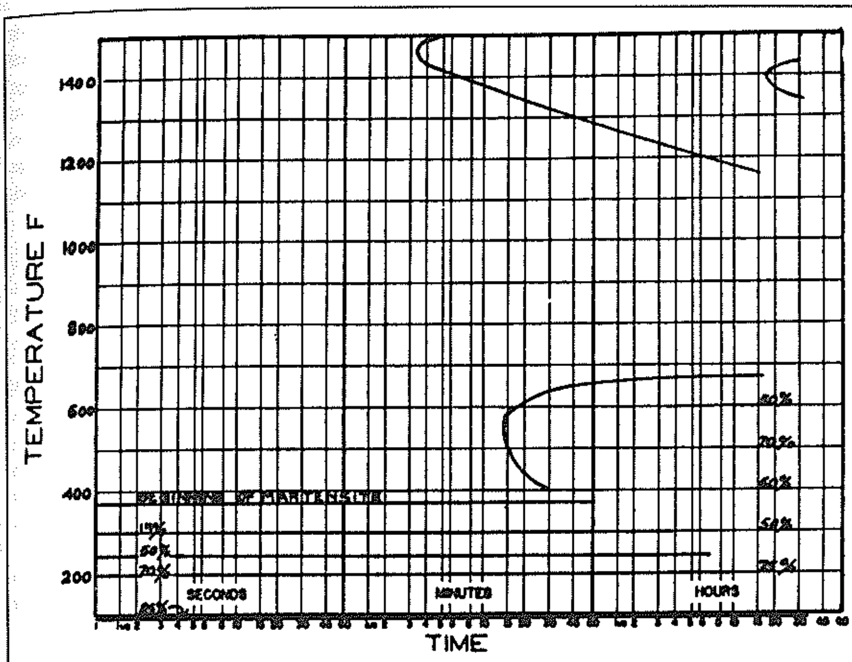


M10: Hardness vs Time at Tempering Temperature. Contains 8 Mo, 4 Cr, 2 V. Oil quenched from 1215 °C (2220 °F)



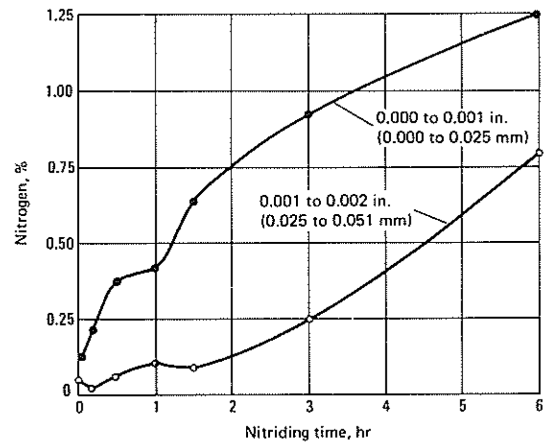
M10: Hardness vs Tempering Temperature. Austenitized at 1205 °C (2200 °F), 1175 °C (2150 °F), and 1150 °C (2100 °F) and double tempered. Source: Universal-Cyclops



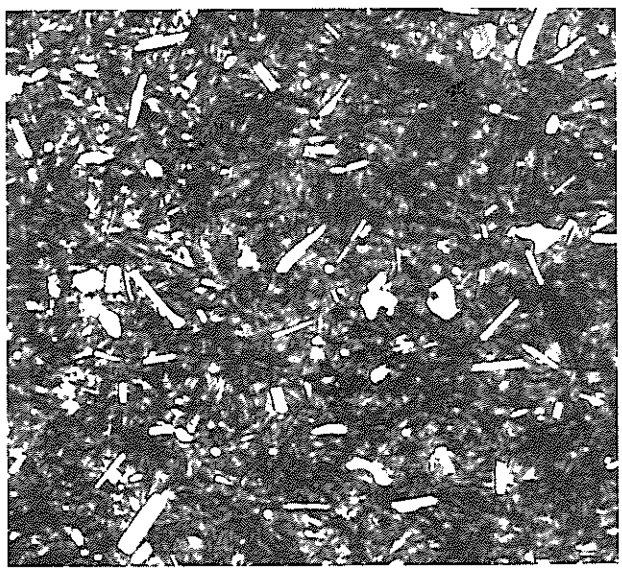


M10: Isothermal Transformation Diagram. Composition: 0.88 C, 4.00 Cr, 8.00 Mo, 1.90 V. Austenitized at 1220 °C (2225 °F)

M10: Nitriding Time vs Nitrogen Content. Nitrided at 565 °C (1050 °F). Effect of nitriding time on the nitrogen content of the surface layers of 0.000 to 0.025 mm (0.000 to 0.001 in.) and 0.025 to 0.050 mm (0.001 to 0.002 in.)



M10: Microstructure. 6% nital, 750×. 12.7 mm (0.50 in.) diam bar, austenitized at 1175 °C (2150 °F), oil quenched, double tempered (2 h plus 2 h) at 565 °C (1050 °F). Spheroidal, angular, and rod-shape carbide particles in tempered martensite



M30

Chemical Composition. **AISI:** Nominal. 0.80 C, 4.00 Cr, 8.00 Mo, 1.25 V, 2.00 W, 5.00 Co. **AISI/UNS:** Composition: 0.75 to 0.85 C, 0.15 to 0.40 Mn, 0.20 to 0.45 Si, 0.30 Ni max, 3.50 to 4.25 Cr, 7.75 to 9.00 Mo, 1.00 to 1.40 V, 1.30 to 2.30 W, 4.50 to 5.50 Co

Similar Steels (U.S. and/or Foreign). ASTM A600 (M-30); FED QQ-T-590 (M-30); (Ger.) DIN 1.3249; (U.K.) B.S. 4659 BM34

Characteristics. A relatively economical 5% cobalt grade which has molybdenum as the principal alloying element. One of the high-speed steels rating highest in resistance to softening at elevated temperature. Has a low toughness rating among tool steels in general as do other high-speed steels; using a lower austenitizing temperature results in lower hardness and improved impact resistance. Very high in wear resistance, has medium machinability, and low decarburization resistance

Forging. Start forging at 1040 to 1150 °C (1905 to 2100 °F). Do not forge after temperature of forging stock drops below 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Pack annealing in tightly closed containers or using a controlled atmosphere or vacuum is required to minimize decarburization. The packing material can be dry sand or lime to which a small amount of charcoal has been added. Burned cast iron chips are also satisfactory. Use a container that is only slightly larger than the load to minimize the amount of packing material required. This allows the pack to heat rapidly. After the steel has reached the annealing temperature, it should be held at temperature for 1 h per inch of thickness of the container. Cool slowly in furnace to 650 °C (1200 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 235 to 269 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

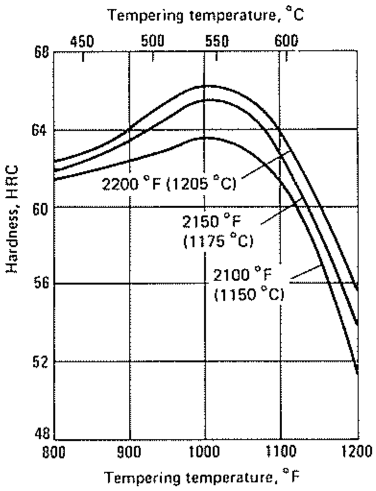
Hardening. Preheat at 730 to 845 °C (1350 to 1555 °F). Double preheating in one furnace at 540 to 650 °C (1000 to 1200 °F) and in another at 845 to 870 °C (1555 to 1600 °F) will minimize thermal shock. Preheating time, after all sections of the tool have reached equal temperature, should be twice the length of time required at the austenitizing temperature. Heat rapidly from the preheating to the austenitizing temperature. Austenitize at 1205 to 1230 °C (2200 to 2245 °F) for 2 to 5 min. Use 14 °C (25 °F) lower when hardening from salt.. Use shorter time for small sections and longer time for large sections. Tools austenitized at the lower end of the temperature range will have greater toughness, when compared to tools austenitized at the upper end of the range where greater alloy solution serves to impart higher hardness and hot hardness. Quench in oil, air, or salt. As-quenched hardness, 64 to 66 HRC

Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at −100 to −195 °C (−150 to −320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 540 to 595 °C (1000 to 1105 °F) for at least 2 h, cool to room temperature, and retemper for 2 h. Approximate tempered hardness as it corresponds to tempering temperature, 65 to 60 HRC

Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/double
- Final grind to size



M30: Hardness vs Tempering Temperature. Austenitized at 1205 °C (2200 °F), 1175 °C (2150 °F), and 1150 °C (2100 °F) and double tempered. Source: Universal-Cyclops

M33

Chemical Composition. **AISI:** Nominal. 0.90 C, 4.00 Cr, 9.50 Mo, 1.15 V, 1.50 W, 8.00 Co. **AISI/UNS:** Composition: 0.85 to 0.92 C, 0.15 to 0.40 Mn, 0.15 to 0.50 Si, 0.30 Ni max, 3.50 to 4.00 Cr, 9.00 to 10.00 Mo, 1.00 to 1.35 V, 1.30 to 2.10 W, 7.75 to 8.75 Co

Similar Steels (U.S. and/or Foreign). ASTM A600 (M-33); FED QQ-T-590 (M-33); (Ger.) DIN 1.3249; (U.K.) B.S. 4659 BM34

Characteristics. This grade contains 8% cobalt and ranks highest among high-speed steels in resistance to softening at elevated temperature, as do other grades containing 8 or 12% cobalt. The principal alloying element is molybdenum, which makes it relatively economical for the hot hardness properties it provides. Very high resistance. Has a low toughness rating among tool steels in general, as do other high-speed steels. Using a lower austenitizing temperature, however, results in lower hardness and improved impact resistance. Has medium machinability and low decarburization resistance

Forging. Start forging at 1040 to 1150 °C (1905 to 2100 °F). Do not forge after temperature of forging stock drops below 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Pack annealing in tightly closed containers or using a controlled atmosphere or vacuum is required to minimize decarburization. The packing material can be dry sand or lime to which a small amount of charcoal has been added. Burned cast iron chips are also satisfactory. Use a container that is only slightly larger than the load to minimize the amount of packing material required. This allows the pack to heat rapidly. After the steel has reached the annealing temperature, it should be held at temperature for 1 h per inch of thickness of the container. Cool slowly in furnace to 650 °C (1200 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 235 to 269 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

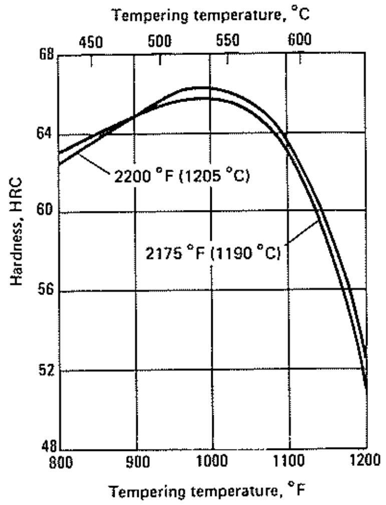
Hardening. Preheat at 730 to 845 °C (1350 to 1555 °F). Double preheating in one furnace at 540 to 650 °C (1000 to 1200 °F) and in another at 845 to 870 °C (1555 to 1600 °F) will minimize thermal shock. Preheating time, after all sections of the tool have reached equal temperature, should be twice the length of time required at the austenitizing temperature. Heat rapidly from the preheating to the austenitizing temperature. Austenitize at 1205 to 1230 °C (2200 to 2245 °F) for 2 to 5 min. Use 14 °C (25 °F) lower when hardening from salt. Use shorter time for small sections and longer time for large sections. Tools austenitized at the lower end of the temperature range will have greater toughness, when compared to tools austenitized at the upper end of the range where greater alloy solution serves to impart higher hardness and hot hardness. Quench in oil, air, or salt. As-quenched hardness, 64 to 66 HRC

Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to –320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 540 to 595 °C (1000 to 1105 °F) for at least 2 h, cool to room temperature, and retemper for 2 h. Approximate tempered hardness as it corresponds to tempering temperature, 65 to 60 HRC

Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/double
- Final grind to size



M33: Hardness Tempering Temperature. Austenitized at 1190 °C (2175 °F) and 1205 °C (2200 °F) and double tempered. Source: Universal-Cyclops

M34

Chemical Composition. **AISI:** Nominal. 0.90 C, 4.00 Cr, 8.00 Mo, 2.00 V, 2.00 W, 8.00 Co. **AISI/UNS:** Composition: 0.85 to 0.92 C, 0.15 to 0.40 Mn, 0.20 to 0.45 Si, 0.30 Ni max, 3.50 to 4.00 Cr, 7.75 to 9.20 Mo, 1.90 to 2.30 V, 1.40 to 2.10 W, 7.75 to 8.75 Co

Similar Steels (U.S. and/or Foreign). ASTM A600 (M-34); FED QQ-T-590 (M-34); (Ger.) DIN 1.3249; (U.K.) B.S. 4659 BM34

Characteristics. This grade contains 8% cobalt and ranks highest among high-speed steels in resistance to softening at elevated temperature as do the other grades containing 8 and 12% cobalt. The principal alloying element is molybdenum, which makes it relatively economical for the hot hardness properties it provides. Very high wear resistance. Has a low toughness rating among tool steels in general, as do the other high-speed steels. However, using a lower austenitizing temperature results in lower hardness and improved impact resistance. Has medium machinability and low decarburization resistance

Forging. Start forging at 1040 to 1150 °C (1905 to 2100 °F). Do not forge after temperature of forging stock drops below 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Pack annealing in tightly closed containers or using a controlled atmosphere or vacuum is required to minimize decarburization. The packing material can be dry sand or lime to which a small amount of charcoal has been added. Burned cast iron chips are also satisfactory. Use a container that is only slightly larger than the load to minimize the amount of packing material required. This allows the pack

› heat rapidly. After the steel has reached the annealing temperature, it hould be held at temperature for 1 h per inch of thickness of the container. :ool slowly in furnace to 650 °C (1200 °F) at a rate not to exceed 22 °C 40 °F) per h, after which a faster cooling rate will not affect final hardness. ypical annealed hardness, 235 to 269 HB

;tress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) nd hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

lardening. Preheat at 730 to 815 °C (1350 to 1500 °F). Double preheat-ıg in one furnace at 540 to 650 °C (1000 to 1200 °F) and in another at 845 › 870 °C (1555 to 1600 °F) will minimize thermal shock. Preheating time, fter all sections of the tool have reached equal temperature, should be vice the length of time required at the austenitizing temperature. Heat apidly from the preheating to the austenitizing temperature. Austenitize at 205 to 1230 °C (2200 to 2245 °F) for 2 to 5 min. Use 14 °C (25 °F) lower /hen hardening from salt. Use shorter time for small sections and longer me for large sections. Tools austenitized at the lower end of the tempera-ıre range will have greater toughness, when compared to tools austenitized t the upper end of the range where greater alloy solution serves to impart higher hardness and hot hardness. Quench in oil, air, or salt. As-quenched hardness, 64 to 66 HRC

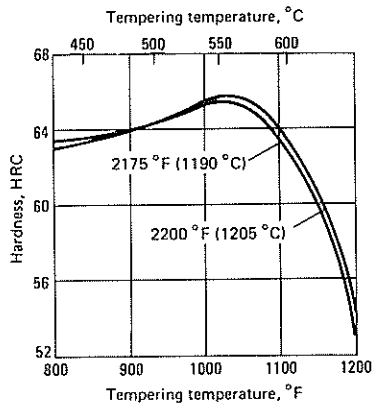
Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to –320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 540 to 595 °C (1000 to 1105 °F) for at least 2 h, cool to room temperature, and retemper for 2 h. Approximate tempered hardness as it corresponds to tempering temperature, 65 to 60 HRC

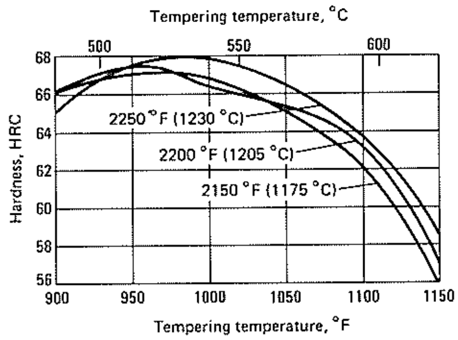
Recommended Processing Sequence

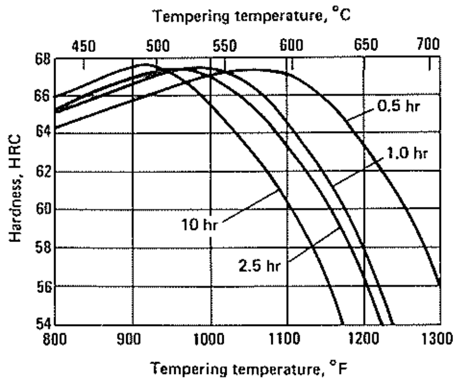
- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/double
- Final grind to size

M34: Hardness vs Tempering Temperature. Austenitized at 1190 °C (2175 °F) and 1205 °C (2200 °F) and double tempered. Source: Universal-Cyclops



M34: Hardness vs Austenitizing and Tempering Temperature. Austenitized at 1230 °C (2245 °F), 1205 °C (2200 °F), and 1175 °C (2150 °F). Double tempered (2 h plus 2 h)





M34: Hardness vs Time and Tempering Temperature. Austenitized at 1210 °C (2210 °F) and tempered at the times and temperatures indicated

M35

Chemical Composition. **AISI/UNS (T11335):** 0.82 to 0.88 C, 0.15 to 0.40 Mn, 0.20 to 0.45 Si, 0.30 Ni max, 3.75 to 4.50 Cr, 4.50 to 5.50 Mo, 1.75 to 2.20 V, 5.50 to 6.75 W, 4.50 to 5.50 Co

Similar Steels (U.S. and/or Foreign). (Ger.) DIN 1.3243; (Fr.) AFNOR A35-590 4371 Z 85 WDKCV 06-05-05-0402, A35-590 4372 Z 90 WDKC 06-05-05-04; (Jap.) JIS G4403 SKH 55; (U.K.) B.S. 4659 BM34

M36

Chemical Composition. **AISI:** Nominal. 0.80 C, 4.00 Cr, 5.00 Mo, 2.00 V, 6.00 W, 8.00 Co. **AISI/UNS:** Composition: 0.80 to 0.90 C, 0.15 to 0.40 Mn, 0.20 to 0.45 Si, 0.30 Ni max, 3.75 to 4.50 Cr, 4.50 to 5.50 Mo, 1.75 to 2.25 V, 5.50 to 6.50 W, 7.75 to 8.75 Co

Similar Steels (U.S. and/or Foreign). ASTM A600 (M-36); FED QQ-T-590 (M-36); (Ger.) DIN 1.3243; (Fr.) AFNOR A35-590 4371 Z 85 WDYCV 06-05-05-04; (Jap.) JIS G4403 SKH 55; (Swed.) SS 2723

Characteristics. This grade has the popular M2 analysis with 8% cobalt added. This addition imparts much greater resistance to softening at elevated temperatures, and it ranks among the highest of the high-speed grades in this property. Wear resistance is very high. Has a low toughness rating among tool steels in general, as do the other high-speed steels. However, using a lower austenitizing temperature results in lower hardness and improved impact resistance. Has medium machinability and low decarburization resistance

Forging. Start forging at 1040 to 1150 °C (1905 to 2100 °F). Do not forge after temperature of forging stock drops below 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Pack annealing in tightly closed containers or using a controlled atmosphere or vacuum is required to minimize decarburization. The packing material can be dry sand or lime to which a small amount of charcoal has been added. Burned cast iron chips are also satisfactory. Use a container that is only slightly larger than the load to minimize the amount of packing material required. This allows the pack to heat rapidly. After the steel has reached the annealing temperature, it should be held at temperature for 1 h per inch of thickness of the container. Cool slowly in furnace to 650 °C (1200 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 235 to 269 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Preheat at 730 to 845 °C (1350 to 1555 °F). Double preheating in one furnace at 540 to 650 °C (1000 to 1200 °F) and in another at 845 to 870 °C (1555 to 1600 °F) will minimize thermal shock. Preheating time, after all sections of the tool have reached equal temperature, should be twice the length of time required at the austenitizing temperature. Heat rapidly from the preheating to the austenitizing temperature. Austenitize at 1220 to 1245 °C (2225 to 2275 °F) for 2 to 5 min. Use 14 °C (25 °F) lower when hardening from salt. Use shorter time for small sections and longer time for large sections. Tools austenitized at the lower end of the temperature range will have greater toughness, when compared to tools austenitized at the upper end of the range where greater alloy solution serves to impart higher hardness and hot hardness. Quench in oil, air, or salt. As-quenched hardness, 64 to 66 HRC

Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to –320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 540 to 595 °C (1000 to 1105 °F) for at least 2 h, cool to room temperature, and retemper for 2 h. Approximate tempered hardness as it corresponds to tempering temperature, 65 to 60 HRC

Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/double
- Final grind to size

M41

Chemical Composition. **AISI:** Nominal. 1.10 C, 4.25 Cr, 3.75 Mo, 2.00 V, 6.75 W, 5.00 Co. **AISI/UNS:** Composition: 1.05 to 1.15 C, 0.20 to 0.60 Mn, 0.15 to 0.50 Si, 0.30 Ni max, 3.75 to 4.50 Cr, 3.25 to 4.25 Mo, 1.75 to 2.25 V, 6.25 to 7.00 W, 7.75 to 8.75 Co

Similar Steels (U.S. and/or Foreign). ASTM A600 (M-41); FED QQ-T-590 (M-41); (Ger.) DIN 1.3245, 1.3246; (Fr.) AFNOR A35-590 4374 Z 110 WKCDV 07-05-05-04; (Jap.) JIS G4403 SKH 55; (Swed.) SS 2736

Characteristics. The high carbon and cobalt content of this grade impart super high-speed properties. Hardness as high as 70 HRC is obtainable. Along with other high-speed cobalt grades, it ranks highest in resistance to softening at elevated temperatures. Has a low toughness rating among tool steels in general, as do other high-speed steels. However, using a lower austenitizing temperature results in lower hardness and improved impact resistance. Has medium machinability and low decarburization resistance

Forging. Start forging at 1040 to 1150 °C (1905 to 2100 °F). Do not forge after temperature of forging stock drops below 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Pack annealing in tightly closed containers or using a controlled atmosphere or vacuum is required to minimize decarburization. The packing material can be dry sand or lime to which a small amount of charcoal has been added. Burned cast iron chips are also satisfactory. Use a container that is only slightly larger than the load to minimize the amount of packing material required. This allows the pack to heat rapidly. After the steel has reached the annealing temperature, it should be held at temperature for 1 h per inch of thickness of the container. Cool slowly in furnace to 650 °C (1200 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 235 to 269 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Preheat at 730 to 845 °C (1350 to 1555 °F). Double preheating in one furnace at 540 to 650 °C (1000 to 1200 °F) and in another at 845 to 870 °C (1555 to 1600 °F) will minimize thermal shock. Preheating time, after all sections of the tool have reached equal temperature, should be twice the length of time required at the austenitizing temperature. Heat rapidly from the preheating to the austenitizing temperature. Austenitize at 1190 to 1215 °C (2175 to 2220 °F) for 2 to 5 min. Use 14 °C (25 °F) lower when hardening from salt. Use shorter time for small sections and longer time for large sections. Tools austenitized at the lower end of the temperature range will have greater toughness, when compared to tools austenitized at the upper end of the range where greater alloy solution serves to impart higher hardness and hot hardness. Quench in oil, air, or salt. As-quenched hardness, 63 to 65 HRC

Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to –320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 540 to 595 °C (1000 to 1105 °F) for at least 2 h, cool to room temperature, and retemper for 2 h. A third temper is recommended. Approximate tempered hardness as it corresponds to tempering temperature, 70 to 65 HRC

Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/triple
- Final grind to size

M42

Chemical Composition. **AISI:** Nominal. 1.10 C, 3.75 Cr, 9.50 Mo, 1.15 V, 1.50 W, 8.00 Co. **AISI/UNS:** Composition: 1.05 to 1.15 C, 0.15 to 0.40 Mn, 0.15 to 0.65 Si, 0.30 Ni max, 3.50 to 4.25 Cr, 9.00 to 10.00 Mo, 0.95 to 1.35 V, 1.15 to 1.85 W, 7.75 to 8.75 Co

Similar Steels (U.S. and/or Foreign). ASTM A600 (M-42); FED QQ-T-590 (M-42); (Ger.) DIN 1.3247; (Fr.) AFNOR A35-590 4475 Z 110 DKCWV 09-08-04-02-01; (Jap.) JIS G4403 SKH 59; (U.K.) B.S. 4659 BM42

Characteristics. The high carbon and cobalt content of this grade impart super high-speed properties. Hardness as high as 70 HRC is obtainable. Especially suitable for demanding cutting, such as heavy chip removal of super alloys. Along with other cobalt high-speed grades, it ranks highest in resistance to softening at elevated temperatures. The principal alloying element is molybdenum, making it an economical grade for the high-speed properties it provides. Has a low toughness rating among tool steels in general, as do other high-speed steels. However, using a lower austenitizing temperature results in lower hardness and improved impact resistance. Has medium machinability and low decarburization resistance

Forging. Start forging at 1040 to 1150 °C (1905 to 2100 °F). Do not forge after temperature of forging stock drops below 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Pack annealing in tightly closed containers or using a controlled atmosphere or vacuum is required to minimize decarburization. The packing material can be dry sand or lime to which a small amount of charcoal has been added. Burned cast iron chips are also satisfactory. Use a container that is only slightly larger than the load to minimize the amount of packing material required. This allows the pack to heat rapidly. After the steel has reached the annealing temperature, it should be held at temperature for 1 h per inch of thickness of the container. Cool slowly in furnace to 650 °C (1200 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 235 to 269 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

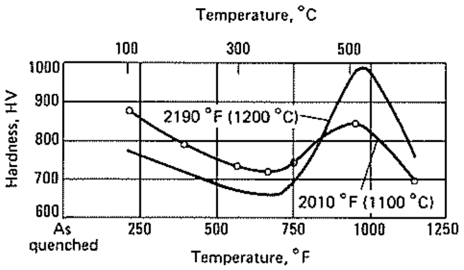
Hardening. Preheat at 730 to 845 °C (1350 to 1555 °F). Double preheating in one furnace at 540 to 650 °C (1000 to 1200 °F) and in another at 845 to 870 °C (1555 to 1600 °F) will minimize thermal shock. Preheating time, after all sections of the tool have reached equal temperature, should be twice the length of time required at the austenitizing temperature. Heat rapidly from the preheating to the austenitizing temperature. Austenitize at 1165 to 1190 °C (2125 to 2175 °F) for 2 to 5 min. Use 14 °C (25 °F) lower when hardening from salt. This grade is available in two silicon contents, 0.30 and 0.55%. When 0.55% silicon is used, the maximum suggested hardening temperature is 1175 °C (2150 °F) rather than 1190 °C (2175 °F), which is the usual listed maximum temperature for this grade. This reduction, when added to the 14 °C (25 °F) normally employed with salt-bath hardening, establishes 1165 °C (2125 °F) as the maximum in salt. Use shorter time for small sections and longer time for large sections. Tools austenitized at the lower end of the temperature range will have greater toughness, when compared to tools austenitized at the upper end of the range where greater alloy solution serves to impart higher hardness and hot hardness. Quench in oil, air, or salt. As-quenched hardness, 63 to 65 HRC

Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to –320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 510 to 595 °C (950 to 1105 °F) for at least 2 h, cool to room temperature, and retemper for 2 h. A third temper is recommended. Approximate tempered hardness as it corresponds to tempering temperature, 70 to 65 HRC

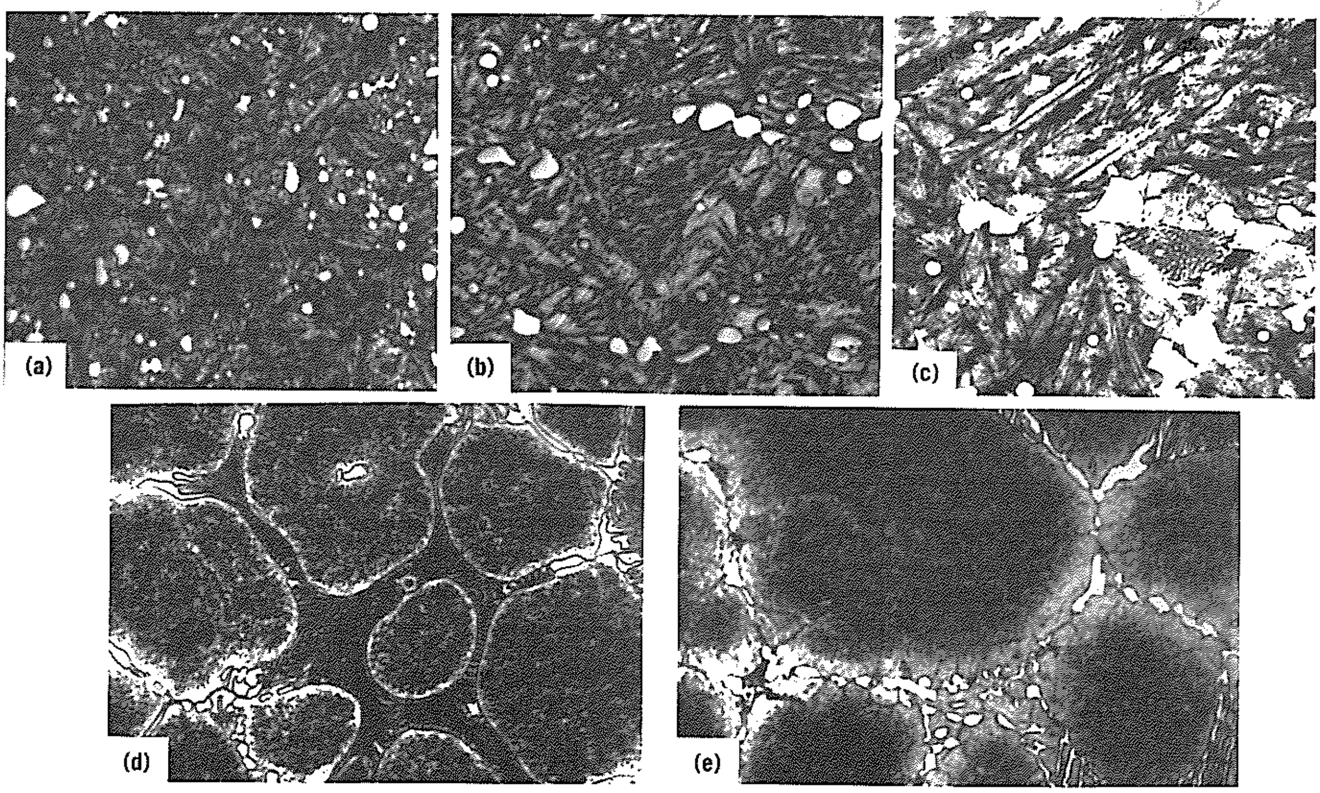
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/triple
- Final grind to size

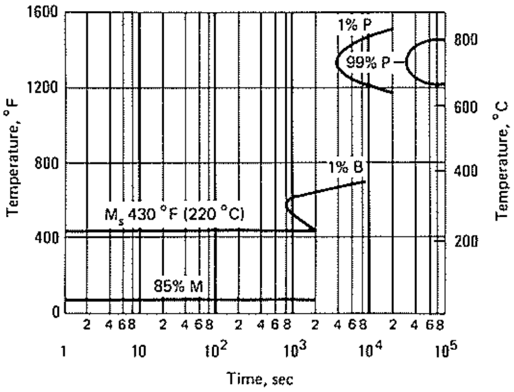


M42: Hardness vs Tempering Temperature. Austenitized at 1200 °C (2190 °F) and 1100 °C (2010 °F) and triple tempered (2 h plus 2 h plus 2 h). Source: Stora Steels and Climax Molybdenum

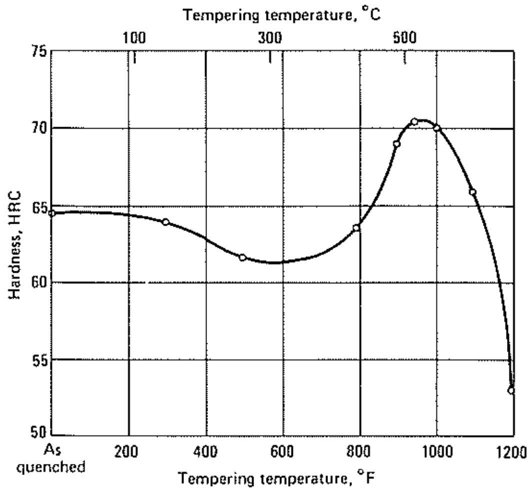
M42: Microstructures. (a) 6% nital, 750×. Austenitized at 1180 °C (2155 °F), oil quenched, triple tempered (2 h each) at 525 °C (975 °F). Spheroidal and angular carbide particles in matrix of tempered martensite. (b) 2% nital, 1000×. Austenitized at 1190 °C (2175 °F), salt quenched, air cooled, triple tempered (2 h each) at 540 °C (1000 °F). Alloy carbide particles in matrix of tempered martensite. (c) 2% nital, 1000×. Austenitized at 1225 °C (2240 °F), salt quenched, air cooled, triple tempered (2 h each) at 540 °C (1000 °F). Alloy carbide in matrix of martensite coarsened by overheating. (d) 6% nital, 500×. A disk 12 mm (½ in.) thick by 76 mm (3 in.) diam, as cast. Mixture of coarse martensite grains outlined by some spheroidal carbide particles, retained austenite, and eutectic (lamellar, near top). (e) 6% nital, 500×. Same as (d), except heated to 900 °C (1650 °F), austenitized at 1190 °C (2175 °F), salt quenched at 595 °C (1105 °F), air cooled, triple tempered (2 h each) at 550 °C (1020 °F). Tempered martensite and grain-boundary carbide



M42: Isothermal Transformation Diagram. Austenitized at 1225 °C (2240 °F). Source: Stora Steels



M42: Hardness vs Tempering Temperature. Quenched from 1205 °C (2200 °F). Source: Teledyne VASCO



M43

:hemical Composition. **AISI:** Nominal. 1.20 C, 3.75 Cr, 8.00 Mo, .60 V, 2.75 W, 8.25 Co. **AISI/UNS:** Composition: 1.15 to 1.25 C, 0.20 to).40 Mn, 0.15 to 0.65 Si, 0.30 Ni max, 3.50 to 4.25 Cr, 7.50 to 8.50 Mo, .50 to 1.75 V, 2.25 to 3.00 W, 7.75 to 8.75 Co

;imilar Steels (U.S. and/or Foreign). ASTM A600 (M-43); 'ED QQ-T-590 (M-43); (Fr.) AFNOR A35-590 4475 Z 110 DKCWV)9-08-04-02-01

:haracteristics. The high carbon and cobalt content of this grade mpart super high-speed properties. Hardness as high as 70 HRC is obtain-ıble. Especially suitable for demanding cutting, such as heavy chip re-noval of super alloys. Along with other cobalt high-speed grades, it ranks ighest in resistance to softening at elevated temperatures. Very high wear esistance. The principal alloying element is molybdenum, making it an :conomical grade for the high-speed properties it provides. Has a low oughness rating among tool steels in general, as do other high-speed teels. However, using a lower austenitizing temperature results in lower ıardness and improved impact resistance. Has medium machinability and ow decarburization resistance

=orging. Start forging at 1040 to 1150 °C (1905 to 2100 °F). Do not orge after temperature of forging stock drops below 925 °C (1695 °F)

?ecommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for ;mall sections and upper limit for large sections. Pack annealing in tightly :losed containers or using a controlled atmosphere or vacuum is required o minimize decarburization. The packing material can be dry sand or lime o which a small amount of charcoal has been added. Burned cast iron chips ıre also satisfactory. Use a container that is only slightly larger than the load o minimize the amount of packing material required. This allows the pack o heat rapidly. After the steel has reached the annealing temperature, it ;hould be held at temperature for 1 h per inch of thickness of the container. :ool slowly in furnace to 650 °C (1200 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 248 to 269 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Preheat at 730 to 845 °C (1350 to 1555 °F). Double preheating in one furnace at 540 to 650 °C (1000 to 1200 °F) and in another at 845 to 870 °C (1555 to 1600 °F) will minimize thermal shock. Preheating time, after all sections of the tool have reached equal temperature, should be twice the length of time required at the austenitizing temperature. Heat rapidly from the preheating to the austenitizing temperature. Austenitize at 1150 to 1175 °C (2100 to 2150 °F) for 2 to 5 min. Use 14 °C (25 °F) lower when hardening from salt. Use shorter time for small sections and longer time for large sections. Tools austenitized at the lower end of the temperature range will have greater toughness, when compared to tools austenitized at the upper end of the range where greater alloy solution serves to impart higher hardness and hot hardness. Quench in oil, air, or salt. As-quenched hardness, 63 to 65 HRC

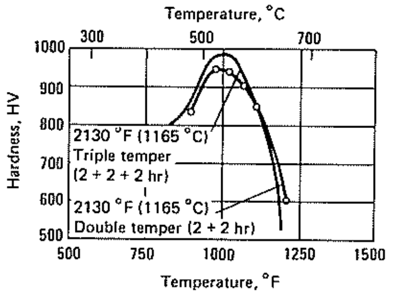
Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to –320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 510 to 595 °C (950 to 1105 °F) for at least 2 h, cool to room temperature, and retemper for 2 h. A third temper is recommended. Approximate tempered hardness as it corresponds to tempering temperature, 70 to 65 HRC

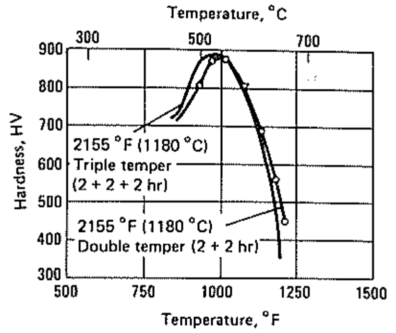
Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/triple
- Final grind to size

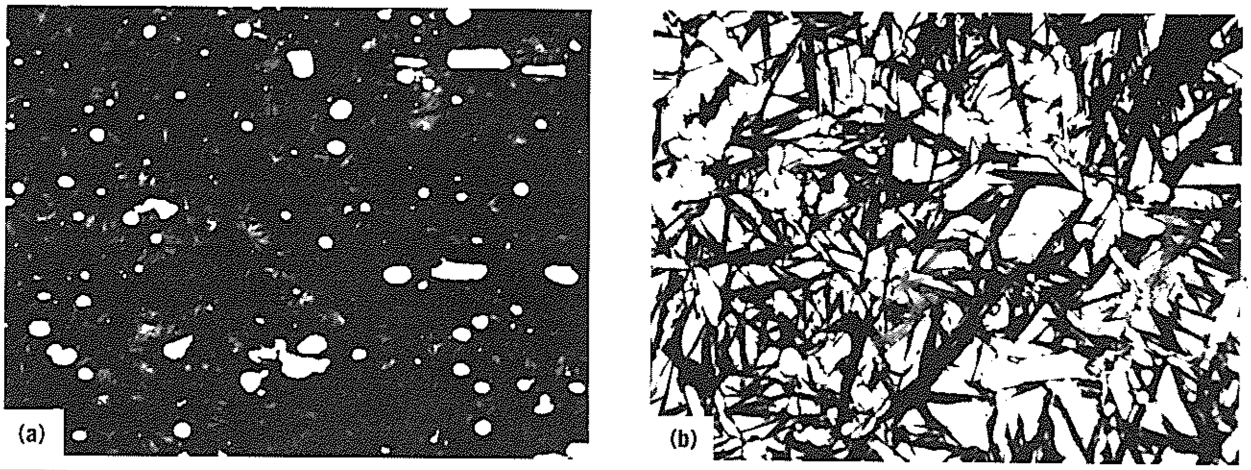
M43: Hardness vs Tempering Temperature. Austenitized at 1165 °C (2125 °F) and triple tempered (2 h plus 2 h, plus 2 h). Austenitized at 1165 °C (2125 °F) and double tempered (2 h plus 2 h). Source: Climax Molybdenum



M43: Hardness vs Tempering Temperature. Tempering curves for M43 austenitized at 1180 °C (2155 °F) and triple tempered (2 h plus 2 h, plus 2 h) and double tempered (2 h plus 2 h). Source: Climax Molybdenum



M43: Microstructures. (a) 4% nital, 1000×. Austenitized at 1190 °C (2175 °F), salt quenched at 565 °C (1050 °F), air cooled, double tempered (2 h plus 2 h) at 565 °C (1050 °F). Alloy carbide particles (white) in matrix of tempered martensite. (b) 4% nital, 1000×. Severely overheated by austenitizing at a temperature above 1205 °C (2200 °F). Tailed, fused, and angular particles of carbide in coarse martensite and retained austenite. See (a)



M44

Chemical Composition. **AISI:** Nominal. 1.15 C, 4.25 Cr, 6.25 Mo, 2.00 V, 5.25 W, 12.00 Co. **AISI/UNS:** Composition: 1.10 to 1.20 C, 0.20 to 0.40 Mn, 0.30 to 0.55 Si, 0.30 Ni max, 4.00 to 4.75 Cr, 6.00 to 7.00 Mo, 1.85 to 2.20 V, 5.00 to 5.75 W, 11.00 to 12.25 Co

Similar Steels (U.S. and/or Foreign). ASTM A600 (M-44); FED QQ-T-590 (M-44); (Ger.) DIN 1.3207; (Fr.) AFNOR A35-590 4376 Z 130 KWDCV 12-07-06-04-03; (Jap.) JIS G4403 SKH 57; (U.K.) B.S. 4659 (USA M44)

Characteristics. Has extreme hot hardness and is suitable for high-speed cutting of superalloys. Qualifies as a super high-speed steel. Hardness as high as 70 HRC is attainable. Very high wear resistance. Has low toughness when rated among tool steels in general, as do other high-speed steels. Using a lower austenitizing temperature results in lower hardness and improved impact resistance. Has medium machinability and low decarburization resistance

Forging. Start forging at 1040 to 1150 °C (1905 to 2100 °F). Do not forge after temperature of forging stock drops below 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Pack annealing in tightly closed containers or using a controlled atmosphere or vacuum is required to minimize decarburization. The packing material can be dry sand or lime to which a small amount of charcoal has been added. Burned cast iron chips are also satisfactory. Use a container that is only slightly larger than the load to minimize the amount of packing material required. This allows the pack to heat rapidly. After the steel has reached the annealing temperature, it should be held at temperature for 1 h per inch of thickness of the container. Cool slowly in furnace to 650 °C (1200 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 248 to 285 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

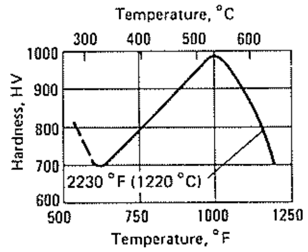
Hardening. Preheat at 730 to 845 °C (1350 to 1555 °F). Double preheating in one furnace at 540 to 650 °C (1000 to 1200 °F) and in another at 845 to 870 °C (1555 to 1600 °F) will minimize thermal shock. Preheating time, after all sections of the tool have reached equal temperature, should be twice the length of time required at the austenitizing temperature. Heat rapidly from the preheating to the austenitizing temperature. Austenitize at 1200 to 1225 °C (2190 to 2240 °F) for 2 to 5 min. Use 14 °C (25 °F) lower when hardening from salt. Use shorter time for small sections and longer time for large sections. Tools austenitized at the lower end of the temperature range will have greater toughness, when compared to tools austenitized at the upper end of the range where greater alloy solution serves to impart higher hardness and hot hardness. Quench in oil, air, or salt. As-quenched hardness, 63 to 65 HRC

Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to –320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 540 to 625 °C (1000 to 1160 °F) for at least 2 h, cool to room temperature, and retemper for 2 h. A third temper is recommended. Approximate tempered hardness as it corresponds to tempering temperature, 70 to 62 HRC

Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/triple
- Final grind to size



M44: Hardness vs Tempering Temperature. Austenitized at 1220 °C (2225 °F). Source: Climax Molybdenum

M46

Chemical Composition. **AISI:** Nominal. 1.25 C, 4.00 Cr, 8.25 Mo, 3.20 V, 2.00 W, 8.25 Co. **AISI/UNS:** Composition: 1.22 to 1.30 C, 0.20 to 0.40 Mn, 0.40 to 0.65 Si, 0.30 Ni max, 3.70 to 4.20 Cr, 8.00 to 8.50 Mo, 3.00 to 3.30 V, 1.90 to 2.20 W, 7.80 to 8.80 Co

Similar Steels (U.S. and/or Foreign). ASTM A600 (M-46); FED QQ-T-590 (M-46); (Ger.) DIN 1.3247

Characteristics. Has excellent hot hardness and wear resistance. Hardness to 69 HRC is attainable. Rates as a super high-speed steel. Has low toughness when rated among tool steels in general, as do other high-speed steels. Using a lower austenitizing temperature results in lower hardness and improved impact resistance. Has medium machinability and low decarburization resistance

Forging. Start forging at 1040 to 1150 °C (1905 to 2100 °F). Do not forge after temperature of forging stock drops below 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Pack annealing in tightly closed containers or using a controlled atmosphere or vacuum is required to minimize decarburization. The packing material can be dry sand or lime to which a small amount of charcoal has been added. Burned cast iron chips are also satisfactory. Use a container that is only slightly larger than the load to minimize the amount of packing material required. This allows the pack to heat rapidly. After the steel has reached the annealing temperature, it should be held at temperature for 1 h per inch of thickness of the container. Cool slowly in furnace to 650 °C (1200 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 235 to 269 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

Hardening. Preheat at 730 to 845 °C (1350 to 1555 °F). Double preheating in one furnace at 540 to 650 °C (1000 to 1200 °F) and in another at 845 to 870 °C (1555 to 1600 °F) will minimize thermal shock. Preheating time, after all sections of the tool have reached equal temperature, should be twice the length of time required at the austenitizing temperature. Heat rapidly from the preheating to the austenitizing temperature. Austenitize at 1190 to 1220 °C (2175 to 2225 °F) for 2 to 5 min. Use 14 °C (25 °F) lower when hardening from salt. Use shorter time for small sections and longer time for large sections. Tools austenitized at the lower end of the temperature range will have greater toughness, when compared to tools austenitized at the upper end of the range where greater alloy solution serves to impart higher hardness and hot hardness. Quench in oil, air, or salt. As-quenched hardness, 63 to 65 HRC

Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at –100 to –195 °C (–150 to –320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 525 to 565 °C (975 to 1050 °F) for at least 2 h, cool to room temperature, and retemper for 2 h. A third temper is recommended. Approximate tempered hardness, 69 to 67 HRC

Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/triple
- Final grind to size

M47

Chemical Composition. AISI: Nominal. 1.10 C, 3.75 Cr, 9.50 Mo, 1.25 V, 1.50 W, 5.00 Co. **AISI/UNS:** Composition: 1.05 to 1.15 C, 0.15 to 0.40 Mn, 0.20 to 0.45 Si, 0.30 Ni max, 3.50 to 4.00 Cr, 9.25 to 10.00 Mo, 1.15 to 1.35 V, 1.30 to 1.80 W, 4.75 to 5.25 Co

Similar Steels (U.S. and/or Foreign). ASTM A600 (M-47); (Ger.) DIN 1.3247

Characteristics. Similar to M1 grade with higher carbon and 5% cobalt added. Has extreme hot hardness and is suitable for high-speed cutting of super alloys. Qualifies as a super high-speed steel. Hardness as high as 70 HRC is attainable. Very high wear resistance. Has low toughness when rated among tool steels in general, as do other high-speed steels. Using a lower austenitizing temperature results in lower hardness and improved impact resistance. Has medium machinability and low decarburization resistance

Forging. Start forging at 1040 to 1150 °C (1905 to 2100 °F). Do not forge after temperature of forging stock drops below 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Heat to 870 to 900 °C (1600 to 1650 °F). Use lower limit for small sections and upper limit for large sections. Pack annealing in tightly closed containers or using a controlled atmosphere or vacuum is required to minimize decarburization. The packing material can be dry sand or lime to which a small amount of charcoal has been added. Burned cast iron chips are also satisfactory. Use a container that is only slightly larger than the load to minimize the amount of packing material required. This allows the pack to heat rapidly. After the steel has reached the annealing temperature, it should be held at temperature for 1 h per inch of thickness of the container. Cool slowly in furnace to 650 °C (1200 °F) at a rate not to exceed 22 °C (40 °F) per h, after which a faster cooling rate will not affect final hardness. Typical annealed hardness, 235 to 269 HB

Stress Relieving. Optional. Heat to 650 to 675 °C (1200 to 1245 °F) and hold for 1 h per inch of cross section (minimum of 1 h). Cool in air

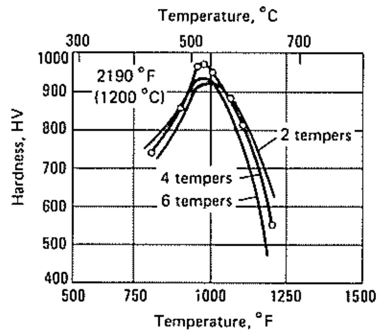
Hardening. Preheat at 730 to 845 °C (1350 to 1555 °F). Double preheating in one furnace at 540 to 650 °C (1000 to 1200 °F) and in another at 845 to 870 °C (1555 to 1600 °F) will minimize thermal shock. Preheating time, after all sections of the tool have reached equal temperature, should be twice the length of time required at the austenitizing temperature. Heat rapidly from the preheating to the austenitizing temperature. Austenitize at 1175 to 1205 °C (2150 to 2200 °F) for 2 to 5 min. Use 14 °C (25 °F) lower when hardening from salt. Use shorter time for small sections and longer time for large sections. Tools austenitized at the lower end of the temperature range will have greater toughness, when compared to tools austenitized at the upper end of the range where greater alloy solution serves to impart higher hardness and hot hardness. Quench in oil, air, or salt. As-quenched hardness, 63 to 65 HRC

Stabilizing. Optional. For intricate shapes, stress relieve temper at 150 to 160 °C (300 to 320 °F) briefly. Refrigerate at −100 to −195 °C (−150 to −320 °F). Temper immediately after part reaches room temperature

Tempering. Temper at 525 to 595 °C (975 to 1105 °F) for at least 2 h, cool to room temperature, and retemper for 2 h. A third temper is recommended. Approximate tempered hardness as it corresponds to tempering temperature, 70 to 65 HRC

Recommended Processing Sequence

- Rough machine
- Stress relieve (optional)
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper/triple
- Final grind to size



M47: Effect of Tempering on Hardness. Austenitized at 1200 °C (2190 °F) and tempered as indicated. Source: Climax Molybdenum

M48

Chemical Composition. AISI/UNS (T11348): 1.42 to 1.52 C, 0.15 to 0.40 Mn, 0.15 to 0.40 Si, 0.30 Ni max, 3.50 to 4.00 Cr, 4.75 to 5.50 Mo, 2.75 to 3.25 V, 9.50 to 10.50 W, 8.00 to 10.00 Co

Characteristics. Powder metallurgy steel said to be a suitable alternative for ASTM M40 alloys, particularly where high red hardness, high abrasion resistance, and good toughness are required. M48 is heat treatable to HRC 70. It is subject to decarburization in hardening, but the potential problem is avoided with proper control of furnace atmosphere. Hot rolling and rotary forging capabilities impart minimal distortion characteristics

Forging. Parts are heated slowly and uniformly to 1105 to 1135 °C (2025 to 2075 °F) and equalized to furnace temperature. If workpiece temperature falls below 925 °C (1695 °F), parts are reheated. After forging, parts are low cooled in mica to room temperature, then subcritically annealed, or ot parts may be subcritically annealed after forging. Full annealing should recede hardening

ɿecommended Heat Treating Practice

ʌnnealing. This process takes place after forging and before hardening. 'arts are fully annealed by heating uniformly to 870 °C (1600 °F), held at ɜmperature 2 h, followed by slow cooling to below 540 °C (1000 °F) at a ate not to exceed 15 °C (25 °F) per h, and air cooled to room temperature. 'ull annealed hardness is 285 to 311 BHN

ɟardening. It is customary to use two furnaces: one to preheat parts to 15 to 845 °C (1500 to 1555 °F); the second to rapidly heat from preheating ɜmperature to the hardening temperature of 1190 to 1205 °C (2175 to 2200 F) in atmosphere furnaces, or 1175 to 1195 °C (2150 to 2185 °F) in salt ıaths. Quenching is in oil or a salt bath maintained at 540 to 595 °C (1000 ɔ 1105 °F). In oil quenching, an interrupted quench is recommended, ıarticularly when parts are large in section or complicated in design. Oil ǀuenching should continue until parts reach approximately 540 to 595 °C 1000 to 1105 °F) (dull red color); then removed from oil and allowed to ir cool to below 66 °C (150 °F), or until parts can be touched comfortably vith a bare hand. In salt bath practice, parts are quenched into the bath and ıeld long enough for them to cool to bath temperature. At this point, they re removed from the bath and allowed to cool to below 66 °C (150 °F). 'arts large in section that have been salt bath quenched generally are lower n hardness than those processed with an interrupted quench

Straightening. This step should be done from the quench at any temperature down to 425 °C (795 °F)

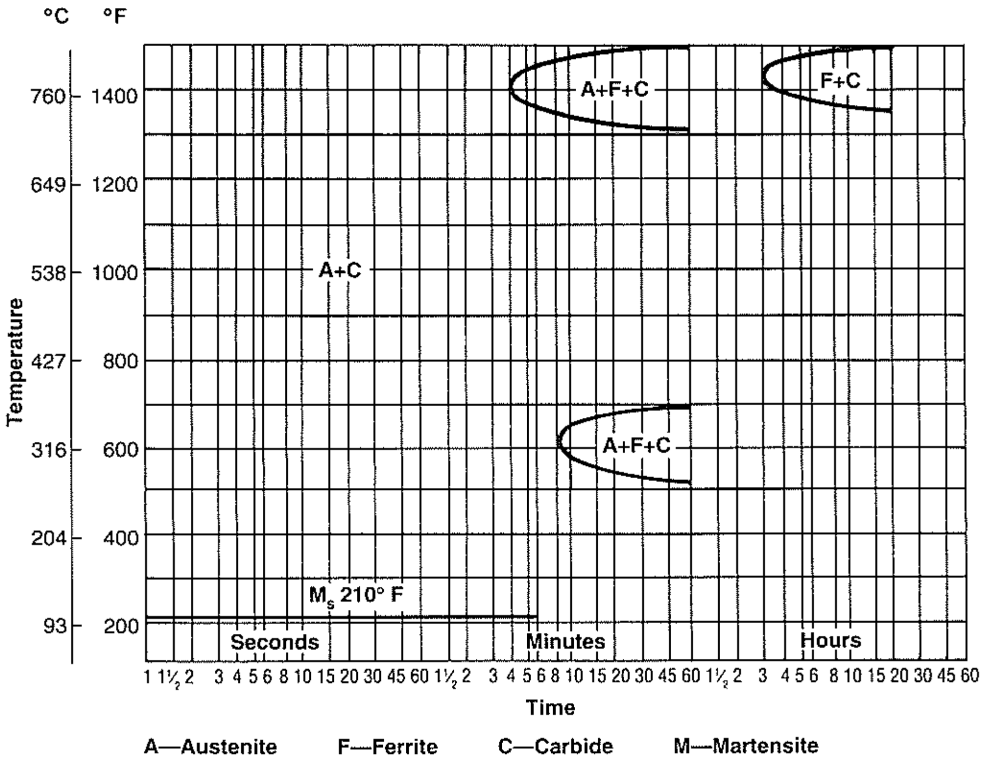
Tempering. This process should follow immediately after quenching and cooling parts to below 66 °C (150 °F). Tempering temperature used varies with the application and desired hardness. Triple tempering is required, and four tempers are desirable. Typical practice is 540 °C (1000 °F) for 2 h, followed by air cooling to room temperature. The cycle is repeated twice to get triple tempering

M48: Effect of Hardening and Tempering Temperatures on Hardness

Typical HRC values are based on austenitizing in a salt bath for 2 min at temperature, oil quenching, and triple tempering 2 plus 2 plus 2 h at indicated temperatures. Source: Carpenter Technology Corporation

Tempering Temperature		Austenitizing Temperature, Salt Bath	
°C	°F	1163 °C (2125 °F)	1191 °C (2175 °F)
As-Quenched		63/61	66/64
538	1000	69/67	70/68
552	1025	69/67	70/68
566	1050	68/66	69/67
593	1100	67/65	68/66
621	1150	63/61	65/63
649	1200	58/56	59/57

M48: Isothermal Transformation Diagram. Austenitizing temperature: 1190 °C (2175 °F); critical (A_1) temperature: 835 °C (1535 °F); prior condition: annealed. Source: Carpenter Technology Corporation



M50 (Carpenter VIM-VAR M-50 H5S)

Chemical Composition. **AISI M50-UNS T11350:** 0.78 to 0.88 C, 0.15 to 0.45 Mn, 0.20 to 0.60 Si, 0.30 Ni max, 3.75 to 4.50 Cr, 3.90 to 4.75 Mo, 0.80 to 1.25 V

Similar Steels (U.S. and/or Foreign). (Ger.) DIN 1.2369, 1.3551; (Fr.) AFNOR A35-590 480 DCV 42.16; (Swed.) (USA M50)

Characteristics. A high-speed steel with excellent resistance to multiaxial stresses and softening at high service temperatures, plus good resistance to oxidation. Compressive strength is high. When refined using vacuum induction melting (VIM) and vacuum arc remelting (VAR), the cleanliness of the product makes it possible to finish parts with a high luster. Applications range from those in bearings and the missile industry to tooling. Generally, a small amount of growth can be expected as-hardened, which is returned to almost zero with proper tempering. With air hardening, less size change and warpage are exhibited, but oil hardening and salt quenching are the common practices. Parts are normally machined in the fully annealed condition at a maximum hardness of HB 230. In this condition, the alloy's machinability rating is approximately 65% of AISI 1095 or 50% that of AISI B1112 steel

Decarburization. M50 must be heat treated from a relatively high temperature, and protected from changes in surface chemistry during the hardening operation. Treatment in neutral salt baths or in controlled atmosphere furnaces is recommended. A dew point of –9.5 to –6.5 °C (15 to 20 °F) is usually satisfactory

Forging. Parts are preheated to 760 to 815 °C (1400 to 1500 °F) and given time to equalize. From this point, furnace temperature is increased to 1065 to 1120 °C (1950 to 2050 °F). Forging should not be done below 980 °C (1795 °F). Parts may be reheated as often as necessary to maintain forging temperature. Following forging, parts may be cooled in the furnace or in lime or ashes. After cooling, forgings should be annealed

Recommended Heat Treating Practice

Normalizing. Not recommended when alloy is VIM-VAR refined

Annealing. Parts are heated uniformly to 845 to 900 °C (1555 to 1650 °F), then cooled slowly in the furnace at a rate not to exceed 10 °C (20 °F) per h. Slow cooling should be maintained until furnace is black. At that point, furnace may be turned off and allowed to cool naturally. A maximum hardness of HB 235 is the result. Because of susceptibility to decarburization, parts must be protected by packing in suitable containers with clean, cast iron borings or by annealing in a controlled atmosphere furnace

Stress Relieving. Relief of machining stresses provides for greater accuracy in hardening. Procedure: rough machine; anneal below critical at 650 to 675 °C (1200 to 1245 °F) for minimum of 1 h at temperature; slow cool; finish machine

Hardening. The recommended processing sequence is as follows: preheat to 815 °C (1500 °F) and equalize; then transfer parts to superheated furnace at 1100 °C (2010 °F). Superheat only long enough to allow parts to reach temperature of superheated furnace; follow immediately by quenching to room temperature. Then cool part to approximately –75 °C (–105 °F) and hold for 1 h. Next, double temper at 540 °C (1000 °F), which should produce a hardness of HRC 62 to 64 and optimum stability in terms of size change in service.

An alternative general hardening recommendation: preheat to 815 to 870 °C (1500 to 1600 °F). Parts may be oil, air, or high-temperature salt quenched

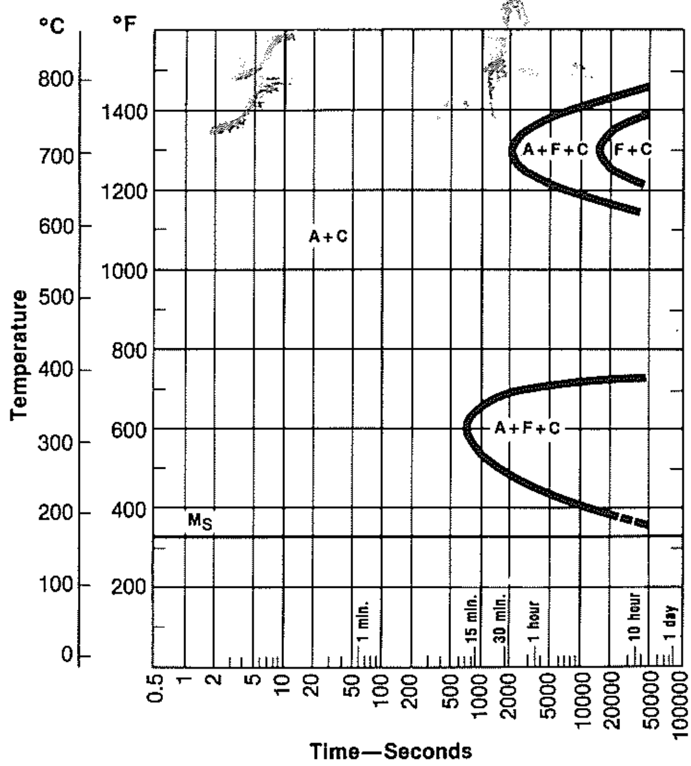
Tempering. After parts have been cooled in quenching, tempering should immediately follow. Normal tempering range is from 525 to 550 °C (975 to 1020 °F). Double tempering (2 h at heat for each temper) is recommended. Parts should be cooled back to room temperature between tempers

M50: Effect of Tempering Temperature

Austenitized at 1105 °C (2025 °F); oil quenched; double tempered (each temper, 2 h). (Source: Carpenter Technology Corporation)

Tempering Temperature °C	Tempering Temperature °F	Hardness, Rockwell C
As quenched		64/65
482	900	60/62
510	950	61/63
538	1000	62/64
566	1050	61/63
593	1100	60/62
621	1150	55/58
649	1200	53/56

M50: Isothermal Transformation Diagram. Austenitizing temperature: 1107 °C (2025 °F). Source: Carpenter Technology Corporation



Ultrahigh-Strength Steels

Introduction

Structural steels with very high strength levels are often referred to as ultrahigh-strength steels. The designation ultrahigh-strength is arbitrary because no universally accepted strength level for the term has been established. Also, as structural steels with greater and greater strength have been developed, the strength range for which the term is applied has gradually increased. This article describes those commercial structural steels capable of a minimum yield strength of 1380 MPa (200 ksi).

In addition to the steels discussed in this article, many other proprietary and standard steels are used for essentially the same types of applications, but at strength levels slightly below the arbitrary, lower limit of 1380 MPa (200 ksi) established above for the ultrahigh-strength class of constructional steels.

The ultrahigh-strength class of constructional steels is quite broad and includes several distinctly different families of steels. This article covers only medium-carbon low-alloy steels, medium-alloy air-hardening steels, and high fracture toughness steels.

This chapter is made up of articles on ten ultrahigh strength steels. Of these, seven are also the subjects of articles in other chapters: five as alloy steels (4130, 4140, 4340, 6150, and 8640) and two as tool steels (H-11 and H-13). The other steels (300M, D6a and D6ac, AF1410 and HP-9-4-30) are additions to this new edition of the *Heat Treater's Guide for Steels*.

Medium-Carbon Low-Alloy Steels. The medium-carbon low-alloy family of ultrahigh-strength steels includes AISI/SAE 4130, the higher-strength 4140, and the deeper hardening higher-strength 4340. Several modifications of the basic 4340 steel have been developed. In one modification (300M), silicon content is increased to prevent embrittlement when the steel is tempered at the low temperatures required for very high strength. Ladish D-6ac contains the grain refiner vanadium; slightly higher carbon, chromium, and molybdenum than 4340; and slightly lower nickel. Other less widely used steels that may be included in this family are 6150 and 8640. Chemical compositions are given in the adjoining table.

Medium-Alloy, Air-Hardening Steels. The ultrahigh-strength steels H11 modified (H11 mod) and H13, which are popularly known as 5% Cr hot-work die steels, are discussed in this section. Besides being extensively used in dies, these steels are widely used for structural applications, but not as widely as they once were, primarily because of the development of several other steels at essentially the same cost but with substantially greater fracture toughness at equivalent strength. Nonetheless, H11 mod and H13 possess some attractive features. Both can be hardened through in large sections by air cooling. The chemical compositions of these steels are given in the adjoining table.

High Fracture Toughness Steels. High-strength, high fracture toughness steels as described in this article are commercial structural steels capable of a yield strength of 1380 MPa (200 ksi) and a K_{Ic} of 100 MPa $\sqrt{m}$ (91 ksi $\sqrt{in.}$). (These steels also exhibit stress corrosion cracking resistance.) A number of developmental steels that are not fully commercial alloys are excluded from this discussion. The HP-9-4-30 and AF1410 steels, however, are discussed below.

Both these alloys are of the Ni-Co-Fe type and have a number of similar characteristics. Both are weldable, and the melt practice requires a minimum of VAR. Control of residual elements to low levels is required for optimum toughness. The machining practices used for 4340 steel are generally satisfactory; however, Ni-Co-Fe alloys are considered more difficult to machine than are alloy steels.

Compositions of the Ultrahigh-Strength Steels

Designation or trade name	Composition, wt% (a)							
	C	Mn	Si	Cr	Ni	Mo	V	Co
Medium-carbon low-alloy steels								
4130	0.28-0.33	0.40-0.60	0.20-0.35	0.80-1.10	...	0.15-0.25	...	...
4140	0.38-0.43	0.75-1.00	0.20-0.35	0.80-1.10	...	0.15-0.25	...	...
4340	0.38-0.43	0.60-0.80	0.20-0.35	0.70-0.90	1.65-2.00	0.20-0.30	...	...
AMS 6434	0.31-0.38	0.60-0.80	0.20-0.35	0.65-0.90	1.65-2.00	0.30-0.40	0.17-0.23	...
300M	0.40-0.46	0.65-0.90	1.45-1.80	0.70-0.95	1.65-2.00	0.30-0.45	0.05 min	...
D-6a	0.42-0.48	0.60-0.90	0.15-0.30	0.90-1.20	0.40-0.70	0.90-1.10	0.05-0.10	...
6150	0.48-0.53	0.70-0.90	0.20-0.35	0.80-1.10	...	...	0.15-0.25	...
8640	0.38-0.43	0.75-1.00	0.20-0.35	0.40-0.60	0.40-0.70	0.15-0.25	...	...
Medium-alloy air-hardening steels								
H11 mod	0.37-0.43	0.20-0.40	0.80-1.00	4.75-5.25	...	1.20-1.40	0.40-0.60	...
H13	0.32-0.45	0.20-0.50	0.80-1.20	4.75-5.50	...	1.10-1.75	0.80-1.20	...
High fracture toughness steels								
AF1410(b)	0.13-0.17	0.10 max	0.10 max	1.80-2.20	9.50-10.50	0.90-1.10	...	13.50-14.50
HP 9-4-30(c)	0.29-0.34	0.10-0.35	0.20 max	0.90-1.10	7.0-8.0	0.90-1.10	0.06-0.12	4.25-4.75

(a) P and S contents may vary with steelmaking practice. Usually, these steels contain no more than 0.035 P and 0.040 S. (b) AF1410 is specified to have 0.008 P and 0.005S composition. Ranges utilized by some producers are narrower. (c) HP 9-4-30 is specified to have 0.10 max P and 0.10 max S. Ranges utilized by some producers are narrower.

130, 4130H, 4130RH

hemical Composition. **4130. AISI and UNS:** 0.28 to 0.33 C, 0.40 0.60 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.80 to 1.10 Cr, 0.15 0.25 Mo. **UNS H41300 and SAE/AISI 4130H:** 0.27 to 0.33 C, 0.30 to .70 Mn, 0.15 to 0.35 Si, 0.75 to 1.20 Cr, 0.15 to 0.25 Mo. **4130RH:** 0.28 0.33 C, 0.40 to 0.60 Mn, 0.15 to 0.35 Si, 0.80 to 1.10 Cr, 0.15 to 0.25 Mo

imilar Steels (U.S. and/or Foreign). **4130.** UNS G41300; AMS 350, 6356, 6360, 6361, 6362, 6370, 6371, 6373; ASTM A322, A331, 505, A513, A519, A646; MIL SPEC MIL-S-16974; SAE J404, J412, 770; (Ger.) DIN 1.7218; (Fr.) AFNOR 25 CD 4(S); (Ital.) UNI 25 CrMo , 25 CrMo 4 KB; (Jap.) JIS SCM 2, SCCrM 1; (Swed.) SS_{14} 2225; (U.K.) .S. CDS 110. **4130H.** UNS H41300; ASTM A304, A914; SAE J1268, 1868; (Ger.) DIN 1.7218; (Fr.) AFNOR 25 CD 4(S); (Ital.) UNI 25 CrMo , 25 CrMo 4 KB; (Jap.) JIS SCM 2, SCCrM 1; (Swed.) SS_{14} 2225; (U.K.) .S. CDS 110

haracteristics. A water hardening alloy with low to intermediate ardenability. Retains good tensile, fatigue, and impact properties up to pproximately 370 °C (700 °F). Impact properties at cryogenic temperaures are poor, but the alloy is not subject to temper embrittlement, and can e nitrided. 4130H is produced in a number of product forms including ubing. 4130H has been used extensively for structures such as airframes hat are fabricated from tubing. 4130H is weldable, but because of its fairly igh hardenability, preheating and postheating must be used

orging. Alloy usually is forged at 1100 to 1200 °C (2010 to 2190 °F). inishing temperatures should not drop below 980 °C (1795 °F)

ecommended Heat Treating Practice

ormalizing. Heat to 870 to 925 °C (1600 to 1695 °F): holding time lepends on section thickness; air cool. Parts may be tempered at 480 °C 895 °F) or above after normalizing to increase yield strength.

In aerospace practice, parts are normalized at 900 °C (1650 °F)

nnealing. For a predominately pearlitic structure, heat to 855 °C (1575 F), cool fairly rapidly to 760 °C (1400 °F), then to 665 °C (1230 °F) at a rate not to exceed 18 °C (35 °F) per h; or heat to 855 °C (1575 °F), cool rapidly to 675 °C (1245 °F), and hold for 4 h. For a predominately spheroidized structure, heat to 750 °C (1380 °F), cool from 750 °C (1380 °F) to 665 °C (1230 °F) at a rate not to exceed 6 °C (10 °F) per h; cool rapidly from 750 °C (1380 °F) to 675 °C (1245 °F), and hold for 8 h.

In aerospace practice, parts are annealed at 845 °C (1555 °F). Parts are cooled to below 540 °C (1000 °F) at a rate not to exceed 95 °C (200 °F) per h.

Hardening. Heat to 845 to 870 °C (1555 to 1600 °F) and hold, then water quench; or heat to 860 to 885 °C (1580 to 1625 °F), hold, then oil quench. Holding time depends on section thickness.

Suitable treatment processes: flame hardening, ion nitriding, gas nitriding, and carbonitriding; austempering and martempering are alternative processes.

In aerospace practice, parts are austenitized at 855 °C (1575 °F). Quenched in oil, water, or polymer

Tempering. Hold at least 30 min at 200 to 700 °C (390 to 1290 °F). Tempering temperature and time at temperature depend mainly on desired hardness or strength level. See tables for suggested tempering temperatures in aerospace practice for different strength levels and suggested tempering temperatures based on as-quenched hardness

Spheroidizing. Heat to 760 to 775 °C (1400 to 1425 °F); hold 6 to 12 h; cool slowly

Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize and quench
- Temper
- Finish machine

130: Suggested Tempering Temperatures (Aerospace Practice)

Tensile strength				
20 to 860 MPa (90 to 125 ksi)	860 to 1035 MPa (125 to 150 ksi)	1035 to 1175 MPa (150 to 170 ksi)	1175 to 1240 MPa (160 to 180 ksi)	1240 to 1380 MPa (180 to 200 ksi)
50 °C(1) 1200 °F)	565 °C (1050 °F)	495 °C (925 °F)	425 °C (800 °F)	
75 °C(2) 1250 °F)	595 °C (1100 °F)	525 °C (975 °F)	470 °C (875 °F)	370 °C (700 °F)

1) Quench in oil or polymer. (2) Quench in water. Source: AMS 2759/1

130: Suggested Tempering Temperatures Based on As-Quenched Hardness (Aerospace Practice)

ensile strength range	RC 47 to 49	RC 50 to 52	RC 53 to 55
60-1035 MPa (125-150 ksi)	500 °C (1025 °F)	595 °C (1100 °F)	650 °C (1200 °F)
65-1105 MPa (140-160 ksi)	510 °C (950 °F)	550 °C (1025 °F)	595 °C (1100 °F)
1035-1175 MPa (150-170 ksi)	470 °C (875 °F)	510 °C (950 °F)	550 °C (1025 °F)
1175-1310 MPa (170-190 ksi)	425 °C (800 °F)	480 °C (900 °F)	525 °C (975 °F)
1240-1380 MPa (180-200 ksi)	400 °C (750 °F)	455 °C (850 °F)	495 °C (925 °F)

Source: AMS 2759/1

4130: Typical Mechanical Properties of Heat-Treated Parts

Tempering temperature		Tensile strength		Yield strength		Elongation in 50 mm (2 in.), %	Reduction in area, %	Hardness, HB	Izod impact energy	
°C	°F	MPa	ksi	MPa	ksi				J	ft · lbf
Water quenched and tempered(a)										
205	400	1765	256	1520	220	10.0	33.0	475	18	13
260	500	1670	242	1430	208	11.5	37.0	455	14	10
315	600	1570	228	1340	195	13.0	41.0	425	14	10
370	700	1475	214	1250	182	15.0	45.0	400	20	15
425	800	1380	200	1170	170	16.5	49.0	375	34	25
540	1000	1170	170	1000	145	20.0	56.0	325	81	60
650	1200	965	140	830	120	22.0	63.0	270	135	100
Oil quenched and tempered(b)										
205	400	1550	225	1340	195	11.0	38.0	450	...	...
260	500	1500	218	1275	185	11.5	40.0	440	...	...
315	600	1420	206	1210	175	12.5	43.0	418	...	...
370	700	1320	192	1120	162	14.5	48.0	385	...	...
425	800	1230	178	1030	150	16.5	54.0	360	...	...
540	1000	1030	150	840	122	20.0	60.0	305	...	...
650	1200	830	120	670	97	24.0	67.0	250	...	...

(a) 25 mm (1 in.) diam round bars quenched from 845 to 870 °C (1550 to 1600 °F). (b) 25 mm (1 in.) diam round bars quenched from 860 °C (1575 °F)

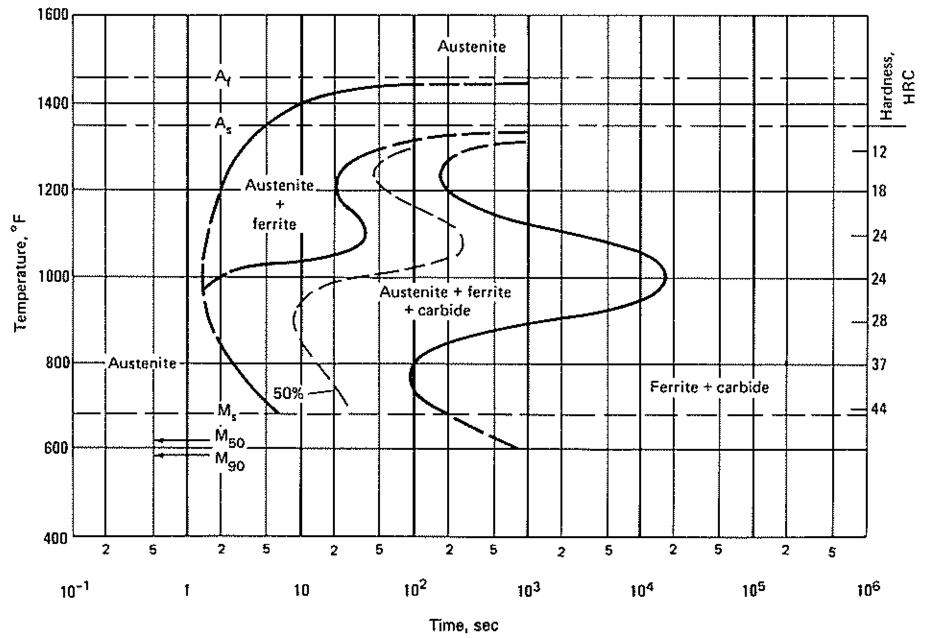
4130: Effects of Mass on Typical Properties

Round bars oil quenched from 845 °C (1555 °F) and tempered at 540 °C (1000 °F)

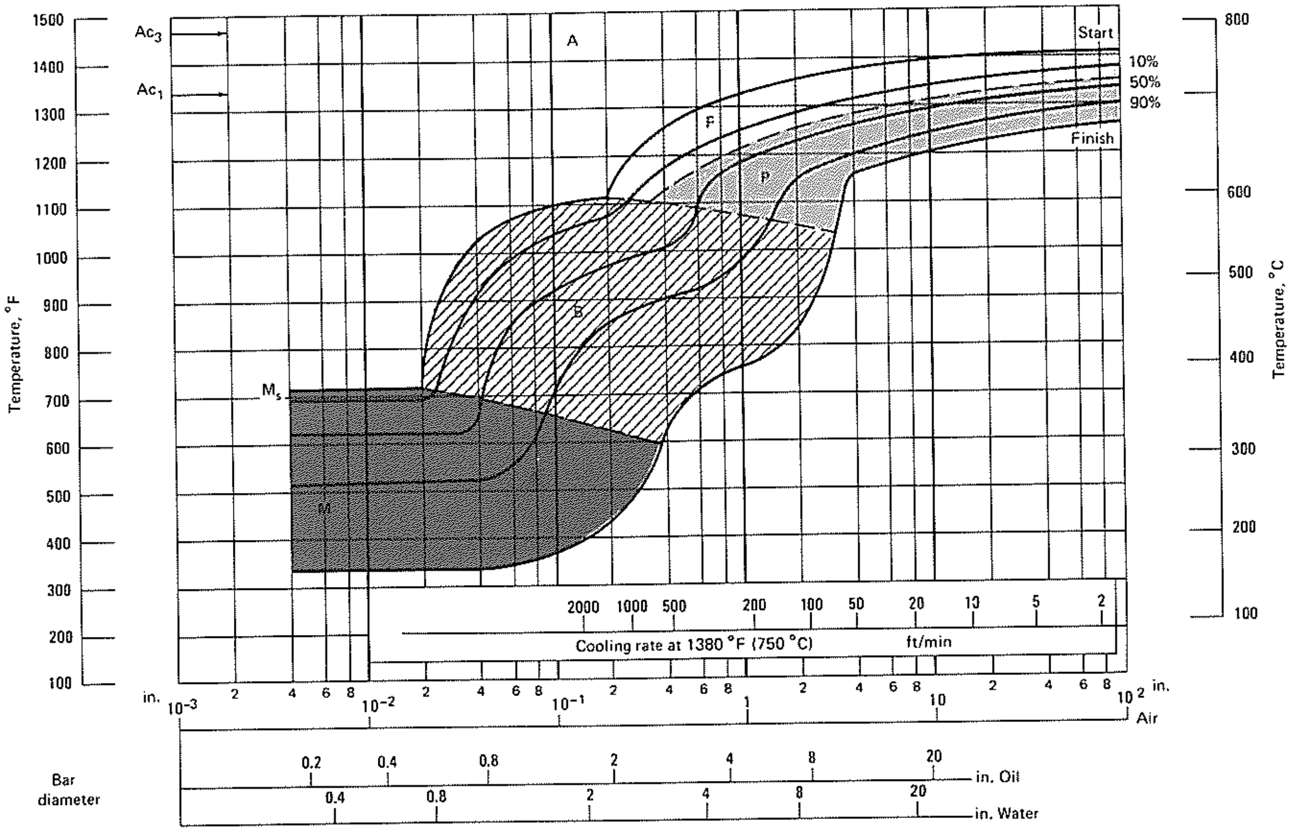
Bar size(a)		Tensile strength		Yield strength		Elongation in 50 mm (2 in.), %	Reduction in area, %	Surface hardness, HB
mm	in.	MPa	ksi	MPa	ksi			
25	1	1040	151	880	128	18.0	55.0	307
50	2	740	107	570	83	20.0	58.0	223
75	3	710	103	540	78	22.0	60.0	217

(a) 12.83 mm (0.505 in.) diam tensile specimens were cut from center of 25 mm diam bar and from midradius of 50 and 75 mm diam bars.

4130: Isothermal Transformation Diagram. Composition: 0.33 C, 0.53 Mn, 0.90 Cr, 0.18 Mo. Austenitized at 845 °C (1555 °F). Grain size: 9 to 10

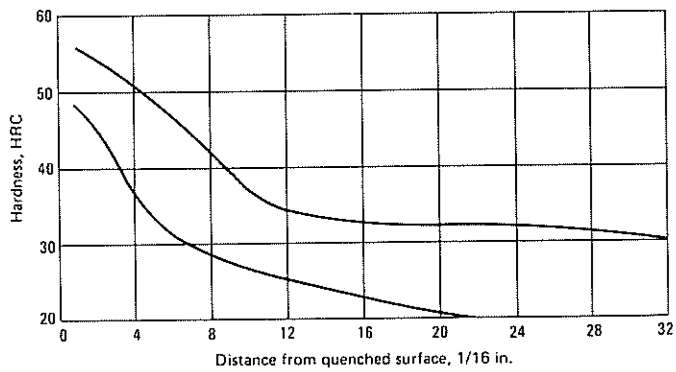


ɫ130: CCT Diagram. Composition: 0.30 C, 0.50 Mn, 0.020 P, 0.020 S, 0.25 Si, 1.00 Cr, 0.20 Mo. Austenitized at 850 °C (1560 °F)



4130H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max	min	Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max	min
1	1.58	56	49	13	20.54	34	24
2	3.16	55	46	14	22.12	34	24
3	4.74	53	42	15	23.70	33	23
4	6.32	51	38	16	25.28	33	23
5	7.90	49	34	18	28.44	32	22
6	9.48	47	31	20	31.60	32	21
7	11.06	44	29	22	34.76	32	20
8	12.64	42	27	24	37.92	31	...
9	14.22	40	26	26	41.08	31	...
10	15.80	38	26	28	44.24	30	...
11	17.38	36	25	30	47.40	30	...
12	18.96	35	25	32	50.56	29	...

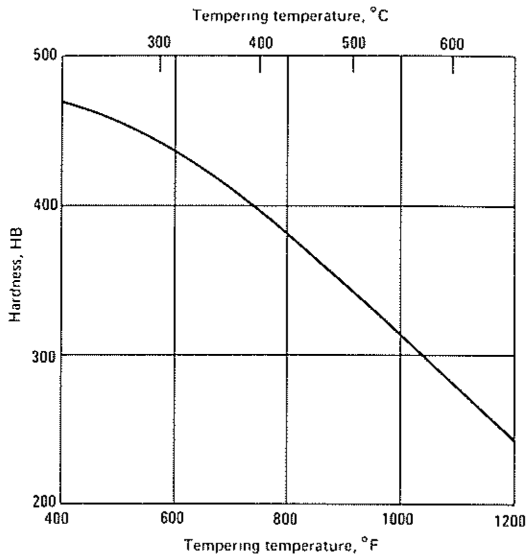


ɫ130: As-Quenched Hardness

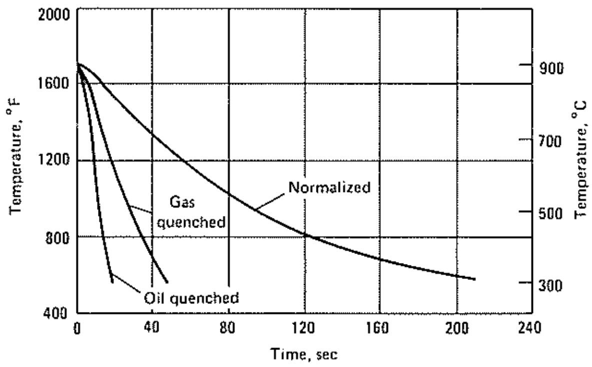
Specimens were quenched in water

Size round in.	mm	Hardness, HRC Surface	½ radius	Center
½	13	51	50	50
1	25	51	50	44
2	51	47	32	31
4	102	45.5	25	24.5

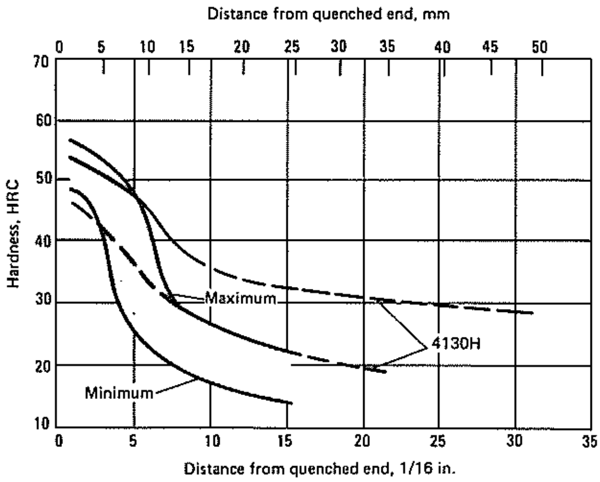
Source: Bethlehem Steel



4130: Hardness vs Tempering Temperature. Normalized at 900 °C (1650 °F). Quenched from 870 °C (1600 °F) in water and tempered at 56 °C (100 °F) intervals in 13.7 mm (0.540 in.) rounds. Source: Republic Steel

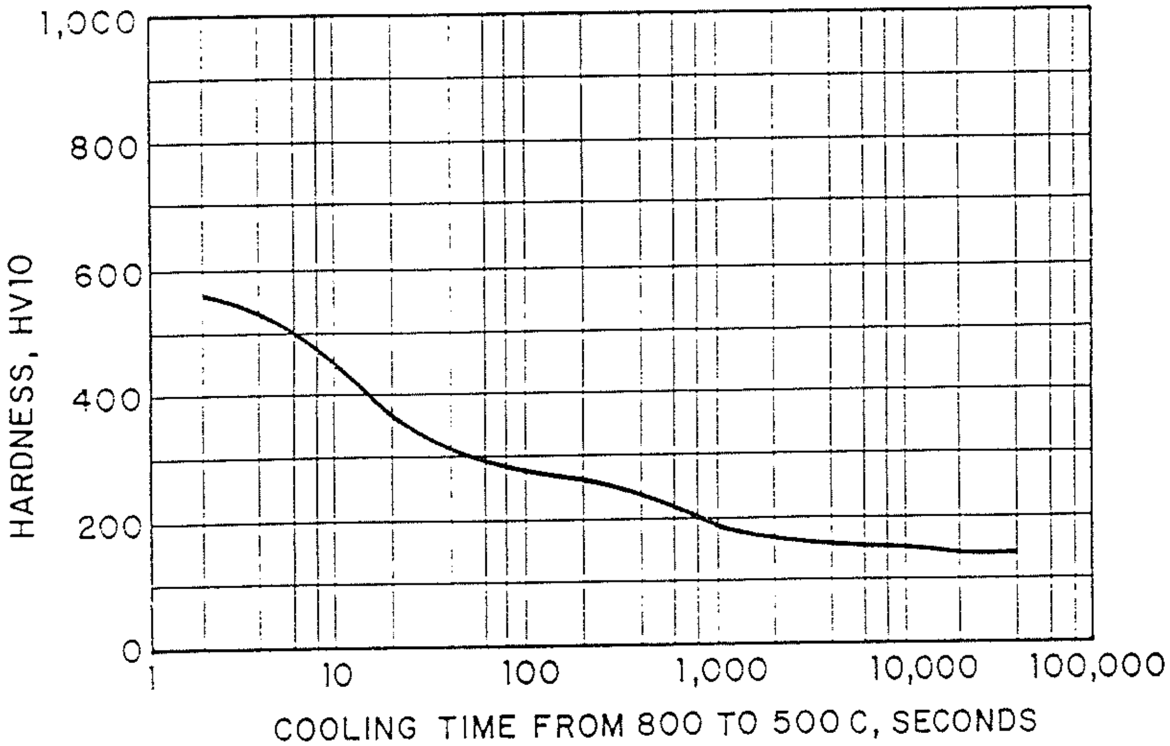


4130: Cooling Curves. Steel tubing. 31.75 mm (1.25 in.) outside diameter by 1.651 mm (0.065 in.) wall

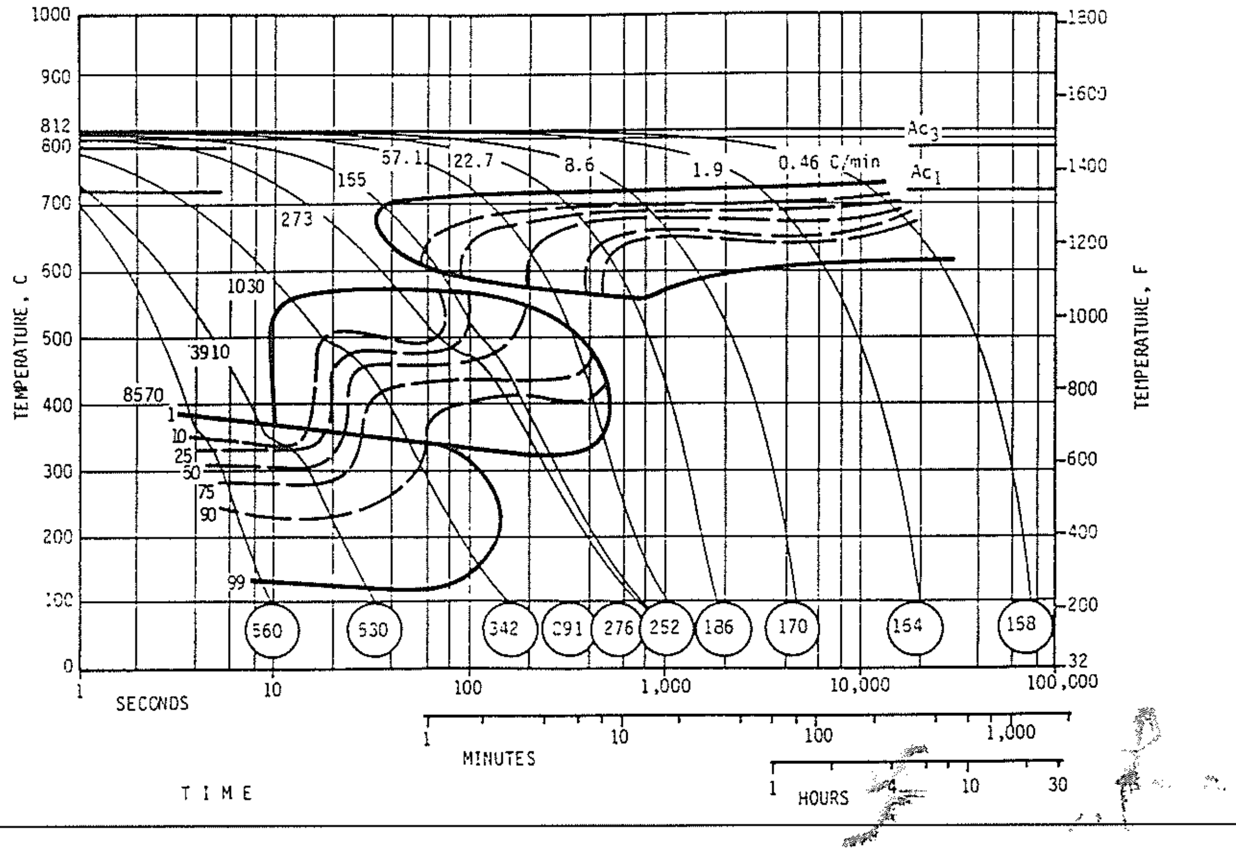


4130H: End-Quench Hardenability. 48 heats of 14B35 containing 0.35 to 0.39 C, 0.65 to 1.10 Mn, 0.13 Ni max, 0.05 Cr max, 0.03 Mo max and boron treated; compared with 4130H

4130: Cooling Curve. Half cooling time. Source: Datasheet I-301. Climax Molybdenum Company



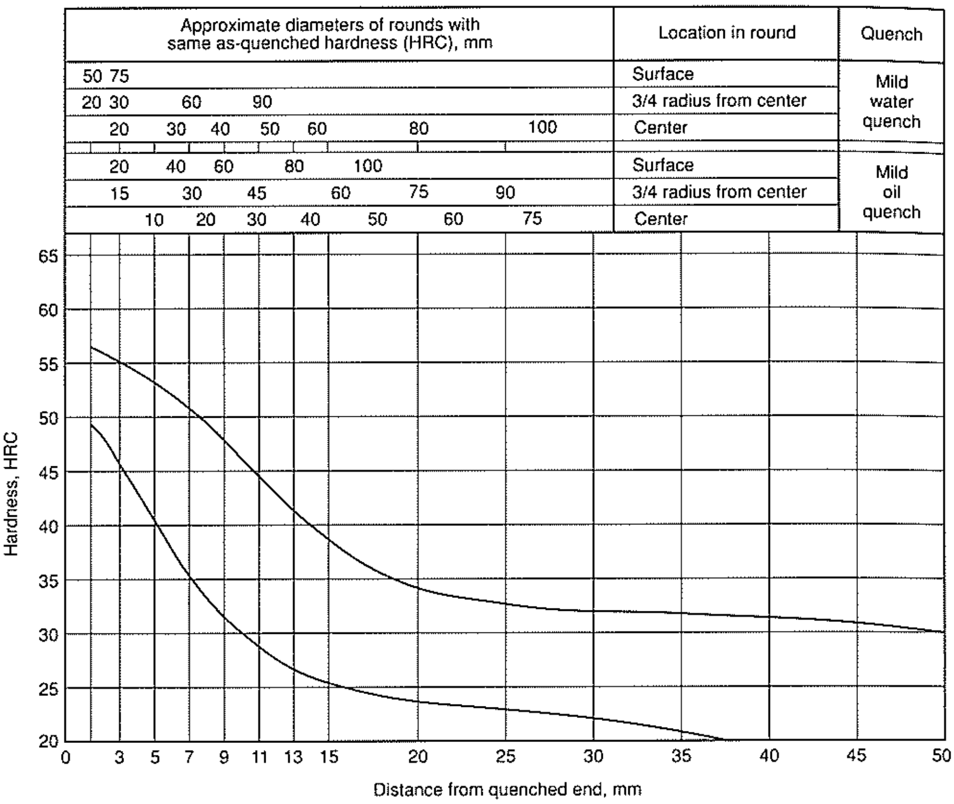
4130: CCT Diagram. Commercial steel composition: 0.32 C, 0.20 Si, 0.52 Mo, 0.010 P, 0.023 S, 0.88 Cr, 0.29 Ni, 0.22 Mo, 0.16 Cu, 0.033 Al. Machined dilametric specimens were prepared bar of commercial heat of vacuum arc remelted steel. No details of processing. Austenitized for 20 min at 812 °C (1495 °F). Research objective: characterize a candidate steel for heavy section, oil country tubular goods. In this application, steel should exhibit a martensitic structure as-quenched to maximize resistance to sulfide stress cracking. Source: Datasheet I-301. Climax Molybdenum Company



4130H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 900 °C (1650 °F). Austenitize: 870 °C (1600 °F)

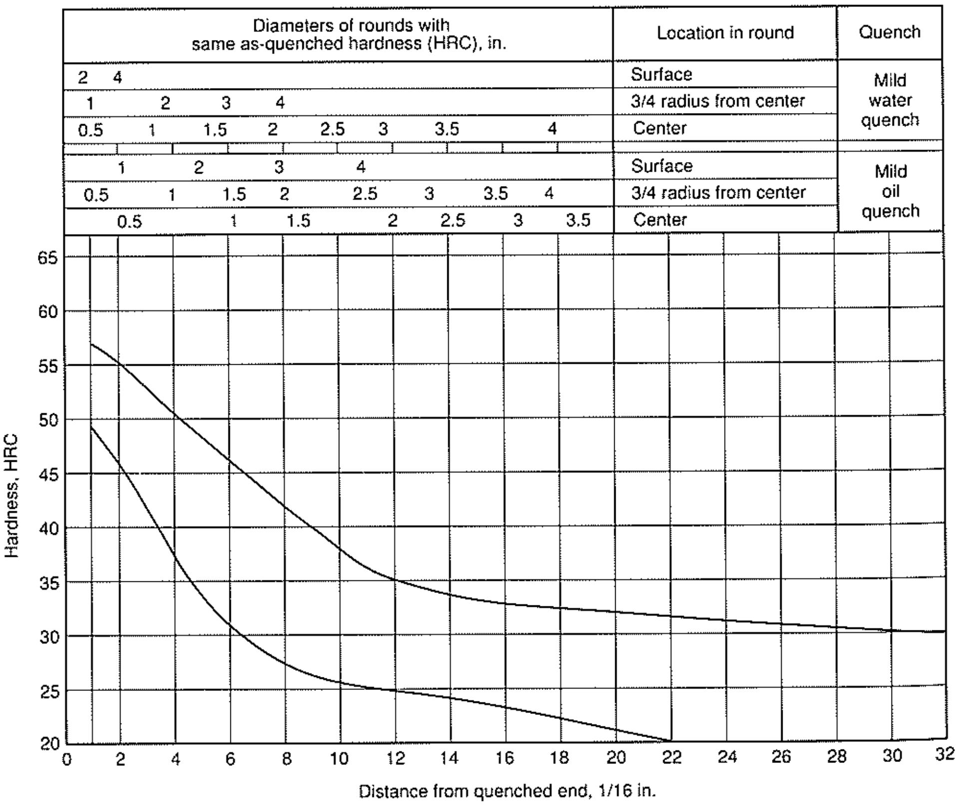
Hardness Limits for Specification Purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	56	49
3	55	46
5	53	40
7	51	36
9	48	32
11	44	28
13	41	26
15	39	25
20	34	24
25	33	23
30	33	22
35	32	20
40	31	...
45	31	...
50	30	...

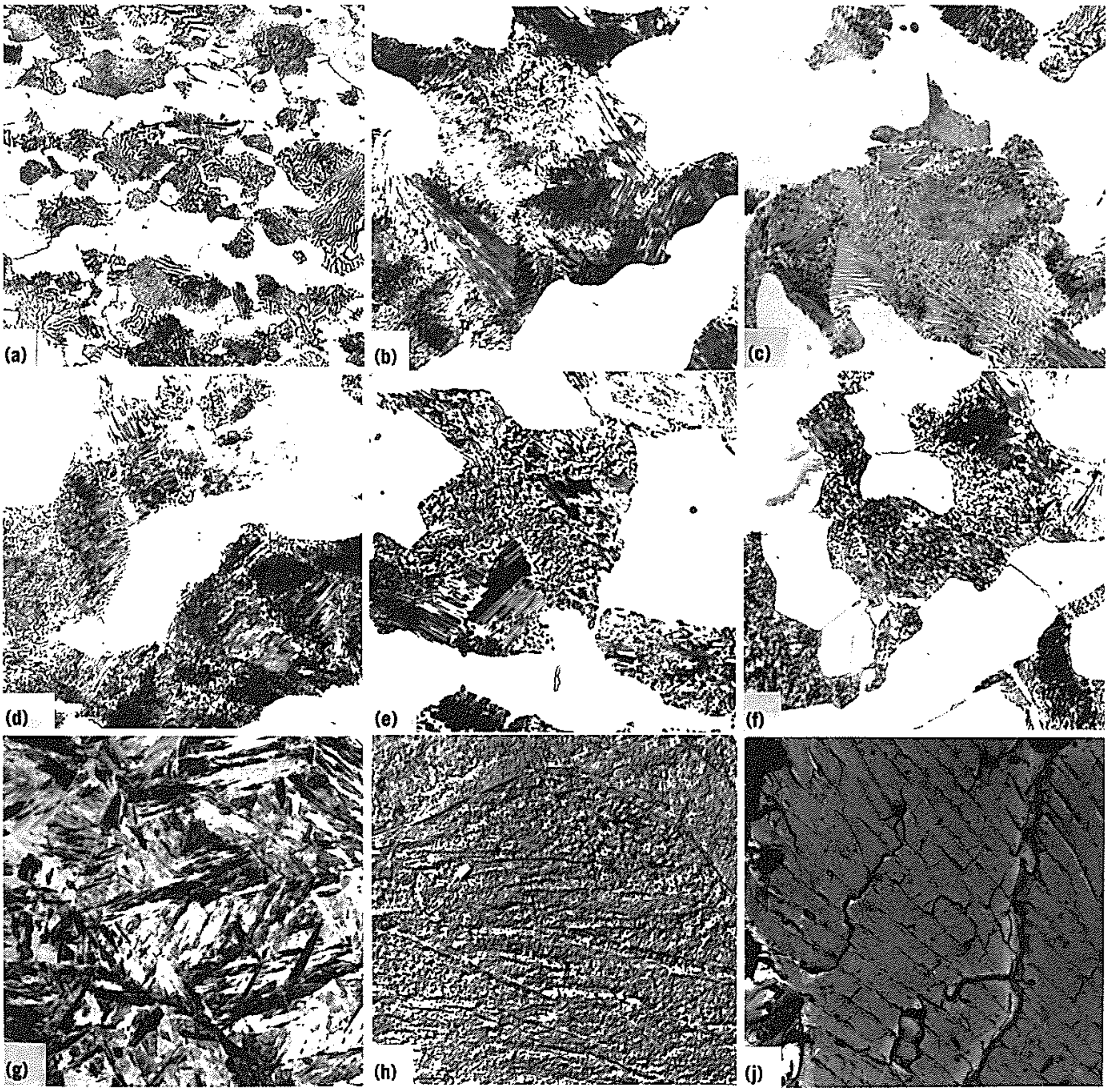


Hardness Limits for Specification Purposes

J distance, ¹⁄₁₆ in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	56	49
2	55	46
3	53	42
4	51	38
5	49	34
6	47	31
7	44	29
8	42	27
9	40	26
10	38	26
11	36	25
12	35	25
13	34	24
14	34	24
15	33	23
16	33	23
18	32	22
20	32	21
22	32	20
24	31	...
26	31	...
28	30	...
30	30	...
32	29	...



4130: Microstructures. (a) 2% nital, 500×. Normalized by austenitizing at 870 °C (1600 °F) and air cooling to room temperature. Ferrite (white areas) and lamellar pearlite (dark areas). Specimen shows slight banding. (b) 2% nital, 750×. Hot rolled steel bar, 25.4 mm (1 in.) diam, annealed by austenitizing at 845 °C (1555 °F) and cooling slowly in the furnace. Coarse lamellar pearlite (dark areas) in a matrix of ferrite (white). (c) 2% nital, 750×. Hot rolled steel bar 25.4 mm (1 in.) diam, austenitized at 845 °C (1555 °F). for 1 h, cooled to 675 °C (1245 °F) and held for 2 h, and air cooled. Partly spheroidized pearlite (dark) in a matrix of ferrite (white). (d) 2% nital, 750×. Same as (c), except the time at 675 °C (1245 °F) was increased to 4 h. Structure essentially the same as (c), except the degree of spheroidization of the pearlite is greater. (e) 2% nital, 750×. Same as (c) and (d), except the time at 675 °C (1245 °F) was increased to 8 h. Structure is similar to those shown in (c) and (d), except the degree of spheroidization of the pearlite has increased further. (f) 2% nital, 750×. Same as (c), (d), and (e), except that the time at 675 °C (1245 °F) was increased to 16 h. The degree of spheroidization is greater than in (e). (g) 2% nital, 750×. Hot rolled steel bar, 25.4 mm (1 in.) diam, austenitized at 870 °C (1600 °F) for 1 h and water quenched. Untempered martensite. (h) 5% picric acid, 2½% HNO_3, in ethanol; 11,000×. Same as (g), but an electron micrograph of a platinum-carbon-shadowed two-stage carbon replica. Untempered martensite. (j) Not polished, not etched; 8600×. Annealed. Replica electron fractograph. Note fatigue striations, resolved only at high magnification



ł140, 4140H, 4140RH

;hemical Composition. 4140. AISI and UNS: 0.38 to 0.43 C, 0.75) 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.80 to 1.10 Cr, 0.15) 0.25 Mo. **4140H. UNS H41400 and SAE/AISI:** 0.37 to 0.44 C, 0.65 to .10 Mn, 0.15 to 0.35 Si, 0.75 to 1.20 Cr, 0.15 to 0.25 Mo. **4140RH:** 0.38) 0.43 C, 0.75 to 1.00 Mn, 0.15 to 0.35 Si, 0.80 to 1.10 Cr, 0.15 to 0.25 Mo

;imilar Steels (U.S. and/or Foreign). 4140. UNS G41400; AMS 381, 6382, 6390, 6395; ASTM A322, A331, A505, A519, A547, A646; 4IL SPEC MIL-S-16974; SAE J404, J412, J770; (Ger.) DIN 1.7225; (Fr.) ,FNOR 40 CD 4, 42 CD 4; (Ital.) UNI 40 CrMo 4, G 40 CrMo 4, 38 CrMo KB; (Jap.) JIS SCM 4 H, SCM 4; (Swed.) SS_{14} 2244; (U.K.) B.S. 708 A 2, 708 M 40, 709 M 40. **4140H.** UNS H41400; ASTM A304, A914; SAE 1268, J1868; (Ger.) DIN 1.7225; (Fr.) AFNOR 40 CD 4, 42 CD 4; (Ital.) JNI G 40 CrMo 4, 40 CrMo 4, 38 CrMo 4 KB; (Jap.) JIS SCM 4 H, SCM ; (Swed.) SS_{14} 2244; (U.K.) B.S. 708 A 42, 708 M 40, 709 M 40

:haracteristics. This alloy is used where a combination of moderate ıardenability and good strength and toughness is required, and where ervice conditions are only moderately severe. Strength and hardenability re greater than those of 4130, but there is something of a tradeoff in ormability and weldability. Tensile strengths of up to 1650 MPa (240 ksi) re readily available through conventional quench and temper treatments. ;ervice temperatures can be as high as 480 °C (895 °F). Above this level, trength drops rapidly with increasing temperature. The alloy is readily ıitrided. At low temperatures, it undergoes a transition from ductile to ırittle behavior—the transition temperature varies with heat treatment and tress concentration. The alloy is subject to hydrogen embrittlement when t is heat treated to high strength levels. Ductility is restored by baking 2 to ł h at 190 °C (375 °F)

⁼orging. This steel is readily forged, usually at 1100 to 1200 °C (2010 o 2190 °F). Finishing temperatures should not be below 980 °C (1795 °F). ²arts should be cooled slowly after hot forming

Recommended Heat Treating Practice

Normalizing. Heat to 845 to 900 °C (1555 to 1650 °F) and hold for ɔeriod dictated by section thickness; air cool.

In aerospace practice, normalize at 900 °C (1650 °F)

Annealing. Heat to 845 to 870 °C (1555 to 1600 °F) and hold for time lictated by section thickness and furnace load; furnace cool.

In aerospace practice, parts are annealed at 845 °C (1555 °F), then :ooled to below 540 °C (1000 °F) at a rate not to exceed 95 °C (170 °F) per h

Hardening. Heat to 830 to 870 °C (1525 to 1600 °F) and hold; then oil quench. [For water quenching, rarely used, hardening temperatures are 815 to 845 °C (1500 to 1555 °F).] Holding time depends on section thickness.

In aerospace practice, parts are austenitized at 845 °C (1555 °F). Oil and polymer are suitable quenchants.

Treatment processes include flame hardening, boriding, ion nitriding, liquid nitriding, gas nitriding, and carbonitriding. Austempering and martempering are alternative processes

Tempering. Hold at least 30 min at 175 to 230 °C (345 to 445 °F); air cool or water quench. Tempering temperature and time at temperature depend mainly on desired hardness. To avoid blue brittleness, the alloy usually is not tempered between 230 to 370 °C (445 to 700 °F). The steel is not subject to temper embrittlement.

Aerospace practice for basing tempering temperatures on desired strength levels and as-quenched hardness are found in adjoining tables

Spheroidizing. Parts are heated to 760 to 775 °C (1400 to 1425 °F); held 6 to 12 h; then slow cooled

Nitriding. 4140H responds to the ammonia gas nitriding process, resulting in a thin, file hard case, the outer portion of which is composed of epsilon nitride. This constituent not only provides an abrasion-resistant surface, but also increases fatigue strength of components such as shafts by as much as 30%. However, if nitriding is considered, the steel must be pretreated (hardened and tempered), and nitriding must be done on finished parts because any finishing operation will remove the most useful portion of the case. A typical processing cycle that includes nitriding is:

- Rough machine
- Austenitize at 845 °C (1555 °F)
- Oil quench
- Temper at 620 °C (1150 °F)
- Finish machine
- Nitride at 525 °C (975 °F) for 24 h, using an ammonia dissociation of 30%; or nitride at 525 °C (975 °F) for 5 h with an ammonia dissociation of 25%, then at 565 °C (1050 °F) for 20 h with an ammonia dissociation of 75 to 80%

Certain proprietary salt bath nitriding processes are also applicable for surface hardening of 4140H

Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize
- Quench
- Temper
- Finish machine
- Nitride (optional)

4140: Typical Mechanical Properties After Heat Treatment

Round bars of 13 mm (0.50 in.) diam, oil quenched from 845 °C (1555 °F)

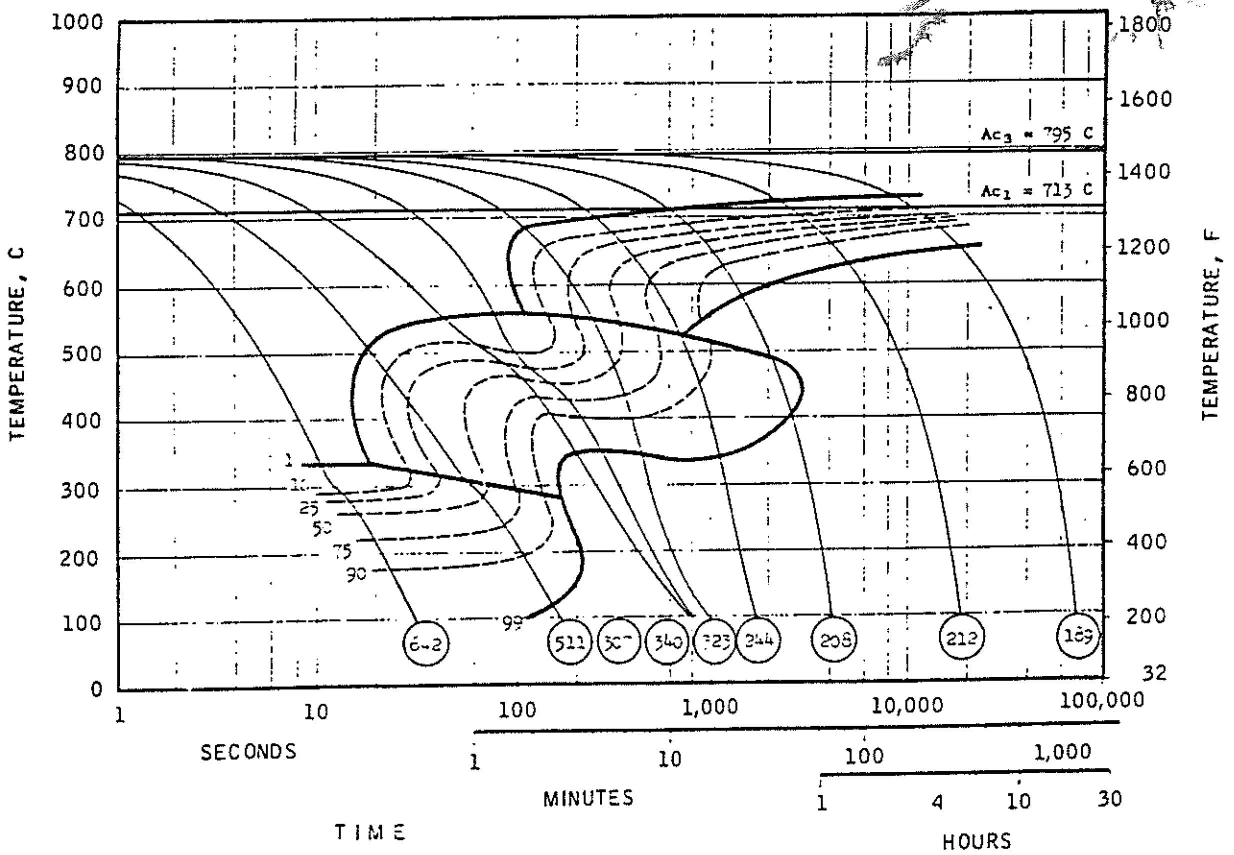
Tempering temperature		Tensile strength		Yield strength		Elongation in 50 mm (2 in.), %	Reduction in area, %	Hardness, HB	Izod impact energy	
°C	°F	MPa	ksi	MPa	ksi				J	ft · lbf
205	400	1965	285	1740	252	11.0	42	578	15	11
260	500	1860	270	1650	240	11.0	44	534	11	8
315	600	1720	250	1570	228	11.5	46	495	9	7
370	700	1590	231	1460	212	12.5	48	461	15	11
425	800	1450	210	1340	195	15.0	50	429	28	21
480	900	1300	188	1210	175	16.0	52	388	46	34
540	1000	1150	167	1050	152	17.5	55	341	65	48
595	1100	1020	148	910	132	19.0	58	311	93	69
650	1200	900	130	790	114	21.0	61	277	112	83
705	1300	810	117	690	100	23.0	65	235	136	100

4140: Effects of Mass on Typical Properties of Heat-Treated Parts

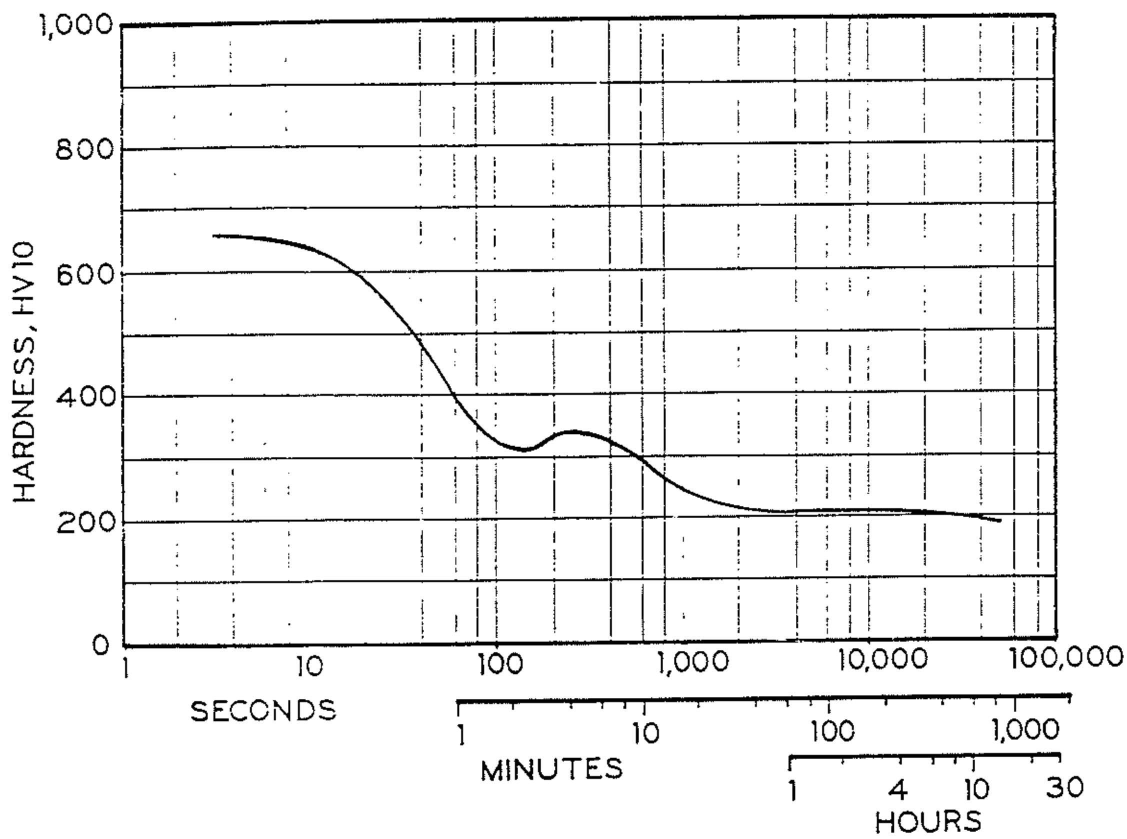
Diameter of bar(a)		Tensile strength		Yield strength		Elongation in 50 mm (2 in.), %	Reduction in area, %	Surface hardness, HB
mm	in.	MPa	ksi	MPa	ksi			
25	1	1140	165	985	143	15	50	335
50	2	920	133	750	109	18	55	302
75	3	860	125	655	95	19	55	293

(a) Round bars oil quenched from 845 °C (1550 °F) and tempered at 540 °C (1000 °F). 12.83 mm (0.505 in.) diam tensile specimens were cut from center of 25 mm (1 in.) diam bars and from midradius of 50 and 75 mm (2 and 3 in.) diam bars.

4140: CCT Diagram. Constructional alloy steel composition: 0.39 C, 0.26 Si, 0.82 Mn, 0.013 P, 0.025 S, 1.00 Cr, 0.038 Ni, 0.21 Mo, 0.058 Cu. Commercial heat of bar stock was used in study. Steel was austenitized for 20 min at 845 °C (1555 °F). Source: Datasheet I-217. Climax Molybdenum Company



4140: Cooling Curve. Half cooling time. Source: Datasheet I-217. Climax Molybdenum Company



4140: Suggested Tempering Temperatures (Aerospace Practice)(a)

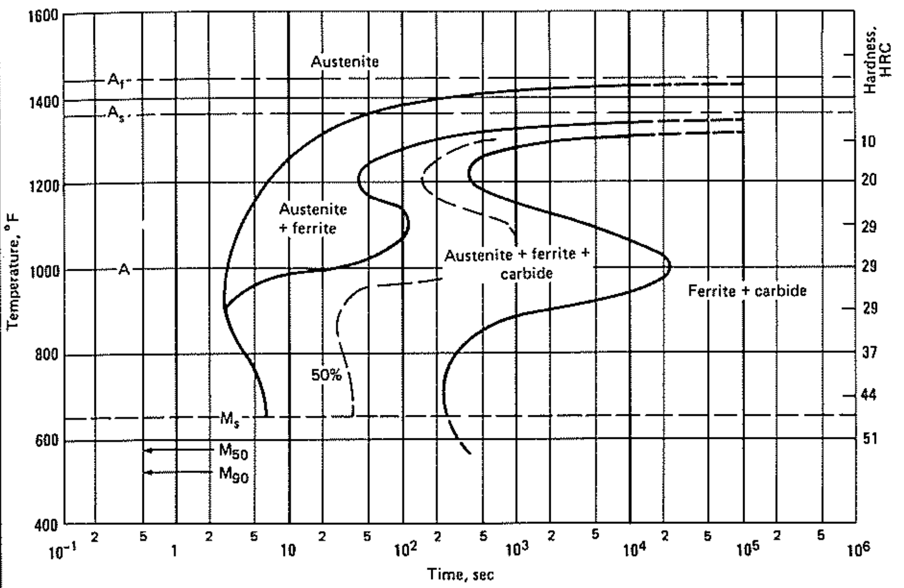
Tensile Strength					
620-860 MPa (90-125 ksi)	860-1035 MPa (125-150 ksi)	1035-1175 MPa (150-170 ksi)	1175-1240 MPa (160-180 ksi)	1240-1380 MPa (180-200 ksi)	1380-1520 MPa (200-220 ksi)
705 °C (1300 °F)	635 °C (1175 °F)	580 °C (1075 °F)	510 °C (950 °F)	455 °C (850 °F)	385 °C (725 °F)

(a) Quench in oil or polymer. Source: AMS 2759/1

4140: Suggested Tempering Temperatures Based on As-Quenched Hardness (Aerospace Practice)

Tensile strength range	RC 47-49	RC 50-52	RC 53-55	RC 56-58
620-1035 MPa (125-150 ksi)	595 °C (1100 °F)	620 °C (1150 °F)	650 °C (1200 °F)	675 °C (1250 °F)
965-1105 MPa (140-160 ksi)	525 °C (975 °F)	550 °C (1025 °F)	595 °C (1100 °F)	635 °C (1175 °F)
1035-1175 MPa (150-170 ksi)	470 °C (875 °F)	510 °C (950 °F)	550 °C (1025 °F)	595 °C (1100 °F)
1105-1240 MPa (160-180 ksi)	...	480 °C (900 °F)	525 °C (975 °F)	565 °C (1050 °F)
1175-1310 MPa (170-190 ksi)	...	440 °C (825 °F)	495 °C (925 °F)	540 °C (1000 °F)
1240-1380 MPa (180-200 ksi)	...	410 °C (775 °F)	470 °C (875 °F)	510 °C (950 °F)
1310-1450 MPa (190-210 ksi)	...	385 °C (725 °F)	440 °C (825 °F)	495 °C (925 °F)
1380-1515 MPa (200-220 ksi)	...	...	410 °C (775 °F)	470 °C (875 °F)

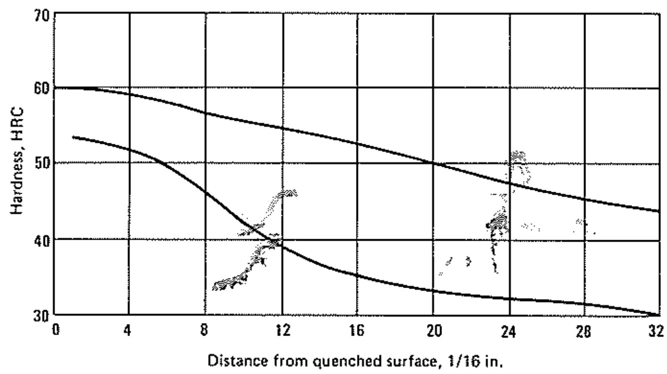
Source: AMS 2759/1



4140: Isothermal Transformation Diagram. Composition: 0.37 C, 0.77 Mn, 0.98 Cr, 0.21 Mo. Austenitized at 845 °C (1555 °F) Grain size: 7 to 8

4140H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max	min	Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max	min
1	1.58	60	53	13	20.54	55	38
2	3.16	60	53	14	22.12	54	37
3	4.74	60	52	15	23.70	54	36
4	6.32	59	51	16	25.28	53	35
5	7.90	59	51	18	28.44	52	34
6	9.48	58	50	20	31.60	51	33
7	11.06	58	48	22	34.76	49	33
8	12.64	57	47	24	37.92	48	32
9	14.22	57	44	26	41.08	47	32
10	15.80	56	42	28	44.24	46	31
11	17.38	56	40	30	47.40	45	31
12	18.96	55	39	32	50.56	44	30



4140: Effect of Microstructure on Tool Life

Feed was 0.25 mm/rev (0.010 in./rev) for all specimens; depth of cut was 2.5 mm (0.100 in.)

Steel condition	Hardness, HB	Microstructure constituent, %: Pearlite	Ferrite	Tempered martensite	Cutting speed: mm/s	ft/min
Normalized	192	90	10	...	1520	300
Annealed	180	65	35	...	1830	360
Quenched, tempered	300	...	...	100	1520	300

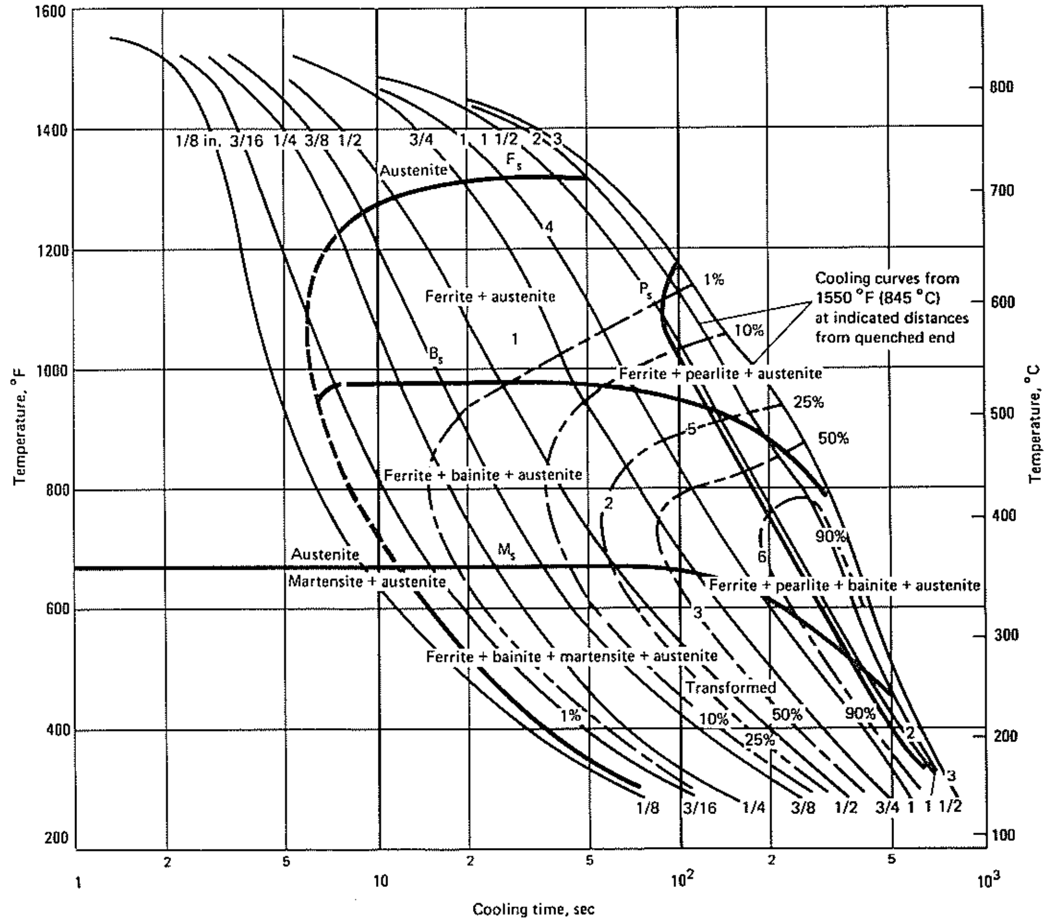
4140: As-Quenched Hardness

Specimens quenched in oil

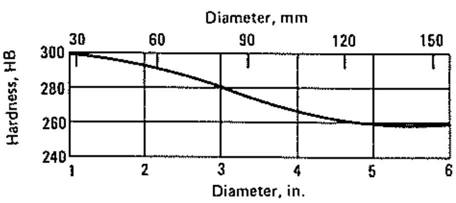
Size round: in.	mm	Hardness, HRC: Surface	½ radius	Center
½	13	57	56	55
1	25	55	55	50
2	51	49	43	38
4	102	36	34.5	34

Source: Bethlehem Steel

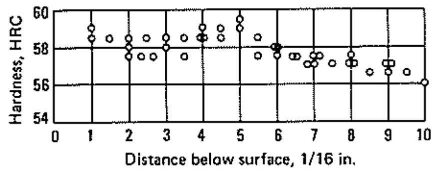
4140: Cooling Transformation Diagram. Composition: 0.44 C, 1.04 Mn, 0.29 Si, 1.13 Cr, 0.15 Mo. Austenitized at 845 °C (1555 °F) Grain size: 9. Ac_3, 795 °C (1460 °F); Ac_1, 750 °C (1380 °F). A: austenite, F: ferrite, P: pearlite, B: bainite, M: martensite. Source: Bethlehem Steel

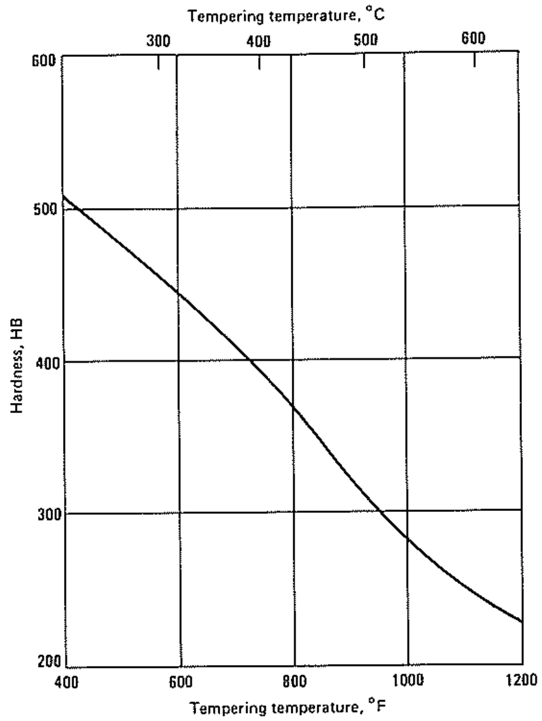


4140: Effect of Mass. Composition: 0.38 to 0.43 C, 0.75 to 1.00 Mn, 0.040 P max, 0.040 S max, 0.20 to 0.35 Si, 0.80 to 1.10 Cr, 0.15 to 0.25 Mo. Approximate critical points: Ac_1, 730 °C (1350 °F); Ac_3, 805 °C (1480 °F); Ar_3, 745 °C (1370 °F); Ar_1, 680 °C (1255 °F). Recommended thermal treatment: forge at 1205 °C (2200 °F) maximum, anneal at 815 to 870 °C (1500 to 1600 °F) for a maximum hardness of 197 HB, normalize at 845 to 900 °C (1555 to 1650 °F) for an approximate hardness of 311 HB; quench from 830 to 855 °C (1525 to 1575 °F) in oil. Test specimens were normalized at 870 °C (1600 °F) in over-sized rounds, quenched from 845 °C (1555 °F) in oil in sizes shown, tempered at 540 °C (1000 °F), tested on 12.827 mm (0.505 in.) rounds. Tests from 38.1 mm (1½ in.) diam bars and over are taken at half radius position. Source: Republic Steel

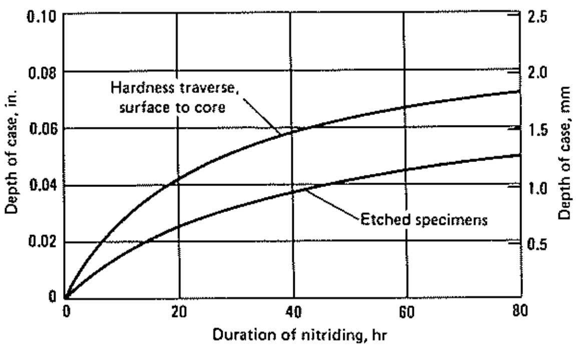


4140: Depth of Hardness. 31.75 mm (1.25 in.) diam bars, through hardened by induction

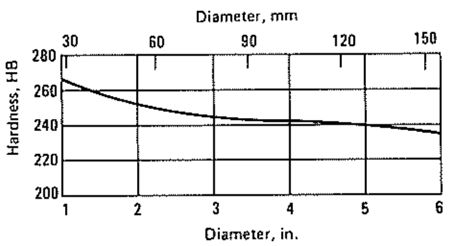




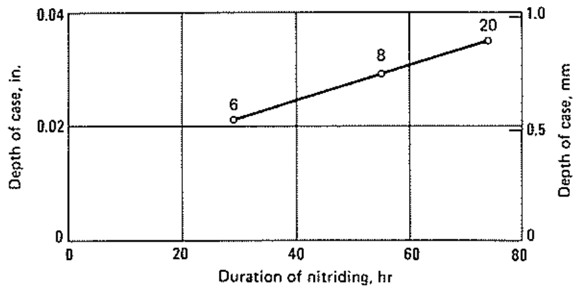
4140: Hardness vs Tempering Temperature. Normalized at 870 °C (1600 °F). Quenched from 845 °C (1555 °F) in oil and tempered in 56 °C (100 °F) intervals in 13.716 mm (0.540 in.) rounds. Tested in 12.827 mm (0.505 in.) rounds. Source: Republic Steel



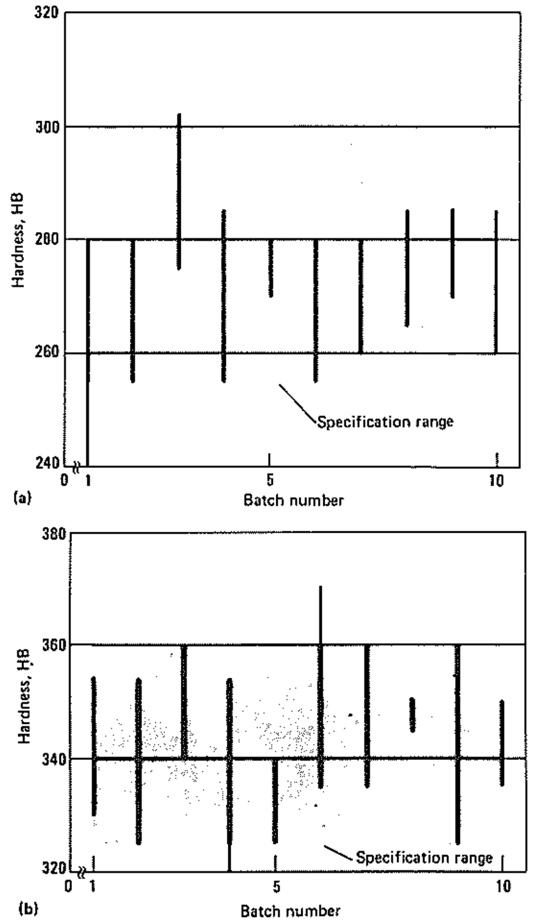
4140: Gas Nitriding. Oil quenched from 845 °C (1555 °F), tempered at 595 °C (1105 °F), and nitrided at 550 °C (1020 °F)



4140: Effect of Mass. Composition: 0.38 to 0.43 C, 0.75 to 1.00 Mn, 0.040 P max, 0.040 S max, 0.20 to 0.35 Si, 0.80 to 1.10 Cr, 0.15 to 0.25 Mo. Approximate critical points: Ac_1, 730 °C (1350 °F); Ac_3, 805 °C (1480 °F); Ar_3, 745 °C (1370 °F); Ar_1, 680 °C (1255 °F). Recommended thermal treatment: forge at 1205 °C (2200 °F) maximum, anneal at 815 to 870 °C (1500 to 1600 °F) for a maximum hardness of 197 HB, normalize at 845 to 900 °C (1555 to 1650 °F) for an approximate hardness of 311 HB; quench from 830 to 855 °C (1525 to 1575 °F) in oil. Test specimens were normalized at 870 °C (1600 °F) in over-sized rounds, quenched from 845 °C (1555 °F) in sizes shown, tempered at 650 °C (1200 °F), tested on 12.827 mm (0.505 in.) rounds. Tests from 38.1 mm (1½ in.) diam bars and over are taken at half radius position. Source: Republic Steel

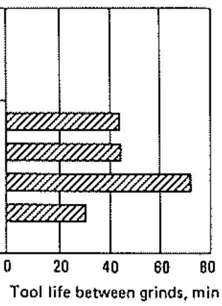


4140: Depth of Case vs Duration of Nitriding. Double stage nitrided at 525 °C (975 °F). Numbers indicate hours of nitriding at 15 to 25% dissociation. Remainder of cycle at 83 to 85% dissociation



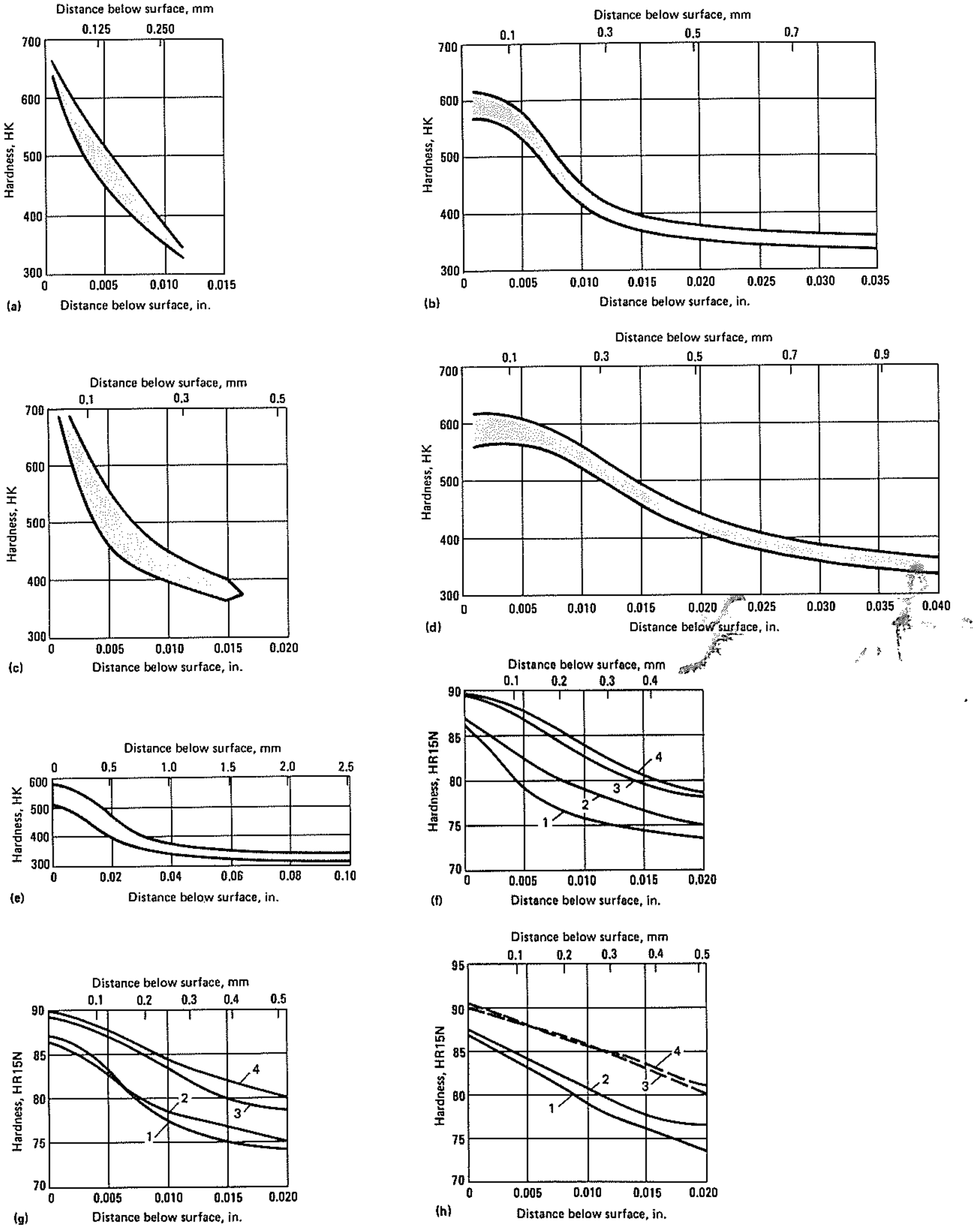
4140: Variations in Hardness after Production Tempering. (a) 76.2 mm (3 in.) diam valve bonnets. Steel from one mill heat. Parts heated at 870 °C (1600 °F), oil quenched, and tempered at 605 °C (1125 °F) to a hardness of 255 to 302 HB. (b) Valve segments, 12.7 to 25.4 mm (0.50 to 1 in.) section thickness. Steel from one mill heat. Parts heated at 870 °C (1600 °F), oil quenched, and tempered at 580 °C (1075 °F) to a hardness of 321 to 363 HB

Steel condition	Cutting speed ft/min	Cutting speed m/s	Metal removed between grinds in.^{3}	Metal removed between grinds m^3
Normalized	300	1.5	165	2.3×10^{-3}
Annealed	360	1.8	190	3.1×10^{-3}
Annealed	300	1.5	260	4.3×10^{-3}
Quenched and tempered	300	1.5	115	1.9×10^{-3}

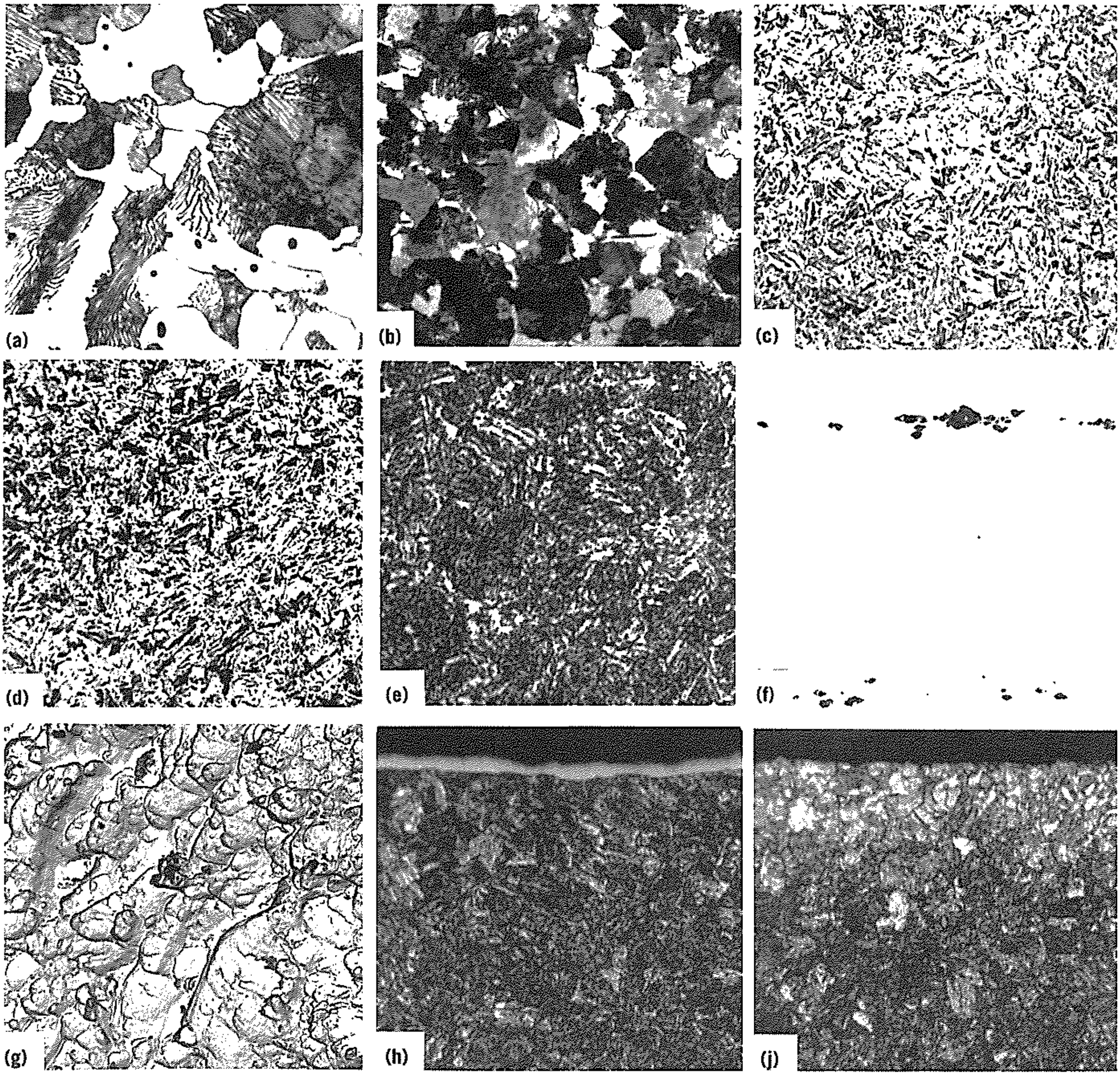


4140: Effect of Microstructure on Tool Life

4140: Gas Nitriding. (a) 7 h, 2 suppliers, 20 to 30% dissociation; (b) 9 h, 2 heats, 25 to 30% dissociation; (c) 24 h, 2 suppliers, 20 to 30% dissociation; (d) 40 h, 5 heats, 25 to 30% dissociation; (e) 90 h, 9 heats, 25 to 35% dissociation; (f) 25 h, 20 to 30% dissociation; (g) 35 h, 20 to 30% dissociation; (h) 50 h, 20 to 30% dissociation. For (f), (g), (h), 1: 21 to 23 HRC; 2: 26 to 28 HRC; 3: 33 to 35 HRC; 4: 36 to 37 HRC core hardness.



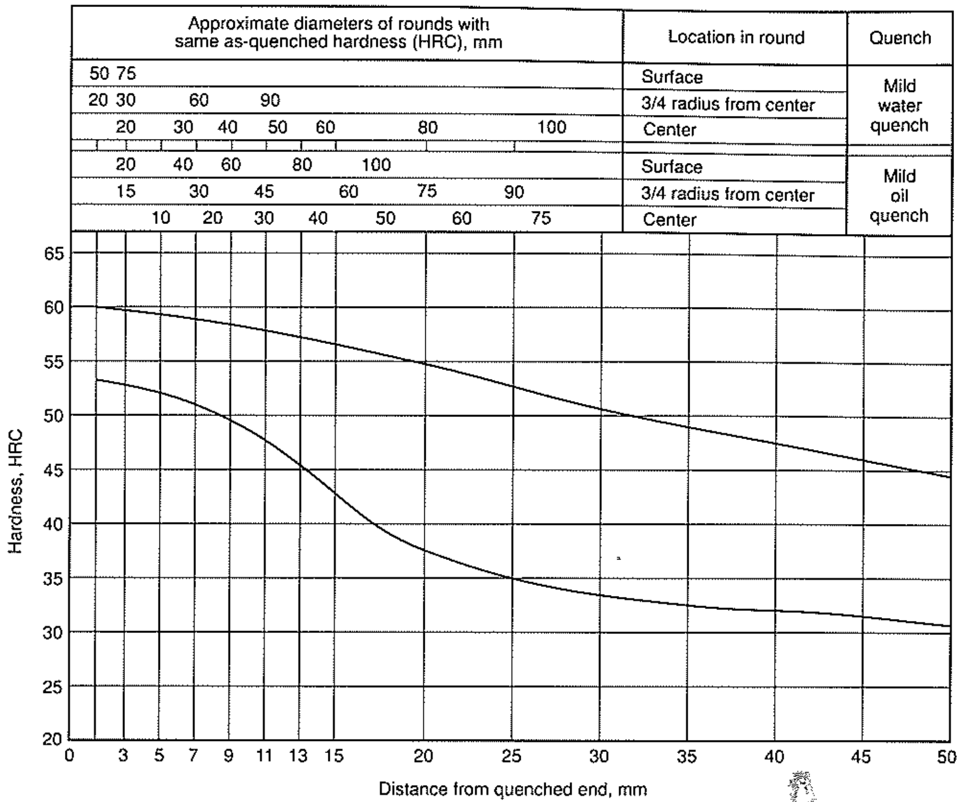
4140: Microstructures. (a) 2% nital, 825×. Resulfurized forging normalized by austenitizing at 900 °C (1650 °F) ½ h, air cooling; annealed by heating at 815 °C (1500 °F) 1 h, furnace cooling to 540 °C (1000 °F), air cooling. Blocky ferrite and fine-to-coarse lamellar pearlite. Black dots are sulfide. (b) Nital, 500×. 25.4 mm (1 in.) diam, austenitized at 845 °C (1555 °F) 1 h, cooled to 650 °C (1200 °F), and held 1 h for isothermal transformation, then air cooled to room temperature. White areas, ferrite; gray and black areas, pearlite with fine and coarse lamellar spacing. (c) 2% nital, 500×. Hot rolled steel round bar. 25.4 mm (1 in.) diam, austenitized at 845 °C (1555 °F) for 1 h and water quenched. Fine, homogeneous, untempered martensite. Tempering at 150 °C (300 °F) would result in a darker etching structure. (d) 2% nital, 500×. Same as (c), except the steel was quenched in oil rather than water, resulting in the presence of bainite (black constituent) along with the martensite (light). (e) 2% nital, 750×. Steel bar austenitized at 845 °C (1555 °F), oil quenched to 66 °C (150 °F), and tempered 2 h at 620 °C (1150 °F). Martensite-ferrite-carbide aggregate. (f) As polished (not etched), 200×. Oxide inclusions (stringers) in a steel bar, 25.4 mm (1 in.) diam. Stringers parallel to the direction of rolling on the as-polished surface of the bar. (g) Not polished, not etched, 8600×. Replica electron fractograph showing the dimpled structure typical of the overstress mode of failure. (h) 2% nital, 400×. Oil quenched from 845 °C (1555 °F), tempered for 2 h at 620 °C (1150 °F), surface activated in manganese phosphate, gas nitrided for 24 h at 525 °C (975 °F), 20 to 30% dissociation. 0.0050 to 0.0076 mm (0.0002 to 0.0003 in.) white surface layer Fe_2N, iron nitride, and tempered martensite. (j) 2% nital, 400×. Same steel and prenitriding conditions as (h), except double stage gas nitrided: 5 h at 525 °C (975 °F), 20 to 30% dissociation; 20 h at 565 °C (1050 °F), 75 to 80% dissociation. High second-stage dissociation caused absence of white layer. Diffused nitride layer and a matrix of tempered martensite



4140H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

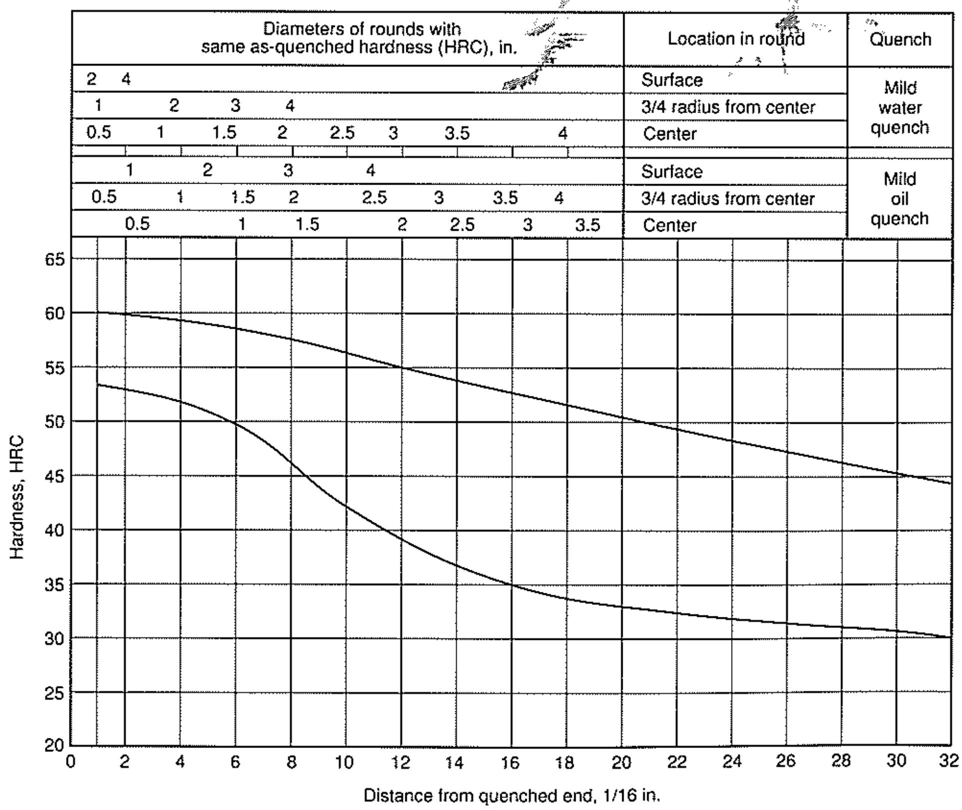
Hardness Limits for Specification Purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	60	53
3	60	52
5	60	52
7	59	51
9	59	50
11	58	48
13	57	46
15	57	43
20	55	38
25	53	35
30	51	33
35	49	32
40	48	32
45	46	31
50	45	30



Hardness Limits for Specification Purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	60	53
2	60	53
3	60	52
4	59	51
5	59	51
6	58	50
7	58	48
8	57	47
9	57	44
10	56	42
11	56	40
12	55	39
13	55	38
14	54	37
15	54	36
16	53	35
18	52	34
20	51	33
22	49	33
24	48	32
26	47	32
28	46	31
30	45	31
32	44	30



ı340, 4340H

hemical Composition. **UNS H43400 and SAE/AISI 4340 com-›sition:** 0.37 to 0.44 C, 0.55 to 0.90 Mn, 0.15 to 0.35 Si, 1.55 to 2.00 Ni, 55 to 0.95 Cr, 0.20 to 0.30 Mo. **UNS H43406 and SAE/AISI E4340H mposition:** 0.37 to 0.44 C, 0.60 to 0.95 Mn, 0.15 to 0.35 Si, 1.55 to 2.00 ., 0.65 to 0.95 Cr, 0.20 to 0.30 Mo

imilar Steels (U.S. and/or Foreign). **4340.** UNS G43400; AMS 31, 6359, 6414, 6415; ASTM A322, A331, A505, A519, A547, A646; IL SPEC MIL-S-16974; SAE J404, J412, J770; (W. Ger.) DIN 1.6565; ıp.) JIS SNCM 8; (U.K.) B.S. 817 M 40, 3111 Type 6, 2 S 119, 3 S 95. **ı40H.** UNS H43400; ASTM A304; SAE J1268; (W. Ger.) DIN 1.6565; ıp.) JIS SNCM 8; (U.K.) B.S. 817 M 40, 3111 Type 6, 2 S 119, 3 S 95

haracteristics. A high-hardenability steel, higher in hardenability an any other standard AISI grade. When the elements that contribute to ırdenability are on the high side of their allowable ranges, the upper curve the hardenability band is virtually a straight line, thus indicating that ı40H would be air-hardening in thin sections. Depending on the precise ırbon content, as-quenched hardness ranges from 54 to 59 HRC. Har-ınability of E4340H is more restricted than that of conventional 4340H. ɛcause of high hardenability, 4340H is not considered suitable for weld-g by conventional means, although it can be welded by sophisticated ocesses such as electron beam welding. 4340H can be forged without fficulty, although its hot strength is considerably higher than that of ırbon or lower alloy grades, requiring more powerful forging machines. achinability is relatively poor

orging. Forging usually is in the range of 1065 to 1230 °C (1950 to 250 °F); after forging parts may be air cooled in a dry place, or preferably, rnace cooled

ecommended Heat Treating Practice

ormalizing. Heat to 845 to 900 °C (1555 to 1650 °F) and hold for time ctated by section thickness; air cool.

In aerospace practice, parts are normalized at 900 °C (1650 °F)

nnealing. Heat to 830 to 860 °C (1525 to 1580 °F), and hold for time ctated by section thickness or furnace load; furnace cool.

In aerospace practice, parts are annealed at 845 °C (1555 °F). They are ›oled to below 425 °C (795 °F) at a rate not to exceed 95 °C (170 °F) per h

Stress Relieving. After straightening, forming, or machining, parts may be stress relieved at 650 to 675 °C (1200 to 1245 °F)

Hardening. Heat to 800 to 845 °C (1475 to 1555 °F), and hold for 15 min for each 25 mm (1 in.) of thickness (15 min minimum); oil quench to below 65 °C (150 °F), or quench in fused salt at 200 to 210 °C (390 to 410 °F), hold for 10 min, then air cool to below 65 °C (150 °F).

In aerospace practice, parts are austenitized at 815 °C (1500 °F) and quenched in oil or polymer.

In standard practice, flame hardening, ion nitriding, liquid nitriding, gas nitriding, and laser hardening are suitable processes. Parts are quenched in oil, polymer, and fluidized bed furnaces. Thin sections may be fully hardened by air cooling. E4340H may be gas nitrided and quenched in polymer. Austempering and martempering are alternative processes

Tempering. Hold at least 30 min at 200 to 650 °C (390 to 1200 °F); air cool. Tempering and time at temperature depend mainly on desired hardness.

In aerospace practice, see tables on tempering temperatures based on as-quenched hardness and tensile strength ranges

Spheroidizing. The preferred schedule is to preheat to 690 °C (1275 °F); hold 2 h; then increase temperature to 745 °C (1375 °F); hold 2 h; cool to 650 °C (1200 °F), and hold 6 h to approximately 600 °C (1110 °F); and finally air cool to room temperature. An alternative schedule is to heat to 730 to 745 °C (1350 to 1375 °F), hold several hours, then furnace cool to room temperature

Baking. To avoid hydrogen embrittlement, plated parts must be baked at least 8 h at 185 to 195 °C (365 to 385 °F) as soon after plating as possible

Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize, quench, and temper
- Finish machine
- Nitride (optional)

340: Effects of Mass on Mechanical Properties

Section diameter, mm	Section diameter, in.	Tensile strength, MPa	Tensile strength, ksi	Yield strength, MPa	Yield strength, ksi	Elongation in 50 mm (2 in.), %	Reduction in area, %	Hardness, HB
il quenched and tempered(a)								
13	½	1460	212	1380	200	13	51	...
38	1½	1450	210	1365	198	11	45	...
75	3	1420	206	1325	192	10	38	...
'ater quenched and tempered(b)								
75	3	1055	153	930	135	18	52	340
100	4	1035	150	895	130	17	50	330
150	6	1000	145	850	123	16	44	322

) Austenitized at 845 °C (1555 °F); tempered at 425 °C (800 °F). (b) 75 mm (3 in.) diam bar austenitized at 800 °C (1475 °F); 100 and 150 mm (4 and 6 in.) diam bars austenitized 815 °C (1500 °F). All sizes tempered at 650 °C (1200 °F). Test specimens taken at midradius

4340: Typical Mechanical Properties

Oil quenched from 845 °C (1555 °F) and tempered at various temperatures

Tempering temperature		Tensile strength		Yield strength		Elongation in 50 mm (2 in.), %	Reduction in area, %	Hardness		Izod impact energy	
°C	°F	MPa	ksi	MPa	ksi			HB	HRC	J	ft · lbf
205	400	1980	287	1860	270	11	39	520	53	20	15
315	600	1760	255	1620	235	12	44	490	49.5	14	10
425	800	1500	217	1365	198	14	48	440	46	16	12
540	1000	1240	180	1160	168	17	53	360	39	47	35
650	1200	1020	148	860	125	20	60	290	31	100	74
705	1300	860	125	740	108	23	63	250	24	102	75

4340: Notch Toughness, Fracture Toughness, and K_{Iscc} Steel Tempered to Different Hardnesses

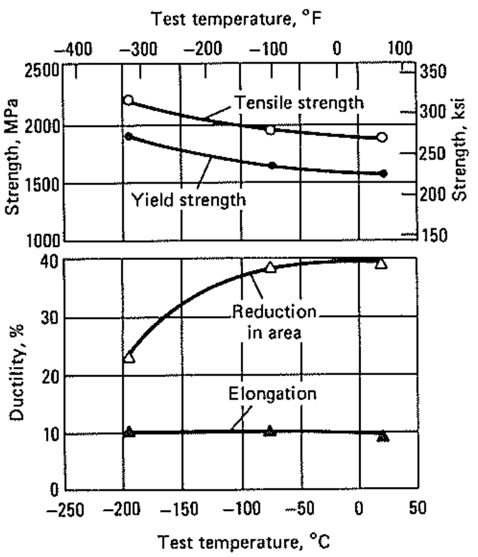
Hardness, HB	Equivalent tensile strength(a)		Charpy V-notch impact energy		Plane-strain fracture toughness (K_{Ic})		K_{Iscc} in seawater	
	MPa	ksi	J	ft · lbf	MPa$\sqrt{m}$	ksi$\sqrt{in.}$	MPa$\sqrt{m}$	ksi$\sqrt{in.}$
550	2040	296	19	14	53	48	8	7
430	1520	220	30	22	75	68	30	27
380	1290	187	42	31	110	100	33	30

(a) Estimated from hardness

4340: Suggested Tempering Temperatures Based on As-Quenched Hardness (Aerospace Practice)

Tensile strength range	RC 47-49	RC 50-52	RC 53-55	RC 56-58	RC 59 and over
965-1105 MPa (140-160 ksi)	540 °C (1000 °F)	565 °C (1050 °F)	595 °C (1100 °F)	635 °C (1175 °F)	665 °C (1225 °F)
1035-1175 MPa (150-170 ksi)	495 °C (925 °F)	525 °C (975 °F)	550 °C (1025 °F)	595 °C (1100 °F)	620 °C (1150 °F)
1105-1240 MPa (160-180 ksi)	...	480 °C (900 °F)	525 °C (975 °F)	565 °C (1050 °F)	595 °C (1100 °F)
1175-1310 MPa (170-190 ksi)	...	455 °C (850 °F)	495 °C (925 °F)	540 °C (1000 °F)	565 °C (1050 °F)
1240-1380 MPa (180-200 ksi)	...	425 °C (800 °F)	470 °C (875 °F)	510 °C (950 °F)	540 °C (1000 °F)
1310-1450 MPa (190-210 ksi)	...	385 °C (725 °F)	425 °C (800 °F)	480 °C (900 °F)	525 °C (975 °F)
1380-1515 MPa (200-220 ksi)	...	...	400 °C (750 °F)	455 °C (850 °F)	510 °C (950 °F)

Source: AMS 2759/1



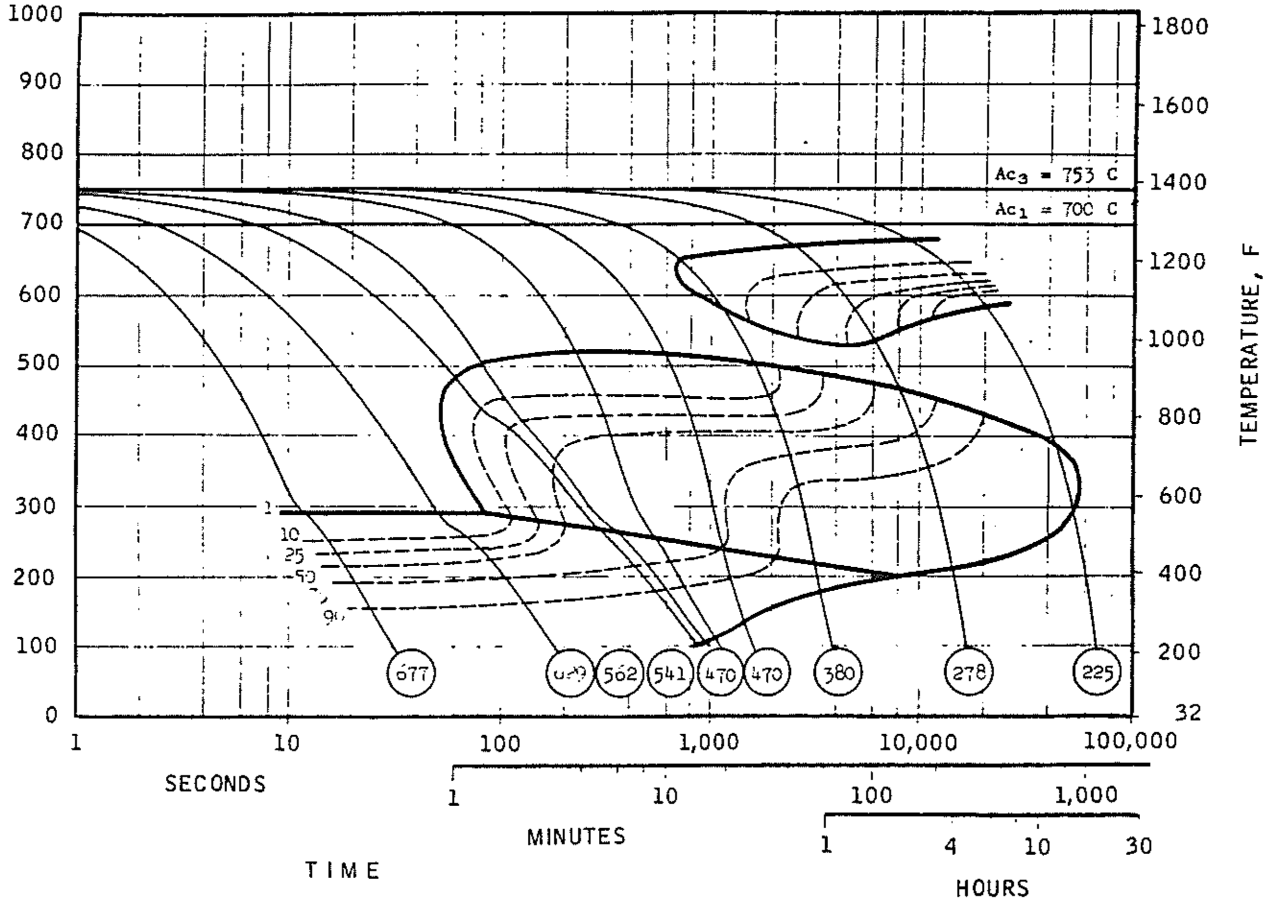
4340: Low Temperature Tensile Properties. Oil quenched from 860 °C (1580 °F); double tempered at 230 °C (445 °F)

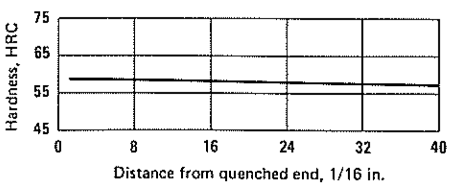
340: Suggested Tempering Temperatures (Aerospace Practice)(a)

Tensile strength				
60-1035 MPa (25-150 ksi)	1035-1175 MPa (150-170 ksi)	1175-1240 MPa (160-180 ksi)	1240-1380 MPa (180-200 ksi)	1380-1500 MPa (200-220 ksi)
50 °C (200 °F)	595 °C (1100 °F)	550 °C (1025 °F)	495 °C (925 °F)	440 °C(b) (825 °F)

a) Quench in oil or polymer. (b) At least two tempering operations are required. Source: AMS 2759/1

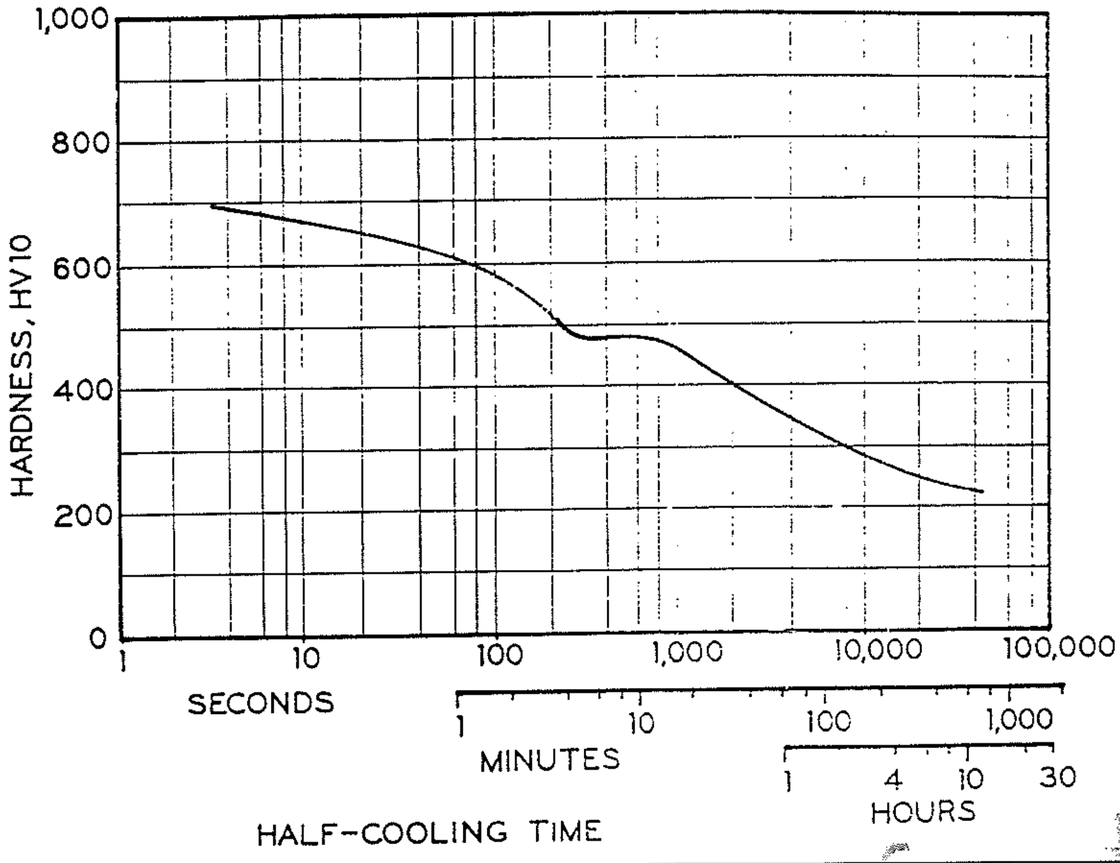
4340: CCT Diagram. Chemical composition: 0.39 C, 0.28 Si, 0.72 Mn, 0.012 P, 0.0155, 0.77 Cr, 1.78 Ni, 0.28 Mo, 0.140 Cu. Bar stock from commercial heat was used in study. Steel was austenitized for 20 min at 845 °C (1555 °F). Source: Datasheet I-218. Climax Molybdenum Company





4340 + Si: End-Quench Hardenability. Composition: 0.42 C, 0.83 Mn, 1.50 Si, 1.85 Ni, 0.90 Cr, 0.41 Mo. Quenched from 845 °C (1555 °F). Source: Bethlehem Steel

4340: Cooling curve. Half cooling time. Source: Datasheet I-218. Climax Molybdenum Company



4340: Tempered Hardness vs Austenitizing Temperature and Section Size

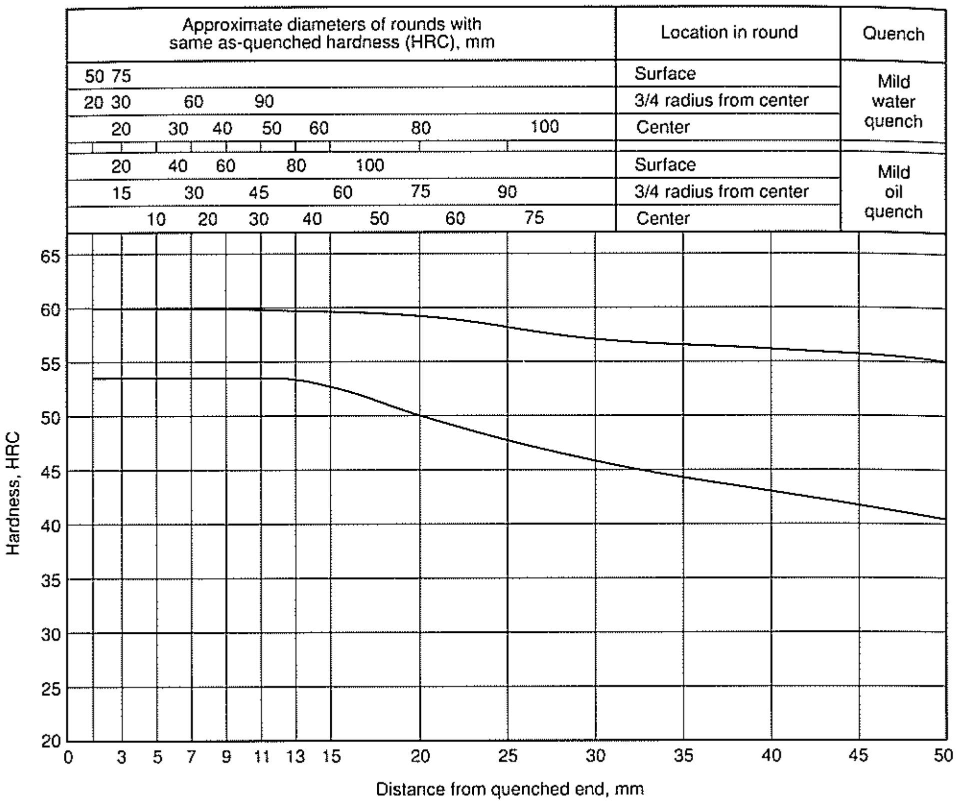
Specimens were quenched in oil

Austenitizing temperature		Section size		Hatdness, HRC Tempered for 2 hr at				
°F	°C	in.	mm	400 °F (205 °C)	600 °F (315 °C)	800 °F (425 °C)	1000 °F (540 °C)	1200 °F (650 °C)
1500	815	½	12.7	53.5	50.0	44.5	39.0	29.5
		1¼	31.8	53.5	50.0	45.5	40.0	28.5
		2⅛	54	51.0	49.0	44.0	37.5	28.0
1555	845	½	12.7	53.5	49.5	44.0	39.0	29.0
		1¼	31.8	53.0	50.0	45.0	39.5	27.0
		2⅛	54	52.0	48.0	43.0	38.0	27.5
1600	870	½	12.7	53.5	50.0	45.0	40.0	29.5
		1¼	31.8	53.5	50.0	45.5	39.5	29.0
		2⅛	54	52.5	48.5	44.0	39.0	28.0

4340H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 870 °C (1600 °F). Austenitize: 845 °C (1555 °F)

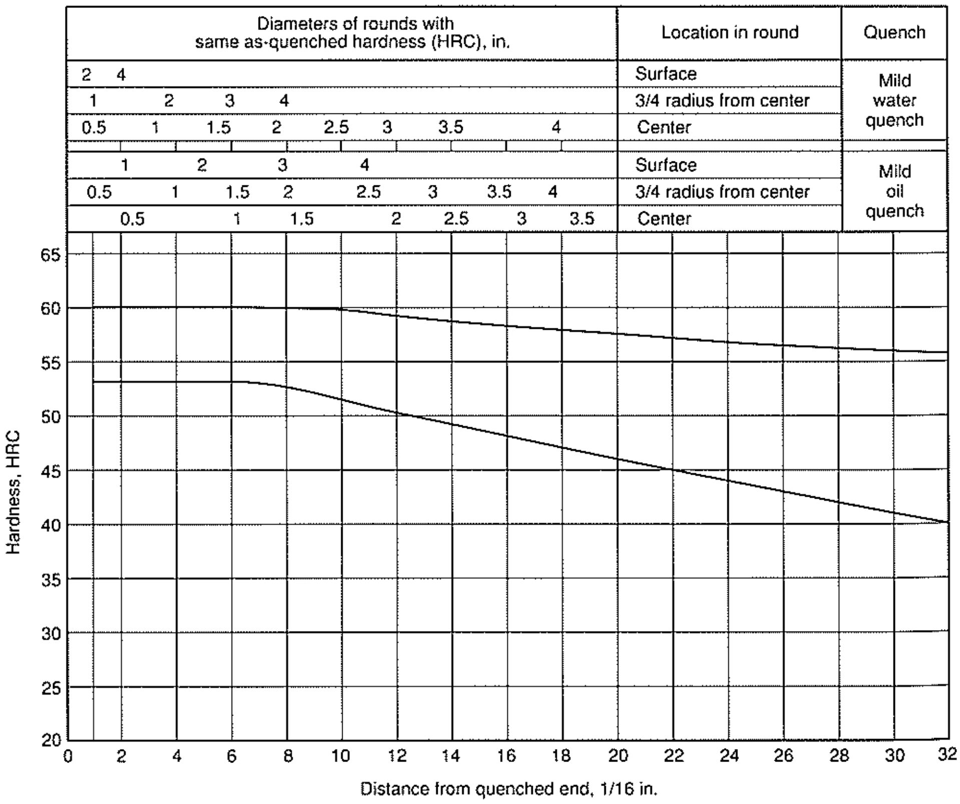
Hardness Limits for Specification Purposes

distance, mm	Hardness, HRC Maximum	Minimum
.5	60	53
	60	53
	60	53
	60	53
	60	53
1	60	53
3	60	52
5	60	52
0	59	50
5	58	48
0	58	46
5	57	44
0	57	43
5	56	42
0	56	40

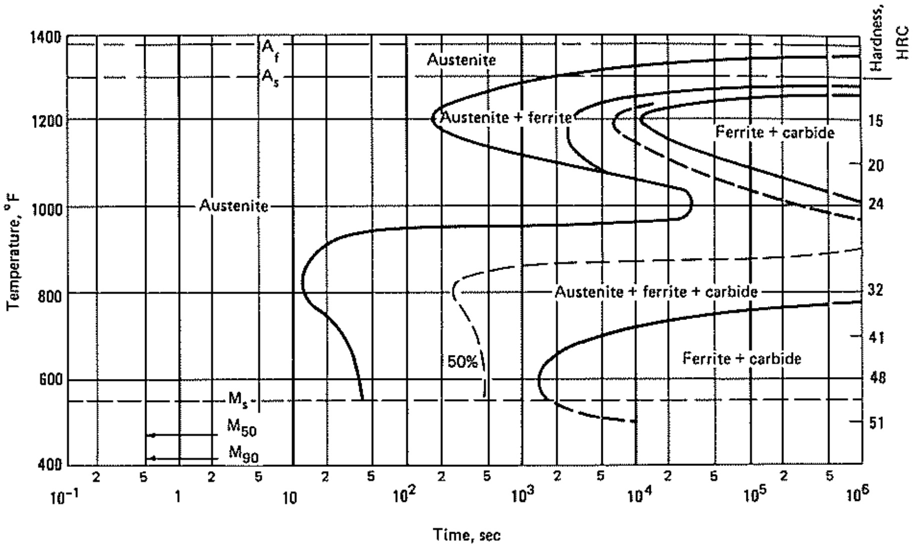


Hardness Limits for Specification Purposes

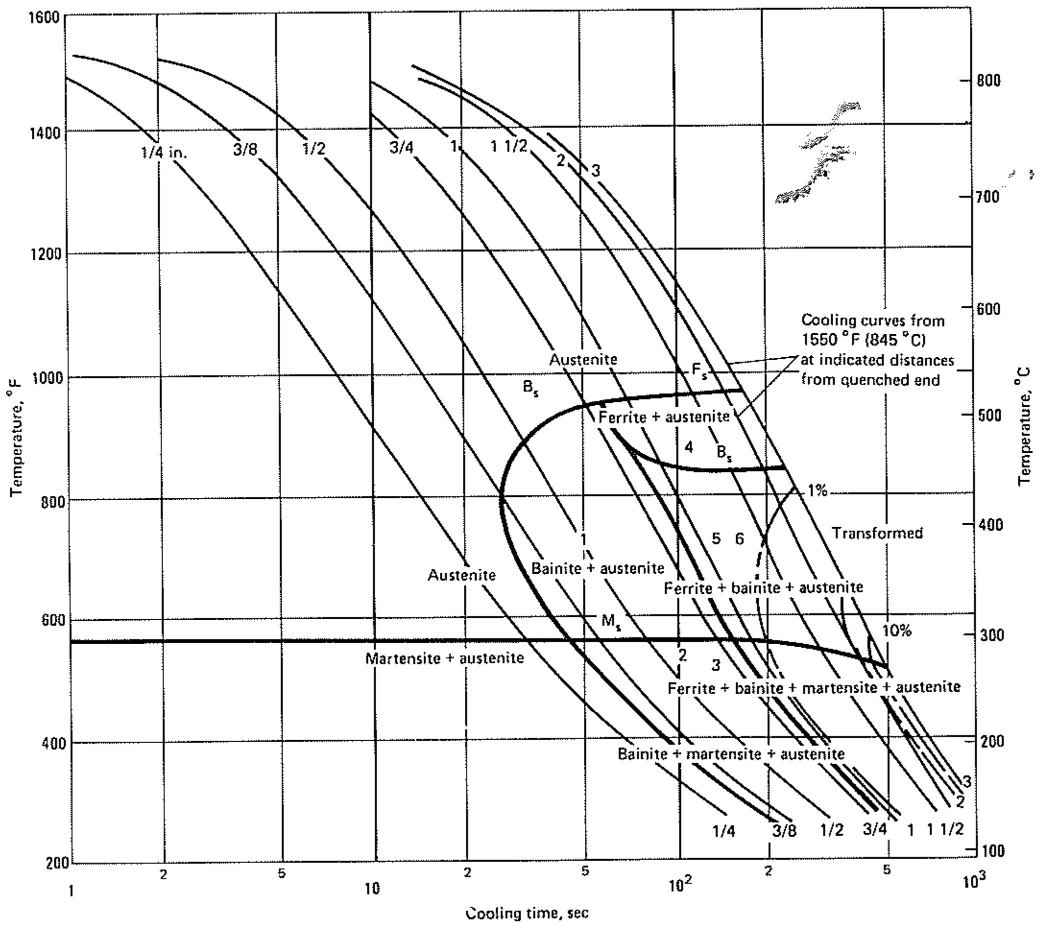
distance, 1/16 in.	Hardness, HRC Maximum	Minimum
	60	53
	60	53
	60	53
	60	53
	60	53
	60	53
	60	53
	60	52
	60	52
0	60	52
1	59	51
2	59	51
3	59	50
4	58	49
5	58	49
6	58	48
8	58	47
0	57	46
2	57	45
4	57	44
6	57	43
8	56	42
0	56	41
2	56	40



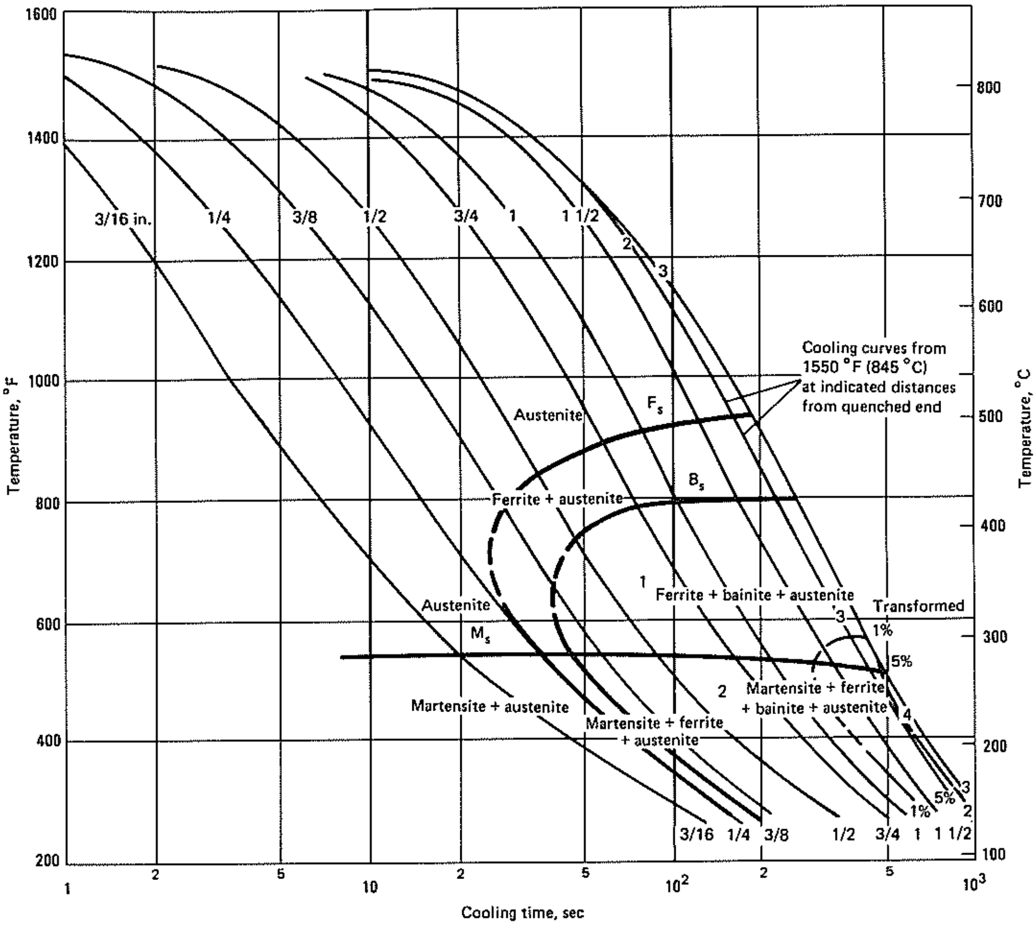
4340: Isothermal Transformation Diagram. Composition: 0.42 C, 0.78 Mn, 1.79 Ni, 0.80 Cr, 0.33 Mo. Austenitized at 845 °C (1555 °F). Grain size: 7 to 8



4340: Cooling Transformation Diagram. Composition: 0.41 C, 0.87 Mn, 0.28 Si, 1.83 Ni, 0.72 Cr, 0.20 Mo. Austenitized at 845 °C (1555 °F). Grain size: 7. Ac_3, 755 °C (1390 °F); Ac_1, 720 °C (1330 °F). A: austenite, F: ferrite, B: bainite, M: martensite. Source: Bethlehem Steel

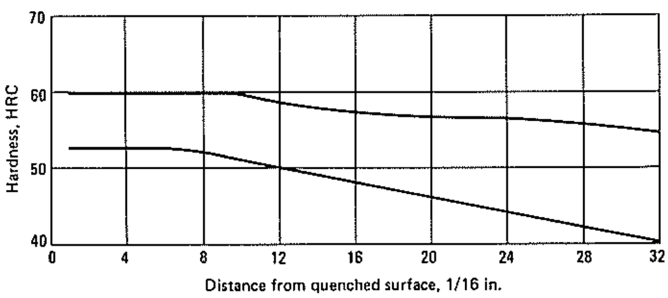


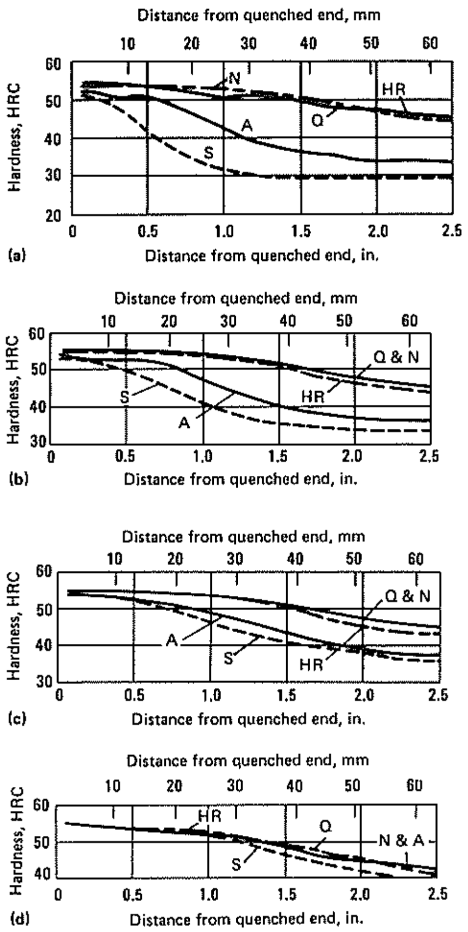
4340 + Si: Cooling Transformation Diagram. Composition 0.43 C, 0.83 Mn, 1.55 Si, 1.84 Ni, 0.91 Cr, 0.40 Mn, 0.12 V, 0.083 Al. Austenitized at 870 °C (1600 °F). Grain size: 8. Ac_3, 805 °C (1480 °F); Ac_1, 760 °C (1400 °F). A: austenite, F: ferrite, B: bainite, M: martensite. Source: Bethlehem Steel



4340H: End-Quench Hardenability

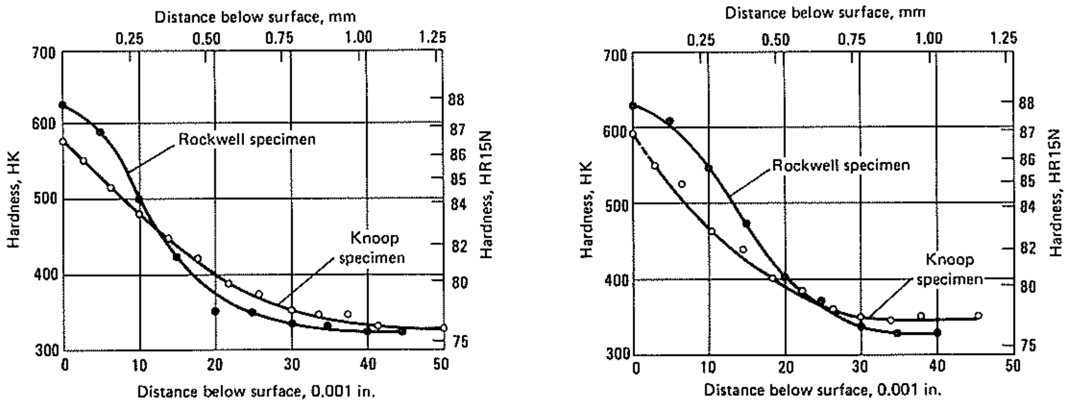
Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	Distance from quenched surface, mm	Hardness, HRC max	Hardness, HRC min
1	1.58	60	53	13	20.54	59	50
2	3.16	60	53	14	22.12	58	49
3	4.74	60	53	15	23.70	58	49
4	6.32	60	53	16	25.28	58	48
5	7.90	60	53	18	28.44	58	47
6	9.48	60	53	20	31.60	57	46
7	11.06	60	53	22	34.76	57	45
8	12.64	60	52	24	37.92	57	44
9	14.22	60	52	26	41.08	57	43
10	15.80	60	52	28	44.24	56	42
11	17.38	59	51	30	47.40	56	41
12	18.96	59	51	32	50.56	56	40

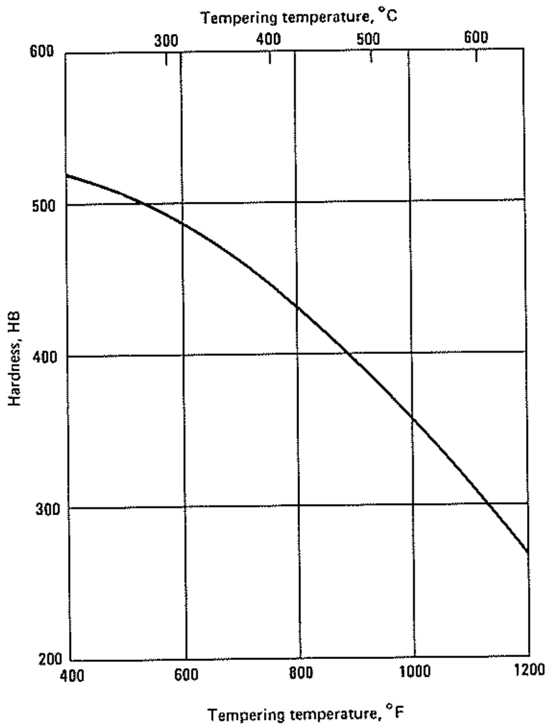




4340H: End-Quench Hardenability. Influence of initial structure and time at 845 °C (1555 °F). HR: hot rolled, N: normalized, A: annealed, S: spheroidized. (a) 0 min; (b) 10 min; (c) 40 min; (d) 4 h

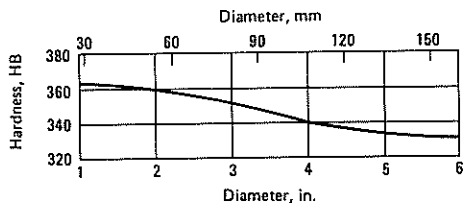
4340: Gas Nitriding. Two tests. Nitrided at 550 °C (1020 °F) for 20 h, 20 to 50% dissociation



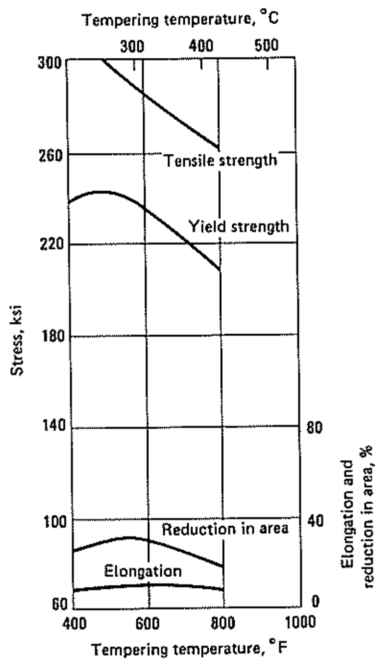


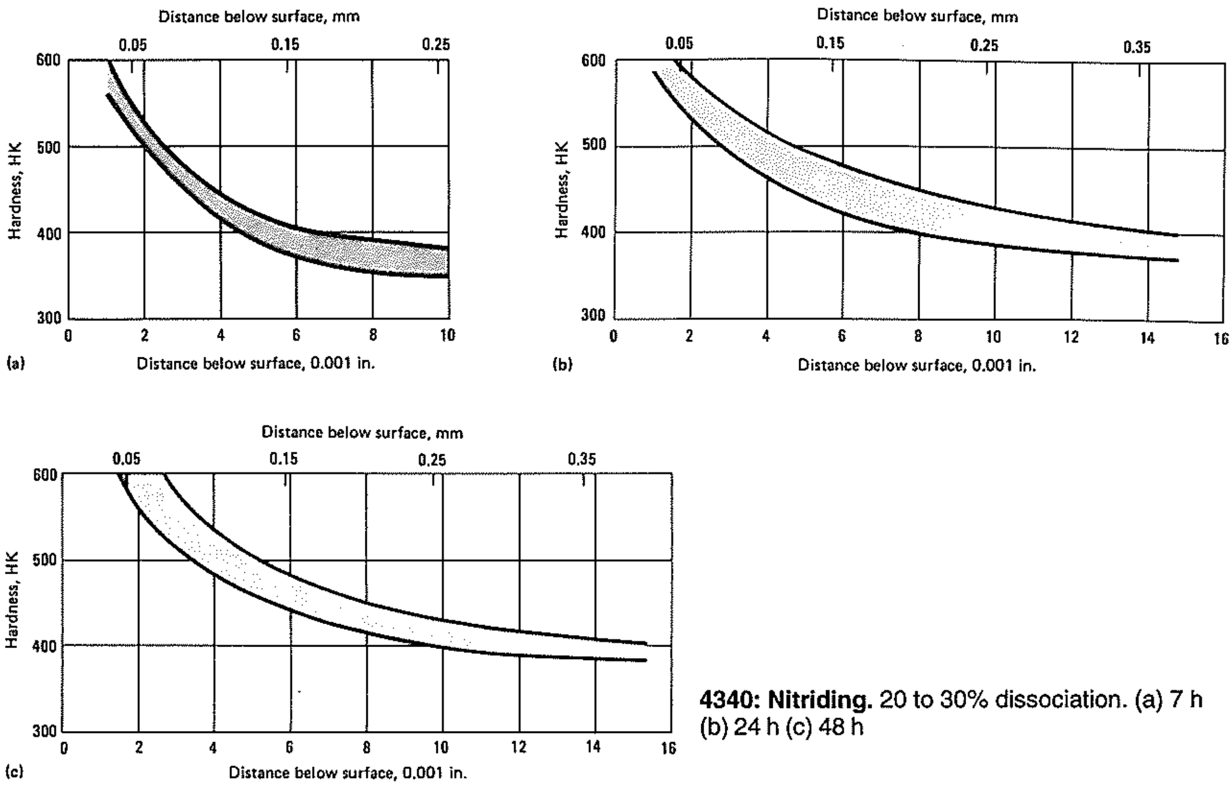
4340: Hardness vs Tempering Temperature. Normalized at 870 °C (1600 °F), quenched from 845 °C (1555 °F), and tempered at 56 °C (100 °F) intervals in 13.7 mm (0.540 in.) rounds. Tested in 12.8 mm (0.505 in.) rounds. Source: Republic Steel

l340: Hardness vs Diameter. 0.38 to 0.43 C, 0.60 to 0.80 Mn,).040 P max, 0.040 S max, 0.20 to 0.35 Si, 1.65 to 2.00 Ni, 0.70 to).90 Cr, 0.20 to 0.30 Mo. Approximate critical points: Ac_1, 725 °C 1335 °F); Ac_3, 775 °C (1425 °F); Ar_3, 710 °C (1310 °F); Ar_1, 655 °C 1210 °F). Forge at 1230 °C (2250 °F) maximum; anneal at 595 to 360 °C (1100 to 1225 °F) for a maximum hardness of 223 HB; normalize at 845 to 900 °C (1555 to 1650 °F) for an approximate hardness of 415 HB; quench in oil from 830 to 855 °C (1525 to 1575 °F). Test specimens normalized at 870 °C (1600 °F) in over-sized rounds, quenched from 845 °C (1555 °F) in oil, tempered at 540 °C (1000 °F). Tested in 12.8 mm (0.505 in.) rounds. Tests from 38 mm (1½ in.) diam bars and over are taken at half radius position. Source: Republic Steel

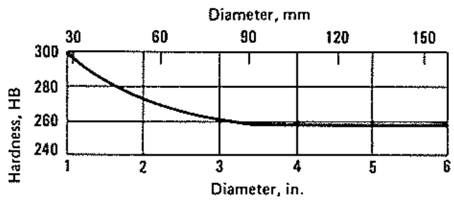


4340 + Si: Tensile Strength, Yield Strength Elongation, and Reduction in Area. Composition: 0.43 C, 0.83 Mn, 1.55 Si, 1.84 Ni, 0.91 Cr, 0.40 Mo, 0.12 V, 0.083 Al. Normalized at 900 °C (1650 °F), austenitized at 855 °C (1575 °F), quenched in agitated oil, tempered for 1 h. Source: Bethlehem Steel



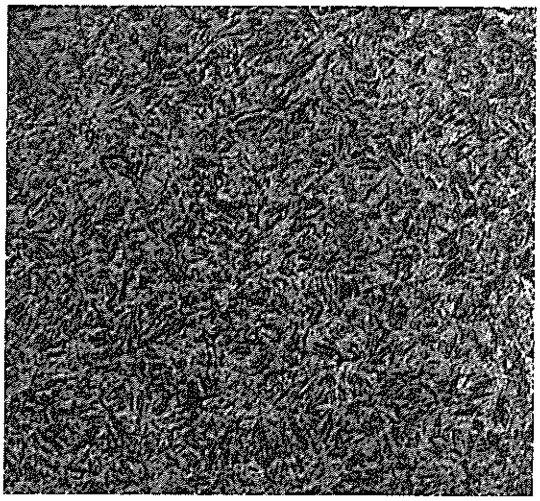


4340: Nitriding. 20 to 30% dissociation. (a) 7 h (b) 24 h (c) 48 h

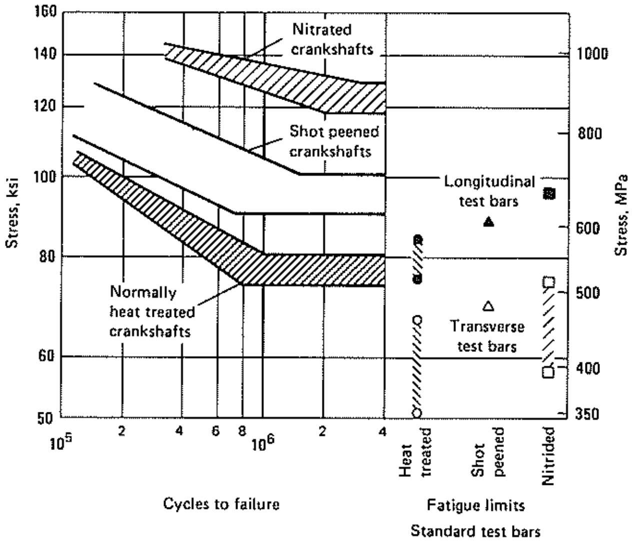


4340: Hardness vs Diameter. Composition: 0.38 to 0.43 C, 0.60 to 0.80 Mn, 0.040 P max, 0.040 S max, 0.20 to 0.35 Si, 1.65 to 2.00 Ni, 0.70 to 0.90 Cr, 0.20 to 0.30 Mo. Approximate critical points: Ac_1, 725 °C (1335 °F); Ac_3, 775 °C (1425 °F); Ar_3, 710 °C (1310 °F); Ar_1, 655 °C (1210 °F). Recommended thermal treatment: forge at 1230 °C (2250 °F) maximum; anneal at 595 to 660 °C (1100 to 1225 °F) for a maximum hardness of 223 HB; normalize at 845 to 900 °C (1555 to 1650 °F) for an approximate hardness of 415 HB; quench from 830 to 855 °C (1525 to 1575 °F) in oil. Test specimens were normalized at 870 °C (1600 °F) in over-sized rounds, quenched from 845 °C (1555 °F) in oil, tempered at 650 °C (1200 °F). Tested in 12.8 mm (0.505 in.) rounds. Tests from 38 mm (1½ in.) diam bars and over are taken at half radius position. Source: Republic Steel

;40: Microstructure. 2% nital, 500×. Quenched in oil from 845 : (1555 °F) and tempered at 315 °C (600 °F). Tempered marten- e



4340: Effect of Nitriding and Shot Peening on Fatigue Behavior. Comparison between fatigue limits of crankshafts (*S-N* bands) and fatigue limits for separate test bars, indicated by plotted points at right



)OM

əmical Composition. **300M:** 0.40 to 0.46 C, 0.65 to 0.90 Mn, to 1.80 Si, 0.70 to 0.95 Cr, 1.65 to 2.00 Ni, 0.30 to 0.45 Mo, 0.05 V

ıracteristics. Basically silicon-modified (1.6% Si) with slightly .er carbon and molybdenum, plus vanadium. Has deep hardenability, g with ductility and toughness at tensile strength of 1860 to 2070 MPa) to 300 ksi). Many properties are similar to those of 4340. Exceptions to higher silicon content include deeper hardenability, greater solid-so- ın strengthening, and better resistance to softening at elevated tempera- ;. Also, greater relief of quenching stresses is due to a higher tempering ›erature. However, because of high silicon and molybdenum content, M is particularly prone to decarburization; and when the alloy is heat ed to strength levels above 1380 MPa (200 ksi), it is susceptible to ·ogen embrittlement. When 300M is properly baked after plating, ›erties are better than those of 4340 or D-6ac of equal strength

'ging. Forging is at 1065 to 1095 °C (1950 to 2005 °F), and should ›e continued below 925 °C (1695 °F). Slow cooling in a furnace after ing is preferred. Cooling in air in a dry place is permissible

commended Heat Treating Practice

'malizing. Heat to 915 to 940 °C (1680 to 1725 °F); holding time is d on section thickness; air cool. If parts are normalized to improve hinability, charge them into a tempering furnace at 650 to 675 °C (1200 !45 °F) before parts reach room temperature.

In aerospace practice, normalize at 925 °C (169.

Spheroidizing-Annealing. For either process, heat to 775 °C (1425 °F) and hold for time dictated by section thickness or furnace load; cool to 480 °C (895 °F) at a rate not to exceed 10 °C (20 °F) per h; air cool to room temperature.

In aerospace practice, anneal at 845 °C (1555 °F)

Hardening. Austenitize at 860 to 885 °C (1580 to 1625 °F). Oil quench to below 70 °C (160 °F), or quench in salt at 200 to 210 °C (390 to 410 °F), hold 10 min, then air cool to 70 °C (160 °F) or below.

In aerospace practice, parts are austenitized at 870 °C (1600 °F). Quenching is in oil or polymer. Parts are in the normalized or in the normalized and tempered condition prior to initial austenitizing with one exception: parts normalized but not tempered shall be preheated prior to austenitizing

Tempering. Hold 2 to 4 h at 260 to 315 °C (500 to 600 °F). Double tempering is recommended. Tempering outside this range of temperatures can cause severe deterioration of properties.

In aerospace practice, parts are tempered to a tensile strength range of 1865 to 2000 MPa (270 to 290 ksi) at temperatures in the range of 290 to 315 °C (555 to 600 °F) and at 300 °C (570 °F) for tensile strengths in the range of 1930 to 2105 MPa (280 to 305 ksi). At least two tempering operations are required

300M: Typical Mechanical Properties

Round bars, 25 mm (1 in.) in diameter, oil quenched from 860 °C (1575 °F) and tempered at various temperatures

Tempering temperature		Tensile strength		Yield strength		Elongation in 50 mm	Reduction	Charpy V-notch impact energy		Hardness,
°C	°F	MPa	ksi	MPa	ksi	(2 in.), %	in area, %	J	ft · lbf	HRC
90	200	2340	340	1240	180	6.0	10.0	17.6	13.0	56.0
205	400	2140	310	1650	240	7.0	27.0	21.7	16.0	54.5
260	500	2050	297	1670	242	8.0	32.0	24.4	18.0	54.0
315	600	1990	289	1690	245	9.5	34.0	29.8	22.0	53.0
370	700	1930	280	1620	235	9.0	32.0	23.7	17.5	51.0
425	800	1790	260	1480	215	8.5	23.0	13.6	10.0	45.5

300M: Effects of Mass on Tensile and Impact Properties

Round bars, normalized at 900 °C (1650 °F), oil quenched from 860 °C (1575 °F), and tempered at 315 °C (600 °F)

Bar diameter		Tensile strength		Yield strength		Elongation in 50 mm	Reduction	Charpy V-notch impact energy when tested at 21 °C (70 °F)		−46 °C (−50 °F)		−73 °C (−100 °F)	
mm	in.	MPa	ksi	MPa	ksi	(2 in.), %	in area, %	J	ft · lbf	J	ft · lbf	J	ft · lbf
25	1	1990	289	1690	245	9.5	34.1	30	22	26	19	24	18
75	3	1940	281	1630	236	9.5	35.0	26	19	19	14	12	9
145	5¾	2120	308	1800	261	7.3	22.3	12	9	9	7	7	5

300M: Transverse Tensile Properties of Air-Melted and Vacuum Arc Remelted Steel

Tempering temperature		Tensile strength		Yield strength		Elongation in 50 mm	Reduction
°C	°F	MPa	ksi	MPa	ksi	(2 in.), %	in area, %
Air melted							
315	600	1960	284	1620	235	5.0	11
425	800	1760	255	1540	223	7.0	14
540	1000	1585	230	1480	215	9.0	22
Vacuum arc remelted							
260	500	2020	293	1620	235	7.0	25
425	800	1760	255	1550	225	10.0	34
540	1000	1585	230	1480	215	11.0	35

300M: Average Mechanical Properties of Air-Melted and Vacuum Arc Remelted Heats

Hot reduced 96 to 98% to round-cornered square billets, about 100 × 100 mm (4 × 4 in.). Specimens were normalized at 925 °C (1700 °F), oil quenched from 870 °C (1600 °F), refrigerated, and double tempered, 2 + 2 h at 315 °C (600 °F)

Specimen	Tensile strength		Yield strength		Reduction	Plane-strain fracture toughness (K_{Ic})	
direction	MPa	ksi	MPa	ksi	in area, %	MPa$\sqrt{m}$	ksi$\sqrt{in.}$
Air melted							
Longitudinal	2095	304	1805	262	44.8	49.3	44.9
Transverse	2035	295	1750	254	23.6	58.7(a)	53.4(a)
						61.4(b)	55.9(b)
Vacuum arc remelted							
Longitudinal	2080	302	1785	259	47.8	57.4	52.2
Transverse	2015	292	1760	255	33.6	64.1(a)	58.3(a)
						61.4(b)	55.9(b)

(a) WR orientation. (b) WW orientation

-6a, D-6ac

emical Composition. D-6a: 0.42 to 0.48 C, 0.60 to 0.90 Mn, 0.15 .30 Si, 0.90 to 1.20 Cr, 0.40 to 0.70 Ni, 0.90 to 1.10 Mo, 0.05 to 0.10 V

nilar Steels (U.S. and/or Foreign). No foreign equivalents

aracteristics. D-6a is air melted in electric furnace. In processing ac, vacuum arc remelting follows air melting. Mechanical properties somewhat different. Other characteristics are identical. D-6a is a low y steel developed for aircraft and missile structural applications. It is igned primarily for use at room temperature tensile strengths of 1800 to 0 MPa (260 to 290 ksi). A very high ratio of yield strength to tensile ngth is maintained up to a tensile strength of 1930 MPa (280 ksi), ıbined with good ductility. Notch toughness is good, resulting in high stance to impact loading. The alloy is deeper hardening than 4340 and s not exhibit temper embrittlement. High strength is maintained at ated temperatures. Susceptibility of D-6a to stress corrosion cracking corrosion fatigue in moist and aqueous environments is comparable to of 300M steel at the same strength level

rging. Heat (D-6a) to temperature of 1230 °C (2250 °F) max; forging uld be finished above 980 °C (1795 °F). Finished forgings should be led slowly in furnace, or embedded in a suitable insulating medium such shes or lime

commended Heat Treating Practice

rmalizing. Heat to 870 to 955 °C (1600 to 1750 °F); hold for time ated by section thickness; air cool.

In aerospace practice, parts are normalized at 940 °C (1725 °F). All s are in the normalized or the normalized and tempered condition prior nitial austenitizing treatment. An exception: parts normalized but not pered are preheated prior to austenitizing

Annealing. Heat to 815 to 845 °C (1500 to 1555 °F) to time dictated by section thickness and furnace load. Furnace cool to 540 °C (1000 °F) at a rate not to exceed 28 °C (50 °F) per h; air cool to room temperature.

In aerospace practice, parts are annealed at 845 °C (1555 °F), then cooled to below 540 °C (1000 °F) at a rate not to exceed 95 °C (170 °F) per h

Stress Relieving. Heat to an appropriate temperature in the range of 540 to 675 °C (1000 to 1245 °F) and hold for 1 to 2 h; air cool

Hardening. Austenitize at 845 to 900 °C (1555 to 1650 °F) for ½ to 2 h. Sections no thicker than 25 mm (1 in.) may be air cooled. Sections thicker than 25 mm (1 in.) may be oil quenched to 65 °C (150 °F) or salt quenched to 205 °C (400 °F) and then air cooled. For optimum dimensional stability, aus-bay quench in a furnace at 525 °C (975 °F), equalize the temperature, then quench in an oil bath held at 60 °C (140 °F) or quench in 205 °C (400 °F) salt and air cool. Cooling rate during quenching significantly affects fracture toughness. For high fracture toughness, especially in heavy sections, austenitize at 925 °C (1695 °F), aus-bay quench to 525 °C (975 °F), equalize, and oil quench to 60 °C (140 °F).

In aerospace practice, parts are austenitized at 885 °C (1625 °F). All parts must be in the normalized or normalized and tempered condition prior to the initial austenitizing treatment, with this exception: parts normalized but not tempered must be preheated prior to austenitizing. An austenitizing temperature of 925 °C (1695 °F) is permitted for D-6ac parts when approved by the cognizant engineering authority

Tempering. Immediately after hardening, parts are held 2 to 4 h, in the range of 200 to 700 °C (390 to 1290 °F) depending on the desired strength or hardness

Spheroidizing. Heat to 730 °C (1350 °F) and hold 5 h; increase temperature to 760 °C (1400 °F) and hold 1 h; furnace cool to 690 °C (1275 °F) and hold 10 h; air cool to room temperature

;a: Typical Mechanical Properties of Bar

malized at 900 °C (1650 °F), oil quenched from 845 °C (1555 °F), and tempered at various temperatures

Tempering temperature		Tensile strength		Yield strength		Elongation in 50 mm	Reduction	Charpy V-notch impact energy	
°C	°F	MPa	ksi	MPa	ksi	(2 in.), %	in area, %	J	ft · lbf
150	300	2060	299	1450	211	8.5	19.0	14	10
205	400	2000	290	1620	235	8.9	25.7	15	11
315	600	1840	267	1700	247	8.1	30.0	16	12
425	800	1630	236	1570	228	9.6	36.8	16	12
540	1000	1450	210	1410	204	13.0	45.5	26	19
650	1200	1030	150	970	141	18.4	60.8	41	30

;a: Room-Temperature Properties After Various nes at 540 °C (1000 °F)

el normalized at 900 °C (1650 °F), oil quenched from 845 °C 55 °F), and tempered at 565 °C (1050 °F)

e at °C 0 °F), h	Tensile strength		Yield strength		Elongation in 50 mm	Reduction in area,
	MPa	ksi	MPa	ksi	(2 in.), %	%
	1410	204	1340	195	14.8	50.5
	1410	204	1330	193	14.5	52.0
	1330	193	1260	183	14.8	51.0

D-6ac: Room and Elevated Temperature Fatigue Limits

Smooth specimens heat treated to a tensile strength of 1860 MPa (270 ksi); test speed, 186 kHz

Test temperature		Tension-tension(a)		Tension-compression(b)	
°C	°F	MPa	ksi	MPa	ksi
24	75	1035	150	690	100
232	450	930	135	550	80
288	550	930	135	575	75

(a) Mean stress equal to alternating stress ($R = 0$). (b) Mean stress equal to zero ($R = -1$)

D-6ac: Tensile Properties of Double-Tempered D-6ac Billet

Austenitized 1 h at 900 °C (1650 °F), quenched in fused salt at 205 °C (400 °F) for 5 min, then air cooled to room temperature. Tempered 1 h at 205 °C; second temper, 4 h at indicated temperature

Second tempering temperature		Tensile strength		Yield strength		Elongation in 50 mm (2 in.), %	Reduction in area, %
°C	°F	MPa	ksi	MPa	ksi		
480	900	1686.5	244.6	1540.3	223.4	11.1	40.0
510	950	1652.7	239.7	1519.7	220.4	13.2	44.1
540	1000	1613.4	234.0	1483.8	215.2	13.7	47.2

D6-ac: Suggested Tempering Temperatures (Aerospace Practice)(a)

Tensile strength		
1175-1240 MPa 160-180 ksi	1240-1380 MPa 180-200 ksi	1380-1520 MPa 200-220 ksi
650 °C(b) (1200 °F)	(c)	(d)

(a) Quench in oil or polymer. (b) At least two tempering operations required. (c) 1st temper; 595 °C (1100 °F) min; 2nd temper; 600 to 650 °C (1115 to 1200 °F). (d) 1st temper 565 °C (1050 °F) min; 2nd temper; 590 to 620 °C (1095 to 1145 °F). Source: AMS 2759/1

6150, 6150H

Chemical Composition. **6150. AISI and UNS:** Nominal. 0.48 to 0.53 C, 0.70 to 0.90 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.80 to 1.10 Cr, 0.15 V min. **UNS H61500. SAE/AISI 6150H composition:** 0.47 to 0.54 C, 0.60 to 1.00 Mn, 0.15 to 0.35 Si, 0.75 to 1.20 Cr, 0.15 V min

Similar Steels (U.S. and/or Foreign). **6150.** UNS G61500; AMS 6448, 6450, 6455; ASTM A322, A331; MIL SPEC MIL-S-8503; SAE J404, J412, J770; (Ger.) DIN 1.8159; (Fr.) AFNOR 50 CV 4; (Ital.) UNI 50 CrV 4; (Jap.) JIS SUP 10; (Swed.) SS_{14} 2230; (U.K.) B.S. 735 A 50, En. 47. **6150H.** UNS H61500; ASTM A304; SAE J1268; (Ger.) DIN 1.8159; (Fr.) AFNOR 50 CV 4; (Ital.) UNI 50 CrV 4; (Jap.) JIS SUP 10; (Swed.) SS_{14} 2230; (U.K.) B.S. 735 A 50, En. 47

Characteristics. A tough, shock-resisting, shallow-hardening, chromium-vanadium steel with high fatigue and impact resistance in the heat treated condition. Can be nitrided for maximum surface hardness and abrasion resistance; nitriding characteristics are similar to those for 4140 and 4340

Forging. May be forged from temperatures up to 1200 °C (2190 °F), but usual temperature range is 950 to 1175 °C (1740 to 2150 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 to 925 °C (1600 to 1695 °F); hold for time dictated by section thickness; air cool.

In aerospace practice, parts are normalized at 900 °C (1650 °F)

Annealing. Heat to 845 to 870 °C (1555 to 1600 °F); hold for time dictated by section thickness and furnace load; furnace cool.

In aerospace practice, parts are annealed at 845 °C (1555 °F), then cooled to below 540 °C (1000 °F) at a rate not to exceed 95 °C (170 °F) per h

Hardening. Austenitize at 815 to 845 °C (1500 to 1555 °F); quench in oil or water. Suitable hardening processes are liquid nitriding, gas nitriding, carbonitriding, and ion nitriding. Austempering and martempering are alternative processes.

In aerospace practice, parts are austenitized at 870 °C (1600 °F), and quenched in oil or polymer

Tempering. Hold at least ½ h at 200 to 650 °C (390 to 1200 °F). For suggested tempering temperatures in different tensile strength ranges in aerospace practice, see table

Spheroidizing. Heat to 800 to 830 °C (1475 to 1525 °F); hold until heated through, furnace cool to 650 °C (1200 °F); hold several hours; cool slowly to room temperature

Austempering. For many spring applications, this steel is austempered by austenitizing at 870 °C (1600 °F), quenching in an agitated molten salt bath at 315 °C (600 °F), holding for 1 h, and air cooling. No tempering is required. Hardness after this treatment generally ranges from approximately 46 to 51 HRC

Recommended Processing Sequence

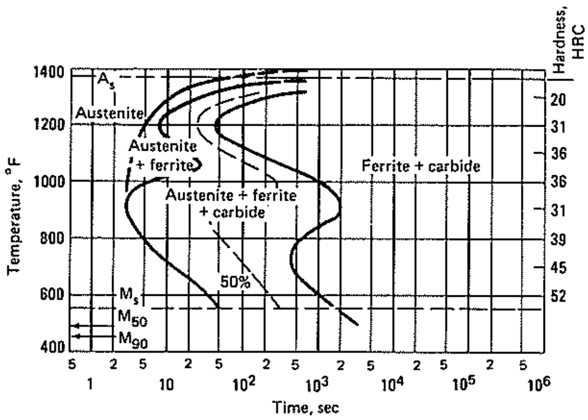
- Forge
- Normalize
- Anneal
- Rough machine
- Austenitize and quench (or austemper)
- Temper (or austemper)
- Finish machine

50: Suggested Tempering Temperatures (Aerospace Practice)(a)

Tensile strength				
860-1035 MPa (125-150 ksi)	1035-1175 MPa (150-170 ksi)	1175-1240 MPa (160-180 ksi)	1240-1380 MPa (180-200 ksi)	1380-1520 MPa (200-220 ksi)
650 °C (1200 °F)	595 °C (1100 °F)	540 °C (1000 °F)	495 °C (925 °F)	440 °C(b) (825 °F)

Quench in oil or polymer. (b) Spring temper. Source: AMS 2759/1

150: Isothermal Transformation Diagram. Composition: 0.53 , 0.67 Mn, 0.93 Cr, 0.18 V. Austenitized at 845 °C (1555 °F). rain size 9



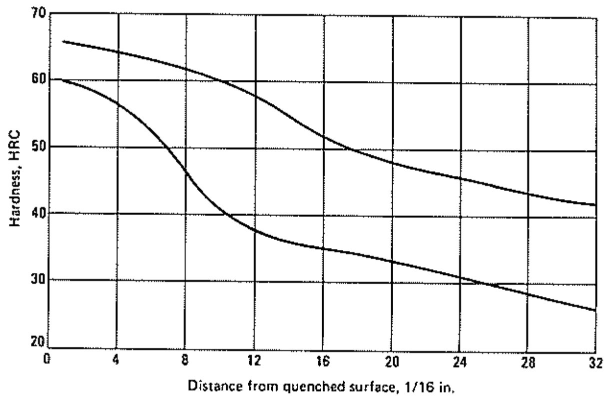
6150: Equipment Requirements for Salt Martempering Gears

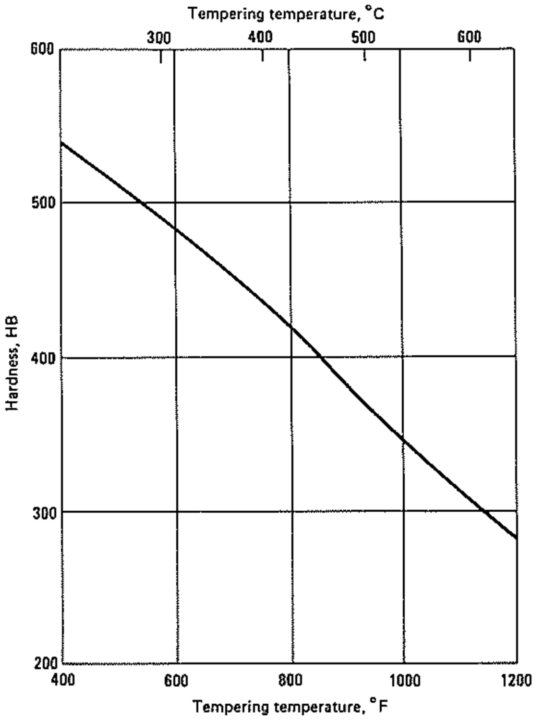
Production requirements	
Weight of each piece	0.9 kg (2 lb)
Pieces per furnace load	32
Production per hour(a):	
Number of pieces	128
Net work load	116 kg (256 lb)
Gross furnace load(b)	152 kg (336 lb)
Equipment requirements	
Martempering furnace	Immersion-heated salt pot(c)
Size of salt pot	610 by 381 by 838 mm (24 by 15 by 33 in.)
Capacity of salt pot	272 kg (600 lb)
Type of salt	Nitrate-nitrite (2% water added)
Quenching capacity of salt pot	181 kg/h (400 lb/h)
Operating temperature	205 °C (400 °F)
Agitation	Air-operated stirrer

(a) Cycle time, 15 min. (b) Work and fixtures. Each fixture weighed 9.1 kg (20 lb) empty and contained eight gears. (c) Salt pot rated at 21 kV · A (3 phase, 60 cycle, 220 to 440 V) for heating to temperature range of 175 to 400 °C (350 to 750 °F). Blower (½ hp, 3 phase, 60 cycles, 220 V) used for cooling by driving room-temperature air between wall of pot and exterior shell of furnace

150H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max	Hardness, HRC min	Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max	Hardness, HRC min
1	1.58	65	59	13	20.54	57	37
2	3.16	65	58	14	22.12	55	36
3	4.74	64	57	15	23.70	54	35
4	6.32	64	56	16	25.28	52	35
5	7.90	63	55	18	28.44	50	34
6	9.48	63	53	20	31.60	48	32
7	11.06	62	50	22	34.76	47	31
8	12.64	61	47	24	37.92	46	30
9	14.22	61	43	26	41.08	45	29
10	15.80	60	41	28	44.24	44	27
11	17.38	59	39	30	47.40	43	26
12	18.96	58	38	32	50.56	42	25





6150: Hardness vs Tempering Temperature. Normalized at 900 °C (1650 °F), quenched from 870 °C (1600 °F) in oil, tempered in 56 °C (100 °F) intervals in 13.7 mm (0.540 in.) rounds. Tested in 12.8 mm (0.505 in.) rounds. Source: Republic Steel

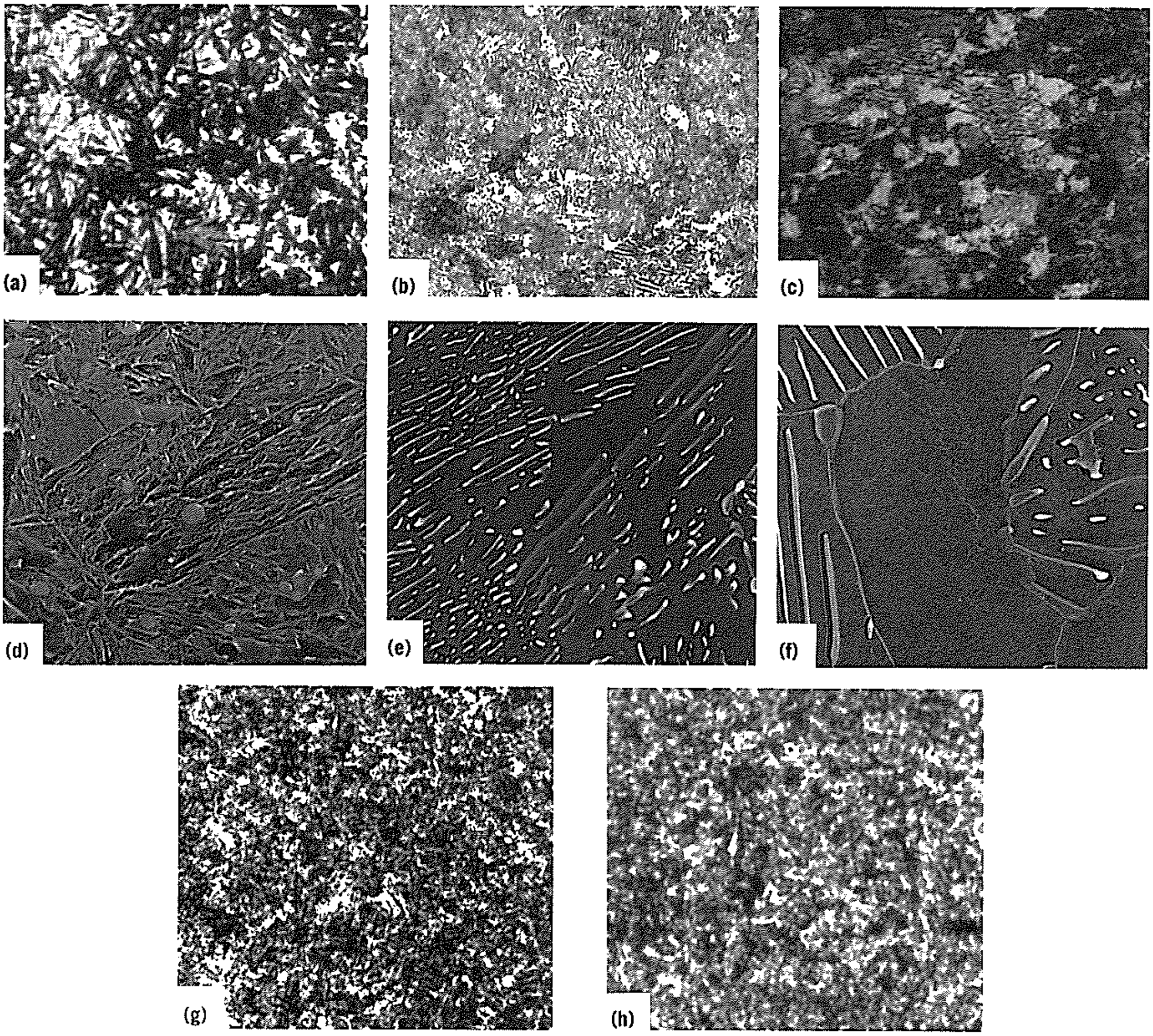
6150: As-Quenched Hardness (Oil)

Single heat results; grade: 0.48 to 0.53 C, 0.70 to 0.90 Mn, 0.20 to 0.35 Si, 0.80 to 1.10 Cr, 0.15 V minimum; ladle: 0.51 C, 0.80 Mn, 0.014 P, 0.015 S, 0.35 Si, 0.11 Ni, 0.95 Cr, 0.01 Mo, 0.18 V; grain size: 5 to 6 for 70%, 2 to 4 for 30%

Size round		Hardness, HRC		
in.	mm	Surface	½ radius	Center
½	13	61	60	60
1	25	60	58	57
2	51	54	47	44
4	102	42	36	35

Source: Bethlehem Steel

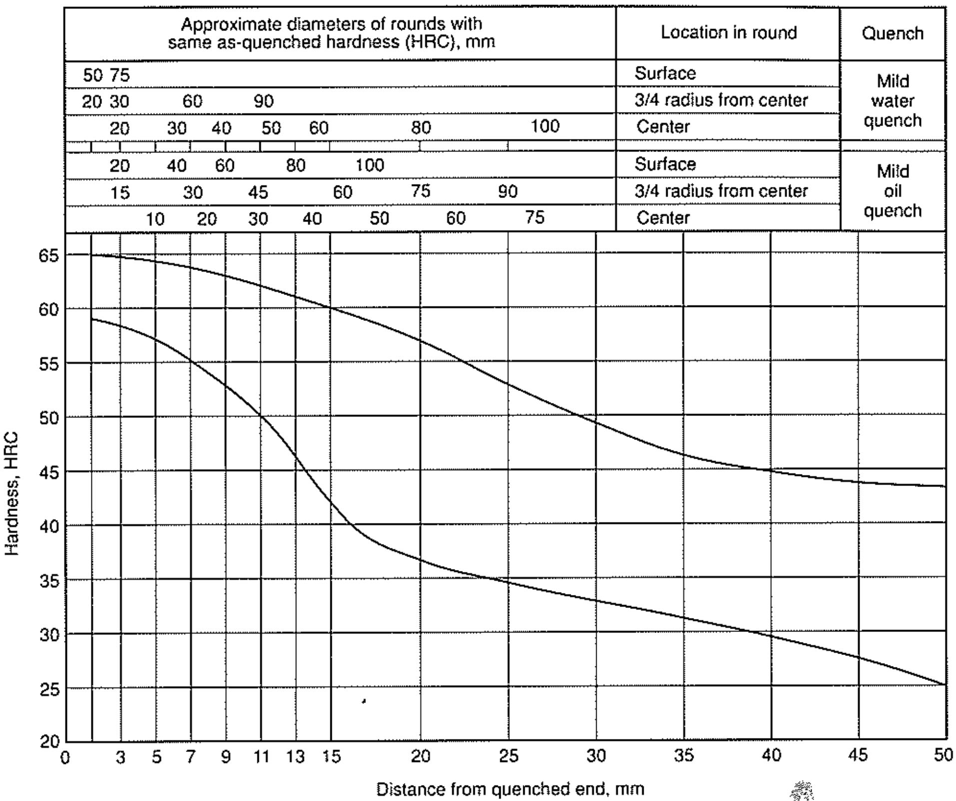
150: Microstructures. (a) 2% nital, 550×. Steel wire, austenitized at 900 °C (1650 °F) for 20 min and slack quenched in oil to room temerature. Lower bainite (dark) and untempered martensite (light). (b) Picral, 550×. Austenitized at 880 °C (1620 °F) for ½ h, cooled to 730 C (1350 °F) held 5 h, cooled to 650 °C (1200 °F) at 28 °C (50 °F) per h, held 1 h, air cooled. Pearlite and ferrite. (c) 4% nital, 500×. Steel ire, austenitized at 885 °C (1625 °F) for 20 min, quenched to 675 °C (1245 °F) for 20 min, oil quenched to room temperature. Structure nainly pearlite. (d) 4% nital, 5000×. Steel wire, austenitized at 845 °C (1555 °F) for ½ h, oil quenched, tempered at 150 °C (300 °F). An lectron micrograph of a replica rotary-shadowed with chromium. Tempered martensite and some spheroidal carbide particles. (e) 4% nital, 0,000×. Steel wire, austenitized at 870 °C (1600 °F), held for 2 h, quenched in lead to 650 °C (1200 °F), held for 2 h, water quenched. An lectron micrograph of a replica rotary-shadowed with chromium. Partly spheroidized carbide in a ferrite matrix. (f) 4% nital, 10 000×. Steel ire, austenitized at 870 °C (1600 °F) for 2 h, quenched in lead to 720 °C (1330 °F), held 2 h, water quenched. An electron micrograph of a eplica rotary-shadowed with chromium. Partly spheroidized and partly lamellar pearlite in ferrite. (g) Nital, 535×. Steel rod, 13 mm (½ in.) liam, austenitized at 845 °C (1555 °F) for 1 h, quenched to 315 °C (600 °F), held 16 min, air cooled. Mostly bainite, probably lower bainite. h) Nital, 1000×. Same steel, rod diameter, and heat treatment as (g), except at higher magnification. Austempering was heat treatment.



6150H: Hardenability Curves. Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only): 900 °C (1650 °F). Austenitize: 870 °C (1600 °F)

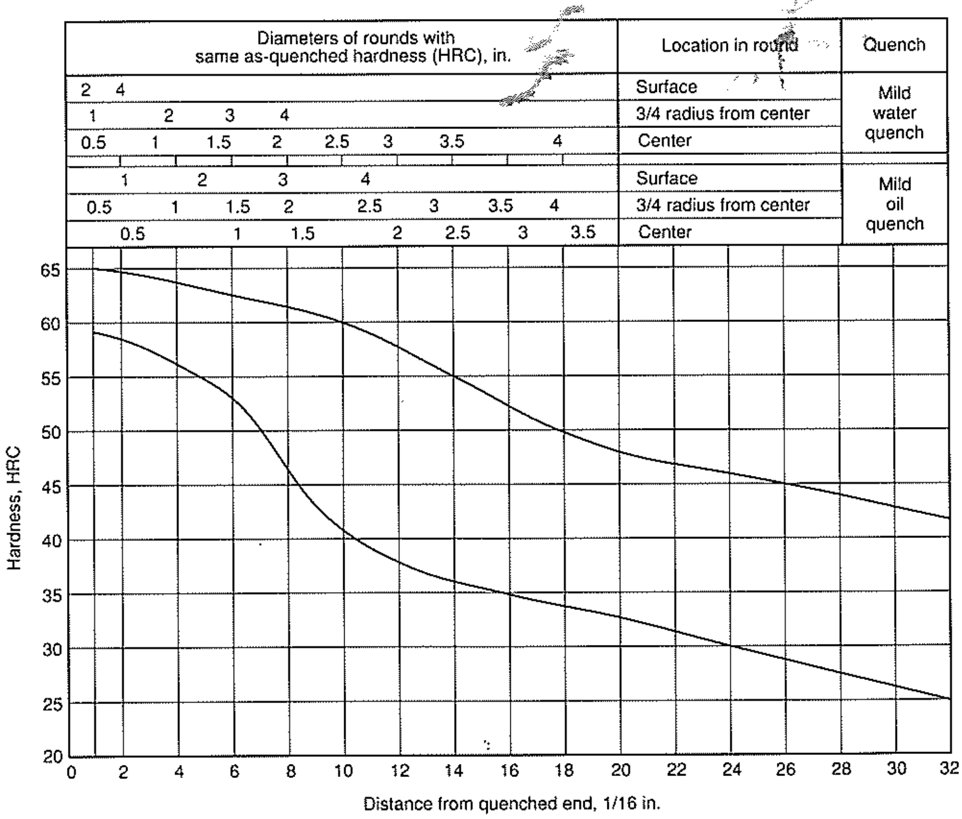
Hardness Limits for Specification Purposes

J distance, mm	Hardness, HRC Maximum	Hardness, HRC Minimum
1.5	65	59
3	65	58
5	65	57
7	64	55
9	63	53
11	63	50
13	61	46
15	60	42
20	58	37
25	53	35
30	50	33
35	47	31
40	45	29
45	44	27
50	43	25



Hardness Limits for Specification Purposes

J distance, 1/16 in.	Hardness, HRC Maximum	Hardness, HRC Minimum
1	65	59
2	65	58
3	64	57
4	64	56
5	63	55
6	63	53
7	62	50
8	61	47
9	61	43
10	60	41
11	59	39
12	58	38
13	57	37
14	55	36
15	54	35
16	52	35
18	50	34
20	48	32
22	47	31
24	46	30
26	45	29
28	44	27
30	43	26
32	42	25



3640, 8640H

hemical Composition. 8640. AISI and UNS: Nominal. 0.38 to .43 C, 0.75 to 1.00 Mn, 0.035 P max, 0.040 S max, 0.15 to 0.30 Si, 0.40) 0.70 Ni, 0.40 to 0.60 Cr, 0.15 to 0.25 Mo. **UNS H86400. SAE/AISI 640H composition:** 0.37 to 0.44 C, 0.70 to 1.05 Mn, 0.15 to 0.35 Si, 0.35) 0.65 Cr, 0.15 to 0.25 Mo

imilar Steels (U.S. and/or Foreign). 8640. UNS G86400; STM A304, A322; MIL SPEC MIL-S-16974; SAE J404, J412, J770; Ger.) DIN 1.6546; (Ital.) UNI 40 NiCrMo 2 KB; (U.K.) B.S. Type 7. **640H.** UNS H86400; ASTM A304; SAE J1268; (Ger.) DIN 1.6546; (Ital.) JNI 40 NiCrMo 2 KB; (U.K.) B.S. Type 7

haracteristics. This alloy is designed to provide maximum har-enability and best combination of properties possible with minimum lloying additions. It is an oil-hardening steel, but may be water hardened precautions are taken to prevent cracking. Properties are similar to those f 4340, except that strength is not so high

orging. Forging may be at temperatures up to 1200 °C (2190 °F), but sual practice is to forge in the range of 950 to 1175 °C (1740 to 2150 °F). orged parts are cooled slowly from the forging temperature, then annealed rior to machining

ecommended Heat Treating Practice

lormalizing. Heat to 870 to 975 °C (1600 to 1780 °F); hold for time ictated by section thickness; air cool

nnealing. Heat to 845 to 870 °C (1555 to 1600 °F); hold for time ictated by section thickness or furnace load; furnace cool

lardening. Austenitize at 815 to 845 °C (1500 to 1555 °F); quench in l or water. Flame hardening, ion nitriding, gas nitriding, and carbonitriding are suitable processes. Austempering and martempering are alternative processes

Tempering. Hold at least ½ h at 200 to 650 °C (390 to 1200 °F)

Spheroidizing. Heat to 705 to 720 °C (1300 to 1330 °F); hold several hours; furnace cool

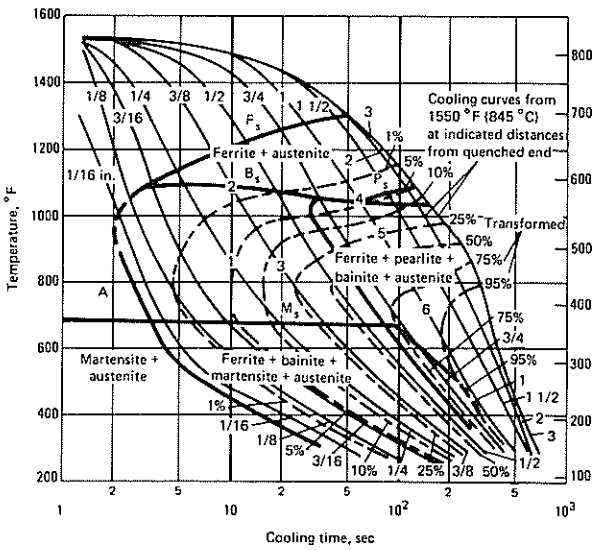
Nitriding. Responds well to ammonia gas nitriding as well as to nitriding in any one of several proprietary molten salt baths. The following is a commonly used cycle for ammonia gas nitriding:

- Parts are austenitized, quenched, and tempered at 540 °C (1000 °F) or higher. (Tempering temperature must always be higher than the nitriding temperature)
- Finish machine
- Nitride in ammonia gas for 10 to 12 h with an ammonia gas dissociation of 25 to 30%

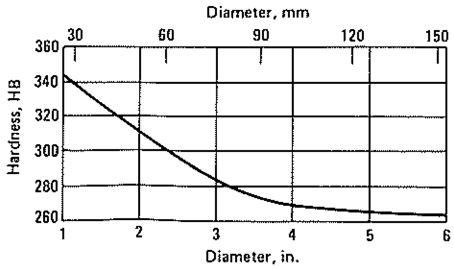
See processing data for 4140H for other nitriding cycles

Recommended Processing Sequence

- Forge
- Normalize
- Anneal
- Rough and semifinish machine
- Austenitize and quench
- Temper
- Finish machine (grind if required)
- Nitride (optional)



8640: Continuous Cooling Curves. Composition: 0.37 C, 0.87 Mn, 0.25 Si, 0.56 Ni, 0.44 Cr, 0.18 Mo. Austenitized at 845 °C (1555 °F). Grain size: 7. Ac_3, 795 °C (1460 °F); Ac_1, 745 °C (1370 °F). A: austenite, F: ferrite, P: pearlite, B: bainite, M: martensite



8640: Hardness vs Diameter. Composition: 0.38 to 0.43 C, 0.75 to 1.00 Mn, 0.040 P max, 0.040 S max, 0.20 to 0.35 Si, 0.40 to 0.70 Ni, 0.40 to 0.60 Cr, 0.15 to 0.25 Mo. Test specimens were normalized at 870 °C (1600 °F) in over-sized rounds, quenched from 845 °C (1555 °F) in oil in sizes shown, tempered at 540 °C (1000 °F). Tested in 12.8 mm (0.505 in.) rounds. Tests from bars 38 mm (1.50 in.) diam were taken at half radius position. Source: Republic Steel

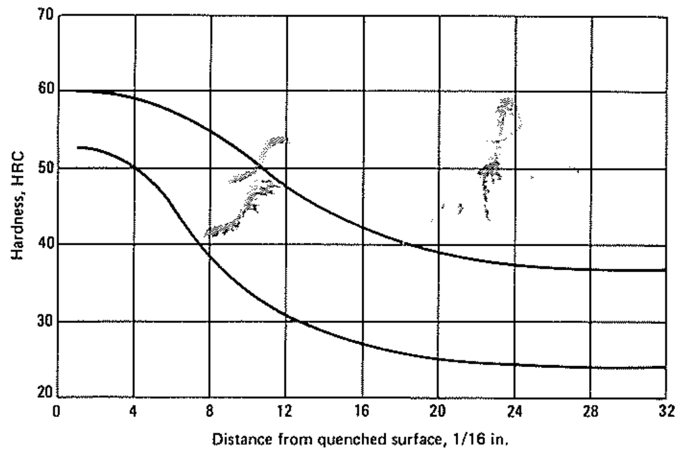
8640: Approximate Critical Points

Critical point	Temperature °F	Temperature °C
Ac_1	1350	730
Ac_3	1435	780
Ar_3	1340	725
Ar_1	1230	665

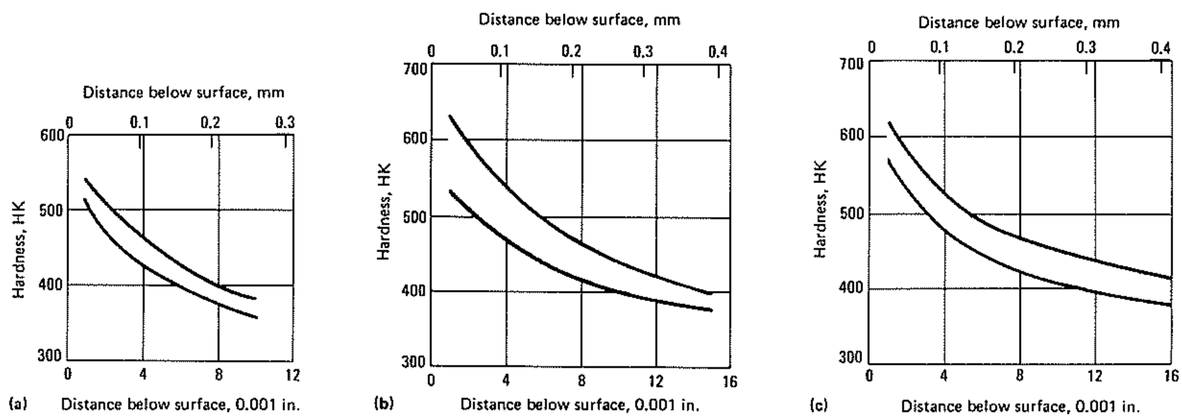
Source: Republic Steel

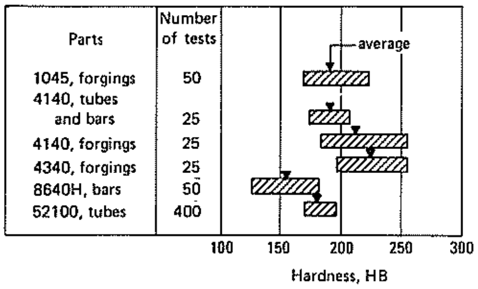
8640H: End-Quench Hardenability

Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max	min	Distance from quenched surface, 1/16 in.	mm	Hardness, HRC max	min
1	1.58	60	53	13	20.54	47	30
2	3.16	60	53	14	22.12	45	29
3	4.74	60	52	15	23.70	44	28
4	6.32	59	51	16	25.28	42	28
5	7.90	59	49	18	28.44	41	26
6	9.48	58	46	20	31.60	39	26
7	11.06	57	42	22	34.76	38	25
8	12.64	55	39	24	37.92	38	25
9	14.22	54	36	26	41.08	37	24
10	15.80	52	34	28	44.24	37	24
11	17.38	50	32	30	47.40	37	24
12	18.96	49	31	32	50.56	37	24



8640: Hardness Gradients. Nitrided to 20 to 30% dissociation. (a) Nitrided for 7 h; (b) nitrided for 24 h; (c) nitrided for 48 h





8640H: Variation of Brinell Hardness Measurements. Tests done on annealed plain carbon and low-alloy steels

11 Modified

ıemical Composition. **H11 Mod:** 0.37 to 0.43 C, 0.20 to 0.40 Mn, to 1.00 Si, 4.75 to 5.25 Cr, 1.20 to 1.40 Mo, 0.40 to 0.60 V

ıaracteristics. This is a modification of the martensitic, hot-work steel, AISI H11. The significant difference between the two is that H11 dified has a slightly higher carbon content. The alloy can be heat treated strengths above 2070 MPa (300 ksi). It is air hardened, resulting in ıimal residual stress after hardening. H11 mod is a secondary hardening :l. Optimum properties are developed when it is tempered at tempera- :s above 510 °C (950 °F). High tempering temperatures also provide stantial stress relief and stabilization of properties, meaning that the ıy can be used at elevated temperatures. Another benefit is that heat ıted parts can be warm worked at temperatures as high as 55 °C (100 °F) ow the prior tempering temperature, or be preheated for welding. At high ngth levels [those exceeding 1800 MPa (260 ksi)], H11 mod has good tility, impact strength, notch toughness, and fatigue life, as well as high :p and rupture strength at temperatures up to approximately 650 °C 00 °F). The alloy is selected for parts requiring maximum levels of ngth, ductility, toughness, fatigue resistance, and thermal stability at ıperatures between –75 to 540 °C (–100 to 1000 °F). At elevated ıperatures, parts should be protected from corrosion (oxidation) by 'ace treatment. The alloy has good formability in the annealed condition is readily welded. It is subject to hydrogen embrittlement, and fracture ghness is rather low. If used in critical applications, at yield strength :ls above 1380 MPa (200 ksi), care should be taken to eliminate small :ontinuities. Parts for elevated temperature service are commonly kel-cadmium plated. Such parts should be baked to avoid hydrogen ıced, delayed cracking. Part surfaces may be protected from oxidation ıot dipping in aluminum or by applying heat-resistant paint

rging. The alloy is readily forged at temperatures ranging from 1120 150 °C (2050 to 2100 °F). Preferably, stock should be preheated at 790 15 °C (1455 to 1500 °F), then heated uniformly to the forging tempera- :. Forging should not be continued below 925 °C (1695 °F). Stock may eheated as often an necessary. Because the alloy is air hardening, it must :ooled slowly after forging to prevent stress cracks. After forging, parts uld be charged into a furnace at approximately 790 °C (1455 °F); soaked :l the temperature is uniform; then slowly cooled, either while retained he furnace or buried in an insulating medium such as lime, mica, or a :eous filler material such as silocel. When forgings are cooled, they uld be annealed

Recommended Heat Treating Practice

Normalizing. Generally not necessary. For effective homogenization, heat to approximately 1065 °C (1950 °F); soak 1 h for each 25 mm (1 in.) of thickness; air cool. Anneal immediately after part reaches room temperature. There is a possibility that H11 mod may crack during this treatment

Annealing. Heat to 845 to 885 °C (1555 to 1625 °F) and hold to equalize temperature; cool very slowly in furnace to approximately 480 °C (895 °F), then more rapidly to room temperature. Treatment should produce fully spheroidized microstructure free of grain boundary carbide networks

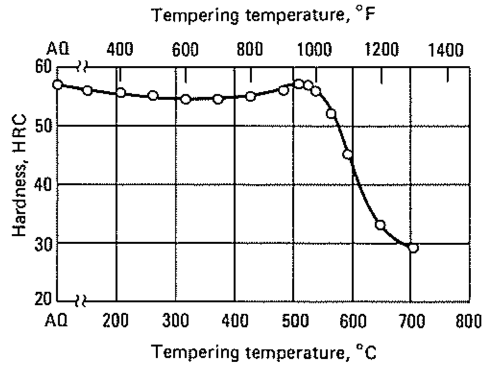
Stress Relieving. Heat to 650 to 675 °C (1200 to 1245 °F); cool slowly to room temperature. Treatment is often used to get greater dimensional accuracy in heat treated parts by stress relieving rough machined parts, which is followed by finish machining, and finally, heat treating to the desired hardness

Hardening. Preheat at 760 to 815 °C (1400 to 1500 °F), then raise temperature to 995 to 1025 °C (1825 to 1875 °F) and hold 20 min plus 5 min for each 25 mm (1 in.) of thickness; air cool. In some applications, parts may be oil quenched from low end of the hardening temperature. Air cooling, which produces less distortion than oil quenching, is more commonly used

Tempering. Heat at the secondary hardening temperature of approximately 510 °C (950 °F) for maximum hardness and strength, or above the secondary hardening peak to temper back to a lower hardness or strength. A minimum of 1 h at temperature should be allowed, but preferably, parts should be double tempered: Hold 2 h at temperature, cool to room temperature, then hold 2 h more at temperature. Triple tempering is more desirable, especially for critical parts. For high temperature applications, parts should be tempered at a temperature above the maximum service temperature to guard against unwanted changes in properties during service

Nitriding. Finished machined and heat treated parts should be gas or liquid nitrided at temperatures of approximately 525 °C (975 °F). Depth of the nitrided case depends on time at temperature. For example, gas nitriding in 20 to 30% dissociated ammonia for 8 to 48 h normally produces a case depth of approximately 0.2 to 0.35 mm (0.008 to 0.014 in.)

Baking. After plating in an acid bath, or after other processing that might introduce hydrogen into the metal, parts should be baked 24 h or longer at 190 °C (375 °F) or above



H11 mod: Variations in Hardness with Tempering Temperatures. Specimens were cooled from 1010 °C (1850 °F) and double tempered 2 + 2 h at temperature. AQ, as quenched

H11 mod: Typical Short-Time Elevated-Temperature Properties

Longitudinal specimens taken from bar stock air cooled from 1010 °C (1850 °F) and double tempered, 2 + 2 h at indicated tempering temperature

Test temperature		Tensile strength		Yield strength		Elongation in 50 mm (2 in.), %	Reduction in area, %	Charpy V-notch impact energy	
°C	°F	MPa	ksi	MPa	ksi			J	ft · lbf
Tempered at 540 °C (1000 °F)									
260	500	1860	270	1520	220	9.9	33.2	...	...
315	600	1840	267	1490	216	10.3	34.5	...	...
425	800	1670	242	1440	209	12.0	42.6	...	...
480	900	1580	229	1365	198	12.3	46.1	...	...
540	1000	1480	215	1255	182	13.7	48.2	...	...
650	1200	610	88	583	84.5	24.8	95.2	...	...
Tempered at 565 °C (1050 °F)									
Room	Room	1810	262	1480	215	9.8	35.4	...	...
150	300	1700	246	1365	198	10.1	36.1	29.4	21.7
260	500	1610	233	1340	195	10.2	35.8	41.2	30.4
315	600	1600	231.5	1330	193	10.3	36.0	42.7	31.5
425	800	1500	217	1270	184	11.4	38.8	40.0	29.5
480	900	1420	206	1140	166	12.2	39.3	39.7	29.3
540	1000	1240	180	970	141	12.2	41.3	41.4	30.5
595	1100	980	142	720	105	12.8	46.8	45.0	33.2
650	1200	590	85	440	64	19.0	66.8	80.0	59.0
Tempered at 595 °C (1100 °F)									
260	500	1340	195	1130	164	10.0	45.0	44	33
315	600	1310	190	1100	160	10.0	48.1	...	...
425	800	1230	178	1010	146	12.4	52.2	41	30
480	900	1130	164	900	131	13.5	56.0	...	...
540	1000	980	142	790	115	15.5	62.0	...	...

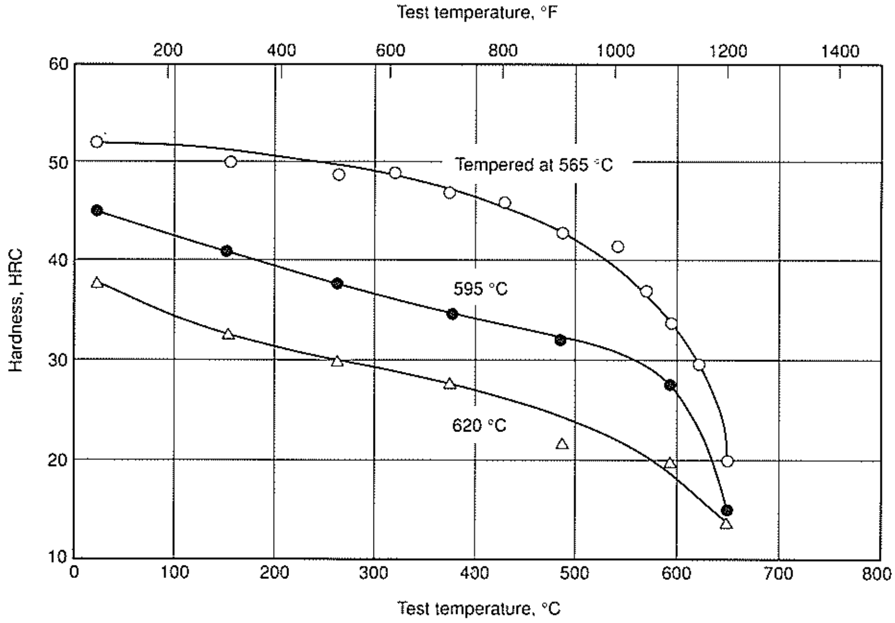
H11 mod: Typical Stress-Rupture Properties

Air cooled from 1010 °C (1850 °F); double tempered

Exposure temperature		Exposure time, h	Tensile strength		Yield strength		Elongation in 50 mm (2 in.), %	Reduction in area, %
°C	°F		MPa	ksi	MPa	ksi		
510(a)	950(a)	100	1790	260	1760	255	11.5	42.8
540(b)	1000(b)	10	1650	239	1410	204	12.4	49.9
		100	1450	210	1300	188	13.7	52.9
540(c)	1000(c)	10	1385	201	1190	173	14.1	52.4
		100	1300	189	1100	160	15.2	58.2

(a) Tempered 2 + 2 h at 540 °C (1000 °F). (b) Tempered 2 + 2 h at 565 °C (1050 °F). (c) Tempered 2 + 2 h at 595 °C (1100 °F)

ꟷ11 mod: Typical Hot Hardness. Specimens air-cooled from 1010 °C (1850 °F), and double tempered 2 + 2 h at indicated temperatures. Rockwell was converted from microhardness values



I13

hemical Composition. **H13:** 0.32 to 0.45 C, 0.20 to 0.50 Mn, 0.80 1.20 Si, 4.75 to 5.50 Cr, 1.10 to 1.75 Mo, 0.80 to 1.20 V

haracteristics. Has not been as widely used as H11 mod as an rahigh strength constructional steel, but similarities in properties make 13 equally attractive in such applications. (A separate article on H13 is ɔated in the chapter on tool steels.) The application niche for H13 is for rts going into noncritical service where this alloy's resistance to wear is ghtly higher than that of H11 mod. This advantage is due to H13's higher nadium content (0.80 to 1.20 V versus 0.40 to 0.60 V in H11 mod). For s reason, H13 has a greater dispersion of hard vanadium carbides, which ɔvides higher wear resistance. Like H11 mod, H13 is a secondary harding steel. It has good temper resistance and maintains high hardness and ength at elevated temperatures. It is deep hardening, which allows large ɔtions to be hardened by air cooling. The alloy can be heat treated to engths exceeding 2070 MPa (300 ksi); like H11 mod it has good ductility d impact strength. Resistance to thermal fatigue is good. However, it is bject to hydrogen embrittlement

ɔrging. H13 is heated slowly and uniformly to a temperature of 1090 1150 °C (2000 to 2100 °F), preferably after preheating at 760 to 815 °C 400 to 1500 °F). The steel should be thoroughly heated before forging, ɪich should not be performed below 900 °C (1650 °F). Parts may be ɪeated as often as necessary. Because H13 is air hardening, parts should cooled slowly after forging. Simple forgings may be cooled in an ɪulating medium such as dry ashes, lime, or expanded mica. For large rgings, best practice is to place them in a furnace heated at approximately 0 °C (1455 °F), soak them until the temperature is uniform, shut off the rnace, and let the parts cool slowly. They should then be given a full heroidizing anneal

Recommended Heat Treating Practice

Normalizing. Not recommended for this alloy. Some improvement in homogeneity can be obtained by preheating to approximately 790 °C (1455 °F), heating slowly and uniformly to 1040 to 1065 °C (1905 to 1950 °F), holding 1 h for each 25 mm (1 in.) of thickness, then air cooling. Just before parts reach room temperature, they should be recharged into a furnace and given a full anneal. There is a risk of cracking during this treatment, especially if the furnace atmosphere is not controlled to prevent surface decarburization

Annealing. Heat uniformly to 860 to 900 °C (1580 to 1650 °F) in a furnace with controlled atmosphere, or with the part packed in a neutral compound, so that decarburization is prevented. Cool very slowly in furnace to approximately 480 °C (895 °F); then cool faster to room temperature. This treatment provides a full spheroidized microstructure

Stress Relieving. Heat to 650 to 675 °C (1200 to 1245 °F) and soak 1 h or more; cool slowly to room temperature. This treatment is often used to get greater dimensional accuracy in heat treated parts by stress relieving rough-machined parts, then finish machining, then heat treating to desired hardness

Hardening. Heat slowly and uniformly to 905 to 1225 °C (1660 to 2240 °F) and soak 20 min plus 5 min for each 25 mm (1 in.) of thickness; preheating at 790 to 815 °C (1455 to 1500 °F) is usually recommended for thick parts. Air cool in still air. Air cooling usually is done from the high side of the hardening temperature range. In some applications, H13 may be oil quenched from the low side of the hardness temperature, but at the risk of distortion or cracking

Tempering. Heat at the secondary hardening temperature of approximately 510 °C (950 °F) for maximum hardness and strength, or at higher temperatures to temper back to a lower level of hardness or strength.

ouble tempering (2 h at temperature, air cooling, then 2 h more at emperature) is recommended. Occasionally, triple tempering may be desirable

litriding. Finished machined and heat treated parts may be nitrided to roduce highly wear resistant surfaces. Because nitriding is carried out at the normal tempering temperature, it can serve as the second temper in a double-tempering treatment. Nitrided case depth depends on time at temperature. For example, gas nitriding at 510 °C (950 °F) for 10 to 12 h produces a case depth of 0.10 to 0.13 mm (0.004 to 0.005 in.). Copper plating is preferred for stopoff areas that are not to be nitrided. Stopoffs containing lead should be avoided because lead embrittles H13

113: Typical Longitudinal Room-Temperature Mechanical Properties

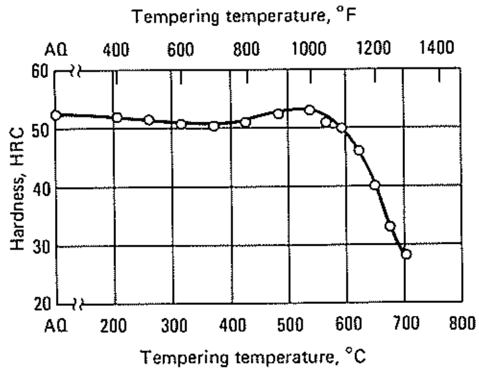
ound bars, oil quenched from 1010 °C (1850 °F) and double tempered, 2 + 2 h at indicated temperature

Tempering temperature		Tensile strength		Yield strength		Elongation in 4D gage length, %	Reduction in area, %	Charpy V-notch impact energy		Hardness, HRC
°C	°F	MPa	ksi	MPa	ksi			J	ft · lbf	
527	980	1960	284	1570	228	13.0	46.2	16	12	52
555	1030	1835	266	1530	222	13.1	50.1	24	18	50
575	1065	1730	251	1470	213	13.5	52.4	27	20	48
593	1100	1580	229	1365	198	14.4	53.7	28.5	21	46
605	1120	1495	217	1290	187	15.4	54.0	30	22	44

113: Longitudinal Impact Properties of H13 Bar Tempered at Different Temperatures

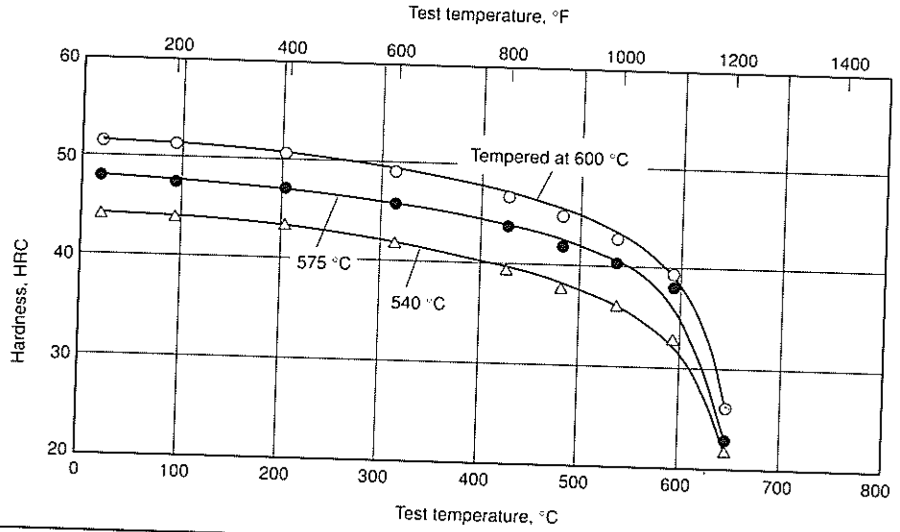
Tempering temperature(a)		Hardness(b), HRC	Charpy V-notch impact energy at test temperature of: −73 °C (−100 °F)		21 °C (70 °F)		260 °C (500 °F)		540 °C (1000 °F)		595 °C (1100 °F)	
°C	°F		J	ft · lbf	J	ft · lbf	J	ft · lbf	J	ft · lbf	J	ft · lbf
524	975	54	7	5	14	10	27	20	31	23	...	...
565	1050	52	7	5	14	10	30	22	34	25	34(c)	25(c)
607	1125	47	8	6	24	18	41	30	45	33	43	32
615	1140	43	9.5	7	24	18	52	38	60	44	57	42

a) Air cooled from 1010 °C (1850 °F) and double tempered, 2 + 2 h at indicated temperature. (b) At room temperature. (c) At 565 °C (1050 °F)



H13: Variations in Hardness with Tempering Temperature. All specimens air cooled from 1025 °C (1875 °F) and tempered 2 h at temperature. AQ, as quenched

H13: Typical Hot Hardness Values. Specimens oil quenched from 1025 °C (1875 °F) and double tempered, at 2 + 2 h, at indicated tempering temperatures



AF1410

Chemical Composition. **AF1410:** 0.13 to 0.17 C, 0.10 Mn max, 0.10 Si max, 1.80 to 2.20 Cr, 9.50 to 10.50 Ni, 0.90 to 1.10 Mo, 13.50 to 14.50 Co

Characteristics. This alloy has significant resistance to stress corro-sion cracking. Ultimate tensile strength is typically 1650 MPa (235 ksi). At :his level, a K_{Ic} value of 154 MPa $\sqrt{m}$ (140 ksi $\sqrt{in.}$) is maintained. The :ombination of strength and toughness exceeds that of other commercial ;teels, and the alloy, which is used in aircraft structural components, has)een considered as an alternative to titanium in certain aircraft parts. The ılloy is air hardenable in sections up to 75 mm (3 in.) thick. Current ›referred melting practice is vacuum induction melting, followed by vac-ıum arc remelting. Weldability is good with the gas tungsten arc (GTAW) ›rocess, provided high purity wire is used and oxygen contamination is voided. The microstructure of this alloy consists of Fe-Ni lath martensite.)uenching from the austenitizing temperature produces a highly dislocated ıth martensite that has high toughness, as measured by Charpy V-notch npact testing. Aging produces a complex series of changes in carbide :ructure. At approximately 425 °C (795 °F), Fe_3C is precipitated. At 455 : (850 °F) Fe-Cr-Mo M_2C carbide is obtained, which at 480 °C (895 °F) 'ill produce a pure Mo-Cr M_2C carbide. By raising the temperature to 510 : (950 °F), the M_2C will begin to be replaced by M_6C, which has little rengthening effect. The steel is normally austenitized and aged. The :condary hardening, due to aging, produces a maximum tensile strength hen aged at 480 °C (895 °F), with an aging time of 5 h. When aging in e range between 425 to 540 °C (795 to 1000 °F), maximum impact energy obtained at 508 °C (947 °F). At aging temperatures above 540 °C (1000 ') impact energy drops rather sharply. The best combination of strength d ductility is obtained by aging at 510 °C (950 °F)

ɔrging. The alloy is forgeable at 1120 °C (2050 °F), but at least 40% ɗuction must be obtained below 900 °C (1650 °F) to obtain maximum ɔperties

ecommended Heat Treating Practice

ɔrmalizing. The alloy is normally supplied in this condition for best .chinability. Heat between 880 to 900 °C (1620 to 1650 °F), hold 1 h for each 25 mm (1 in.) of thickness; air cool and overage at 675 °C (1245 °F) for 5 h minimum.

In aerospace practice, parts are normalized at 900 °C (1650 °F). To facilitate machining, parts (after normalizing) are heated to 675 °C (1245 °F) for 6 h minimum, then air cooled

Annealing. Usually, normalizing and overaging are used to soften and stress relieve parts. A stress relief of 675 °C (1245 °F) may be applied to relieve mechanical stress.

In aerospace practice, parts are annealed at 900 °C (1650 °F). To facilitate machining, parts (after normalizing) are heated to 675 °C (1245 °F) for 6 h minimum; then air cooled

Hardening. Double austenitize, first at 870 to 900 °C (1600 to 1650 °F); hold 1 h for each 25 mm (1 in.) of thickness; oil or water quench, or air cool, depending on section size. Reaustenitize at 800 to 815 °C (1475 to 1500 °F); oil or water quench, or air cool. An alternative is to single austenitize at 800 to 815 °C (1475 to 1500 °F), hold 1 h for each 25 mm (1 in.) of thickness; oil or water quench, or air cool, depending on section size.

In aerospace practice, parts are austenitized at 850 °C (1560 °F). Quench in oil or polymer. Immediately after quenching, refrigerate parts at –70 °C (–90 °F) or lower, hold for 1 h minimum; then air warm to room temperature

Tempering. In aerospace practice, parts are tempered at 495 °C (925 °F) to obtain tensile strengths in the range of 1515 to 1655 MPa (220 to 240 ksi)

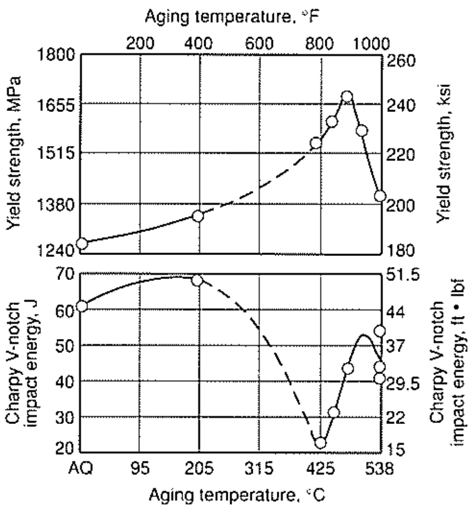
Quenching. Air cooling from the austenitizing temperature produces tensile strength, toughness, and fatigue strength essentially equal to values obtained in oil or water quenching in section sizes up to 75 mm (3 in.). Refrigeration at –73 °C (–100 °F) is optional. The aim is to reduce retained austenite, but there is no real evidence that the treatment has any substantial effect on the material or its mechanical properties

Aging. Age at 480 to 510 °C (895 to 950 °F) for 5 to 8 h. Air cooling is the usual practice

AF1410: Effects of Different Heat Treatments on Mechanical Properties

Heat treatment(a)(b)	Ultimate strength, MPa	Ultimate strength, ksi	Yield strength, MPa	Yield strength, ksi	Elongation, %	Reduction in area, %	Charpy V-notch, J	Charpy V-notch, ft · lbf
Plate of 15 mm (5/8 in.) thickness								
X + water quench per (c) + Z	1580	229	1515	220	16	60	91	67
X + refrigeration treatment per (d) + Z	1650	239	1550	225	17	69	83	61
X + vermiculite cool and refrigeration per (e) + Z	1620	235	1490	216	17	70	84	62
X + reaustenitization and refrigeration per (f) + Z	1660	241	1525	221	17	73	113	83
Average for several heats								
Heat treatment per (g)	1675	243	1590	231	...	...	92	68
Plate of 75 mm (3 in.) thickness								
Y + water quench per (c) + Z	1585	230	1540	223	16	66	65	48
Y + refrigeration treatment per (d) + Z	1680	244	1540	223	17	70	81	60
Y + vermiculite cool and refrigeration per (c) + Z	1480	215	1380	200	18	68	58	43
Y + reaustenitization, air cool, and refrigeration per (f) + Z	1670	242	1540	223	17	69	95	70

(a) Time at 900 °C (1650 °F) or 815 °C (1500 °F) is as follows: 1 h for the 15 mm (5/8 in.) plate or 3 h for the 75 mm (3 in.) plate. (b) Initial and final heat treatments: X = 900 °C (1650 °F) for 1 h with air cooling and 675 °C (1250 °F) for 8 h with air cooling; Y = 900 °C (1650 °F) for 3 h with air cooling and 675 °C (1250 °F) for 8 h with air cooling; Z = 510 °C (950 °F) for 5 h with air cooling. (c) 815 °C (1500 °F) for the time per (a) and water quenching. (d) 815 °C (1500 °F) for the time per (a) with air cooling and a refrigeration treatment of –73 °C (–100 °F). (e) 815 °C (1500 °F) for the time per (a) with vermiculite cool and a refrigeration treatment of –73 °C (–100 °F). (f) 900 °C (1650 °F) for time per (a) with air cooling, 815 °C (1500 °F) for time per (a) with air cooling, and refrigeration at –73 °C (–100 °F). (g) 900 °C (1650 °F) for time per (a) with water quench, 815 °C (1500 °F) for time per (a) with water quench, and 510 °C (950 °F) for 5 h with air cooling



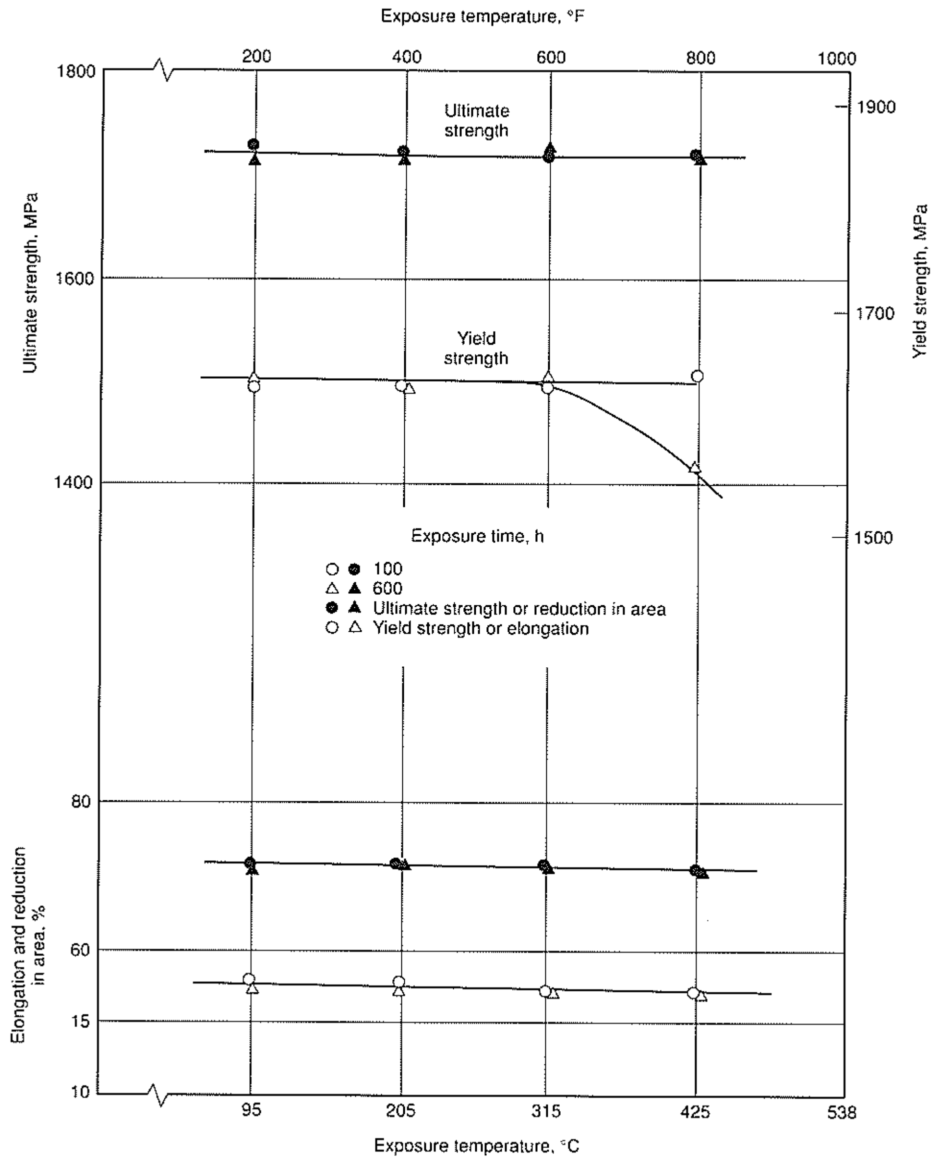
AF1410: Effect of Aging Temperature on Impact Strength and Yield Strength. VIM/VAR plate is 15 mm (0.625 in.) thick. Heat treatments: Heat at 900 °C (1650 °F) for ½ h and water quench; heat at 815 °C (1500 °F) for ½ h and water quench; age for 5 h at indicated temperatures and air cool. AQ, as quenched

AF1410: Mechanical Properties in Various Quenching Media

Test specimens were 50 mm (2 in.) plate from VIM/VAR melt with the heat treatment: 675 °C (1245 °F) for 8 h with air cooling, 900 °C (1650 °F) for 1 h, quenching, 830 °C (1525 °F) for 1 h, quenching, refrigeration at –73 °C (–100 °F) for 1 h, 510 °C (950 °F) for 5 h, and air cooling

Quench medium	Ultimate strength, MPa	Ultimate strength, ksi	Yield strength, MPa	Yield strength, ksi	Elongation, %	Reduction in area, %	Charpy V-notch, J	Charpy V-notch, ft · lbf	Plane-strain fracture toughness (K_{Ic}), MPa$\sqrt{m}$	Plane-strain fracture toughness (K_{Ic}), ksi$\sqrt{in.}$
Air	1680	244	1475	214	16	69	69	51	174	158
Oil	1750	254	1545	224	16	69	65	48	154	140
Water	1710	248	1570	228	16	70	65	48	160	146

AF1410: Effect of Elevated Temperature on Room-Temperature Tensile Properties. VIM/VAR plate 30 mm (1.25 in.) thick. Heat treatment: Heat at 900 °C (1650 °F) for ½ h and water quench, heat at 815 °C (1500 °F) for ½ h and water quench, and then heat at 510 °C (950 °F) for 5 h and air cool



ꟷP-9-4-30

hemical Composition. **HP-9-4-30:** 0.29 to 0.34 C, 0.10 to 0.35 n, 0.20 Si max, 0.90 to 1.10 Cr, 7.0 to 8.0 Ni, 0.90 to 1.10 Mo, 0.06 to 12 V, 4.25 to 4.75 Co

haracteristics. This alloy is usually electric arc melted, then vacuum c remelted. Tensile strength in the range of 1520 to 1650 MPa (220 to 240 i)) and a plain-strain fracture toughness of 100 MPa $\sqrt{m}$ (91 ksi $\sqrt{in.}$) is ›ssible. The steel has deep hardenability and can be fully hardened to artensite in sections up to 150 mm (6 in.) thick. In the heat treated ›ndition, it can be formed by bending, rolling, or shear spinning. Parts are adily welded. Tungsten arc welding under inert-gas shielding is the preferred process. Neither postheating nor postweld heat treated is required. After welding, parts may be stress relieved at approximately 540 °C (1000 °F) for 24 h. This is a stress relieving treatment and has no adverse effect on the strength or toughness of the weld metal or the base metal

Forging. Temperatures should not exceed 1120 °C (2050 °F)

Recommended Heat Treating Practice

Normalizing. Heat to 870 to 925 °C (1600 to 1695 °F); hold 1 h for each 25 mm (1 in.) of thickness (1 h min): air cool

Annealing. Heat to 620 °C (1150 °F) and hold 24 h; air cool

Stress Relieving. Usually required only after welding restrained sections. Heat to 540 °C (1000 °F); hold 2 h; air cool to room temperature

Hardening. Austenitize at 830 to 860 °C (1525 to 1580 °F) and hold 1 h for each 25 mm (1 in.) of thickness (1 h min); water or oil quench. Complete martensitic transformation by refrigerating at least 1 h at –87 to –60 °C (–125 to –75 °F); allow to warm to room temperature

Tempering. Hold at 200 to 600 °C (390 to 1110 °F), depending on desired final strength; double tempering is preferred (2 h at temperature, air cooling, followed by 2 h more at temperature, ranging from 540 to 580 °C (1000 to 1075 °F)

HP-9-4-30: Room-Temperature Mechanical Properties

Property	Typical value for hardness of 49-53 HRC(a)	44-48 HRC(b)	Minimum value(c)
Tensile strength, MPa (ksi)	1650-1790 (240-260)	1520-1650 (220-240)	1520 (220)
Yield strength, MPa (ksi)	1380-1450 (200-210)	1310-1380 (190-200)	1310 (190)
Elongation in 4*D* gage length, %	8-12	12-16	10
Reduction in area, %	25-35	35-50	35
Charpy V-notch impact energy, J (ft · lbf)	20-27 (15-20)	24-34 (18-25)	24 (18)
Fracture toughness (K_{Ic}), MPa$\sqrt{m}$ (ksi$\sqrt{in.}$)	66-99 (60-90)	99-115 (90-105)	...

(a) Oil quenched from 845 °C (1555 °F), refrigerated to –73 °C (–100 °F) and double tempered at 205 °C (400 °F). (b) Same heat treatment as (a) except double tempered at 550 °C (1025 °F). (c) For sections forged to 75 mm (3 in.) or less in thickness (or to less than 0.016 m^2, or 25 in.^{2}, in total cross-sectional area), quenched to martensite and double tempered at 540 °C (1000 °F)

HP-9-4-30: Room-Temperature Mechanical Properties after 1000 h at Various Elevated Temperatures

All specimens austenitized, quenched to martensite, and tempered at 540 °C (1000 °F)

Temperature of exposure °C	°F	Tensile strength MPa	ksi	Yield strength MPa	ksi	Elongation in 25 mm (1 in.), %	Reduction in area, %	Charpy V-notch impact energy J	ft · lbf
Not exposed		1650	239	1350	196	14	52	39	29
205	400	1585	230	1405	204	16	60	41	30
345	650	1585	230	1440	209	15	56	38	28
425	800	1650	239	1400	203	14	50	34	25
480	900	1565	227	1395	202	15	51	26	19

Stainless Steels

Introduction

Historically, various means of retarding or preventing corrosion of iron and steel products have been and still are extensively used. These include painting or coating with metals or sometimes nonmetals that proved helpful in inhibiting corrosion in the specific environments to which the products would be subjected. As a rule, however, coatings have limited life. They require periodic replacement to prevent corrosion, which will eventually take place.

A generally more desirable approach for minimizing or preventing corrosion is by alloying. This not only provides surface protection, but also protection against corrosion throughout the cross section of the iron or steel product. A large family of heat and corrosion resisting alloys has been developed to satisfy many requirements for resistance to corrosion, heat, or both. They are known as the stainless steels.

Classification of Wrought and Cast Stainless Steels

The American Iron and Steel Institute has adopted standard compositions and designation numbers for over 50 grades of wrought stainless steels (Tables 1 to 4). These alloys are generally known as the standard compositions. In addition to the steels listed in Tables 1 to 4, there are at least 100 (perhaps many more) nonstandard compositions which are marketed under proprietary names. These nonstandard grades are produced in relatively small quantities so that AISI has not elected to list them as standard grades. In most instances, the nonstandard compositions have been developed to resist corrosion, heat, or both, in some quite specific environments.

Standard Wrought Grades. AISI type numbers are in general use by producers as well as users of stainless steels. The entire family of stainless steels is divided into four major groups. The basic characteristics of each group and the AISI means of designation are summarized briefly in the paragraphs which follow.

Austenitic Grades. The austenitic grades carry identifying numbers of either 200 or 300 (Table 1). However, most of the steels in Table 1 are 300 series alloys, the chromium-nickel grades. The 200 series represents a more recent addition to the austenitic series, in which some of the nickel has been replaced by manganese. The austenitic grades are used more widely in corrosive environments, although some grades, most notably type 310, are used for elevated temperature surface up to 650 °C (1200 °F).

Because the austenitic grades do not change their crystal structure upon heating, they do not respond to conventional quench-hardening treatments. Therefore, the only heat treatments that are used for these grades are: (a) full annealing by rapid cooling from elevated temperatures, (b) stress relieving, and (c) surface hardening by nitriding.

Ferritic Grades. The compositions listed represent the important ferritic steels and are identified as the 400 series. In corrosion resistance, these steels generally rank higher than the martensitic grades, but substantially lower than most of the austenitic grades.

The ferritic grades are so named because their structure is ferritic at all temperatures. Like the austenitic grades, they cannot be hardened by heating and quenching. Annealing to lower hardnesses developed by cold working is the only heat treatment applied to the ferritic grades, except for nitriding, which is used in some instances.

Martensitic Grades. This group is so named because the steels included are capable of changing their crystal structure upon heating and cooling. They can be quench hardened to fully martensitic structures, much the same as alloy steels.

The martensitic group is comprised of 12 steels, compositions of which are listed in Table 1. Steels of this group also carry the 400 series designation. Nickel is specified in only two grades, and even then, the maximum amount is 2.5%. The chromium content is generally lower than for the austenitic grades. It follows that, in general, the corrosion resistance of the martensitic grades is far lower than that of the austenitic grades and, in most instances, somewhat lower than that of the ferritic grades.

All of the martensitic grades have extremely high hardenability to the extent that they can be fully hardened by quenching in still air from their austenitizing temperatures.

In addition to quench hardening, all of the martensitic grades having less than approximately 0.40 carbon respond to surface hardening by nitriding.

The maximum hardness that can be developed in the martensitic steels depends on the carbon content, just as is true for conventional alloy steels. Types 403 and 410 are capable of being hardened to 40 HRC or slightly higher, and the higher carbon grades can be hardened to 66 HRC or often slightly higher. Types 403 and 410 have essentially the same compositions, but type 403 is a special quality grade used largely in turbine applications.

Precipitation-Hardening Grades. Standard types of these steels are now known as the 600 Series, which includes the PH13-8Mo, 15-5PH, 17-4PH, and the 17-7PH standard grades listed in Table 1. In addition, nonstandard grades are listed in Table 2. In corrosion resistance, these steels may vary considerably among the different grades within the group, but in general their corrosion resistance approaches that of the austenitic grades.

Most of the precipitation-hardening grades can be hardened to at least 44 HRC and often higher, but not by the conventional quench-hardening techniques used for the martensitic grades. Hardening techniques for the precipitation-hardening grades are like those used for nonferrous metals. That is, the general approach is to solution treat by heating to an elevated temperature, cooling rapidly, then age hardening by heating to an intermediate temperature. There is, however, much difference in the techniques for the various grades.

Similarities and Differences Among Grades

The element chromium is the key to the corrosion resistance of stainless steels. One common characteristic to all grades of stainless steels is that they contain a minimum of 11.5 percent chromium. This is approximately the minimum amount required for a stainless steel, which is generally conceded to be complete resistance to rusting in a noncontaminated outdoor environment, even when humidity approaches 100%. Grades 403 and 410 are those grades which are the lowest in chromium content, but they still meet the above requirement. Another characteristic that is common to all stainless steels listed in Tables 1 to 5 is their high resistance to all oxidizing acids, such as nitric acid.

As previously stated, specific requirements for corrosion or heat resistance have led to the development of approximately 50 grades that are considered standard, plus 100 or more nonstandard grades that have been developed for specialized applications.

ıble 1 Composition of Standard Grades of Wrought Austenitic Stainless Steels

pe	UNS No.	Chemical composition(a), %								
		C	Mn	P	S	Si	Cr	Ni	Mo	Other elements
	S20100	0.15	5.50-7.50	0.060	0.030	1.00	16.00-18.00	3.50-5.50	...	0.25 N
	S20200	0.15	7.50-10.00	0.060	0.030	1.00	17.00-19.00	4.00-6.00	...	0.25 N
	S20500	0.12-0.25	14.00-15.50	0.060	0.030	1.00	16.50-18.00	1.00-1.75	...	0.32-0.40 N
	S30100	0.15	2.00	0.045	0.030	1.00	16.00-18.00	6.00-8.00	...	...
	S30200	0.15	2.00	0.045	0.030	1.00	17.00-19.00	8.00-10.00	...	...
B	S30215	0.15	2.00	0.045	0.030	2.00-3.00	17.00-19.00	8.00-10.00	...	...
	S30300	0.15	2.00	0.200	0.150 min	1.00	17.00-19.00	8.00-10.00	0.60(b)	...
Se	S30323	0.15	2.00	0.200	0.060	1.00	17.00-19.00	8.00-10.00	...	0.15 Se min
	S30400	0.08	2.00	0.045	0.030	1.00	18.00-20.00	8.00-10.50	...	...
H	S30409	0.04-0.10	2.00	0.045	0.030	1.00	18.00-20.00	8.00-10.50	...	...
L	S30403	0.03	2.00	0.045	0.030	1.00	18.00-20.00	8.00-12.00	...	...
LN	S30453	0.03	2.00	0.045	0.030	1.00	18.00-20.00	8.00-12.00	...	0.10-0.16N
N	S30451	0.08	2.00	0.045	0.030	1.00	18.00-20.00	8.00-10.50	...	0.10-0.16 N
	S30500	0.12	2.00	0.045	0.030	1.00	17.00-19.00	10.50-13.00	...	...
	S30800	0.08	2.00	0.045	0.030	1.00	19.00-21.00	10.00-12.00	...	...
	S30900	0.20	2.00	0.045	0.030	1.00	22.00-24.00	12.00-15.00	...	...
S	S30908	0.08	2.00	0.045	0.030	1.00	22.00-24.00	12.00-15.00	...	...
	S31000	0.25	2.00	0.045	0.030	1.50	24.00-26.00	19.00-22.00	...	...
S	S31008	0.08	2.00	0.045	0.030	1.50	24.00-26.00	19.00-22.00	...	...
	S31400	0.25	2.00	0.045	0.030	1.50-3.00	23.00-26.00	19.00-22.00	...	...
	S31600	0.08	2.00	0.045	0.030	1.00	16.00-18.00	10.00-14.00	2.00-3.00	...
F	S31620	0.08	2.00	0.200	0.100 min	1.00	16.00-18.00	10.00-14.00	1.75-2.50	...
H	...	0.04-0.10	2.00	0.045	0.035	1.00	16.00-18.00	10.00-14.00	2.00-3.00	...
L	S31603	0.03	2.00	0.045	0.030	1.00	16.00-18.00	10.00-14.00	2.00-3.00	...
LN	...	0.03	2.00	0.045	0.035	1.00	16.00-18.00	10.00-14.00	2.00-3.00	0.10-0.16N
N	S31651	0.08	2.00	0.045	0.030	1.00	16.00-18.00	10.00-14.00	2.00-3.00	0.10-0.16 N
	S31700	0.08	2.00	0.045	0.030	1.00	18.00-20.00	11.00-15.00	3.00-4.00	...
L	S31703	0.03	2.00	0.045	0.030	1.00	18.00-20.00	11.00-15.00	3.00-4.00	...
	S32100	0.08	2.00	0.045	0.030	1.00	17.00-19.00	9.00-12.00	...	5 × C Ti min
H	S32109	0.04-0.10	2.00	0.045	0.030	1.00	17.00-19.00	9.00-12.00	...	5 × %C Ti min
	S32900	0.10	2.00	0.040	0.030	1.00	25.00-30.00	3.00-6.00	1.00-2.00	...
	N08330	0.08	2.00	0.040	0.030	0.75-1.50	17.00-20.00	34.00-37.00	...	...
	S34700	0.08	2.00	0.045	0.030	1.00	17.00-19.00	9.00-13.00	...	10 × C Cb + Ta min
H	S34709	0.04-0.10	2.00	0.045	0.030	1.00	17.00-19.00	9.00-13.00	...	8 × %C min to 1.00 max Nb
	S34800	0.08	2.00	0.045	0.030	1.00	17.00-19.00	9.00-13.00	...	10 × C Cb + Ta min, 0.10 Ta max, 0.20 Co max
H	S34809	0.04-0.10	2.00	0.045	0.030	1.00	17.00-19.00	9.00-13.00	...	8 × %C min to 1.0 max Nb, 0.10 Ta
	S38400	0.08	2.00	0.045	0.030	1.00	15.00-17.00	17.00-19.00	...	...

Maximum, unless otherwise noted. (b) May be added at the manufacturer's option. Source: *AISI Steel Products Manual*

Major variations from basic types are shown in Table 6. For .mple, types 202 and 302 are shown as the basic types for the austenitic up. Then, the modification and a reason for the modification are shown other austenitic grades. Similarly, the basic types for the martensitic and ·itic grades are types 410 and 430, respectively. Details on physical, chanical, and chemical properties can be found in *Metals Handbook*, 9th , Vol 3, Properties and Selection: Stainless Steels, Tool Materials, and :cial Purpose Metals.

ırnaces, Temperature Controls, ıd Atmospheres for Heat Treating

The heat treating information given in the following paragraphs ap- :s to stainless steels in general. In a few instances, certain groups or des demand special considerations, which will be dealt with separately ;ucceeding sections. All grades of stainless steels are more sensitive to iations in heat treatment than are carbon and alloy steels, and equipment l control of the process must be maintained at a higher level of quality, less than that used for the high-alloy tool steels.

Furnaces. Direct-fired and semimuffle furnaces are not well suited heating stainless steels, largely because of the lack of uniformity of ıperature. Radiant-tube heated and electric furnaces heated by either :allic or silicon carbide resistors are satisfactory for most stainless steel heat processing operations. The use of vacuum furnaces for this type of work is steadily increasing as the number of vacuum furnaces increases. Extremely hard vacuums are not required. In fact, they may be undesirable because of the danger of losing chromium by outgassing. The degree of vacuum that can be attained with a mechanical pump is usually sufficient.

Molten salt baths are suitable for some, but not all, heat treating operations involving stainless steels. If the baths are kept in first class condition, they are very good for heating the martensitic grades before quenching or air cooling. However, the salt used for the heating medium at 955 to 1065 °C (1750 to 1950 °F) is composed mostly of barium chloride, which is very difficult to remove unless it is quenched at approximately 595 °C (1105 °F) into a salt which is soluble in hot water. This intermediate quench does not in any way interfere with the hardening process. Molten salt baths are also satisfactory for heating the ferritic grades for annealing, because the temperatures used for this operation are accommodated by salts that can be readily removed.

As a rule, salt baths are not suitable for heating austenitic grades for annealing, because the temperatures involved require barium salts, and very poor results are likely if the cooling process is arrested at 595 °C (1105 °F).

Temperature Control. Regardless of the type of furnace used, the best possible temperature control systems should be used, and mainte-

Table 2 Composition of Standard Grades of Wrought Ferritic Stainless Steels

Type	UNS No.	Chemical composition(a), % C	Mn	P	S	Si	Cr	Mo	Other elements
405	S40500	0.08	1.00	0.040	0.030	1.00	11.50-14.50	...	0.10-0.30 Al
409	S40900	0.08	1.00	0.045	0.045	1.00	10.50-11.75	...	6×C Ti min, 0.75 max
429	S42900	0.12	1.00	0.040	0.030	1.00	14.00-16.00	...	...
430	S43000	0.12	1.00	0.040	0.030	1.00	16.00-18.00	...	...
430F	S43020	0.12	1.25	0.060	0.150 min	1.00	16.00-18.00	0.60(b)	...
430FSe	S43023	0.12	1.25	0.060	0.060	1.00	16.00-18.00	...	0.15 Se min
434	S43400	0.12	1.00	0.040	0.030	1.00	16.00-18.00	0.75-1.25	...
436	S43600	0.12	1.00	0.040	0.030	1.00	16.00-18.00	0.75-1.25	5×C Cb + Ta min, 0.70 max
439	S43035	0.07	1.00	0.040	0.030	1.00	17.00-19.00	...	0.50 Ni, 0.15 Al, 12×%C min-1.10 Ti
442	S44200	0.20	1.00	0.040	0.030	1.00	18.00-23.00	...	...
446	S44600	0.20	1.50	0.040	0.030	1.00	23.00-27.00	...	0.25 N

(a) Maximum, unless otherwise noted. (b) May be added at the manufacturer's option. Source: *AISI Steel Products Manual*

Table 3 Composition of Standard Wrought Grades of Martensitic Stainless Steels

Type	UNS No.	Chemical composition(a), % C	Mn	P	S	Si	Cr	Ni	Mo	Other elements
403	S40300	0.15	1.00	0.040	0.030	0.50	11.50-13.00	...	...	...
410	S41000	0.15	1.00	0.040	0.030	1.00	11.50-13.50	...	...	...
414	S41400	0.15	1.00	0.040	0.030	1.00	11.50-13.50	1.25-2.50	...	...
416	S41600	0.15	1.25	0.060	0.150 min	1.00	12.00-14.00	...	0.60(b)	...
416Se	S41623	0.15	1.25	0.060	0.060	1.00	12.00-14.00	...	...	0.15 Se min
420	S42000	Over 0.15	1.00	0.040	0.030	1.00	12.00-14.00	...	...	...
420F	S42020	Over 0.15	1.25	0.060	0.150 min	1.00	12.00-14.00	...	0.60(b)	...
422	S42200	0.20-0.25	1.00	0.025	0.025	0.75	11.00-13.00	0.50-1.00	0.75-1.25	0.15-0.30 V 0.75-1.25 W
431	S43100	0.20	1.00	0.040	0.030	1.00	15.00-17.00	1.25-2.50	...	...
440A	S44002	0.60-0.75	1.00	0.040	0.030	1.00	16.00-18.00	...	0.75	...
440B	S44003	0.75-0.95	1.00	0.040	0.030	1.00	16.00-18.00	...	0.75	...
440C	S44004	0.95-1.20	1.00	0.040	0.030	1.00	16.00-18.00	...	0.75	...

Table 4 Composition of Standard Grades of Precipitation-Hardening Stainless Steels

AISI No.	UNS No.	Chemical composition(a), % C	Mn	Si	Cr	Ni	Mo	Other elements
Martensitic type								
630	S17400	0.07	1.0	1.0	17.0	4.0	...	4.0 Cu, 0.15-0.45 Cb + Ta
Semiaustenitic types								
631	S17700	0.09	1.0	1.0	17.0	7.0	...	1.0 Al
632	S15700	0.09	1.0	1.0	15.0	7.0	2.2	1.2 Al
633	S35000	0.08	0.8	0.25	16.5	4.3	2.75	0.1 N
634	S35500	0.13	0.95	0.25	15.5	4.3	2.75	0.1 N
Austenitic type								
660	K66286	0.08	1.4	0.4	15.0	26.0	1.3	0.3 V, 2.0 Ti, 0.35 Al, 0.003 B

(a) Maximum, unless otherwise noted

nance of the control systems by experienced technicians on an organized basis is mandatory. Temperatures are usually sensed by one or more correctly located thermocouples, so that true workpiece temperatures are sensed. Type K thermocouples are most often used, although types R and S may also be used. The accuracy of all thermocouples should be checked at least every two weeks, sometimes more often. The thermocouple should be discarded when its drift exceeds –3 °C (5 °F).

Radiation sensor detectors that respond to radiation are also used for sensing temperatures in furnaces used for heat treatment of stainless steels. With this type of sensor, the lens is focused on the work. The pay back of sensing temperatures by changes in emf (thermocouples) or by changes in radiation depends largely on furnace design and the type of workpieces being processed.

Temperature control systems that employ proportioning control rather than on-off as a means of supplying energy to the process are preferred for furnaces used for processing stainless steel, because the proportioning type of input provides better temperature control.

Prepared Atmospheres. Selection of atmosphere for heating stainless steels often depends on whether or not any stock will be removed in finishing the heat treated workpieces. When the workpieces will be

able 5 Standard Designations and Chemical Composition Ranges for Corrosion-Resistant Cast Alloys

loy asting stitute signation	Nearest AISI type	Chemical composition, %						
		C	Mn	Si	Cr	Ni	Mo	Other elements
-6NM	...	0.06	1.00	1.00	11.5-14	3.5-4.5	0.4-1.0	...
-15	410	0.15	1.00	1.50	11.5-14	1.0	0.5	...
	416	0.15	1.00	1.50	11.5-14	1.0	...	0.20-0.35 Se
-40	420	0.20-0.40	1.00	1.50	11.5-14	1.0	0.5	...
	430	0.12	1.00	1.50	14-18	...	...	...
3-30	431	0.30	1.00	1.50	18-22	2.0	...	...
	431	0.16-0.22	1.00	1.00	15-16.5	1.5-2.5	0.5	...
3-7Cu	17-4PH	0.07	0.70	1.00	15.5-17.7	3.6-4.6	...	2.5-3.2 Cu, 0.20-0.35 Cb
	440A	0.60-0.75	1.00	1.50	16-18	0.50	...	...
	440C	0.95-1.20	1.00	1.50	16-18	0.50	...	...
-50	446	0.50	1.00	1.50	26-30	4.0	...	...
)-4M Cu	...	0.04	1.00	1.00	25-27	4.75-6.0	1.75-2.25	2.75-3.25 Cu
3-30	312	0.30	1.50	2.00	26-30	8-11	...	...
-3	304L	0.03	1.50	2.00	17-21	8-12	...	...
-8	304	0.08	1.50	2.00	18-21	8-11	...	...
-20	302	0.20	1.50	2.00	18-21	8-11	...	...
-3M	316L	0.03	1.50	1.50	17-21	9-13	2.0-3.0	...
-8M	316	0.08	1.50	2.00	18-21	9-12	2.0-3.0	...
-8C	347	0.08	1.50	2.00	18-21	9-12	...	8×C-1.0 Cb
-12M		0.12	1.50	2.00	18-21	9-12	2.0-3.0	...
-16F	303	0.16	1.50	2.00	18-21	9-12	1.5	0.20-0.35 Se
3-8M	317	0.08	1.50	1.50	18-21	9-13	3.0-4.0	...
I-20	309	0.20	1.50	2.00	22-26	12-15	...	...
(-20	310	0.20	1.50	2.00	23-27	19-22	...	...
N-7M	...	0.07	1.50	1.50	19-22	27.5-30.5	2.0-3.0	3.0-4.0 Cu

ible 6 Major Variations From the Basic Types of Stainless Steels

SI type	Changes in analyses from basic type
stenitic, chromium nickel	
1	Cr and Ni lower for more work hardening
2	Basic type, 18% Cr + 8% Ni
2B	Si higher for more scaling resistance
3	P and S added for easier machining
3Se	Se added to improve machinability
4	C lower to avoid carbide precipitation
4L	C lower for welding application
5	Ni higher for less work hardening
8	Cr and Ni higher with C low for more corrosion and scaling resistance
9	Cr and Ni still higher for more corrosion and scaling resistance
9CT	Cb and Ta added to avoid carbide precipitation
9S	C lower to avoid carbide precipitation
0	Cr and Ni highest to increase scaling resistance
4	Si higher to increase scaling resistance
5	Mo added for more corrosion resistance
5L	C lower for welding application
7	Mo higher for more corrosion resistance and greater strength at high temperatures
8	Cb and Ta added to avoid carbide precipitation
1	Ti added to avoid carbide precipitation
7	Cb and Ta added to avoid carbide precipitation
7Se	Se added to improve machinability
8	Similar to 347, but low tantalum content (0.10)
4	Ni higher than 305 for severe cold heading
5	Similar to 384, but lower Cr and Ni

AISI type	Changes in analyses from basic type
Austenitic, chromium nickel manganese	
201	Cr and Ni lower for more work hardening
202	Basic type, 18% Cr + 5% Ni + 8% Mn
204	C lower to avoid carbide precipitation
204L	C lower for welding application
Martensitic, straight chromium	
403	12% Cr adjusted for special mechanical properties
410	Basic type, 12% Cr
414	Ni added to increase corrosion resistance and mechanical properties
416	P and S added for easier machining
416Se	Se added to improve machinability
418Spec	W added to improve high-temperature properties
420	C higher for cutting purposes
420F	P and S added for easier machining
431	Cr higher and Ni added for better resistance and properties
440A	C higher for cutting applications
440B	C higher for cutting applications
440C	C still higher for wear resistance
440Se	Se added for easier machining
Ferritic, straight chromium	
405	Al added to 12% Cr to prevent hardening
430	Basic type, 17% Cr
430F	P and S added for easier machining
430Ti	Titanium stabilized
442	Cr higher to increase scaling resistance
446	Cr much higher for improved scaling resistance

urce: Allegheny Ludlum Industries

ound, the surface conditions are sometimes not critical and some oxida-n, decarburization, or even carburization can be tolerated.

In addition to a vacuum atmosphere and the salt bath as a means of rface protection, several gaseous atmospheres can be used under specific conditions. Their advantages and limitations are discussed in the paragraphs that follow.

Exothermic atmospheres with a gas ratio of 6.5 to 7 to 1 are usually satisfactory for austenitizing or annealing stainless steels when their carbon content does not exceed 0.15%. The higher carbon grades are strongly susceptible to decarburizing in the exothermic atmospheres. The workpieces will usually be covered with a thin film of greenish oxide, which should be removed in finishing for maximum corrosion resistance.

Endothermic atmospheres have been used extensively for various stainless steels. The principal disadvantage in using these atmospheres is the danger of carburizing if the carbon potential of the atmosphere is not precisely controlled to match the carbon content of the steel being treated. Carburization is literally poison to surfaces of stainless steels.

Vacuum provides the near perfect atmosphere for heat treating stainless steels.

While the thermal conductivity of stainless steels does vary to some extent among grades, this variation is seldom of any practical significance in planning the heating cycles. However, the differences in thermal conductivity between carbon or alloy steels and stainless steels must be considered in establishing the heating cycles.

For stainless steels, the thermal conductivity is roughly one half that of carbon and alloy steels. For this reason, the time cycle beginning with the time the instruments shown "at heat" should be approximately twice as long for a stainless steel workpiece as compared with a part of similar size and weight of carbon or alloy steel.

Austenitic Stainless Steels

ıtroduction

The austenitic stainless steels may be divided into three groups: (a) the ·mal unstabilized compositions, such as types 201, 202, 205, 301, 302, 3, 304, 304N, 305, 308, 309, 310, 316, 316N, 329, 330, and 384 (of se, 201, 202, 304N, and 316N are high-nitrogen grades); (b) the stabi- ːd compositions, principally types 321, 347, and 348; (c) the extra- ·-carbon grades, such as types 304L, 316L, and 317L.

ːcommended Heat Treating Practice

The steels listed in the table on this page cannot be hardened except by d working. Only three types of heat treatments are applicable: (a) full ıealing, (b) stress relieving, and (c) nitriding.

Regardless of the treatment used, loading austenitic stainless parts into furnace requires special consideration because of their high thermal ɔansion, approximately 50% greater than for carbon or alloy steels. ːrefore, spacing between the parts must be adequate to allow for this ɔansion. Stacking, when necessary, should be employed judiciously to ɔid deformation of the parts at elevated temperature.

Annealing the Unstabilized Grades. Steels of the 200 series, mbers of the 300 series from 301 through 317, and types 329, 330, and ɬ are all unstabilized. These steels are annealed to ensure maximum rosion resistance and to restore maximum softness and ductility, which ult from cold working. During annealing, carbides, which markedly ːrease resistance to intergranular corrosion, are dissolved. Annealing ıperatures, which vary somewhat with the composition of the steel, are en in the adjoining table.

Because carbide precipitation can occur at temperatures between 425 1 900 °C (795 and 1650 °F), annealing temperature should be safely ɔve this limit. Moreover, because all carbides should be in solution ore cooling begins and because the chromium carbide dissolves slowly, highest practical temperature consistent with limited grain growth is ected. This temperature is in the vicinity of 1095 °C (2005 °F).

Cooling from the annealing temperature must be rapid, no more than ɔroximately 3 min in cooling from 870 to 425 °C (1600 to 795 °F), but nust also be consistent with limitations of distortion. Whenever consid- tions of distortion permit, water quenching is used, thus ensuring that solved carbides remain in solution. Because they precipitate carbides re rapidly, types 309 and 310 invariably require water quenching. Where ctical considerations of distortion rule out such a rapid cooling rate, ɔling in an air blast is often used. With some thin-section parts, even this ːrmediate rate of cooling produces excessive distortion, and parts must cooled in still air. If cooling in still air does not provide a rate sufficient ɔrevent carbide precipitation, maximum corrosion resistance will not be ained. A solution to this problem is the use of a stabilized grade.

Annealing the Stabilized Grades. Types 321, 347, and 348 ıtain controlled amounts of titanium or columbium plus tantalum, which der the steel nearly immune to intergranular precipitation of chromium bide and its adverse effects on corrosion resistance. Nevertheless, these ɔys may require annealing to relieve stresses, increase softness and ːtility, or provide additional stabilization.

To obtain maximum softness and ductility, the stabilized grades are ıealed at the temperatures shown in the Table below. Unlike the unsta- ized grades, these steels do not usually require water quenching or other ːeleration of cooling from the annealing temperature to prevent sub- uent intergranular corrosion. Air cooling is generally adequate. How- ːr, sections thicker than approximately 6.4 mm (0.25 in.) should be ːnched in oil or water.

Full Annealing Temperatures for Austenitic Stainless Steels

Type		Annealing temperature	
AISI	UNS	°F	°C
201	S20100	1850-2050	1010-1120
202	S20200	1850-2050	1010-1120
205	S20500	1950	1065
301	S30100	1850-2050	1010-1120
302	S30200	1850-2050	1010-1120
302B	S30215	1850-2050	1010-1120
303	S30300	1850-2050	1010-1120
303Se	S30323	1850-2050	1010-1120
304	S30400	1850-2050	1010-1120
304L	S30403	1850-2050	1010-1120
...	S30430	1850-2050	1010-1120
304N	S30451	1850-2050	1010-1120
305	S30500	1850-2050	1010-1120
308	S30800	1850-2050	1010-1120
309	S30900	1900-2050	1040-1120
309S	S30908	1900-2050	1040-1120
310	S31000	1900-2100	1040-1150
310S	S31008	1900-2100	1040-1150
314	S31400	2100	1150
316	S31600	1850-2050	1010-1120
316L	S31603	1850-2050	1010-1120
316F	S31620	2000	1095
316N	S31651	1850-2050	1010-1120
317	S31700	1850-2050	1010-1120
317L	S31703	1900-2000	1040-1095
321	S32100	1750-2050	955-1120
329	S32900	1750-1800	955-980
330	N08330	1950-2150	1065-1175
347	S34700	1850-2050	1010-1120
348	S34800	1850-2050	1010-1120
384	S38400	1900-2100	1040-1150

When maximum corrosion resistance of type 321 is required, using a corrective heat stabilizing treatment may be necessary. This treatment consists of holding at 845 to 900 °C (1555 to 1650 °F) for up to 5 h, depending on section thickness. Such a treatment may be applied before or during the course of fabrication. If needed, this treatment may be followed by a short stress relieving treatment at 705 °C (1300 °F) without danger of carbide precipitation. This treatment is seldom, if ever, used for grades 347 and 348.

Annealing the Extra-Low-Carbon Grades. Types 304L (extra low carbon), 316L, and 317L are intermediate in precipitation of chromium carbides to the stabilized and unstabilized grades. Carbon content (0.03 maximum) is low enough to reduce precipitation of intergranular carbides to a safe level. Thus, these steels can be held in the sensitizing range of 425 to 815 °C (795 to 1500 °F) for periods up to 2 h and cooled slowly through this range, without danger of susceptibility to intergranular corrosion in natural atmospheric environments. This characteristic is of particular value in welding, flame cutting, and other hot working operations. These grades do not require the quenching treatment that unstabilized grades require to retain carbon in solid solution. Nevertheless, the low-carbon alloys are not satisfactory for long service in the sensitizing temperature range, because they are not completely immune to the formation of carbides deleterious to corrosion resistance.

Stress Relieving the Austenitic Grades. Quenching from the annealing temperature range within the usual period of 3 min is a drastic thermal treatment. This treatment may generate new stresses, particularly if the overall cooling is not uniform or if the fabricated article is not of symmetrical contour. Excessive warpage (thermal distortion) may be encountered. Cooling rates should be as uniform as possible, regardless of whether the fabricated article is fast cooled in air, by water sprays, or by complete immersion.

Stress relieving of the quench-annealed parts may be accomplished by heating them within the temperature range of 230 to 400 °C (445 to 750 °F) for relatively long periods of time, often several hours. This treatment will not impair corrosion resistance or mechanical properties. It can be applied to any of the austenitic grades, although it is most often used for the unstabilized grades because they are more often subjected to drastic quenching, as described above.

Nitriding the Austenitic Grades. Austenitic stainless steels can be nitrided by the gas process, wherein the ammonia is dissociated in a separate cracking unit prior to its entry into the workpiece zone.

Only the stabilized or extra-low-carbon grades are recommended for nitriding, for the obvious reason that the nitriding temperature of approximately 540 °C (1000 °F) is in the sensitizing range.

Further, the nitrided case that can be achieved on the austenitic grades is very thin, seldom more than 0.125 mm (0.005 in.). Therefore, no finishing operations can be permitted or the case will be removed. In addition, nitriding seriously impairs resistance to corrosion in most media. Thus, nitriding of austenitic stainless steels is done only for highly specialized applications; for example, where the material must be nonmagnetic and still have an abrasion-resisting surface.

Forging the Austenitic Grades. These steels are more difficult to forge than are carbon or alloy steels, because austenitic stainless steels have high hot strength. However, because they do not undergo a phase change, most of them can be forged over a reasonably broad temperature range above 925 °C (1695 °F). Exceptions to the above are types 309, 310, and 314, which should not be forged at temperatures much above 1095 °C (2005 °F) because they are susceptible to formation of delta ferrite, which impairs forgeability.

In forging of the austenitic grades, the finishing temperatures are more important. Preferably, finishing temperature should not drop below 925 °C (1695 °F) and never below 870 °C (1600 °F).

All but the stabilized grades 321, 347, and 348 and those bearing the suffix letter L (extra low carbon) should be cooled, liquid quenched if necessary, from approximately 870 °C (1600 °F) to a black heat in no more than 3 min. Cooling rates for the stabilized and the extra-low-carbon grades are less critical. In addition, the more highly alloyed grades 309, 310, and 314 are limited in finishing temperature, because at lower temperatures they are susceptible to both hot tearing and formation of sigma phase.

201

Chemical Composition. **AISI/UNS (S20100):** 0.15 C max, 5.50 to 7.5 Mn, 0.060 P max, 0.030 S max, 1.00 Si max, 3.50 to 5.50 Ni, 16.00 to 18.00 Cr, 0.25 N max

Similar Steels (U.S. and/or Foreign). ASME SA412; ASTM A412, A429, A666; FED QQ-S-766; SAE J405 (30201)

Characteristics. An austenitic grade using a combination of manganese and nickel. Used primarily in corrosive environments or where bright metal appearance is required. Hardenable by cold work only. Heat treatment limited to: annealing to restore maximum corrosion resistance, softness, and ductility after cold working; stress relieving when required for stresses that occur from drastic quench from annealing temperature; and, on rare occasion, nitriding to impart thin, wear-resistant surface

Forging. Start forging at 1150 to 1230 °C (2100 to 2245 °F). Do not forge after forging stock drops below 925 °C (1695 °F). Cool to black color in less than 3 min, using liquid quench if necessary

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Anneal at 1010 to 1120 °C (1850 to 2050 °F). To guard against distortion of thin, delicate parts, leave ample room for expansion between parts. Stainless grades expand about twice as much as carbon and low-alloy steels. Allow enough time for through heating after thermocouple has reached temperature. Stainless grades have approximately half the thermal conductivity of carbon and low-alloy steels. Choice of atmosphere depends on finish desired and whether surface stock will be removed. For bright annealing, use vacuum or an atmosphere of hydrogen or dissociated ammonia at dew point of −62 to −74 °C (−80 to −100 °F). Parts must be thoroughly clean and dry. Inert gases argon and helium (although expensive) and nitrogen, with dew points of less than −54 °C (−65 °F), can be used. They lack the reducing effect of hydrogen, so slight discoloration in the form of chrome oxide can result. Salt, exothermic, or endothermic atmospheres are satisfactory for nonbright annealing. Salt is difficult to remove, and rinse quenching at 595 °C (1105 °F) is not recommended, because interrupted quench at elevated temperature cannot be tolerated. Exothermic and endothermic atmospheres must be carefully controlled at equivalent carbon potential to avoid carburization, which will seriously lower corrosion resistance. Same problem with atmosphere annealing. If oxidizing conditions are present, scale will form. Difficult to remove in subsequent descaling operations.

Cool rapidly from annealing temperature; no more than 3 min to black color. Section size determines quenching medium: water for heavy sections, air blast for intermediate sizes, and still air for thin sections. Carbides can precipitate at grain boundaries when parts are cooled too slowly between 425 to 900 °C (795 to 1650 °F).

In aerospace practice, parts are annealed at a set temperature of 1065 °C (1950 °F) and quenched in water with one exception: parts under 2.5 mm (0.10 in.) thick may be air cooled or polymer quenched to minimize distortion. See table for soaking times. Note: approval of the cognizant engineering organization is required for annealing material in a strain-hardened condition, such as ¼ hard; for stress relieving; or for dimensional stabilization. Heat treating or slow cooling unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L

Stress Relieving. Parts can be relieved after quenching to achieve dimensional stability, by heating to 230 to 400 °C (445 to 750 °F) for up to several hours, depending on section size and without change in metallographic structure.

In aerospace practice, parts are stress relieved at 900 °C (1650 °F), and quenched in water. As an alternative, parts may be stress relieved at annealing temperatures. Sections under 2.5 mm (0.10 in.) thick may be air cooled to minimize distortion. Parts fabricated from steel in the strain-hardened condition, such as ½ hard, shall not be stress relieved without permission of the cognizant engineering authority. When stress relieving after welding, hold for 30 min minimum at the stress relieving temperature. Heat treating or slow cooling of unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for soaking times

Nitriding. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners ould be replaced with radii of not less than 1.59 mm (0.06 in.). Film of marily chromium oxide, that protects stainless alloys from oxidation and rrosion, must be removed prior to nitriding. Accomplished by wet blast-, pickling, chemical reduction in reducing atmosphere, submersion in olten salt, or by one of several proprietary processes. If doubt exists that mplete and uniform depassivation has occurred, further reduction of the ide may be accomplished in furnace by means of reducing hydrogen nosphere or suitable proprietary agent. After depassivation, avoid con-nination of surface by finger or hand marking. Single-stage nitriding is equate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h (depending on se depth required). Dissociation rates for single-stage cycle are 20 to %. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle produces case extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

Recommended Processing Sequence

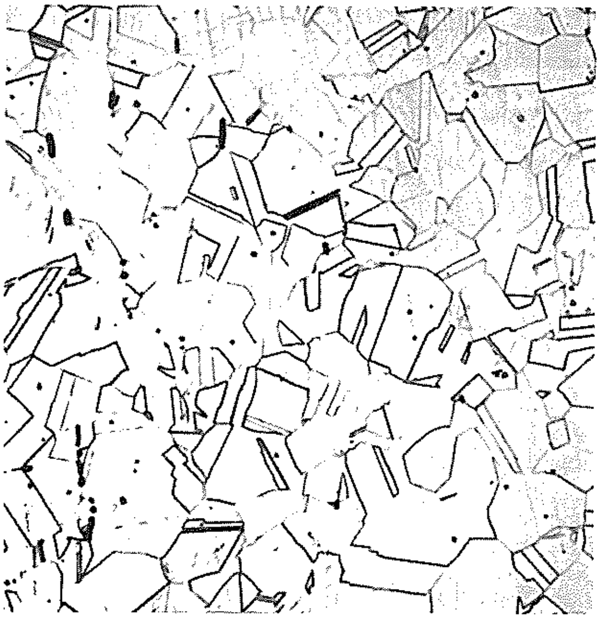
- Cold work
- Anneal and quench
- Remove surface contamination (if required)
- Stress relieve
- Depassivate (if nitriding)
- Nitride (if required)

1: Soaking Times (Aerospace Practice)

ameter or thickness(a) maximum section n (in.) inclusive	Minimum soaking time Atmosphere furnace min	Salt bath min
to 2.50 (0.100)	20	17
r 2.50 to 6.25 (0.100 to 0.250)	25	18
r 6.25 to 12.50 (0.259 to 0.500)	45	35
r 12.50 to 25.00 (0.500 to 1.00)	60	40
r 25.00 to 37.50 (1.00 to 1.50)	75	45
r 37.50 to 50.00 (1.50 to 2.00)	90	50
r 50.00 to 62.50 (2.00 to 2.50)	105	55
r 62.50 to 75.00 (2.50 to 3.00)	120	60
r 75.00 (3.00)	(b)	(c)

Thickness is minimum dimension of heaviest section of part or nested load of parts. 2.25 h plus 15 min for every 12.5 mm (0.5 in.) or increment of 12.5 mm (0.5 in.) over mm (3 in.). (c) 1 h, 5 min plus 5 min for every 12.5 mm (0.5 in.) or increment of 12.5 5 in.) over 75 mm (3 in.). Source: AMS 2759/4

201: Microstructure. HNO_3-acetic-HCl-glycerol, 250X. Strip, annealed at 1065°C (1950 °F) for 5 min. Cooled rapidly to room temperature. Equiaxed austenite grains and annealing twins



02

hemical Composition. AISI/UNS (S20200): 0.15 C, 0.06 P, 0.030 1.00 Si, 4.0 to 6.0 Ni, 17.00 to 19.00 Cr, 7.50 to 10.00 Mo, 0.25 N

milar Steels (U.S. and/or Foreign). ASTM A314, A412, A429, 763, A666; FED QQ-S-763, QQ-S-766 STD-66; SAE J405 (30202)

haracteristics. A basic, highly available austenitic grade. Similar to e 302, except some nickel replaced by manganese. Used primarily in rrosive environments or where bright metal appearance is required. rdenable by cold work only. Heat treating limited to: annealing to restore ximum corrosion resistance, softness, and ductility after cold working; ess relieving when required for stresses that occur from drastic quench m annealing temperature; and, on rare occasions, nitriding to impart n, wear-resistant surface

rging. Start forging at 1150 to 1230 °C (2100 to 2245 °F). Do not forge er forging stock drops below 925 °C (1695 °F). Cool to black color in s than 3 min, using liquid quench if necessary

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Anneal at 1010 to 1120 °C (1850 to 2050 °F). To guard against distortion of thin, delicate parts, leave ample room for expansion between parts. Stainless grades expand about twice as much as carbon and low-alloy steels. Allow enough time for through heating after thermocouple has reached temperature. Stainless grades have approximately half the thermal conductivity of carbon and low-alloy steels. Choice of atmosphere depends on finish desired and whether surface stock will be removed. For bright annealing, use vacuum or an atmosphere of hydrogen or dissociated ammonia at dew point of –62 to –74 °C (–80 to –100 °F). Parts must be thoroughly clean and dry. Inert gases argon and helium (although expensive) and nitrogen, with dew points of less than –54 °C (–65 °F), can be used. They lack the reducing effect of hydrogen, so slight discoloration in the form of chrome oxide can result. Salt, exothermic, or endothermic atmospheres are satisfactory for nonbright annealing. Salt is difficult to remove, and rinse quenching at 595 °C (1105 °F) is not recommended, because interrupted quench at elevated temperature cannot be tolerated. Exothermic and endothermic atmospheres must be carefully controlled at equivalent carbon potential to avoid carburization, which will seriously lower corrosion resistance. Same problem with atmosphere annealing. If oxidizing conditions are present, scale will form. Difficult to remove in subsequent descaling operations.

Cool rapidly from annealing temperature; no more than 3 min to black color. Section size determines quenching medium: water for heavy sections, air blast for intermediate sizes, and still air for thin sections. Carbides can precipitate at grain boundaries when parts are cooled too slowly between 425 to 900 °C (795 to 1650 °F).

In aerospace practice, parts are annealed at a set temperature of 1065 °C (1950 °F) and quenched in water with one exception: parts under 2.5 mm (0.10 in.) thick may be air cooled or polymer quenched to minimize distortion. See table for soaking times. Note: approval of the cognizant engineering organization is required for annealing material in a strain-hardened condition, such as ¼ hard; for stress relieving; or for dimensional stabilization. Heat treating or slow cooling unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L

Stress Relieving. Parts can be relieved after quenching to achieve dimensional stability, by heating to 230 to 400 °C (445 to 750 °F) for up to several hours, depending on section size and without change in metallographic structure.

In aerospace practice, parts are stress relieved at 900 °C (1650 °F), and quenched in water. As an alternative, parts may be stress relieved at annealing temperatures. Sections under 2.5 mm (0.10 in.) thick may be air cooled to minimize distortion. Parts fabricated from steel in the strain-hardened condition, such as ½ hard, shall not be stress relieved without permission of the cognizant engineering authority. When stress relieving after welding, hold for 30 min minimum at the stress relieving temperature. Heat treating or slow cooling of unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for soaking times

Nitriding. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners should be replaced with radii of not less than 1.59 mm (0.06 in.). Film of primarily chromium oxide, that protects stainless alloys from oxidation and corrosion, must be removed prior to nitriding. Accomplished by wet blasting, pickling, chemical reduction in reducing atmosphere, submersion in molten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid contamination of surface by finger or hand marking. Single-stage nitriding adequate at 525 to 550 °C (975 to 1020 °F), 20 to 48 h (depending on case depth required). Dissociation rates for single-stage cycle are 20 to 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle produces case extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

Recommended Processing Sequence

- Cold work
- Anneal and quench
- Remove surface contamination (if required)
- Stress relieve
- Depassivate (if nitriding)
- Nitride (if required)

202: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time: Atmosphere furnace min	Minimum soaking time: Salt bath min
up to 2.50 (0.100)	20	17
over 2.50 to 6.25 (0.100 to 0.250)	25	18
over 6.25 to 12.50 (0.259 to 0.500)	45	35
over 12.50 to 25.00 (0.500 to 1.00)	60	40
over 25.00 to 37.50 (1.00 to 1.50)	75	45
over 37.50 to 50.00 (1.50 to 2.00)	90	50
over 50.00 to 62.50 (2.00 to 2.50)	105	55
over 62.50 to 75.00 (2.50 to 3.00)	120	60
over 75.00 (3.00)	(b)	(c)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) 2.25 h plus 15 min for every 12.5 mm (0.5 in.) or increment of 12.5 mm (0.5 in.) over 75 mm (3 in.). (c) 1 h, 5 min plus 5 min for every 12.5 mm (0.5 in.) or increment of 12.5 (0.5 in.) over 75 mm (3 in.). Source: AMS 2759/4

205

Chemical Composition. AISI: Nominal. 0.12 to 0.25 C max, 14.00 to 15.50 Mn, 0.060 P max, 0.030 S max, 1.00 Si max, 1.00 to 1.75 Ni, 16.50 to 18.00 Cr, 0.32 to 0.40 N. **AISI/UNS (S20500):** 0.12 to 0.25 C, 14.0 to 15.5 Mn, 0.06 P, 0.03 S, 1.00 Si, 1.0 to 1.75 Ni, 0.32 to 0.40 N

Characteristics. Lower rate of work hardening and less change of magnetic permeability than type 202 when cold worked. Used for spinning and special drawing operations

Forging. Start forging at 1230 °C (2245 °F). Do not forge after forging stock drops below 925 °C (1695 °F). Cool to black color in less than 3 min, using liquid quench if necessary

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Anneal at 1065 °C (1950 °F). To guard against distortion of thin, delicate parts, leave ample room for expansion between parts. Stainless grades expand about twice as much as carbon and low-alloy steels. Allow enough time for through heating after thermocouple has reached temperature. Stainless grades have approximately half the thermal conductivity of carbon and low-alloy steels. Choice of atmosphere depends on finish desired and whether surface stock will be removed. For bright annealing, use vacuum or an atmosphere of hydrogen or dissociated ammonia at dew point of –62 to –74 °C (–80 to –100 °F). Parts must be thoroughly clean and dry. Inert gases argon and helium (although expensive) and nitrogen, with dew points of less than –54 °C (–65 °F), can be used. They lack the reducing effect of hydrogen, so slight discoloration in the form of chrome oxide can result. Salt, exothermic, or endothermic atmospheres are satisfactory for nonbright annealing. Salt is difficult to remove, and rinse quenching at 595 °C (1105 °F) is not recommended, because interrupted quench at elevated temperature cannot be tolerated. Exothermic and endothermic atmospheres must be carefully controlled at equivalent carbon potential to avoid carburization, which will seriously lower corrosion resistance. Same problem with atmosphere annealing. If oxidizing condi-ıs are present, scale will form. Difficult to remove in subsequent descal- operations.

Cool rapidly from annealing temperature; no more than 3 min to black or. Section size determines quenching medium: water for heavy sec- ıs, air blast for intermediate sizes, and still air for thin sections. Carbides ı precipitate at grain boundaries when parts are cooled too slowly ween 425 to 900 °C (795 to 1650 °F)

ress Relieving. Parts can be relieved after quenching to achieve ıensional stability by heating to 230 to 400 °C (445 to 750 °F) for up to 'eral hours, depending on section size and without change in metal- ,raphic structure

triding. Not recommended. Case seriously impairs corrosion resis- ce in most media. Case seldom more than 0.127 mm (0.005 in.) deep. ly used in specialized applications where material must be nonmagnetic 1 have wear-resistant surface. If nitrided, parts must be in annealed ıdition to prevent flaking or blistering of nitrided case. All sharp corners ɔuld be replaced with radii of not less than 1.59 mm (0.06 in.). Film of marily chromium oxide, that protects stainless alloys from oxidation and rosion, must be removed prior to nitriding. Accomplished by wet blast- ;, pickling, chemical reduction in reducing atmosphere, submersion in molten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid contamination of surface by finger or hand marking. Single-stage nitriding is adequate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h (depending on case depth required). Dissociation rates for single-stage cycle are 20 to 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle produces case extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

Recommended Processing Sequence

- Cold work
- Anneal and quench
- Remove surface contamination (if required)
- Stress relieve
- Depassivate (if nitriding)
- Nitride (if required)

01

ıemical Composition. **AISI/UNS (S30100):** 0.15 C, 2.00 Mn ıx, 0.045 P, 0.030 S, 1.00 Si max, 6.0 to 8.0 Ni, 16.00 to 18.00 Cr

milar Steels (U.S. and/or Foreign). AMS 5517, 5518, 5519; ;TM A167, A177, A554, A666; FED QQ-S-766; MIL SPEC MIL-S- 59; SAE J405 (30301); (Ger.) DIN 1.4310; (Fr.) AFNOR Z 12 CN 17.08; ıl.) UNI X 12 CrNi 17 07; (Jap.) JIS SUS 301

ıaracteristics. Used under mild by corrosive conditions, this steel is ɔable of high tensile strength and ductility with moderate or severe cold ırking. Nonmagnetic when annealed. Magnetic when cold worked

ɔrging. Start forging at 1150 to 1260 °C (2100 to 2300 °F). Do not forge er forging stock drops below 925 °C (1695 °F). Cool to black color in s than 3 min, using liquid quench if necessary

ecommended Heat Treating Practice

ɔrmalizing. Do not normalize

ınealing. Anneal at 1010 to 1120 °C (1850 to 2050 °F). For maximum ctility and softness, use minimum annealing temperature of 1040 °C 905 °F). To guard against distortion of thin, delicate parts, leave ample ɔm for expansion between parts. Stainless grades expand about twice as ıch as carbon and low-alloy steels. Allow enough time for through ating after thermocouple has reached temperature. Stainless grades have proximately half the thermal conductivity of carbon and low-alloy steels. ıoice of atmosphere depends on finish desired and whether surface stock ll be removed. For bright annealing, use vacuum or an atmosphere of drogen or dissociated ammonia at dew point of –62 to –74 °C (–80 to 00 °F). Parts must be thoroughly clean and dry. Inert gases argon and lium (although expensive) and nitrogen, with dew points of less than –54 : (–65 °F), can be used. They lack the reducing effect of hydrogen, so ght discoloration in the form of chrome oxide can result. Salt, exother- :c, or endothermic atmospheres are satisfactory for nonbright annealing. .lt is difficult to remove, and rinse quenching at 595 °C (1105 °F) is not :ommended, because interrupted quench at elevated temperature cannot tolerated. Exothermic and endothermic atmospheres must be carefully ntrolled at equivalent carbon potential to avoid carburization, which will riously lower corrosion resistance. Same problem with atmosphere an- aling. If oxidizing conditions are present, scale will form. Difficult to move in subsequent descaling operations.

Cool rapidly from annealing temperature; no more than 3 min to black color. Section size determines quenching medium: water for heavy sections, air blast for intermediate sizes, and still air for thin sections. Carbides can precipitate at grain boundaries when parts are cooled too slowly between 425 to 900 °C (795 to 1650 °F).

In aerospace practice, parts are annealed at a set temperature of 1065 °C (1950 °F) and quenched in water with one exception: parts under 2.5 mm (0.10 in.) thick may be air cooled or polymer quenched to minimize distortion. See table for soaking times. Note: approval of the cognizant engineering organization is required for annealing material in a strain-hardened condition, such as ¼ hard; for stress relieving; or for dimensional stabilization. Heat treating or slow cooling unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L

Stress Relieving. Parts can be relieved after quenching to achieve dimensional stability, by heating to 230 to 400 °C (445 to 750 °F) for up to several hours, depending on section size and without change in metallographic structure.

In aerospace practice, parts are stress relieved at 900 °C (1650 °F), and quenched in water. As an alternative, parts may be stress relieved at annealing temperatures. Sections under 2.5 mm (0.10 in.) thick may be air cooled to minimize distortion. Parts fabricated from steel in the strain-hardened condition, such as ½ hard, shall not be stress relieved without permission of the cognizant engineering authority. When stress relieving after welding, hold for 30 min minimum at the stress relieving temperature. Heat treating or slow cooling of unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for soaking times

Nitriding. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners should be replaced with radii of not less than 1.59 mm (0.06 in.). Film of primarily chromium oxide, that protects stainless alloys from oxidation and corrosion, must be removed prior to nitriding. Accomplished by wet blasting, pickling, chemical reduction in reducing atmosphere, submersion in molten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid contamination of surface by finger or hand marking. Single-stage nitriding adequate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h (depending on case depth required). Dissociation rates for single-stage cycle are from 20 to 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle produces case extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

Recommended Processing Sequence

- Cold work
- Anneal and quench
- Remove surface contamination (if required)
- Stress relieve
- Depassivate (if nitriding)
- Nitride (if required)

301: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time: Atmosphere furnace min	Salt bath min
up to 2.50 (0.100)	20	17
over 2.50 to 6.25 (0.100 to 0.250)	25	18
over 6.25 to 12.50 (0.259 to 0.500)	45	35
over 12.50 to 25.00 (0.500 to 1.00)	60	40
over 25.00 to 37.50 (1.00 to 1.50)	75	45
over 37.50 to 50.00 (1.50 to 2.00)	90	50
over 50.00 to 62.50 (2.00 to 2.50)	105	55
over 62.50 to 75.00 (2.50 to 3.00)	120	60
over 75.00 (3.00)	(b)	(c)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) 2.25 h plus 15 min for every 12.5 mm (0.5 in.) or increment of 12.5 mm (0.5 in.) over 75 mm (3 in.). (c) 1 h, 5 min plus 5 min for every 12.5 mm (0.5 in.) or increment of 12.5 (0.5 in.) over 75 mm (3 in.). Source: AMS 2759/4

302

Chemical Composition. AISI/UNS (S30200): 0.15 C, 2.00 Mn, 0.045 P, 0.030 S, 1.00 Si, 8.00 to 10.00 Ni, 17.00 to 19.00 Cr

Similar Steels (U.S. and/or Foreign). AMS 5515, 5516, 5636, 5637, 5688; ASME SA240, SA479; ASTM A176, A240, A313, A314, A368, A473, A478, A479, A492, A493, A511, A554, A666; FED QQ-S-763, QQ-S-766, QQ-W-423; MIL SPEC MIL-S-862; SAE J230, J405 (30302)

Characteristics. Can be cold worked to high tensile strengths, but with slightly lower ductility than type 301. Nonmagnetic when annealed. Slightly magnetic when cold worked

Forging. Start forging at 1150 to 1260 °C (2100 to 2300 °F). Do not forge after forging stock drops below 925 °C (1695 °F). Cool to black color in less than 3 min, using liquid quench if necessary

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Anneal at 1010 to 1120 °C (1850 to 2050 °F). To guard against distortion of thin, delicate parts, leave ample room for expansion between parts. Stainless grades expand about twice as much as carbon and low-alloy steels. Allow enough time for through heating after thermocouple has reached temperature. Stainless grades have approximately half the thermal conductivity of carbon and low-alloy steels. Choice of atmosphere depends on finish desired and whether surface stock will be removed. For bright annealing, use vacuum or an atmosphere of hydrogen or dissociated ammonia at dew point of –62 to –74 °C (–80 to –100 °F). Parts must be thoroughly clean and dry. Inert gases argon and helium (although expensive) and nitrogen, with dew points of less than –54 °C (–65 °F), can be used. They lack the reducing effect of hydrogen, so slight discoloration in the form of chrome oxide can result. Salt, exothermic, or endothermic atmospheres are satisfactory for nonbright annealing. Salt is difficult to remove, and rinse quenching at 595 °C (1105 °F) is not recommended, because interrupted quench at elevated temperature cannot be tolerated. Exothermic and endothermic atmospheres must be carefully controlled at equivalent carbon potential to avoid carburization, which will seriously lower corrosion resistance. Same problem with atmosphere annealing. If oxidizing conditions are present, scale will form. Difficult to remove in subsequent descaling operations.

Cool rapidly from annealing temperature; no more than 3 min to black color. Section size determines quenching medium: water for heavy sections, air blast for intermediate sizes, and still air for thin sections. Carbides can precipitate at grain boundaries when parts are cooled too slowly between 425 to 900 °C (795 to 1650 °F).

In aerospace practice, parts are annealed at a set temperature of 1065 °C (1950 °F) and quenched in water with one exception: parts under 2.5 mm (0.25 in.) thick may be air cooled or polymer quenched to minimize distortion. See table for soaking times. Note: approval of the cognizant engineering organization is required for annealing material in a strain-hardened condition, such as ¼ hard; for stress relieving; or for dimensional stabilization. Heat treating or slow cooling unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L

Stress Relieving. Parts can be relieved after quenching to achieve dimensional stability, by heating to 230 to 400 °C (445 to 750 °F) for up to several hours, depending on section size and without change in metallographic structure.

In aerospace practice, parts are stress relieved at 900 °C (1650 °F), and quenched in water. As an alternative, parts may be stress relieved at annealing temperatures. Sections under 2.5 mm (0.10 in.) thick may be air cooled to minimize distortion. Parts fabricated from steel in the strain-hardened condition, such as ½ hard, shall not be stress relieved without permission of the cognizant engineering authority. When stress relieving after welding, hold for 30 min minimum at the stress relieving temperature. Heat treating or slow cooling of unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for soaking times

Nitriding. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners should be replaced with radii of not less than 1.59 mm (0.06 in.). Film of primarily chromium oxide, that protects stainless alloys from oxidation and corrosion, must be removed prior to nitriding. Accomplished by wet blasting, pickling, chemical reduction in reducing atmosphere, submersion in molten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen ıosphere or suitable proprietary agent. After depassivation, avoid con-ıination of surface by finger or hand marking. Single-stage nitriding quate at 525 to 550 °C (975 to 1020 °F), 20 to 48 h (depending on case th required). Dissociation rates for single-stage cycle, from 20 to 35%. ·dness is as high as 1000 to 1350 HK on surface. 48-h cycle produces ɜ extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 . Case will rapidly drop to 200 HK core hardness, at approximately 55 mm (0.0065 in.)

·commended Processing Sequence

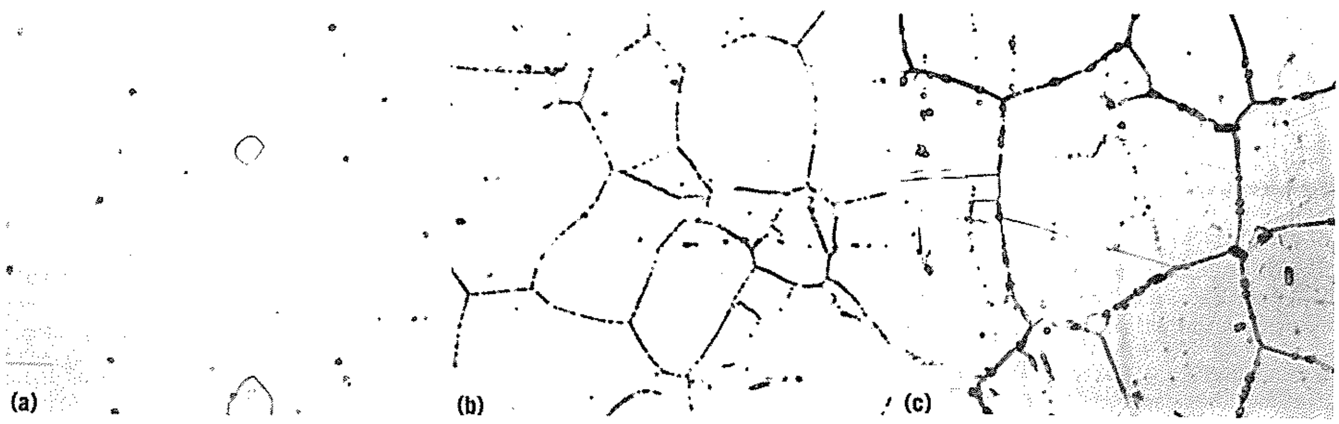
- Cold work
- Anneal and quench
- Remove surface contamination (if required)
- Stress relieve
- Depassivate (if nitriding)
- Nitride (if required)

302: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time Atmosphere furnace min	Salt bath min
up to 2.50 (0.100)	20	17
over 2.50 to 6.25 (0.100 to 0.250)	25	18
over 6.25 to 12.50 (0.259 to 0.500)	45	35
over 12.50 to 25.00 (0.500 to 1.00)	60	40
over 25.00 to 37.50 (1.00 to 1.50)	75	45
over 37.50 to 50.00 (1.50 to 2.00)	90	50
over 50.00 to 62.50 (2.00 to 2.50)	105	55
over 62.50 to 75.00 (2.50 to 3.00)	120	60
over 75.00 (3.00)	(b)	(c)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) 2.25 h plus 15 min for every 12.5 mm (0.5 in.) or increment of 12.5 mm (0.5 in.) over 75 mm (3 in.). (c) 1 h, 5 min plus 5 min for every 12.5 mm (0.5 in.) or increment of 12.5 (0.5 in.) over 75 mm (3 in.). Source: AMS 2759/4

)2: Microstructures. (a) Electrolytic: 10% sodium cyanide, 500×. Strip, 1.56 mm (0.062 in.) thick. Annealed at 1065 °C (1950 °F). Cooled ·pidly to room temperature. Ferrite pools (globules) in austenite matrix. (b) Electrolytic: 10% sodium cyanide, 500×. Containing 0.15 car-)n. Sensitized 1 h at 650 °C (1200 °F). Etched 5 min. Almost continuous network of carbide at austenite grain boundaries. (c) Electrolytic:)% chromic acid, 500×. Same as (b), except etch was in 10% chromic acid for ½ min. Grain-boundary carbide network, twinning, and evi-ɜnce of carbon diffusion within austenite grains



)2B

ɘmical Composition. **AISI/UNS (S30215):** 0.15 C, 2.00 Mn, ·5 P, 0.03 S, 2.0 to 3.0 Si, 8.0 to 10.0 Ni, 17.00 to 19.00 Cr

ıilar Steels (U.S. and/or Foreign). ASTM A167, A276, A314, 3, A580; SAE J405 (30302 B)

aracteristics. Resistance to scaling at elevated temperatures supe- to type 302 because of added silicon. Nonmagnetic when annealed. htly magnetic when cold worked

'ging. Start forging at 1120 to 1230 °C (2050 to 2245 °F). Do not forge · forging stock drops below 925 °C (1695 °F). Cool to black color in than 3 min, using liquid quench if necessary

commended Heat Treating Practice

rmalizing. Do not normalize

ıealing. Anneal at 1010 to 1120 °C (1850 to 2050 °F). For maximum ility and softness, use a minimum annealing temperature of 1040 °C)5 °F). To guard against distortion of thin, delicate parts, leave ample room for expansion between parts. Stainless grades expand about twice as much as carbon and low-alloy steels. Allow enough time for through heating after thermocouple has reached temperature. Stainless grades have approximately half the thermal conductivity of carbon and low-alloy steels. Choice of atmosphere depends on finish desired and whether surface stock will be removed. For bright annealing, use vacuum or an atmosphere of hydrogen or dissociated ammonia at dew point of −62 to −74 °C (−80 to −100 °F). Parts must be thoroughly clean and dry. Inert gases argon and helium (although expensive) and nitrogen, with dew points of less than −54 °C (−65 °F), can be used. They lack the reducing effect of hydrogen, so slight discoloration in the form of chrome oxide can result. Salt, exothermic, or endothermic atmospheres are satisfactory for nonbright annealing. Salt is difficult to remove, and rinse quenching at 595 °C (1105 °F) is not recommended, because interrupted quench at elevated temperature cannot be tolerated. Exothermic and endothermic atmospheres must be carefully controlled at equivalent carbon potential to avoid carburization, which will seriously lower corrosion resistance. Same problem with atmosphere annealing. If oxidizing conditions are present, scale will form. Difficult to remove in subsequent descaling operations.

Cool rapidly from annealing temperature; no more than 3 min to black color. Section size determines quenching medium: water for heavy sections, air blast for intermediate sizes, and still air for thin sections. Carbides can precipitate at grain boundaries when parts are cooled too slowly between 425 to 900 °C (795 to 1650 °F).

In aerospace practice, parts are annealed at a set temperature of 1065 °C (1950 °F) and quenched in water with one exception: parts under 2.5 mm (0.10 in.) thick may be air cooled or polymer quenched to minimize distortion. See table for soaking times. Note: approval of the cognizant engineering organization is required for annealing material in a strain-hardened condition, such as ¼ hard; for stress relieving; or for dimensional stabilization. Heat treating or slow cooling unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L

Stress Relieving. Parts can be relieved after quenching to achieve dimensional stability, by heating to 230 to 400 °C (445 to 750 °F) for up to several hours, depending on section size and without change in metallographic structure.

In aerospace practice, parts are stress relieved at 900 °C (1650 °F), and quenched in water. As an alternative, parts may be stress relieved at annealing temperatures. Sections under 2.5 mm (0.10 in.) thick may be air cooled to minimize distortion. Parts fabricated from steel in the strain-hardened condition, such as ½ hard, shall not be stress relieved without permission of the cognizant engineering authority. When stress relieving after welding, hold for 30 min minimum at the stress relieving temperature. Heat treating or slow cooling of unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for soaking times

Nitriding. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners should be replaced with radii of not less than 1.59 mm (0.06 in.). Film of primarily chromium oxide, that protects stainless alloys from oxidation and corrosion, must be removed prior to nitriding. Accomplished by wet blasting, pickling, chemical reduction in reducing atmosphere, submersion in molten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid contamination of surface by finger or hand marking. Single-stage nitriding adequate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h (depending on case depth required). Dissociation rates for single-stage cycle are from 20 to 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle produces case extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

Recommended Processing Sequence

- Cold work
- Anneal and quench
- Remove surface contamination (if required)
- Stress relieve
- Depassivate (if nitriding)
- Nitride (if required)

302B: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time: Atmosphere furnace min	Minimum soaking time: Salt bath min
up to 2.50 (0.100)	20	17
over 2.50 to 6.25 (0.100 to 0.250)	25	18
over 6.25 to 12.50 (0.259 to 0.500)	45	35
over 12.50 to 25.00 (0.500 to 1.00)	60	40
over 25.00 to 37.50 (1.00 to 1.50)	75	45
over 37.50 to 50.00 (1.50 to 2.00)	90	50
over 50.00 to 62.50 (2.00 to 2.50)	105	55
over 62.50 to 75.00 (2.50 to 3.00)	120	60
over 75.00 (3.00)	(b)	(c)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) 2.25 h plus 15 min for every 12.5 mm (0.5 in.) or increment of 12.5 mm (0.5 in.) over 75 mm (3 in.). (c) 1 h, 5 min plus 5 min for every 12.5 mm (0.5 in.) or increment of 12.5 (0.5 in.) over 75 mm (3 in.). Source: AMS 2759/4

303

Chemical Composition. AISI/UNS (S30300): 0.15 C, 2.00 Mn, 0.200 P, 0.150 S min, 1.00 Si, 8.00 to 10.00 Ni, 17.00 to 19.00 Cr, 0.60 Mo (optional)

Similar Steels (U.S. and/or Foreign). AMS 5640 (1); ASME SA194, SA320; ASTM A194, A314, A320, A473, A581, A582; MIL SPEC MIL-S-862; SAE J405 (30303); (Ger.) DIN 1.4305; (Fr.) AFNOR Z 10 CNF 18.09; (Ital.) UNI X 10 CrNiS 18 09; (Jap.) JIS SUS 303; (Swed.) SS_{14} 2346; (U.K.) B.S. 303 S 21

Characteristics. The addition of sulfur aids machinability. Used to minimize seizing or galling. Must be annealed after welding. Suitable for use in automatic screw machines. Less resistant to corrosion than other 300 steels. Shows good resistance to oxidation up to 925 °C (1695 °F)

Forging. Start forging at 1150 to 1290 °C (2100 to 2355 °F). Finish forging at 925 to 955 °C (1695 to 1750 °F). Cool to black color in less than 3 min, using liquid quench if necessary

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Anneal at 1010 to 1120 °C (1850 to 2050 °F). To guard against distortion of thin, delicate parts, leave ample room for expansion between parts. Stainless grades expand about twice as much as carbon and low-alloy steels. Allow enough time for through heating after thermocouple has reached temperature. Stainless grades have approximately half the thermal conductivity of carbon and low-alloy steels. Choice of atmosphere depends on finish desired and whether surface stock will be removed. For bright annealing, use vacuum or an atmosphere of hydrogen or dissociated ammonia at dew point of –62 to –74 °C (–80 to –100 °F). Parts must be thoroughly clean and dry. Inert gases argon and helium (although expensive) and nitrogen, with dew points of less than –54 °C (–65 °F), can be used. They lack the reducing effect of hydrogen, so slight discoloration in the form of chrome oxide can result. Salt, exothermic, or endothermic atmospheres are satisfactory for nonbright annealing. Salt is difficult to remove, and rinse quenching at 595 °C (1105 °F) is not recommended, because interrupted quench at elevated temperature cannot be tolerated. Exothermic and endothermic atmospheres must be carefully controlled at equivalent carbon potential to avoid carburization, which will seriously lower corrosion resistance. Same problem with atmosphere annealing. If oxidizing conditions are present, scale will form. Difficult to remove in subsequent descaling operations.

Cool rapidly from annealing temperature; no more than 3 min to black or. Section size determines quenching medium: water for heavy secis, air blast for intermediate sizes, and still air for thin sections. Carbides precipitate at grain boundaries when parts are cooled too slowly veen 425 to 900 °C (795 to 1650 °F).

In aerospace practice, parts are annealed at a set temperature of 1065 (1950 °F) and quenched in water with one exception: parts under 2.5 (0.10 in.) thick may be air cooled or polymer quenched to minimize ortion. See table for soaking times. Note: approval of the cognizant ineering organization is required for annealing material in a strain-hardd condition, such as ¼ hard; for stress relieving; or for dimensional ilization. Heat treating or slow cooling unstabilized grades between to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L

ess Relieving. Parts can be relieved after quenching to achieve ensional stability, by heating to 230 to 400 °C (445 to 750 °F) for up to eral hours, depending on section size and without change in metalaphic structure.

In aerospace practice, parts are stress relieved at 900 °C (1650 °F), and nched in water. As an alternative, parts may be stress relieved at ealing temperatures. Sections under 2.5 mm (0.10 in.) thick may be air led to minimize distortion. Parts fabricated from steel in the strain-hard-d condition, such as ½ hard, shall not be stress relieved without nission of the cognizant engineering authority. When stress relieving r welding, hold for 30 min minimum at the stress relieving temperature. t treating or slow cooling of unstabilized grades between 470 to 815 °C 5 to 1500 °F) is prohibited, except for 304L and 316L. See table for king times

riding. Not recommended. Case seriously impairs corrosion resise in most media. Case seldom more than 0.127 mm (0.005 in.) deep. y used in specialized applications where material must be nonmagnetic have wear-resistant surface. If nitrided, parts must be in annealed dition to prevent flaking or blistering of nitrided case. All sharp corners ıld be replaced with radii of not less than 1.59 mm (0.06 in.). Film of narily chromium oxide, that protects stainless alloys from oxidation and osion, must be removed prior to nitriding. Accomplished by wet blastpickling, chemical reduction in reducing atmosphere, submersion in ten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid contamination of surface by finger or hand marking. Single-stage nitriding adequate at 525 to 550 °C (975 to 1020 °F for 20 to 48 h (depending on case depth required). Dissociation rates for single-stage cycle are from 20 to 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle produces case extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

Recommended Processing Sequence

- Cold work
- Anneal and quench
- Remove surface contamination (if required)
- Stress relieve
- Depassivate (if nitriding)
- Nitride (if required)

303: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time	
	Atmosphere furnace min	Salt bath min
up to 2.50 (0.100)	20	17
over 2.50 to 6.25 (0.100 to 0.250)	25	18
over 6.25 to 12.50 (0.259 to 0.500)	45	35
over 12.50 to 25.00 (0.500 to 1.00)	60	40
over 25.00 to 37.50 (1.00 to 1.50)	75	45
over 37.50 to 50.00 (1.50 to 2.00)	90	50
over 50.00 to 62.50 (2.00 to 2.50)	105	55
over 62.50 to 75.00 (2.50 to 3.00)	120	60
over 75.00 (3.00)	(b)	(c)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) 2.25 h plus 15 min for every 12.5 mm (0.5 in.) or increment of 12.5 mm (0.5 in.) over 75 mm (3 in.). (c) 1 h, 5 min plus 5 min for every 12.5 mm (0.5 in.) or increment of 12.5 (0.5 in.) over 75 mm (3 in.). Source: AMS 2759/4

)3Se

emical Composition. AISI/UNS (S30323): 0.15 C, 2.00 Mn, 0 P, 0.060 S min, 1.00 Si, 8.0 to 10.0 Ni, 17.0 to 19.0 Cr, 0.15 Se

ilar Steels (U.S. and/or Foreign). AMS 5640 (Type 2), l, 5738; ASME SA194, SA320; ASTM A194, A314, A320, A473, 1, A582; MIL SPEC MIL-S-862; SAE J405 (30303 Se)

aracteristics. Selenium addition promotes machinability. Used to mize seizing or galling. Must be annealed after welding. Suitable for n automatic screw machines. Less resistant to corrosion than other 300 s. Shows good resistance to oxidation up to 925 °C (1695 °F)

ging. Start forging at 1150 to 1290 °C (2100 to 2355 °F). Finish ing at 925 to 955 °C (1695 to 1750 °F). Cool to black color in less than n, using liquid quench if necessary

commended Heat Treating Practice

malizing. Do not normalize

nealing. Anneal at 1010 to 1120 °C (1850 to 2050 °F). To guard nst distortion of thin, delicate parts, leave ample room for expansion een parts. Stainless grades expand about twice as much as carbon and low-alloy steels. Allow enough time for through heating after thermocouple has reached temperature. Stainless grades have approximately half the thermal conductivity of carbon and low-alloy steels. Choice of atmosphere depends on finish desired and whether surface stock will be removed. For bright annealing, use vacuum or an atmosphere of hydrogen or dissociated ammonia at dew point of −62 to −74 °C (−80 to −100 °F). Parts must be thoroughly clean and dry. Inert gases argon and helium (although expensive) and nitrogen, with dew points of less than −54 °C (−65 °F), can be used. They lack the reducing effect of hydrogen, so slight discoloration in the form of chrome oxide can result. Salt, exothermic, or endothermic atmospheres are satisfactory for nonbright annealing. Salt is difficult to remove, and rinse quenching at 595 °C (1105 °F) is not recommended, because interrupted quench at elevated temperature cannot be tolerated. Exothermic and endothermic atmospheres must be carefully controlled at equivalent carbon potential to avoid carburization, which will seriously lower corrosion resistance. Same problem with atmosphere annealing. If oxidizing conditions are present, scale will form. Difficult to remove in subsequent descaling operations.

Cool rapidly from annealing temperature; no more than 3 min to black color. Section size determines quenching medium: water for heavy sections, air blast for intermediate sizes, and still air for thin sections. Carbides can precipitate at grain boundaries when parts are cooled too slowly between 425 to 900 °C (795 to 1650 °F).

In aerospace practice, parts are annealed at a set temperature of 1065 °C (1950 °F) and quenched in water with one exception: parts under 2.5 mm (0.10 in.) thick may be air cooled or polymer quenched to minimize distortion. See table for soaking times. Note: approval of the cognizant engineering organization is required for annealing material in a strain-hardened condition, such as ¼ hard; for stress relieving; or for dimensional stabilization. Heat treating or slow cooling unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L

Stress Relieving. Parts can be relieved after quenching to achieve dimensional stability, by heating to 230 to 400 °C (445 to 750 °F) for up to several hours, depending on section size and without change in metallographic structure.

In aerospace practice, parts are stress relieved at 900 °C (1650 °F), and quenched in water. As an alternative, parts may be stress relieved at annealing temperatures. Sections under 2.5 mm (0.10 in.) thick may be air cooled to minimize distortion. Parts fabricated from steel in the strain-hardened condition, such as ½ hard, shall not be stress relieved without permission of the cognizant engineering authority. When stress relieving after welding, hold for 30 min minimum at the stress relieving temperature. Heat treating or slow cooling of unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for soaking times

Nitriding. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners should be replaced with radii of not less than 1.59 mm (0.06 in.). Film of primarily chromium oxide, that protects stainless alloys from oxidation and corrosion, must be removed prior to nitriding. Accomplished by wet blasting, pickling, chemical reduction in reducing atmosphere, submersion in molten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid contamination of surface by finger or hand marking. Single-stage nitriding adequate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h (depending on case depth required). Dissociation rates for single-stage cycle are from 20 to 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle produces case extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

Recommended Processing Sequence

- Cold work
- Anneal and quench
- Remove surface contamination (if required)
- Stress relieve
- Depassivate (if nitriding)
- Nitride (if required)

303Se: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time Atmosphere furnace min	Salt bath min
up to 2.50 (0.100)	20	17
over 2.50 to 6.25 (0.100 to 0.250)	25	18
over 6.25 to 12.50 (0.259 to 0.500)	45	35
over 12.50 to 25.00 (0.500 to 1.00)	60	40
over 25.00 to 37.50 (1.00 to 1.50)	75	45
over 37.50 to 50.00 (1.50 to 2.00)	90	50
over 50.00 to 62.50 (2.00 to 2.50)	105	55
over 62.50 to 75.00 (2.50 to 3.00)	120	60
over 75.00 (3.00)	(b)	(c)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) 2.25 h plus 15 min for every 12.5 mm (0.5 in.) or increment of 12.5 mm (0.5 in.) over 75 mm (3 in.). (c) 1 h, 5 min plus 5 min for every 12.5 mm (0.5 in.) or increment of 12.5 (0.5 in.) over 75 mm (3 in.). Source: AMS 2759/4

304

Chemical Composition. AISI/UNS (S30400): 0.08 C, 2.00 Mn, 0.045 P, 0.030 S, 1.00 Si, 8.0 to 10.5 Ni, 18.0 to 20.0 Cr

Similar Steels (U.S. and/or Foreign). AMS 5501, 5513, 5560, 5565, 5566, 5567, 5639, 5697; ASME SA182, SA194 (8), SA213, SA240, SA249, SA312, SA320 (B8), SA358, SA376, SA403, SA409, SA430, SA479, SA688; ASTM A167, A182, A193, A194, A213, A240, A249, A269, A270, A271, A276, A312, A313, A314, A320, A368, A376, A409, A430, A473, A478, A479, A492, A493, A511, A554, A580, A632, A651, A666, A688; FED QQ-W-423, Q763, QQ-S-766, STD-66; MIL SPEC MIL-F-20138, MIL-S-862, MIL-S-5059, MIL-S-23195, MIL-S-23196, MIL-T-6845, MIL-T-8504, MIL-T-8506; SAE J405 (30304); (Ger.) DIN 1.4301; (Fr.) AFNOR Z 6 CN 18.09; (Ital.) UNI X 5 CrNi 18 10; (Jap.) JIS SUS 304; (Swed.) SS_{14} 2332; (U.K.) B.S. 304 S 15, 302 S 17, 304 S 16, 304 S 18, 304 S 25, 304 S 40, En. 58 E

Characteristics. Corrosion resistance higher than type 302. Nonmagnetic when annealed. Slightly magnetic when cold worked. Less susceptible to precipitation of carbides during welding

Forging. Start forging at 1150 to 1260 °C (2100 to 2300 °F). Do not forge after forging stock drops below 925 °C (1695 °F). Cool to black color in less than 3 min, using liquid quench if necessary

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Anneal at 1010 to 1120 °C (1850 to 2050 °F). For maximum ductility and softness, use a minimum annealing temperature of 1040 °C (1905 °F). To guard against distortion of thin, delicate parts, leave ample room for expansion between parts. Stainless grades expand about twice as much as carbon and low-alloy steels. Allow enough time for through heating after thermocouple has reached temperature. Stainless grades have approximately half the thermal conductivity of carbon and low-alloy steels. Choice of atmosphere depends on finish desired and whether surface stock will be removed. For bright annealing, use vacuum or an atmosphere of hydrogen or dissociated ammonia at dew point of –62 to –74 °C (–80 to –100 °F). Parts must be thoroughly clean and dry. Inert gases argon and helium (although expensive) and nitrogen, with dew points of less than –54 °C (–65 °F), can be used. They lack the reducing effect of hydrogen, so slight discoloration in the form of chrome oxide can result. Salt, exothermic, or endothermic atmospheres are satisfactory for nonbright annealing. Salt is difficult to remove, and rinse quenching at 595 °C (1105 °F) is not recommended, because interrupted quench at elevated temperature cannot be tolerated. Exothermic and endothermic atmospheres must be carefully controlled at equivalent carbon potential to avoid carburization, which will ously lower corrosion resistance. Same problem with atmosphere an-ling. If oxidizing conditions are present, scale will form. Difficult to iove in subsequent descaling operations.

Cool rapidly from annealing temperature; no more than 3 min to black ɔr. Section size determines quenching medium: water for heavy sec-ıs, air blast for intermediate sizes, and still air for thin sections. Carbides precipitate at grain boundaries when parts are cooled too slowly veen 425 to 900 °C (795 to 1650 °F).

In aerospace practice, parts are annealed at a set temperature of 1065 (1950 °F) and quenched in water with one exception: parts under 2.5 ı (0.10 in.) thick may be air cooled or polymer quenched to minimize ortion. See table for soaking times. Note: approval of the cognizant ineering organization is required for annealing material in a strain-hard-d condition, such as ¼ hard; for stress relieving; or for dimensional ilization. Heat treating or slow cooling unstabilized grades between to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L

'ess Relieving. Parts can be relieved after quenching to achieve ensional stability, by heating to 230 to 400 °C (445 to 750 °F) for up to eral hours, depending on section size and without change in metal-aphic structure.

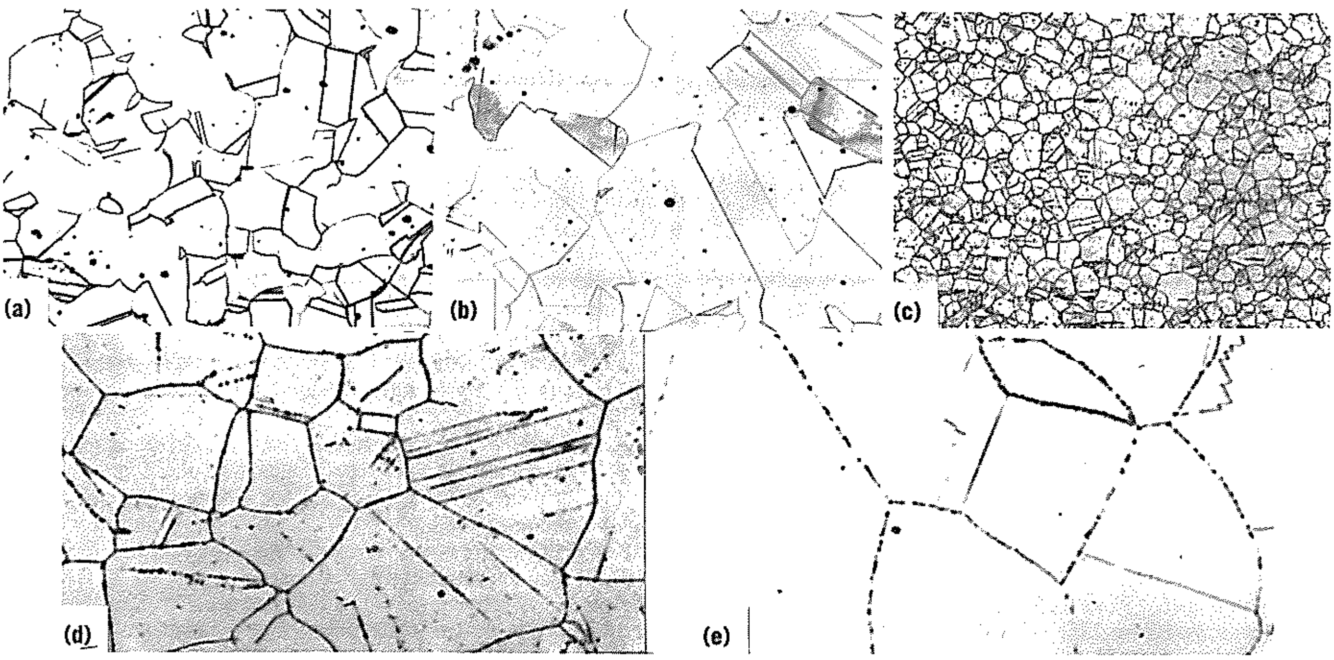
In aerospace practice, parts are stress relieved at 900 °C (1650 °F), and nched in water. As an alternative, parts may be stress relieved at ealing temperatures. Sections under 2.5 mm (0.10 in.) thick may be air led to minimize distortion. Parts fabricated from steel in the strain-hard-d condition, such as ½ hard, shall not be stress relieved without nission of the cognizant engineering authority. When stress relieving r welding, hold for 30 min minimum at the stress relieving temperature. t treating or slow cooling of unstabilized grades between 470 to 815 °C 5 to 1500 °F) is prohibited, except for 304L and 316L. See table for king times

Nitriding. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners should be replaced with radii of not less than 1.59 mm (0.06 in.). Film of primarily chromium oxide, that protects stainless alloys from oxidation and corrosion, must be removed prior to nitriding. Accomplished by wet blasting, pickling, chemical reduction in reducing atmosphere, submersion in molten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid contamination of surface by finger or hand marking. Single-stage nitriding adequate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h (depending on case depth required). Dissociation rates for single-stage cycle are from 20 to 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle produces case extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

Recommended Processing Sequence

- Cold work
- Anneal and quench
- Remove surface contamination (if required)
- Stress relieve
- Depassivate (if nitriding)
- Nitride (if required)

)4: Microstructures. (a) HNO_3-acetic-HCl-glycerol, 250×. Strip. Annealed 5 min at 1065 °C (1950 °F). Cooled in air. Equiaxed austenite ains and annealing twins. (b) Electrolytic: 10% oxalic acid, 100×. Forging. Annealed at 1065 °C (1950 °F), 1 h. Quenched in water. Irregular ıstenite grains. Etch pits at dispersed carbide particles. (c) Electrolytic: HNO_3-acetic, then 10% oxalic acid, 100×. Strip. Annealed 2 min at)65 °C (1950 °F). Air cooled. Equiaxed austenite grains (ASTM No. 8), annealing twins, small stringer inclusions. (d) Electrolytic: 10% oxic acid, 500×. Strip. Annealed at 1040 °C (1905 °F). Sensitized by reheating at 650 °C (1200 °F), 1 h. Carbide precipitation at grain bounda-ɜs and at twin boundaries. (e) Boiling Murakami's reagent, 500×. Plate with 0.062 carbon content. Annealed for carbide agglomeration by ɜing held at 1065 °C (1950 °F), 1 h. Sensitized by cooling to 800 °C (1475 °F) and held at temperature, 100 h. Water quenched. Precipitation chromium carbide at austenite grain boundaries

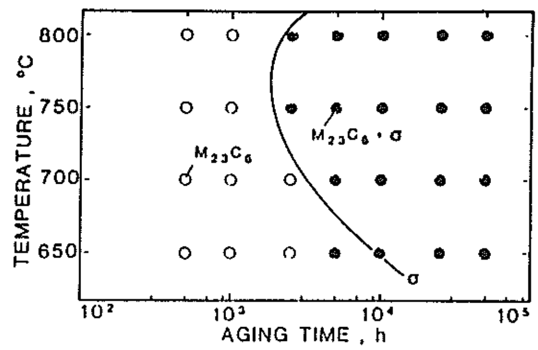


304: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time Atmosphere furnace min	Salt bath min
up to 2.50 (0.100)	20	17
over 2.50 to 6.25 (0.100 to 0.250)	25	18
over 6.25 to 12.50 (0.259 to 0.500)	45	35
over 12.50 to 25.00 (0.500 to 1.00)	60	40
over 25.00 to 37.50 (1.00 to 1.50)	75	45
over 37.50 to 50.00 (1.50 to 2.00)	90	50
over 50.00 to 62.50 (2.00 to 2.50)	105	55
over 62.50 to 75.00 (2.50 to 3.00)	120	60
over 75.00 (3.00)	(b)	(c)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) 2.25 h plus 15 min for every 12.5 mm (0.5 in.) or increment of 12.5 mm (0.5 in.) over 75 mm (3 in.). (c) 1 h, 5 min plus 5 min for every 12.5 mm (0.5 in.) or increment of 12.5 (0.5 in.) over 75 mm (3 in.). Source: AMS 2759/4

304: Precipitation Diagram. Composition: 0.05 C, 1.73 Mn, 0.60 Si, 0.028 P, 0.012 S, 9.0 Ni, 18.7 Cr, 0.026 N. Solution treated at 1050 °C (1920 °F) for 30 min, water quenched, aged at 600 to 800 °C (1110 to 1470 °F) for up to 50,000 h



304H

Chemical Composition. AISI/UNS (S30409): 0.04 to 0.10 C, 2.00 Mn, 0.045 P, 0.03 S, 1.00 Si, 8.0 to 10.5 Ni, 18.0 to 20.0 Cr

Recommended Heat Treating Practice

Annealing. In aerospace practice, parts are annealed at a set temperature of 1065 °C (1950 °F) and quenched in water with one exception: parts under 2.5 mm (0.10 in.) thick may be air cooled or polymer quenched to minimize distortion. See table for soaking times. Note: approval of the cognizant engineering organization is required for annealing material in a strain-hardened condition, such as ¼ hard; for stress relieving; or for dimensional stabilization. Heat treating or slow cooling unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L

Stress Relieving. In aerospace practice, parts are stress relieved at 900 °C (1650 °F), and quenched in water. As an alternative, parts may be stress relieved at annealing temperatures. Sections under 2.5 mm (0.10 in.) thick may be air cooled to minimize distortion. Parts fabricated from steel in the strain-hardened condition, such as ½ hard, shall not be stress relieved without permission of the cognizant engineering authority. When stress relieving after welding, hold for 30 min minimum at the stress relieving temperature. Heat treating or slow cooling of unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for soaking times

304H: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time Atmosphere furnace min	Salt bath min
up to 2.50 (0.100)	20	17
over 2.50 to 6.25 (0.100 to 0.250)	25	18
over 6.25 to 12.50 (0.259 to 0.500)	45	35
over 12.50 to 25.00 (0.500 to 1.00)	60	40
over 25.00 to 37.50 (1.00 to 1.50)	75	45
over 37.50 to 50.00 (1.50 to 2.00)	90	50
over 50.00 to 62.50 (2.00 to 2.50)	105	55
over 62.50 to 75.00 (2.50 to 3.00)	120	60
over 75.00 (3.00)	(b)	(c)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) 2.25 h plus 15 min for every 12.5 mm (0.5 in.) or increment of 12.5 mm (0.5 in.) over 75 mm (3 in.). (c) 1 h, 5 min plus 5 min for every 12.5 mm (0.5 in.) or increment of 12.5 (0.5 in.) over 75 mm (3 in.). Source: AMS 2759/4

304L

Chemical Composition. AISI/UNS (S30403): 0.03 C, 2.00 Mn, 0.045 P, 0.030 S, 1.00 Si, 8.0 to 12.0 Ni, 18.0 to 20.0 Cr

Similar Steels (U.S. and/or Foreign). AMS 5511, 5647; ASME SA182, SA213, SA240, SA249, SA312, SA403, SA479, SA688; ASTM A167, A182, A213, A240, A249, A276, A312, A314, A403, A473, A478, A479, A511, A554, A580, A632, A688; FED QQ-S-763, QQ-S-766; MIL SPEC MIL-S-862, MIL-S-23195, MIL-S-23196; SAE J405 (30304 L); (Ger.) DIN 1.4306; (Ital.) UNI X 2 CrNi 18 11, X 3 CrNi 18 11, X 2 CrNi 18 11 KG, X 2 CrNi 18 11 KW; (Jap.) JIS SUS 304 L, SCS 19; (Swed.) SS_{14} 2352; (U.K.) B.S. 304 S 12, 304 S 14, 304 S 22, S 536

Characteristics. Extra low-carbon version of type 304 for restriction of carbide precipitation during welding. Ranks between stabilized and unstabilized grades, because of tendency to precipitate chromium carbides. Used extensively for welding applications, particularly on parts which cannot be subsequently annealed. Parts are limited to service up to 425 °C (795 °F). Hardenable by cold work only. Heat treating limited to: annealing to restore maximum corrosion resistance, softness, and ductility after cold rking; stress relieving when required for stresses occurring from water :nch, when this rapid quench is necessary; and on rare occasion, nitrid- to impart thin, wear-resistant surface

ɪrging. Start forging at 1150 to 1260 °C (2100 to 2300 °F). Do not forge :r forging stock drops below 925 °C (1695 °F)

:commended Heat Treating Practice

ɪrmalizing. Do not normalize

ınealing. Anneal at 1010 to 1120 °C (1850 to 2050 °F). For maximum :tility, use a minimum annealing temperature of 1040 °C (1905 °F). Parts ı be air cooled from annealing temperature. Water quenching not neces- y. At 815 to 425 °C (1500 to 795 °F), slow cooling can occur for up to 2 /ithout subsequent danger of susceptibility to intergranular corrosion in ural atmospheric environments. However, for some applications in the :mical industry, intergranular corrosion would result from this treatment.

In aerospace practice, parts are annealed at a set temperature of 1065 (1950 °F) and quenched in water with one exception: parts under 2.5 ı (0.10 in.) thick may be air cooled or polymer quenched to minimize tortion. See table for soaking times. Note: approval of the cognizant ;ineering organization is required for annealing material in a strain-hard- :d condition, such as ¼ hard; for stress relieving; or for dimensional ɔilization. Heat treating or slow cooling unstabilized grades between) to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L

ress Relieving. Parts can be relieved after quenching to achieve ıensional stability, by heating to 230 to 400 °C (445 to 750 °F) for up to eral hours, depending on section size and without change in metal- raphic structure.

In aerospace practice, parts are stress relieved at 900 °C (1650 °F), and :nched in water. As an alternative, parts may be stress relieved at ıealing temperatures. Sections under 2.5 mm (0.10 in.) thick may be air ıled to minimize distortion. Parts fabricated from steel in the strain-hard-ened condition, such as ½ hard, shall not be stress relieved without permission of the cognizant engineering authority. When stress relieving after welding, hold for 30 min minimum at the stress relieving temperature. Heat treating or slow cooling of unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for soaking times

Recommended Processing Sequence

- Cold work
- Anneal and cool
- Stress relieve (optional)
- Depassivate (if nitriding)
- Nitride (if required)

304L: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time	
	Atmosphere furnace min	Salt bath min
up to 2.50 (0.100)	20	17
over 2.50 to 6.25 (0.100 to 0.250)	25	18
over 6.25 to 12.50 (0.259 to 0.500)	45	35
over 12.50 to 25.00 (0.500 to 1.00)	60	40
over 25.00 to 37.50 (1.00 to 1.50)	75	45
over 37.50 to 50.00 (1.50 to 2.00)	90	50
over 50.00 to 62.50 (2.00 to 2.50)	105	55
over 62.50 to 75.00 (2.50 to 3.00)	120	60
over 75.00 (3.00)	(b)	(c)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) 2.25 h plus 15 min for every 12.5 mm (0.5 in.) or increment of 12.5 mm (0.5 in.) over 75 mm (3 in.). (c) 1 h, 5 min plus 5 min for every 12.5 mm (0.5 in.) or increment of 12.5 (0.5 in.) over 75 mm (3 in.). Source: AMS 2759/4

30430

ıemical Composition. **AISI/UNS (S30430):** 0.8 C max, 2.00 Mn x, 0.045 P max, 0.030 S max, 1.00 Si max, 8.00 to 10.00 Ni, 17.00 to 00 Cr, 3.04 to 4.0 Cu

nilar Steels (U.S. and/or Foreign). ASTM A493 (XM-7)

ıaracteristics. Lower work hardening rate than type 305. Used for ere cold heading applications

rging. Start forging at 1150 to 1260 °C (2100 to 2300 °F). Do not forge :r forging stock drops below 925 °C (1695 °F). Cool to black color in ; than 3 min, using liquid quench if necessary

:commended Heat Treating Practice

ɪrmalizing. Do not normalize

ınealing. Anneal at 1010 to 1120 °C (1850 to 2050 °F). For maximum :tility and softness, use a minimum annealing temperature of 1040 °C 05 °F). To guard against distortion of thin, delicate parts, leave ample m for expansion between parts. Stainless grades expand about twice as ch as carbon and low-alloy steels. Allow enough time for through ting after thermocouple has reached temperature. Stainless grades have ɪroximately half the thermal conductivity of carbon and low-alloy steels. ɔice of atmosphere depends on finish desired and whether surface stock l be removed. For bright annealing, use vacuum or an atmosphere of lrogen or dissociated ammonia at dew point of –62 to –74 °C (–80 to)0 °F). Parts must be thoroughly clean and dry. Inert gases argon and ium (although expensive) and nitrogen, with dew points of less than –54 °C (–65 °F), can be used. They lack the reducing effect of hydrogen, so slight discoloration in the form of chrome oxide can result. Salt, exothermic, or endothermic atmospheres are satisfactory for nonbright annealing. Salt is difficult to remove, and rinse quenching at 595 °C (1105 °F) is not recommended, because interrupted quench at elevated temperature cannot be tolerated. Exothermic and endothermic atmospheres must be carefully controlled at equivalent carbon potential to avoid carburization, which will seriously lower corrosion resistance. Same problem with atmosphere annealing. If oxidizing conditions are present, scale will form. Difficult to remove in subsequent descaling operations.

Cool rapidly from annealing temperature; no more than 3 min to black color. Section size determines quenching medium: water for heavy sections, air blast for intermediate sizes, and still air for thin sections. Carbides can precipitate at grain boundaries when parts are cooled too slowly between 425 to 900 °C (795 to 1650 °F).

In aerospace practice, parts are annealed at a set temperature of 1065 °C (1950 °F) and quenched in water with one exception: parts under 2.5 mm (0.10 in.) thick may be air cooled or polymer quenched to minimize distortion. See table for soaking times. Note: approval of the cognizant engineering organization is required for annealing material in a strain-hardened condition, such as ¼ hard; for stress relieving; or for dimensional stabilization. Heat treating or slow cooling unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L

Stress Relieving. Parts can be relieved after quenching to achieve dimensional stability, by heating to 230 to 400 °C (445 to 750 °F) for up to several hours, depending on section size and without change in metallographic structure.

In aerospace practice, parts are stress relieved at 900 °C (1650 °F), and quenched in water. As an alternative, parts may be stress relieved at annealing temperatures. Sections under 2.5 mm (0.10 in.) thick may be air cooled to minimize distortion. Parts fabricated from steel in the strain hardened condition, such as ½ hard, shall not be stress relieved without permission of the cognizant engineering authority. When stress relieving after welding, hold for 30 min minimum at the stress relieving temperature. Heat treating or slow cooling of unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for soaking times

Nitriding. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners should be replaced with radii of not less than 1.59 mm (0.06 in.). Film of primarily chromium oxide, that protects stainless alloys from oxidation and corrosion, must be removed prior to nitriding. Accomplished by wet blasting, pickling, chemical reduction in reducing atmosphere, submersion in molten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid contamination of surface by finger or hand marking. Single-stage nitriding adequate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h (depending on case depth required). Dissociation rates for single-stage cycle are from 20 to 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle produces case extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

Recommended Processing Sequence

- Cold work
- Anneal and quench
- Remove surface contamination (if required)
- Stress relieve
- Depassivate (if nitriding)
- Nitride (if required)

S30430: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time	
	Atmosphere furnace min	Salt bath min
up to 2.50 (0.100)	20	17
over 2.50 to 6.25 (0.100 to 0.250)	25	18
over 6.25 to 12.50 (0.259 to 0.500)	45	35
over 12.50 to 25.00 (0.500 to 1.00)	60	40
over 25.00 to 37.50 (1.00 to 1.50)	75	45
over 37.50 to 50.00 (1.50 to 2.00)	90	50
over 50.00 to 62.50 (2.00 to 2.50)	105	55
over 62.50 to 75.00 (2.50 to 3.00)	120	60
over 75.00 (3.00)	(b)	(c)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) 2.25 h plus 15 min for every 12.5 mm (0.5 in.) or increment of 12.5 mm (0.5 in.) over 75 mm (3 in.). (c) 1 h, 5 min plus 5 min for every 12.5 mm (0.5 in.) or increment of 12.5 (0.5 in.) over 75 mm (3 in.). Source: AMS 2759/4

304LN

Chemical Composition. **AISI/UNS (S30453):** 0.03 C, 2.00 Mn, 0.045 P, 0.03 S, 1.00 Si, 8.0 to 12.0 Ni, 18.0 to 20.0 Cr, 0.10 to 0.16 N

Recommended Heat Treating Practice

Annealing. In aerospace practice, parts are annealed at a set temperature of 1065 °C (1950 °F) and quenched in water with one exception: parts under 2.5 mm (0.10 in.) thick may be air cooled or polymer quenched to minimize distortion. See table for soaking times. Note: approval of the cognizant engineering organization is required for annealing material in a strain-hardened condition, such as ¼ hard; for stress relieving; or for dimensional stabilization. Heat treating or slow cooling unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L

Stress Relieving. In aerospace practice, parts are stress relieved at 900 °C (1650 °F), and quenched in water. As an alternative, parts may be stress relieved at annealing temperatures. Sections under 2.5 mm (0.10 in.) thick may be air cooled to minimize distortion. Parts fabricated from steel in the strain-hardened condition, such as ½ hard, shall not be stress relieved without permission of the cognizant engineering authority. When stress relieving after welding, hold for 30 min minimum at the stress relieving temperature. Heat treating or slow cooling of unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for soaking times

304LN: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time	
	Atmosphere furnace min	Salt bath min
up to 2.50 (0.100)	20	17
over 2.50 to 6.25 (0.100 to 0.250)	25	18
over 6.25 to 12.50 (0.259 to 0.500)	45	35
over 12.50 to 25.00 (0.500 to 1.00)	60	40
over 25.00 to 37.50 (1.00 to 1.50)	75	45
over 37.50 to 50.00 (1.50 to 2.00)	90	50
over 50.00 to 62.50 (2.00 to 2.50)	105	55
over 62.50 to 75.00 (2.50 to 3.00)	120	60
over 75.00 (3.00)	(b)	(c)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) 2.25 h plus 15 min for every 12.5 mm (0.5 in.) or increment of 12.5 mm (0.5 in.) over 75 mm (3 in.). (c) 1 h, 5 min plus 5 min for every 12.5 mm (0.5 in.) or increment of 12.5 (0.5 in.) over 75 mm (3 in.). Source: AMS 2759/4

04N

,emical Composition. AISI/UNS (S30451): 0.08 C max, 2.00 max, 0.045 P max, 0.030 S max, 1.00 Si max, 8.00 to 10.50 Ni, 18.00 :0.00 Cr, 0.10 to 0.16 N

nilar Steels (U.S. and/or Foreign). ASME SA182, SA213, 240, SA249, SA312, SA358, SA376, SA430, SA479; ASTM A182, 13, A240, A249, A312, A358, A376, A403, A430, A479

ıaracteristics. Contains added nitrogen to increase strength with ıimum effect on ductility and corrosion resistance. Type 304N is nongnetic when annealed. More resistant to increased magnetic permeabilon cold working than type 304

rging. Start forging at 1150 to 1260 °C (2100 to 2300 °F). Do not forge :r forging stock drops below 925 °C (1695 °F). Cool to black color in ; than 3 min, using liquid quench if necessary

:commended Heat Treating Practice

ırmalizing. Do not normalize

ınealing. Anneal at 1010 to 1120 °C (1850 to 2050 °F). For maximum :tility and softness, use minimum annealing temperature of 1040 °C 05 °F). To guard against distortion of thin, delicate parts, leave ample m for expansion between parts. Stainless grades expand about twice as ch as carbon and low-alloy steels. Allow enough time for through .ting after thermocouple has reached temperature. Stainless grades have ıroximately half the thermal conductivity of carbon and low-alloy steels. ɔice of atmosphere depends on finish desired and whether surface stock l be removed. For bright annealing, use vacuum or an atmosphere of lrogen or dissociated ammonia at dew point of –62 to –74 °C (–80 to)0 °F). Parts must be thoroughly clean and dry. Inert gases argon and ium (although expensive) and nitrogen, with dew points of less than –54 (–65 °F), can be used. They lack the reducing effect of hydrogen, so ;ht discoloration in the form of chrome oxide can result. Salt, exother- :, or endothermic atmospheres are satisfactory for nonbright annealing. t is difficult to remove, and rinse quenching at 595 °C (1105 °F) is not ommended, because interrupted quench at elevated temperature cannot tolerated. Exothermic and endothermic atmospheres must be carefully ıtrolled at equivalent carbon potential to avoid carburization, which will iously lower corrosion resistance. Same problem with atmosphere anılling. If oxidizing conditions are present, scale will form. Difficult to ɪove in subsequent descaling operations.

Cool rapidly from annealing temperature; no more than 3 min to black or. Section size determines quenching medium: water for heavy secıs, air blast for intermediate sizes, and still air for thin sections. Carbides ı precipitate at grain boundaries when parts are cooled too slowly ween 425 to 900 °C (795 to 1650 °F).

In aerospace practice, parts are annealed at a set temperature of 1065 (1950 °F) and quenched in water with one exception: parts under 2.5 ı (0.10 in.) thick may be air cooled or polymer quenched to minimize tortion. See table for soaking times. Note: approval of the cognizant ;ineering organization is required for annealing material in a strain-hard- :d condition, such as ¼ hard; for stress relieving; or for dimensional bilization. Heat treating or slow cooling unstabilized grades between) to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L

ress Relieving. Parts can be relieved after quenching to achieve ıensional stability, by heating to 230 to 400 °C (445 to 750 °F) for up to 'eral hours, depending on section size and without change in metal- ;raphic structure.

In aerospace practice, parts are stress relieved at 900 °C (1650 °F), and :nched in water. As an alternative, parts may be stress relieved at annealing temperatures. Sections under 2.5 mm (0.10 in.) thick may be air cooled to minimize distortion. Parts fabricated from steel in the strain-hardened condition, such as ½ hard, shall not be stress relieved without permission of the cognizant engineering authority. When stress relieving after welding, hold for 30 min minimum at the stress relieving temperature. Heat treating or slow cooling of unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for soaking times

Nitriding. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners should be replaced with radii of not less than 1.59 mm (0.06 in.). Film of primarily chromium oxide, that protects stainless alloys from oxidation and corrosion, must be removed prior to nitriding. Accomplished by wet blasting, pickling, chemical reduction in reducing atmosphere, submersion in molten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid contamination of surface by finger or hand marking. Single-stage nitriding adequate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h (depending on case depth required). Dissociation rates for single-stage cycle are from 20 to 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle produces case extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

Recommended Processing Sequence

- Cold work
- Anneal and quench
- Remove surface contamination (if required)
- Stress relieve
- Depassivate (if nitriding)
- Nitride (if required)

304N: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time: Atmosphere furnace min	Minimum soaking time: Salt bath min
up to 2.50 (0.100)	20	17
over 2.50 to 6.25 (0.100 to 0.250)	25	18
over 6.25 to 12.50 (0.259 to 0.500)	45	35
over 12.50 to 25.00 (0.500 to 1.00)	60	40
over 25.00 to 37.50 (1.00 to 1.50)	75	45
over 37.50 to 50.00 (1.50 to 2.00)	90	50
over 50.00 to 62.50 (2.00 to 2.50)	105	55
over 62.50 to 75.00 (2.50 to 3.00)	120	60
over 75.00 (3.00)	(b)	(c)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) 2.25 h plus 15 min for every 12.5 mm (0.5 in.) or increment of 12.5 mm (0.5 in.) over 75 mm (3 in.). (c) 1 h, 5 min plus 5 min for every 12.5 mm (0.5 in.) or increment of 12.5 (0.5 in.) over 75 mm (3 in.). Source: AMS 2759/4

305

Chemical Composition. **AISI/UNS (S30500):** 0.12 C max, 2.00 Mn max, 0.045 P max, 0.030 S max, 1.00 Si max, 10.50 to 13.00 Ni, 17.00 to 19.00 Cr

Similar Steels (U.S. and/or Foreign). AMS 5514, 5685, 5686; ASME SA193, SA194, SA240; ASTM A167, A240, A249, A276, A313, A314, A368, A473, A478, A493, A511, A554, A580; FED QQ-S-763, QQ-W-423; SAE J405 (30305); (Ger.) DIN 1.4303; (Ital.) UNI X 8 CrNi 19 10; (Jap.) JIS SUS 305, SUS J1

Characteristics. This austenitic chromium-nickel steel has lower rate of work hardening than types 302 and 304. Less change of magnetic permeability. Used for spinning, special drawing, and cold heading applications

Forging. Start forging at 1150 to 1260 °C (2100 to 2300 °F). Do not forge after forging stock drops below 925 °C (1695 °F). Cool to black color in less than 3 min, using liquid quench if necessary

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Anneal at 1010 to 1120 °C (1850 to 2050 °F). For maximum ductility and softness, use a minimum annealing temperature of 1040 °C (1905 °F). To guard against distortion of thin, delicate parts, leave ample room for expansion between parts. Stainless grades expand about twice as much as carbon and low-alloy steels. Allow enough time for through heating after thermocouple has reached temperature. Stainless grades have approximately half the thermal conductivity of carbon and low-alloy steels. Choice of atmosphere depends on finish desired and whether surface stock will be removed. For bright annealing, use vacuum or an atmosphere of hydrogen or dissociated ammonia at dew point of –62 to –74 °C (–80 to –100 °F). Parts must be thoroughly clean and dry. Inert gases argon and helium (although expensive) and nitrogen, with dew points of less than –54 °C (–65 °F), can be used. They lack the reducing effect of hydrogen, so slight discoloration in the form of chrome oxide can result. Salt, exothermic, or endothermic atmospheres are satisfactory for nonbright annealing. Salt is difficult to remove, and rinse quenching at 595 °C (1105 °F) is not recommended, because interrupted quench at elevated temperature cannot be tolerated. Exothermic and endothermic atmospheres must be carefully controlled at equivalent carbon potential to avoid carburization, which will seriously lower corrosion resistance. Same problem with atmosphere annealing. If oxidizing conditions are present, scale will form. Difficult to remove in subsequent descaling operations.

Cool rapidly from annealing temperature; no more than 3 min to black color. Section size determines quenching medium: water for heavy sections, air blast for intermediate sizes, and still air for thin sections. Carbides can precipitate at grain boundaries when parts are cooled too slowly between 425 to 900 °C (795 to 1650 °F).

In aerospace practice, parts are annealed at a set temperature of 1065 °C (1950 °F) and quenched in water with one exception: parts under 2.5 mm (0.10 in.) thick may be air cooled or polymer quenched to minimize distortion. See table for soaking times. Note: approval of the cognizant engineering organization is required for annealing material in a strain-hardened condition, such as ¼ hard; for stress relieving; or for dimensional stabilization. Heat treating or slow cooling unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L

Stress Relieving. Parts can be relieved after quenching to achieve dimensional stability, by heating to 230 to 400 °C (445 to 750 °F) for up to several hours, depending on section size and without change in metallographic structure.

In aerospace practice, parts are stress relieved at 900 °C (1650 °F), and quenched in water. As an alternative, parts may be stress relieved at annealing temperatures. Sections under 2.5 mm (0.10 in.) thick may be air cooled to minimize distortion. Parts fabricated from steel in the strain-hardened condition, such as ½ hard, shall not be stress relieved without permission of the cognizant engineering authority. When stress relieving after welding, hold for 30 min minimum at the stress relieving temperature. Heat treating or slow cooling of unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for soaking times

Nitriding. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners should be replaced with radii of not less than 1.59 mm (0.06 in.). Film of primarily chromium oxide, that protects stainless alloys from oxidation and corrosion, must be removed prior to nitriding. Accomplished by wet blasting, pickling, chemical reduction in reducing atmosphere, submersion in molten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid contamination of surface by finger or hand marking. Single-stage nitriding adequate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h (depending on case depth required). Dissociation rates for single-stage cycle are from 20 to 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle produces case extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

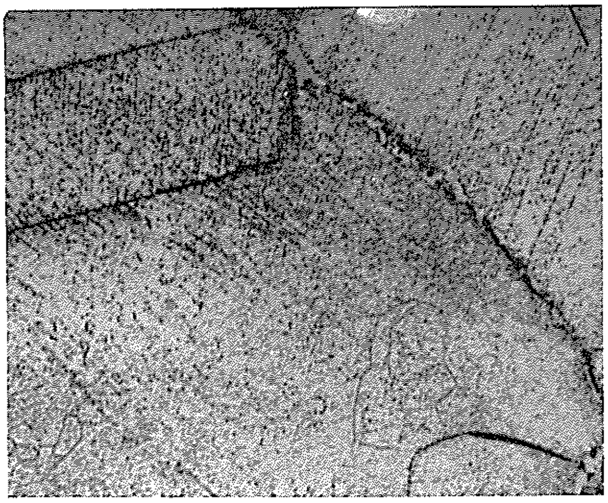
Recommended Processing Sequence

- Cold work
- Anneal and quench
- Remove surface contamination (if required)
- Stress relieve
- Depassivate (if nitriding)
- Nitride (if required)

305: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time: Atmosphere furnace min	Salt bath min
up to 2.50 (0.100)	20	17
over 2.50 to 6.25 (0.100 to 0.250)	25	18
over 6.25 to 12.50 (0.259 to 0.500)	45	35
over 12.50 to 25.00 (0.500 to 1.00)	60	40
over 25.00 to 37.50 (1.00 to 1.50)	75	45
over 37.50 to 50.00 (1.50 to 2.00)	90	50
over 50.00 to 62.50 (2.00 to 2.50)	105	55
over 62.50 to 75.00 (2.50 to 3.00)	120	60
over 75.00 (3.00)	(b)	(c)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) 2.25 h plus 15 min for every 12.5 mm (0.5 in.) or increment of 12.5 mm (0.5 in.) over 75 mm (3 in.). (c) 1 h, 5 min plus 5 min for every 12.5 mm (0.5 in.) or increment of 12.5 (0.5 in.) over 75 mm (3 in.). Source: AMS 2759/4



305: Microstructure. Electrolytic: 50% phosphoric acid, 1000×. Creep-rupture specimen. Annealed at 1120 °C (2050 °F), ½ h. Tested at 650 °C (1200 °F), 371 h. Carbon migration and precipitation of chromium carbide ($Cr_{23}C_6$) at austenite grain boundaries.

08

ıemical Composition. **AISI/UNS (S30800):** 0.08 C, 2.00 Mn, ı45 P, 0.030 S, 1.00 Si, 10.0 to 12.0 Ni, 19.00 to 21.00 Cr

milar Steels (U.S. and/or Foreign). ASTM A167, A276, 14, A473, A580; SAE J405 (30308); (Ger.) DIN 1.4303; (Ital.) UNI X 8 Ni 19 10; (Jap.) JIS SUS 305, SUS 305 J 1

ıaracteristics. Corrosion and heat resistance superior to type 304. ed for welding wire. Nonmagnetic when annealed. Slightly magnetic ıen cold worked

ırging. Start forging at 1150 to 1260 °C (2100 to 2300 °F). Do not forge er forging stock drops below 925 °C (1695 °F). Cool to black color in s than 3 min, using liquid quench if necessary

ecommended Heat Treating Practice

ɔrmalizing. Do not normalize

nnealing. Anneal at 1010 to 1120 °C (1850 to 2050 °F). For maximum ctility and softness, use a minimum annealing temperature of 1040 °C ͻ05 °F). To guard against distortion of thin, delicate parts, leave ample ɔm for expansion between parts. Stainless grades expand about twice as ıch as carbon and low-alloy steels. Allow enough time for through ating after thermocouple has reached temperature. Stainless grades have proximately half the thermal conductivity of carbon and low-alloy steels. ıoice of atmosphere depends on finish desired and whether surface stock ll be removed. For bright annealing, use vacuum or an atmosphere of drogen or dissociated ammonia at dew point of –62 to –74 °C (–80 to 00 °F). Parts must be thoroughly clean and dry. Inert gases argon and lium (although expensive) and nitrogen, with dew points of less than –54 (–65 °F), can be used. They lack the reducing effect of hydrogen, so ght discoloration in the form of chrome oxide can result. Salt, exotheric, or endothermic atmospheres are satisfactory for nonbright annealing. ılt is difficult to remove, and rinse quenching at 595 °C (1105 °F) is not commended, because interrupted quench at elevated temperature cannot tolerated. Exothermic and endothermic atmospheres must be carefully ntrolled at equivalent carbon potential to avoid carburization, which will riously lower corrosion resistance. Same problem with atmosphere an-ealing. If oxidizing conditions are present, scale will form. Difficult to move in subsequent descaling operations.

Cool rapidly from annealing temperature; no more than 3 min to black ılor. Section size determines quenching medium: water for heavy sections, air blast for intermediate sizes, and still air for thin sections. Carbides can precipitate at grain boundaries when parts are cooled too slowly between 425 to 900 °C (795 to 1650 °F).

In aerospace practice, parts are annealed at a set temperature of 1065 °C (1950 °F) and quenched in water with one exception: parts under 2.5 mm (0.10 in.) thick may be air cooled or polymer quenched to minimize distortion. See table for soaking times. Note: approval of the cognizant engineering organization is required for annealing material in a strain-hardened condition, such as ¼ hard; for stress relieving; or for dimensional stabilization. Heat treating or slow cooling unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L

Stress Relieving. Parts can be relieved after quenching to achieve dimensional stability, by heating to 230 to 400 °C (445 to 750 °F) for up to several hours, depending on section size and without change in metallographic structure.

In aerospace practice, parts are stress relieved at 900 °C (1650 °F), and quenched in water. As an alternative, parts may be stress relieved at annealing temperatures. Sections under 2.5 mm (0.10 in.) thick may be air cooled to minimize distortion. Parts fabricated from steel in the strain-hardened condition, such as ½ hard, shall not be stress relieved without permission of the cognizant engineering authority. When stress relieving after welding, hold for 30 min minimum at the stress relieving temperature. Heat treating or slow cooling of unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for soaking times

Nitriding. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners should be replaced with radii of not less than 1.59 mm (0.06 in.). Film of primarily chromium oxide, that protects stainless alloys from oxidation and corrosion, must be removed prior to nitriding. Accomplished by wet blasting, pickling, chemical reduction in reducing atmosphere, submersion in molten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid contamination of surface by finger or hand marking. Single-stage nitriding adequate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h (depending on case depth required). Dissociation rates for single-stage cycle are from 20 to 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle produces case extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

Recommended Processing Sequence

- Cold work
- Anneal and quench
- Remove surface contamination (if required)
- Stress relieve
- Depassivate (if nitriding)
- Nitride (if required)

308: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time	
	Atmosphere furnace min	Salt bath min
up to 2.50 (0.100)	20	17
over 2.50 to 6.25 (0.100 to 0.250)	25	18
over 6.25 to 12.50 (0.259 to 0.500)	45	35
over 12.50 to 25.00 (0.500 to 1.00)	60	40
over 25.00 to 37.50 (1.00 to 1.50)	75	45
over 37.50 to 50.00 (1.50 to 2.00)	90	50
over 50.00 to 62.50 (2.00 to 2.50)	105	55
over 62.50 to 75.00 (2.50 to 3.00)	120	60
over 75.00 (3.00)	(b)	(c)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) 2.25 h plus 15 min for every 12.5 mm (0.5 in.) or increment of 12.5 mm (0.5 in.) over 75 mm (3 in.). (c) 1 h, 5 min plus 5 min for every 12.5 mm (0.5 in.) or increment of 12.5 (0.5 in.) over 75 mm (3 in.). Source: AMS 2759/4

309

Chemical Composition. AISI/UNS (S30900): 0.20 C, 2.00 Mn, 0.045 P, 0.030 S, 1.00 Si max, 12.0 to 15.0 Ni, 22.0 to 24.0 Cr

Similar Steels (U.S. and/or Foreign). ASME SA249, SA312, SA358, SA403, SA409; ASTM A167, A249, A276, A312, A314, A358, A403, A409, A473, A511, A554, A580; FED QQ-S-763, QQ-S-766; MIL SPEC MIL-S-862; SAE J405 (30309); (Ger.) DIN 1.4828; (Ital.) UNI X 16 CrNi 23 14

Characteristics. High heat resisting qualities. Used for welding wire applications

Forging. Start forging at 1150 to 1230 °C (2100 to 2245 °F). Finish forging at 980 to 1010 °C (1795 to 1850 °F). Cool to black color in less than 3 min, using liquid quench if necessary

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Anneal at 1040 to 1120 °C (1905 to 2050 °F). To guard against distortion of thin, delicate parts, leave ample room for expansion between parts. Stainless grades expand about twice as much as carbon and low-alloy steels. Allow enough time for through heating after thermocouple has reached temperature. Stainless grades have approximately half the thermal conductivity of carbon and low-alloy steels. Choice of atmosphere depends on finish desired and whether surface stock will be removed. For bright annealing, use vacuum or an atmosphere of hydrogen or dissociated ammonia at dew point of −62 to −74 °C (−80 to −100 °F). Parts must be thoroughly clean and dry. Inert gases argon and helium (although expensive) and nitrogen, with dew points of less than −54 °C (−65 °F), can be used. They lack the reducing effect of hydrogen, so slight discoloration in the form of chrome oxide can result. Salt, exothermic, or endothermic atmospheres are satisfactory for nonbright annealing. Salt is difficult to remove, and rinse quenching at 595 °C (1105 °F) is not recommended, because interrupted quench at elevated temperature cannot be tolerated. Exothermic and endothermic atmospheres must be carefully controlled at equivalent carbon potential to avoid carburization, which will seriously lower corrosion resistance. Same problem with atmosphere annealing. If oxidizing conditions are present, scale will form. Difficult to remove in subsequent descaling operations.

Cool rapidly from annealing temperature; no more than 3 min to black color. Section size determines quenching medium: water for heavy sections, air blast for intermediate sizes, and still air for thin sections. Carbides can precipitate at grain boundaries when parts are cooled too slowly between 425 to 900 °C (795 to 1650 °F).

In aerospace practice, parts are annealed at a set temperature of 1065 °C (1950 °F) and quenched in water with one exception: parts under 2.5 mm (0.10 in.) thick may be air cooled or polymer quenched to minimize distortion. See table for soaking times. Note: approval of the cognizant engineering organization is required for annealing material in a strain-hardened condition, such as ¼ hard; for stress relieving; or for dimensional stabilization. Heat treating or slow cooling unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L

Stress Relieving. Parts can be relieved after quenching to achieve dimensional stability, by heating to 230 to 400 °C (445 to 750 °F) for up to several hours, depending on section size and without change in metallographic structure.

In aerospace practice, parts are stress relieved at 900 °C (1650 °F), and quenched in water. As an alternative, parts may be stress relieved at annealing temperatures. Sections under 2.5 mm (0.10 in.) thick may be air cooled to minimize distortion. Parts fabricated from steel in the strain-hardened condition, such as ½ hard, shall not be stress relieved without permission of the cognizant engineering authority. When stress relieving after welding, hold for 30 min minimum at the stress relieving temperature. Heat treating or slow cooling of unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for soaking times

Nitriding. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners should be replaced with radii of not less than 1.59 mm (0.06 in.). Film of primarily chromium oxide, that protects stainless alloys from oxidation and corrosion, must be removed prior to nitriding. Accomplished by wet blasting, pickling, chemical reduction in reducing atmosphere, submersion in molten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid contamination of surface by finger or hand marking. Single-stage nitriding adequate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h (depending on case depth required). Dissociation rates for single-stage cycle are from 20 to 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle duces case extending to 0.127 mm (0.005 in.) with approximately 800 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

ecommended Processing Sequence

- Cold work
- Anneal and quench
- Remove surface contamination (if required)
- Stress relieve
- Depassivate (if nitriding)
- Nitride (if required)

309: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time Atmosphere furnace min	Salt bath min
up to 2.50 (0.100)	20	17
over 2.50 to 6.25 (0.100 to 0.250)	25	18
over 6.25 to 12.50 (0.259 to 0.500)	45	35
over 12.50 to 25.00 (0.500 to 1.00)	60	40
over 25.00 to 37.50 (1.00 to 1.50)	75	45
over 37.50 to 50.00 (1.50 to 2.00)	90	50
over 50.00 to 62.50 (2.00 to 2.50)	105	55
over 62.50 to 75.00 (2.50 to 3.00)	120	60
over 75.00 (3.00)	(b)	(c)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) 2.25 h plus 15 min for every 12.5 mm (0.5 in.) or increment of 12.5 mm (0.5 in.) over 75 mm (3 in.). (c) 1 h, 5 min plus 5 min for every 12.5 mm (0.5 in.) or increment of 12.5 (0.5 in.) over 75 mm (3 in.). Source: AMS 2759/4

09S

emical Composition. AISI/UNS **(S30908):** 0.08 C, 2.00 Mn, 45 P, 0.030 S, 1.00 Si, 12.00 to 15.00 Ni, 22.00 to 24.00 Cr

milar Steels (U.S. and/or Foreign). AMS 5523, 5574, 5650; ME SA240; ASTM A167, A240, A276, A314, A511, A554, A580; SAE 5 (30309 S); (Ger.) DIN 1.4833; (Fr.) AFNOR Z 15 CN 24.13; (Ital.) II X 6 CrNi 23 14

aracteristics. High heat resisting qualities. Used for welding wire plications

rging. Start forging at 1120 to 1230 °C (2050 to 2245 °F). Finish ging at 980 to 1010 °C (1795 to 1850 °F). Cool to black color in less than nin, using liquid quench if necessary

ecommended Heat Treating Practice

rmalizing. Do not normalize

nealing. Anneal at 1040 to 1120 °C (1905 to 2050 °F). To guard inst distortion of thin, delicate parts, leave ample room for expansion ween parts. Stainless grades expand about twice as much as carbon and -alloy steels. Allow enough time for through heating after thermocouple reached temperature. Stainless grades have approximately half the rmal conductivity of carbon and low-alloy steels. Choice of atmosphere ends on finish desired and whether surface stock will be removed. For ght annealing, use vacuum or an atmosphere of hydrogen or dissociated monia at dew point of –62 to –74 °C (–80 to –100 °F). Parts must be roughly clean and dry. Inert gases argon and helium (although expene) and nitrogen, with dew points of less than –54 °C (–65 °F), can be d. They lack the reducing effect of hydrogen, so slight discoloration in form of chrome oxide can result. Salt, exothermic, or endothermic nospheres are satisfactory for nonbright annealing. Salt is difficult to nove, and rinse quenching at 595 °C (1105 °F) is not recommended, ause interrupted quench at elevated temperature cannot be tolerated. othermic and endothermic atmospheres must be carefully controlled at uivalent carbon potential to avoid carburization, which will seriously ver corrosion resistance. Same problem with atmosphere annealing. If idizing conditions are present, scale will form. Difficult to remove in sequent descaling operations.

Cool rapidly from annealing temperature; no more than 3 min to black or. Section size determines quenching medium: water for heavy secns, air blast for intermediate sizes, and still air for thin sections. Carbides can precipitate at grain boundaries when parts are cooled too slowly between 425 to 900 °C (795 to 1650 °F).

In aerospace practice, parts are annealed at a set temperature of 1065 °C (1950 °F) and quenched in water with one exception: parts under 2.5 mm (0.10 in.) thick may be air cooled or polymer quenched to minimize distortion. See table for soaking times. Note: approval of the cognizant engineering organization is required for annealing material in a strain-hardened condition, such as ¼ hard; for stress relieving; or for dimensional stabilization. Heat treating or slow cooling unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L

Stress Relieving. Parts can be relieved after quenching to achieve dimensional stability, by heating to 230 to 400 °C (445 to 750 °F) for u to several hours, depending on section size and without change in tallographic structure.

In aerospace practice, parts are stress relieved at 900 °C (1650 °F), and quenched in water. As an alternative, parts may be stress relieved at annealing temperatures. Sections under 2.5 mm (0.10 in.) thick may be air cooled to minimize distortion. Parts fabricated from steel in the strain-hardened condition, such as ½ hard, shall not be stress relieved without permission of the cognizant engineering authority. When stress relieving after welding, hold for 30 min minimum at the stress relieving temperature. Heat treating or slow cooling of unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for soaking times

Nitriding. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners should be replaced with radii of not less than 1.59 mm (0.06 in.). Film of primarily chromium oxide, that protects stainless alloys from oxidation and corrosion, must be removed prior to nitriding. Accomplished by wet blasting, pickling, chemical reduction in reducing atmosphere, submersion in molten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid contamination of surface by finger or hand marking. Single-stage nitriding adequate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h (depending on case depth required). Dissociation rates for single-stage cycle are from 20 to 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle produces case extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

Recommended Processing Sequence

- Cold work
- Anneal and quench
- Remove surface contamination (if required)
- Stress relieve
- Depassivate (if nitriding)
- Nitride (if required)

309S: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time: Atmosphere furnace min	Minimum soaking time: Salt bath min
up to 2.50 (0.100)	20	17
over 2.50 to 6.25 (0.100 to 0.250)	25	18
over 6.25 to 12.50 (0.259 to 0.500)	45	35
over 12.50 to 25.00 (0.500 to 1.00)	60	40
over 25.00 to 37.50 (1.00 to 1.50)	75	45
over 37.50 to 50.00 (1.50 to 2.00)	90	50
over 50.00 to 62.50 (2.00 to 2.50)	105	55
over 62.50 to 75.00 (2.50 to 3.00)	120	60
over 75.00 (3.00)	(b)	(c)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) 2.25 h plus 15 min for every 12.5 mm (0.5 in.) or increment of 12.5 mm (0.5 in.) over 75 mm (3 in.). (c) 1 h, 5 min plus 5 min for every 12.5 mm (0.5 in.) or increment of 12.5 (0.5 in.) over 75 mm (3 in.). Source: AMS 2759/4

310

Chemical Composition. **AISI/UNS (S31000):** 0.25 C, 2.00 Mn, 0.045 P, 0.030 S, 1.50 Si, 19.00 to 22.00 Ni, 24.00 to 26.00 Cr

Similar Steels (U.S. and/or Foreign). AMS 5694, 5695; ASME SA182, SA213, SA249, SA312, SA358, SA403, SA409; ASTM A167, A182, A240, A213, A249, A276, A312, A314, A358, A403, A409, A473, A511, A632; FED QQ-S-763, QQ-S-766, QQ-W-423, STD-66; MIL SPEC MIL-S-862; SAE J405 (30310); (Ger.) DIN 1.4841; (Fr.) AFNOR Z 12 CNS 25.20; (Ital.) UNI X 16 CrNiSi 25 20, X 22 CrNi 25 20; (Jap.) JIS SUS Y 310; (U.K.) B.S. 310 S 24

Characteristics. High heat resistant qualities, plus resistant to corrosion and oxidation at high temperatures. Very ductile. Easily welded

Forging. Start forging at 1095 to 1230 °C (2005 to 2245 °F). Finish forging at 980 to 1010 °C (1795 to 1850 °F). Cool to black color in less than 3 min, using liquid quench if necessary

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Anneal at 1040 to 1150 °C (1905 to 2100 °F) and hold at least ½ h. To guard against distortion of thin, delicate parts, leave ample room for expansion between parts. Stainless grades expand about twice as much as carbon and low-alloy steels. Allow enough time for through heating after thermocouple has reached temperature. Stainless grades have approximately half the thermal conductivity of carbon and low-alloy steels. Choice of atmosphere depends on finish desired and whether surface stock will be removed. For bright annealing, use vacuum or an atmosphere of hydrogen or dissociated ammonia at dew point of −62 to −74 °C (−80 to −100 °F). Parts must be thoroughly clean and dry. Inert gases argon and helium (although expensive) and nitrogen, with dew points of less than −54 °C (−65 °F), can be used. They lack the reducing effect of hydrogen, so slight discoloration in the form of chrome oxide can result. Salt, exothermic, or endothermic atmospheres are satisfactory for nonbright annealing. Salt is difficult to remove, and rinse quenching at 595 °C (1105 °F) is not recommended, because interrupted quench at elevated temperature cannot be tolerated. Exothermic and endothermic atmospheres must be carefully controlled at equivalent carbon potential to avoid carburization, which will seriously lower corrosion resistance. Same problem with atmosphere annealing. If oxidizing conditions are present, scale will form. Difficult to remove in subsequent descaling operations.

Cool rapidly from annealing temperature; no more than 3 min to black color. Section size determines quenching medium: water for heavy sections, air blast for intermediate sizes, and still air for thin sections. Carbides can precipitate at grain boundaries when parts are cooled too slowly between 425 to 900 °C (795 to 1650 °F).

In aerospace practice, parts are annealed at a set temperature of 1065 °C (1950 °F) and quenched in water with one exception: parts under 2.5 mm (0.10 in.) thick may be air cooled or polymer quenched to minimize distortion. See table for soaking times. Note: approval of the cognizant engineering organization is required for annealing material in a strain-hardened condition, such as ¼ hard; for stress relieving; or for dimensional stabilization. Heat treating or slow cooling unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L

Stress Relieving. Parts can be relieved after quenching to achieve dimensional stability, by heating to 230 to 400 °C (445 to 750 °F) for up to several hours, depending on section size and without change in metallographic structure.

In aerospace practice, parts are stress relieved at 900 °C (1650 °F), and quenched in water. As an alternative, parts may be stress relieved at annealing temperatures. Sections under 2.5 mm (0.10 in.) thick may be air cooled to minimize distortion. Parts fabricated from steel in the strain-hardened condition, such as ½ hard, shall not be stress relieved without permission of the cognizant engineering authority. When stress relieving after welding, hold for 30 min minimum at the stress relieving temperature. Heat treating or slow cooling of unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for soaking times

Nitriding. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners should be replaced with radii of not less than 1.59 mm (0.06 in.). Film of primarily chromium oxide, that protects stainless alloys from oxidation and corrosion, must be removed prior to nitriding. Accomplished by wet blasting, pickling, chemical reduction in reducing atmosphere, submersion in molten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid contamination of surface by finger or hand marking. Single-stage nitriding

:quate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h (depending on ;e depth required). Dissociation rates for single-stage cycle are from 20 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle)duces case extending to 0.127 mm (0.005 in.) with approximately 800 1000 HK. Case will rapidly drop to 200 HK core hardness, at approxi- tely 0.165 mm (0.0065 in.)

ecommended Processing Sequence

- Cold work
- Anneal and quench
- Remove surface contamination (if required)
- Stress relieve
- Depassivate (if nitriding)
- Nitride (if required)

310: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time: Atmosphere furnace min	Minimum soaking time: Salt bath min
up to 2.50 (0.100)	20	17
over 2.50 to 6.25 (0.100 to 0.250)	25	18
over 6.25 to 12.50 (0.259 to 0.500)	45	35
over 12.50 to 25.00 (0.500 to 1.00)	60	40
over 25.00 to 37.50 (1.00 to 1.50)	75	45
over 37.50 to 50.00 (1.50 to 2.00)	90	50
over 50.00 to 62.50 (2.00 to 2.50)	105	55
over 62.50 to 75.00 (2.50 to 3.00)	120	60
over 75.00 (3.00)	(b)	(c)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) 2.25 h plus 15 min for every 12.5 mm (0.5 in.) or increment of 12.5 mm (0.5 in.) over 75 mm (3 in.). (c) 1 h, 5 min plus 5 min for every 12.5 mm (0.5 in.) or increment of 12.5 (0.5 in.) over 75 mm (3 in.). Source: AMS 2759/4

10S

iemical Composition. AISI/UNS (S31008): 0.08 C, 2.00 Mn,)45 P, 0.030 S, 1.50 Si, 19.00 to 22.00 Ni, 24.00 to 26.00 Cr

milar Steels (U.S. and/or Foreign). AMS 5521, 5572, 5577, 51; ASME SA240, SA479; ASTM A167, A240, A276, A314, A473, ·79, A511, A554, A580; SAE J405 (30310 S)

iaracteristics. High heat resistant qualities, plus resistant to corro- n and oxidation at high temperatures. Very ductile. Easily welded

)rging. Start forging at 1095 to 1230 °C (2005 to 2245 °F). Finish ging at 980 to 1010 °C (1795 to 1850 °F). Cool to black color in less than nin, using liquid quench if necessary

ecommended Heat Treating Practice

)rmalizing. Do not normalize

inealing. Anneal at 1040 to 1150 °C (1905 to 2100 °F) and hold at ıst ½ h. To guard against distortion of thin, delicate parts, leave ample)m for expansion between parts. Stainless grades expand about twice as ıch as carbon and low-alloy steels. Allow enough time for through ating after thermocouple has reached temperature. Stainless grades have proximately half the thermal conductivity of carbon and low-alloy steels. ıoice of atmosphere depends on finish desired and whether surface stock ll be removed. For bright annealing, use vacuum or an atmosphere of drogen or dissociated ammonia at dew point of –62 to –74 °C (–80 to 00 °F). Parts must be thoroughly clean and dry. Inert gases argon and lium (although expensive) and nitrogen, with dew points of less than –54 (–65 °F), can be used. They lack the reducing effect of hydrogen, so ght discoloration in the form of chrome oxide can result. Salt, exother- c, or endothermic atmospheres are satisfactory for nonbright annealing. It is difficult to remove, and rinse quenching at 595 °C (1105 °F) is not :ommended, because interrupted quench at elevated temperature cannot tolerated. Exothermic and endothermic atmospheres must be carefully ntrolled at equivalent carbon potential to avoid carburization, which will ·iously lower corrosion resistance. Same problem with atmosphere an- aling. If oxidizing conditions are present, scale will form. Difficult to nove in subsequent descaling operations.

Cool rapidly from annealing temperature; no more than 3 min to black lor. Section size determines quenching medium: water for heavy sec- ns, air blast for intermediate sizes, and still air for thin sections. Carbides n precipitate at grain boundaries when parts are cooled too slowly tween 425 to 900 °C (795 to 1650 °F).

In aerospace practice, parts are annealed at a set temperature of 1065 °C (1950 °F) and quenched in water with one exception: parts under 2.5 mm (0.10 in.) thick may be air cooled or polymer quenched to minimize distortion. See table for soaking times. Note: approval of the cognizant engineering organization is required for annealing material in a strain-hardened condition, such as ¼ hard; for stress relieving; or for dimensional stabilization. Heat treating or slow cooling unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L

Stress Relieving. Parts can be relieved after quenching to achieve dimensional stability, by heating to 230 to 400 °C (445 to 750 °F) for up to several hours, depending on section size, and without change in metallographic structure.

In aerospace practice, parts are stress relieved at 900 °C (1650 °F), and quenched in water. As an alternative, parts may be stress relieved at annealing temperatures. Sections under 2.5 mm (0.10 in.) thick may be air cooled to minimize distortion. Parts fabricated from steel in the strain-hardened condition, such as ½ hard, shall not be stress relieved without permission of the cognizant engineering authority. When stress relieving after welding, hold for 30 min minimum at the stress relieving temperature. Heat treating or slow cooling of unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for soaking times

Nitriding. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners should be replaced with radii of not less than 1.59 mm (0.06 in.). Film of primarily chromium oxide, that protects stainless alloys from oxidation and corrosion, must be removed prior to nitriding. Accomplished by wet blasting, pickling, chemical reduction in reducing atmosphere, submersion in molten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid contamination of surface by finger or hand marking. Single-stage nitriding adequate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h (depending on case depth required). Dissociation rates for single-stage cycle are from 20 to 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle produces case extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

Recommended Processing Sequence

- Cold work
- Anneal and quench
- Remove surface contamination (if required)
- Stress relieve
- Depassivate (if nitriding)
- Nitride (if required)

310S: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time: Atmosphere furnace min	Salt bath min
up to 2.50 (0.100)	20	17
over 2.50 to 6.25 (0.100 to 0.250)	25	18
over 6.25 to 12.50 (0.259 to 0.500)	45	35
over 12.50 to 25.00 (0.500 to 1.00)	60	40
over 25.00 to 37.50 (1.00 to 1.50)	75	45
over 37.50 to 50.00 (1.50 to 2.00)	90	50
over 50.00 to 62.50 (2.00 to 2.50)	105	55
over 62.50 to 75.00 (2.50 to 3.00)	120	60
over 75.00 (3.00)	(b)	(c)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) 2.25 h plus 15 min for every 12.5 mm (0.5 in.) or increment of 12.5 mm (0.5 in.) over 75 mm (3 in.). (c) 1 h, 5 min plus 5 min for every 12.5 mm (0.5 in.) or increment of 12.5 (0.5 in.) over 75 mm (3 in.). Source: AMS 2759/4

314

Chemical Composition. AISI/UNS (S31400): 0.25 C, 2.00 Mn, 1.50 to 3.00 Si, 23.0 to 26.00 Cr, 19.00 to 22.00 Ni, 0.045 P, 0.030 S

Similar Steels (U.S. and/or Foreign). AMS 5522, 5652; ASTM A276, A314, A473, A580; SAE J405 (30314); (Ger.) DIN 1.4841; (Fr.) AFNOR Z 12 CNS 25.20; (Ital.) UNI X 16 CrNiSi 25 20, X 22 CrNi 25 20; (Jap.) JIS SUS Y 310; (U.K.) B.S. 310 S 24

Characteristics. Highest heat resistance properties of all the chromium-nickel steels. Essentially nonmagnetic. Subject to embrittlement when exposed for long periods of time to temperatures of 650 to 815 °C (1200 to 1500 °F). Brittleness only evident at room temperature and can be eliminated by holding steel at 980 to 1040 °C (1795 to 1905 °F), 1 to 2 h

Forging. Start forging at 1040 to 1120 °C (1905 to 2050 °F). Do not forge after forging stock drops below 925 °C (1695 °F). Cool to black color in less than 3 min, using liquid quench if necessary

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Anneal at 1150 °C (2100 °F). To guard against distortion of thin, delicate parts, leave ample room for expansion between parts. Stainless grades expand about twice as much as carbon and low-alloy steels. Allow enough time for through heating after thermocouple has reached temperature. Stainless grades have approximately half the thermal conductivity of carbon and low-alloy steels. Choice of atmosphere depends on finish desired and whether surface stock will be removed. For bright annealing, use vacuum or an atmosphere of hydrogen or dissociated ammonia at dew point of −62 to −74 °C (−80 to −100 °F). Parts must be thoroughly clean and dry. Inert gases argon and helium (although expensive) and nitrogen, with dew points of less than −54 °C (−65 °F), can be used. They lack the reducing effect of hydrogen, so slight discoloration in the form of chrome oxide can result. Salt, exothermic, or endothermic atmospheres are satisfactory for nonbright annealing. Salt is difficult to remove, and rinse quenching at 595 °C (1105 °F) is not recommended, because interrupted quench at elevated temperature cannot be tolerated. Exothermic and endothermic atmospheres must be carefully controlled at equivalent carbon potential to avoid carburization, which will seriously lower corrosion resistance. Same problem with atmosphere annealing. If oxidizing conditions are present, scale will form. Difficult to remove in subsequent descaling operations.

Cool rapidly from annealing temperature: no more than 3 min to black color. Section size determines quenching medium: water for heavy sections, air blast for intermediate sizes, and still air for thin sections. Carbides can precipitate at grain boundaries when parts are cooled too slowly between 425 to 900 °C (795 to 1650 °F).

In aerospace practice, parts are annealed at a set temperature of 1095 °C (2005 °F) and quenched in water with one exception: parts under 2.5 mm (0.10 in.) thick may be air cooled or polymer quenched to minimize distortion. Parts fabricated from steel in a strain-hardened condition, such as ½ hard, shall not be annealed, stress relieved, or dimensionally stabilized without permission of the cognizant engineering authority. Also, heat treating or slow cooling unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for soaking times

Stress Relieving. Parts can be relieved after quenching to achieve dimensional stability, by heating to 230 to 400 °C (445 to 750 °F) for up to several hours, depending on section size and without change in metallographic structure.

In aerospace practice, parts are stress relieved at 900 °C (1650 °F), and quenched in water. As an alternative, parts may be stress relieved at annealing temperatures. Sections under 2.5 mm (0.10 in.) thick may be air cooled to minimize distortion. Parts fabricated from steel in the strain-hardened condition, such as ½ hard, shall not be stress relieved without permission of the cognizant engineering authority. When stress relieving after welding, hold for 30 min minimum at the stress relieving temperature. Heat treating or slow cooling of unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for soaking times

Nitriding. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners should be replaced with radii of not less than 1.59 mm (0.06 in.). Film of primarily chromium oxide, that protects stainless alloys from oxidation and corrosion, must be removed prior to nitriding. Accomplished by wet blasting, pickling, chemical reduction in reducing atmosphere, submersion in molten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid con-

:amination of surface by finger or hand marking. Single-stage nitriding ıdequate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h (depending on :ase depth required). Dissociation rates for single-stage cycle are from 20 o 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle ›roduces case extending to 0.127 mm (0.005 in.) with approximately 800 o 1000 HK. Case will rapidly drop to 200 HK core hardness, at approxi-nately 0.165 mm (0.0065 in.)

Recommended Processing Sequence

- Cold work
- Anneal and quench
- Remove surface contamination (if required)
- Stress relieve
- Depassivate (if nitriding)
- Nitride (if required)

314: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time	
	Atmosphere furnace min	Salt bath min
up to 2.50 (0.100)	20	17
over 2.50 to 6.25 (0.100 to 0.250)	25	18
over 6.25 to 12.50 (0.259 to 0.500)	45	35
over 12.50 to 25.00 (0.500 to 1.00)	60	40
over 25.00 to 37.50 (1.00 to 1.50)	75	45
over 37.50 to 50.00 (1.50 to 2.00)	90	50
over 50.00 to 62.50 (2.00 to 2.50)	105	55
over 62.50 to 75.00 (2.50 to 3.00)	120	60
over 75.00 (3.00)	(b)	(c)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) 2.25 h plus 15 min for every 12.5 mm (0.5 in.) or increment of 12.5 mm (0.5 in.) over 75 mm (3 in.). (c) 1 h, 5 min plus 5 min for every 12.5 mm (0.5 in.) or increment of 12.5 (0.5 in.) over 75 mm (3 in.). Source: AMS 2759/4

316

Chemical Composition. **AISI/UNS (S31600):** 0.08 C, 2.00 Mn, .00 Si, 16.00 to 18.00 Cr, 10.00 to 14.00 Ni, 0.045 P, 0.030 S, 2.00 to 3.00 Mo

Similar Steels (U.S. and/or Foreign). AMS 5524, 5573, 5648, 690, 5691; ASME SA182, SA193, SA194, SA213, SA240, SA249, A312, SA320, SA358, SA376, SA403, SA409, SA430, SA479, SA688; ASTM A167, A182, , A193, A194, A213, A240, A249, A269, A276, A312, A313, A314, A320, A358, A368, A376, A403, A409, A430, A473, A478, A479; FED QQ-S-763, QQ-S-766, QQ-W-423; MIL SPEC MIL-S-862, MIL-S-5059; SAE J405 (30316); (Ger.) DIN 1.4401; (Fr.) AFNOR Z 6 ND 17.11; (Ital.) UNI X 5 CrNiMo 17 12; (Jap.) JIS SUS 316, SUH 309, US Y 316; (Swed.) SS_{14} 2347; (U.K.) B.S. 316 S 16, 316 S 18, 316 S 25, 16 S 26, 316 S 30, 316 S 40, 316 S 41, En. 58 H

Characteristics. Superior corrosion resistance vs other chromium-ickel steels, when exposed to many types of chemical corrodents as well s marine atmospheres. Superior creep strength at elevated temperatures. 'ery resistant to corrosion by sulfuric acid

Forging. Start forging at 1150 to 1260 °C (2100 to 2300 °F). Do not ›rge after forging stock drops below 925 °C (1695 °F). Cool to black color ı less than 3 min, using liquid quench if necessary

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Anneal at 1040 to 1120 °C (1905 to 2050 °F). Within this ınge, lower temperatures are sufficient for sheet and strip, but higher :mperatures should be used for plates and bars. To guard against distortion f thin, delicate parts, leave ample room for expansion between parts. tainless grades expand about twice as much as carbon and low-alloy eels. Allow enough time for through heating after thermocouple has :ached temperature. Stainless grades have approximately half the thermal ›nductivity of carbon and low-alloy steels. Choice of atmosphere depends ı finish desired and whether surface stock will be removed. For bright ınealing, use vacuum or an atmosphere of hydrogen or dissociated ammo-a at dew point of −62 to −74 °C (−80 to −100 °F). Parts must be thoroughly ean and dry. Inert gases argon and helium (although expensive) and trogen, with dew points of less than −54 °C (−65 °F), can be used. They ck the reducing effect of hydrogen, so slight discoloration in the form of ırome oxide can result. Salt, exothermic, or endothermic atmospheres are .tisfactory for nonbright annealing. Salt is difficult to remove, and rinse quenching at 595 °C (1105 °F) is not recommended, because interrupted quench at elevated temperature cannot be tolerated. Exothermic and endothermic atmospheres must be carefully controlled at equivalent carbon potential to avoid carburization, which will seriously lower corrosion resistance. Same problem with atmosphere annealing. If oxidizing conditions are present, scale will form. Difficult to remove in subsequent descaling operations.

Cool rapidly from annealing temperature; no more than 3 min to black color. Section size determines quenching medium: water for heavy sections, air blast for intermediate sizes, and still air for thin sections. Carbides can precipitate at grain boundaries when parts are cooled too slowly between 425 to 900 °C (795 to 1650 °F).

In aerospace practice, parts are annealed at a set temperature of 1095 °C (2005 °F) and quenched in water with one exception: parts under 2.5 mm (0.10 in.) thick may be air cooled or polymer quenched to minimize distortion. Parts fabricated from steel in a strain-hardened condition, such as ½ hard, shall not be annealed, stress relieved, or dimensionally stabilized without permission of the cognizant engineering authority. Also, heat treating or slow cooling unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for soaking times

Stress Relieving. Parts can be relieved after quenching to achieve dimensional stability, by heating to 230 to 400 °C (445 to 750 °F) for up to several hours, depending on section size and without change in metallographic structure.

In aerospace practice, parts are stress relieved at 900 °C (1650 °F), and quenched in water. As an alternative, parts may be stress relieved at annealing temperatures. Sections under 2.5 mm (0.10 in.) thick may be air cooled to minimize distortion. Parts fabricated from steel in the strain-hardened condition, such as ½ hard, shall not be stress relieved without permission of the cognizant engineering authority. When stress relieving after welding, hold for 30 min minimum at the stress relieving temperature. Heat treating or slow cooling of unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for soaking times

Nitriding. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners should be replaced with radii of not less than 1.59 mm (0.06 in.). Film of primarily chromium oxide, that protects stainless alloys from oxidation and corrosion, must be removed prior to nitriding. Accomplished by wet blasting, pickling, chemical reduction in reducing atmosphere, submersion in molten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid contamination of surface by finger or hand marking. Single-stage nitriding adequate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h (depending on case depth required). Dissociation rates for single-stage cycle are from 20 to 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle produces case extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

Recommended Processing Sequence

- Cold work
- Anneal and quench
- Remove surface contamination (if required)
- Stress relieve
- Depassivate (if nitriding)
- Nitride (if required)

316: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time: Atmosphere furnace min	Minimum soaking time: Salt bath min
up to 2.50 (0.100)	20	17
over 2.50 to 6.25 (0.100 to 0.250)	25	18
over 6.25 to 12.50 (0.259 to 0.500)	45	35
over 12.50 to 25.00 (0.500 to 1.00)	60	40
over 25.00 to 37.50 (1.00 to 1.50)	75	45
over 37.50 to 50.00 (1.50 to 2.00)	90	50
over 50.00 to 62.50 (2.00 to 2.50)	105	55
over 62.50 to 75.00 (2.50 to 3.00)	120	60
over 75.00 (3.00)	(b)	(c)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) 2.25 h plus 15 min for every 12.5 mm (0.5 in.) or increment of 12.5 mm (0.5 in.) over 75 mm (3 in.). (c) 1 h, 5 min plus 5 min for every 12.5 mm (0.5 in.) or increment of 12.5 (0.5 in.) over 75 mm (3 in.). Source: AMS 2759/4

316F

Chemical Composition. AISI/UNS (S20100): 0.08 C, 2.00 Mn, 1.00 Si, 16.00 to 18.00 Cr, 10.00 to 14.00 Ni, 0.200 P, 0.100 S min, 1.75 to 2.50 Mo

Similar Steels (U.S. and/or Foreign). AMS 5649

Characteristics. Similar to type 316, except elements have been added to improve machining and nonseizing characteristics. Suitable for automatic screw machines

Forging. Start forging at 1205 °C (2200 °F). Do not forge after forging stock drops below 925 °C (1695 °F). Cool to black color in less than 3 min, using liquid quench if necessary

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Anneal at 1095 °C (2005 °F). To guard against distortion of thin, delicate parts, leave ample room for expansion between parts. Stainless grades expand about twice as much as carbon and low-alloy steels. Allow enough time for through heating after thermocouple has reached temperature. Stainless grades have approximately half the thermal conductivity of carbon and low-alloy steels. Choice of atmosphere depends on finish desired and whether surface stock will be removed. For bright annealing, use vacuum or an atmosphere of hydrogen or dissociated ammonia at dew point of –62 to –74 °C (–80 to –100 °F). Parts must be thoroughly clean and dry. Inert gases argon and helium (although expensive) and nitrogen, with dew points of less than –54 °C (–65 °F), can be used. They lack the reducing effect of hydrogen, so slight discoloration in the form of chrome oxide can result. Salt, exothermic, or endothermic atmospheres are satisfactory for nonbright annealing. Salt is difficult to remove, and rinse quenching at 595 °C (1105 °F) is not recommended, because interrupted quench at elevated temperature cannot be tolerated. Exothermic and endothermic atmospheres must be carefully controlled at equivalent carbon potential to avoid carburization, which will seriously lower corrosion resistance. Same problem with atmosphere annealing. If oxidizing conditions are present, scale will form. Difficult to remove in subsequent descaling operations.

Cool rapidly from annealing temperature; no more than 3 min to black color. Section size determines quenching medium: water for heavy sections, air blast for intermediate sizes, and still air for thin sections. Carbides can precipitate at grain boundaries when parts are cooled too slowly between 425 to 900 °C (795 to 1650 °F).

In aerospace practice, parts are annealed at a set temperature of 1095 °C (2005 °F) and quenched in water with one exception: parts under 2.5 mm (0.10 in.) thick may be air cooled or polymer quenched to minimize distortion. Parts fabricated from steel in a strain-hardened condition, such as ½ hard, shall not be annealed, stress relieved, or dimensionally stabilized without permission of the cognizant engineering authority. Also, heat treating or slow cooling unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for soaking times

Stress Relieving. Parts can be relieved after quenching to achieve dimensional stability, by heating to 230 to 400 °C (445 to 750 °F) for up to several hours, depending on section size and without change in metallographic structure.

In aerospace practice, parts are stress relieved at 900 °C (1650 °F), and quenched in water. As an alternative, parts may be stress relieved at annealing temperatures. Sections under 2.5 mm (0.10 in.) thick may be air cooled to minimize distortion. Parts fabricated from steel in the strain-hardened condition, such as ½ hard, shall not be stress relieved without permission of the cognizant engineering authority. When stress relieving after welding, hold for 30 min minimum at the stress relieving temperature. Heat treating or slow cooling of unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for soaking times

Nitriding. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners should be replaced with radii of not less than 1.59 mm (0.06 in.). Film of primarily chromium oxide, that protects stainless alloys from oxidation and corrosion, must be removed prior to nitriding. Accomplished by wet blasting, pickling, chemical reduction in reducing atmosphere, submersion in molten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid contamination of surface by finger or hand marking. Single-stage nitriding adequate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h (depending on case depth required). Dissociation rates for single-stage cycle areE from 20 to 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle produces case extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

Recommended Processing Sequence

- Cold work
- Anneal and quench
- Remove surface contamination (if required)
- Stress relieve
- Depassivate (if nitriding)
- Nitride (if required)

316F: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time(b)	
	Atmosphere furnace min	Salt bath min
up to 2.50 (0.100)	40	37
over 2.50 to 6.25 (0.100 to 0.250)	45	38
over 6.25 to 12.50 (0.259 to 0.500)	65	55
over 12.50 to 25.00 (0.500 to 1.00)	80	60
over 25.00 to 37.50 (1.00 to 1.50)	95	65
over 37.50 to 50.00 (1.50 to 2.00)	110	70
over 50.00 to 62.50 (2.00 to 2.50)	125	75
over 62.50 to 75.00 (2.50 to 3.00)	140	80
over 75.00 (3.00)	(c)	(d)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) Parts should be held for sufficient time to ensure that center of most massive section has reached temperature and necessary transformation and diffusion have taken place. (c) 2 h, 35 min plus 15 min for every 12.5 mm (0.50 in.) or increment of 12.50 mm (0.50 in.) over 75.0 mm (3 in.). (d) 1 h, 25 min plus 5 min for every 12.50 mm (0.50 in.) or increment of 12.5 mm (0.50 in.) over 75.0 mm (3 in.). Source: AMS 2759/4

316H

:hemical Composition. AISI/UNS: 0.04 to 0.10 C, 2.00 Mn, 1.00 ;i, 16.00 to 18.00 Cr, 10.00 to 14.00 Ni, 0.045 P, 0.035 S, 2.00 to 3.00 Mo

ecommended Heat Treating Practice

nnealing. In aerospace practice, parts are annealed at a set temperature f 1095 °C (2005 °F) and quenched in water with one exception: parts nder 2.5 mm (0.10 in.) thick may be air cooled or polymer quenched to ninimize distortion. Parts fabricated from steel in a strain-hardened condion, such as ½ hard, shall not be annealed, stress relieved, or dimensionlly stabilized without permission of the cognizant engineering authority. lso, heat treating or slow cooling unstabilized grades between 470 to 815 C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for oaking times

tress Relieving. In aerospace practice, parts are stress relieved at 00 °C (1650 °F), and quenched in water. As an alternative, parts may be ress relieved at annealing temperatures. Sections under 2.5 mm (0.10 in.) ick may be air cooled to minimize distortion. Parts fabricated from steel the strain hardened condition, such as ½ hard, shall not be stress relieved ithout permission of the cognizant engineering authority. When stress lieving after welding, hold for 30 min minimum at the stress relieving mperature. Heat treating or slow cooling of unstabilized grades between 70 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. e table for soaking times

316H: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time(b)	
	Atmosphere furnace min	Salt bath min
up to 2.50 (0.100)	40	37
over 2.50 to 6.25 (0.100 to 0.250)	45	38
over 6.25 to 12.50 (0.259 to 0.500)	65	55
over 12.50 to 25.00 (0.500 to 1.00)	80	60
over 25.00 to 37.50 (1.00 to 1.50)	95	65
over 37.50 to 50.00 (1.50 to 2.00)	110	70
over 50.00 to 62.50 (2.00 to 2.50)	125	75
over 62.50 to 75.00 (2.50 to 3.00)	140	80
over 75.00 (3.00)	(c)	(d)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) Parts should be held for sufficient time to ensure that center of most massive section has reached temperature and necessary transformation and diffusion have taken place. (c) 2 h, 35 min plus 15 min for every 12.5 mm (0.50 in.) or increment of 12.50 mm (0.50 in.) over 75.0 mm (3 in.). (d) 1 h, 25 min plus 5 min for every 12.50 mm (0.50 in.) or increment of 12.5 mm (0.50 in.) over 75.0 mm (3 in.). Source: AMS 2759/4

16L

hemical Composition. AISI/UNS (S31603): 0.030 C, 2.00 Mn, 00 Si, 16.00 to 18.00 Cr, 10.00 to 14.00 Ni, 0.045 P, 0.030 S, 2.00 to 3.00 o

imilar Steels (U.S. and/or Foreign). AMS 5507, 5653; ASME 182, SA213, SA240, SA249, SA312, SA403, SA479, SA688; ASTM 167, A182, A213, A240, A249, A269, A276, A312, A314, A403, A473, 178, A479, A511, A554, A580, A632, A688; FED QQ-S-763, QQ-S-766; MIL SPEC MIL-S-862; SAE J405 (30316 L); (Ger.) DIN 1.4404; (Fr.) AFNOR Z 2 CND 17.12; (Ital.) UNI X 2 CrNiMo 17 12; (Jap.) JIS SUS 316 L, SUH 310; (Swed.) SS_{14} 2348; (U.K.) B.S. 316 S 12, 316 S 14. 316 S 22, 316 S 24, 316 S 29, 316 S 30, 316 S 31, 316 S 37, 316 S 82, S. 537

Characteristics. Similar to type 316, except more resistant to intergranular corrosion after welding or stress relieving. Recommended for parts which are fabricated by welding and cannot be subsequently annealed. Generally limited to service temperatures up to 425 °C (800 °F)

Forging. Start forging at 1150 to 1260 °C (2100 to 2300 °F). Do not forge after forging stock drops below 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Anneal at 1040 to 1105 °C (1905 to 2025 °F). Use 1040 °C (1905 °F) minimum for maximum ductility. Parts can be air cooled from annealing temperature. Water quenching not necessary. Slow cooling can occur through the 815 to 425 °C (1500 to 795 °F) range for up to 2 h, without subsequent danger of susceptibility to intergranular corrosion in natural atmospheric environments.

In aerospace practice, parts are annealed at a set temperature of 1095 °C (2005 °F) and quenched in water with one exception: parts under 2.5 mm (0.10 in.) thick may be air cooled or polymer quenched to minimize distortion. Parts fabricated from steel in a strain-hardened condition, such as ½ hard, shall not be annealed, stress relieved, or dimensionally stabilized without permission of the cognizant engineering authority. Also, heat treating or slow cooling unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for soaking times

Stress Relieving. In aerospace practice, parts are stress relieved at 900 °C (1650 °F), and quenched in water. As an alternative, parts may be stress relieved at annealing temperatures. Sections under 2.5 mm (0.10 in.) thick may be air cooled to minimize distortion. Parts fabricated from steel in the strain-hardened condition, such as ½ hard, shall not be stress relieved without permission of the cognizant engineering authority. When stress relieving after welding, hold for 30 min minimum at the stress relieving temperature. Heat treating or slow cooling of unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for soaking times

Stabilizing. Because type 316L contains molybdenum, it is susceptible to sigma-phase formation as a result of long exposure at 650 to 870 °C (1200 to 1600 °F). Corrosion resistance improved by employing a stabilizing treatment (ASTM A262C), consisting of holding at 885 °C (1625 °F) for 2 h prior to stress relieving at 675 °C (1245 °F)

Nitriding. Rare. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners should be replaced with radii of not less than 1.59 mm (0.06 in.). Film of primarily chromium oxide, that protects stainless alloys from oxidation and corrosion, must be removed prior to nitriding. Accomplished by wet blasting, pickling, chemical reduction in reducing atmosphere, submersion in molten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid contamination of surface by finger or hand marking. Single-stage nitriding adequate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h (depending on case depth required). Dissociation rates for single-stage cycle are from 20 to 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle produces case extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

Recommended Processing Sequence

- Cold work
- Anneal and cool
- Stabilize and stress relieve (if necessary)
- Depassivate (if nitriding)
- Nitride (if required)

316L: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time Atmosphere furnace min	Salt bath min
up to 2.50 (0.100)	20	17
over 2.50 to 6.25 (0.100 to 0.250)	25	18
over 6.25 to 12.50 (0.259 to 0.500)	45	35
over 12.50 to 25.00 (0.500 to 1.00)	60	40
over 25.00 to 37.50 (1.00 to 1.50)	75	45
over 37.50 to 50.00 (1.50 to 2.00)	90	50
over 50.00 to 62.50 (2.00 to 2.50)	105	55
over 62.50 to 75.00 (2.50 to 3.00)	120	60
over 75.00 (3.00)	(b)	(c)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) 2.25 h plus 15 min for every 12.5 mm (0.5 in.) or increment of 12.5 mm (0.5 in.) over 75 mm (3 in.). (c) 1 h, 5 min plus 5 min for every 12.5 mm (0.5 in.) or increment of 12.5 (0.5 in.) over 75 mm (3 in.). Source: AMS 2759/4

316N

Chemical Composition. AISI/UNS (S31651): 0.08 C, 2.00 Mn, 1.00 Si, 16.00 to 18.00 Cr, 10.00 to 14.00 Ni, 0.045 P, 0.03 S, 2.00 to 3.00 Mo, 0.10 to 0.16 N

Similar Steels (U.S. and/or Foreign). ASME SA182, SA213, SA240, SA249, SA312, SA358, SA376, SA403, SA430, SA479; ASTM A182, A213, A240, A249, A276, A312, A358, A376, A403, A430, A479

Characteristics. Has added nitrogen, which increases strength without affecting ductility and corrosion resistance

Forging. Start forging at 1150 to 1260 °C (2100 to 2300 °F). Do not forge after forging stock drops below 925 °C (1695 °F). Cool to black color in less than 3 min, using liquid quench if necessary

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Anneal at 1010 to 1120 °C (1850 to 2050 °F). To guard against distortion of thin, delicate parts, leave ample room for expansion between parts. Stainless grades expand about twice as much as carbon and low-alloy steels. Allow enough time for through heating after thermocouple has reached temperature. Stainless grades have approximately half the thermal conductivity of carbon and low-alloy steels. Choice of atmosphere depends on finish desired and whether surface stock will be removed. For bright annealing, use vacuum or an atmosphere of hydrogen or dissociated ammonia at dew point of –62 to –74 °C (–80 to –100 °F). Parts must be thoroughly clean and dry. Inert gases argon and helium (although expensive) and nitrogen, with dew points of less than –54 °C (–65 °F), can be used. They lack the reducing effect of hydrogen, so slight discoloration in the form of chrome oxide can result. Salt, exothermic, or endothermic atmospheres are satisfactory for nonbright annealing. Salt is difficult to remove, and rinse quenching at 595 °C (1105 °F) is not recommended, because interrupted quench at elevated temperature cannot be tolerated. Exothermic and endothermic atmospheres must be carefully controlled at

:quivalent carbon potential to avoid carburization, which will seriously ower corrosion resistance. Same problem with atmosphere annealing. If ›xidizing conditions are present, scale will form. Difficult to remove in ubsequent descaling operations.

Cool rapidly from annealing temperature; no more than 3 min to black olor. Section size determines quenching medium: water for heavy sec-.ons, air blast for intermediate sizes, and still air for thin sections. Carbides an precipitate at grain boundaries when parts are cooled too slowly etween 425 to 900 °C (795 to 1650 °F).

In aerospace practice, parts are annealed at a set temperature of 1095 C (2000 °F) and quenched in air, oil, polymer, or water. Sections over 6.25 ım (0.25 in.) thick should be water quenched to minimize distortion. Parts ıbricated from steel in a strain-hardened condition should not be annealed, ress relieved, or dimensionally stabilized without permission of the cog-izant engineering authority. Heat treating or slow cooling of unstabilized rades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for)4L and 316L. See table for soaking times

tress Relieving. Parts can be relieved after quenching to achieve mensional stability, by heating to 230 to 400 °C (445 to 750 °F) for up to :veral hours, depending on section size and without change in metal-graphic structure

itriding. Not recommended. Case seriously impairs corrosion resis-nce in most media. Case seldom more than 0.127 mm (0.005 in.) deep. nly used in specialized applications where material must be nonmagnetic .d have wear-resistant surface. If nitrided, parts must be in annealed ndition to prevent flaking or blistering of nitrided case. All sharp corners ould be replaced with radii of not less than 1.59 mm (0.06 in.). Film of imarily chromium oxide, that protects stainless alloys from oxidation and rrosion, must be removed prior to nitriding. Accomplished by wet blast-ȝ, pickling, chemical reduction in reducing atmosphere, submersion in)lten salt, or by one of several proprietary processes. If doubt exists that mplete and uniform depassivation has occurred, further reduction of the ide may be accomplished in furnace by means of reducing hydrogen nosphere or suitable proprietary agent. After depassivation, avoid con-nination of surface by finger or hand marking. Single-stage nitriding adequate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h (depending on case depth required). Dissociation rates for single-stage cycle are from 20 to 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle produces case extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

Recommended Processing Sequence

- Cold work
- Anneal and quench
- Remove surface contamination (if required)
- Stress relieve
- Depassivate (if nitriding)
- Nitride (if required)

316N: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time(b) Atmosphere furnace min	Salt bath min
up to 2.50 (0.100)	40	37
over 2.50 to 6.25 (0.100 to 0.250)	45	38
over 6.25 to 12.50 (0.259 to 0.500)	65	55
over 12.50 to 25.00 (0.500 to 1.00)	80	60
over 25.00 to 37.50 (1.00 to 1.50)	95	65
over 37.50 to 50.00 (1.50 to 2.00)	110	70
over 50.00 to 62.50 (2.00 to 2.50)	125	75
over 62.50 to 75.00 (2.50 to 3.00)	140	80
over 75.00 (3.00)	(c)	(d)

(q) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) Parts should be held for sufficient time to ensure that center of most massive section has reached temperature and necessary transformation and diffusion have taken place. (c) 2 h, 35 min plus 15 min for every 12.5 mm (0.50 in.) or increment of 12.50 mm (0.50 in.) over 75.0 mm (3 in.). (d) 1 h, 25 min plus 5 min for every 12.50 mm (0.50 in.) or increment of 12.5 mm (0.50 in.) over 75.0 mm (3 in.). Source: AMS 2759/4

16LN

ıemical Composition. **AISI/UNS:** 0.03 C, 2.00 Mn, 1.00 Si, 00 to 18.00 Cr, 10.00 to 14.00 Ni, 0.045 P, 0.035 S, 2.00 to 3.00 Mo, 0 to 0.16 N

:commended Heat Treating Practice

nealing. In aerospace practice, parts are annealed at a set temperature 1095 °C (2005 °F) and quenched in water with one exception: parts .er 2.5 mm (0.10 in.) thick may be air cooled or polymer quenched to :imize distortion. Parts fabricated from steel in a strain-hardened condi-., such as ½ hard, shall not be annealed, stress relieved, or dimension-stabilized without permission of the cognizant engineering authority. ɔ, heat treating or slow cooling unstabilized grades between 470 to 815 ;875 to 1500 °F) is prohibited, except for 304L and 316L. See table for ‹ing times

ess Relieving. In aerospace practice, parts are stress relieved at °C (1650 °F), and quenched in water. As an alternative, parts may be ;s relieved at annealing temperatures. Sections under 2.5 mm (0.10 in.) ‹ may be air cooled to minimize distortion. Parts fabricated from steel e strain-hardened condition, such as ½ hard, shall not be stress relieved out permission of the cognizant engineering authority. When stress ving after welding, hold for 30 min minimum at the stress relieving ›erature. Heat treating or slow cooling of unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L. See table for soaking times

316LN: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time(b) Atmosphere furnace min	Salt bath min
up to 2.50 (0.100)	40	37
over 2.50 to 6.25 (0.100 to 0.250)	45	38
over 6.25 to 12.50 (0.259 to 0.500)	65	55
over 12.50 to 25.00 (0.500 to 1.00)	80	60
over 25.00 to 37.50 (1.00 to 1.50)	95	65
over 37.50 to 50.00 (1.50 to 2.00)	110	70
over 50.00 to 62.50 (2.00 to 2.50)	125	75
over 62.50 to 75.00 (2.50 to 3.00)	140	80
over 75.00 (3.00)	(c)	(d)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) Parts should be held for sufficient time to ensure that center of most massive section has reached temperature and necessary transformation and diffusion have taken place. (c) 2 h, 35 min plus 15 min for every 12.5 mm (0.50 in.) or increment of 12.50 mm (0.50 in.) over 75.0 mm (3 in.). (d) 1 h, 25 min plus 5 min for every 12.50 mm (0.50 in.) or increment of 12.5 mm (0.50 in.) over 75.0 mm (3 in.). Source: AMS 2759/4

317

Chemical Composition. AISI/UNS (S31700): 0.08 C, 2.00 Mn, 1.00 Si, 18.00 to 20.00 Cr, 11.00 to 15.00 Ni, 0.045 P, 0.03 S, 3.00 to 4.00 Mo

Similar Steels (U.S. and/or Foreign). ASME SA240, SA249, SA312, SA403, SA409; ASTM A167, A249, A269, A276, A312, A314, A403, A409, A473, A478, A511, A554, A580, A632; FED QQ-S-763; MIL SPEC MIL-S-862; SAE J405; (Ger.) DIN 1.4449; (Ital.) UNI X 5 CrNiMo 18 15; (Jap.) JIS SUS 317

Characteristics. Exhibits excellent corrosion resistance in special applications, especially where pitting corrosion is a problem

Forging. Start forging at 1150 to 1260 °C (2100 to 2300 °F). Do not forge after forging stock drops below 925 °C (1695 °F). Cool to black color in less than 3 min, using liquid quench if necessary

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Anneal at 1010 to 1120 °C (1850 to 2050 °F). To guard against distortion of thin, delicate parts, leave ample room for expansion between parts. Stainless grades expand about twice as much as carbon and low-alloy steels. Allow enough time for through heating after thermocouple has reached temperature. Stainless grades have approximately half the thermal conductivity of carbon and low-alloy steels. Choice of atmosphere depends on finish desired and whether surface stock will be removed. For bright annealing, use vacuum or an atmosphere of hydrogen or dissociated ammonia at dew point of –62 to –74 °C (–80 to –100 °F). Parts must be thoroughly clean and dry. Inert gases argon and helium (although expensive) and nitrogen, with dew points of less than –54 °C (–65 °F), can be used. They lack the reducing effect of hydrogen, so slight discoloration in the form of chrome oxide can result. Salt, exothermic, or endothermic atmospheres are satisfactory for nonbright annealing. Salt is difficult to remove, and rinse quenching at 595 °C (1105 °F) is not recommended, because interrupted quench at elevated temperature cannot be tolerated. Exothermic and endothermic atmospheres must be carefully controlled at equivalent carbon potential to avoid carburization, which will seriously lower corrosion resistance. Same problem with atmosphere annealing. If oxidizing conditions are present, scale will form. Difficult to remove in subsequent descaling operations.

Cool rapidly from annealing temperature; no more than 3 min to black color. Section size determines quenching medium: water for heavy sections, air blast for intermediate sizes, and still air for thin sections. Carbides can precipitate at grain boundaries when parts are cooled too slowly between 425 to 900 °C (795 to 1650 °F)

Stress Relieving. Parts can be relieved after quenching to achieve dimensional stability, by heating to 230 to 400 °C (445 to 750 °F) for up to several hours, depending on section size and without change in metallographic structure

Nitriding. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners should be replaced with radii of not less than 1.59 mm (0.06 in.). Film of primarily chromium oxide, that protects stainless alloys from oxidation and corrosion, must be removed prior to nitriding. Accomplished by wet blasting, pickling, chemical reduction in reducing atmosphere, submersion in molten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid contamination of surface by finger or hand marking. Single-stage nitriding adequate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h (depending on case depth required). Dissociation rates for single-stage cycle are from 20 to 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle produces case extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

Recommended Processing Sequence

- Cold work
- Anneal and quench
- Remove surface contamination (if required)
- Stress relieve
- Depassivate (if nitriding)
- Nitride (if required)

317L

Chemical Composition. AISI/UNS (S31703): 0.03 C, 2.00 Mn, 1.00 Si, 18.00 to 20.00 Cr, 11.00 to 15.00 Ni, 0.045 P, 0.03 S, 3.00 to 4.00 Mo

Similar Steels (U.S. and/or Foreign). ASME SA240; ASTM A167, A240; (Ger.) DIN 1.4438; (Fr.) AFNOR Z 2 CND 19.5; (Swed.) SS14 2367; (U.K.) B.S. 317 S 12

Characteristics. Similar to type 317, except more resistant to intergranular corrosion after welding or stress relieving. Recommended for parts which are fabricated by welding and cannot be subsequently annealed. Generally limited to service temperatures up to 425 °C (795 °F)

Forging. Start forging at 1230 °C (2245 °F). Do not forge after forging stock drops below 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Anneal at 1040 to 1105 °C (1905 to 2025 °F). Use 1040 °C (1905 °F) minimum for maximum ductility. Parts can be air cooled from annealing temperature. Water quenching not necessary. Slow cooling can occur through the 815 to 425 °C (1500 to 795 °F) range for up to 2 h, without subsequent danger of susceptibility to intergranular corrosion in natural atmospheric environments

Stabilizing. Because type 317L contains molybdenum, it is susceptible to sigma-phase formation as a result of long exposure at 650 to 870 °C (1200 to 1600 °F). Corrosion resistance improved by employing a stabilizing treatment (ASTM A262C), consisting of holding at 885 °C (1625 °F) for 2 h prior to stress relieving at 675 °C (1245 °F)

Nitriding. Rare. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners should be replaced with radii of not less than 1.59 mm (0.06

ı.). Film of primarily chromium oxide, that protects stainless alloys from xidation and corrosion, must be removed prior to nitriding. Accomplished y wet blasting, pickling, chemical reduction in reducing atmosphere, ıbmersion in molten salt, or by one of several proprietary processes. If oubt exists that complete and uniform depassivation has occurred, further :duction of the oxide may be accomplished in furnace by means of :ducing hydrogen atmosphere or suitable proprietary agent. After depas-vation, avoid contamination of surface by finger or hand marking. Single-age nitriding adequate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h lepending on case depth required). Dissociation rates for single-stage /cle are from 20 to 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle produces case extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

Recommended Processing Sequence

- Cold work
- Anneal and cool
- Stabilize and stress relieve (if necessary)
- Depassivate (if nitriding)
- Nitride (if required)

321

hemical Composition. **AISI/UNS (S32100):** 0.08 C, 2.00 Mn, 00 Si, 17.00 to 19.00 Cr, 9.00 to 12.00 Ni, 0.045 P, 0.03 S, 5 × %C Ti min

imilar Steels (U.S. and/or Foreign). AMS 5510, 5557, 5559, 570, 5576, 5645, 5689; ASME SA182, SA193, SA194, SA213, SA240, A249, SA312, SA320, SA358, SA376, SA403, SA409, SA430, SA479; STM A167, A182, A193, A194, A213, A240, A249, A269, A271, A276, 312, A314, A320, A358, A376, A403, A409, A430, A473, A479, A493, 511; FED QQ-S-763, QQ-S-766, QQ-W-423; MIL SPEC MIL-S-862; AE J405 (31321); (Ger.) DIN 1.4541; (Fr.) AFNOR Z 6 CNT 18.10; (Ital.) NI X 6 CrNiTi 18 11, X 6 CrNiTi 18 11 KG, X 6 CrNiTi 18 11 KW, X 6 rNiTi 18 11 KT, ICL 472 T; (Jap.) JIS SUS 321; (Swed.) SS_{14} 2337; J.K.) B.S. CDS-20, 321 S 12, 321 S 18, 321 S 22, 321 S 27, 321 S 40, 321 49, 321 S 50, 321 S 59, 321 S 87, En. 58 C

haracteristics. Stabilized by the addition of titanium, this grade is :arly immune to intergranular precipitation of chromium carbide and its lverse effect on corrosion resistance. Recommended for parts which will : fabricated by welding and cannot be subsequently annealed. Recom-ended for use between 425 to 900 °C (795 to 1650 °F). Not recommended r decorative use. Hardenable by cold work only. To impart maximum ırrosion resistance, use a stabilizing anneal in addition to annealing and :ess relieving

orging. Start forging at 1150 to 1260 °C (2100 to 2300 °F). Do not rge after forging stock drops below 925 °C (1695 °F)

ecommended Heat Treating Practice

ormalizing. Do not normalize

nnealing. Anneal at 955 to 1120 °C (1750 to 2050 °F) to relieve :esses, increase softness and ductility, or to provide additional stabiliza-ın. See comments on protective atmospheres for annealing for type 201. oes not require water quenching. To ensure maximum retention of stenite, oil or water quench sections thicker than 6.4 mm (0.25 in.).

In aerospace practice, parts are annealed at 980 °C (1795 °F) and ıenched in air, oil, polymer or water. Sections over 6.25 mm (0.25 in.) ick should be water quenched to minimize distortion. Parts fabricated om steel in a strain-hardened condition, such as ½ hard, shall not be nealed, stress relieved, or dimensionally stabilized without permission of : cognizant engineering authority. See table for soaking times

Stress Relieving. In aerospace practice, parts are stress relieved at 900 °C (1650 °F), then quenched in air, polymer, or water. When stress relieving after welding, parts are held 30 min minimum at the annealing temperature, or 2 h minimum at the stress relieving temperature (see table for soaking times). Sections over 6.25 mm (0.25 in.) thick should be water quenched to minimize carbide precipitation. Heat treating or slow cooling of unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L

Stabilizing. For maximum corrosion resistance, use corrective stabilizing anneal by holding at 845 to 900 °C (1555 to 1650 °F) up to 5 h, depending on section thickness. Process applied before or during fabrication. May be followed by stress relieving at 705 °C (1300 °F) for a short time without harmful carbide precipitation

Nitriding. Optional. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners should be replaced with radii of not less than 1.59 mm (0.06 in.). Film of primarily chromium oxide, that protects stainless alloys from oxidation and corrosion, must be removed prior to nitriding. Accomplished by wet blasting, pickling, chemical reduction in reducing atmosphere, submersion in molten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid contamination of surface by finger or hand marking. Single-stage nitriding adequate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h (depending on case depth required). Dissociation rates for single-stage cycle are from 20 to 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle produces case extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

Recommended Processing Sequence

- Cold work
- Anneal and cool
- Stabilize and stress relieve (optional)
- Depassivate (if nitriding)
- Nitride (if necessary)

321: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time(b) Atmosphere furnace min	Salt bath min
up to 2.50 (0.100)	40	37
over 2.50 to 6.25 (0.100 to 0.250)	45	38
over 6.25 to 12.50 (0.259 to 0.500)	65	55
over 12.50 to 25.00 (0.500 to 1.00)	80	60
over 25.00 to 37.50 (1.00 to 1.50)	95	65
over 37.50 to 50.00 (1.50 to 2.00)	110	70
over 50.00 to 62.50 (2.00 to 2.50)	125	75
over 62.50 to 75.00 (2.50 to 3.00)	140	80
over 75.00 (3.00)	(c)	(d)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) Parts should be held for sufficient time to ensure that center of most massive section has reached temperature and necessary transformation and diffusion have taken place. (c) 2 h, 35 min plus 15 min for every 12.5 mm (0.50 in.) or increment of 12.50 mm (0.50 in.) over 75.0 mm (3 in.). (d) 1 h, 25 min plus 5 min for every 12.50 mm (0.50 in.) or increment of 12.5 mm (0.50 in.) over 75.0 mm (3 in.). Source: AMS 2759/4

321H

Chemical Composition. UNS (S32109): 0.04 to 0.10 C, 2.00 Mn, 1.00 Si, 17.00 to 19.00 Cr, 9.00 to 12.00 Ni, 0.045 P, 0.03 S, 5 × %C Ti min

Recommended Heat Treating Practice

Annealing. In aerospace practice, parts are annealed at 980 °C (1795 °F) and quenched in air, oil, polymer, or water. Sections over 6.25 mm (0.25 in.) thick should be water quenched to minimize carbide precipitation. In stress relieving after welding, parts are held 30 min minimum at the annealing temperature, or 2 h minimum at the stress relieving temperature (see table for holding times). Parts fabricated from steel in a strain-hardened condition, such as ½ hard, shall not be annealed, stress relieved, or dimensionally stabilized without permission of the cognizant engineering authority

Stress Relieving. In aerospace practice, parts are stress relieved at 900 °C (1650 °F), and quenched in air, polymer, or water. When stress relieving after welding, hold for 30 min minimum at the annealing temperature or 2 h minimum at the stress relieving temperature (see table for soaking times). Sections over 6.25 mm (0.25 in.) thick should be water quenched to minimize carbide precipitation. Heat treating or slow cooling of unstabilized grades between 470 to 815 °C (875 to 1500 °F) is prohibited, except for 304L and 316L.

321H: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time(b) Atmosphere furnace min	Salt bath min
up to 2.50 (0.100)	40	37
over 2.50 to 6.25 (0.100 to 0.250)	45	38
over 6.25 to 12.50 (0.259 to 0.500)	65	55
over 12.50 to 25.00 (0.500 to 1.00)	80	60
over 25.00 to 37.50 (1.00 to 1.50)	95	65
over 37.50 to 50.00 (1.50 to 2.00)	110	70
over 50.00 to 62.50 (2.00 to 2.50)	125	75
over 62.50 to 75.00 (2.50 to 3.00)	140	80
over 75.00 (3.00)	(c)	(d)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) Parts should be held for sufficient time to ensure that center of most massive section has reached temperature and necessary transformation and diffusion have taken place. (c) 2 h, 35 min plus 15 min for every 12.5 mm (0.50 in.) or increment of 12.50 mm (0.50 in.) over 75.0 mm (3 in.). (d) 1 h, 25 min plus 5 min for every 12.50 mm (0.50 in.) or increment of 12.5 mm (0.50 in.) over 75.0 mm (3 in.). Source: AMS 2759/4

329

Chemical Composition. AISI/UNS (S32900): 0.10 C, 2.00 Mn, 1.00 Si, 25.00 to 30.00 Cr, 3.00 to 6.00 Ni, 0.045 P, 0.03 S, 1.00 to 2.00 Mo

Similar Steels (U.S. and/or Foreign). ASME SA268; ASTM A268, A511

Characteristics. Similar to type 316, except exhibits superior resistance to stress corrosion cracking. Capable of age hardening, but becomes brittle if hardened and should be restricted to compressive forces in this condition. This is an austenitic-ferritic (duplex) stainless steel

Forging. Start forging at 1095 °C (2005 °F). Do not forge after forging stock drops below 925 °C (1695 °F). Cool to black color in less than 3 min, using liquid quench if necessary

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Anneal at 925 to 955 °C (1695 to 1750 °F). Harden at 730 °C (1350 °F). Hold 12 h and cool slowly in air or furnace. To guard against distortion of thin, delicate parts, leave ample room for expansion between parts. Stainless grades expand about twice as much as carbon and low-alloy eels. Allow enough time for through heating after thermocouple has ached temperature. Stainless grades have approximately half the thermal ›nductivity of carbon and low-alloy steels. Choice of atmosphere depends ı finish desired and whether surface stock will be removed. For bright ınealing, use vacuum or an atmosphere of hydrogen or dissociated ammo-a at dew point of –62 to –74 °C (–80 to –100 °F). Parts must be thoroughly ean and dry. Inert gases argon and helium (although expensive) and trogen, with dew points of less than –54 °C (–65 °F), can be used. They ck the reducing effect of hydrogen, so slight discoloration in the form of ırome oxide can result. Salt, exothermic, or endothermic atmospheres are tisfactory for nonbright annealing. Salt is difficult to remove, and rinse ıenching at 595 °C (1105 °F) is not recommended, because interrupted ıench at elevated temperature cannot be tolerated. Exothermic and endo-ermic atmospheres must be carefully controlled at equivalent carbon ›tential to avoid carburization, which will seriously lower corrosion sistance. Same problem with atmosphere annealing. If oxidizing condi-›ns are present, scale will form. Difficult to remove in subsequent descal-g operations.

Cool rapidly from annealing temperature; no more than 3 min to black ›lor. Section size determines quenching medium: water for heavy sec-›ns, air blast for intermediate sizes, and still air for thin sections. Carbides n precipitate at grain boundaries when parts are cooled too slowly :tween 425 to 900 °C (795 to 1650 °F)

tress Relieving. Parts can be relieved after quenching to achieve mensional stability, by heating to 230 to 400 °C (445 to 750 °F) for up to veral hours, depending on section size and without change in metal-graphic structure

Nitriding. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners should be replaced with radii of not less than 1.59 mm (0.06 in.). Film of primarily chromium oxide, that protects stainless alloys from oxidation and corrosion, must be removed prior to nitriding. Accomplished by wet blasting, pickling, chemical reduction in reducing atmosphere, submersion in molten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid contamination of surface by finger or hand marking. Single-stage nitriding adequate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h (depending on case depth required). Dissociation rates for single-stage cycle are from 20 to 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle produces case extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

Recommended Processing Sequence

- Cold work
- Anneal and quench
- Remove surface contamination (if required)
- Stress relieve
- Depassivate (if nitriding)
- Nitride (if required)

›30

hemical Composition. AISI/UNS (N08330): 0.08 C, 2.00 Mn, 75 to 1.50 Si, 17.00 to 20.00 Cr, 34.00 to 37.00 Ni, 0.040 P, 0.030 S

milar Steels (U.S. and/or Foreign). AMS 5592, 5716; ANSI 34.31, H34.30; ASTM B511, B512, B535, B536, B546; SAE J405)330), J412 (30330)

ıaracteristics. Has good resistance to carburization and to heat and :rmal shock. Magnetic in all conditions

›rging. Start forging at 1150 to 1175 °C (2100 to 2150 °F). Do not forge er forging stock drops below 925 °C (1695 °F). Cool to black color in s than 3 min, using liquid quench if necessary

ecommended Heat Treating Practice

›rmalizing. Do not normalize

ınealing. Anneal at 1065 to 1175 °C (1950 to 2150 °F). To guard ainst distortion of thin, delicate parts, leave ample room for expansion :ween parts. Stainless grades expand about twice as much as carbon and v-alloy steels. Allow enough time for through heating after thermocouple s reached temperature. Stainless grades have approximately half the :rmal conductivity of carbon and low-alloy steels. Choice of atmosphere ›ends on finish desired and whether surface stock will be removed. For ght annealing, use vacuum or an atmosphere of hydrogen or dissociated ımonia at dew point of –62 to –74 °C (–80 to –100 °F). Parts must be ›roughly clean and dry. Inert gases argon and helium (although expen-e) and nitrogen, with dew points of less than –54 °C (–65 °F), can be :d. They lack the reducing effect of hydrogen, so slight discoloration in : form of chrome oxide can result. Salt, exothermic, or endothermic ıospheres are satisfactory for nonbright annealing. Salt is difficult to remove, and rinse quenching at 595 °C (1105 °F) is not recommended, because interrupted quench at elevated temperature cannot be tolerated. Exothermic and endothermic atmospheres must be carefully controlled at equivalent carbon potential to avoid carburization, which will seriously lower corrosion resistance. Same problem with atmosphere annealing. If oxidizing conditions are present, scale will form. Difficult to remove in subsequent descaling operations.

Cool rapidly from annealing temperature; no more than 3 min to black color. Section size determines quenching medium: water for heavy sections, air blast for intermediate sizes, and still air for thin sections. Carbides can precipitate at grain boundaries when parts are cooled too slowly between 425 to 900 °C (795 to 1650 °F)

Stress Relieving. Parts can be relieved after quenching to achieve dimensional stability, by heating to 230 to 400 °C (445 to 750 °F) for up to several hours, depending on section size and without change in metallographic structure

Nitriding. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners should be replaced with radii of not less than 1.59 mm (0.06 in.). Film of primarily chromium oxide, that protects stainless alloys from oxidation and corrosion, must be removed prior to nitriding. Accomplished by wet blasting, pickling, chemical reduction in reducing atmosphere, submersion in molten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid contamination of surface by finger or hand marking. Single-stage nitriding adequate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h (depending on case depth required). Dissociation rates for single-stage cycle are from 20 to 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle produces case extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

Recommended Processing Sequence

- Cold work
- Anneal and quench
- Remove surface contamination (if required)
- Stress relieve
- Depassivate (if nitriding)
- Nitride (if required)

347

Chemical Composition. AISI/UNS (S34700): 0.08 C, 2.00 Mn, 1.00 Si, 17.00 to 19.00 Cr, 9.00 to 13.00 Ni, 0.045 P, 0.030 S, 10 × %C, Nb + Ta min

Similar Steels (U.S. and/or Foreign). AMS 5512, 5556, 5558, 5571, 5575, 5646, 5654, 5674, 5680; ASME SA182, SA193, SA194, SA213, SA240, SA249, SA312, SA320, SA358, SA376, SA403, SA409, SA430, SA479; ASTM A167, A182, A193, A194, A213, A249, A269, A271, A276, A312, A314, A320, A358, A376, A403, A409, A430, A473, A479, A493, A511, A554, A580, A633; FED QQ-S-763, QQ-S-766, QQ-W-423; MIL SPEC MIL-S-862, MIL-S-23195, MIL-S-23196; SAE J405 (30347); (Ger.) DIN 1.4550; (Fr.) AFNOR Z 6 CNNb 18.10; (Ital.) UNI X 8 CrNiNb 18 11; (Jap.) JIS SUS 347; (Swed.) SS_{14} 2338; (U.K.) B.S. 347 S 17, En. 58 F, En. 58 G, ANC 3 Grade B

Characteristics. Stabilized by the addition of niobium plus tantalum, this grade is nearly immune to intergranular precipitation of chromium carbide and its adverse effects on corrosion resistance. Thin sections do not require water quenching from annealing temperature. Stabilizing anneal at 870 °C (1600 °F) seldom required. Hardenable by cold work only

Forging. Start forging at 1150 to 1260 °C (2100 to 2300 °F). Do not forge after forging stock drops below 925 °C (1695 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Anneal at 1010 to 1120 °C (1850 to 2050 °F). See recommended heat treating practice for type 201 for information on protective atmosphere for annealing. For thin sections, anneal to obtain maximum softness and ductility. Air cool. For sections over 6.25 mm (0.25 in.), oil or water quench to ensure maximum retention of austenite. For titanium-stabilized type 321, a stabilizing anneal at approximately 870 °C (1600 °F) is often used. Seldom used on niobium-stabilized grades.

In aerospace practice, parts are annealed at 1040 °C (1905 °F) then quenched in air, oil, polymer, or water. Sections over 6.25 mm (0.25 in.) thick should be water quenched to minimize carbide precipitation. Parts fabricated from steel in a strain-hardened condition, such as ½ hard, shall not be annealed, stress relieved, or dimensionally stabilized without permission of the cognizant engineering authority. See table for soaking times

Stress Relieving. In aerospace practice, parts are stress relieved at 900 °C (1650 °F). As an alternative, this alloy may be stress relieved at annealing temperatures. Quenching is in air, polymer, or water. Sections over 6.25 mm (0.25 in.) thick should be water quenched to minimize carbide precipitation. Parts fabricated in the strain-hardened condition, such as ½ hard, shall not be stress relieved without permission of the cognizant engineering authority. See table for soaking times

Nitriding. Optional. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners should be replaced with radii of not less than 1.59 mm (0.06 in.). Film of primarily chromium oxide, that protects stainless alloys from oxidation and corrosion, must be removed prior to nitriding. Accomplished by wet blasting, pickling, chemical reduction in reducing atmosphere, submersion in molten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid contamination of surface by finger or hand marking. Single-stage nitriding adequate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h (depending on case depth required). Dissociation rates for single-stage cycle are from 20 to 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle produces case extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

Recommended Processing Sequence

- Cold work
- Anneal and cool
- Depassivate (if nitriding)
- Nitride (if necessary)

347: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time(b) Atmosphere furnace min	Salt bath min
up to 2.50 (0.100)	40	37
over 2.50 to 6.25 (0.100 to 0.250)	45	38
over 6.25 to 12.50 (0.259 to 0.500)	65	55
over 12.50 to 25.00 (0.500 to 1.00)	80	60
over 25.00 to 37.50 (1.00 to 1.50)	95	65
over 37.50 to 50.00 (1.50 to 2.00)	110	70
over 50.00 to 62.50 (2.00 to 2.50)	125	75
over 62.50 to 75.00 (2.50 to 3.00)	140	80
over 75.00 (3.00)	(c)	(d)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) Parts should be held for sufficient time to ensure that center of most massive section has reached temperature and necessary transformation and diffusion have taken place. (c) 2 h, 35 min plus 15 min for every 12.5 mm (0.50 in.) or increment of 12.50 mm (0.50 in.) over 75.0 mm (3 in.). (d) 1 h, 25 min plus 5 min for every 12.50 mm (0.50 in.) or increment of 12.5 mm (0.50 in.) over 75.0 mm (3 in.). Source: AMS 2759/4

‡7H

ɜmical Composition. **AISI/UNS (S34709):** 0.04 to 0.10 C, 2.00 1.00 Si, 17.00 to 19.00 Cr, 9.00 to 13.00 Ni, 0.045 P, 0.030 S, 8 × %C to 1.00 max Nb

commended Heat Treating Practice

ıealing. In aerospace practice, parts are annealed at 1040 °C (1905 then quenched in air, oil, polymer, or water. Sections over 6.25 mm 5 in.) thick should be water quenched to minimize carbide precipita- . Parts fabricated from steel in a strain-hardened condition, such as ½ , shall not be annealed, stress relieved, or dimensionally stabilized out permission of the cognizant engineering authority. See table for ing times

ɜss Relieving. In aerospace practice, parts are stress relieved at °C (1650 °F). As an alternative, this alloy may be stress relieved at ıaling temperatures. Quenching is in air, polymer, or water. Sections 6.25 mm (0.25 in.) thick should be water quenched to minimize ide precipitation. Parts fabricated in the strain-hardened condition, as ½ hard, shall not be stress relieved without permission of the ıizant engineering authority. See table for soaking times

347H: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time(b) Atmosphere furnace min	Salt bath min
up to 2.50 (0.100)	40	37
over 2.50 to 6.25 (0.100 to 0.250)	45	38
over 6.25 to 12.50 (0.259 to 0.500)	65	55
over 12.50 to 25.00 (0.500 to 1.00)	80	60
over 25.00 to 37.50 (1.00 to 1.50)	95	65
over 37.50 to 50.00 (1.50 to 2.00)	110	70
over 50.00 to 62.50 (2.00 to 2.50)	125	75
over 62.50 to 75.00 (2.50 to 3.00)	140	80
over 75.00 (3.00)	(c)	(d)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) Parts should be held for sufficient time to ensure that center of most massive section has reached temperature and necessary transformation and diffusion have taken place. (c) 2 h, 35 min plus 15 min for every 12.5 mm (0.50 in.) or increment of 12.50 mm (0.50 in.) over 75.0 mm (3 in.). (d) 1 h, 25 min plus 5 min for every 12.50 mm (0.50 in.) or increment of 12.5 mm (0.50 in.) over 75.0 mm (3 in.). Source: AMS 2759/4

‡8

ɜmical Composition. **AISI/UNS (S34800):** 0.08 C, 2.00 Mn, Si, 17.00 to 19.00 Cr, 9.00 to 13.00 Ni, 0.045 P, 0.030 S, 0.2 Co, 10 × ɜin Nb, 0.10 Ta

ıilar Steels (U.S. and/or Foreign). ASME SA182, SA213, 40, SA249, SA312, SA358, SA376, SA403, SA409, SA479; ASTM 7, A182, A213, A240, A249, A269, A276, A312, A314, A358, A376, 3, A479, A580, A632; FED QQ-S-766; MIL SPEC MIL-S-23195, -S-23196; SAE J405 (30348); (Ger.) DIN 1.4546; (U.K.) B.S. 347 S 47 S 18, 347 S 40, 2 S. 130, S. 525, S. 527

ıracteristics. Similar to type 347, except tantalum content re- ed to 0.10 max and niobium to 0.20 max. Used where restricted tity of these elements is required, as in radioactive service. Hardenable ɔld work only

ɡing. Start forging at 1150 to 1260 °C (2100 to 2300 °F). Do not after forging stock drops below 925 °C (1695 °F)

ːommended Heat Treating Practice

malizing. Do not normalize

ıealing. Anneal at 1010 to 1120 °C (1850 to 2050 °F). See recom- led heat treating practice for type 201, for information on protective sphere for annealing. For thin sections, anneal to obtain maximum ess and ductility. Air cool. For sections over 6.25 mm (0.25 in.), oil or quench to ensure maximum retention of austenite. For titanium-sta- ːd type 321, a stabilizing anneal at approximately 870 °C (1600 °F) is used. Seldom used on niobium-stabilized grades.

n aerospace practice, parts are annealed at 1040 °C (1905 °F) then ːhed in air, oil, polymer, or water. Sections over 6.25 mm (0.25 in.) should be water quenched to minimize carbide precipitation.. Parts ːated from steel in a strain-hardened condition, such as ½ hard, shall e annealed, stress relieved, or dimensionally stabilized without per- on of the cognizant engineering authority. See table for soaking times

Stress Relieving. In aerospace practice, parts are stress relieved at 900 °C (1650 °F). As an alternative, this alloy may be stress relieved at annealing temperatures. Quenching is in air, polymer, or water. Sections over 6.25 mm (0.25 in.) thick should be water quenched to minimize carbide precipitation. Parts fabricated in the strain-hardened condition, such as ½ hard, shall not be stress relieved without permission of the cognizant engineering authority. See table for soaking times

Nitriding. Optional. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners should be replaced with radii of not less than 1.59 mm (0.06 in.). Film of primarily chromium oxide, that protects stainless alloys from oxidation and corrosion, must be removed prior to nitriding. Accomplished by wet blasting, pickling, chemical reduction in reducing atmosphere, submersion in molten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid contamination of surface by finger or hand marking. Single-stage nitriding adequate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h (depending on case depth required). Dissociation rates for single-stage cycle are from 20 to 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle produces case extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

Recommended Processing Sequence

- Cold work
- Anneal and cool
- Depassivate (if nitriding)
- Nitride (if necessary)

48: Soaking Times (Aerospace Practice)

iameter or thickness(a) 'maximum section m (in.) inclusive	Minimum soaking time(b) Atmosphere furnace min	Salt bath min
) to 2.50 (0.100)	40	37
ver 2.50 to 6.25 (0.100 to 0.250)	45	38
ver 6.25 to 12.50 (0.259 to 0.500)	65	55
ver 12.50 to 25.00 (0.500 to 1.00)	80	60
ver 25.00 to 37.50 (1.00 to 1.50)	95	65
ver 37.50 to 50.00 (1.50 to 2.00)	110	70
ver 50.00 to 62.50 (2.00 to 2.50)	125	75
ver 62.50 to 75.00 (2.50 to 3.00)	140	80
ver 75.00 (3.00)	(c)	(d)

) Thickness is minimum dimension of heaviest section of part or nested load of parts.) Parts should be held for sufficient time to ensure that center of most massive section as reached temperature and necessary transformation and diffusion have taken place.) 2 h, 35 min plus 15 min for every 12.5 mm (0.50 in.) or increment of 12.50 mm (0.50 .) over 75.0 mm (3 in.). (d) 1 h, 25 min plus 5 min for every 12.50 mm (0.50 in.) or icrement of 12.5 mm (0.50 in.) over 75.0 mm (3 in.). Source: AMS 2759/4

348H

hemical Composition. AISI/UNS (S34809): 0.04 to 0.10 C, 2.00 In, 1.00 Si, 17.00 to 19.00 Cr, 9.00 to 13.00 Ni, 0.045 P, 0.030 S, 0.2 Co, × %C min to 1.00 max Nb, 0.10 Ta

ecommended Heat Treating Practice

nnealing. In aerospace practice, parts are annealed at 1040 °C (1905 F) then quenched in air, oil, polymer, or water. Sections over 6.25 mm 0.25 in.) thick should be water quenched to minimize carbide precipitaion.. Parts fabricated from steel in a strain-hardened condition, such as ½ ard, shall not be annealed, stress relieved, or dimensionally stabilized vithout permission of the cognizant engineering authority. See table for oaking times

tress Relieving. In aerospace practice, parts are stress relieved at 00 °C (1650 °F). As an alternative, this alloy may be stress relieved at nnealing temperatures. Quenching is in air, polymer, or water. Sections ver 6.25 mm (0.25 in.) thick should be water quenched to minimize arbide precipitation. Parts fabricated in the strain-hardened condition, uch as ½ hard, shall not be stress relieved without permission of the ognizant engineering authority. See table for soaking times

348H: Soaking Times (Aerospace Practice)

Diameter or thickness(a) of maximum section mm (in.) inclusive	Minimum soaking time(b) Atmosphere furnace min	Salt bath min
up to 2.50 (0.100)	40	37
over 2.50 to 6.25 (0.100 to 0.250)	45	38
over 6.25 to 12.50 (0.259 to 0.500)	65	55
over 12.50 to 25.00 (0.500 to 1.00)	80	60
over 25.00 to 37.50 (1.00 to 1.50)	95	65
over 37.50 to 50.00 (1.50 to 2.00)	110	70
over 50.00 to 62.50 (2.00 to 2.50)	125	75
over 62.50 to 75.00 (2.50 to 3.00)	140	80
over 75.00 (3.00)	(c)	(d)

(a) Thickness is minimum dimension of heaviest section of part or nested load of parts. (b) Parts should be held for sufficient time to ensure that center of most massive section has reached temperature and necessary transformation and diffusion have taken place. (c) 2 h, 35 min plus 15 min for every 12.5 mm (0.50 in.) or increment of 12.50 mm (0.50 in.) over 75.0 mm (3 in.). (d) 1 h, 25 min plus 5 min for every 12.50 mm (0.50 in.) or increment of 12.5 mm (0.50 in.) over 75.0 mm (3 in.). Source: AMS 2759/4

384

hemical Composition. AISI/UNS (S38400): 0.08 C, 2.00 Mn, .00 Si, 15.00 to 17.00 Cr, 17.00 to 19.00 Ni, 0.045 P, 0.030 S

imilar Steels (U.S. and/or Foreign). ASTM A493; SAE J405 30384)

Characteristics. Has a lower cold work hardening rate than type 305. Used when severe cold heading or cold forming operations are required

Forging. Start forging at 1150 to 1230 °C (2100 to 2245 °F). Do not forge after forging stock drops below 925 °C (1695 °F). Cool to black color in less than 3 min, using liquid quench if necessary

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Anneal at 1040 to 1150 °C (1905 to 2100 °F). To guard against distortion of thin, delicate parts, leave ample room for expansion between parts. Stainless grades expand about twice as much as carbon and low-alloy steels. Allow enough time for through heating after thermocouple has reached temperature. Stainless grades have approximately half the thermal conductivity of carbon and low-alloy steels. Choice of atmosphere depends on finish desired and whether surface stock will be removed. For bright annealing, use vacuum or an atmosphere of hydrogen or dissociated ammonia at dew point of −62 to −74 °C (−80 to −100 °F). Parts must be thoroughly clean and dry. Inert gases argon and helium (although expensive) and nitrogen, with dew points of less than –54 °C (–65 °F), can be used. They lack the reducing effect of hydrogen, so slight discoloration in the form of chrome oxide can result. Salt, exothermic, or endothermic atmospheres are satisfactory for nonbright annealing. Salt is difficult to remove, and rinse quenching at 595 °C (1105 °F) is not recommended, because interrupted quench at elevated temperature cannot be tolerated. Exothermic and endothermic atmospheres must be carefully controlled at equivalent carbon potential to avoid carburization, which will seriously lower corrosion resistance. Same problem with atmosphere annealing. If oxidizing conditions are present, scale will form. Difficult to remove in subsequent descaling operations.

Cool rapidly from annealing temperature; no more than 3 min to black color. Section size determines quenching medium: water for heavy sections, air blast for intermediate sizes, and still air for thin sections. Carbides can precipitate at grain boundaries when parts are cooled too slowly between 425 to 900 °C (795 to 1650 °F)

Stress Relieving. Parts can be relieved after quenching to achieve dimensional stability, by heating to 230 to 400 °C (445 to 750 °F) for up to several hours, depending on section size and without change in metallographic structure

Nitriding. Not recommended. Case seriously impairs corrosion resistance in most media. Case seldom more than 0.127 mm (0.005 in.) deep. Only used in specialized applications where material must be nonmagnetic and have wear-resistant surface. If nitrided, parts must be in annealed condition to prevent flaking or blistering of nitrided case. All sharp corners should be replaced with radii of not less than 1.59 mm (0.06 in.). Film of primarily chromium oxide, that protects stainless alloys from oxidation and corrosion, must be removed prior to nitriding. Accomplished by wet blasting, pickling, chemical reduction in reducing atmosphere, submersion in molten salt, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in furnace by means of reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid contamination of surface by finger or hand marking. Single-stage nitriding adequate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h (depending on case depth required). Dissociation rates for single-stage cycle are from 20 to 35%. Hardness is as high as 1000 to 1350 HK on surface. 48-h cycle produces case extending to 0.127 mm (0.005 in.) with approximately 800 to 1000 HK. Case will rapidly drop to 200 HK core hardness, at approximately 0.165 mm (0.0065 in.)

Recommended Processing Sequence

- Cold work
- Anneal and quench
- Remove surface contamination (if required)
- Stress relieve
- Depassivate (if nitriding)
- Nitride (if required)

Ferritic Stainless Steels

Introduction

The ferritic stainless steels remain ferritic at all temperatures, theoretically, and thus they are not allotropic and cannot be hardened by heating and quenching. However, this is not always completely true. Some ferritic steels are borderline to the extent that if the chromium is on the low side and the carbon is on the high side some transformation to austenite can take place on heating. This, in turn, can transform to martensite upon cooling. The extent to which this takes place, however, is not usually of great practical significance.

Therefore, the principal heat treatment applied to the ferritic grades is annealing, which is usually achieved by rapid cooling from elevated temperature. In their annealed condition, ferritic stainless steels develop maximum softness, ductility, and corrosion resistance.

Annealing serves primarily to relieve stresses resulting from welding or cold working. Secondarily, it provides a more nearly homogeneous structure by eliminating patches of transformation product developed during welding or as a result of 475 °C (885 °F) embrittlement.

Ferritic steels usually are annealed at temperatures above the range for 475 °C (885 °F) embrittlement and below temperatures at which austenite might form. The table included in this section summarizes current annealing practices for the ferritic grades.

Even ferritic grades can retain austenite or untempered martensite from partial transformation to austenite at high temperatures. Aluminum has been added to type 405 to eliminate or minimize austenite formation and decomposition during welding. When fusion welding heats this grade above 1095 °C (2000 °F), embrittlement may still result. This is corrected by a subsequent heat treatment at 650 to 815 °C (1200 to 1500 °F).

When type 430 is cooled rapidly from above 925 °C (1700 °F), it may become brittle from austenite transforming to as much as 30% martensite. The austenite may be retained, if it is cooled rapidly from temperatures much above 1095 °C (2000 °F). This may be corrected by heating to 760 to 815 °C (1400 to 1500 °F).

A form of brittleness peculiar to the ferritic grades can develop from prolonged exposure to, or slow cooling within, the temperature range from about 400 to 525 °C (750 to 975 °F), with a maximum effect variously asserted as occurring at 470, 475, or 480 °C (875, 885, or 900 °F). Notch impact strength is most adversely affected. The brittleness is believed to be caused by precipitation of a high-chromium ferrite. Its effects increase rapidly with chromium content, reaching a maximum in type 446. Certain heat treatments, such as furnace cooling for maximum ductility, must be controlled to avoid embrittlement. The brittle condition can be eliminated by any of the treatments listed in the table, using temperatures clearly above the upper boundary of embrittlement, followed by rapid cooling to prevent a recurrence.

Annealing Treatments of Ferritic Stainless Steels

Type	Temperature(a) °F	Temperature(a) °C	Cooling method(b)
405	1345 to 1500	735 to 815	AC or WQ
409	1625 to 1650	885 to 900	AC
429	1450 to 1555	780 to 845	AC or WQ
430	1400 to 1500	760 to 815	AC or WQ
430F	1250 to 1400	675 to 760	AC or WQ
430FSe	1250 to 1400	675 to 760	AC or WQ
434	1455 to 1555	790 to 845	AC or WQ
436	1455 to 1555	790 to 845	AC or WQ
442	1355 to 1505	735 to 815	AC or WQ
446	1455 to 1600	790 to 870	AC or WQ

(a) Time at temperature depends on section thickness, but is usually 1 to 2 h, except for sheet which may be soaked 3 to 5 min per 2.5 mm (0.10 in.) of thickness. (b) AC, air cool; WQ, water quench

Sigma phase is a crystallographic constituent that forms slowly at elevated temperatures in straight-chromium steels containing more than about 16% Cr and in chromium-nickel steels containing more than about 18% Cr. Sigma phase increases hardness, which is sometimes useful, but it decreases ductility, notch toughness, and corrosion resistance. The lower temperature limit for its formation depends exponentially on exposure time. For practical purposes, it can be placed near 540 °C (1000 °F). The upper boundary varies with alloy content.

Nitriding. In general, the ferritic grades are more easily nitrided than are the austenitic grades. Somewhat deeper cases can be formed on the ferritic grades, using the same practice as used for the austenitic steels described in this Volume. Just as it is true for the austenitic grades, nitriding also impairs corrosion resistance of the ferritic grades, so that applications for nitrided ferritic stainless steels are limited.

Forging. For the most part, the allowable forging temperature range for these steels is fairly broad, restricted somewhat at high temperature because of grain growth and structural weakness. Type 405 is the only one of this group for which finishing temperature is closely restricted. This is because this specific grade develops grain boundary weakness caused by development of small amounts of austenite. Other ferritic grades are commonly finished at temperatures as low as 760 °C (1400 °F). For forging of type 446, the final 10% reduction is preferably made below 870 °C (1600 °F) to achieve grain refinement and room temperature ductility. Forgings of ferritic steels should always be annealed.

05

ıemical Composition. **AISI/UNS (S40500):** 0.08 C, 1.00 Mn, 0 Si, 11.50 to 14.50 Cr, 0.040 P, 0.030 S, 0.10 to 0.30 Al

nilar Steels (U.S. and/or Foreign). ASME SA240, SA268, 479; ASTM A176, A240, A268, A276, A314, A473, A479, A511, A580; D QQ-S-763; MIL SPEC MIL-S-862; SAE J405 (51405); (Ger.) DIN 002; (Fr.) AFNOR Z 6 CA 13; (Ital.) UNI X 6 CrAl 13; (Jap.) JIS SUS ;; (U.K.) B.S. 405 S 17

ıaracteristics. Nonhardenable grade where air-hardening types such 10 or 403 are objectionable. Can be cooled from elevated temperatures without significant hardening. Not susceptible to hardening cracks during welding. Ductile. Easily machined

Forging. Start forging at 1065 to 1120 °C (1950 to 2050 °F). Finish at 870 to 925 °C (1600 to 1695 °F)

Recommended Heat Treating Practice

Annealing. Low anneal temperatures range from 735 to 815 °C (1345 to 1500 °F). Air cool or water quench

09

ıemical Composition. **AISI/UNS (S40900):** 0.08 C, 1.00 Mn, 0 Si, 0.50 Ni, 0.045 P, 0.045 S, 10.50 to 11.75 Cr, 6 × %C min, 0.75 Ti x

nilar Steels (U.S. and/or Foreign). ASME SA268; ASTM 76, A268, A651; SAE J405 (51409); (Ger.) DIN 1.4512; (Jap.) JIS SUH ; (U.K.) B.S. 409 S 17

Characteristics. A general purpose construction steel. Intended for applications where appearance is secondary to mechanical and corrosion resistance properties

Recommended Heat Treating Practice

Annealing. Annealing temperatures range from 885 to 900 °C (1625 to 1650 °F). Air cool

29

emical Composition. **AISI/UNS (S42900):** 0.12 C, 1.00 Mo,) Si, 14.00 to 16.00 Cr, 0.040 P, 0.030 S

nilar Steels (U.S. and/or Foreign). ASME SA182, SA240, 268; ASTM A176, A182, A240, A268, A276, A314, A473, A493, A511, 54; FED QQ-S-763, QQ-S-766, QQ-W-423; MIL SPEC MIL-S-862; E J405 (51429)

aracteristics. This corrosion and heat resisting steel has better dability than type 430. Applications include nitric acid and nitrogen ıtion equipment

Forging. Start forging at 1040 to 1120 °C (1905 to 2050 °F). Finish can be as low as 760 °C (1400 °F)

Recommended Heat Treating Practice

Annealing. Temperatures range from 780 to 845 °C (1450 to 1550 °F). Air cool or water quench

30

emical Composition. **AISI/UNS (S43000):** 0.12 C, 1.00 Mn,) Si, 16.00 to 18.00 Cr, 0.04 P, 0.03 S

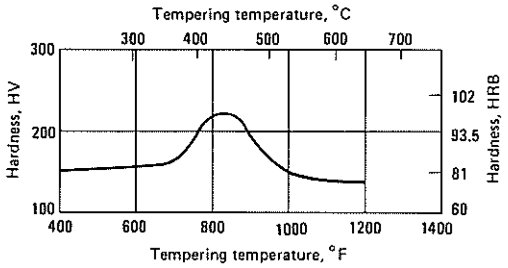
nilar Steels (U.S. and/or Foreign). AMS 5503, 5627; ASME 182, SA240, SA268, SA479; ASTM A176, A182, A240, A268, A276, 14, A473, A479, A493, A511, A554, A580, A651; FED QQ-S-763, -S-766, QQ-S-423, STD-66; MIL SPEC MIL-S-862; SAE J405 430); (Ger.) DIN 1.4016; (Fr.) AFNOR Z 8 C 17; (Ital.) UNI X 8 Cr 17; ı.) JIS SUS 430; (Swed.) SS_{14} 2320; (U.K.) B.S. 430 S 15

Characteristics. General purpose, nonhardenable chromium-type alloy. Corrosion and heat resistance properties are superior to 410

Forging. Start forging at 1040 to 1120 °C (1905 to 2050 °F). Finish at 760 to 815 °C (1400 to 1500 °F)

Recommended Heat Treating Practice

Annealing. Parts are annealed at 760 to 815 °C (1400 to 1500 °F). Annealing should be followed by water quenching or very rapid cooling



430: Hardness vs Tempering Temperature. Composition: 0.07 C, 0.33 Mn, 0.020 S, 0.019 P, 1.00 Si, 16.96 Cr. Bar heated 400 h. Source: Allegheny Ludlum Industries

430F

Chemical Composition. AISI/UNS (S43020): 0.12 C, 1.25 Mn, 1.00 Si, 16.00 to 18.00 Cr, 0.06 P, 0.15 S min, 0.6 Mo (optional)

Similar Steels (U.S. and/or Foreign). ASTM A314, A581, A582; MIL SPEC MIL-S-862; SAE J405 (51430F); (Ger.) DIN 1.4104; (Fr.) AFNOR Z 10 CF 17; (Ital.) UNI X 10 CrS 17; (Jap.) JIS SUS 430 F; (Swed.) SS_{14} 2383

Characteristics. Free-machining variation of 430 for heavier cuts. Suitable for use on automatic screw machines

Forging. Start forging at 1065 to 1150 °C (1950 to 2100 °F). Finish at 760 to 815 °C (1400 to 1500 °F)

Recommended Heat Treating Practice

Annealing. Anneal at 675 to 760 °C (1245 to 1400 °F). Air cool or water quench

430FSe

Chemical Composition. AISI/UNS (S43023): 0.12 C, 1.25 Mn, 1.00 Si, 16.00 to 18.00 Cr, 0.06 P, 0.06 S, 0.15 Se min

Similar Steels (U.S. and/or Foreign). ASTM A314, A473, A581, A582; MIL SPEC MIL-S-862; SAE J405 (51430FSe)

Characteristics. Free-machining variation of 430 for lighter cuts. Suitable for use in automatic screw machines attained by selenium additions

Forging. Start forging at 1065 to 1150 °C (1950 to 2100 °F). Finish at 760 to 815 °C (1400 to 1500 °F)

Recommended Heat Treating Practice

Annealing. Temperature is 675 to 760 °C (1245 to 1400 °F). Air cool or water quench

434

Chemical Composition. AISI/UNS (S43400): 0.12 C, 1.00 Mn, 1.00 Si, 16.00 to 18.00 Cr, 0.4 P, 0.3 S, 0.75 to 1.25 Mo

Similar Steels (U.S. and/or Foreign). ASTM A651; SAE J405 (51434); (Ger.) DIN 1.4113; (Fr.) AFNOR Z 8 CD 17.01; (Ital.) UNI X 8 CrMo 17; (Jap.) JIS SUS 434; (Swed.) SS_{14} 2325; (U.K.) B.S. 434 S 19

Characteristics. Designed for use as automotive trim to resist corrosion because of winter road conditioning

Forging. Start forging at 1040 to 1120 °C (1905 to 2050 °F). Finish can be as low as 760 °C (1400 °F)

Recommended Heat Treating Practice

Annealing. Anneal at 790 to 845 °C (1455 to 1555 °F). Air cool or water quench

·36

hemical Composition. AISI/UNS (S43600): 0.12 C, 1.00 Mn,)0 Si, 16.00 to 18.00 Cr, 0.04 P, 0.03 S, 0.75 to 1.25 Mo, 5 X %C min to 70 max

milar Steels (U.S. and/or Foreign). SAE J405 (51436)

ıaracteristics. Adaptable for general corrosion and heat resisting plications. Similar to types 430 and 434. Used where low "roping" or dging" is required

Forging. Start forging at 1065 to 1120 °C (1950 to 2050 °F). Finish can be as low as 870 to 925 °C (1600 to 1695 °F)

Recommended Heat Treating Practice

Annealing. Temperature is 790 to 845 °C (1455 to 1555 °F). Air cool or water quench

39

ıemical Composition. AISI/UNS (S43035): 0.07 C, 1.00 Mn, ·0 Si, 0.50 Ni, 17.00 to 19.00 Cr, 0.04 P, 0.03 S, 0.15 Al, 12 × %C min - 0 Ti

ıaracteristics. A low interstial grade

Recommended Heat Treating Practice

Annealing. Annealing is at 870 to 925 °C (1600 to 1695 °F). Air cool or water quench

42

ıemical Composition. AISI/UNS (S44200): 0.20 C, 1.00 Mn,) Si, 18.00 to 23.00 Cr, 0.04 P, 0.03 S

nilar Steels (U.S. and/or Foreign). ASTM A176; SAE J405 442)

aracteristics. Used mainly for parts which must resist scaling at ı temperatures. Maximum temperature resistance is 980 °C (1795 °F) 040 °C (1905 °F) for intermittent use

Forging. Start forging at 870 to 1150 °C (1600 to 2100 °F). Finish can be as low as 760 °C (1400 °F)

Recommended Heat Treating Practice

Annealing. Temperature is 735 to 815 °C (1355 to 1505 °F). Air cool or water quench

46

emical Composition. AISI/UNS (S44600): Nominal. 0.20 C,) Mn, 1.00 Si, 23.00 to 27.00 Cr, 0.040 P, 0.030 S, 0.25 N

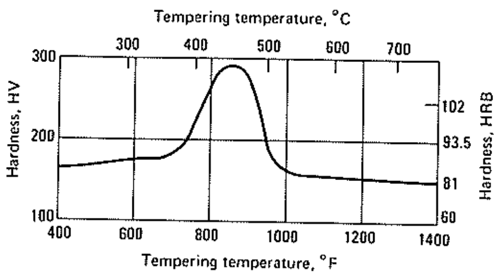
ıilar Steels (U.S. and/or Foreign). ASME SA268; ASTM '6, A268, A276, A314, A473, A511, A580; FED QQ-S-763, QQ-S-766; . SPEC MIL-S-862; SAE J405 (51446)

aracteristics. Has the maximum amount of chromium of ferritic ıless steels. Used for parts which must resist scaling at high temperatures. Withstands destructive scaling up to 1095 °C (2005 °F). Often used in sulfur-bearing atmospheres

Forging. Start forging at 1065 to 1120 °C (1950 to 2050 °F). Finishing can be done as low as 760 °C (1400 °F)

Recommended Heat Treating Practice

Annealing. Anneal at 790 to 870 °C (1455 to 1600 °F). Air cool or water quenching



446: Hardness vs Tempering Temperature. Bar heated 400 h. Source: Allegheny Ludlum Industries

Martensitic Stainless Steels

Introduction

The martensitic stainless steels represent one portion of the 400 Series of stainless steels. The remainder consists of the ferritic steels, which cannot be heat treated for hardening. The heat treating of the martensitic stainless steels is essentially the same as that for carbon and low-alloy steels. Their potential for developing maximum strength and hardness depends primarily on carbon content. The principal metallurgical difference is the high alloy content of the stainless grades. This causes the transformation to martensite to be sluggish and the hardenability to be high. For these reasons, maximum hardness is produced by air cooling in the center of sections approximately 305 mm (12 in.) thick. Chromium is the principal alloying element in these steels.

The martensitic stainless steels are more sensitive to heat treating variables than are carbon and low-alloy steels. Therefore, rejection rates because of faults in heat treating are correspondingly high. Because of the initial high cost of these stainless steels and the cost of processing them into parts, there is no advantage in using them unless superior corrosion resistance is required. Consequently, the hardening procedures discussed in this section are limited to those that preserve corrosion resistance.

To avoid contamination, all parts and heat treating fixtures must be cleaned completely before they are placed in the furnace. Racks and fixtures should be made of stainless steel or one of several nickel-base alloys containing appreciable amounts of chromium, such as the Inconel alloys. Proper cleaning is particularly important when the heat treatment is to be performed in a protective atmosphere.

Martensitic stainless steels are normally hardened by being heated above the transformation range to temperatures of 925 to 1065 °C (1695 to 1950 °F) and cooled in air. Because of the poor thermal conductivity of stainless steels, high thermal gradients and high stresses during rapid heating may cause warping or cracking in some parts. To avoid these problems, preheating is usually recommended before annealing or hardening, especially for thin-gage parts, parts with both thin and thick sections, parts with sharp corners and re-entrant angles, heavily ground parts, parts machined with deep cuts, parts that have been cold formed or straightened, and previously hardened parts that are being reheat treated. Preheating is normally accomplished at 760 to 790 °C (1400 to 1455 °F), and heating need be continued only long enough to ensure that all portions of each part have reached the preheating temperature. Types 403, 413, and 416 require less preheating than the higher carbon stainless steels, such as 420 and 440.

When maximum corrosion resistance and strength are desired, these steels should be austenitized at the high end of the temperature range. For alloys that are to be tempered above 565 °C (1050 °F), the low side of the austenitizing range is recommended, because it enhances ductility and impact properties. Soaking times represent a compromise between (a) achieving maximum solution of chromium-iron carbides for maximum strength and corrosion resistance and (b) avoiding decarburization, excessive grain growth, retained austenite, brittleness, and quench cracking.

Because of their high hardenability, all martensitic stainless steels can be quenched in either oil or air. Oil quenching guarantees maximum corrosion resistance and ductility in all alloys. Air quenching may cause some decrease in ductility and corrosion resistance in types 414, 420, 431, and 440. These steels may precipitate carbides at grain boundaries, if heavy sections are cooled slowly through the temperature range of approximately 870 to 540 °C (1600 to 1000 °F). The higher carbon steels, such as 440C, and the higher nickel 431 are likely to retain large amounts of untransformed austenite in the as-quenched structure, frequently as much as 30% by volume. A portion of the retained austenite may be transformed by subzero cooling (stabilizing), followed by tempering. For fully hardened steels, increasing degrees of recovery toward the annealed condition are given by (a) stress relieving, (b) tempering, (c) subcritical annealing, and (d) full annealing. The martensitic stainless steels are sometimes nitrided to increase surface hardness and wear resistance and to achieve a lower coefficient of friction.

In aerospace practice, austenitizing in atmospheres containing hydrogen is limited to parts to be tempered above 540 °C (1000 °F). Annealing in hydrogen-containing atmospheres is permitted. Atmospheres containing nitrogen at 980 °C (1800 °F) and higher are not permitted when parts have finished machined surfaces. Endothermic and carbon-containing, nitrogen-base atmospheres are prohibited in treating 431 or any alloy to 1240 MPa (180 ksi) or higher.

403

Chemical Composition. **AISI/UNS (S40300):** 0.15 C, 1.00 Mn, 0.50 Si, 11.50 to 13.00 Cr, 0.04 P, 0.03 S

Similar Steels (U.S. and/or Foreign). AMS 5611, 5612; ASTM A176, A276, A314, A473, A479, A508, A511; FED QQ-S-763; MIL SPEC MIL-S-862; SAE J405 (51403); (Ger.) DIN 1.4024; (Jap.) JIS SUS 403, SUS 416; (U.K.) B.S. 420 S 29, En. 56 B

Characteristics. Special quality grade used for turbine blades and similar applications. Otherwise comparable to type 410. May be quenched in oil or air. Can be martempered. Capable of hardening to 42 HRC or slightly higher. Can be tempered to provide a wide range of strength and impact resistance. Extremely deep hardening. Maximum hardness obtained by air quenching sections up to approximately 305 mm (12 in.) thick. Can be full, process, or cycle annealed. Good corrosion resistance. Susceptible to stress corrosion cracking in corrosive environments, when stress is above threshold level for that particular environment. Magnetic in all conditions. Fair machinability. Resists oxidation up to 815 °C (1500 °F)

Forging. Start forging at 1095 to 1205 °C (2005 to 2200 °F). Do not forge after temperature of forging stock drops below 870 to 925 °C (1600 to 1695 °F)

Recommended Heat Treating Practice

Normalizing. Do not normalize

nealing. Can be process, isothermal, or full annealed:

rocess anneal in subcritical temperature range of 650 to 760 °C (1200 ı 1400 °F). Use clean, rectified salt bath or an atmosphere that is ›mpatible with this temperature range. Soaking time dependent on size f work. Air cool. Hardness, 86 to 92 HRB

othermal anneal by heating at 830 to 885 °C (1525 to 1625 °F). Cool owly to 705 °C (1300 °F). Hold for 6 h. Hardness, approximately 85 RB

ull anneal at 815 to 900 °C (1500 to 1650 °F). Cool slowly to 595 °C 105 °F) at a rate not to exceed 17 to 22 °C (30 to 40 °F) per h. After ıis, cooling rate has no effect on hardness. Avoid carburization or ›carburization. Can use atmospheric protection in the form of a vac- ım, the inert gases argon or helium (both expensive), or nitrogen. All ıould have dew point below –51 °C (–60 °F). Exothermic- or endother- ic-generated atmospheres can be used, providing carbon potential of e gas matches carbon content of the steel. Hardness, 75 to 85 HRB. ıll annealing is expensive and time consuming. Should not be used, ‹cept as required for subsequent severe forming or difficult machining

In aerospace practice, parts are annealed at 845 °C (1555 °F) and ›nitized at 980 °C (1795 °F), then quenched in oil or polymer. Cooling r or other gases is permitted for parts less than 6.25 mm (0.250 in.) in imum thickness provided they are not racked or densely packed. In ›aling, parts are cooled to below 595 °C (1105 °F) at a rate not to exceed C (55 °F) per h, followed by air cooling to ambient. An austenitizing ›erature of 955 °C (1750 °F) is permitted for thin sections to minimize ›age

'dening. Atmospheric protection rules for annealing apply to hard- g. Parts must be completely clean and free of oil and shop contamina- Thermal conductivity is significantly lower than that of carbon and ı steels. High thermal gradients and high stresses during rapid heating cause warpage and cracking in delicate or intricate parts. Preheat at to 790 °C (1400 to 1455 °F), only long enough to equalize temperature l sections. Extremely delicate or intricate parts would benefit from an tional prior preheat of 540 °C (1000 °F). Austenitized at 925 to 1010 1695 to 1850 °F). Use upper end of range for larger sections or when imum corrosion resistance and strength are required. If tempering ›erature exceeds 565 °C (1050 °F), use low side of the austenitizing range. It enhances ductility and impact resistance. Soaking time of 30 to 60 min is adequate for sections up to 13 mm (0.50 in.). Allow an additional 30 min for each additional inch or fraction thereof. Double soaking time if parts have been full or isothermal annealed. Increase time by 50%, if process annealed for long periods above 705 °C (1300 °F). Quench in oil or air. Oil quenching preferred, because it guarantees maximum corrosion resistance and ductility. Martempering in hot oil or salt is practicable because of high hardenability. As-quenched hardness, approximately 375 to 415 HB

Stabilizing. Optional. To transform essentially all retained austenite, use stabilizing or subzero treatment of –76 to –195 °C (–105 to –320 °F). Temper immediately to temper the new martensite to avoid cracking

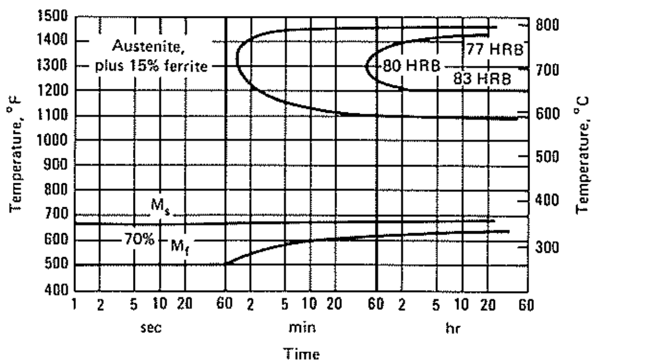
Tempering. Temper at 205 to 760 °C (400 to 1400 °F). Temper at 205 to 370 °C (400 to 700 °F) for hardness approximately 38 to 45 HRC. Temper at 565 to 605 °C (1050 to 1125 °F) for hardness approximately 25 to 31 HRC. Tempering at 370 to 650 °C (700 to 1200 °F) not recommended for parts requiring high toughness and optimum corrosion resistance. Causes a marked dip in impact resistance and lowered stress corrosion cracking resistance. Double tempering beneficial. Cool to room temperature between tempers

Nitriding.
Can be nitrided to case depth of approximately 0.203 mm (0.008 in.) in 48 h. See type 410 for further information

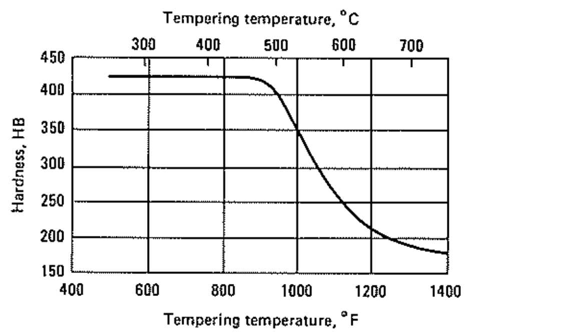
Recommended Processing Sequence

- Forge
- Anneal
- Rough machine
- Stress relieve
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size
- Nitride (if required)

3: Isothermal Transformation Diagram. Composition: 0.15 C ıx, 1.00 Mn max, 0.040 P max, 0.030 S max, 0.05 Si max, 11.50 13.00 Cr. Austenitized at 980 °C (1795 °F). As-quenched hard- ss, 41 HRC



403: Hardness vs Tempering Temperature. Composition: 0.10 to 0.115 C, 0.30 to 0.45 Mn, 0.014 to 0.018 P, 0.012 S max, 0.28 to 0.45 Si, 12.18 to 12.34 Cr, 0.34 to 0.63 Ni, 0.02 to 0.08 Mo. Heat treated at 1010 °C (1850 °F), ½ h. Oil quenched: 66 to 94 °C (150 to 200 °F). Double stress releived at 175 °C (345 °F), 15 min. Water quenched. Tempered 2 h. Heat treated, 14 mm (0.550 in.) round. Tested, 12.8 mm (0.505 in.) round. Source: Republic Steel

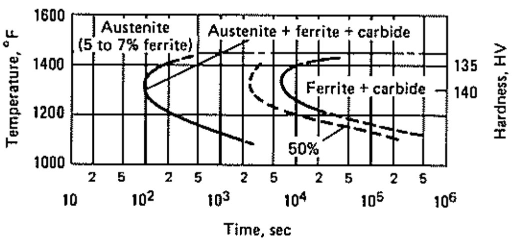


403: Soak Time for Annealing and Austenitizing (Aerospace Practice)

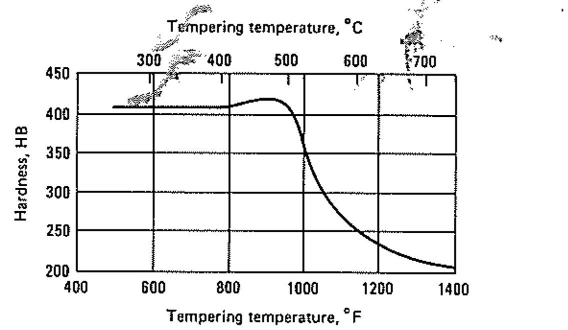
Thickness(a)		Minimum soak time (b,c,d,e,f) air or atmosphere		Minimum soak time (b,c,d,e,f) salt	
mm	in.	h	min	hours	min
Up to 5	Up to 0.250	...	25	...	18
5 to 15	Over 0.250 to 0.500	...	45	...	35
15 to 25	Over 0.500 to 1.000	1	...	...	40
25 to 40	Over 1.000 to 1.500	1	15	...	45
40 to 50	Over 1.500 to 2.000	1	30	...	50
50 to 65	Over 2.000 to 2.500	1	45	...	55
65 to 75	Over 2.500 to 3.000	2	...	1	...
75 to 90	Over 3.000 to 3.500	2	15	1	5
90 to 100	Over 3.500 to 4.000	2	30	1	10
100 to 115	Over 4.000 to 4.500	2	45	1	15
115 to 125	Over 4.500 to 5.000	3	...	1	20
125 to 200	Over 5.000 to 8.000	3	30	1	40
Over 200	Over 8.000	(g)		(h)	

(a) Thickness is the minimum dimension of the heaviest section of the part. (b) Soaking shall commence when all control, indicating, and recording thermocouples reach the specified set temperature, or if load thermocouples are used, when the part temperature reaches the minimum of the furnace uniformity tolerance at the set temperature. Parts coated with copper plate or similar reflective coatings that tend to reflect radiant heat shall have their soaking time increased by at least 50%, unless load thermocouples are used. (c) When load thermocouples are used, the soaking time shall be not less than 30 minutes. (d) In all cases, the parts shall be held for sufficient time to ensure that the center of the most massive area has reached temperature and the necessary transformation and diffusion have taken place. (e) Maximum soak time shall be twice the minimum specified, except for subcritical annealing. (f) Longer times may be necessary for parts with complex shapes or parts that won't heat uniformly. (g) 4 h plus 30 min for every 75 mm (3 in.), or portion thereof greater than 200 mm (8 in.). (h) 2 h plus 20 min for every 75 mm (3 in.), or portion thereof greater than 200 mm (8 in.). Source: AMS 2759/5

403: Partial Isothermal Transformation Diagram. Modified turbine grade. Composition: 0.074 C, 0.39 Mn, 0.034 P, 0.010 S, 0.27 Si, 0.30 Ni, 12.22 Cr, 0.52 Mo, 0.039 N. Austenitized at 1065 °C (1950 °F). Grain size: 6 to 8



403: Hardness vs Tempering Temperature. Composition: 0.115 C, 0.45 Mn, 0.014 P, 0.012 S, 0.45 Si, 12.18 Cr, 0.63 Ni, 0.08 Mo. Heat treated at 925 °C (1695 °F), ½ h. Oil quenched: 66 to 94 °C (150 to 200 °F). Double stress relieved at 175 °C (345 °F), 15 min. Water quenched. Tempered 1 h. Heat treated, 14 mm (0.550 in.) round. Tested, 12.8 mm (0.505 in.) round. Source: Republic Steel



410

Chemical Composition. AISI/UNS (S41000): 0.15 C, 1.00 Mn, 1.00 Si, 11.50 to 13.50 Cr, 0.04 P, 0.03 S

Similar Steels (U.S. and/or Foreign). AMS 5504, 5505, 5591, 5613, 5776, 5821; ASME SA194 (6), SA240, SA268, SA479; ASTM A176, A193, A194, A240, A276, A314, A473, A479, A493, A511, A580; FED QQ-S-763, QQ-W-423; MIL SPEC MIL-S-862; SAE J405 (51410), J412 (51410); (Ger.) DIN 1.4006; (Fr.) AFNOR Z 10 C 13, Z 10 C 14, Z 12 C 13; (Ital.) UNI X 12 Cr 13, X 10 Cr 13, X 12 Cr 13 KG, X 12 Cr 13 KW; (Jap.) JIS SUS 410; (Swed.) SS_{14} 2302; (U.K.) B.S. 410 S 21, En. 56 A, ANC 1 Grade A, 3 S. 61, S. 141

Characteristics. General purpose, heat treatable stainless steel. Corrosion resistant and heat resistant. Capable of hardening to 42 HRC or slightly higher. Can be tempered to wide range of strength and impact resistance. Can be quenched in oil or air. Oil quenching guarantees maximum corrosion resistance. High alloy content causes sluggish transformation and high hardenability. For these reasons, maximum hardness is obtainable by air quenching in the center of sections up to approximately 305 mm (12 in.) thick. Can be martempered with ease. Can be full, process, or isothermal annealed. Has good corrosion resistance. Susceptible to stress corrosion cracking in corrosive environments, when stress is above threshold level for that particular environment. Magnetic in all conditions. Fair machinability. Resists oxidation up to 815 °C (1500 °F)

Forging. Start forging at 1095 to 1205 °C (2005 to 2200 °F). Do not forge after temperature of forging stock drops below 870 to 925 °C (1600 to 1695 °F)

ɘcommended Heat Treating Practice

ɔrmalizing. Do not normalize

ınealing. Can be process, isothermal, or full annealed:

Process anneal in subcritical temperature range of 650 to 760 °C (1200 ːo 1400 °F). Use clean, rectified salt bath or an atmosphere that is ːompatible with this temperature range. Soaking time dependent on size ɔf work. Air cool. Hardness, 86 to 92 HRB

Isothermal anneal by heating at 830 to 885 °C (1525 to 1625 °F). Cool ːlowly to 705 °C (1300 °F). Hold for 6 h. Hardness, approximately 85 HRB

Full anneal at 830 to 885 °C (1525 to 1625 °F). Cool slowly to 595 °C (1105 °F) at a rate not to exceed 17 to 22 °C (30 to 40 °F) per h. After ːhis, cooling rate has no effect on hardness. Avoid carburization or decarburization. Can use atmospheric protection in the form of a vacıum, the inert gases argon or helium (both expensive), or nitrogen. All ːhould have dew point below −51 °C (−60 °F). Exothermic- or endothernic-generated atmospheres can be used, providing carbon potential of he gas matches carbon content of the steel. Annealed hardness, 75 to 85 HRB. Full annealing is expensive and time consuming. Should not be ısed, except as required for subsequent severe forming

ıerospace practice, parts are annealed at 845 °C (1555 °F) and austenitized ɔ80 °C (1795 °F), then quenched in oil or polymer. Cooling in air or other es is permitted for parts less than 6.25 mm (0.250 in.) in maximum ːkness, provided they are not racked or densely packed. In annealing, parts cooled to below 595 °C (1105 °F) at a rate not to exceed 30 °C (55 °F) per ollowed by air cooling to ambient. An austenitizing temperature of 955 °C 50 °F) is permitted for thin sections to minimize warpage

ırdening. Atmospheric protection rules for annealing apply to hardng. Parts must be completely clean and free of oil and shop contaminaı. Thermal conductivity is significantly lower than that of carbon and ɔy steels. High thermal gradients and high stresses during rapid heating y cause warpage and cracking in delicate or intricate parts. Preheat at) to 790 °C (1400 to 1455 °F), only long enough to equalize temperature ıll sections. Extremely delicate or intricate parts would benefit from an litional prior preheat of 540 °C (1000 °F). Austenitized at 925 to 1010 (1695 to 1850 °F). Use upper end of range for larger sections or when ximum corrosion resistance and strength are required. If tempering ıperature exceeds 565 °C (1050 °F), use low side of the austenitizing ge. It enhances ductility and impact resistance. Soaking time of 30 to 60 ı is adequate for sections up to 13 mm (0.50 in.). Allow an additional 30 ı for each additional inch or fraction thereof. Double soaking time if ts have been full or isothermal annealed. Increase time by 50%, if cess annealed for long periods above 675 °C (1245 °F). Quench in oil ıir. Oil quenching preferred, because it guarantees maximum corrosion resistance and ductility. Martempering in hot oil or salt is practicable because of high hardenability. As-quenched hardness, approximately 375 to 415 HB

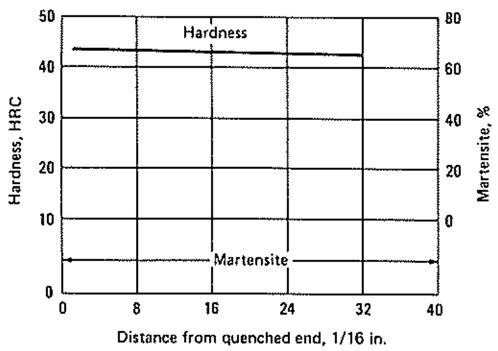
Stabilizing. To transform essentially all retained austenite, use stabilizing or subzero treatment of −76 to −195 °C (−105 to −320 °F). Temper immediately to temper the new martensite to avoid cracking

Tempering. Temper at 205 to 705 °C (400 to 1300 °F). Temper at 205 to 370 °C (400 to 700 °F) for hardness approximately 38 to 47 HRC. Temper at 565 to 605 °C (1050 to 1125 °F) for hardness approximately 25 to 31 HRC. Tempering at 370 to 565 °C (700 to 1050 °F) not recommended for parts requiring high toughness and optimum corrosion resistance. Causes a marked dip in impact resistance and lowered stress corrosion cracking resistance. Double tempering beneficial. Cool to room temperature between tempers

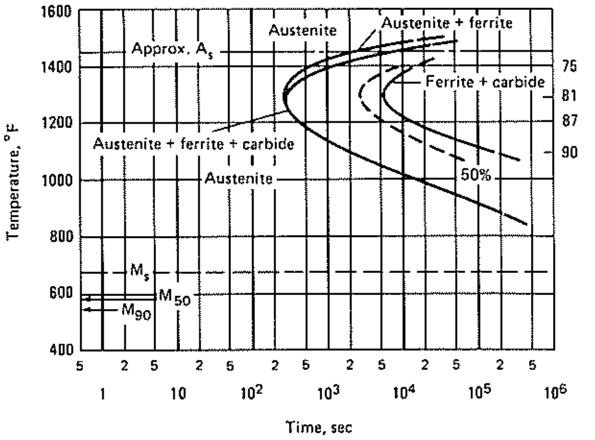
Nitriding. Not recommended for severe corrosive environment. Nitrided case impairs resistance to corrosion in most media. Maximum case obtainable is about 0.203 mm (0.008 in.) in 48 h. Before nitriding, parts should be quenched and tempered, with tempering at least 14 °C (25 °F) higher than the nitriding temperature. All sharp corners should be replaced with radii of not less than 1.588 mm (0.06 in.). The film of oxide that protects stainless alloys from oxidation and corrosion must be removed. This may be accomplished by wet blasting, pickling, chemical reduction in a reducing atmosphere, submersion in molten salts, or by one of several proprietary processes. If doubt exists that complete and uniform depassivation has occurred, further reduction of the oxide may be accomplished in a furnace by reducing hydrogen atmosphere or suitable proprietary agent. After depassivation, avoid contamination of surface by finger or hand marking. Single-stage nitriding usually adequate at 525 to 550 °C (975 to 1020 °F) for 20 to 48 h, depending on case depth required. Hardness above 1000 HK can be expected for several thousandths of an inch before hardness gradient blends into core

Recommended Processing Sequence

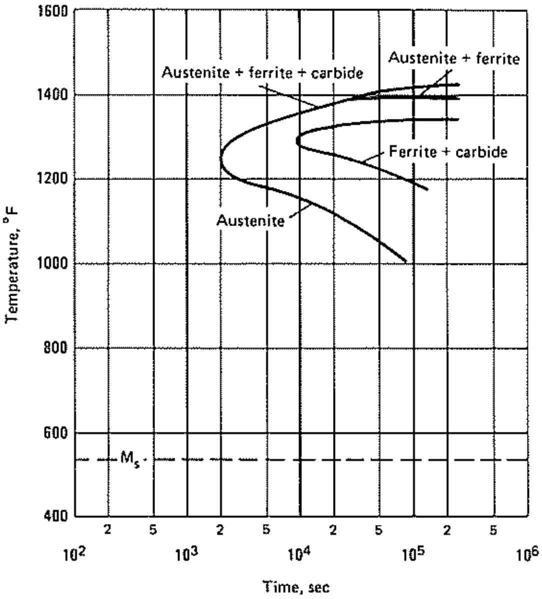
- Forge
- Anneal
- Rough machine
- Stress relieve
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size
- Nitride (if required)



410: End-Quench Hardenability

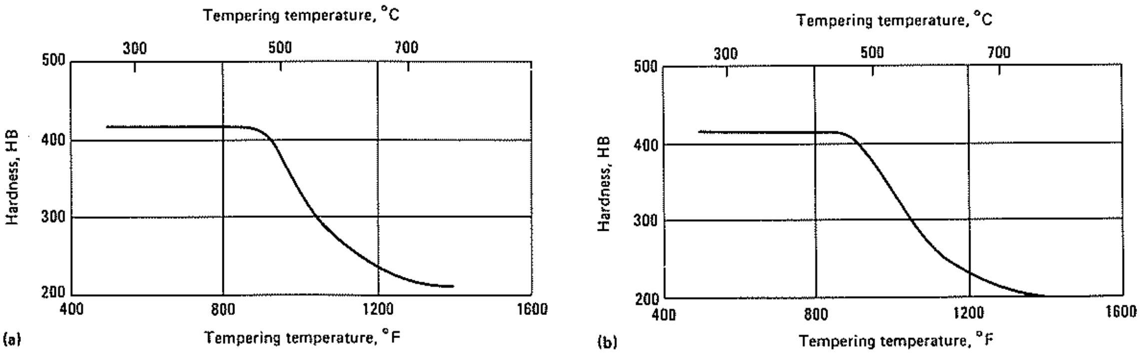


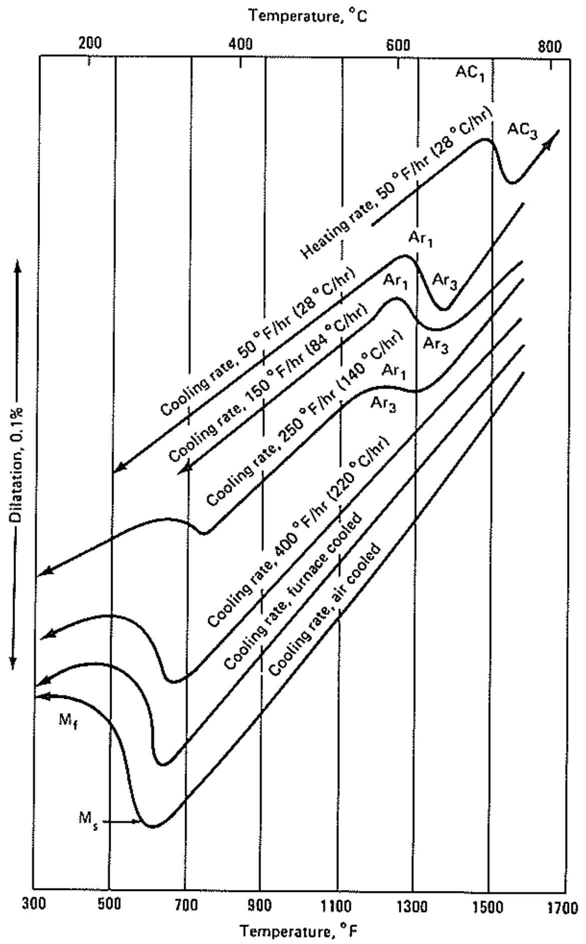
410: Isothermal Transformation Diagram. Composition: 0.11 C, 0.44 Mn, 0.37 Si, 0.16 Ni, 12.18 Cr. Austenitized at 980 °C (1795 °F). Grain size, 6 to 7



410: Isothermal Transformation Diagram. Modified 410. Composition: 0.22 C, 0.54 Mn, 0.64 Ni, 12.46 Cr, 0.99 Mo, 0.29 V. Austenitized at 1010 °C (1850 °F). Grain size, 4 to 5

410: Hardness vs Tempering Temperature. (a) Quenched from 925 °C (1695 °F). (b) Quenched from 1010 °C (1850 °F)





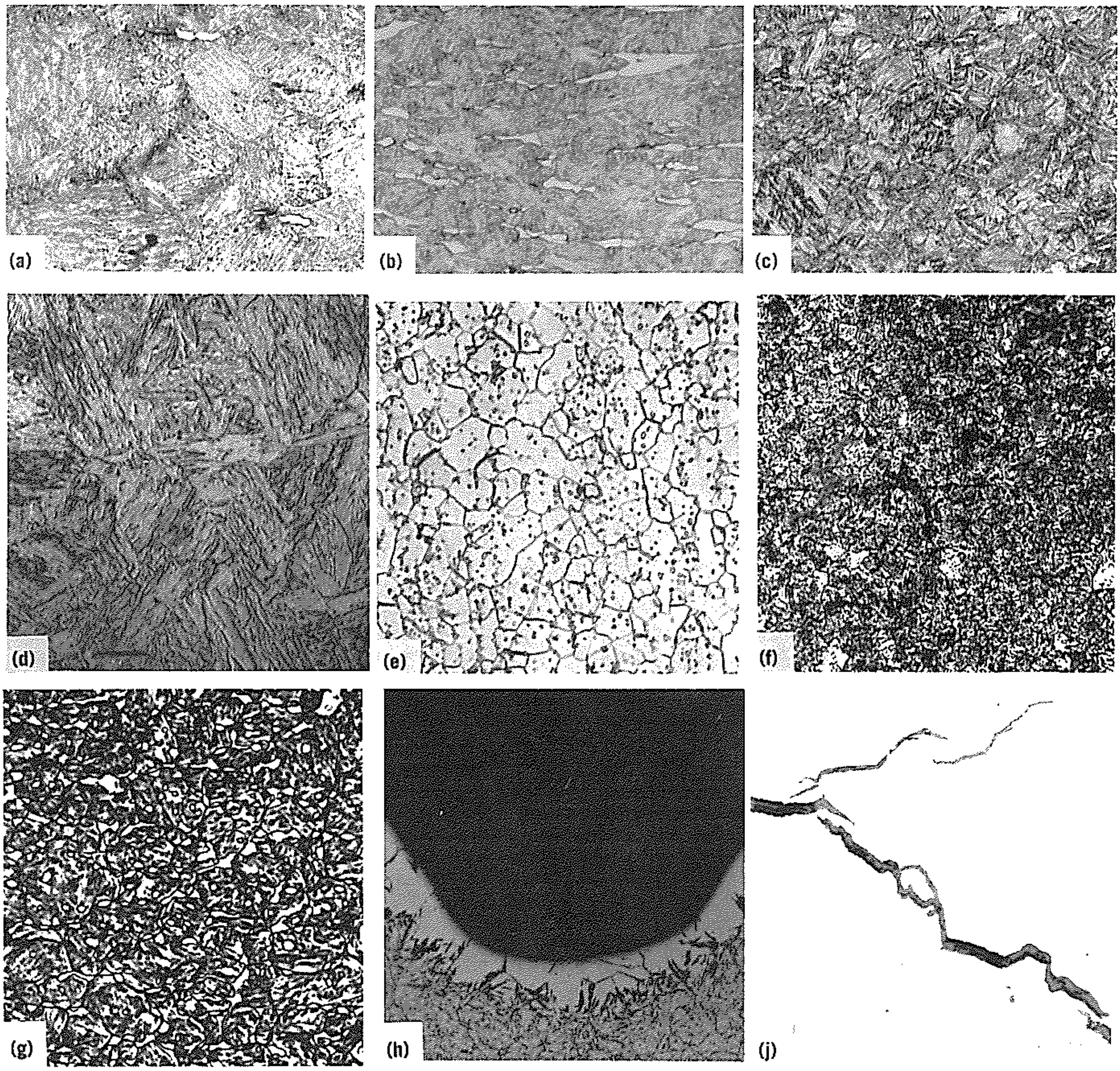
410: Dilatometric Curve. Effects of cooling rates on transformation of a chromium stainless steel. Composition: 0.098 C, 0.41 Mn, 0.023 P, 0.010 S, 0.62 Si, 0.30 Ni, 12.30 Cr, 0.03 Mo, 0.21 Cu. Region of Ar_3 to Ar_1 transformation is for slowly cooled dilatometer tests. Ferrite and carbide formation occurs through this range, on slow cooling. Continuation of cooling curves through transformation of austenite to martensite, starting at M_s point and finishing at M_f point. Note the large amount of expansion typical of the martensite reaction. Source: Republic Steel

: Soak Time for Annealing and Austenitizing (Aerospace Practice)

Thickness(a)		Minimum soak Time (b,c,d,e,f) air or atmosphere		Minimum soak Time (b,c,d,e,f) salt	
mm	in.	h	min	h	min
Up to 5	Up to 0.250	...	25	...	18
5 to 15	Over 0.250 to 0.500	...	45	...	35
15 to 25	Over 0.500 to 1.000	1	...	...	40
25 to 40	Over 1.000 to 1.500	1	15	...	45
40 to 50	Over 1.500 to 2.000	1	30	...	50
50 to 65	Over 2.000 to 2.500	1	45	...	55
65 to 75	Over 2.500 to 3.000	2	...	1	...
75 to 90	Over 3.000 to 3.500	2	15	1	5
90 to 100	Over 3.500 to 4.000	2	30	1	10
100 to 115	Over 4.000 to 4.500	2	45	1	15
115 to 125	Over 4.500 to 5.000	3	...	1	20
125 to 200	Over 5.000 to 8.000	3	30	1	40
Over 200	Over 8.000	(g)		(h)	

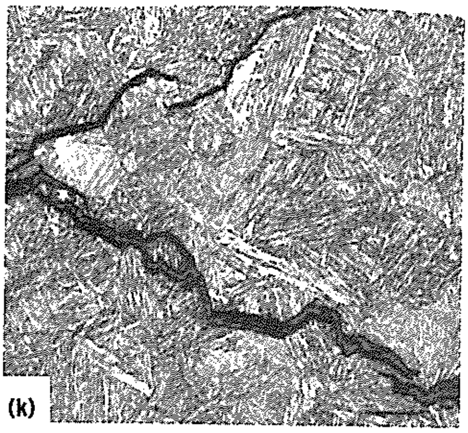
ickness is the minimum dimension of the heaviest section of the part. (b) Soaking shall commence when all control, indicating, and recording thermocouples reach the speci- et temperature, or if load thermocouples are used, when the part temperature reaches the minimum of the furnace uniformity tolerance at the set temperature. Parts coated with r plate or similar reflective coatings that tend to reflect radiant heat shall have their soaking time increased by at least 50%, unless load thermocouples are used. (c) When load ocouples are used, the soaking time shall be not less than 30 min. (d) In all cases, the parts shall be held for sufficient time to ensure that the center of the most massive area has ed temperature and the necessary transformation and diffusion have taken place. (e) Maximum soak time shall be twice the minimum specified, except for subcritical anneal-) Longer times may be necessary for parts with complex shapes or parts that won't heat uniformly. (g) 4 h hour plus 30 min for every 75 mm (3 in.), or portion thereof greater 00 mm (8 in.). (h) 2 h plus 20 min for every 75 mm (3 in.), or portion thereof greater than 200 mm (8 in.). Source: AMS 2759/5

410: Microstructures. (a) Kalling's reagent, 100×. Stainless-steel in as-forged condition. Hot worked structure is banded delta ferrite (horizontal, light) in martensite matrix. (b) Vilella's reagent, 100×. Stainless steel, as-forged. Hot worked structure consists of larger, more elongated banded delta ferrite than (a), in martensite matrix. (c) Vilella's reagent, 100×. Forging. Hardened by: holding 1 h at 980 °C (1795 °F); air quenched; tempered 2 h at 565 °C (1050 °F); and air cooled. Tempered martensite and carbide. (d) Vilella's reagent, 500×. Strip hardened by rapid air cooling from 980 °C (1795 °F) to room temperature. Tempered 4 h at 205 °C (400 °F). Martensite with precipitated carbide particles. Oblique illumination. (e) Vilella's reagent, 500×. Strip annealed by holding at 815 °C (1500 °F). Furnace cool to 595 °C (1105 °F). Air cool to room temperature. Matrix of equiaxed ferrite grains with randomly dispersed particles of chromium carbide. (f) Electrolytic: HCl-methanol, 500×. Strip in hardened condition: after annealing at 800 °C (1475 °F); holding for 30 min at 955 °C (1750 °F); and air cooled. Ferrite-free martensite. (g) Electrolytic: HCl-methanol, 500×. Same as (f), except less balanced composition. Causes martensite matrix to have islands of ferrite (white). (h)Super picral, 250×. Section through rolled thread on hardened fastener. Austenite reversion at surface, resulting from nitrogen pickup during heat treatment. (j) As-polished, not etched. 100×. Forging: hardened and tempered. Quench crack acquired oxide scale during air tempering.

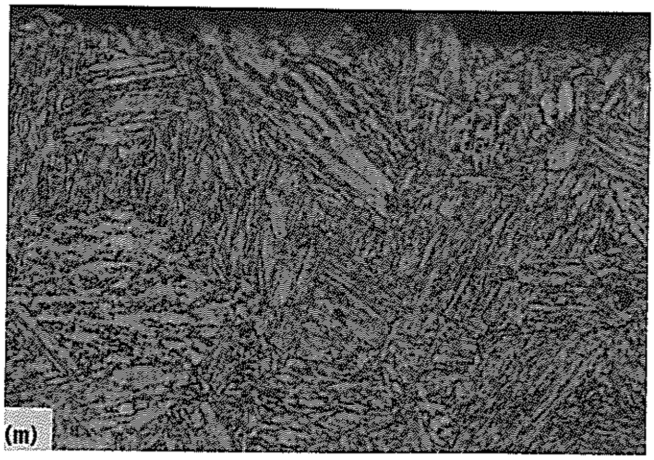


(continued)

l10: Microstructures (continued).(k) Vilella's reagent, 100×. Same as (j). After etching, the crack was accentuated and revealed tempered nartensite and carbide. (m) Super picral, 500×. Hardened and tempered. Cross section shows as-machined surface, after electrochemical nachining. Note complete absence of disturbed metal



(k)



(m)

14

iemical Composition. **AISI/UNS (S41400):** 0.15 C, 1.00 Mn, 0 Si, 1.25 to 2.50 Ni, 11.50 to 13.50 Cr, 0.04 P, 0.03 S

nilar Steels (U.S. and/or Foreign). AMS 5615; ASTM A276, 14, A473, A511, A580; FED QQ-S-763; SAE J405 (51414)

iaracteristics. Similar to type 410. Nickel added to increase corro- n resistance and strength. Capable of hardening to approximately 45 .C. Requires about 28 to 42 °C (55 to 75 °F) higher tempering tempera- : than type 410 to attain same final hardness. Can be quenched in oil or Can be martempered. Oil quenching guarantees maximum corrosion istance. High alloy content causes sluggish transformation and high denability. For these reasons, maximum hardness is obtainable by air nching in center of sections up to approximately 305 mm (12 in.) thick. nealing restricted to process anneal. Good corrosion resistance. Suscep- e to stress corrosion cracking in corrosive environments, when stress is ve threshold level for that particular environment. Magnetic in all ditions. Fair machinability

rging. Start forging at 1150 to 1205 °C (2100 to 2200 °F). Do not ;e after temperature of forging stock drops below 870 to 980 °C (1600 795 °F). Cool slowly from finishing temperature. Anneal

:commended Heat Treating Practice

rmalizing. Do not normalize

nealing. For best machinability, heat to 955 °C (1750 °F). Temper n 650 to 730 °C (1200 to 1350 °F). Annealed hardness, 99 HRB to 24 C. When the steel is to be subsequently hardened and tempered, tem- ng at 650 to 730 °C (1200 to 1350 °F) is sufficient for good machinabil- When this treatment does not provide machinability necessary for 1-speed tools, it may be advantageous to air cool steel from low tem- iture, 815 to 845 °C (1500 to 1555 °F), with subsequent temper at 620 05 °C (1150 to 1300 °F). Exact temperature range governed by actual amount of nickel present in the particular heat being annealed. Full annealing not recommended

Hardening. Can use atmospheric protection in the form of vacuum, inert gas, salt baths, endothermic- or exothermic-generated gas. Parts must be completely clean and free of oil and shop contamination. Thermal conductivity is significantly lower than that of carbon and alloy steels. High thermal gradients and high stresses during rapid heating may cause warpage and cracking in delicate or intricate parts. Preheat at 760 to 790 °C (1400 to 1455 °F), only long enough to equalize temperature in all sections. Extremely delicate or intricate parts would benefit from an additional prior preheat of 540 °C (1000 °F). Austenitized at 925 to 1050 °C (1695 to 1920 °F). Use upper end of range for larger sections or when maximum corrosion resistance and strength are required. If tempering temperature exceeds 565 °C (1050 °F), use low side of the austenitizing range. It enhances ductility and impact resistance. Soaking time of 30 to 60 min is adequate for sections up to 13 mm (0.50 in.). Allow an additional 30 min for each additional inch or fraction thereof. Increase soaking time by at least 50% if process annealed for long periods above 675 °C (1245 °F). Quench in oil or air. Oil quenching preferred, because it guarantees maximum corrosion resistance and ductility. Martempering in hot oil or salt is suitable because of high hardenability. As-quenched hardness, approximately 388 to 456 HB

Stabilizing. To transform essentially all retained austenite, use stabilizing or subzero treatment of –76 to –195 °C (–105 to –320 °F). Temper immediately to temper the new martensite to avoid cracking

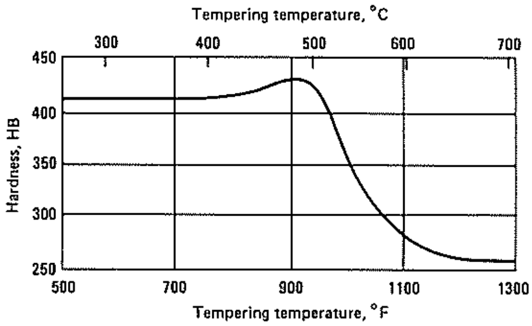
Tempering. Temper at 230 to 650 °C (445 to 1200 °F). Temper at 230 to 370 °C (445 to 700 °F) for hardness approximately 45 HRC. Temper at 595 to 650 °C (1105 to 1200 °F) for hardness approximately 25 to 31 HRC. Tempering at 370 to 595 °C (700 to 1105 °F) not recommended for parts requiring high toughness and optimum corrosion resistance. Causes a marked dip in impact resistance and lowered stress corrosion cracking resistance. Double tempering beneficial. Cool to room temperature between tempers

Nitriding. Can be nitrided to case depth of approximately 0.203 mm (0.008 in.) in 48 h. See type 410 for further information

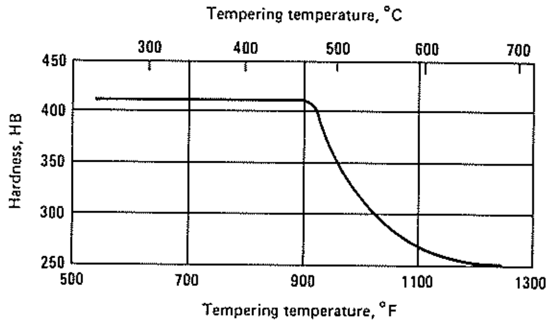
Recommended Processing Sequence

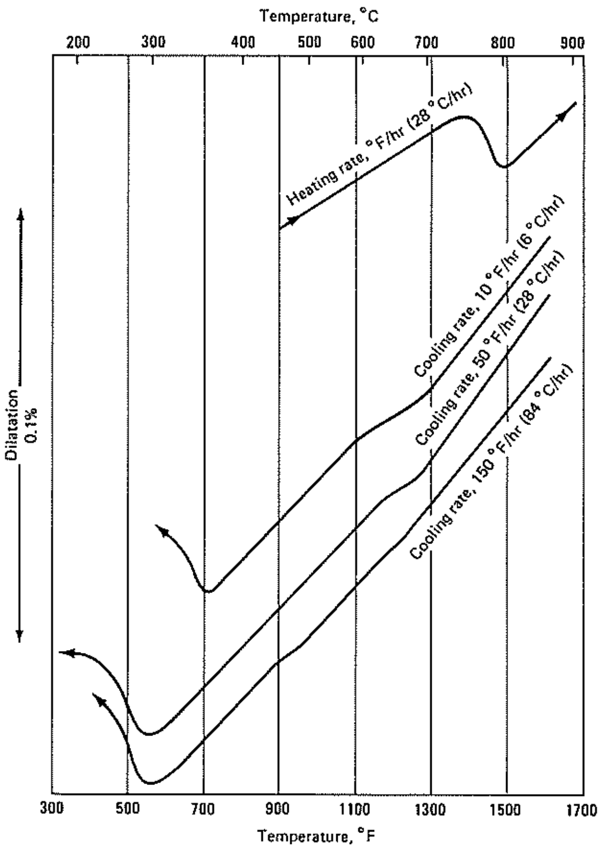
- Forge
- Anneal
- Rough machine
- Stress relieve
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size
- Nitride (if required)

414: Hardness vs Tempering Temperature. Composition: 0.13 C, 0.54 Mn, 0.021 P, 0.023 S, 0.34 Si, 1.77 Ni, 13.36 Cr, 0.19 Mo. Heat treated at 1040 °C (1905 °F), ½ h. Oil quenched at 66 to 94 °C (150 to 200 °F). Double stress relieved at 175 °C (345 °F), 15 min. Water quenched. Tempered 2 h. Heat treated, 14 mm (0.550 in.) round. Tested, 12.8 mm (0.505 in.) round. Source: Republic Steel



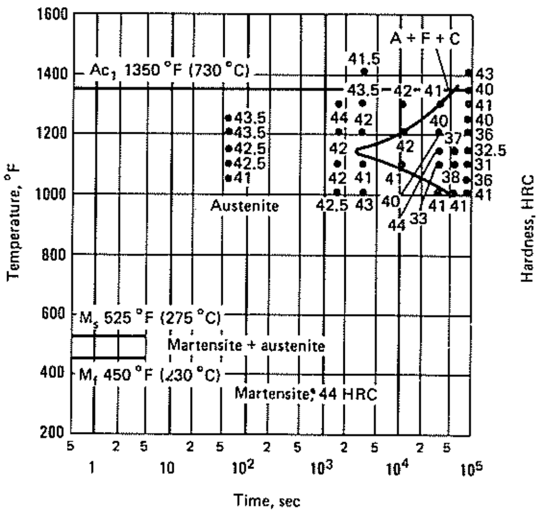
414: Hardness vs Tempering Temperature. Composition: 0.13 C, 0.54 Mn, 0.021 P, 0.023 S, 0.34 Si, 1.77 Ni, 13.36 Cr, 0.19 Mo. Heat treated at 925 °C (1700 °F), ½ h. Oil quenched at 66 to 94 °C (150 to 200 °F). Double stress relieved at 175 °C (345 °F), 15 min. Water quenched. Tempered 2 h. Source: Republic Steel



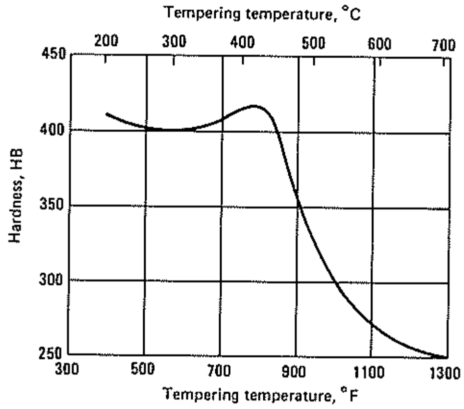


414: Dilatometric Curves. Composition: 0.104 C, 0.46 Mn, 0.019 P, 0.012 S, 0.32 Si, 1.86 Ni, 12.55 Cr, 0.08 Mo. Transformation characteristics shown. Source: Republic Steel

414: Isothermal Transformation Diagram. Composition: 0.10 C, 0.46 Mn, 0.018 P, 0.015 S, 0.33 Si, 1.86 Ni, 12.65 Cr, 0.05 Mo. Austenitized at 1040 °C (1905 °F). Rockwell C hardness measured after 24 h at isotherm. Source: Republic Steel



414: Hardness vs Tempering Temperature. 1010 °C (1850 °F). Oil quenched. Tempered 2 h at temperature indicated



·16, 416Se

hemical Composition. 416. **AISI/UNS (S41600):** 0.15 C, 1.25 n, 1.00 Si, 12.00 to 14.00 Cr, 0.06 P, 0.15 S min, 0.6 Mo (optional). .6Se. **AISI/UNS (S41623):** 0.15 C, 1.25 Mn, 1.00 Si, 12.00 to 14.00 Cr,)6 P, 0.06 S, 0.15 Se min

imilar Steels (U.S. and/or Foreign). 416. ASME SA194; ;TM A194, A314, A473, A581, A582; FED QQ-W-423; MIL SPEC IL-S-862; SAE J405 (51416); (Ger.) DIN 1.4005; (Fr.) AFNOR Z 12 CF ; (Ital.) UNI X 12 CrS 13; (Swed.) SS_{14} 2380; (U.K.) B.S. 416 S 21. .6Se. AMS 5610; ASME SA194; ASTM A194, A314, A473, A511, A581, ;82; MIL SPEC MIL-S-862; SAE J405 (51416 Se)

haracteristics. Another version of type 410, where S (type 416) or : (type 416Se) has been added to improve machinability. Popular selec-›n for machining in screw machines or turret lathes. Capable of hardening 42 HRC or slightly higher. Can be tempered to wide range of strength d impact resistance. Deep hardening. Oil quenching recommended. Can martempered. Tempering in the 370 to 565 °C (700 to 1050 °F) range wers impact resistance. Can be full, process, or isothermal annealed. ›od nonseizing and nongalling properties. Good corrosion resistance. ısceptible to stress corrosion cracking in corrosive environments, when ess is above threshold level for that particular environment. Magnetic in conditions. Resists oxidation up to 760 °C (1400 °F)

›rging. Not recommended for forging operations requiring severe de-·mation. Sulfur or selenium, added to enhance machinability, tends to ;ate hot shortness. When forged, start forging at 1150 to 1260 °C (2100 2300 °F). Do not forge after temperature of forging stock drops below 0 to 980 °C (1600 to 1795 °F)

ecommended Heat Treating Practice

›rmalizing. Do not normalize

ınealing. Can be process, isothermal, or full annealed:

- *Process anneal* in subcritical temperature range of 650 to 760 °C (1200 to 1400 °F). Use clean, rectified salt bath or an atmosphere that is compatible with this temperature range. Soaking and softening time dependent on size of work. Air cool. Hardness, 86 to 92 HRB
- *Isothermal anneal* by heating at 830 to 885 °C (1525 to 1625 °F). Cool slowly to 720 °C (1330 °F). Hold for 2 h. Hardness, approximately 85 HRB
- *Full anneal* at 830 to 885 °C (1525 to 1625 °F). Cool slowly to 595 °C (1105 °F) at a rate not to exceed 17 to 22 °C (30 to 40 °F) per h. After this, cooling rate has no effect on hardness. Avoid carburization or decarburization. Can use atmospheric protection in the form of a vacuum, the inert gases argon or helium (both expensive), or nitrogen. All should have dew point below –51 °C (–60 °F). Exothermic- or endothermic-generated atmospheres can be used, providing carbon potential of the gas matches carbon content of the steel. Hardness, 75 to 85 HRB. Full annealing is expensive and time consuming. Should not be used, except as required for subsequent severe forming

In aerospace practice, parts are annealed at 870 °C (1600 °F) and austenitized at 1025 °C (1875 °F), then quenched in oil or polymer. In annealing, parts are cooled to below 595 °C (1105 °F) at a rate not to exceed 30 °C (55 °F) per h, followed by air cooling to ambient. An austenitizing temperature of 955 °C (1750 °F) is permitted for thin sections to minimize warpage

Hardening. Atmospheric protection rules for annealing apply to hardening. Parts must be completely clean and free of oil and shop contamination. Thermal conductivity is significantly lower than that of carbon and alloy steels. High thermal gradients and high stresses during rapid heating may cause warpage and cracking in delicate or intricate parts. Preheat at 760 to 790 °C (1400 to 1455 °F), only long enough to equalize temperature in all sections. Extremely delicate or intricate parts would benefit from an additional prior preheat of 540 °C (1000 °F). Austenitized at 925 to 1010 °C (1695 to 1850 °F). Use upper end of range for larger sections or when maximum corrosion resistance and strength are required. If tempering temperature exceeds 565 °C (1050 °F), use low side of the austenitizing range. It enhances ductility and impact resistance. Soaking time of 30 to 60 min is adequate for sections up to 13 mm (0.50 in.). Allow an additional 30 min for each additional inch or fraction thereof. Double soaking time if parts have been full or process annealed. Increase time by 50% if process annealed above 675 °C (1245 °F). Oil quench. Martempering in hot oil or salt is suitable because of high hardenability. As-quenched hardness, approximately 375 to 415 HB

Stabilizing. To transform essentially all retained austenite, use stabilizing or subzero treatment of –76 to –195 °C (–105 to –320 °F). Temper immediately to temper the new martensite to avoid cracking

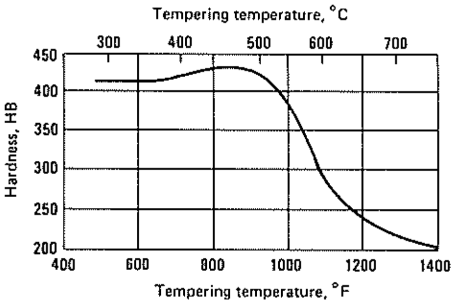
Tempering. Temper at 205 to 760 °C (400 to 1400 °F). Temper at 205 to 370 °C (400 to 700 °F) for hardness approximately 35 to 45 HRC. Temper at 565 to 605 °C (1050 to 1125 °F) for hardness approximately 25 to 31 HRC. Tempering at 370 to 565 °C (700 to 1050 °F) not recommended for parts requiring high toughness and optimum corrosion resistance. Causes a marked dip in impact resistance and lowered stress corrosion cracking resistance. Double tempering beneficial. Cool to room temperature between tempers

Nitriding. Can be nitrided to case depth of approximately 0.203 mm (0.008 in.) in approximately 48 h. See type 410 for further information

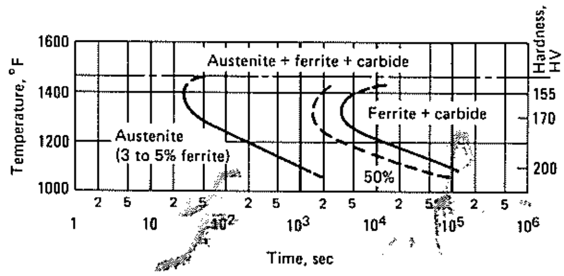
Recommended Processing Sequence

- Forge
- Anneal
- Rough machine
- Stress relieve
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (optional)
- Temper
- Final grind to size
- Nitride (if required)

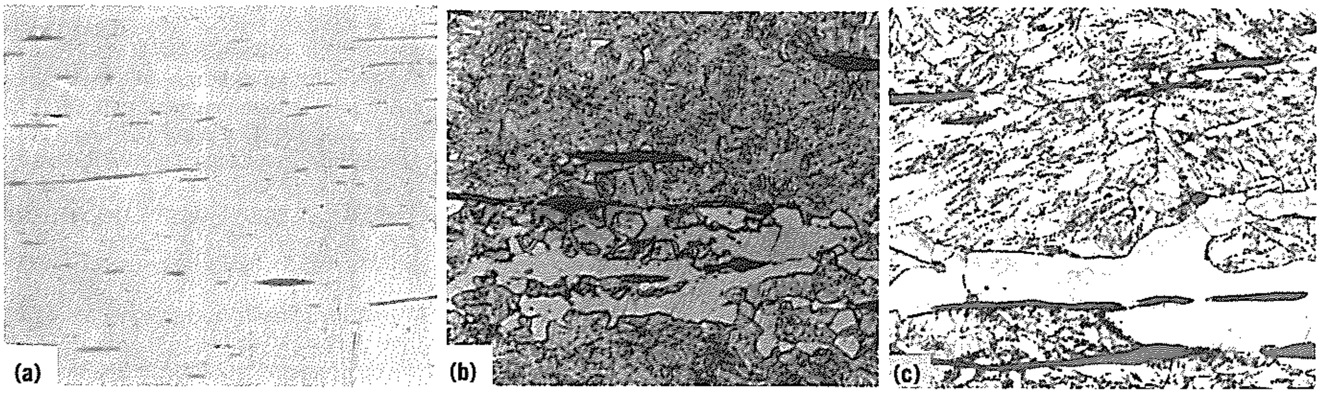
416: Hardness vs Tempering Temperature. Composition: 0.11 C, 0.87 Mn, 0.018 P, 0.360 S, 0.42 Si, 0.33 Ni, 13.06 Cr, 0.09 Mo. Heat treated at 980 °C (1795 °F), ½ h. Oil quenched at 66 to 94 °C (150 to 200 °F). Double stress relieved at 175 °C (345 °F), 15 min. Water quenched. Tempered 2 h. Heat treated 14 mm (0.550 in.) round. Tested, 12.8 mm (0.505 in.) round. Source: Republic Steel

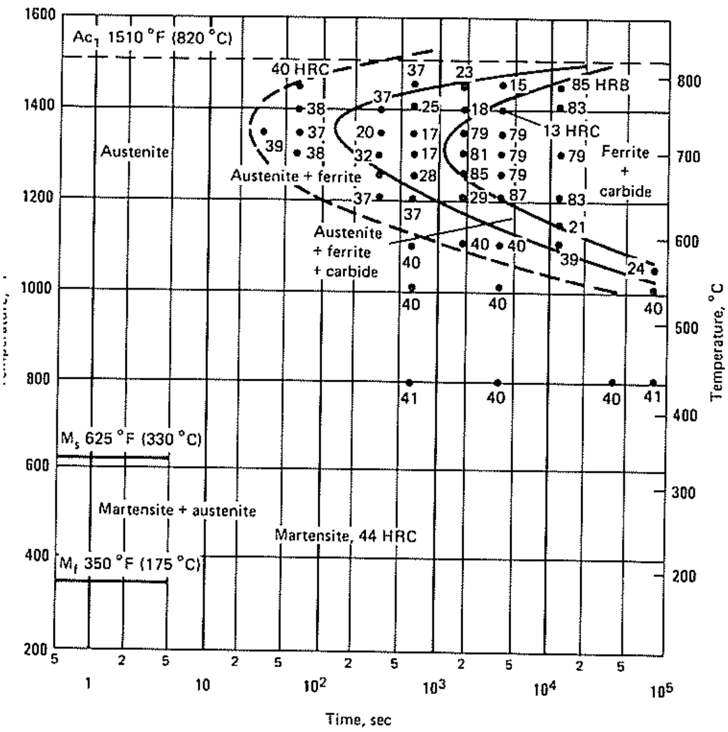


416: Partial Isothermal Transformation Diagram. Free-machining steel. Composition: 0.12 C, 0.79 Mn, 0.017 P, 0.190 S, 0.74 Si, 0.25 Ni, 12.82 Cr, 0.05 Mo, 0.037 N, 0.08 Zr. Austenitized at 980 °C (1795 °F). Grain size, 7 to 9

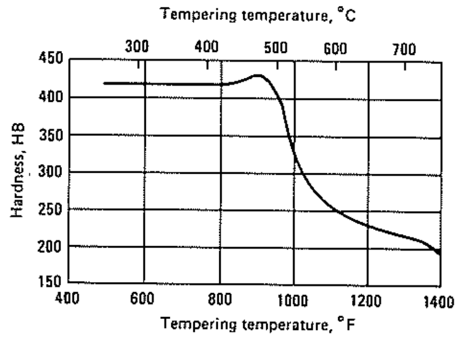


416: Microstructures. (a) Polished, not etched. 250×. Bar stock with 0.150 S max, to promote chip breakage and improve machinability. Longitudinal section. Cross section shows elongated, stringer-type inclusions of manganese sulfide (horizontal dark streaks). (b) Vilella's reagent, 500×. Bar, austenitized at 980 to 1010 °C (1795 to 1850 °F). Oil quenched. Tempered at 565 °C (1050 °F). Stringers of manganese sulfide (dark) and blocky ferrite (light, outlined). Matrix of tempered martensite. (c) 5% picric acid and 1% hydrochloric acid, 750×. Bar in annealed condition. Longitudinal cross section. Delta ferrite (light etching) in matrix of tempered martensite. Stringers of manganese sulfide (dark, elongated)





416: Isothermal Transformation Diagram. Free-machining steel. Composition: 0.10 C, 0.94 Mn, 0.025 P, 0.350 S, 0.44 Si, 0.31 Ni, 12.40 Cr, 0.44 Mo. Austenitized at 900 °C (1650 °F). Source: Republic Steel



416: Hardness vs Tempering Temperature. Composition: 0.11 C, 0.87 Mn, 0.018 P, 0.360 S, 0.42 Si, 0.33 Ni, 13.06 Cr, 0.09 Mo. Heat treated at 925 °C (1695 °F), ½ h. Oil quenched at 66 to 94 °C (150 to 200 °F). Double stress relieved at 175 °C (350 °F), 15 min. Water quenched. Tempered 2 h. Heat treated 14 mm (0.550 in.) round. Tested, 12.8 mm (0.505 in.) round. Source: Republic Steel

416: Soak Time for Annealing and Austenitizing (Aerospace Practice)

Thickness(a)		Minimum soak Time (b,c,d,e,f) air or atmosphere		Minimum soak Time (b,c,d,e,f) salt	
mm	in.	h	min	h	min
Up to 5	Up to 0.250	...	25	...	18
5 to 15	Over 0.250 to 0.500	...	45	...	35
15 to 25	Over 0.500 to 1.000	1	...	...	40
25 to 40	Over 1.000 to 1.500	1	15	...	45
40 to 50	Over 1.500 to 2.000	1	30	...	50
50 to 65	Over 2.000 to 2.500	1	45	...	55
65 to 75	Over 2.500 to 3.000	2	...	1	...
75 to 90	Over 3.000 to 3.500	2	15	1	5
90 to 100	Over 3.500 to 4.000	2	30	1	10
100 to 115	Over 4.000 to 4.500	2	45	1	15
115 to 125	Over 4.500 to 5.000	3	...	1	20
125 to 200	Over 5.000 to 8.000	3	30	1	40
Over 200	Over 8.000	(g)		(h)	

(a) Thickness is the minimum dimension of the heaviest section of the part. (b) Soaking shall commence when all control, indicating, and recording thermocouples reach the specified set temperature, or if load thermocouples are used, when the part temperature reaches the minimum of the furnace uniformity tolerance at the set temperature. Parts coated with copper plate or similar reflective coatings that tend to reflect radiant heat shall have their soaking time increased by at least 50%, unless load thermocouples are used. (c) When load thermocouples are used, the soaking time shall be not less than 30 min. (d) In all cases, the parts shall be held for sufficient time to ensure that the center of the most massive area has reached temperature and the necessary transformation and diffusion have taken place. (e) Maximum soak time shall be twice the minimum specified, except for subcritical annealing. (f) Longer times may be necessary for parts with complex shapes or parts that won't heat uniformly. (g) 4 h hour plus 30 min for every 75 mm (3 in.), or portion thereof greater than 200 mm (8 in.). (h) 2 h plus 20 min for every 75 mm (3 in.), or portion thereof greater than 200 mm (8 in.). Source: AMS 2759/5

420, 420F

Chemical Composition. **420. AISI/UNS (S42000):** 0.15 C min, 1.00 Mn, 0.04 P, 0.03 S, 1.00 Si, 12.00 to 14.00 Cr. **420F. (UNS S42020):** 0.15 C min, 1.25 Mn, 1.00 Si, 12.00 to 14.00 Cr, 0.06 P, 0.15 S min, 0.6 Mo (optional)

Similar Steels (U.S. and/or Foreign). **420.** AMS 5506, 5621; ASTM A276, A314, A473, A580; FED QQ-S-763, QQ-S-766, QQ-W-423; MIL SPEC MIL-S-862; SAE J405 (51420); (Ger.) DIN 1.4021; (Fr.) AFNOR Z 20 CB; (Ital.) UNI X 20 Cr 13 X 1; (Jap.) JIS SUS 420 J1; (Swed.) SS_{14} 2303; (U.K.) B.S. 420 S 37, CDS-18, En. 56 C, 3 S. 62. **420F.** AMS 5620; SAE J405 (51420 F)

Characteristics. Deep hardening. Can be hardened to slightly over 500 HB. Quenched in oil or air. Can be readily martempered. Magnetic in all conditions. Optimum corrosion resistance in hardened and tempered condition. Can be full, process, or isothermal annealed. Used for cutlery and general use where strength, ductility, and corrosion resistance are desired. Type 420F is a free-machining version of 420. Sulfur added to 420F to improve machining and nonseizing characteristics. Processing the same as for 420, except a higher initial forging temperature used to minimize hot short cracking

Forging. For type 420, start forging at 1065 to 1205 °C (1950 to 2200 °F). Do not forge after temperature of forging stock drops below 900 °C (1650 °F). For type 420F, forge at 1120 to 1230 °C (2050 to 2245 °F). Cool very slowly from finishing temperature. Anneal

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Can be process, isothermal, or full annealed:

- *Process anneal* in subcritical temperature range of 675 to 760 °C (1245 to 1400 °F). Use clean, rectified salt bath or an atmosphere that is compatible with this temperature range. Soaking and softening time dependent on size of work. Air cool. Hardness, 94 to 97 HRB
- *Isothermal anneal* by heating at 830 to 885 °C (1525 to 1625 °F). Cool slowly to 705 °C (1300 °F). Hold for 2 h. Hardness, approximately 95 HRB
- *Full anneal* at 830 to 885 °C (1525 to 1625 °F). Cool to 595 °C (1105 °F) at a rate not to exceed 17 to 22 °C (30 to 40 °F) per h. After this, cooling rate has no effect on hardness. Avoid carburization or decarburization. Can use atmospheric protection in the form of a vacuum, the inert gases argon or helium (both expensive), or nitrogen. All should have dew point below –51 °C (–60 °F). Endothermic-generated atmospheres can be used by holding dew point at 0.20 to 0.25 carbon for annealing temperature used. Annealed hardness, 86 to 95 HRB. Full annealing is expensive and time consuming. Should not be used, except as required for subsequent severe forming or specialized metal cutting operations

In aerospace practice, 420 is annealed at 870 °C (1600 °F). It is cooled to below 595 °C (1105 °F) at a rate not to exceed 30 °C (55 °F) per h, followed by slow cooling to ambient. Parts are austenitized at 1025 °C (1875 °F), and quenched in oil or polymer

Hardening. Atmospheric protection rules for annealing apply to hardening. Parts must be completely clean and free of oil and shop contamination. Thermal conductivity is significantly lower than that of carbon and alloy steels. High thermal gradients and high stresses during rapid heating may cause warpage and cracking in delicate or intricate parts. Preheat at 760 to 790 °C (1400 to 1455 °F), only long enough to equalize temperature in all sections. Extremely delicate or intricate parts would benefit from an additional prior preheat of 540 °C (1000 °F). Austenitized at 980 to 1065 °C (1795 to 1950 °F). Use upper end of range for larger sections or when maximum corrosion resistance and strength are required. If tempering temperature exceeds 565 °C (1050 °F), use low side of the austenitizing range. It enhances ductility and impact resistance. Soaking time of 30 to 60 min is adequate for sections up to 13 mm (0.50 in.). Allow an additional 30 min for each additional inch or fraction thereof. Double soaking time if parts have been full or isothermal annealed. Increase time by 50%, if process annealed for long periods above 705 °C (1300 °F). Quench in oil or air. Oil quenching preferred, because it guarantees maximum corrosion esistance and ductility. Martempering in hot oil or salt is suitable because of high hardenability. As-quenched hardness, approximately 448 to 564 HB

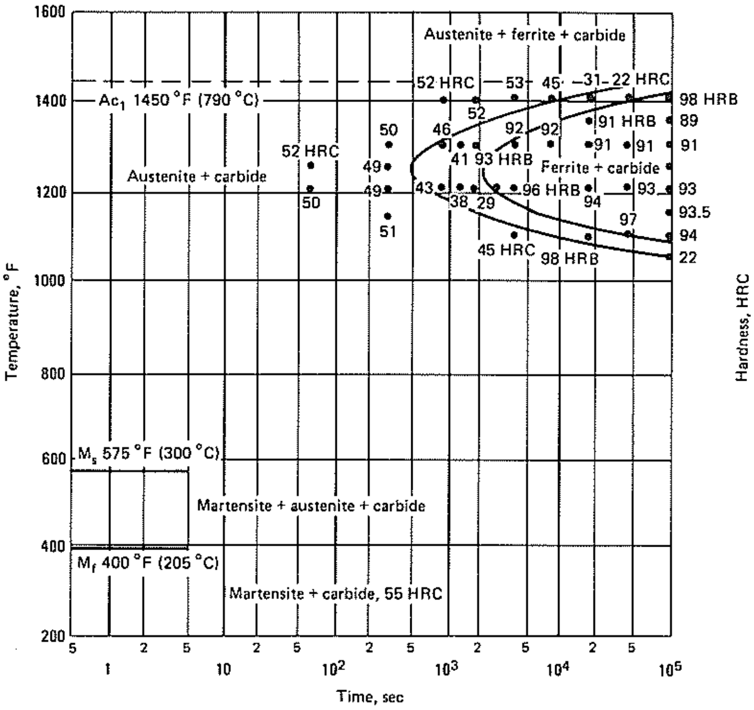
Stabilizing. For minimum retained austenite and maximum dimensional stability, use subzero treatment at –74 °C (–100 ± 20 °F). This should incorporate continuous cooling from austenitizing temperature to the cold transformation temperature

Tempering. Temper at 205 to 370 °C (400 to 700 °F). Hardness of 48 to 56 HRC. Double tempering beneficial. Cool to room temperature between tempers

Nitriding. Can be nitrided to case depth of approximately 0.203 mm (0.008 in.) in 48 h. See type 410 for further information

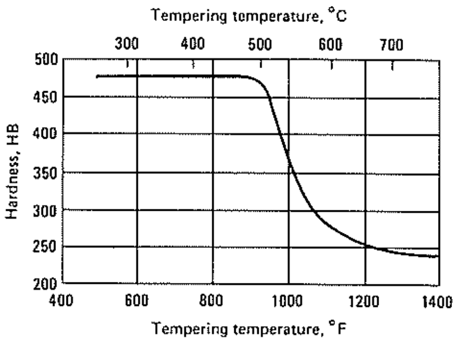
Recommended Processing Sequence

- Forge
- Anneal
- Rough machine
- Stress relieve
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (not mandatory, but beneficial)
- Temper
- Final grind to size
- Nitride (if required)

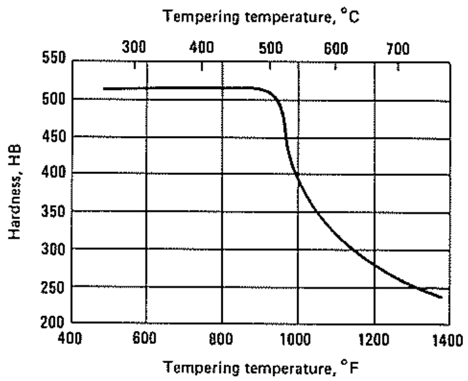


420: Isothermal Transformation Diagram. Composition: 0.35 C, 0.42 Mn, 0.018 P, 0.013 S, 0.45 Si, 0.31 Ni, 13.00 Cr, 0.10 Mo. Austenitized at 980 °C (1795 °F). Rockwell C hardness measured after 24 h at isotherm. Source: Republic Steel

420: Hardness vs Tempering Temperature. Composition: 0.31 C, 0.43 Mn, 0.022 P, 0.011 S, 0.45 Si, 0.44 Ni, 13.12 Cr. Heat treated at 925 °C (1695 °F), ½ h. Oil quenched from 66 to 94 °C (150 to 200 °F). Double stress relieved at 175 °C (345 °F), 15 min. Water quenched. Tempered 2 h. Heat treated, 14 mm (0.550 in.) round. Tested, 12.8 mm (0.505 in.) round. Source: Republic Steel



420: Hardness vs Tempering Temperature. Composition: 0.31 C, 0.43 Mn, 0.022 P, 0.011 S, 0.45 Si, 0.44 Ni, 13.12 Cr. Heat treated at 1025 °C (1875 °F), 1 h. Oil quenched from 66 to 94 °C (150 to 200 °F). Double stress relieved at 175 °C (345 °F), 15 min. Water quenched. Tempered 2 h. Heat treated, 14 mm (0.550 in.) round. Tested, 12.8 mm (0.505 in.) round. Source: Republic Steel



420, 420F: Soak Time for Annealing and Austenitizing (Aerospace Practice)

Thickness(a)		Minimum soak Time (b,c,d,e,f) air or atmosphere		Minimum soak Time (b,c,d,e,f) salt	
mm	in.	h	min	h	min
Up to 5	Up to 0.250	...	25	...	18
5 to 15	Over 0.250 to 0.500	...	45	...	35
15 to 25	Over 0.500 to 1.000	1	...	...	40
25 to 40	Over 1.000 to 1.500	1	15	...	45
40 to 50	Over 1.500 to 2.000	1	30	...	50
50 to 65	Over 2.000 to 2.500	1	45	...	55
65 to 75	Over 2.500 to 3.000	2	...	1	...
75 to 90	Over 3.000 to 3.500	2	15	1	5
90 to 100	Over 3.500 to 4.000	2	30	1	10
100 to 115	Over 4.000 to 4.500	2	45	1	15
115 to 125	Over 4.500 to 5.000	3	...	1	20
125 to 200	Over 5.000 to 8.000	3	30	1	40
Over 200	Over 8.000	(g)		(h)	

(a) Thickness is the minimum dimension of the heaviest section of the part. (b) Soaking shall commence when all control, indicating, and recording thermocouples reach the specified set temperature, or if load thermocouples are used, when the part temperature reaches the minimum of the furnace uniformity tolerance at the set temperature. Parts coated with copper plate or similar reflective coatings that tend to reflect radiant heat shall have their soaking time increased by at least 50%, unless load thermocouples are used. (c) When load thermocouples are used, the soaking time shall be not less than 30 min. (d) In all cases, the parts shall be held for sufficient time to ensure that the center of the most massive area has reached temperature and the necessary transformation and diffusion have taken place. (e) Maximum soak time shall be twice the minimum specified, except for subcritical annealing. (f) Longer times may be necessary for parts with complex shapes or parts that won't heat uniformly. (g) 4 h hour plus 30 min for every 75 mm (3 in.), or portion thereof greater than 200 mm (8 in.). (h) 2 h plus 20 min for every 75 mm (3 in.), or portion thereof greater than 200 mm (8 in.). Source: AMS 2759/5

422

Chemical Composition. AISI/UNS (S42200): 0.20 to 0.25 C, 1.00 Mn, 0.04 P, 0.03 S, 0.75 Si, 0.5 to 1.0 Ni, 11.50 to 13.50 Cr, 0.75 to 1.25 Mo; 0.15 to 0.3 V; 0.75 to 1.25 W

Similar Steels (U.S. and/or Foreign). AMS 5655; ASTM A565 (616); SAE J467; (Ger.) DIN 1.4935; (Jap.) JIS SUH 616

Characteristics. Designed for service temperatures up to 650 °C (1200 °F) with a combination of high strength and toughness. Carbon content, 0.20 to 0.25. Carbide-forming elements, Mo, V, and W added for high-temperature strength. Somewhat restricted use, primarily for turbine blades and high-strength fasteners for corrosive environment application. Deep hardening. Hardened by air cooling or oil quenching. Process annealing, rather than full annealing, recommended. Magnetic in all conditions. Medium to low machinability

Forging. Start forging at 1150 °C (2100 °F). Do not forge after temperature of forging stock drops below 955 °C (1750 °F). Cool very slowly from finishing temperature. Anneal

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Process anneal at 730 to 790 °C (1350 to 1455 °F). Air cool.

In aerospace practice, parts are annealed at 870 °C (1600 °F). They are cooled to 705 °C (1300 °F), held for 5 to 7 h, cooled to below 540 °C (1000 °F) at a rate not to exceed 30 °C (55 °F) per h, and air cooled to ambient

Hardening. Parts must be completely clean and free of oil and shop contamination. Thermal conductivity is significantly lower than that of carbon and alloy steels. High thermal gradients and high stresses during rapid heating may cause warpage and cracking in delicate or intricate parts. Preheat at 760 to 790 °C (1400 to 1455 °F), only long enough to equalize temperature in all sections. Extremely delicate or intricate parts would benefit from an additional prior preheat of 540 °C (1000 °F). Austenitized at 1040 °C (1905 °F) for 1 h. Air cool or water quench.

In aerospace practice, parts are austenitized at 1055 °C (1930 °F), and quenched in oil, polymer, or salt. Salt temperature must be 190 to 275 °C (375 to 525 °F); parts are held in salt 10 to 15 min; then removed and cooled in air to room temperature

Stabilizing. For minimum retained austenite and maximum dimensional stability, use a subzero treatment of –74 °C (–100 ± 20 °F). This should incorporate continuous cooling from the austenitizing temperature to the cold transformation temperature

Tempering. Temper at 650 °C (1200 °F) or at least to maximum service temperature for 2 h. Hardened and tempered hardness, approximately 320 HB.

Nitriding. Can be nitrided to case depth of approximately 0.203 mm (0.008 in.) in 48 h. See type 410 for further information

Recommended Processing Sequence

- Forge
- Anneal
- Rough machine
- Stress relieve
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (not mandatory, but beneficial)
- Temper
- Final grind to size
- Nitride (if required)

22: Soak Time for Annealing and Austenitizing (Aerospace Practice)

Thickness(a)		Minimum soak Time (b,c,d,e,f) air or atmosphere		Minimum soak Time (b,c,d,e,f) salt	
mm	in.	h	min	h	min
Up to 5	Up to 0.250	...	25	...	18
5 to 15	Over 0.250 to 0.500	...	45	...	35
15 to 25	Over 0.500 to 1.000	1	...	...	40
25 to 40	Over 1.000 to 1.500	1	15	...	45
40 to 50	Over 1.500 to 2.000	1	30	...	50
50 to 65	Over 2.000 to 2.500	1	45	...	55
65 to 75	Over 2.500 to 3.000	2	...	1	...
75 to 90	Over 3.000 to 3.500	2	15	1	5
90 to 100	Over 3.500 to 4.000	2	30	1	10
100 to 115	Over 4.000 to 4.500	2	45	1	15
115 to 125	Over 4.500 to 5.000	3	...	1	20
125 to 200	Over 5.000 to 8.000	3	30	1	40
Over 200	Over 8.000	(g)		(h)	

) Thickness is the minimum dimension of the heaviest section of the part. (b) Soaking shall commence when all control, indicating, and recording thermocouples reach the speci- :d set temperature, or if load thermocouples are used, when the part temperature reaches the minimum of the furnace uniformity tolerance at the set temperature. Parts coated with ıpper plate or similar reflective coatings that tend to reflect radiant heat shall have their soaking time increased by at least 50%, unless load thermocouples are used. (c) When load ermocouples are used, the soaking time shall be not less than 30 min. (d) In all cases, the parts shall be held for sufficient time to ensure that the center of the most massive area has ached temperature and the necessary transformation and diffusion have taken place. (e) Maximum soak time shall be twice the minimum specified, except for subcritical anneal- g. (f) Longer times may be necessary for parts with complex shapes or parts that won't heat uniformly. (g) 4 h hour plus 30 min for every 75 mm (3 in.), or portion thereof greater an 200 mm (8 in.). (h) 2 h plus 20 min for every 75 mm (3 in.), or portion thereof greater than 200 mm (8 in.). Source: AMS 2759/5

;arpenter 636 (Type 422)

hemical Composition. 0.20 to 0.25 C, 1.00 Mn max, 0.04 P max, 03 S max, 1.00 Si max, 0.50 to 1.00 Ni, 11.50 to 13.50 Cr, 0.75 to 1.25 :o, 0.20 to 0.50 V, 0.75 to 1.25 W, iron, balance

haracteristics. A type 422, nonstandard grade, designed for service mperatures up to 650 °C (1200 °F). High mechanical properties can be :veloped with heat treatment. Resistance to scaling and oxidation are ıod in continuous service at temperatures up to 760 °C (1400 °F). Is adily machined in the annealed condition, but is difficult to weld due to ack sensitivity. Applications include buckets and blades in compressors ıd steam turbines, high temperature bolting, compressor and turbine heels, valves and valve trim, and aircraft parts

orging. Large sections should be preheated to 650 to 760 °C (1200 to ł00 °F), then heated to 1038 to 1175 °C (1900 to 2150 °F). Long heating 'cles should be avoided because excessive decarburization can result. ırgings should be cooled slowly and annealed or tempered as soon as ıssible after reaching room temperature. Hardening should not be at- mpted without an intermediate anneal or preheating in the range of 650 760 °C (1200 to 1400 °F)

Recommended Heat Treating Practice

Annealing. Parts are heated to 730 to 770 °C (1350 to 1420 °F), held 4 h, furnace or air cooled. Hardness is 21 to 25 HRC. Microstructure is tempered martensite.

In isothermal annealing, parts are heated to 1038 °C (1900 °F), cooled to 690 °C (1275 °F), held 24 to 48 h, then air cooled. Hardness is 90 to 95 HRB. Microstructure is alpha ferrite plus carbide. Parts must be rehardened at 1038 to 1065 °C (1900 to 1950 °F) and tempered to develop optimum mechanical properties

Hardening. Parts are heated to 1038 °C (1900 °F), oil quenched. Resulting hardness is 45 to 50 HRC.

Intricate shapes are marquenched to 340 °C (650 °F) and air cooled

Tempering. Temper at 150 to 370 °C (300 to 700 °F) for hardness approximately 48 to 57 HRC. Double tempering beneficial. Cool to room temperature between tempers. This treatment should take place immediately after parts reach room temperature following hardening

Recommended Processing Sequence

- Forge
- Anneal
- Rough machine

431

Chemical Composition. AISI/UNS (S43100): 0.20 C, 1.00 Mn, 1.00 Si, 1.25 to 2.50 Ni, 15.00 to 17.00 Cr, 0.04 P, 0.03 S

Similar Steels (U.S. and/or Foreign). AMS 5628; ASTM A276, A314, A473, A493, A579 (63), A580; MIL SPEC MIL-S-862; SAE J405 (51431); (Ger.) DIN 1.4057; (Ital.) UNI X 16 CrNi 16; (Jap.) JIS SUS 431; (Swed.) SS_{14} 2321; (U.K.) B.S. 431 S. 29, 5 S 80

Characteristics. Designed for heat treating to high mechanical properties by higher additions of Cr and Ni. Also causes increased corrosion resistance over types 410, 420, 430, and 440. Quenched in oil or air. Can be martempered. Tempering from 370 to 565 °C (700 to 1050 °F) not recommended. Generally benefits from subzero treatment after quench. Process anneal only. Annealed hardness, 22 to 30 HRC. Magnetic in all conditions. Low machinability

Forging. Start forging at 1150 to 1230 °C (2100 to 2245 °F). Do not forge after temperature of forging stock drops below 925 °C (1695 °F). Cool very slowly from finishing temperature. Anneal

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Full or isothermal annealing not recommended. Process anneal by holding at 620 to 705 °C (1150 to 1300 °F) for sufficient time to achieve desired ductility or machinability, 6 h minimum at temperature. A clean, rectified molten salt bath can be used. Air cool parts from annealing temperature.

In aerospace practice, parts are annealed at 870 °C (1600 °F), then air cooled to ambient temperature followed by heating to 650 °C (1200 °F) for 10 to 12 h and air cooled

Hardening. For endothermic atmosphere, use dew point of 15 to 18 °C (60 to 65 °F) for austenitizing temperature of 980 °C (1795 °F). Parts must be completely clean and free of oil and shop contamination. Thermal conductivity is significantly lower than that of carbon and alloy steels. High thermal gradients and high stresses during rapid heating may cause warpage and cracking in delicate or intricate parts. Preheat at 760 to 790 °C (1400 to 1455 °F), only long enough to equalize temperature in all sections. Extremely delicate or intricate parts would benefit from an additional prior preheat of 540 °C (1000 °F). Austenitized at 980 to 1065 °C (1795 to 1950 °F). Use upper end of range for larger sections or when maximum corrosion resistance and strength are required. If tempering temperature exceeds 565 °C (1050 °F), use low side of the austenitizing range. It enhances ductility and impact resistance. Soaking time of 30 to 60 min is adequate for sections up to 13 mm (0.50 in.). Allow an additional 30 min for each additional inch or fraction thereof. Double soaking time if parts have been full or isothermal annealed. Increase time by 50%, if process annealed at 675 °C (1245 °F). Quench in oil or air. Oil quenching preferred, because it guarantees maximum corrosion resistance and ductility. Martempering in hot oil or salt is suitable because of high hardenability. As-quenched hardness, approximately 401 to 444 HB. Tendency to exhibit segregation or banding. Prevents uniform hardening and may seriously reduce mechanical properties, particularly in the transverse direction. For limited austenite segregation, heat slowly to 1205 °C (2200 °F). Hold for 1 h. Cool slowly to room temperature. Repeat the above heating, holding and cooling twice, for a total of three cycles. Heat to 815 °C (1500 °F). Air cool.

In aerospace practice, parts are austenitized at 1025 °C (1875 °F), and quenched in oil, polymer, or salt. Salt temperatures range from 190 to 275 °C (375 to 525 °F). Parts are held in salt for 10 to 15 min, then removed and air cooled to room temperature. After the hardening quench, 431 and 440C parts are cooled by immersing them in cold water to ambient temperature water. They are then refrigerated at –70 °C (–95 °F) or lower for not less than 2 h

Stabilizing. For minimum retained austenite and maximum dimensional stability, use subzero treatment at –74 °C (–100 ± 20 °F). This should incorporate continuous cooling from austenitizing temperature to the cold transformation temperature

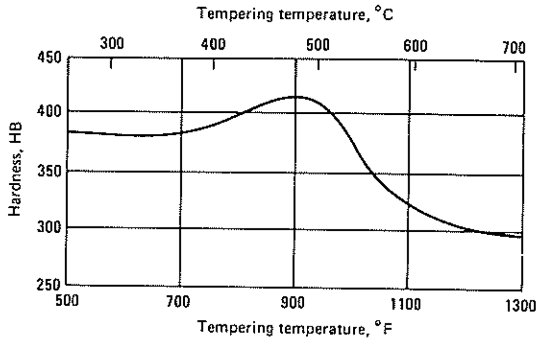
Tempering. Temper at 230 to 605 °C (445 to 1125 °F). Temper at 230 to 370 °C (445 to 700 °F) for hardness approximately 40 to 47 HRC. Temper at 565 to 605 °C (1050 to 1125 °F) for hardness approximately 26 to 34 HRC. Tempering at 370 to 565 °C (700 to 1050 °F) not recommended for parts requiring high toughness and optimum corrosion resistance. Causes a marked dip in impact resistance and lowered stress corrosion cracking resistance. Double tempering beneficial. Cool to room temperature between tempers

Nitriding. Can be nitrided to case depth of approximately 0.203 mm (0.008 in.) in 48 h. See type 410 for further information

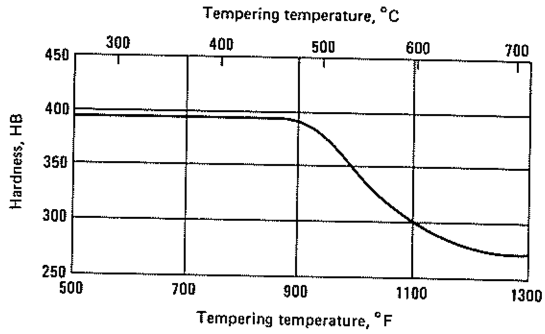
Recommended Processing Sequence

- Forge
- Anneal
- Rough machine
- Stress relieve
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (not mandatory, but beneficial)
- Temper
- Final grind to size
- Nitride (if required)

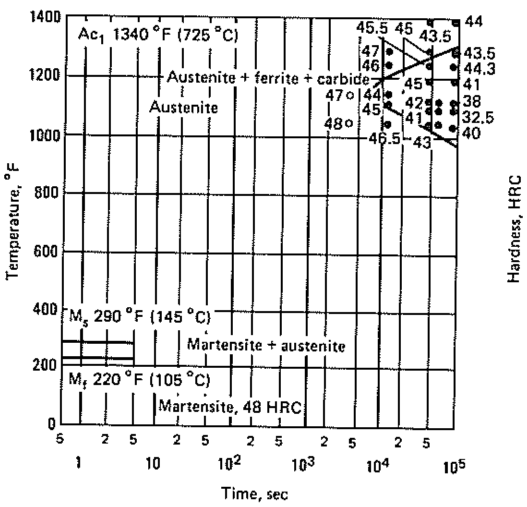
431: Hardness vs Tempering Temperature. Composition: 0.14 C, 0.46 Mn, 0.014 P, 0.012 S, 0.44 Si, 2.18 Ni, 16.40 Cr, 0.10 Mo. Heat treated at 1040 °C (1905 °F), ½ h. Oil quenched from 66 to 94 °C (150 to 200 °F), 15 min. Water quenched. Tempered 2 h. Heat treated, 14 mm (0.550 in.) round. Tested, 12.8 mm (0.505 in.) round. Source: Republic Steel



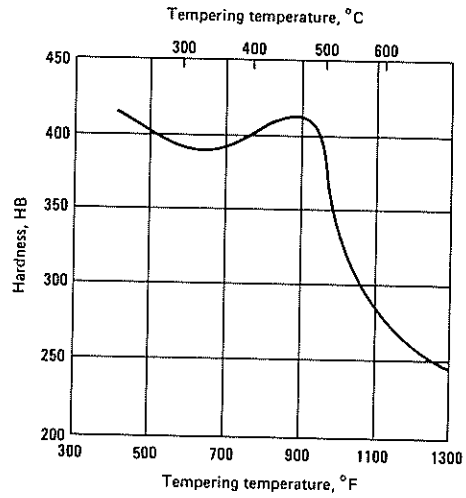
431: Hardness vs Tempering Temperature. Composition: 0.14 C, 0.46 Mn, 0.014 P, 0.012 S, 0.44 Si, 2.18 Ni, 16.40 Cr, 0.10 Mo. Heat treated at 925 °C (1695 °F), ½ h. Oil quenched from 66 to 94 °C (150 to 200 °F). Double stress relieved at 175 °C (345 °F), 15 min. Water quenched. Tempered 2 h. Heat treated, 14 mm (0.550 in.) round. Tested, 12.8 mm (0.505 in.) round. Source: Republic Steel



431: Isothermal Transformation Diagram. Composition: 0.16 C, 0.40 Mn, 0.018 P, 0.010 S, 0.43 Si, 2.44 Ni, 16.42 Cr. Austenitized at 1040 °C (1905 °F). Rockwell C hardness measured after 24 h at isotherm. Source: Republic Steel



431: Hardness vs Tempering Temperature. Oil quenched and tempered 2 h at 980 °C (1795 °F)



431: Soak Time for Annealing and Austenitizing (Aerospace Practice)

Thickness(a)		Minimum soak Time (b,c,d,e,f) air or atmosphere		Minimum soak Time (b,c,d,e,f) salt	
mm	in.	h	min	h	min
Up to 5	Up to 0.250	...	25	...	18
5 to 15	Over 0.250 to 0.500	...	45	...	35
15 to 25	Over 0.500 to 1.000	1	...	...	40
25 to 40	Over 1.000 to 1.500	1	15	...	45
40 to 50	Over 1.500 to 2.000	1	30	...	50
50 to 65	Over 2.000 to 2.500	1	45	...	55
65 to 75	Over 2.500 to 3.000	2	...	1	...
75 to 90	Over 3.000 to 3.500	2	15	1	5
90 to 100	Over 3.500 to 4.000	2	30	1	10
100 to 115	Over 4.000 to 4.500	2	45	1	15
115 to 125	Over 4.500 to 5.000	3	...	1	20
125 to 200	Over 5.000 to 8.000	3	30	1	40
Over 200	Over 8.000	(g)		(h)	

(a) Thickness is the minimum dimension of the heaviest section of the part. (b) Soaking shall commence when all control, indicating, and recording thermocouples reach the specified set temperature, or if load thermocouples are used, when the part temperature reaches the minimum of the furnace uniformity tolerance at the set temperature. Parts coated with copper plate or similar reflective coatings that tend to reflect radiant heat shall have their soaking time increased by at least 50%, unless load thermocouples are used. (c) When load thermocouples are used, the soaking time shall be not less than 30 min. (d) In all cases, the parts shall be held for sufficient time to ensure that the center of the most massive area has reached temperature and the necessary transformation and diffusion have taken place. (e) Maximum soak time shall be twice the minimum specified, except for subcritical annealing. (f) Longer times may be necessary for parts with complex shapes or parts that won't heat uniformly. (g) 4 h hour plus 30 min for every 75 mm (3 in.), or portion thereof greater than 200 mm (8 in.). (h) 2 h plus 20 min for every 75 mm (3 in.), or portion thereof greater than 200 mm (8 in.). Source: AMS 2759/5

440A

Chemical Composition. **AISI/UNS (S44002):** 0.65 to 0.75 C, 1.00 Mn, 1.00 Si, 16.00 to 18.00 Cr, 0.04 P, 0.03 S, 0.75 Mo

Similar Steels (U.S. and/or Foreign). AMS 5631; ASTM A276, A314, A473, A511, A580; FED QQ-S-763; MIL SPEC MIL-S-862; SAE J405 (51440 A)

Characteristics. Greater hardenability than type 420. Greater toughness than 440B or 440C, because of lower carbon. Good corrosion resistance, particularly in hardened and tempered condition. Quenched in oil or air. Can be martempered. Can be full, process, or isothermal annealed. Magnetic in all conditions. Low machinability. Used for cutlery, bearings, and surgical tools

Forging. Start forging at 1040 to 1205 °C (1905 to 2200 °F). Do not forge after temperature of forging stock drops below 955 °C (1750 °F). Cool slowly from finishing temperature. Anneal

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Can be process, isothermal, or full annealed:

- *Process anneal* in subcritical temperature range of 675 to 760 °C (1245 to 1400 °F) for hardness of 90 HRB to 22 HRC. Use clean, rectified bath or an atmosphere that is compatible (such as vacuum). Soaking and softening time dependent on size of work. Air cool
- *Isothermal anneal* by heating at 845 to 900 °C (1555 to 1650 °F). Cool slowly to 690 °C (1275 °F). Hold for 4 h. Hardness, approximately 98 HRB
- *Full anneal* at 845 to 900 °C (1555 to 1650 °F). Cool to 595 °C (1105 °F) at a rate not to exceed 17 to 22 °C (30 to 40 °F) per h. After this, cooling rate has no effect on hardness. Avoid decarburization. Can use atmospheric protection in the form of a vacuum, the inert gases argon or helium (both expensive), or nitrogen. All should have dew point below −51 °C (−60 °F). Endothermic-generated atmospheres can be used by holding dew point in the 0.60 to 0.75 carbon range, for the annealing temperature used. Annealed hardness, 94 to 98 HRB. Full annealing is expensive and time consuming. Should not be used, except as required for subsequent severe forging or specialized metal-cutting operations

Hardening. Atmospheric protection rules for annealing apply to hardening. Parts must be completely clean and free of oil and shop contamination. Thermal conductivity is significantly lower than that of carbon and alloy steels. High thermal gradients and high stresses during rapid heating may cause warpage and cracking in delicate or intricate parts. Preheat at 760 to 790 °C (1400 to 1455 °F), only long enough to equalize temperature in all sections. Extremely delicate or intricate parts would benefit from an additional prior preheat of 540 °C (1000 °F). Austenitize at 1010 to 1065 °C (1850 to 1950 °F). Use upper end of range for larger sections or when maximum corrosion resistance and strength are required. Soaking time of 30 to 60 min is adequate for sections up to 13 mm (0.50 in.). Allow an additional 30 min for each additional inch or fraction thereof. Double soaking time if parts have been full or isothermal annealed. Increase time by 50%, if process annealed above 675 °C (1245 °F). Quench in oil or air. Oil quenching preferred, because it guarantees maximum corrosion resistance and ductility. Martempering in hot oil or salt is suitable because of high hardenability. As-quenched hardness, approximately 52 to 57 HRC

Stabilizing. For minimum retained austenite and maximum dimensional stability, use subzero treatment at −74 °C (−100 ± 20 °F). This should incorporate continuous cooling from austenitizing temperature to the cold transformation temperature

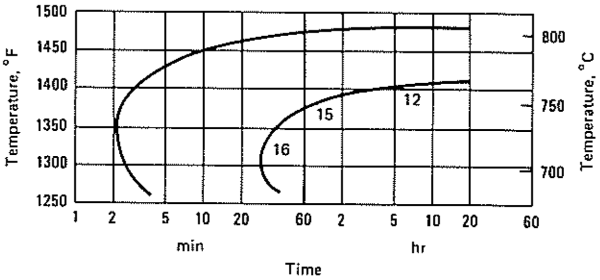
Tempering. Temper at 150 to 370 °C (300 to 700 °F) for hardness approximately 48 to 57 HRC. Double tempering beneficial. Cool to room temperature between tempers

Nitriding. Can be nitrided to case depth of approximately 0.203 mm (0.008 in.) in 48 h. See type 410 for further information

ſecommended Processing Sequence

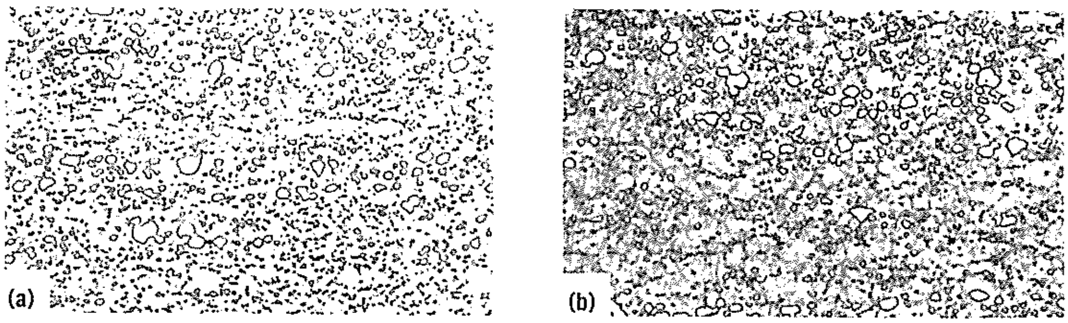
Forge
Anneal
Rough machine
Stress relieve
Finish machine
Preheat

- Austenitize
- Quench
- Stabilize (not mandatory, but beneficial)
- Temper
- Final grind to size
- Nitride (if required)



440A: Partial Isothermal Transformation Diagram. Composition: 0.62 C, 0.30 Mn, 0.17 Si, 16.59 Cr. Austenitized at 870 °C (1600 °F)

440A: Microstructures. (a) 5% picric acid and 3% HCl, in alcohol. 500×. Bar in annealed condition. Longitudinal cross section. Chromium carbide particles in ferrite matrix. (b) 1% picric acid and 5% HCl, in alcohol. 500×. Austenitized at 1010 °C (1850 °F), ½ h. Air cooled. Tempered at 595 °C (1105 °F), ½ h. Partly spheroidized particles of chromium carbide in martensite matrix



·40B

hemical Composition. AISI/UNS (S44003): 0.75 to 0.95 C, 1.00 n, 1.00 Si, 16.00 to 18.00 Cr, 0.04 P, 0.03 S, 0.75 Mo

imilar Steels (U.S. and/or Foreign). ASTM A276, A314, ·73, A580; FED QQ-S-763; MIL SPEC MIL-S-862; SAE J405 (51440 ; (Ger.) DIN 1.4112; (Jap.) JIS SUS 440 B

haracteristics. Greater hardenability than type 420 and 440A. ·eater toughness than 440C. Good corrosion resistance, particularly in rdened and tempered condition. Quenched in oil or air. Can be martemred. Can be full, process, or isothermal annealed. Magnetic in all condi·ns. Low machinability. Used for cutlery, valve parts, and instrument arings

›rging. Start forging at 1040 to 1175 °C (1905 to 2150 °F). Do not ·ge after temperature of forging stock drops below 955 °C (1750 °F). ›ol slowly from finishing temperature. Anneal

ecommended Heat Treating Practice

›rmalizing. Do not normalize

ınealing. Can be process, isothermal, or full annealed:

- *Process anneal* in subcritical temperature range of 675 to 760 °C (1245 to 1400 °F) for hardness of 98 HRB to 23 HRC. Use clean, rectified salt bath or an atmosphere that is compatible with this temperature range. Soaking and softening time dependent on size of work. Air cool
- *Isothermal anneal* by heating at 845 to 900 °C (1555 to 1650 °F). Cool slowly to 690 °C (1275 °F). Hold for 4 h. Hardness, approximately 20 HRC
- *Full anneal* at 845 to 900 °C (1555 to 1650 °F). Cool to 595 °C (1105 °F) at a rate not to exceed 17 to 22 °C (30 to 40 °F) per h. After this, cooling rate has no effect on hardness. Avoid decarburization. Can use atmospheric protection in the form of a vacuum, the inert gases argon or helium (both expensive), or nitrogen. All should have dew point below −51 °C (−60 °F). Endothermic-generated atmospheres can be used by holding dew point in the 0.75 to 0.95 carbon range for the annealing temperature used. Annealed hardness, 94 to 98 HRB. Full annealing is expensive and time consuming. Should not be used, except as required for subsequent forming or specialized metal cutting operations

Hardening. Atmospheric protection rules for annealing apply to hardening. Parts must be completely clean and free of oil and shop contamination. Thermal conductivity is significantly lower than that of carbon and alloy steels. High thermal gradients and high stresses during rapid heating may cause warpage and cracking in delicate or intricate parts. Preheat at 760 to 790 °C (1400 to 1455 °F), only long enough to equalize temperature in all sections. Extremely delicate or intricate parts would benefit from an additional prior preheat of 540 °C (1000 °F). Austenitize at 1010 to 1065 °C (1850 to 1950 °F). Use upper end of range for larger sections or when maximum corrosion resistance and strength are required. Soaking time of 30 to 60 min is adequate for sections up to 13 mm (0.50 in.). Allow an additional 30 min for each additional inch or fraction thereof. Double soaking time if parts have been full or isothermal annealed. Increase time by 50%, if process annealed above 705 °C (1300 °F). Quench in oil or air. Oil quenching preferred, because it guarantees maximum corrosion resistance and ductility. Martempering in hot oil or salt is suitable because of high hardenability. As-quenched hardness, approximately 56 to 59 HRC

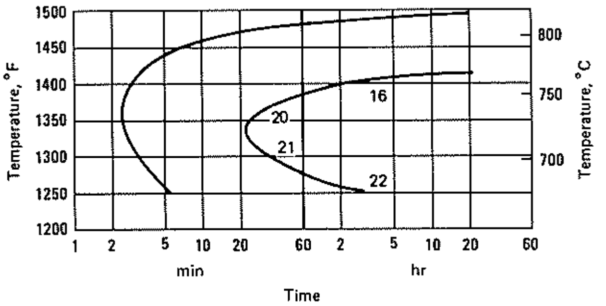
Stabilizing. For minimum retained austenite and maximum dimensional stability, use subzero treatment at –74 °C (–100 ±20 °F). This should incorporate continuous cooling from austenitizing temperature to the cold transformation temperature

Tempering. Temper at 150 to 370 °C (300 to 700 °F) for hardness of 53 to 59 HRC. Double tempering beneficial. Cool to room temperature between tempers

Nitriding. Can be nitrided to case depth of approximately 0.203 mm (0.008 in.) in 48 h. See type 410 for further information

Recommended Processing Sequence

- Forge
- Anneal
- Rough machine
- Stress relieve
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (not mandatory, but beneficial)
- Temper
- Final grind to size
- Nitride (if required)



440B: Partial Isothermal Transformation Diagram. Composition: 0.93 C, 0.49 Mn, 0.43 Si, 18.40 Cr, 0.55 Mo. Austenitized at 870 °C (1600 °F)

440C

Chemical Composition. AISI/UNS (S44004): 0.95 to 1.20 C, 1.00 Mn, 1.00 Si, 16.00 to 18.00 Cr, 0.04 P, 0.03 S, 0.75 Mo

Similar Steels (U.S. and/or Foreign). AMS 5618, 5630; ASTM A276, A314, A473, A493, A580; FED QQ-S-763; MIL SPEC MIL-S-862; SAE J405 (51440 C); (Ger.) DIN 1.4125; (Jap.) JIS SUS 440 C

Characteristics. Highest hardness of hardenable stainless steels. Good corrosion resistance, particularly in hardened and tempered condition. Quenched in oil or air. Can be martempered. Can be full, process, or isothermal annealed. Magnetic in all conditions. Low machinability. Used for bearings, nozzles, valve parts, and wear parts of pumps

Forging. Start forging at 1040 to 1175 °C (1905 to 2150 °F). Do not forge after temperature of forging stock drops below 955 °C (1750 °F). Cool slowly from finishing temperature. Anneal

Recommended Heat Treating Practice

Normalizing. Do not normalize

Annealing. Can be process, isothermal, or full annealed:

- *Process anneal* in subcritical temperature range of 675 to 760 °C (1245 to 1400 °F). Use clean, rectified salt bath or an atmosphere that is compatible with this temperature range. Soaking and softening time dependent on size of work. Air cool. Hardness, 98 HRB to 23 HRC
- *Isothermal anneal* by heating at 845 to 900 °C (1555 to 1650 °F). Cool slowly to 690 °C (1275 °F). Hold for 4 h. Hardness, approximately 25 HRC
- *Full anneal* at 845 to 900 °C (1555 to 1650 °F). Cool to 595 °C (1105 °F) at a rate not to exceed 17 to 22 °C (30 to 40 °F) per h. After this, cooling rate has no effect on hardness. Avoid decarburization. Can use atmospheric protection in the form of a vacuum, the inert gases argon or helium (both expensive), or nitrogen. All should have dew point below –51 °C (–60 °F). Endothermic-generated atmospheres can be used by holding dew point in the 0.95 to 1.20 carbon range for the annealing temperature used. Annealed hardness, 98 HRB to 25 HRC. Full annealing is expensive and time consuming. Should not be used, except as required for subsequent forming or difficult specialized metal cutting operation

In aerospace practice, parts are annealed at 900 °C (1650 °F), then cooled to below 595 °C (1105 °F) at a rate not to exceed 30 °C (55 °F) per h, followed by air cooling to ambient

Hardening. Atmospheric protection rules for annealing apply to hardening. Parts must be completely clean and free of oil and shop contamination. Thermal conductivity is significantly lower than that of carbon and alloy steels. High stresses during rapid heating may cause warpage and cracking in delicate or intricate parts. Preheat at 760 to 790 °C (1400 to 1455 °F), only long enough to equalize temperature in all sections. Extremely delicate or intricate parts would benefit from an additional prior

:eheat of 540 °C (1000 °F). Austenitize at 1010 to 1065 °C (1850 to 1950 ⁼). Use upper end of range for larger sections or when maximum corrosion :sistance and strength are required. Soaking time of 30 to 60 min is lequate for sections up to 13 mm (0.50 in.). Allow an additional 30 min ır each additional inch or fraction thereof. Double soaking time if parts ıve been full or isothermal annealed. Increase time by 50%, if process ınealed above 705 °C (1300 °F). Quench in oil or air. Oil quenching 'eferred, because it guarantees maximum corrosion resistance and ductil-y. Martempering in hot oil or salt is suitable because of high hardenability. s-quenched hardness, approximately 60 to 62 HRC minimum

In aerospace practice, parts are austenitized at 1055 °C (1930 °F), then ıenched in oil or polymer. After the quench, parts are immersed in cold ater to ambient temperature water, then refrigerated at –70 °C (–95 °F) or wer for not less than 2 h

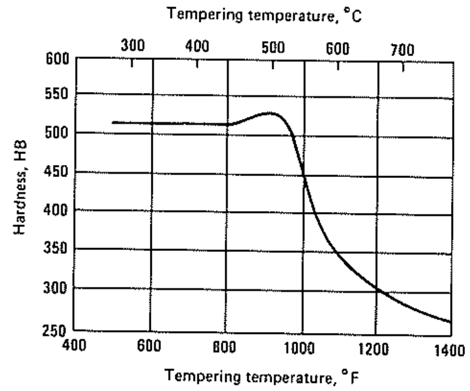
tabilizing. For minimum retained austenite and maximum dimen-ɔnal stability, use subzero treatment at –74 °C (–100 ±20 °F). This should corporate continuous cooling from austenitizing temperature

ɜmpering. Temper at 165 °C (330 °F) or higher, for minimum hardness ' 60 HRC. Temper at 190 °C (375 °F) for 58 HRC minimum; at 230 °C (445 °F) for 57 HRC minimum; and at 357 °C (675 °F), for hardness approximately 52 to 56 HRC. Double tempering beneficial. Cool to room temperature between tempers

Nitriding. Can be nitrided to case depth of 0.203 mm (0.008 in.) in 48 h. See type 410 for further information

Recommended Processing Sequence

- Forge
- Anneal
- Rough machine
- Stress relieve
- Finish machine
- Preheat
- Austenitize
- Quench
- Stabilize (not mandatory, but beneficial)
- Temper
- Final grind to size
- Nitride (if required)

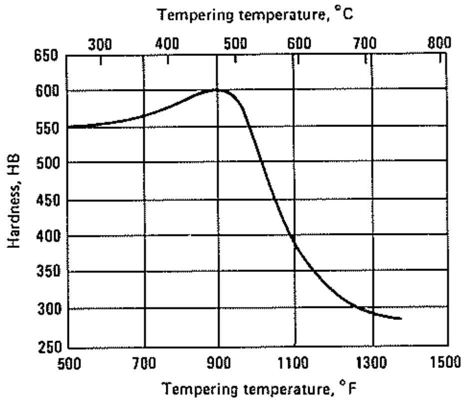


440C: Hardness vs Tempering Temperature. Composition: 1.020 to 1.044 C, 0.40 to 0.48 Mn, 0.017 to 0.019 P, 0.010 to 0.011 S, 0.18 to 0.31 Si, 0.24 to 0.54 Ni, 16.90 to 17.18 Cr, 0.50 to 0.64 Mo. Heat treated at 925 °C (1695 °F), 1 h. Oil quenched from 66 to 94 °C (150 to 200 °F). Double stress relieved at 175 °C (345 °F), 15 min. Water quenched. Tempered 2 h. Heat treated, 14 mm (0.550 in.) round. Tested in 12.8 mm (0.505 in.) round. Source: Republic Steel

⁝0C: Soak Time for Annealing and Austenitizing (Aerospace Practice)

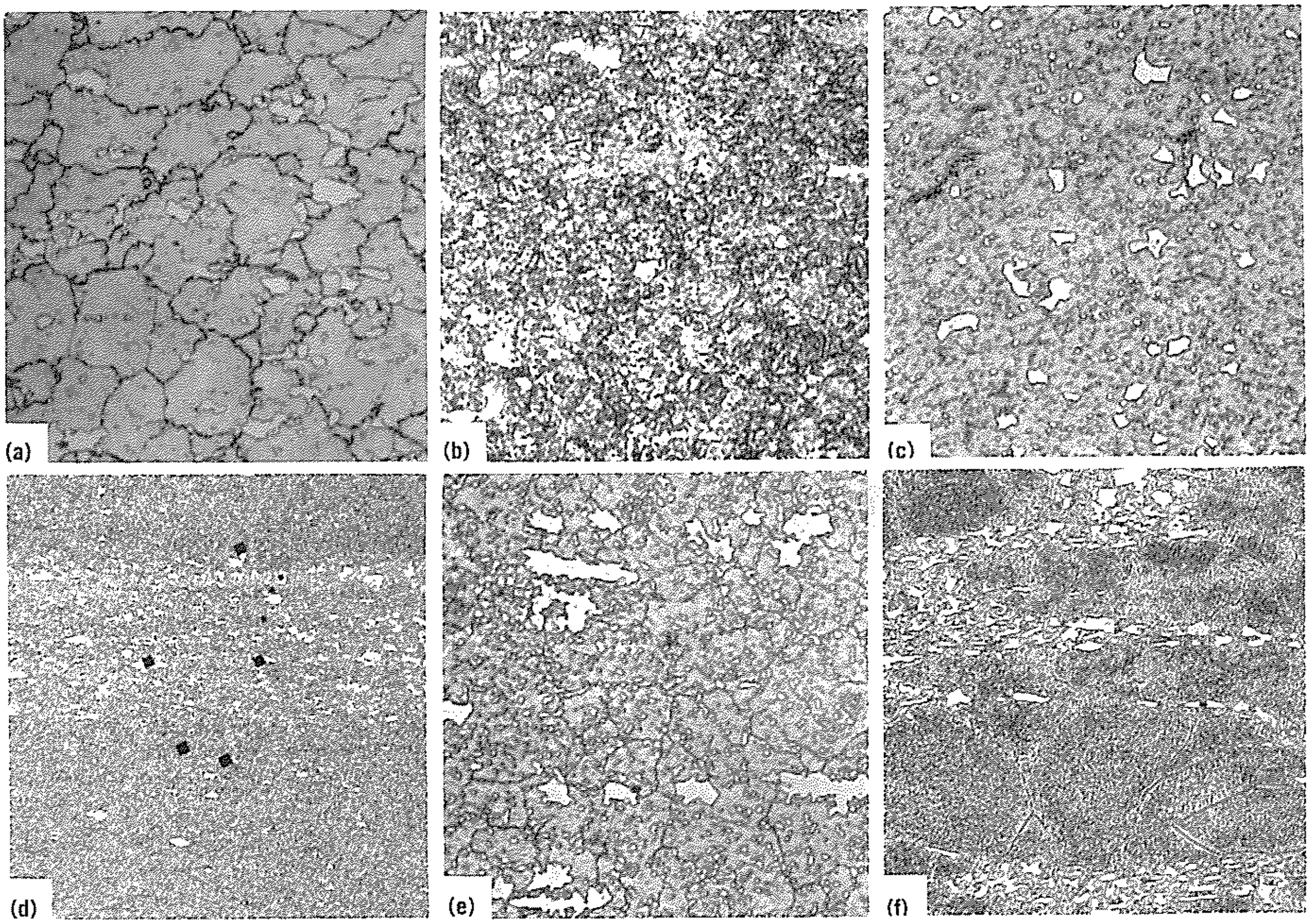
Thickness(a)		Minimum soak Time (b,c,d,e,f) air or atmosphere		Minimum soak Time (b,c,d,e,f) salt	
mm	in.	h	min	h	min
Up to 5	Up to 0.250	...	25	...	18
5 to 15	Over 0.250 to 0.500	...	45	...	35
15 to 25	Over 0.500 to 1.000	1	...	...	40
25 to 40	Over 1.000 to 1.500	1	15	...	45
40 to 50	Over 1.500 to 2.000	1	30	...	50
50 to 65	Over 2.000 to 2.500	1	45	...	55
65 to 75	Over 2.500 to 3.000	2	...	1	...
75 to 90	Over 3.000 to 3.500	2	15	1	5
90 to 100	Over 3.500 to 4.000	2	30	1	10
100 to 115	Over 4.000 to 4.500	2	45	1	15
115 to 125	Over 4.500 to 5.000	3	...	1	20
125 to 200	Over 5.000 to 8.000	3	30	1	40
Over 200	Over 8.000	(g)		(h)	

Thickness is the minimum dimension of the heaviest section of the part. (b) Soaking shall commence when all control, indicating, and recording thermocouples reach the speci-l set temperature, or if load thermocouples are used, when the part temperature reaches the minimum of the furnace uniformity tolerance at the set temperature. Parts coated with per plate or similar reflective coatings that tend to reflect radiant heat shall have their soaking time increased by at least 50%, unless load thermocouples are used. (c) When load mocouples are used, the soaking time shall be not less than 30 min. (d) In all cases, the parts shall be held for sufficient time to ensure that the center of the most massive area has :hed temperature and the necessary transformation and diffusion have taken place. (e) Maximum soak time shall be twice the minimum specified, except for subcritical anneal-(f) Longer times may be necessary for parts with complex shapes or parts that won't heat uniformly. (g) 4 h hour plus 30 min for every 75 mm (3 in.), or portion thereof greater ı 200 mm (8 in.). (h) 2 h plus 20 min for every 75 mm (3 in.), or portion thereof greater than 200 mm (8 in.). Source: AMS 2759/5



440C: Hardness vs Tempering Temperature. Composition: 1.02 C, 0.48 Mn, 0.017 P, 0.011 S, 0.18 Si, 0.54 Ni, 16.90 Cr, 0.64 Mo. Heat treated at 1040 °C (1905 °F), 2 h. Oil quenched from 66 to 94 °C (150 to 200 °F). Double stress relieved at 175 °C (345 °F), 15 min. Water quenched. Tempered 2 h. Heat treated, 9.78 mm (0.385 in.) round. Tested, 9.53 mm (0.375 in.) round. At 260 to 540 °C (500 to 1000 °F). Also, heat treated, 14 mm (0.550 in.) round. Tested, 12.8 mm (0.505 in.) round. At 295 to 760 °C (1100 to 1400 °F). Source: Republic Steel

440C: Microstructures. (a) Vilella's reagent, 500×. As forged. Large primary carbide particles. Heavy carbide precipitation at grain boundaries. Secondary carbide particles. Matrix predominantly retained austenite. (b) Vilella's reagent, 500×. Forging annealed at 870 °C (1600 °F). Furnace cooled to 94 °C (200 °F) in 48 h. Air cooled. Large particles of primary and spheroidized particles of secondary carbide. Ferrite matrix. (c) Vilella's reagent, 500×. Forging hardened by austenitizing at 1010 °C (1850 °F), 1 h. Air cooled. Tempered at 230 °C (445 °F), 2 h. Large primary and tempered secondary carbide particles. Martensite matrix. (d) Vilella's reagent, 100×. Forging, hardened and tempered. Band of carbide segregation. Dispersed carbide particles. Tempered martensite matrix. Microhardness indentations (black). Shows relative hardness of carbide particles and matrix. (e) Super picral, 500×. Bar, preheated at 760 °C (1400 °F), ½ h. Air cooled to 66 °C (150 °F). Double tempered at 425 °C (795 °F), 2 h each. Primary and secondary carbides, light islands and particles. Tempered martensite matrix. (f) Vilella's reagent, 200×. Bar, austenitized at 1010 to 1050 °C (1850 to 1920 °F). Oil quenched. Tempered at 190 °C (375 °F). Segregated stringers of primary carbide (light) and dispersed secondary carbide particles. Tempered martensite matrix



Cast Stainless Steels

troduction

The heat treatment of stainless steel castings follows closely in purpose procedure the thermal processing of comparable wrought materials. ·ever, the differences in detail warrant separate consideration.

In work-hardenable ferritic alloys, machining and grinding stresses are ved at temperatures from approximately 260 to 540 °C (500 to 1000 Castings of the martensitic grades CA-15 and CA-40 do not require ritical annealing to remove the effects of cold working, because they ıot cold worked or cold formed. Casting stresses in other martensitic əs should be relieved by subcritical annealing, before further heat ment. For hardened martensitic castings, the stress-relieving tempera- must be kept below the final tempering or aging temperature.

Homogenization. Alloy segregation and dendritic structures may r in castings. They may be particularly pronounced in heavy sections. , mechanical reduction and soaking treatments are required in the mill əssing of wrought alloys. Therefore, it is frequently necessary to ɔgenize some alloys at temperatures above 1095 °C (2005 °F), to ıote uniformity of chemical composition and microstructure. Full aling of martensitic castings results in recrystallization and maximum ess, but it is less effective than homogenization in eliminating segre- n. Homogenization is a common procedure in the heat treatment of pitation-hardening castings.

Ferritic and Austenitic Grades. The ferritic, austenitic, and d ferritic-austenitic grades are not hardenable by heat treatment. They be used in the as-cast condition, if maximum resistance to corrosion is equired. They can be annealed or stress relieved to improve their sion resistance and machining characteristics.

The ferritic alloys CB-30 and CC-50 are annealed to relieve stresses educe hardness by being heated above 790 °C (1455 °F), as shown in ıble included in this section.

The austenitic grades achieve maximum resistance to intergranular sion by the high-temperature heating and quenching procedure known lution annealing. As-cast structures or castings exposed to tempera- in the range from 425 to 870 °C (795 to 1600 °F) may contain complex nium carbides precipitated preferentially along grain boundaries in ly austenitic grades. This microstructure is susceptible to intergranular sion, especially in oxidizing solutions. In partially ferritic grades, des tend to precipitate in the discontinuous ferrite pools. Thus, these s are less susceptible to intergranular attack. The purpose of solution ıling is to ensure complete solution of carbides in the matrix and to ı these carbides in solid solution.

Solution annealing procedures for all austenitic grades are similar. consist of heating to a temperature of approximately 1095 °C (2005 holding for a time sufficient to accomplish complete solution of des, and quenching at a rate fast enough to prevent reprecipitation of ırbides, particularly while cooling through the range from 870 to 540 °C (1600 to 1000 °F). Temperatures to which castings should be heated before quenching vary somewhat, depending on the alloy.

As shown in the table included in this section, a two-step heat treating procedure may be applied to the niobium-containing CF-8C alloy. The first treatment consists of solution annealing. This is followed by a stabilizing treatment at 870 to 925 °C (1600 to 1695 °F), which precipitates niobium carbides, prevents formation of the damaging chromium carbides, and provides maximum resistance to intergranular attack.

Because of their low carbon contents, CF-3 and CF-3M do not contain enough chromium carbides to cause selective intergranular attack and hence do not require solution annealing.

Martensitic Grades. The hardening procedures for CA-15 castings are similar to those used for the comparable wrought alloy, type 410. Recommended practice for annealing, austenitizing, and tempering CA-15 are in the article on this alloy which follows. In addition, operating information on two other martensitic grades, CA-40 and CA-6NM, is presented in articles.

Compositions. Alloy Casting Institute (ACI) compositions for corrosion resistant cast steels are in the adjoining table, along with information on comparable UNS, wrought, and ASTM grades, plus the most common end-use microstructure for each alloy.

In addition, 15 articles on representative individual alloys are presented. They include:

Ferritic and Austenitic grades	
CB-30	CF-12M
CC-50	CF-16F
CE-30	CF-20
CF-3	CH-20
CF-8C	CK-20
CF-8M	CN-7M
Martensitic grades	
CA-15	
CA-40	
CA-6NM	

Applications and welding conditions for corrosion resistant alloys are listed in adjoining tables.

Heat-Resisting Grades. Information on these casting alloys that follow include ACI compositions; general corrosion characteristics and creep stress values; room temperature properties; short-term tensile properties at elevated temperatures; approximate rates of corrosion in air and flue gas; and corrosion resistance at 900 °C (1650 °F) in various atmospheres.

CI Type: Compositions and Typical Microstructures of Alloy Casting Institute (ACI) Corrosion-Resistant Cast eels

I type	Wrought alloy type(a)	ASTM specifications	Most common end-use microstructure	Composition, % (b) C	Mn	Si	Cr	Ni	Others(c)
romium steels									
-15	410	A743, A217, A487	Martensite	0.15	1.00	1.50	11.5-14.0	1.0	0.50Mo(d)
-15M	...	A743	Martensite	0.15	1.00	0.65	11.5-14.0	1.0	0.15-1.00Mo
-40	420	A743	Martensite	0.40	1.00	1.50	11.5-14.0	1.0	0.5Mo(d)
-40F	...	A743	Martensite	0.2-0.4	1.00	1.50	11.5-14.0	1.0	...
-30	431, 442	A743	Ferrite and carbides	0.30	1.00	1.50	18.0-22.0	2.0	...
-50	446	A743	Ferrite and carbides	0.30	1.00	1.50	26.0-30.0	4.0	...
romium-nickel steels									
-6N	...	A743	Martensite	0.06	0.50	1.00	10.5-12.5	6.0-8.0	...
-6NM	...	A743, A487	Martensite	0.06	1.00	1.00	11.5-14.0	3.5-4.5	0.4-1.0Mo
-28MWV	...	A743	Martensite	0.20-0.28	0.50-1.00	1.00	11.0-12.5	0.50-1.00	0.9-1.25Mo; 0.9-1.25W; 0.2-0.3V
-7Cu-1	...	A747	Martensite, age hardenable	0.07	0.70	1.00	15.5-17.7	3.6-4.6	2.5-3.2Cu; 0.20-0.35Nb; 0.05N max
-7Cu-2	...	A747	Martensite, age hardenable	0.07	0.70	1.00	14.0-15.5	4.5-5.5	2.5-3.2Cu; 0.20-0.35Nb; 0.05N max
)-4MCu	...	A351, A743, A744, A890	Austenite in ferrite, age hardenable	0.04	1.00	1.00	25.0-26.5	4.75-6.0	1.75-2.25Mo; 2.75-3.25Cu
-30	312	A743	Ferrite in austenite	0.30	1.50	2.00	26.0-30.0	8.0-11.0	...
-3(e)	304L	A351, A743, A744	Ferrite in austenite	0.03	1.50	2.00	17.0-21.0	8.0-12.0	...
-3M(e)	316L	A351, A743, A744	Ferrite in austenite	0.03	1.50	2.00	17.0-21.0	8.0-12.0	2.0-3.0Mo
-3MN	...	A743	Ferrite in austenite	0.03	1.50	1.50	17.0-21.0	9.0-13.0	2.0-3.0Mo; 0.10-0.20N
-8(e)	304	A351, A743, A744	Ferrite in austenite	0.08	1.50	2.00	18.0-21.0	8.0-11.0	...
-8C	347	A351, A743, A744	Ferrite in austenite	0.08	1.50	2.00	18.0-21.0	9.0-12.0	Nb(f)
-8M	316	A351, A743, A744	Ferrite in austenite	0.08	1.50	2.00	18.0-21.0	9.0-12.0	2.0-3.0Mo
-10	...	A351	Ferrite in austenite	0.04-0.10	1.50	2.00	18.0-21.0	8.0-11.0	...
-10M	...	A351	Ferrite in austenite	0.04-0.10	1.50	1.50	18.0-21.0	9.0-12.0	2.0-3.0Mo
-10MC	...	A351	Ferrite in austenite	0.10	1.50	1.50	15.0-18.0	13.0-16.0	1.75-2.25Mo
-10SMnN	...	A351, A743	Ferrite in austenite	0.10	7.00-9.00	3.50-4.50	16.0-18.0	8.0-9.0	0.08-0.18N
-12M	316	...	Ferrite in austenite or austenite	0.12	1.50	2.00	18.0-21.0	9.0-12.0	2.0-3.0Mo
-16F	303	A743	Austenite	0.16	1.50	2.00	18.0-21.0	9.0-12.0	1.50Mo max; 0.20-0.35Se
-20	302	A743	Austenite	0.20	1.50	2.00	18.0-21.0	8.0-11.0	...
G-6MMN	...	A351, A743	Ferrite in austenite	0.06	4.00-6.00	1.00	20.5-23.5	11.5-13.5	1.50-3.00Mo; 0.10-0.30Nb; 0.10-30V; 0.20-40N
G-8M	317	A351, A743, A744	Ferrite in austenite	0.08	1.50	1.50	18.0-21.0	9.0-13.0	3.0-4.0Mo
G-12	...	A743	Ferrite in austenite	0.12	1.50	2.00	20.0-23.0	10.0-13.0	...
H-8	...	A351	Ferrite in austenite	0.08	1.50	1.50	22.0-26.0	12.0-15.0	...
H-10	...	A351	Ferrite in austenite	0.04-0.10	1.50	2.00	22.0-26.0	12.0-15.0	...
H-20	309	A351, A743	Austenite	0.20	1.50	2.00	22.0-26.0	12.0-15.0	...
K-3MCuN	...	A351, A743, A744	Ferrite in austenite	0.025	1.20	1.00	19.5-20.5	17.5-19.5	6.0-7.0V; 0.18-0.24N; 0.50-1.00Cu
K-20	310	A743	Austenite	0.20	2.00	2.00	23.0-27.0	19.0-22.0	...
ickel-chromium steel									
N-3M	...	A743	Austenite	0.03	2.00	1.00	20.0-22.0	23.0-27.0	4.5-5.5Mo
N-7M	...	A351, A743, A744	Austenite	0.07	1.50	1.50	19.0-22.0	27.5-30.5	2.0-3.0Mo; 3.0-4.0Cu
N-7MS	...	A743, A744	Austenite	0.07	1.50	3.50(g)	18.0-20.0	22.0-25.0	2.5-3.0Mo; 1.5-2.0Cu
T-15C	...	A351	Austenite	0.05-0.15	0.15-1.50	0.50-1.50	19.0-21.0	31.0-34.0	0.5-1.5V

) Type numbers of wrought alloys are listed only for nominal identification of corresponding wrought and cast grades. Composition ranges of cast alloys are not the same as for rresponding wrought alloys; cast alloy designations should be used for castings only. (b) Maximum unless a range is given. The balance of all compositions is iron. (c) Sulfur ntent is 0.04% in all grades except: CG-6MMN, 0.030% S (max); CF-10SMnN, 0.03% S (max); CT-15C, 0.03% S (max); CK-3MCuN, 0.010% S (max); CN-3M, 0.030% S nax); CA-6N, 0.020% S (max); CA-28MWV, 0.030% S (max); CA-40F, 0.20-0.40% S; CB-7Cu-1 and -2, 0.03% S (max). Phosphorus content is 0.04% (max) in all grades except: F-16F, 0.17% P (max); CF-10SMnN, 0.060% P (max); CT-15C, 0.030% P (max); CK-3MCuN, 0.045% P (max); CN-3M, 0.030% P (max); CA-6N, 0.020% P (max); CA-MWV, 0.030% P (max); CB-7Cu-1 and -2, 0.035% P (max). (d) Molybdenum not intentionally added. (e) CF-3A, CF-3MA, and CF-8A have the same composition ranges as F-3, CF-3M, and CF-8, respectively, but have balanced compositions so that ferrite contents are at levels that permit higher mechanical property specifications than those for re-ted grades. They are covered by ASTM A351. (f) Nb, 8 × %C min (1.0% max); or Nb + Ta × %C (1.1% max). (g) For CN-7MS, silicon ranges from 2.50 to 3.50%

ummary of Applications for Various Corrosion-Resistant Cast Steels

lloy	Characteristics
A-15	Widely used in mildly corrosive environments; hardenable; good erosion resistance
A-40	Similar to CA-15 at higher strength level
A-6NM	Improved properties over CA-15, especially improved resistance to cavitation
A-6N	Outstanding combinations of strength, toughness, and weldability with moderately good corrosion resistance
B-30	Improved performance in oxidizing environments compared to CA-15; excellent resistance to corrosion by nitric acid, alkaline solutions, and many organic chemicals
B-7Cu-1	Hardenable with good corrosion resistance
B-7Cu-2	Superior combination of strength, toughness, and weldability with moderately good corrosion resistance
C-50	Used in highly oxidizing media (hot HNO_3, acid mine waters)
D-4MCu	Similar to CF-8 in corrosion resistance, but higher strength, hardness, and stress-corrosion cracking resistance; excellent resistance to environments involving abrasion or erosion-corrosion; usefully employed in handling both oxidizing and reducing corrodents
E-30	Similar to CC-50, but Ni imparts higher strength and toughness levels. A grade available with controlled ferrite
F-3, CF-8, CF-20, CF-3M, CF-8M, CF-8C, CF-16F	CF types: most widely used corrosion-resistant alloys at ambient and cryogenic temperatures M variations: enhanced resistance to halogen ion and reducing acids C and F variations: used where application does not permit postweld heat treat A grades available with controlled ferrite
G-8M	Greater resistance to pitting and corrosion in reducing media than CF-8M; not suitable for nitric acids or other strongly oxidizing environments
H-20	Superior to CF-8 in specialized chemical and paper applications in resistance to hot H_2SO_3, organic acids, and dilute H_2SO_4; the high nickel and chromium contents also make this alloy less susceptible to intergranular corrosion after exposure to carbide-precipitating temperatures
K-20	Improved corrosion resistance compared to CH-20
N-7M	Highly resistant to H_2SO_4, H_3PO_4, H_2SO_3, salts, and seawater. Good resistance to hot chloride salt solutions, nitric acid, and many reducing chemicals

'elding Conditions for Corrosion-Resistant Steel Castings

CI signation	Type of electrodes used(a)	Preheat °C	Preheat °F	Postweld heat treatment
A-6NM	Same composition	100-150	212-300	590-620 °C (1100-1150 °F)
A-15	410	200-315	400-600	610-760 °C (1125-1400 °F), air cool
A-40	410 or 420	200-315	400-600	610-760 °C (1125-1400 °F), air cool
B-7Cu	Same composition or 308	Not required		480-590 °C (900-1100 °F), air cool
B-30	442	315-425	600-800	790 °C (1450 °F), min, air cool
C-50	446	200-700	400-1300	900 °C (1650 °F), air cool
D-4MCu	Same composition	Not required		Heat to 1120 °C (2050 °F), cool to 1040 °C (1900 °F), quench
E-30	312	Not required		Quench from 1090-1120 °C (2000-2050 °F)
F-3	308L	Not required		Usually unnecessary
F-8	308	Not required		Quench from 1040-1120 °C (1900-2050 °F)
F-8C	347	Not required		Usually unnecessary
F-3M	316L	Not required		Usually unnecessary
F-8M	316	Not required		Quench from 1070-1150 °C (1950-2100 °F)
F-12M	316	Not required		Quench from 1070-1150 °C (1950-2100 °F)
F-16F	308 or 308L	Not required		Quench from 1090-1150 °C (2000-2100 °F)
F-20	308	Not required		Quench from 1090-1150 °C (2000-2100 °F)
G-8M	317	Not required		Quench from 1040-1120 °C (1900-2050 °F)
H-20	309	Not required		Quench from 1090-1150 °C (2000-2100 °F)
K-20	310	Not required		Quench from 1090-1180 °C (2000-2150 °F)
N-7M	320	200	400	Quench from 1120 °C (2050 °F)

te: Metal arc, inert-gas arc, and electroslag welding methods can be used. Suggested electrical settings and electrode sizes for various section thicknesses are:

ction thickness, n (in.)	Electrode diameter, mm (in.)	Current, A	Maximum arc voltage, V
-6.4 (1/8–1/4)	2.4 (3/32)	45-70	24
-6.4 (1/8–1/4)	3.2 (1/8)	70-105	25
-6.4 (1/8–1/4)	4.0 (5/32)	100-140	25
-13 (1/4–1/2)	4.8 (3/16)	130-180	26
3 (1/2)	6.4 (1/4)	210-290	27

Lime-coated electrodes are recommended

Compositions of ACI Heat-Resistant Casting Alloys

ACI designation	UNS number	ASTM specifications(a)	Composition, % (b) C	Cr	Ni	Si (max)
HA	...	A217	0.20 max	8-10	...	1.00
HC	J92605	A297, A608	0.50 max	26-30	4 max	2.00
HD	J93005	A297, A608	0.50 max	26-30	4-7	2.00
HE	J93403	A297, A608	0.20-0.50	26-30	8-11	2.00
HF	J92603	A297, A608	0.20-0.40	19-23	9-12	2.00
HH	J93503	A297, A608, A447	0.20-0.50	24-28	11-14	2.00
HI	J94003	A297, A567, A608	0.20-0.50	26-30	14-18	2.00
HK	J94224	A297, A351, A567, A608	0.20-0.60	24-28	18-22	2.00
HK30	...	A351	0.25-0.35	23.0-27.0	19.0-22.0	1.75
HK40	...	A351	0.35-0.45	23.0-27.0	19.0-22.0	1.75
HL	J94604	A297, A608	0.20-0.60	28-32	18-22	2.00
HN	J94213	A297, A608	0.20-0.50	19-23	23-27	2.00
HP	...	A297	0.35-0.75	24-28	33-37	2.00
HP-50WZ(c)	...	...	0.45-0.55	24-28	33-37	2.50
HT	J94605	A297, A351, A567, A608	0.35-0.75	13-17	33-37	2.50
HT30	...	A351	0.25-0.35	13.0-17.0	33.0-37.0	2.50
HU	...	A297, A608	0.35-0.75	17-21	37-41	2.50
HW	...	A297, A608	0.35-0.75	10-14	58-62	2.50
HX	...	A297, A608	0.35-0.75	15-19	64-68	2.50

(a) ASTM designations are the same as ACI designations. (b) Rem Fe in all compositions. Manganese content: 0.35 to 0.65% for HA, 1% for HC, 1.5% for HD, and 2% for the other alloys. Phosphorus and sulfur contents: 0.04% (max) for all but HP-50WZ. Molybdenum is intentionally added only to HA, which has 0.90 to 1.20% Mo; maximum for other alloys is set at 0.5% Mo. HH also contains 0.2% N (max). (c) Also contains 4 to 6% W, 0.1 to 1.0% Zr, and 0.035% S (max) and P (max)

General Corrosion Characteristics of Heat-Resistant Cast Steels and Typical Limiting Creep Stress Values at Indicated Temperatures

Alloy	Corrosion characteristics	Creep test temperature °C	°F	Limiting creep stress (0.0001 %/h) MPa	ksi
HA	Good oxidation resistance to 650 °C (1200 °F); widely used in oil refining industry	650	1200	21.5	3.1
HC	Good sulfur and oxidation resistance up to 1095 °C (2000 °F); minimal mechanical properties; used in applications where strength is not a consideration or for moderate load bearing up to 650 °C (1200 °F)	870	1600	5.15	0.75
HD	Excellent oxidation and sulfur resistance plus weldability	980	1800	6.2	0.9
HE	Higher temperature and sulfur resistant capabilities than HD	980	1800	9.5	1.4
HF	Excellent general corrosion resistance to 815 °C (1500 °F) with moderate mechanical properties	870	1600	27	3.9
HH(a)	High strength; oxidation resistant to 1090 °C (2000 °F); most widely used	980	1800	7.5 (type I) 14.5 (type II)	1.1 (type I) 2.1 (type II)
HI	Improved oxidation resistance compared to HH	980	1800	13	1.9
HK	Because of its high temperature strength, widely used for stressed parts in structural applications up to 1150 °C (2100 °F); offers good resistance to corrosion by hot gases, including sulfur-bearing gases, in both oxidizing and reducing conditions (although HC, HE, and HI are more resistant in oxidizing gases); used in air, ammonia, hydrogen, and molten neutral salts; widely used for tubes and furnace parts	1040	1900	9.5	1.4
HL	Improved sulfur resistance compared to HK; especially useful where excessive scaling must be avoided	980	1800	15	2.2
HN	Very high strength at high temperatures; resistant to oxidizing and reducing flue gases	1040	1900	11	1.6
HP	Resistant to both oxidizing and carburizing atmospheres at high temperatures	980	1800	19	2.8
HP-50WZ	Improved creep rupture strength at 1090 °C (2000 °F) and above compared to HP	1090	2000	4.8	0.7
HT	Widely used in thermal shock applications; corrosion resistant in air, oxidizing and reducing flue gases, carburizing gases, salts, and molten metals; performs satisfactorily up to 1150 °C (2100 °F) in oxidizing atmospheres and up to 1095 °C (2000 °F) in reducing atmospheres, provided that limiting creep stress values are not exceeded	980	1800	14	2.0
HU	Higher hot strength than HT and often selected for its superior corrosion resistance	980	1800	15	2.2
HW	High hot strength and electrical resistivity; performs satisfactorily to 1120 °C (2050 °F) in strongly oxidizing atmospheres and up to 1040 °C (1900 °F) in oxidizing or reducing products of combustion that do not contain sulfur; resistant to some salts and molten metals	980	1800	9.5	1.4
HX	Resistant to hot-gas corrosion under cycling conditions without cracking or warping; corrosion resistant in air, carburizing gases, combustion gases, flue gases, hydrogen, molten cyanide, molten lead, and molten neutral salts at temperatures up to 1150 °C (2100 °F)	980	1800	11	1.6

(a) Two grades: type I (ferrite in austenite) and type II (wholly austenitic), per ASTM A447

ypical Room-Temperature Properties of ACI Heat-Resistant Casting Alloys

lloy	Condition	Tensile strength, MPa	Tensile strength, ksi	Yield strength, MPa	Yield strength, ksi	Elongation, %	Hardness, HB
IC	As-cast	760	110	515	75	19	223
	Aged(a)	790	115	550	80	18	...
D	As-cast	585	85	330	48	16	90
E	As-cast	655	95	310	45	20	200
	Aged(a)	620	90	380	55	10	270
F	As-cast	635	92	310	45	38	165
	Aged(a)	690	100	345	50	25	190
H, type I	As-cast	585	85	345	50	25	185
	Aged(a)	595	86	380	55	11	200
H, type II	As-cast	550	80	275	40	15	180
	Aged(a)	635	92	310	45	8	200
I	As-cast	550	80	310	45	12	180
	Aged(a)	620	90	450	65	6	200
K	As-cast	515	75	345	50	17	170
	Aged(b)	585	85	345	50	10	190
L	As-cast	565	82	360	52	19	192
N	As-cast	470	68	260	38	13	160
P	As-cast	490	71	275	40	11	170
T	As-cast	485	70	275	40	10	180
	Aged(b)	515	75	310	45	5	200
U	As-cast	485	70	275	40	9	170
	Aged(c)	505	73	295	43	5	190
W	As-cast	470	68	250	36	4	185
	Aged(d)	580	84	360	52	4	205
X	As-cast	450	65	250	36	9	176
	Aged(c)	505	73	305	44	9	185

) Aging treatment: 24 h at 760 °C (1400 °F), furnace cool. (b) Aging treatment: 24 h at 760 °C (1400 °F), air cool. (c) Aging treatment: 48 h at 980 °C (1800 °F), air cool. (d) Aging :atment: 48 h at 980 °C (1800 °F), furnace cool

epresentative Short-Term Tensile Properties of Cast Heat-Resistant Alloys at Elevated Temperatures

loy	760 °C (1400 °F) Ultimate tensile strength, MPa	ksi	Yield strength at 0.2% offset, MPa	ksi	Elongation, %	870 °C (1600 °F) Ultimate tensile strength, MPa	ksi	Yield strength at 0.2% offset, MPa	ksi	Elongation, %	980 °C (1800 °F) Ultimate tensile strength, MPa	ksi	Yield strength at 0.2% offset, MPa	ksi	Elongation, %
A	462(a)	67(a)	220(b)	32(b)	...	...	...	...	...	...	...	...	...	...	...
D	248	36	...	...	14	159	23	...	...	18	103	15	...	...	40
F	262	38	172	25	16	145	21	107	15.5	16	...	...	...	...	...
H (type I)(c)	228	33	117	17	18	127	18.5	93	13.5	30	62	9	43	6.3	45
H (type II)(c)	258	37.4	136	19.8	16	148	21.5	110	16	18	75	10.9	50	7.3	31
I	262	38	...	...	6	179	26	...	...	12	...	...	...	...	...
K	258	37.5	168	24.4	12	161	23	101	15	16	85.5	12.4	60	8.7	42
L	345	50	...	...	...	210	30.5	...	...	...	129	18.7	...	...	...
N	...	...	...	...	...	140	20	100	14.5	37	83	12	66	9.6	51
P	296	43	200	29	15	179	26	121	17.5	27	100	14.5	76	11	46
T	240	35	180	26	10	130	19	103	15	24	76	11	55	8	28
U	275	40	...	...	...	135	19.5	...	...	20	69	10	43	6.2	28
W	220	32	158	23	...	131	19	103	15	...	69	10	55	8	40
X	310(d)	45(d)	138(d)	20(d)	8(d)	141	20.5	121	17.5	48	74	10.7	47	6.9	40

In this instance, test temperature was 540 °C (1000 °F). (b) Test temperature was 590 °C (1095 °F). (c) Type I and II per ASTM A 447. (d) Test temperature was 650 °C (1200 °F)

Approximate Rates of Corrosion for ACI Heat-Resistant Casting Alloys in Air and in Flue Gas

Alloy	Oxidation rate in air, mm/yr, 870 °C (1600 °F)	Oxidation rate in air, mm/yr, 980 °C (1800 °F)	Oxidation rate in air, mm/yr, 1090 °C (2000 °F)	Corrosion rate, mm/yr, at 980 °C (1800 °F) in flue gas with sulfur content of 0.12 g/m³: Oxidizing	0.12 g/m³: Reducing	2.3 g/m³: Oxidizing	2.3 g/m³: Reducing
HB	0.63–	6.25–	12.5–	2.5+	12.5	6.25–	12.5
HC	0.25	1.25	1.25	0.63–	0.63+	0.63	0.63–
HD	0.25–	1.25–	1.25–	0.63–	0.63–	0.63–	0.63–
HE	0.13–	0.63–	0.88–	0.63–	0.63–	0.63–	0.63–
HF	0.13–	1.25+	2.5	1.25+	2.5+	1.25+	6.25
HH	0.13–	0.63–	1.25	0.63–	0.63	0.63	0.63–
HI	0.13–	0.25+	0.88–	0.63–	0.63–	0.63–	0.63–
HK	0.25–	0.25–	0.88–	0.63–	0.63–	0.63–	0.63–
HL	0.25+	0.63–	0.88	0.63–	0.63–	0.63	0.63–
HN	0.13	0.25+	1.25–	0.63–	0.63–	0.63	0.63
HP	0.63–	0.63	1.25	0.63–	0.63–	0.63–	0.63–
HT	0.13–	0.25+	1.25	0.63	0.63–	0.63	2.5
HU	0.13–	0.25–	0.88–	0.63–	0.63–	0.63–	0.63
HW	0.13–	0.25–	0.88	0.63	0.63–	1.25–	6.25
HX	0.13–	0.25–	0.88–	0.63–	0.63–	0.63–	0.63–

Annealing of Ferritic and Austenitic Stainless Steel Castings

Type	Minimum temperature, °C	Minimum temperature, °F	Quench(a)	Tensile strength, ksi(b)	Tensile strength, MPa(b)
For full softness					
CB-30	790	1450	FC+A(c)	95	655
CC-50	790	1450	A	97	669
For maximum corrosion resistance					
CE-30	1095	2000	W,O,A	97	669
CF-3, CF-3M	1040	1900	W,O,A	77	531
CF-8, CF-8C(d)	1040	1900	W,O,A	77	531
CF-8M, CF-12M(e)	1040	1900	W,O,A	80	552
CF-16F, CF-20	1040	1900	W,O,A	77	531
CH-20	1095	2000	W,O,A	88	607
CK-20	1095	2000	W,O,A	76	524
CN-7M	1120	2050	W,O,A	69	476

(a) FC, furnace cool; W, water; O, oil; A, air. (b) Approximate. (c) Furnace cool to 540 °C (1000 °F); then air cool. (d) CF-8C may be reheated to 870 to 925 °C (1600 to 1700 °F); then air cooled for precipitation of niobium carbides. (e) CF-12M should be quenched from a temperature above 1095 °C (2000 °F).

Corrosion Resistance of Heat-Resistant Cast Steels at 980 °C (1800 °F) in 100 h Tests in Various Atmospheres

Alloy	Air	Oxidizing flue gas(b)	Reducing flue gas(b)	Reducing flue gas(c)	Reducing flue gas (constant temperature)(d)	Reducing flue gas cooled to 150 °C (300 °F) every 12 h(d)
	Corrosion rating(a) in indicated atmosphere					
HA	U	U	U	U	U	U
HC	G	G	G	S	G	G
HD	G	G	G	S	G	G
HE	G	G	G	...	G	...
HF	S	G	S	U	S	S
HH	G	G	G	S	G	G
HI	G	G	G	S	G	G
HK	G	G	G	U	G	G
HL	G	G	G	S	G	G
HN	G	G	G	U	S	S
HP	G	G	G	G	G	...
HT	G	G	G	U	S	U
HU	G	G	G	U	S	U
HW	G	G	G	U	U	U
HX	G	G	G	S	G	U

(a) G, good (corrosion rate $r < 1.27$ mm/yr, or 50 mils/yr); S, satisfactory ($r < 2.54$ mm/yr, or 100 mils/yr); U, unsatisfactory ($r > 2.54$ mm/yr, or 100 mils/yr). (b) Contained 2 g of sulfur/m³ (5 grains S/100 ft³). (c) Contained 120 g S/m³ (300 grains S/100 ft³). (d) Contained 40 g/S/m³ (100 grains S/100 ft³)

A-6NM

emical Composition. ACI CA-6NM: 0.06 C, 1.00 Mn, 1.00 Si, to 4.5 Ni, 11.5 to 14.0 Cr, 0.4 to 1.0 Mo

nilar Steels (U.S. and/or Foreign). UNS J91540; ASTM A743, 37

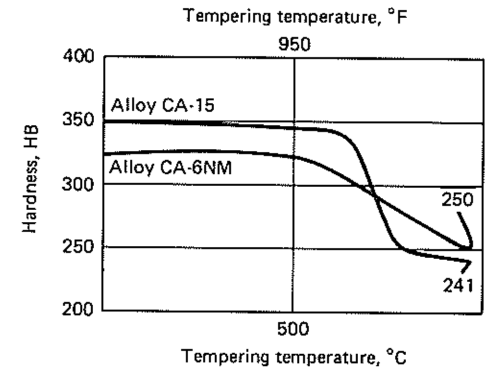
aracteristics. Martensite is most common end-use microstructure

commended Heat Treating Practice

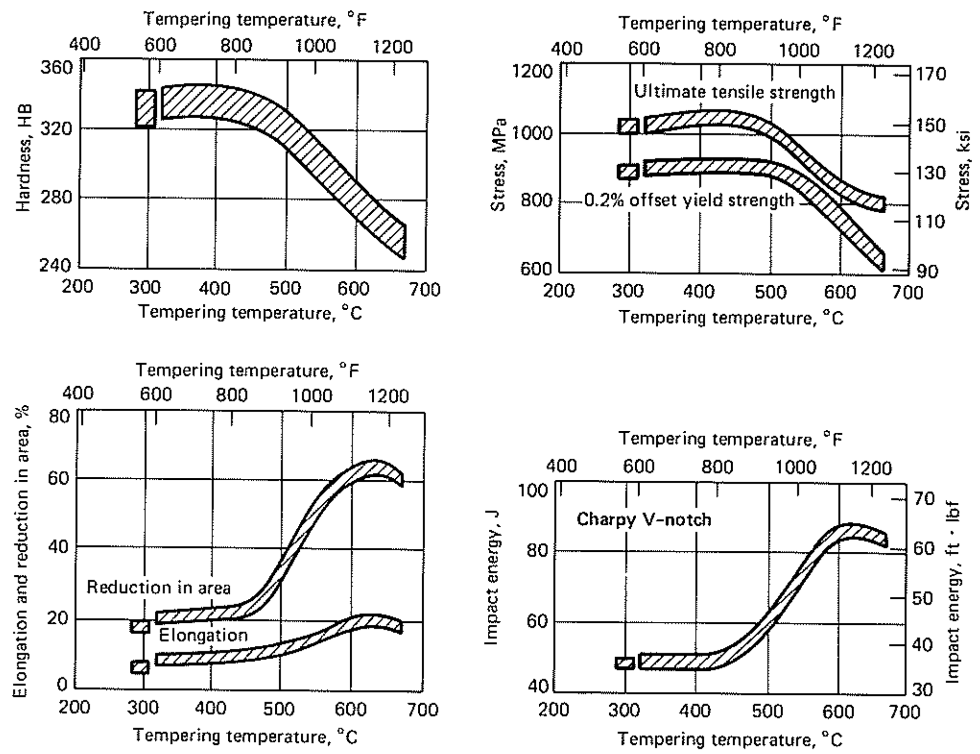
nealing. For maximum softness, parts are annealed at 790 to 815 °C 55 to 1500 °F). The typical ultimate tensile strength obtained is approxi-ely 550 MPa (80 ksi)

stenitizing and Tempering. Following austenitizing, parts are nched in oil or air. In austenitizing at 955 to 980 °C (1750 to 1795 °F) tempering at 595 to 620 °C (1105 to 1150 °F), a typical ultimate tensile ngths of approximately 825 MPa (120 ksi) is obtained

CA-6NM: Influence of Tempering Temperature on Hardness. Source: ESCO Corporation



A-6NM: Effect of Tempering Temperature on Mechanical Properties of Standard Keel Block. Source: ESCO Corporation



;A-15

hemical Composition. **ACI CA-15:** 0.15 C, 1.00 Mn, 1.50 Si, 1.0 i, 11.5 to 14.0 Cr, 0.50 Mo (not intentionally added)

imilar Steels (U.S. and/or Foreign). UNS J91150; wrought pe 410 stainless; ASTM A743, A217, A487

haracteristics. Martensite is most common end-use microstructure

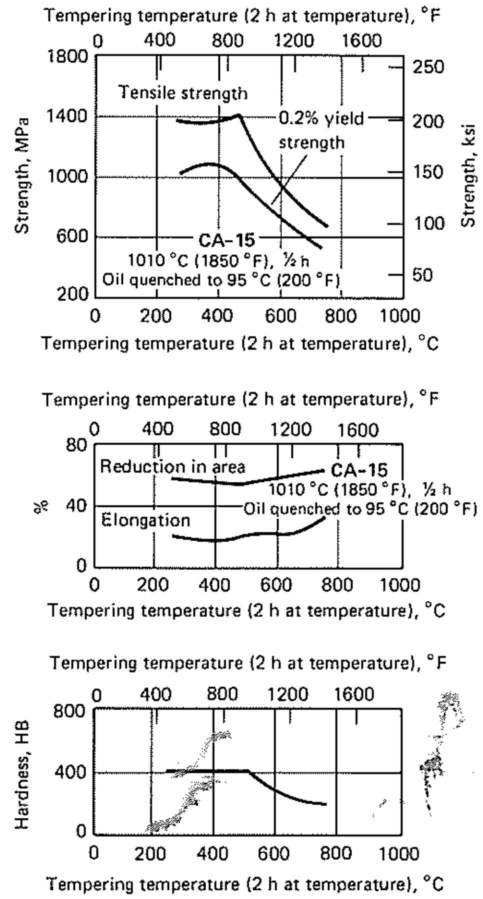
ecommended Heat Treating Practice

nnealing. For maximum softness, parts are annealed at 845 to 900 °C 555 to 1650 °F). The typical ultimate tensile strength obtained is approxi- ately 550 MPa (80 ksi)

ustenitizing and Tempering. Following austenitizing, parts are ıenched in oil or air. Tempering at 370 to 595 °C (700 to 1105 °F) is not commended because in this range impact ductility is low. For this alloy, ırts are held at austenitizing temperature for a minimum of 30 min.

In austenitizing at 925 to 1010 °C (1695 to 1850 °F) and tempering at '0 °C max (700 °F) max, typical ultimate tensile strengths of approxi- ately 1380 MPa (200 ksi) are obtained, while in austenitizing at 925 to)10 °C (1695 to 1850 °F) and tempering at 595 to 760 °C (1105 to 1400 '), typical ultimate tensile strengths of approximately 690 to 930 MPa 00 to 135 ksi) are obtained

CA-15: Effect of Tempering Temperature on Typical Room Temperature Properties



A-15: Effects of Four Methods of Heat Treatment on Typical Room Temperature Properties

pecimens were taken from shell mold cast keel blocks; data indicate results obtained on four specimens treated by each method

eat treatment(a)	Ultimate tensile strength MPa	Ultimate tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation in 50 mm (2 in.), %	Reduction in area, %
'eatment 1	1230	178	1005	146	9.0	13.0
Homogenize: 1 h at 1040 °C (1900 °F), AC	1250	181	970	141	12.5	28.0
Solution anneal: ½ h at 955 °C (1750 °F), OQ	1275	185	985	143	7.0	14.0
Temper: 3 h at 300 °C (575 °F), AC	1315	191	1020	148	8.0	12.5
'eatment 2	1260	183	1115	162	6.5	9.5
Anneal: 1 h at 900 °C (1650 °F), FC	1296	188	1130	164	5.5	16.0
Solution anneal: 1¼ h at 1010 °C (1850 °F), OQ	1340	194	1070	155	9.0	23.0
Temper: 3 h at 370 °C (700 °F), OQ	1380	200	1050	152	12.0	42.0
'eatment 3(b)	795	115	485	70	15.5	60.0
Anneal: 1 h at 900 °C (1650 °F), FC	810	117	630	91	16.5	37.0
Solution anneal: 1¼ h at 1010 °C (1850 °F), OQ	830	120	680	98	9.5	23.0
Temper: 2 h at 620 °C (1150 °F), AC	860	125	585	85	12.5	32.0
'eatment 4(c)	685	99	525	76	21.0	65.0
Anneal: 1 h at 900 °C (1650 °F), FC	710	103	545	79	20.5	56.0
Solution anneal: 1½ h at 995 °C (1825 °F), FAC	710	103	545	79	18.5	61.5
Temper: 2 h at 705 °C (1300 °F), AC	720	104	550	80	20.5	60.0

) Each treatment comprised three processes as listed: AC, air cool; OQ, oil quench; FC, furnace cool; FAC, forced-air cool. (b) AMS 5351-B. (c) MIL-S-16993

A-40

ıemical Composition. **ACI CA-40:** 0.40 C, 1.00 Mn, 1.50 Si, 1.0 11.5 to 14.0 Cr, 0.5 Mo (not intentionally added)

nilar Steels (U.S. and/or Foreign). UNS J91153; wrought e 410 stainless; ASTM A743

ıaracteristics. Martensite is most common end-use microstructure

›commended Heat Treating Practice

ınealing. For maximum softness, parts are annealed at 845 to 900 °C 55 to 1650 °F), then slow furnace cooled from temperature. The typical mate tensile strength obtained is approximately 620 MPa (90 ksi)

Austenitizing and tempering. Following austenitizing, parts are quenched in oil or air. Tempering at 370 to 595 °C (700 to 1105 °F) is not recommended because in this range impact ductility is low.

In austenitizing at 980 to 1010 °C (1795 to 1850 °F) and tempering at 315 °C max (600 °F max), a typical ultimate tensile strength of approximately 1515 MPa (220 ksi) is obtained. At the same austenitizing temperature, typical ultimate tensile strength drops as tempering temperature is increased. At the 595 °C (1105 °F) level, the result is 1035 MPa (150 ksi); at the 650 °C (1200 °F) level, the result is 965 MPa (140 ksi); at the 760 °C (1400 °F) level, the result is 760 MPa (110 ksi)

B-30

ıemical Composition. **ACI CA-15:** 0.30 C, 1.00 Mn, 1.50 Si, 2.0 18.0 to 22.0 Cr

nilar Steels (U.S. and/or Foreign). UNS J91803; type 431, e 442; ASTM A743

ıaracteristics. A chromium grade. The most commonly used microıcture contains ferrite and carbides

Annealing. The minimum annealing temperature for full softness is 790 °C (1455 °F). The quenching procedure is furnace cooling to 540 °C (1000 °F), then air cooling. The typical ultimate tensile strength obtained is approximately 660 MPa (95 ksi)

C-50

ıemical Composition. **ACI CC-50:** 0.30 C, 1.00 Mn, 1.50 Si, 4.0 26.0 to 30.0 Cr

nilar Steels (U.S. and/or Foreign). UNS J92615; type 446; TM A743

ıaracteristics. A chromium grade. The most commonly used microıcture contains ferrite and carbides

Recommended Heat Treating Practice

Annealing. The minimum annealing temperature for full softness is 790 °C (1455 °F). Parts are quenched in air. The typical ultimate tensile strength obtained is approximately 670 MPa (97 ksi)

E-30

ıemical Composition. **ACI CE-30:** 0.30 C, 1.50 Mn, 2.00 Si, 8.0 11.0 Ni, 26.0 to 30.0 Cr

milar Steels (U.S. and/or Foreign). UNS J93423; type 312; TM 743

ıaracteristics. A chromium-nickel grade. Ferrite in austenite is the st commonly used microstructure

Recommended Heat Treating Practice

Annealing. For maximum corrosion resistance, the minimum annealing temperature is 1095 °C (2005 °F). Quenching is in water, oil, or air. The typical ultimate tensile strength obtained is approximately 670 MPa (97 ksi)

CF-3

Chemical Composition. **ACI CF-3:** 0.03 C, 1.50 Mn, 2.00 Si, 8.0 to 12.0 Ni, 17.0 to 21.0 Cr

Note: CF-3A, CF-3MA, and CF-8A have the same composition ranges as CF-3, CF-3M, and CF-8 respectively, but have balanced compositions so that ferrite contents are at levels that permit higher mechanical property specifications than those for related grades. They are covered by ASTM A351

Similar Steels (U.S. and/or Foreign). UNS J92700; type 304L; ASTM A351, A743, A744

Characteristics. A chromium-nickel grade. Ferrite in austenite is the most commonly used microstructure

Recommended Heat Treating Practice

Annealing. The minimum annealing temperature for maximum corrosion resistance is 1040 °C (1905 °F). Quenching is in water, oil, or air. The typical ultimate tensile strength obtained is approximately 530 MPa (77 ksi)

CF-8C

Chemical Composition. **ACI CF-8C:** 0.08 C, 1.50 Mn, 2.00 Si, 9.0 to 12.0 Ni, 18.0 to 21.0 Cr, Nb

Note: Nb, 8 X %C min (1.0 % max); or Nb + Ta X %C (1.1 % max)

Similar Steels (U.S. and/or Foreign). UNS J92600; type 304; ASTM A351, A743, A744

Characteristics. A chromium-nickel grade. Ferrite in austenite is the most commonly used microstructure

Recommended Heat Treating Practice

Annealing. The minimum annealing temperature for maximum corrosion resistance is 1040 °C (1905 °F). Quenching is in water, oil, or air. The typical ultimate tensile strength obtained is approximately 530 MPa (77 ksi). CF-8C may be reheated to 870 to 925 °C (1600 to 1695 °F), then air-cooled to precipitate niobium carbides

CF-8M

Chemical Composition. **ACI CF-8M:** 0.08 C, 1.50 Mn, 2.00 Si, 9.0 to 12.0 Ni, 18.0 to 21.0 Cr, 2.0 to 3.0 Mo

Similar Steels (U.S. and/or Foreign). UNS J92900; type 316; ASTM A351, A743

Characteristics. A chromium-nickel grade. Ferrite in austenite is the most commonly used microstructure

Recommended Heat Treating Practice

Annealing. The minimum annealing temperature for maximum corrosion resistance is 1040 °C (1905 °F). Quenching is in water, oil, or air. The typical ultimate tensile strength obtained is approximately 550 MPa (80 ksi)

CF-12M

Chemical Composition. **ACI CF-12M:** 0.12 C, 1.50 Mn, 2.00 Si, 9.0 to 12.0 Ni, 18.0 to 21.0 Cr, 2.0 to 3.0 Mo

Similar Steels (U.S. and/or Foreign). Type 316

Characteristics. A chromium-nickel grade. Ferrite in austenite or austenite alone is the most commonly used microstructure

Recommended Heat Treating Practice

Annealing. The minimum annealing temperature for maximum corrosion resistance is 1040 °C (1905 °F). The alloy should be quenched from a temperature above 1095 °C (2005 °F). Quenching is in water, oil, or air. The typical ultimate tensile strength obtained is approximately 550 MPa (80 ksi)

CF-16F

Chemical Composition. **ACI CF-16F:** 0.16 C, 1.50 Mn, 2.00 Si, 9.0 to 12.0 Ni, 18.0 to 21.0 Cr, 1.5 Mo max, 0.25 to 0.35 Se

Similar Steels (U.S. and/or Foreign). UNS J92701; type 303; ASTM A743

aracteristics. A chromium-nickel grade. Austenite is the most com-
nly used microstructure

:commended Heat Treating Practice

nealing. The minimum annealing temperature for maximum corro-
ı resistance is 1040 °C (1905 °F). Quenching is in water, oil, or air. The typical ultimate tensile strength obtained is approximately 530 MPa (77 ksi)

F-20

emical Composition. **ACI CF-20:** 0.20 C, 1.50 Mn, 2.00 Si, 8.0
1.0 Ni, 18.0 to 21.0 Cr

nilar Steels (U.S. and/or Foreign). UNS J92602; type 302;
ГM A743

aracteristics. A chromium-nickel grade. Austenite is the most com-
ıly used microstructure

Recommended Heat Treating Practice

Annealing. The minimum annealing temperature for maximum corrosion resistance is 1040 °C (1905 °F). Quenching is in water, oil, or air. The typical ultimate tensile strength obtained is approximately 530 MPa (77 ksi)

H-20

emical Composition. **ACI CH-20:** 0.20 C, 1.50 Mn, 2.00 Si,
) to 15.0 Ni, 22.0 to 26.0 Cr

nilar Steels (U.S. and/or Foreign). UNS J93402; type 309;
ГM A351, A743

aracteristics. A chromium-nickel grade. Austenite is the most com-
ıly used microstructure

Recommended Heat Treating Practice

Annealing. The minimum annealing temperature for maximum corrosion resistance is 1095 °C (2005 °F). Quenching is in water, oil, or air. The typical ultimate tensile strength obtained is approximately 610 MPa (88 ksi)

K-20

emical Composition. **ACI CK-20:** 0.20 C, 2.00 Mn, 2.00 Si,
) to 22.0 Ni, 23.0 to 27.0 Cr

nilar Steels (U.S. and/or Foreign). UNS J94202; type 310;
ГM A743

aracteristics. A chromium-nickel grade. Austenite is the most com-
ıly used microstructure

Recommended Heat Treating Practice

Annealing. The minimum annealing temperature for maximum corrosion resistance is 1095 °C (2005 °F). Quenching is in water, oil, or air. The typical ultimate tensile strength obtained is approximately 525 MPa (76 ksi)

N-7M

emical Composition. **ACI CN-7M:** 0.07 C, 1.50 Mn, 1.50 Si,
i to 30.5 Ni, 19.0 to 22.0 Cr, 2.0 to 3.0 Mo, 3.0 to 4.0 Cu

nilar Steels (U.S. and/or Foreign). UNS N08007; ASTM
i1, A743, A744

aracteristics. A chromium-nickel grade. Austenite is the most com-
ıly used microstructure

Recommended Heat Treating Practice

Annealing. The minimum annealing temperature for maximum corrosion resistance is 1120 °C (2050 °F). Quenching is in water, oil, or air. The typical ultimate tensile strength obtained is approximately 480 MPa (69 ksi)

Cast PH Stainless Steels

ntroduction

Cast PH Steels. It is desirable to subject precipitation-hardenable astings to a high-temperature homogenization treatment to reduce alloy egregation and to obtain more uniform response to subsequent heat treat- ıent. Even investment castings that are cooled slowly from the pouring ꞓmperature exhibit more nearly uniform properties when they have been omogenized. Homogenizing treatments for 17-4 PH and AM-355 are iven in an adjoining Table.

17-4PH Castings. When 17-4PH (ASTM CB-7Cu-1 and CB- Cu-2) is cast in plastic-bonded shell molds, the surface is carburized by ecomposition of the binder. The added carbon prevents proper heat-treat- ıg. Response is obtained when surface carbon is removed prior to the omogenization treatment.

In addition to homogenization, other heat-treating procedures for 17- PH castings include solution annealing and precipitation hardening. De- ıils of these procedures are given in an adjoining table. The preferred ꞓmperature range for precipitation hardening is 480 to 595 °C (900 to 1100 F). The mechanical properties obtained at different aging temperatures are iven in an adjoining Table.

The tendency of 17-4PH castings to overage is reduced by the addition of approximately 0.25% combined niobium plus tantalum to the alloy. The effects of time at aging temperature on the mechanical properties of niobium-free and niobium-containing 17-4PH investment castings are shown in an adjoining Table.

AM-350 and AM-355. Although investment castings made of these alloys do not necessarily require a homogenizing treatment, this treatment provides a more uniform response to subsequent heat treatment. Shell mold and sand castings made of AM-355 that were extremely brittle without homogenization regained ductility after homogenizing at 1095 °C (2000 °F) for 2 h minimum. Heat-treating procedures and effects of tempering temperatures up to 650 °C (1200 °F) on mechanical properties of AM-355 shell mold castings are given in an adjoining Table.

When AM-355 castings are welded, maximum mechanical properties are obtained when the castings are fully heat treated after welding (see adjoining table). Heat treatments prior to welding have little effect on properties when a complete heat treatment follows welding.

17-4PH

hemical Composition. AISI/UNS (S17400): 0.07 C, 1.00 Mn, .00 Si, 3.0 to 5.0 Ni, 15.50 to 17.50 Cr, 0.04 P, 0.03 S, 3.0 to 5.0 Cu, 0.15) 0.45 Nb

imilar Steels (U.S. and/or Foreign). AMS 5342, 5343, 5344, 355, 5604, 5622, 5643, 5825; ASME SA564, SA705; ASTM A564, A693, .705; MIL SPEC MIL-C-24111, MIL-S-81506, MIL-S-81591; SAE J467

haracteristics. Martensitic type 17-4PH combines high strength and ardness with excellent corrosion resistance. Can be hardened by a single ›w-temperature heat treatment that virtually eliminates scaling and distor- on. Similar to 15-5PH, except has slightly higher chromium content. pplications include gears, springs, cutlery, fasteners, aircraft parts, turbine arts

orging. Forge within range of 1040 to 1150 °C (1905 to 2100 °F)

ecommended Heat Treating Practice

For this grade and for most other precipitation-hardening grades, the nal properties can differ somewhat with variations in aging temperature. owever, the following procedure is most commonly used:

- Solution treat by heating at 1025 to 1050 °C (1875 to 1920 °F)
- Oil quench to room temperature
- Age at 480 °C (895 °F) for 1 h and air cool (known as condition H900)
- Following this heat treatment, a hardness of approximately 42 to 44 HRC can be expected

17-4PH: Heat Treating Procedures (Aerospace Practice)

Final heat treat condition(a)	Solution heat treating set temperature °C (°F)(b)	Solution heat treating cooling(c)	Aging set temperature °C (°F)(e)	Aging time, hour(e,f,g)
H 900	1040 (1900)	air, oil, polymer to below 30 °C (90 °F) within 1(d)	480 (900)	1 (g,i)
H 925			495 (925)	4(g,i)
H 950			510 (950)	4
H 1000			540 (1000)	4
H 1025			550 (1025)	4
H 1050			565 (1050)	4
H 1075			580 (1075)	4
H 1100			595 (1100)	4
H 1150			620 (1150)	4
H 1150M(h)			(h)	(h)

(a) See table for specified minimum tensile strength conversions to heat treat condition. (b) See table for soak times. (c) Air means air or atmosphere. (d) Artificial means may be used to cool below ambient temperature when necessary to get below 30 °C (90 °F) or below 15 °C (60 °F). (e) Time, +10, –0 min for 30 min ages; +15, –0 min for 1 h ages; +30 min, –0 min for 1.5 h ages; and +45, –0 for 3, 4, and 16 h ages. (f) To get a lower hardness for pretested material, a set temperature of 5 °C (10 °F) higher than specified may be used. (g) An additional 1 to 1.5 h at the specified temperature or an additional 5 to 10 °C (10 to 20 °F) for an additional 1 to 1.5 h after aging may be used to lower hardness or other engineering properties. (h) H 1150M is an intermediate soft condition that must be re-solution heat treated to obtain a different final condition. To get H 1150M, solution heat treat, then heat at 760 °C (1400 °F), air cool to 30 °C (90 °F) for 2 to 2.5 h plus 620 °C (1150 °F) for 4 h. (i) 17-4PH and 15-5PH castings, H 900 and H 925 time shall be 1.5 h. Source: AMS 2759/3

17-4PH: Soak Times for Solution Heat Treating (Aerospace Practice)

Product form	Minimum soak time, solution heat treating, min(a,b)
Sheet	3 plus 1 min per each 0.25 mm (0.010 in.)
All except sheet	30 per 25 mm (1 in.)

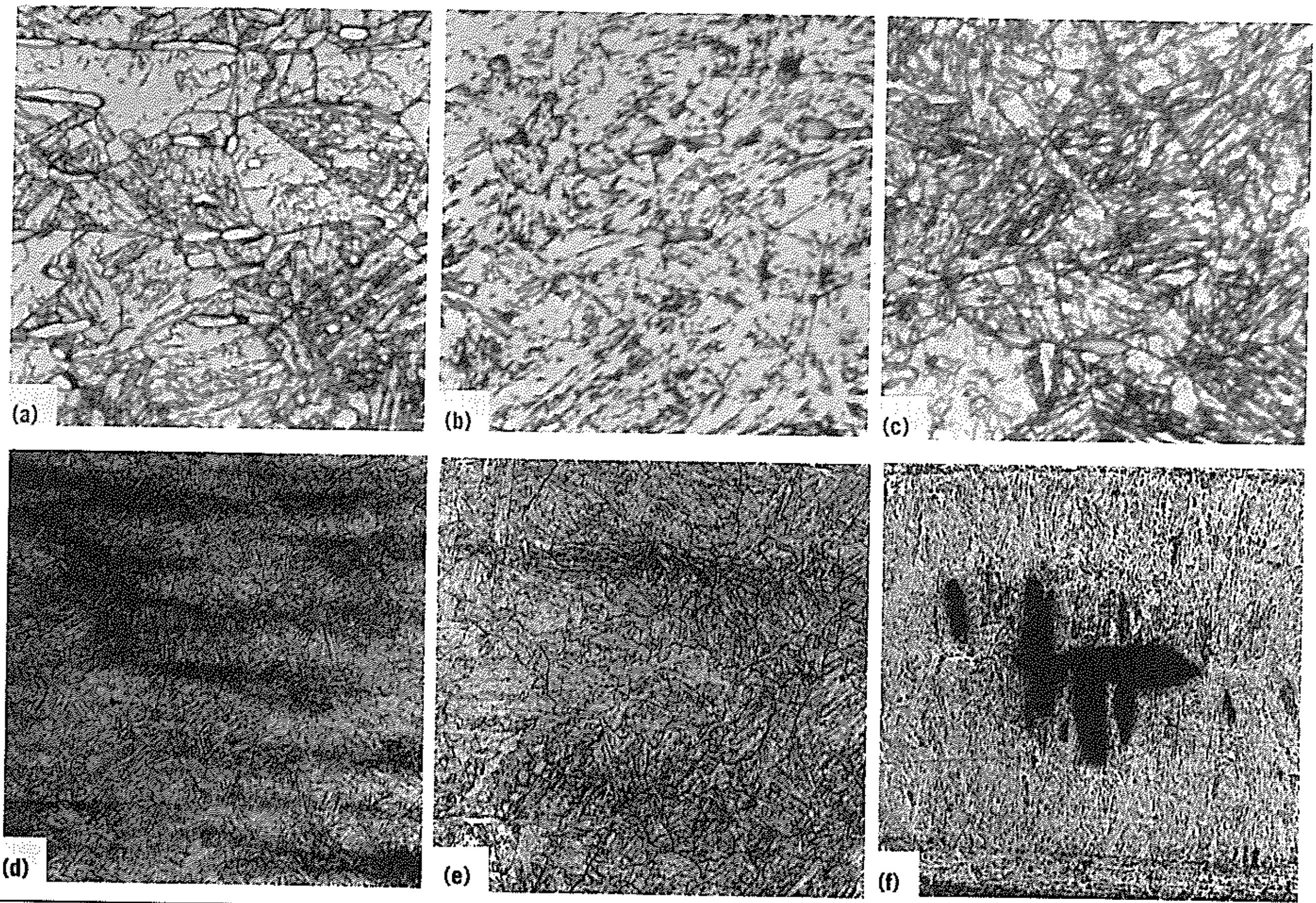
(a) Time, +10, –0 min. (b) In all cases parts are held for sufficient time to ensure that the center of the most massive section has reached temperature and the necessary transformation and diffusion have taken place. Source: AMS 2759/3

17-4PH: Required Hardness After Aging (Aerospace Practice)

Product form	Condition	Hardness, HRC
All	H 900	40 to 47
	H 925	38 to 45
	H 950	37 to 44
	H 1000	36 to 43
	H 1025	34 to 42
	H 1050	32 to 38
	H 1075	31 to 38
	H 1100	30 to 37
	H 1150	28 to 37
	H 1150M	24 to 30

Source: AMS 2759/3

17-4PH: Microstructures. (a) Electrolytic: HNO_3-acetic, then 10% oxalic. 1000×. Solution treated by holding at 1040 °C (1905 °F), 30 min. Air cooled (condition A). Structure: ferrite stringers in martensite matrix. (b) Electrolytic: HNO_3-acetic, then 10% oxalic. 1000×. Solution treated, as (a). Aged 1 h at 480 °C (895 °F). Air cooled (condition H900). Structure: ferrite stringers in martensite matrix. (c) Electrolytic: HNO_3-acetic, then 10% oxalic. 1000×. Solution treated, as (a). Aged 4 h at 550 °C (1020 °F). Air cooled (condition H1025). Structure: small ferrite stringers in martensite matrix. (d) Vilella's reagent, 50×. Bar, solution treated at 1025 to 1050 °C (1875 to 1920 °F): Air cooled. Aged at 575 to 585 °C (1065 to 1085 °F). Air cooled (condition H1075). Banding resulting from alloy segregation appears as dark streaks in a martensite matrix. (e) Vilella's reagent, 200×. Same as (d), except structure shows the banding blending with matrix. (f) Marble's reagent, 75×. Spot welded sheet. Shows void-type defect (black) in the weld zone. Defect the result of microcracking



17-4 PH: Tensile Strength Conversions to Condition (Aerospace Practice)

Product form	Tensile strength minimum, MPa (ksi)	Condition
Bar, forging, tubing, billet	1310 (190)	H 900
Sheet, strip, plate	1310 (190)	H 900
Casting	1240 (180)	H 900
Bar, forging, tubing, billet	1240 (180)	H 925
Sheet, strip, plate	1175 (170)	H 925
Casting	1175 (170)	H 925
Wrought	1140 (165)	H 950
Casting	1035 (150)	H 1000
Bar, forging, tubing, billet	1070 (155)	H 1025
Sheet, strip, plate	1070 (155)	H 1025
Bar, forging, tubing, billet	1000 (145)	H 1075
Sheet, strip, plate	1000 (145)	H 1075
Bar, forging, tubing, billet	965 (140)	H 1100
Sheet, strip, plate	965 (140)	H 1100
Casting	895 (130)	H 1100
Bar, forging, tubing, billet	930 (135)	H 1150
Sheet, strip, plate	930 (135)	H 1150

Source: AMS 2759/3

17-7PH

Chemical Composition. AISI/UNS (S17700): 0.09 C, 1.00 Mn, 0.040 P, 0.040 S, 1.00 Si, 6.50 to 7.75 Ni, 16.00 to 18.00 Cr, 0.75 to 1.50 Al

Similar Steels (U.S. and/or Foreign). AMS 5528, 5529, 5568, 5644, 5673, 5678, 5824; ASME SA705; ASTM A313, A510, A564, A579, A693, A705; MIL SPEC MIL-S-25043, MIL-W-46078; SAE J467; (Ger.) DIN 1.4568

Characteristics. Semiaustenitic type 17-7PH combines high strength and hardness with excellent corrosion resistance. Spring wire can be produced by severe cold drawing, followed by hardening with a single low-temperature heat treatment. Applications include springs, knives, and pressure vessels

Forging. Forge within range of 1040 to 1150 °C (1905 to 2100 °F)

Recommended Heat Treating Practice

There can be variations in the treatment for this type. Details of two different heat treating procedures are:

Heat Treatment No. 1

- Mill anneal at 1065 °C (1950 °F). Fabricate
- Heat to 790 °C (1455 °F) for 1.5 h
- Cool to room temperature within 1 h and hold for 0.5 h (condition T)
- Heat to 565 °C (1050 °F) for 1.5 h and air cool (condition TH1050). Hardness, 43 HRC

Heat Treatment No. 2

- Mill anneal at 1065 °C (1950 °F). Fabricate
- Heat to 955 °C (1750 °F) for 10 min
- Cool to −74 °C (−100 °F) and hold for 8 h (condition R100)
- Heat to 510 °C (950 °F) for 1 h and air cool (condition RH950). Hardness, 47 HRC

17-7PH: Required Hardness After Aging (Aerospace Practice)

Product form	Condition	Hardness, HRC
All	RH 950	42 to 49
	RH 1000	41 to 46
	RH 1050	40 to 45
	RH 1075	38 to 43
	RH 1100	34 to 40
	TH 950	42 to 48
	TH 1000	40 to 46
	TH 1050	38 to 44
	TH 1075	37 to 42
	TH 1100	34 to 39
	CH 900	46 min

Source: AMS 2759/3

17-7PH: Tensile Strength Conversions to Condition (Aerospace Practice)

Product form	Tensile strength minimum, MPa (ksi)	Condition
Sheet, strip	1450 (210)	RH 950
Plate	1380 (200)	RH 950
Bar	1275 (185)	RH 950
Sheet, strip, plate	1240 (180)	RH 1050
Bar	1175 (170)	RH 1050
Wrought	1035 (150)	RH 1100
Sheet, strip, plate, welded tubing	1240 (180)	TH 1050
Bar	1180 (170)	TH 1050
Sheet, strip	(varies with thickness)	CH 900

Source: AMS 2759/3

17-7PH: Heat Treating Procedures (Aerospace Practice)

Final heat treat condition(a)	Solution heat treating set temperatures °C (°F)(b)	Solution heat treating, cooling(c)	Austenite conditioning and transformation °C (°F)(b,c)	Aging set temperature °C (°F)(d)	Aging time, hour (d,e,f)
RH 950	1050 (1925)	Air	955 (1750), (b), air cool to ambient and within 1 h cool to below –70 (–90), soak 8 to 9 h, and air warm to ambient—results in condition R	510 (950)	1
RH 1000	1050 (1925)	Air		540 (1000)	1
RH 1050	1050 (1925)	Air		565 (1050)	1
RH 1075	1050 (1925)	Air		580 (1075)	1
RH 1100	1050 (1925)	Air		595 (1100)	1
TH 950	1050 (1925)	Air	760 (1400) for 90 min to below 15 (60) for not less than 30 min—results in condition T	510 (950)	1.5
TH 1000	1050 (1925)	Air		540 (1000)	1.5
TH 1050	1050 (1925)	Air		565 (1050)	1.5
TH 1075	1050 (1925)	Air		580 (1075)	1.5
TH 1100	1050 (1925)	Air		595 (1100)	1.5

(a) See table for specified minimum tensile strength conversions to heat treat condition. (b) See table for soak times. (c) Air means air or atmosphere. (d) An additional 1 to 1.5 h at the specified temperature or an additional 6 to 10 °C (10 to 20 °F) for an additional 1 to 1.5 h after aging may be used to lower hardness or other engineering properties. (e) Time, +10, –0 min for 30 min ages; +15, –0 min for 1 h ages; +30, –0 min for 1.5 h ages; and +45, –0 min for 3, 4, and 16 h ages. (f) To get a lower hardness for pretested material, a set temperature of 6 °C (10 °F) higher than specified may be used. Source: AMS 2759/3

17-7PH: Soak Times for Solution Treating and Austenite Conditioning (Aerospace Practice)

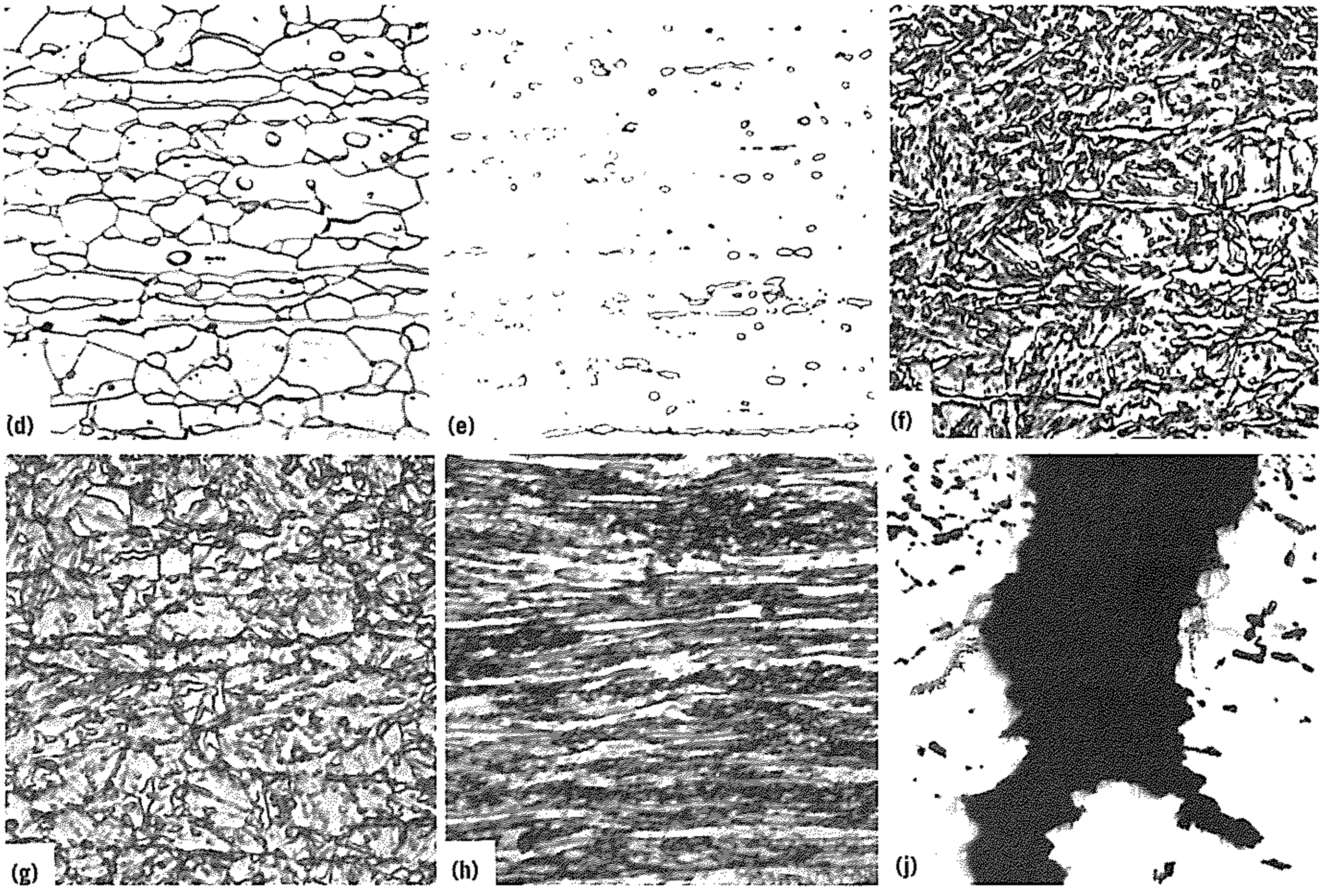
Product form	Minimum soak time, solution heat treating, min(a,b)	Minimum soak time austenite conditioning, min(a,b)
Sheet	3 plus 1 min per each 0.25 mm (0.010 in.)	10 plus 1 min per each 25 mm (0.010 in.)
All except sheet	30 per 25 mm (1 in.)	30 per 25 mm (1 in.)

(a) Time, +10, –0 min. (b) In all cases, parts are held for sufficient time to ensure that the center of the most massive section has reached temperature and the necessary transformation and diffusion have taken place. Source: AMS 2759/3

17-7PH: Microstructures. (a) Fry's reagent, 100×. Forging in as-forged condition. Structure: islands of ferrite in austenite matrix. Concentrations of carbide particles adjacent to ferrite islands. (b) Fry's reagent, 100×. Same as (a). Solution treated 1 h at 1040 °C (1905 °F). Air cooled. Ferrite islands (light etching) are smaller and more dispersed than (a), possibly because of more carbide in solution in the austenite. (c) Fry's reagent, 100×. Same as (b), except reheated at 955 °C (1750 °F). Air cooled to –74 °C (–100 °F). Aged at 510 °C (950 °F). Air cooled to room temperature. Structure: islands of ferrite (darker etching) in martensite matrix

(continued)

17-7PH: Microstructures (continued). (d) Electrolytic: HNO_3-acetic, then 10% oxalic. 1000×. Mill annealed (solution treated, condition A) at 1065 °C (1950 °F). Structure: ferrite stringers in austenite matrix. ASTM grain size, No. 12. (e) Electrolytic: 10% sodium cyanide. 500×. Solution treated at 1065 °C (1950 °F). Etched to emphasize ferrite form. Structure: ferrite stringers and globules in austenite matrix. (f) Vilella's reagent, 1000×. Same as (e), except reheated and held 10 min at 955 °C (1750 °F). Air cooled. Held 8 h at –74 °C (–100 °F). Held 1 h at 510 °C (950 °F). Air cooled (condition RH950). Ferrite stringers in martensite matrix. (g) Vilella's reagent, 1000×. Same as (e), except reheated and held 1.5 h at 760 °C (1400 °F). Air cooled to 15 °C (60 °F). Held 0.5 h. At 565 °C (1050 °F), 1.5 h. Air cooled (condition TH1050). Same structure as (f). More ductile. (h) Electrolytic: HNO_3-acetic, then 10% oxalic. 1000×. Cold rolled at the mill. Held 1 h at 480 °C (895 °F). Air cooled (condition CH900). An essentially martensitic structure. Austenite was transformed by cold rolling. (j) As polished, not etched. 500×. Section through an area of failure (black void) in an annealed part. Failure caused by severe embrittlement due to nitriding during annealing. Dark particles along void are nitrides



PH15-7Mo

Chemical Composition. AISI/UNS (S15700): 0.09 C, 1.00 Mn, 0.040 P, 6.50 to 7.75 Ni, 0.030 S, 1.00 Si, 14.00 to 16.00 Cr, 2.0 to 3.0 Mo, 0.75 to 1.50 Al

Characteristics. A Type 632, nonstandard grade

Forging. Forge within range of 1040 to 1150 °C (1905 to 2100 °F)

Recommended Heat Treating Practice

There can be variations in the treatment for this type. Details of two different heat treating procedures are:

Heat Treatment No. 1

- Mill anneal at 1065 °C (1950 °F). Fabricate
- Heat to 790 °C (1455 °F) for 1.5 h
- Cool to room temperature within 1 h and hold for 0.5 h (condition T)
- Heat to 565 °C (1050 °F) for 1.5 h and air cool (condition TH1050). Hardness, 44 HRC

Heat Treatment No. 2

- Mill anneal at 1065 °C (1950 °F). Fabricate
- Heat to 955 °C (1750 °F) for 10 min
- Cool to –74 °C (–100 °F) and hold for 8 h (condition R100)
- Heat to 510 °C (950 °F) for 1 h and air cool (condition RH950). Hardness, 48 HRC

·I15-7Mo: Required Hardness After Aging (Aerospace ·actice)

ɔduct form	Condition	Hardness, HRC
ɜet	RH 950	46 to 50
	RH 1000	42 to 46
	RH 1050	39 to 45
	RH 1075	38 to 44
	RH 1100	34 to 42
	TH 1050	40 to 46
	TH 1075	39 to 44
	TH 1100	36 to 41
	CH 900	46 min

urce: AMS 2759/3

PH15-7Mo: Tensile Strength Conversions to Condition (Aerospace Practice)

Product form	Tensile strength minimum, MPa (ksi)	Condition
Sheet, strip, plate	1555 (225)	RH 950
Bar	1300 (200)	RH 950
Sheet, strip, plate	1310 (190)	RH 1050
Sheet, strip, plate	1415 (205)	TH 1000
Sheet, strip, plate	1310 (190)	TH 1050
Bar	1175 (170)	TH 1050
Sheet, strip	1655 (240)	CH 900

Source: AMS 2759/3

·I15-7Mo: Heat Treating Procedures (Aerospace Practice)

ıal heat ·at condition(a)	Solution heat treating set temperatures °C (°F)(b)	Solution heat treating, cooling(c)	Austenite conditioning and transformation °C (°F)(b,c)	Aging set temperature °C (°F)(d)	Aging time, hour (d,e,f)
I 950	1050 (1925)	Air	955 (1750), (b), air cool to ambient and within 1 h cool to below –70 (–90), soak 8 to 9 h, and air warm to ambient—results in condition R	510 (950)	1
I 1000	1050 (1925)	Air		540 (1000)	1
I 1050	1050 (1925)	Air		565 (1050)	1
I 1075	1050 (1925)	Air		580 (1075)	1
I 1100	1050 (1925)	Air		595 (1100)	1
I 950	1050 (1925)	Air	760 (1400) for 90 min to below 15 (60) for not less than 30 min—results in condition T	510 (950)	1.5
I 1000	1050 (1925)	Air		540 (1000)	1.5
I 1050	1050 (1925)	Air		565 (1050)	1.5
I 1075	1050 (1925)	Air		580 (1075)	1.5
I 1100	1050 (1925)	Air		595 (1100)	1.5

See table for specified minimum tensile strength conversions to heat treat condition. (b) See table for soak times. (c) Air means air or atmosphere. (d) An additional 1 to 1.5 h at specified temperature or an additional 6 to 10 °C (10 to 20 °F) for an additional 1 to 1.5 h after aging may be used to lower hardness or other engineering properties. (e) Time, +10, min for 30 min ages; +15, –0 min for 1 h ages; +30, –0 min for 1.5 h ages; and +45, –0 min for 3, 4, and 16 h ages. (f) To get a lower hardness for pretested material, a set temperature 5 °C (10 °F) higher than specified may be used. Source: AMS 2759/3

·I15-7Mo: Soak Times for Solution Treating and ustenite Conditioning (Aerospace Practice)

ɔduct form	Minimum soak time, solution heat treating, min(a,b)	Minimum soak time austenite conditioning, min(a,b)
eet	3 plus 1 min per each 0.25 mm (0.010 in.)	10 plus 1 min per each 25 mm (0.010 in.)
l except sheet	30 per 25 mm (1 in.)	30 per 25 mm (1 in.)

Time, +10, –0 min. (b) In all cases, parts are held for sufficient time to ensure that the ıter of the most massive section has reached temperature and the necessary transfor-ıtion and diffusion have taken place. Source: AMS 2759/3

ıM-350

hemical Composition. AISI/UNS (S35000): 0.07 to 0.11 C, 0.5 to ɜ5 Mn, 0.040 P, 0.030 S, 0.50 Si, 4.00 to 5.00 Ni, 16.00 to 17.00 Cr, 2.5 3.25 Mo, 0.07 to 0.13 N

haracteristics. A Type 633, nonstandard grade

ɔrging. Forge within range of 1040 to 1150 °C (1905 to 2100 °F)

Recommended Heat Treating Practice

Maximum mechanical properties may be obtained for this grade by either of the following procedures. The choice between the two procedures often depends upon whether or not the subzero cooling facilities are available

Heat Treatment No. 1 (subzero cooled and tempered)

- Heat to 925 to 955 °C (1695 to 1750 °F)
- Cool to –74 °C (–100 °F) for 3 h
- Heat to 455 to 540 °C (850 to 1000 °F) for 3 h. Hardness, 45 HRC

Heat Treatment No. 2 (double aged)

- Heat to 745 °C (1370 °F) for 3 h
- Cool to room temperature
- Heat to 455 to 540 °C (850 to 1000 °F) for 3 h. Hardness, 41.5 HRC

AM-350: Heat Treating Procedures (Aerospace Practice)

Final heat treat condition(a)	Solution heat treating set temperatures °C (°F)(b)	Solution heat treating, cooling(c)	Austenite conditioning and transformation(b,c)	Aging set temperature °C (°F)(d)	Aging time, hour (d,e,f)
SCT 850	1050 (1925)	Air	955 (1750), (2), air cool below –	455 (850)	3
SCT 950	1050 (1925)	Air	70 (–90), soak for 3 to 5 h, and	510 (950)	3
SCT 1000	1050 (1925)	Air	air warm to ambient	540 (1000)	3
SCT 1100	1050 (1925)	Air		595 (1100)	3

(a) See table for specified minimum tensile strength conversions to heat treat condition. (b) See table for soak times. (c) Air means air or atmosphere. (d) Time, +10, –0 min for 30 min ages; +15, –0 min for 1 h ages; +30, –0 min for 1.5 h ages; and +45, –0 for 3, 4, and 16 h ages. (e) To get a lower hardness for pretested material, a set temperature of 5 °C (10 °F) higher than specified may be used. (f) An additional 1 to 1.5 h after aging may be used to lower hardness or other engineering properties. Source: AMS 2759/3

AM-350: Soak Times for Solution Treating and Austenite Conditioning (Aerospace Practice)

Product form	Minimum soak time, solution heat treating, min(a,b)	Minimum soak time austenite conditioning, min(a,b)
Sheet	3 plus 1 min per each 0.25 mm (0.010 in.)	10 plus 1 min per each 25 mm (0.010 in.)
All except sheet	30 per 25 mm (1 in.)	15 per 25 mm (1 in.)

(a) Time, +10, –0 min. (b) In all cases, parts are held for sufficient time to ensure that the center of the most massive section has reached temperature and the necessary transformation and diffusion have taken place. Source: AMS 2759/3

AM-350: Tensile Strength Conversions to Condition (Aerospace Practice)

Product form	Tensile strength, minimum MPa (ksi)	Condition
Sheet, strip, plate, tubing	1280 (185)	SCT 850
Sheet, strip, plate, tubing	1175 (170)	SCT 950
Bar, forgings, tubing	1140 (165)	SCT 1000

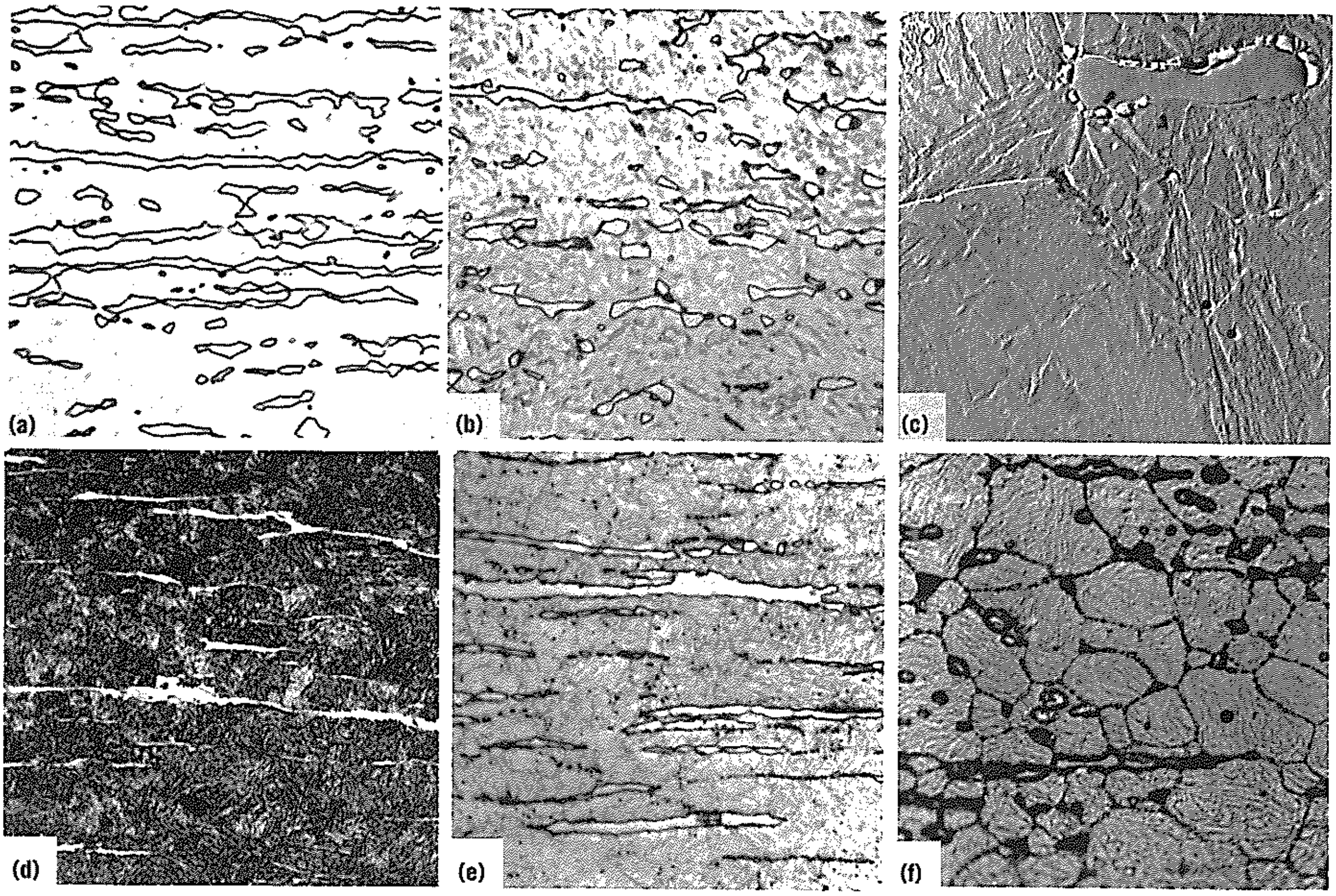
Source: AMS 2759/3

AM-350: Required Hardness After Aging (Aerospace Practice)

Product form	Condition	Hardness, HRC
All	SCT 850	41 to 48
	SCT 950	38 to 45
	SCT 1000	36 to 43
	SCT 1100	35 to 42

Source: AMS 2759/3

AM-350: Microstructures. (a) Electrolytic: 10% ammonium persulfate. 1000×. Strip, solution treated at 1065 °C (1950 °F). Cooled in air. Structure: ferrite pools in austenite matrix. Carbides in solution. Normally, ferrite content is from 10 to 15%. (b) Electrolytic: 10% ammonium persulfate. 1000×. Strip, solution treated at 930 °C (1705 °F), 15 min. Cooled at −74 °C (−100 °F), 3 h. Ferrite islands with precipitated carbides at boundaries. Martensite matrix and retained austenite. (c) Electrolytic: 10% ammonium persulfate. 5000×. Same as (b), except a transmission electron micrograph of a surface replica. Shows carbides precipitated at boundary of a ferrite island. Acicular martensite and retained austenite matrix (smooth areas). (d) Super picral, 100×. Forging, solution treated and aged. Structure: banded ferrite (4% by area, light constituent). Martensite matrix. Same structure as (e), except different etchant and magnification. (e) Vilella's reagent, 500×. Forging in solution treated and aged condition. Structure same as (d), banded ferrite in martensite matrix. Appears different because of different etchant and higher magnification. (f) Electrolytic: 10% oxalic acid. 1000×. Solution treated at brazing temperature. Conditioned 5 to 10 min at 930 °C (1705 °F). Cooled below −87 °C (−125 °F). Aged at 455 °C (850 °F), 3 h. Condition SCT850. Delta ferrite and precipitated carbide in martensite matrix



5-5PH

Chemical Composition. AISI/UNS (S15500): 0.07 C, 1.00 Mn, 0.040 P, 0.030 S, 1.00 Si, 3.50 to 5.50 Ni, 14.50 to 15.50 Cr, 2.5 to 4.5 Cu, 0.15 to 0.45 Nb

Characteristics. A Type 631, martensitic (maraging) stainless steel. Has high strength, hardness, and corrosion resistance. Applications include gears, cams, cutlery, shafting, and aircraft parts

5-5PH: Tensile Strength Conversions to Condition \erospace Practice)

roduct form	Tensile strength minimum, MPa (ksi)	Condition
ar, forging, tubing, billet	1310 (190)	H 900
ıeet, strip, plate	1310 (190)	H 900
asting	1240 (180)	H 900
ar, forging, tubing, billet	1240 (180)	H 925
ıeet, strip, plate	1175 (170)	H 925
asting	1175 (170)	H 925
'rought	1140 (165)	H 950
asting	1035 (150)	H 1000
ar, forging, tubing, billet	1070 (155)	H 1025
heet, strip, plate	1070 (155)	H 1025
ar, forging, tubing, billet	1000 (145)	H 1075
heet, strip, plate	1000 (145)	H 1075
ar, forging, tubing, billet	965 (140)	H 1100
heet, strip, plate	965 (140)	H 1100
asting	895 (130)	H 1100
ar, forging, tubing, billet	930 (135)	H 1150
heet, strip, plate	930 (135)	H 1150

ource: AMS 2759/3

5-5PH: Required Hardness After Aging (Aerospace 'ractice)

roduct form	Condition	Hardness, HRC
.ll	H 900	40 to 47
	H 925	38 to 45
	H 950	37 to 44
	H 1000	36 to 43
	H 1025	34 to 42
	H 1050	32 to 38
	H 1075	31 to 38
	H 1100	30 to 37
	H 1150	28 to 37
	H 1150M	24 to 30

ource: AMS 2759/3

15-5PH: Heat Treating Procedures (Aerospace Practice)

Final heat treat condition(a)	Solution heat treating set temperature °C (°F)(b)	Solution heat treating cooling(c)	Aging set temperature °C (°F)(e)	Aging time, h(e,f,g)
H 900	1040 (1900)	air, oil, polymer to below 30 °C (90 °F) within 1(d)	480 (900)	1 (g,i)
H 925			495 (925)	4(g,i)
H 950			510 (950)	4
H 1000			540 (1000)	4
H 1025			550 (1025)	4
H 1050			565 (1050)	4
H 1075			580 (1075)	4
H 1100			595 (1100)	4
H 1150			620 (1150)	4
H 1150M(h)			(h)	(h)

(a) See table for specified minimum tensile strength conversions to heat treat condition. (b) See table for soak times. (c) Air means air or atmosphere. (d) Artificial means may be used to cool below ambient temperature when necessary to get below 30 °C (90 °F) or below 15 °C (60 °F). (e) Time, +10, –0 min for 30 min ages; +15, –0 min for 1 h ages; +30, –0 min for 1.5 h ages; and +45, –0 for 3, 4, and 16 h ages. (f) To get a lower hardness for pretested material, a set temperature of 5 °C (10 °F) higher than specified may be used. (g) An additional 1 to 1.5 h at the specified temperature or an additional 5 to 10 °C (10 to 20 °F) for an additional 1 to 1.5 h after aging may be used to lower hardness or other engineering properties. (h) H 1150M is an intermediate soft condition that must be re-solution heat treated to obtain a different final condition. To get H 1150M, solution heat treat, then heat at 760 °C (1400 °F), air cool to 30 °C (90 °F) for 2 to 2.5 h plus 620 °C (1150 °F) for 4 h. (j) 17-4 PH and 15-5 PH castings, H 900 and H 925 time shall be 1.5 h. Source: AMS 2759/3

15-5PH: Soak Times for Solution Heat Treating (Aerospace Practice)

Product form	Minimum soak time, solution heat treating, min(a,b)
Sheet	3 plus 1 min per each 0.25 mm (0.010 in.)
All except sheet	30 per 25 mm (1 in.)

(a) Time, +10, –0 min. (b) In all cases, parts are held for sufficient time to ensure that the center of the most massive section has reached temperature and the necessary transformation and diffusion have taken place. Source: AMS 2759/3

\-286

:hemical Composition. **AISI:** Nominal. 0.08 C max, 1.4 Mn max, .4 Si max, 26.00 Ni max, 15.00 Cr max, 1.3 Mo max, 0.003 B max, 0.3 V ıax, 2.0 Ti max, 0.35 Al max. **UNS:** 0.08 C max, 1.50 Mn max, 0.045 P ıax, 0.030 S max, 1.00 Si max, 24.00 to 28.00 Ni, 12.00 to 15.00 Cr, 2.50 ɔ 3.50 Mo, 0.0010 to 0.010 B, 1.55 to 2.00 Ti, 1.50 to 3.00 W, 0.35 Al max

;imilar Steels (U.S. and/or Foreign). UNS K66286; AMS 5525, '731, 5732, 5734, 5735, 5736, 5737, 5804, 5805; ASME SA638; ASTM \453, A638; SAE J467 (A286); (Ger.) DIN 1.4980

:haracteristics. A-286 is also known as an iron-base heat-resisting ılloy. Capable of retaining high strength and good corrosion resistance at ervice temperatures up to 705 °C (1300 °F). Used in aerospace and oil :ountry applications

'orging. Forge within range of 1040 to 1150 °C (1905 to 2100 °F)

Recommended Heat Treating Practice

Maximum mechanical properties may be obtained for this grade by either of the following procedures. The choice between the two procedures often depends upon whether or not the subzero cooling facilities are available.

Heat Treatment No. 1

- Heat to 925 to 955 °C (1695 to 1750 °F)
- Cool to –74 °C (–100 °F) for 3 h
- Heat to 455 to 540 °C (850 to 1000 °F) for 3 h. Hardness, 45 HRC

Heat Treatment No. 2

- Heat to 745 °C (1370 °F) for 3 h
- Cool to room temperature
- Heat to 455 to 540 °C (850 to 1000 °F) for 3 h. Hardness, 41.5 HRC

In aerospace practice, parts are solution treated in the aged condition. :t temperatures for solution treating and set temperatures and times for ;ing are given in an adjoining table. Sheet is cooled in air or atmosphere. ır is oil or polymer quenched. Soak time for all product forms (in min: !0, –0) is 30 min per 25 mm (1 in.). Parts are held for sufficient time to ısure that the center of the most massive section has reached temperature ıd the necessary transformation and diffusion have taken place. Required ırdnesses after aging for different product forms and conditions are given an adjoining table. A-286 is procured in two heat treated conditions: (1))0 °C (1650 °F) for maximum strength and (2) 955 to 980 °C (1750 to '95 °F) for maximum high temperature properties

A-286: Required Hardness After Aging (Aerospace Practice)

Product form	Condition MPa (ksi)	Hardness, HRC
Sheet, plate	860 (125)	24 to 35
All	895 (130)	24 to 36
Sheet, plate	930 (135)	24 to 37
Sheet, plate	965 (140)	24 to 38
Bar, forgings	965 (140)	29 to 38
Bar, wire	1380 (200)	40 min

Source: AMS 2759/3

286: Solution Heat Treating and Aging Requirements (Aerospace Practice)

oduct	Solution heat treat(a)	Aging treatment	Minimum Tensile strength after aging
eet	980 °C (1800 °F)	720 °C (1325 °F), 16 h, min	Varies with thickness from 860 to 965 MPa (125 to 140 ksi)
r and Wire(b)	980 °C (1800 °F), and cold worked(a)	650 to 705 °C (1200 to 1300 °F), 8 h, min	1380 MPa (200 ksi)
r and Forgings(b)	980 °C (1800 °F)	720 °C (1325 °F), 16 h, min	895 MPa (130 ksi)
r and Forgings(b)	900 °C (1650 °F)	720 °C (1325 °F), 16 h, min	965 MPa (140 ksi)
eet and Plate, Welding Grade(b)	980 °C (1800 °F)	720 °C (1325 °F), 16 h, min	Varies with thickness from 860 to 965 MPa (125 to 140 ksi)
r and Forgings, Welding Grade(b)	955 °C (1750 °F)	720 °C (1325 °F), 16 h, min	895 MPa (130 ksi)

Do not re-solution heat treat cold worked material or parts. (b) Consumable electrode remelted. Source: AMS 2759/3

ιM-355

hemical Composition. AISI/UNS (S35500): 0.10 to 0.15 C, 0.5 to 25 Mn, 0.040 P, 0.030 S, 0.50 Si, 4.00 to 5.00 Ni, 15.00 to 16.00 Cr, 2.5 3.25 Mo, 0.07 to 0.13 N

haracteristics. A Type 634, nonstandard grade

ɔrging. Forge within range of 1040 to 1150 °C (1905 to 2100 °F)

ecommended Heat Treating Practice

Maximum mechanical properties may be obtained for this grade by her of the following procedures. The choice between the two procedures ten depends upon whether or not the subzero cooling facilities are ailable

ɘat Treatment No. 1 (subzero cooled and tempered)

Heat to 925 to 955 °C (1695 to 1750 °F)
Cool to –74 °C (–100 °F) for 3 h
Heat to 455 to 540 °C (850 to 1000 °F) for 3 h

ɘat Treatment No. 2 (double aged)

Heat to 745 °C (1370 °F) for 3 h
Cool to room temperature
Heat to 455 to 540 °C (850 to 1000 °F) for 3 h

AM-355: Soak Times for Solution Treating and Austenite Conditioning (Aerospace Practice)

Product form	Minimum soak time, solution heat treating, min(a,b)	Minimum soak time austenite conditioning, min(a,b)
Sheet	3 plus 1 min per each 0.25 mm (0.010 in.)	10 plus 1 min per each 25 mm (0.010 in.)
All except sheet	30 per 25 mm (1 in.)	15 per 25 mm (1 in.)

(a) Time, +10, –0 min. (b) In all cases, parts are held for sufficient time to ensure that the center of the most massive section has reached temperature and the necessary transformation and diffusion have taken place. Source: AMS 2759/3

AM-355: Tensile Strength Conversions to Condition (Aerospace Practice)

Product form	Tensile strength, minimum, MPa (ksi)	Condition
Sheet, strip, plate	1310 (190)	SCT 850
Castings	1240 (180)	SCT 850
Bar, forgings, tubing	1175 (170)	SCT 1000
Sheet, strip, plate	1140 (165)	SCT 1000

Source: AMS 2759/3

.M-355: Heat Treating Procedures (Aerospace Practice)

ınal heat eat condition(a)	Solution heat treating set temperatures °C (°F)(b)	Solution heat treating, cooling(c)	Austenite conditioning and transformation transformation, °C (°F)(b,c)	Aging set temperature °C (°F)(d)	Aging time, hour(d,e,f)
:T 850	1040 (1900)	air or water	955 (1750), (2), water quench, cool below –70 (–90) for 3 to 5 h, and air warm to ambient	455 (850)	3
:T 1000	1040 (1900)	air or water		540 (1000)	3

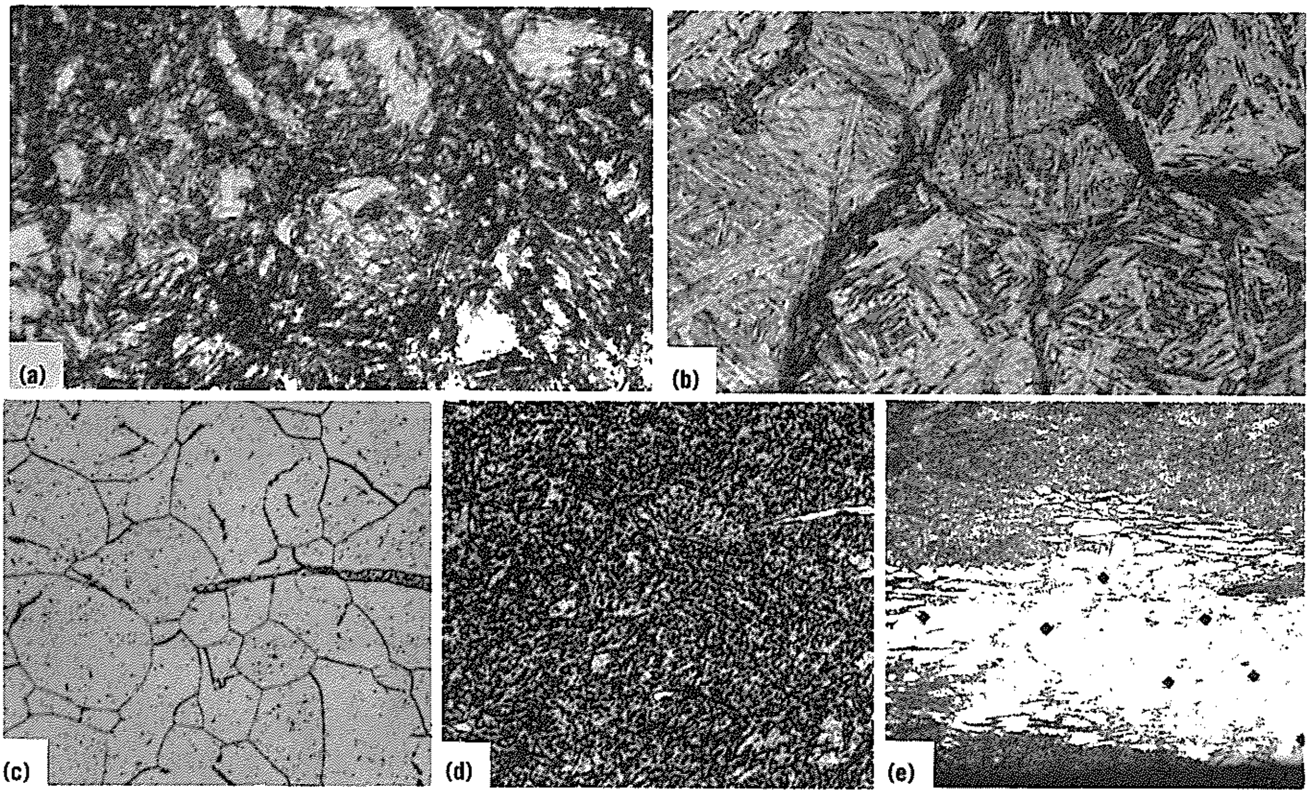
) See table for specified minimum tensile strength conversions to heat treat condition. (b) See table for soak times. (c) Air means air or atmosphere. (d) An additional 1 to 1.5 h at e specified temperature or an additional 6 to 10 °C (10 to 20 °F) for an additional 1 to 1.5 h after aging may be used to lower hardness or other engineering properties. (e) Time, +10,) min for 30 min age; +15, –0 min for 1 h ages; +30, –0 min for 1.5 h ages; and +45, –0 min for 3, 4, and 16 h ages. (f) To get a lower hardness for pretested material, a set temperature '6 °C (10 °F) higher than specified may be used. Source: AMS 2759/3

M-355: Required Hardness After Aging (Aerospace ractice)

·oduct form	Condition	Hardness, HRC
ll	SCT 850	41 to 47
ate	SCT 1000	37 to 43
ır, forgings	SCT 1000	38 to 44

ıurce: AMS 2759/3

AM-355: Microstructures. (a) 5 g (0.2 oz) copper chloride ($CuCl_2$), 100 mL (3.38 fluid oz) hydrochloric acid, 100 mL (3.38 fluid oz) methanol (Kalling's reagent 2), 400×. Forging, forged at 1150 °C (2100 °F). Cooled to –74 °C (–100 °F). Held 3 h. Reheated to 1040 °C (1905 °F). Held 2 h. Furnace cooled to 1025 °C (1875 °F). Oil quenched. Cooled to –74 °C (–100 °F). Held 16 h. Reheated to 775 °C (1425 °F). Held 2 h. Cooled to –74 °C (–100 °F). Held 5 h. Reheated to 525 °C (975 °F). Held 3 h. Air cooled. Alloy segregation resulted in excessive retention of austenite. Structure: large patches of retained austenite in martensite matrix. (b) Same as (a), except specimen has wholly martensitic structure. (c) Electrolytic: 10% ammonium persulfate. 500×. Bar, annealed at 760 °C (1400 °F), 3 h. Water quenched. Aged at 595 °C (1105 °F), 3 h. Carbide precipitated at grain boundaries and throughout martensite matrix. Stringers are delta ferrite with finely precipitated austenite. (d) Electrolytic: 10% ammonium persulfate. 500×. Bar, annealed 5 min at 1040 °C (1905 °F). Cooled at –74 °C (–100 °F), 3 h. Heated at 955 °C (1750 °F), 1 h. Cooled at –74 °C (–100 °F), 3 h. Tempered at 540 °C (1000 °F), 3 h. Air cooled. Dispersed carbide and some ferrite stringers in martensite matrix. (e) Kalling's reagent, 50×. Forging, solution treated and aged. Large white patch is retained austenite caused by alloy segregation. Tempered martensite matrix. Black squares are microhardness indentations



;ustom 450 (XM-25)

ıemical Composition. **AISI/UNS (S45000):** 0.05 C, 1.00 Mn,)0 Si, 14.00 to 16.00 Cr, 5.00 to 7.00 Ni, 0.030 P, 0.030 S, 1.25 to 1.75 ι, 0.5 to 1.0 Mo, 8 x %C min Nb

ıaracteristics. A nonstandard stainless steel

Recommended Heat Treating Practice

In aerospace practice, minimum soak time for Custom 450 is 30 min per 25 mm (1 in.). In all cases, parts are held for sufficient time to ensure that the center of the most massive section has reached temperature and necessary transformation and diffusion have taken place

ıstom 450: Required Hardness After Aging erospace Practice)

)duct form	Condition	Hardness, HRC, minimum
	H 900	39
	H 950	37
	H 1000	36
	H 1050	34
	H 1100	30
	H 1150	26

ırce: AMS 2759/3

Custom 450: Heat Treating Procedures (Aerospace Practice)

Final heat treat condition(a)	Solution heat treating, set temperature, °C (°F)	Solution heat treating, cooling	Aging set temperature, °C (°F)(b)	Aging time, hour(b,c,d)
H 900	1040 (1900)	Air, atmosphere, oil, polymer, water	480 (900)	4
H 950			510 (950)	4
H 1000			540 (1000)	4
H 1025			550 (1025)	4
H 1050			565 (1050)	4
H 1100			595 (1100)	4
			620 (1150)	4

(a) See table for specified minimum tensile strength conversions to heat treated condition. (b) Aging set temperature: time, +10, –0 min for 30 min ages; +15, –0 min for 1 h ages; +30, –0 min for 1.5 h ages; and +45, –0 min for 3, 4, and 16 h ages. (c) To get lower hardness of pretested material, a set temperature up to 6 °C (10 °F) higher than specified may be used. (d) Additional 1 to 1.5 h at the specified temperature or an additional 6 to 10 °C (10 to 20 °F) for an additional 1 to 1.5 h after aging may be used to lower hardness or other engineering properties. Source: AMS 2759/3

ıstom 450: Tensile Strength Conversions to ındition (Aerospace Practice)

ıduct form	Tensile strength, minimum, MPa (ksi)	Condition
)ught	1240 (180)	H 900
)ught	1175 (170)	H 950
)ught	1035 (150)	H 1025
)ught	1000 (145)	H 1050
)ught	895 (130)	H 1100

rce: AMS 2759/3

ustom 455 (XM-16)

ıemical Composition. **AISI/UNS (S45500):** 0.05 C, 0.50 Mn,) Si, 11.00 to 12.50 Cr, 7.50 to 9.50 Ni, 0.040 P, 0.030 S, 1.5 to 2.5 Cu, to 1.4 Ti, 0.1 to 0.5 Nb, 0.5 Mo (XM is ASTM designation)

›commended Heat Treating Practice

In aerospace practice, minimum soak time for Custom 455 is 30 min 25 mm (1 in.). In all cases, parts are held for sufficient time to ensure that the center of the most massive section has reached temperature and necessary transformation and diffusion have taken place

stom 455: Required Hardness After Aging ›rospace Practice)

duct form	Condition	Hardness, HRC minimum
	H 900	47
	H 950	45
	H1000	44

rce: AMS 2759/3

Custom 455: Tensile Strength Conversions to Condition (Aerospace Practice)

Product form	Tensile strength, minimum, MPa (ksi)	Condition
Wrought	1555 (225)	H 950
Wrought	1380 (200)	H1000

Source: AMS 2759/3

stom 455: Heat Treating Procedures (Aerospace ıctice)

ıl heat treat lition(a)	Solution heat treating, set temperature, °C (°F)	Solution heat treating, cooling	Aging set temperature, °C (°F)(b)	Aging time, hour(b,c,d)
0	830 (1525)	Oil, polymer, water	480 (900)	4
:0	830 (1525)		510 (950)	4
ı00	830 (1525)		540 (1000)	4
350(e)	none (none)	none	455 (850)	½

ꞁee table for specified minimum tensile strength conversions to heat treated condi- (b) Aging set temperatures: time, +10, −0 min for 30 min ages; +15, −0 min for 1 h ; +30, −0 min for 1.5 h ages; and +45, −0 min for 3, 4, and 16 h ages. (c) To get lower ness of pretested material, a set temperature up to 6 °C (10 °F) higher than specified be used. (d) An additional 1 to 1.5 h at the specified temperature or an additional 6) °C (10 to 20 °F) for an additional 1 to 1.5 h after aging may be used to lower hard- or other engineering properties. (e) Material in this condition is not resolution heat ed. Source: AMS 2759/3

H13-8Mo

emical Composition. AISI/UNS (S13800): 0.05 C, 0.20 Mn, l P, 0.008 S, 0.10 Si, 7.5 to 8.5 Ni, 12.25 to 13.25 Cr, 2.0 to 2.5 Mo, 0.90 .35 Al, 0.01 N

aracteristics. A martensitic (maraging) stainless that can be hard- d with a single, low temperature heat treatment. Applications include ged aircraft parts

rging. Initial forging temperature is 1175 °C (2150 °F)

ecommended Heat Treating Practice

PH13-8Mo is hardened by heating solution treated material, Condition o 510 to 620 °C (950 to 1150 °F) for 4 h, then air cooled. Heat treatments ow (all times are at temperature):

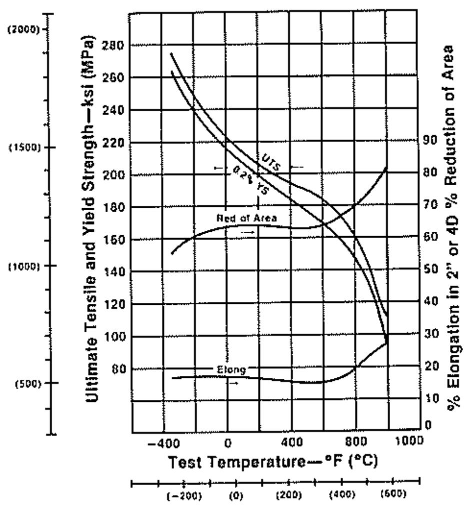
- Condition A (solution treated or annealed): Heat at 925 °C (1695 °F) +8 C (15 °F) (time is dependent on section size). Cool to below 15 °C (60 F) to completely transform material to martensite. Normal practice is to ıold at temperature 1 h. Sections under 230 cm² (36 in.²) can be ꞁuenched in a suitable liquid quenchant. Larger sections should be air ooled
- Condition RH950 (precipitation or age hardened): Solution treated ma- erial is cold treated to −74 °C (−100 °F) for 2 h minimum. Parts are air varmed to room temperature—this must be done within 24 h after olution treatment. Cold treated material is heated to 510 °C (950 °F) for ꞁ h, then air cooled
- Condition H950, H1000, H1050, H1150 (precipitation or age hardened): Solution treated material is heated at specified temperature +6 °C (+10 F) for 4 h, then air cooled
- Condition H1150M (precipitation or age hardened): Solution treated naterial is heated at 760 °C (1400 °F) +6 °C (+10 °F) for 2 h. Air cooled hen treat at 620 °C (1150 °F) +6 °C (+10 °F) for 4 h then air cooled

ıt treating after overaging. In the H1150 and H1150M overaged condition, alloy will not respond to further aging treatment. For forging, optimum cold ding, and machining, the material must be solution treated at 925 °C (1695 after overaging and before subsequent aging. Also, hardness cannot be used listinguish between the H1150 and solution treated conditions because the 150 hardness falls within the hardness range for the solution-treated condi- ı

A predictable size change occurs in treating PH 13-8 Mo. Contraction increases as the aging temperature is increased, as follows:

Age-hardening treatment	Contraction m/m (in./in.)
H 950	0.0006 to 0.0004
H 1000	0.0006 to 0.0004
H 1050	0.0008 to 0.0005
H 1000	0.0012 to 0.0008

PH13-8Mo: Typical Cryogenic and Elevated Temperature Tensile Properties. Specimen was 19 mm (0.75 in.) round bar in H1000 condition. Source: Carpenter Technology Corporation



PH 13-8 Mo: Heat Treating Procedures (Aerospace Practice)

Final heat treat condition(a)	Solution heat treating, set temperatures, °C (°F)(b)	Solution heat treating, cooling(c)	Aging set temperature, °C (°F)(d)	Aging time, hour(d,e,f)
H 950	925 (1700)	Air, oil, or polymer to below 15 °C (60 °F) within 1 h(g)	510 (950)	4
H 1000	925 (1700)		540 (1000)	4
H 1025	925 (1700)		550 (1025)	4
H 1050	925 (1700)		565 (1050)	4
H 1100	925 (1700)		595 (1100)	4
				4
H 1150	925 (1700)		620 (1150)	4
H 1150M(h)	925 (1700)		(h)	(h)

(a) See table for specified minimum tensile strength conversions to heat treated condition. (b) See table for soak times. (c) Air means air or atmosphere. (d) Time, +10, –0 min for 30 min ages; +15, –0 min for 1 h ages; +30 min, –0 min for 1.5 h ages; and +45 min for 3, 4, and 16 h ages. (e) To get lower hardness for pretested material, a set temperature up to 6 °C (10 °F) higher than specified may be used. (f) An additional 1 to 1.5 h at the specified temperature or an additional 6 to 10 °C (10 to 20 °F) for an additional 1 to 1.5 h after aging may be used to lower hardness or other engineering properties. (g) Artificial means may be used to cool below ambient temperature when necessary to get below 30 °C (90 °F) or below 15 °C (60 °F). (h) H 1150M is an intermediate soft condition that must be re-solution heat treated to obtain a different final condition. To obtain H1150M, solution heat treat, then heat at 760 °C (1400 °F), air cool below 30 °C (85 °F) for 2 to 2.5 h, plus 620 °C (1150 °F) for 4 h. Source: AMS 2759/3

PH 13-8 Mo: Soak Times for Solution Heat Treating (Aerospace Practice)

Product form	Minimum soak time, min(a,b)
All	30 per 25 mm (1 in.)(a)

(a) Time, +10, –0. (b) In all cases, parts are held for sufficient time to ensure that the center of the most massive section has reached temperature and the necessary transformation and diffusion have taken place. Source: AMS 2759/3

PH 13-8 Mo: Tensile Strength Conversions to Condition (Aerospace Practice)

Form(a)	Minimum Tensile strength, MPa (ksi)	Condition
B, F, T, Bi, P	1520 (220)	H 950
B, F, T, Bi, P	1415 (205	H 1000
B, F, T, Bi, P	1275 (185)	H 1025
B, F, T, Bi, P	1210 (175)	H 1050
B, F, T, Bi, P	1035 (150)	H 1100
B, F, T, Bi, P	930 (135)	H 1150

(a) B, bar; F, forging; T, tubing; Bi, billet; P, plate. Source: AMS 2759/3

PH 13-8 Mo: Required Hardness After Aging (Aerospace Practice)

Product form	Condition	Hardness, HRC
All	H 950	45 to 49
	H 1000	43 to 47
	H 1025	41 to 46
	H 1050	40 to 46
	H 1100	34 to 42
	H 1150	30 to 38
	H 1150M	28 to 36

Source: AMS 2759/3

Heat Treating Iron Castings and P/M Steels

Heat Treating Cast Irons

General Introduction

Cast irons are alloys of iron, carbon, and silicon. Basic types are white iron, malleable iron, gray iron, ductile iron, compacted graphite iron, and high alloy iron. In the articles that follow, practical how-to information is presented on the heat treatment of gray, ductile, and malleable irons. Greater detail, including in-depth explanations and theory, is found in Vol 4, *Heat Treating, ASM Handbook* and Vol 1, *Properties and Selection: Irons, Steels, and High-Performance Alloys, ASM Handbook.* Articles are generic per type of iron, in contrast with articles on individual steels in other sections of this book. However, as far as possible, article format is based on the same easy-to-read, synoptic style; and information is presented in the same order: compositions, characteristics, recommended heat treating practices, and processing sequences. Additional useful information is found in accompanying figures and tables.

Chemical Composition

- See tables at end of text
- Gray iron contains carbon in the form of graphite flakes. This iron exhibits a gray fracture surface because fracture occurs along graphite plates (flakes)
- Ductile iron contains spherulitic graphite (hence the alternative name, spheroidal graphite iron). In this instance, graphite has a ball-like shape. Ductile iron has measurable ductility in its as-cast condition. Austempered ductile iron combines high strength and ductility. Its microstructure differs from that of austempered steel, and its heat treatment is a specialty
- Malleable iron contains compact nodules of graphite flakes, which form during extended annealing of white iron of a suitable composition

Characteristics

Ductile iron castings have a definite ring when struck with a hammer, but the sound lacks the clear ring of steel. By comparison, a hammer blow on gray iron makes a damped sound. Another difference between the two irons: in breathing on a fresh, ductile iron surface (one that has been filed, ground, or machined), this iron exudes the smell of acetylene gas—the result of moisture in the breath reacting with magnesium carbide in the material.

The primary microstructure of these irons can be modified with heat treatment. But the temperature range is narrow due to the metallurgy of these irons.

Another feature: iron tends to form a protective atmosphere when it is contained in a tight furnace or box. In fact, cast iron chips from machine shops are used as packing material in heat treating other metals because graphite and silicon react with free oxygen in the atmosphere. A protective atmosphere is needed in treating finish machined iron parts.

Heat Treating

Recommended heat treating practices specific to gray, ductile, and malleable iron are presented in the articles that follow. The information in this introduction is confined to two topics generic to heat treating castings; namely internal stresses and measuring them and hardness.

Most castings are essentially free of internal stresses as-cast. The exception arises where one section is much thicker than others, and the thicker section cools at a much slower rate than the thinner ones. Such sections can retain stresses when faster cooling sections restrain the contraction of slower cooling sections.

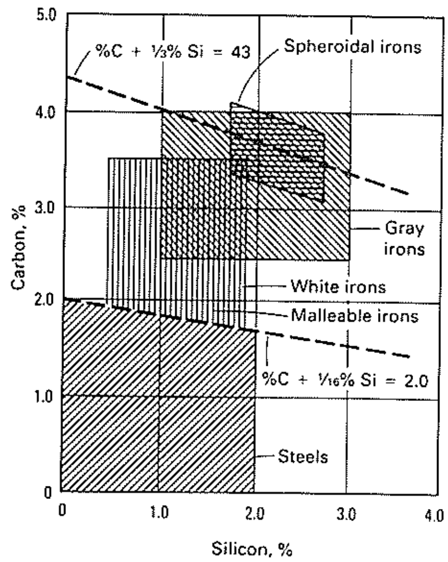
Stresses can be evaluated two ways: with a foil strain gage or by sawing up a casting. In the former method, the strain gage is applied in a critical location. The metal on which the gage is to be mounted is trepanned or otherwise cut from the casting. Retained stress is indicated by readings taken before and after removal of the gage. In the second method, a casting is sawed and retained stress is indicated by changes in the thickness of the kerf. This technique is useful in checking small castings.

Measurement of hardness presents a problem because all castings are heterogeneous alloys with constituents that have widely different hardnesses. Hardness, with the exception of microhardness, is a weight average of constituent hardnesses. The standard Brinnel test with a 10 mm (0.40 in.) ball and 3000 kg (6600 lb) load is commonly used because the impression is large enough to provide a good average hardness even on a course structure.

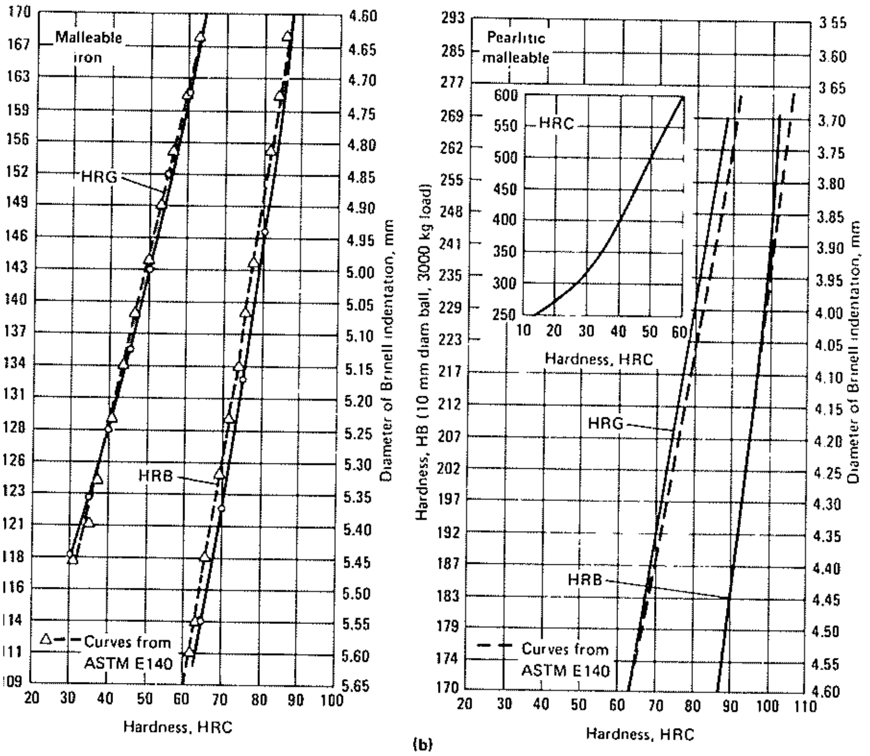
Conversion tables for hardness values are found in Vol 8, 9th ed., of the *M Metals Handbook*. Examples of conversion systems for malleable n are presented in accompanying graphics.

REFERENCE

1. C.F. Walton, Introduction to Heat Treating of Cast Irons, Vol 4, *Heat Treating, ASM Handbook*



Composition ranges for carbon and silicon in common cast irons and steels



(a) Hardness conversions for malleable iron from HB to HRB and HRG scales. (b) Conversions from HB to HRB and HRG scales for pearlitic malleable iron

nparative Hardness Values for Quenched and Tempered Ductile Irons

HB(a)	HRC converted from HB(b)	Observed HRC(c)	Microhardness, HV(d)	HRC converted from HV(b)	HRC converted from HV minus observed HRC
415	44.5	44.4	527	50.9	6.5
444	47.2	45.0	521	50.6	5.6
444	47.2	45.7	530	51.1	5.4
444	47.2	47.6	593	54.9	7.3
461	48.8	46.7	595	55.0	8.3
461	48.8	48.3	560	53.0	4.7
461	48.8	49.1	581	54.2	5.1
477	50.3	49.6	572	53.7	4.1
477	50.3	50.1	618	56.2	6.1
555	55.6	53.4	637	57.2	3.8

verage of three readings for each iron. (b) Values based on SAE-ASM-ASTM hardness conversions for steel. (c) Average of five readings for each iron. (d) Average of a mini-
n of five readings for each iron; 100 kg (220 lb) load

Heat Treating of Gray Iron

Chemical Composition

Gray irons usually contain 2.5 to 4% carbon, 1 to 3% silicon, and additions of manganese (as low as 0.10% in ferritic gray irons and as high as 1.2% in pearlitics). Sulfur and phosphorus are present in small amounts as residual impurities.

Flake graphite is dispersed in a matrix with a microstructure determined by composition and heat treatment.

Matrix structures resulting from heat treatment can vary from ferrite-pearlite to tempered martensite.

Standard compositions are presented in adjoining tables.

General Characteristics

ASTM A 48 classifies gray irons in terms of tensile strength, but in many applications strength is not the critical property. Low strength grades, for example, are superior performers where resistance to heat checking is the prime property. According to the ASTM ratings, class 20, the lowest strength grade, has a minimum tensile strength of 140 MPa (20 ksi); while class 60, the highest strength grade, has a tensile strength of 410 MPa (60 ksi).

Generally it can be assumed that the following properties improve with increasing tensile strength:

- All strength properties, including those at elevated temperatures
- Modulus of elasticity
- Resistance to wear

Conversely, some properties deteriorate with decreasing tensile strength:

- Machinability
- Resistance to thermal shock
- Damping capacity
- Castability—in terms of ability to produce thin sections

Specific Characteristics

User properties of interest include impact resistance, machinability, and wear resistance.

Impact resistance. Gray iron is not recommended where high impact resistance is needed. Two methods of testing for this property are given in ASTM A 327.

Machinability. Most gray iron castings have better machinability than most other irons of equivalent hardness, as well as that of virtually all steel. In addition, substantial gains in machinability are available through annealing (see heat treating section).

Wear. Gray iron, in both the as-cast and hardened conditions, is used widely for machine components that must stand up to various types of wear. Hardening provides the most significant improvement in resistance to normal wear, and is specified for maximum resistance to wear in severe wear applications.

Dimensional Stability. The most demanding applications at elevated temperatures are those in which dimensional accuracy is important.

Dimensional stability is degraded as temperature and exposure time increase. This property is affected by factors such as growth, scaling, and creep rate.

Growth. Breakdown of pearlite to ferrite and graphite is the cause. The remedy: additions of alloying elements such as copper, molybdenum, chromium, tin, vanadium, and manganese. They stabilize the carbide structure.

Scaling. In a series of tests, temperature had a greater effect than time at temperature. For example, the extent of scaling at 350 °C (660 °F) over a period of 11.5 years was 4 mg/cm^2, while exposure of 64 weeks at 500 °C (930 °F) was 16 mg/cm^2. In the same study, it was found that differences in alloy content had only minor effects on scaling.

Creep. This property is improved with additions of chromium and molybdenum. When parts operate at temperatures under 480 °C (895 °F), two more sources of dimensional accuracy must be considered: residual stresses and machining practice.

Residual stresses. Residual stresses are present in all castings in the as-cast condition, but only a small percentage are stress relieved before machining—chiefly those requiring exceptional dimensional accuracy, or those with a combination of high or nonuniform stress associated with low section stiffness or an abrupt change in section size. Castings of class 40, 50, and 60 iron are more likely to contain high residual stresses.

Machining practice. Because the surface of a casting is often the main site of residual stresses, a large amount of stress is relieved by rough machining. If before final machining, the casting is relocated in the machine carefully and supported in cool fixtures, acceptable dimensional accuracy usually is obtained in the finished workpiece.

Annealing. This is another way of improving machinability (discussed in the next section).

Recommended Heat Treating Practices and Processing Sequences

Annealing and stress relieving are the two most common methods of heat treating gray iron castings. Annealing is the most frequently used.

Other suitable processes include normalizing, hardening and tempering, austempering, and martempering. Flame hardening and induction hardening are alternatives to electrically heated, gas, or oil-fired furnaces and salt bath processes. Both annealing and hardening have disadvantages:

- *Annealing*—this process improves machinability, but there is a price: properties are reduced approximately to the next lower grade of gray iron
- *Hardening*—Hardening and quenching from elevated temperatures strengthen castings, but the process ordinarily is not used for this purpose in commercial practice. The more economical route to the desired result is to reduce silicon and total carbon, or by adding alloying elements. When gray iron is quenched and tempered, the common reason is to beef up resistance to wear and abrasion by increasing hardness with a structure consisting of graphite embedded in hard martensite

Annealing Practices. Gray iron normally is subjected to one of these treatments: ferritizing annealing, medium (or full) annealing, and graphitizing annealing.

Ferritizing process. It generally is unnecessary to heat unalloyed or low alloy gray iron to temperatures above the transition range when the sole purpose is to convert pearlitic carbide to ferrite and graphite for improved machinability. The recommended ferritizing annealing temperature for most gray irons lies between 700 to 760 °C (1290 to 1400 °F).

When stress relief is the objective, slow cooling to room temperature is recommended. A cooling rate ranging from 110 °C (230 °F) per h to 290 °C (555 °F) per h is satisfactory for all but the most complex castings.

Medium (full) annealing. This treatment is the choice when a ferritizing anneal would be ineffective because of high alloy content of a particular iron.

Annealing usually is performed at temperatures between 790 to 900 °C (1455 to 1650 °F). Holding times usually are comparable to those for the ferritizing process. However, when temperatures are at the high end of the range, castings must be cooled slowly through the transformation range from approximately 790 to 675 °C (1455 to 1245 °F).

Graphitizing annealing. To break down massive carbides to pearlite and graphite with reasonable speed, temperatures of at least 870 °C (1600 °F) are required. With each additional 55 °C (130 °F) increment in holding temperature, the rate of carbide decomposition doubles. General practice is to use holding temperatures of 900 to 955 °C (1650 to 1750 °F). Holding time at temperature can range from a few minutes to several hours. Cooling rate depends on end use.

For maximum strength and wear resistance, castings should be air cooled from the annealing temperature to approximately 540 °C (1000 °F) to promote the formation of a pearlitic structure.

For maximum machinability, castings should be furnace cooled to 540 °C (1000 °F), and special care should be taken to ensure slow cooling through the transformation range.

In treating for maximum strength and wear resistance and maximum machinability, cooling from 540 °C (1000 °F) to approximately 290 °C (555 °F) at a rate of not more than 110 °C (230 °F) per h is recommended to minimize residual stresses.

Gray iron in the as-cast condition contains residual stresses. Exception: much of the solidification stress is removed when the iron is cooled in the mold.

The stress relieving temperature usually is well below the range for the transformation of pearlite to austenite. For maximum stress relief with minimum carbide deposition in unalloyed irons, a temperature range of 540 to 565 °C (1000 to 1050 °F) is desirable. When almost complete stress relief (>85%) is required in unalloyed iron, a minimum temperature of 595 °C (1105 °F) can be used.

Rate of heating. For stress relief, the heating rate depends on the size and shape of the casting. However, the rate, except for the most complex shapes, is not especially critical.

Rate of cooling. Slow cooling from the stress-relieving temperature, at least in the upper temperature range, is essential. The general recommendation is furnace cooling to 315 °C (600 °F) or lower, before air cooling. When designs are intricate, it may be advisable to continue furnace cooling until a temperature of approximately 95 °C (205 °F) is reached.

Normalizing Practices. Gray iron is normalized by being heated to a temperature above the transformation range; held at this temperature for a period of approximately 1 h per inch of maximum section thickness; then cooled in still air to room temperature.

Normalizing serves a variety of functions, including the enhancement of mechanical properties, such as hardness and tensile strength; and the restoration of as-cast properties modified in other heating processes, such as graphitizing annealing or the preheating and postheating associated with welding.

The temperature range for normalizing is approximately 885 to 925 °C (1625 to 1695 °F).

Tensile strength and hardness depend on combined carbon content, pearlite spacing (distance between cementite plates), and graphite morphology.

Hardness can be partially controlled by allowing castings to cool in the furnace to a temperature below the normalizing temperature.

Hardening and Tempering Practices

Mechanical properties, strength and wear resistance in particular, are improved by these treatments. Hardened and tempered gray iron has approximately five times more resistance to wear than pearlitic gray iron.

Furnace or salt bath hardening have a much broader application range than those of flame and induction hardening. In the latter two processes, a relatively high total carbon content is needed because of the extremely short time available for the solution of carbon in austenite. By contrast, in furnace or salt bath hardening, a casting can be held at a temperature above the transformation range for as long as necessary.

An unalloyed gray iron with a combined carbon content of 0.60% has higher hardenability than a carbon steel with the same carbon content. Reason: the gray iron has a higher silicon content.

The hardenability of gray iron is increased via the addition of a variety of alloying elements: manganese, nickel, copper, and molybdenum. Also, chromium contributes to carbide stabilization, which is especially important in flame hardening. Chromium does not influence the hardenability of gray iron.

Hardening cycle. In austenitizing, castings are heated to a temperature high enough to promote the formation of austenite; held at that temperature until the desired amount of carbon has been dissolved; then quenched at a suitable rate.

Heating temperature is determined by the transformation range of a given gray iron. A formula for determining the approximate A_1 transformation temperature of unalloyed iron is:

$$°C: 730 + 28.0\,(\%\,Si) - 25.0\,(\%Mn)$$
$$°F: 1345 + 50.4\,(\%\,Si) - 45.0\,(\%Mn)$$

Chromium raises the transformation range of gray iron.

Castings should be treated through the lower temperature range slowly to avoid cracking. At temperatures in a range of 595 to 650 °C (1105 to 1200 °F) above the stress relieving range, heating may not be as rapid as desired.

Quenching. Molten salt and oil are the most frequently used quenchants. Water generally is not suitable for quenching furnace-heated gray iron: heat is extracted so rapidly that distortion and cracking in all castings are likely except those simple in design. Water-soluble polymer quenchants are an option to provide cooling rates between those of water and oil and to minimize thermal shock.

Air is the least severe quenching medium. But both unalloyed and low alloy gray iron can't be air quenched because the cooling rate is not fast enough to form martensite. Air, however, is frequently the most desirable cooling method for high alloy grades.

Tempering practice. Castings usually are tempered after quenching at temperatures well below the transformation range for approximately 1 h per inch of thickest section. Hardness decreases with tempering, while, usually, strength and toughness rise.

Austempering and Martempering Practices. The maximum hardness obtainable with austempering usually is less than that available in martempering. However, the difference may be largely offset during the tempering treatment usually required following martempering. But in comparison with conventional oil quenching, less distortion and growth are experienced in austempering and martempering.

Austempering Process. In this treatment, gray iron is quenched from a temperature above the transformation range in a hot quenching bath, and is maintained in the bath at constant temperature until the austempering transformation is complete. Quenching usually is in salt, oil, or lead baths at temperatures in the range of 230 to 425 °C (445 to 795 °F). When high hardness and resistance to wear are specified, quenchant temperature usually is held between 230 to 290 °C (445 to 555 °F).

Holding time for maximum transformation is determined by quenching bath temperature and composition of the iron. The effect of the latter on holding time may be considerable. Alloy additions such as nickel, chromium, and molybdenum increase the time required for transformation.

Martempering Process. In this instance, martensite is produced minus the high stresses that usually accompany its formation. Martempering is similar to conventional hardening, except that distortion is minimized. Also, martensite retains its characteristic brittleness. For this reason, martempered castings are almost always tempered.

Castings are quenched from above the transformation range in salt, oil, or lead baths; held in the range at which martensite forms [200 to 260 °C (390 to 500 °F) for unalloyed irons] only until the casting has reached the bath temperature; then it is cooled to room temperature.

For a wholly martensitic structure, the casting must be held in the hot quenching bath only long enough for it to reach the temperature of the bath.

If dimensional accuracy is important, allowance for growth must be made prior to heat treatment. Some distortion, in comparison with growth, occurs during martempering. Conditions that may promote excessive distortion are: residual stresses from casting, machining, or rapid cooling during previous heat treatments; insufficient time for establishing equilibrium at the austenitizing temperature; and drafts during air cooling after castings have been removed from the quench tank.

Flame Hardening Process. This is the surface hardening process most often applied to gray iron—both unalloyed and alloyed grades. As a rule, combined carbon content should be in the range of 0.50 to 0.70%, but irons with as little as 0.40% combined carbon can be flame hardened. Generally, the process is not recommended for irons containing more than 0.80% carbon because they can crack.

For maximum hardness, it is advisable to use an iron containing as little total carbon consistent with the production of sound castings free from any likelihood of cracking.

Because silicon promotes the formation of graphite and of a low combined carbon content, a relatively low silicon content is advisable, i.e., silicon content should not exceed 2%, and manganese content should be held in the range of 0.80 to 1.00% to increase carbon solubility in austenite.

In addition, gray iron should be as free as possible from porosity and from foreign matter such as sand or slag. Porosity and even small inclusions can produce a rough surface or cause cracking after hardening. In general, alloyed gray irons are easier to flame harden than unalloyed grades, partly because alloys have greater hardenability. Maximum hardness of nonalloys is obtained with a composition of approximately 3% total carbon, 1.7% silicon, 0.60-0.80 manganese. Hardnesses range from 400 to 500 HB.

Stress relieving. When practical or feasible economically, flame hardened castings are stress relieved at 150 to 200 °C (300 to 390 °F) in a furnace, in hot oil, or by passing a flame over the hardened surface. Benefits are minimized distortion or cracking and an increase in the toughness of the hardened layer.

Hardness. The surface of a flame hardened casting is typically lower than that of the metal immediately below the surface. Surface hardness often can be raised by heating in the range of 195 to 250 °C (385 to 480 °F).

Fatigue strength. This value is usually improved because the treatment induces compressive stresses at the surface.

Quenching. Quenchants are selected on the basis of the flame hardening method used:

- *Progressive method:* only nonflammable media are used, such as water, soluble oil mixtures, and water solutions of polymers. Conventional oil can't be used because of the fire hazard
- *Spot hardening* or *spinning methods:* conventional quenching by immersion in hot oil is used. In these methods, the flame head is withdrawn from the part prior to quenching

For best results in using water, water temperatures should be around 30 °C (85 °F).

To suppress cracking, lower quenching rates are obtained by using 5 to 15% soluble oil mixtures, compressed air, or compressed air and water at low pressures. Air quenching is especially suited for highly alloyed irons because of their susceptibility to cracking.

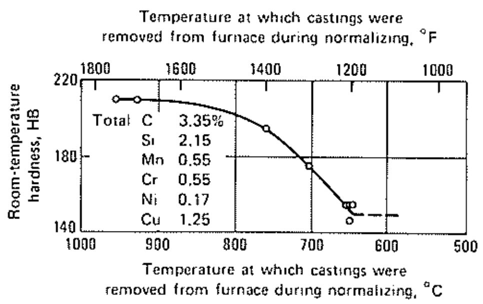
Induction Hardening Process. Hardnesses obtained are influenced by carbon equivalent (% C + ⅓% Si) when this value is measured by conventional Rockwell tests. The amount of graphite in the microstructure can have a negative effect on surface hardness: the higher the volume of graphite, the lower the surface hardness.

Induction hardening causes less distortion than that experienced in parts quenched after treatment in a furnace.

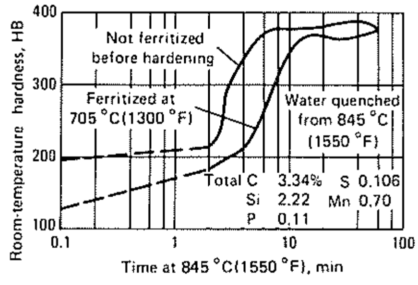
REFERENCES

1. C.V. White, Gray Iron, Vol 1, *ASM Handbook*, p 12-32
2. B. Kovacs, Heat Treating of Gray Irons, Vol 4, *ASM Handbook*, p 670-681

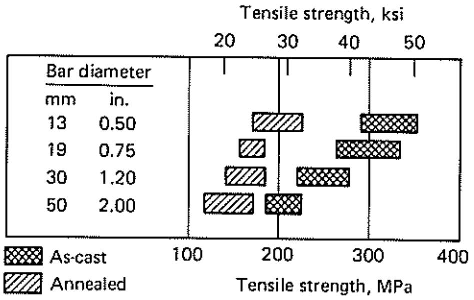
Room-temperature hardness of gray iron after normalizing. Effect of temperature at start of air cooling on hardness on normalized gray iron rings 120 mm (4¼ in.) in outside diameter, 95 mm (3¾ in.) in inside diameter, and 38 mm (1½ in.) in length



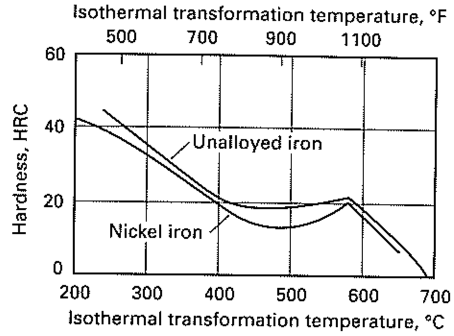
Effect of austenitizing time on room-temperature hardness of quenched gray iron specimens. Specimens were 32 mm (1¼ in.) in diameter by 19 mm (¾ in.) in thickness



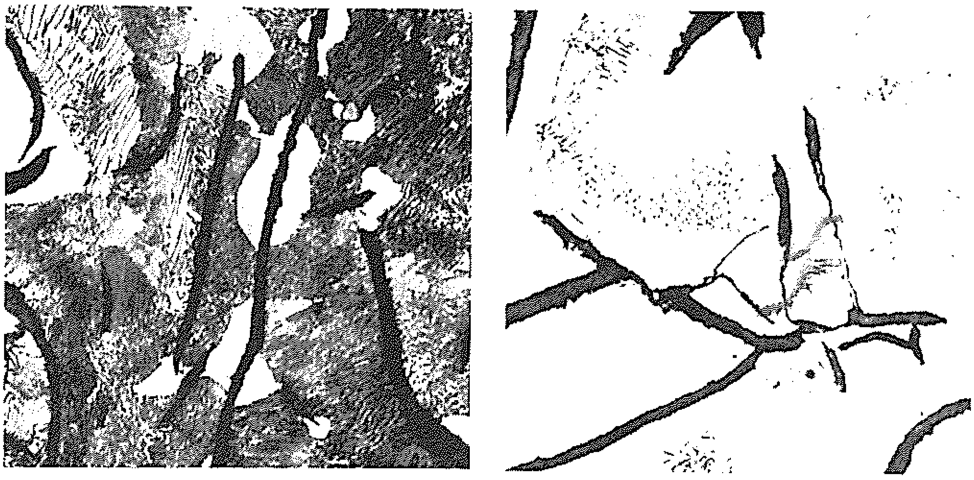
Effect of annealing on tensile strength of class 30 gray iron. Specimens were arbitration bars from 31 heats. Bars were annealed at 925 °C (1695 °F) for 2 h plus 1 h per 25 mm (1 in.) of section over 25 mm (1 in.), and cooled to 925 to 565 °C (1695 to 1050 °F) at a rate not to exceed 160 °C (285 °F) per h. Cooling continued from that level to 200 °C (390 °F) at a rate not to exceed 130 °C (230 °F) per h; bars were then air cooled to room temperature



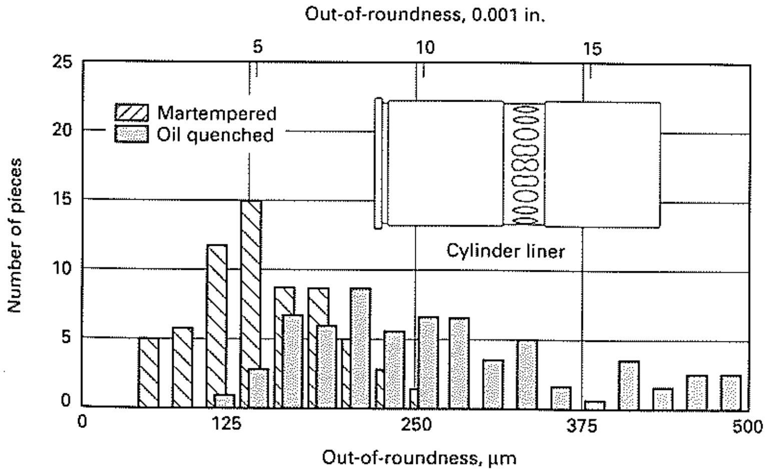
Effect of isothermal transformation temperature on hardness of austempered gray irons. Holding times were sufficient to complete transformation



Microstructures. Conversion of as-cast pearlitic structure of unalloyed gray iron to ferrite and graphite by annealing. (a) As cast; 180 HB. (b) Annealed 1 h at 760 °C (1400 °F); 120 HB. Magnification, 500×

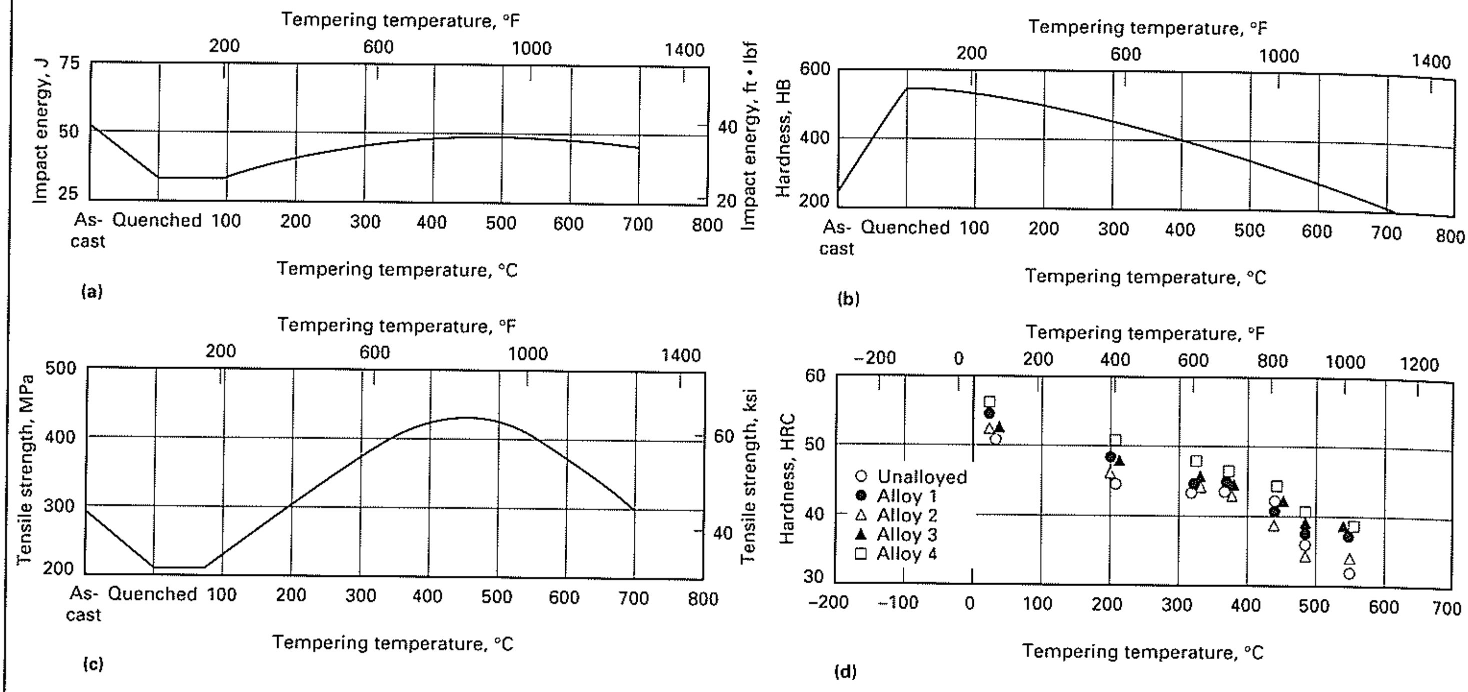


(a) (b)

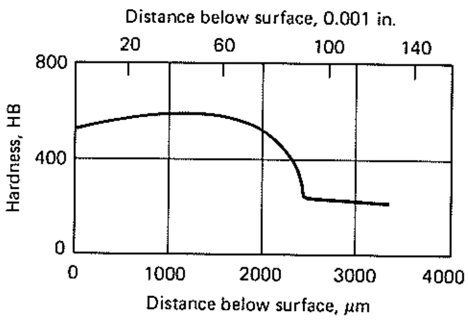


Distortion in gray iron cylinder liners after martempering and after conventional oil quenching. Before being measured, liners were furnace tempered for 2 h at 200 °C (390 °F)

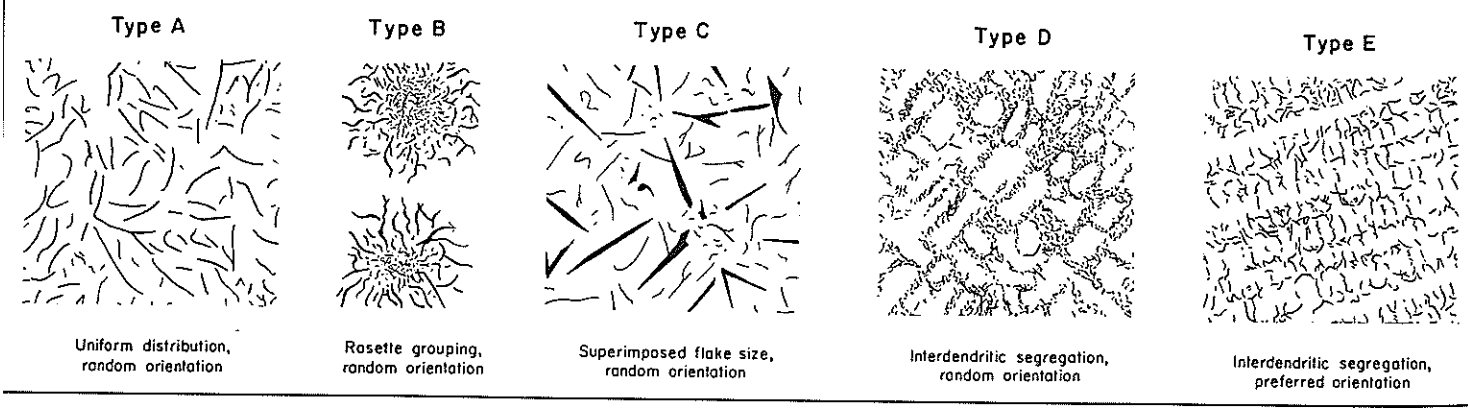
Effect of tempering temperature on gray iron. (a) to (c) Changes in mechanical properties of hardened low-silicon unalloyed gray iron. (d) Hardness of gray iron specimens quenched in oil from 870 °C (1600 °F) and tempered. Each point on this chart represents an average of five hardness readings



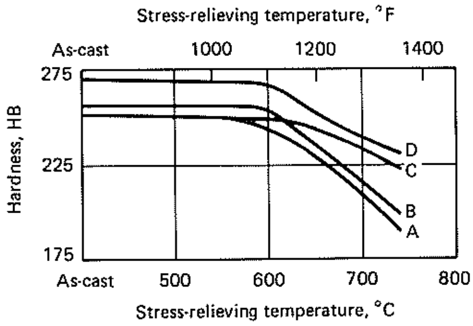
Typical hardness gradient produced in gray iron by flame hardening



Types of graphite flakes in gray iron (AFS-ASTM). In the recommended practice (ASTM A247), these charts are shown at a magnification of 100×. They have been reduced to one-third size for reproduction here



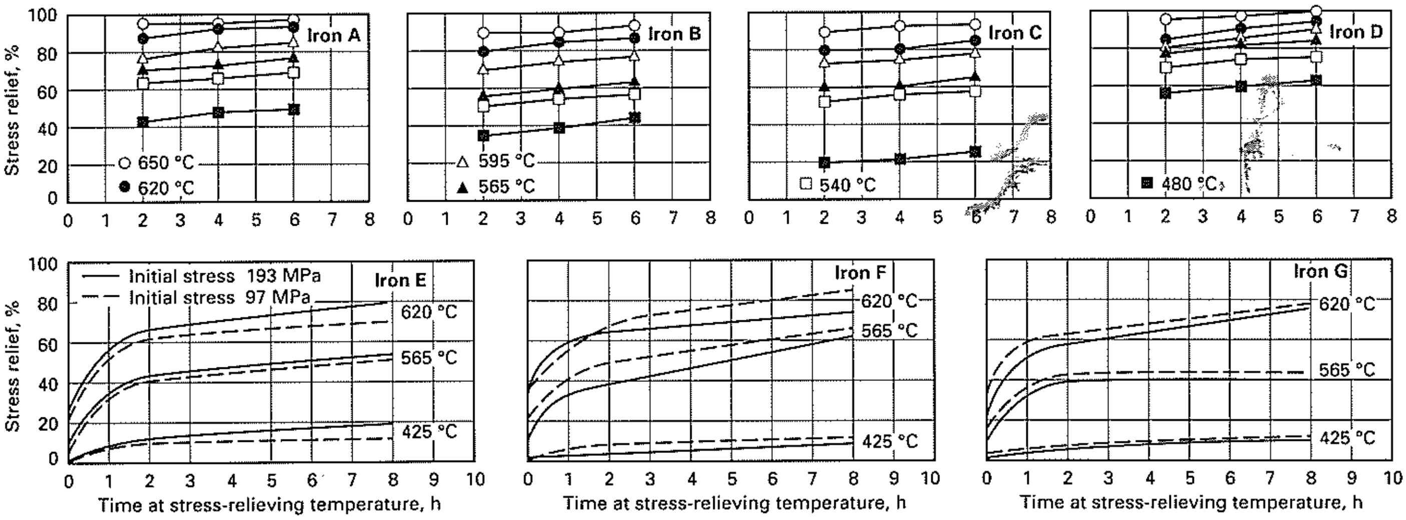
Effect of stress-relieving temperature on hardness of gray irons. Bar specimens 30 mm (1.2 in.) in diameter were held for 1 h at indicated temperatures and then air cooled



Iron	Composition, %					
	TC(a)	CC(b)	Si	Cr	Ni	Mo
A	3.20	0.80	2.43	0.13	0.05	0.17
B	3.29	0.79	2.58	0.24	0.10	0.55
C	3.23	0.70	2.55	0.58	0.06	0.12
D	3.02	0.75	2.38	0.40	0.07	0.43

(a) Total carbon. (b) Combined carbon

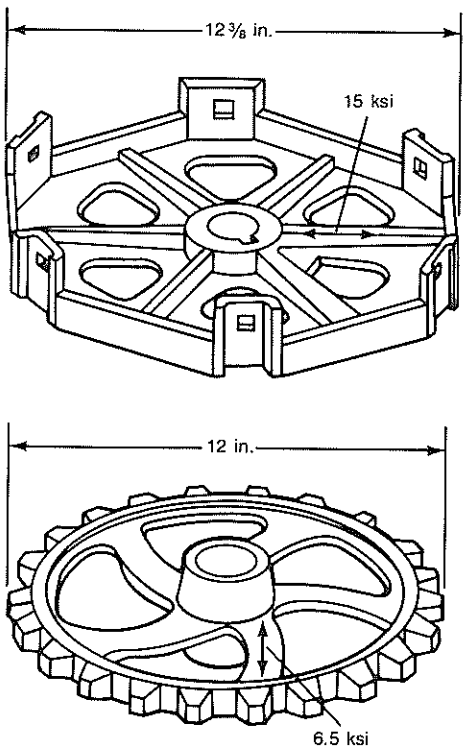
Stress-relieving time and temperature on degree of stress relief obtained in low-alloy gray irons. Table shows compositions and negligible effect of maximum stress-relieving conditions on hardness



Iron	Composition, %										Hardness, HRB	
	C	Si	P	S	Mn	Ni	Cr	Mo	Cu	V	Before stress relieving	After stress relieving for 8 h at 620 °C (1150 °F)
A	2.93	2.14	0.110	0.57	0.47	0.35	0.10	...	...	...	98	94
B	3.43	2.12	0.104	0.70	0.81	0.34	0.18	0.23	...	...	98	94
C	3.24	2.55	0.107	0.62	0.87	0.51	0.20	0.22	...	...	95	95
D	3.91	1.43	0.54	0.25	0.32	1.56	0.06	...	...	...	82	80
E	3.18	2.13	0.73	0.125	0.70	1.03	0.33	0.65	...	...	98	98
F	3.12	1.76	0.075	0.097	0.78	1.02	0.41	0.58	...	...	94	95
G	2.78	1.77	0.065	0.135	0.55	0.36	0.10	0.33	0.46	0.04	96	96

licrostructures. Structure of class 35 iron, as-cast (left) and after annealing

Location and magnitude of residual stresses in two gray castings



ɜct of Carbon Equivalent on Surface Hardness of uction-Hardened Gray Irons

ıposition, % (a)		Carbon	Hardness HRC, converted from		
ː	Si	equivalent(b)	As read	Rockwell 30-N	Microhardness
13	1.50	3.63	50	50	61
14	1.68	3.70	49	50	57
19	1.64	3.74	48	50	61
34	1.59	3.87	47	49	58
42	1.80	4.02	46	47	61
46	2.00	4.13	43	45	59
52	2.14	4.23	36	38	61

ıch iron also contained 0.50 to 0.90 Mn, 0.35 to 0.55 Ni, 0.08 to 0.15 Cr, and 0.15 ·0 Mo. (b) Carbon equivalent = %C + ⅓% Si

Effect of Annealing on Hardness and Strength of Class 35 Gray Iron

Condition	Tensile strength MPa	Tensile strength ksi	Hardness, HB
As-cast	268	38.9	217
Annealed	165	23.9	131

Composition of iron: 3.30% total C, 2.22% Si, 0.027% P, 0.18% S, 0.61% Mn, 0.03% Cr, 0.03% Ni, 0.14% Cu, Mo nil. Annealing treatment consisted of 1 h at 775 °C (1425 °F), followed by cooling in the furnace to 540 °C (1000 °F)

ırdenability Data for Gray Irons Quenched From 855 °C (1575 °F)

e adjoining Table for compositions.

Distance from quenched end		Hardness, HRC					
mm	$\frac{1}{16}$ in. increments	Plain iron	Mo(A)	Mo(B)	Ni-Mo	Cr-Mo	Cr-Ni-Mo
3.2	2	54	56	53	54	56	55
6.4	4	53	56	52	54	55	55
9.5	6	50	56	52	53	56	54
12.7	8	43	54	51	53	55	54
15.9	10	37	52	50	52	55	53
19.0	12	31	51	49	52	54	53
22.2	14	26	51	46	52	54	52
25.4	16	26	49	45	52	54	53
28.6	18	25	46	45	52	53	52
31.8	20	23	46	44	51	50	51
34.9	22	22	45	43	47	50	50
38.1	24	22	43	44	47	49	50
41.3	26	21	43	44	47	47	49
44.4	28	20	40	41	45	47	48
47.6	30	19	39	40	45	44	50
50.8	32	17	39	40	45	41	47
54.0	34	18	36	41	44	38	46
57.2	36	18	40	40	45	36	45
60.3	38	19	38	37	45	34	46
63.5	40	22	38	36	42	35	46
66.7	42	20	35	35	42	32	45

ımpositions of Gray Irons Listed in Adjoining Table

	Composition									
n	TC	CC(a)	GC(b)	Mn	Si	Cr	Ni	Mo	P	S
ın	3.19	0.69	2.50	0.76	1.70	0.03	...	0.013	0.216	0.097
(A)	3.22	0.65	2.57	0.75	1.73	0.03	...	0.47	0.212	0.089
(B)	3.20	0.58	2.62	0.64	1.76	0.005	Trace	0.48	0.187	0.054
Mo	3.22	0.53	2.69	0.66	2.02	0.02	1.21	0.52	0.114	0.067
Mo	3.21	0.60	2.61	0.67	2.24	0.50	0.06	0.52	0.114	0.071
Ni-Mo	3.36	0.61	2.75	0.74	1.96	0.35	0.52	0.47	0.158	0.070

CC, combined carbon. (b) GC, graphite carbon

Heat Treating Ductile Iron

;hemical Composition

;tandard compositions and general uses of ductile iron are listed in an :ompanying table.
Most compositions for standard grades are based on properties, i.e., ›ngth and/or hardness; composition is loosely specified or made subor-ıate to mechanical properties.
)uctile iron is now accepted internationally as the name for these irons. s also called nodular iron or spheroidal graphite (SG).
The unique feature of this iron is the presence of graphite in the form of y spheres, (nodules). See accompanying microstructures.
Microstructures are grouped into two broad classes:

Those in which the major iron-bearing matrix phase is the thermody-ıamically stable, body-centered cubic (ferrite) structure
Those with a matrix phase that is a metastable, face-centered, cubic austenite) structure

The ferrite structure usually is produced in annealing, normalizing, normalizing and tempering, or quenching and tempering.
The austenitic structure is produced by austempering, an isothermal process resulting in a product known as austempered ductile iron (ADI).
Stress relief annealing does not involve major microstructure transformations, while selective surface treatments, i.e., flame and induction hardening, do in selectively controlled areas of a casting.

Similar Cast Irons (U.S. and/or Foreign). Accompanying tables provide information on:

- Mechanical properties and typical applications of standard ductile irons (ASTM, ASME, SAE-AMS specifications)
- Ductile iron property requirements of various national and international standards (ISO, ASTM, and SAE)
- Some tentative specifications for austempered ductile iron (U.S., Swiss, and Great Britain)

eneral Characteristics

;asic differences between ferritic and austenitic ductile iron are ex-ined in an accompanying continuous cooling transformation diagram :T), along with cooling curves for furnace cooling, air cooling, and nching. Examples are shown in an accompanying figure. A second ıre is an isothermal transformation (IT) diagram showing a processing uence for austempering.
'he relatively high strength and toughness of ductile iron give it an antage over gray iron and malleable iron in many structural applica-ıs. In addition, because ductility does not require heat treatment to duce graphite nodules, as does malleable iron to produce temper-carbon ules, it can compete with malleable iron even though it does require a tment and inoculation.
uctile iron has many applications requiring strength and toughness ıbined with good machinability and low cost.
uctile iron has about the same machinability as gray iron of similar dness. At tensile strengths up to approximately 550 MPa (80 ksi) ductile ı has better machinability than that of cast mild steel. At higher hard-ses, differences are less pronounced.
pecial materials and techniques are available to repair weld ductile iron o join it to itself and to other materials such as steel, gray iron, or leable iron. Special precautions are needed to get optimum properties ıe weld metal and in the heat affected zone. The main objective is to id the formation of cementite in the matrix material, which makes the d zone brittle. Another must is to retain graphite in its nodular form. tensite or fine pearlite can be removed by tempering.

commended Heat Treating Practices d Processing Sequences

uctile irons are heat treated primarily to create matrix microstructures associated mechanical properties not readily obtained in the as-cast lition. The most important heat treatments are:

- Stress relieving—a low temperature treatment to reduce or relieve internal stresses remaining after casting
- Annealing—to improve ductility and toughness, to reduce hardness, and to remove carbides
- Normalizing—to improve strength while retaining some ductility
- Hardening and tempering—to increase hardnesses or to improve strength and raise the proof stress ratio
- Austempering—to produce a microstructure that provides high strength with some ductility and good resistance to wear
- Surface hardening—to produce selective wear resistant surfaces with flame, induction, and laser processes, for example

Stress Relieving Ductile Iron. When not otherwise heat treated, complex engineering castings are stress relieved at 510 to 675 °C (950 to 1245 °F). Temperatures at the lower end of the range are adequate in many applications. Those at the higher end eliminate virtually all residual stresses, but at the cost of some reduction in hardness and tensile strength.
Recommended stress-relieving temperatures for different types of ductile iron are as follows:

- Unalloyed: 510 to 565 °C (950 to 1050 °F)
- Low alloys: 565 to 595 °C (1050 to 1105 °F)
- High alloys: 595 to 650 °C (1105 to 1200 °F)
- Austenitic: 620 to 675 °C (1150 to 1245 °F)

Cooling should be uniform to avoid the reintroduction of stresses. Practice is to furnace cool to 290 °C (555 °F), then air cool, if desired. Austenitic iron can be uniformly air cooled from the stress relieving temperature.

Annealing Ductile Iron. Castings usually are given a full ferritizing anneal for good machinability when high strength is not required. The treatment produces ASTM grade 60-40-18. For good machinability, manganese, phosphorus, and molybdenum should be as low as possible.
Recommended practice for castings with differing alloy contents and for castings with and without eutectic carbides follows:

Full anneal for unalloyed 2 to 3% Si iron that does not contain eutectic carbide: heat and hold at 870 to 900 °C (1600 to 1650 °F) for 1 h per inch of section. Furnace cool to 345 °C (655 °F) at 55 °C (100 °F) per h; air cool

Full anneal with carbide present: heat and hold at 900 to 925 °C (1650 to 1695 °F) for 2 h minimum—longer for heavier sections. Furnace cool to 700 °C (1290 °F) at 110 °C (200 °F) per h. Hold 2 h at 700 °C (1290 °F). Furnace cool to 345 °C (655 °F) at 55 °C (100 °F) per h. Air cool

Subcritical anneal to convert pearlite to ferrite: heat and hold at 705 to 720 °C (300 to 1330 °F), 1 h per inch of section. Furnace cool to 345 °C (655 °F) at 55 °C (100 °F) per h. Air cool

Hardenability of Ductile Iron. This is an important parameter for termining the response of a given gray iron to normalizing, to quenching d tempering, or to austempering. Normally this value is determined by ; Jominy test: a standard bar [25.4 mm (1 in.) in diam by 100.16 mm (4) in length] is austenitized and water quenched at one end.

Normalizing Ductile Iron. In this treatment (austenitizing followed air cooling), tensile strength is improved considerably; and the process ıy be used to produce ASTM type 100-70-03 iron. Normalizing tempera- ·es usually range between 870 to 940 °C (1600 to 1725 °F). Standard time temperature is 1 h per inch of section, or a minimum of 1 h. Longer times ıy be needed when alloys contain elements that retard carbon diffusion .o austenite.

Normalizing sometimes is followed by tempering to obtain a desired rdness and to relieve residual stresses that develop in air cooling when ·as of a casting with different section sizes cool at different rates.

Also, tempering after normalizing is a way to obtain high toughness and sistance to impact

Tempering usually consists of reheating to 425 to 650 °C (795 to 1200) and holding at the desired temperature 1 h per inch of cross section.

Quenching and Tempering Ductile Iron. Prior to quenching and tem- ring, commercial castings normally are austenitized at 845 to 925 °C 555 to 1695 °F).

To minimize stresses and quench cracking, oil is the preferred quenchant. ater or brine may be used when shapes are simple. Oil heated to 80 to 100 : (175 to 210 °F) is used to avoid cracks when castings are complicated.

Castings should be tempered immediately after quenching to relieve enching stresses. Tempering in the range of 425 to 600 °C (795 to 1110) reduces hardness, the amount depending on alloy content, initial hard- ss, and time.

Austempering Ductile Iron. An austempered structure of austenite d ferrite provides optimum strength and ductility. The austempered atrix is responsible for a significantly better tensile strength-to-ductility tio than is possible with any other grade of ductile iron. Production of ese properties calls for careful attention to section size and to time/tem- ·rature exposure during austenitizing and austempering.

As section size increases, the rate of temperature change between the stenitizing and austempering temperature decreases.

Quenching and austempering techniques include:

- Hot oil quenching (< 240 °C, or 465 °F, only)
- Nitrate/nitrite salt quenches
- Fluidized bed quenching (only for small, thin parts)
- Lead baths (for tool-type applications)

Austenitizing temperatures between 845 to 925 °C (1555 to 1695 °F) are ›rmal; and times of about 2 h have been shown to recarburize the matrix lly.

Properties obtained in austempering vary with temperature and time. ffects of temperatures ranging from 240 to 440 °C (465 to 825 °F) on yield rength, tensile strength, and impact strength are shown in an accompany- g figure.

Reaching maximum ductility at a given temperature is a time sensitive nction. After maximum ductility is attained, further austempering re- ıces ductility. In an accompanying figure, this relationship is shown at nes of temperature ranging from 8 to approximately 200 min. Tempera- tures run from 357 to 400 °C (675 to 750 °F). Typical austempering times vary from 1 to 4 h.

Surface Hardening of Ductile Iron

This iron readily responds to a variety of surface hardening processes:

- Flame hardening
- Induction hardening
- Nitriding—conventional, salt bath, and plasma processes
- Laser or plasma torch hardening

Pearlitic types of ductile iron, ASTM 80-60-03 and 100-70-03, are preferred for hardening applications because all of these treatments take place in seconds. Irons that do not contain free ferrite in their microstructures respond almost instantly to flame or induction heating and need little holding time at their austenitizing temperatures to become fully hardened.

Given proper technique and temperature control between 845 to 900 °C (1555 to 1650 °F), surface hardnesses that can be expected with different matrices are:

- Fully annealed (ferritic) iron, water quenched behind the flame or induction coil, 35 to 45 HRC
- Predominantly ferritic (partly pearlitic) iron, stress relieved prior to heating, self-quenched, 40 to 45 HRC
- Predominantly ferritic (partly pearlitic) iron, stress relieved prior to heating, water quenched, 50 to 55 HRC
- Mostly pearlitic iron, stress relieved before heating, water quenched, 58 to 62 HRC

Induction hardening. Response depends on the amount of pearlite in the matrix in the as-cast, normalized, and normalized and tempered conditions

Percentages of pearlite or ferrite required in each condition are:

- *As-cast condition*—minimum of 50% pearlite to get satisfactory hardening with heating cycles of 3.5 s and longer at hardening temperatures of 955 to 980 °C (1750 to 1795 °F). Castings can be hardened at higher temperatures when structures contain less pearlite, but at the risk of damaging surfaces. With pearlite above 50%, hardening temperatures may be reduced within the range of 900 to 925 °C (1650 to 1695 °F)
- *Normalized condition*—for quenching cycles of 3.5 s and longer, temperatures of 955 to 980 °C (1750 to 1795 °F), 50% pearlite in a prior structure is a minimum
- *Quenched and tempered*—the response is excellent over a wide range of microstructures containing up to 95% ferrite. Quenching and tempering, as a prior treatment, permits a lower prior hardness, but there is a risk of distortion and quench cracking

Nitriding Ductile Irons. Case hardening can be carried out with conventional nitriding, or in liquid salt baths based on cyanide salts, or in a plasma.

Conventional process. Nitrogen diffuses into surfaces at temperatures ranging approximately 550 to 600 °C (1020 to 1110 °F). Ammonia usually is the source of nitrogen. A surface layer, typically white and featureless in an etched microstructure, of approximately 0.1 mm (0.004 in.) deep is produced. Surface hardness is close to 1100 HV. Additions of alloying elements can increase hardness, i.e., 0.5 to 1% Al, Ni, or Mo. Advantages of nitriding, in addition to very high hardnesses, are: better resistance to wear and scuffing, plus improved fatigue life and resistance to corrosion.

Salt bath treatment. Temperatures are lower, but case depth is less than that obtained with the conventional process.

Nitriding in plasma. A recent development. At this time, the need for special equipment and processing costs may be deterrents to usage.

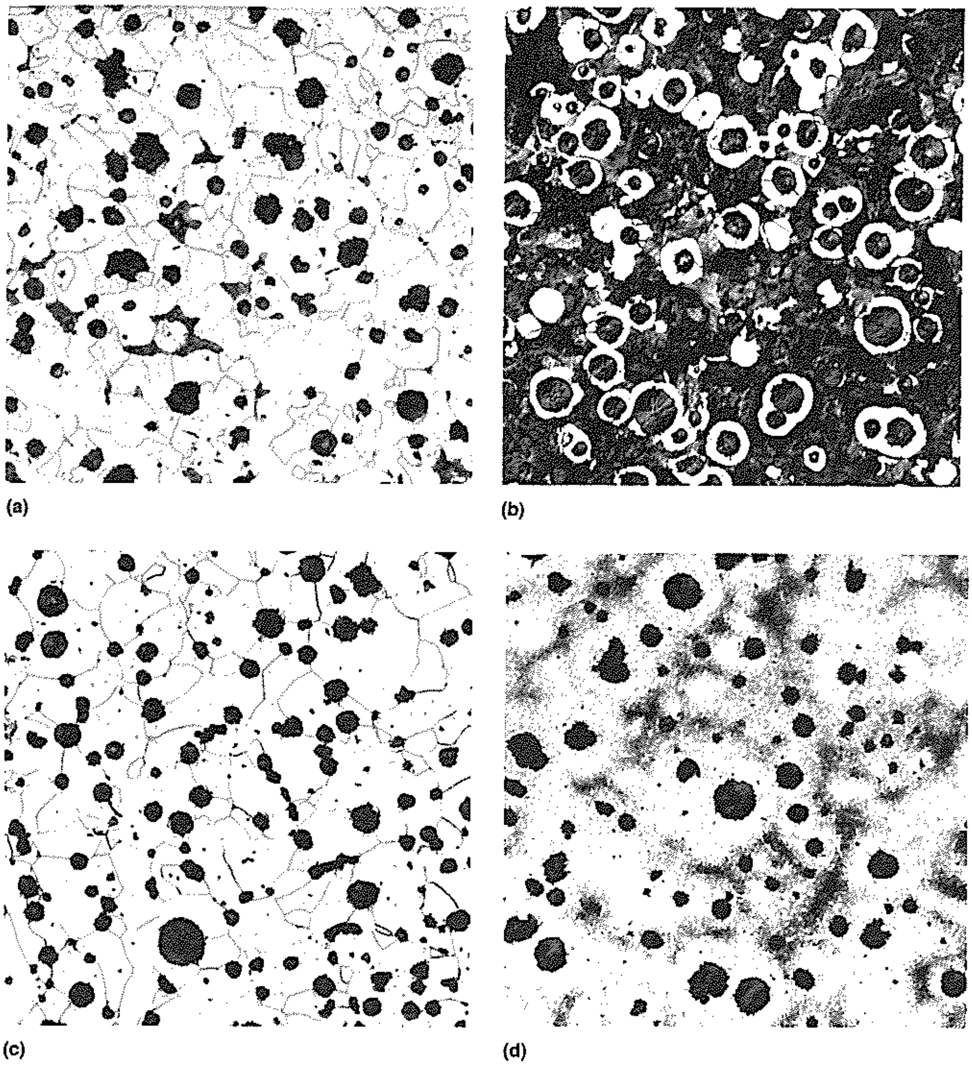
Laser/plasma torch processes. This technology makes it possible to produce tiny, remelted areas on selected surfaces of castings. The heated area rapidly solidifies because of the self-quenching effect of the mass of the casting. The result is a white iron structure that is substantially free of graphite and has a combination of high hardness and resistance to wear.

he area heated by a 2.5 kw laser is typically 1.5 mm (0.06 in.) in neter by 0.5 to 2 mm (0.02 to 0.08 in.) in depth. Hardness of approxi- ely 900 HV is produced without cracking.

REFERENCES

1. L.R. Jenkins and R. D. Forrest, Ductile Iron, Vol 1, *ASM Handbook*
2. K.B. Rundman, Heat Treating of Ductile Iron, Vol 4, *ASM Handbook*

icrostructures. Microstructures of ductile iron. (a) As-cast ferritic. (b) As-cast pearlitic; hardness, 255 HB. (c) Ferritic, annealed 3 h at 700 (1290 °F). (d) Pearlitic ductile iron oil quenched and tempered to 255 HB. All etched in 2% nital. 100×



STM Standard A 897-90 and A 897M-90 Mechanical Property Requirements of Austempered Ductile Iron

rade	Tensile (min) MPa	Tensile (min) ksi	Yield (min) MPa	Yield (min) ksi	Elongation, %	Impact(a) J	Impact(a) ft · lbf	Hardness, HB(c)
5-80-10	...	125	...	80	10	...	75	269-321
0-550-10	850	...	550	...	10	100	...	269-321
0-100-7	...	150	...	100	7	...	60	302-363
50-700-7	1050	...	700	...	7	80	...	302-363
5-125-4	...	175	...	125	4	...	45	341-444
00-850-4	1200	...	850	...	4	60	...	341-444
0-155-1	...	200	...	155	1	...	25	388-477
00-1100-1	1400	...	1100	...	1	35	...	388-477
0-185	...	230	...	185	(b)	...	(b)	444-555
00-1300	1600	...	1300	...	(b)	(b)	...	444-555

Unnotched Charpy bars tested at 72 = 7 °F (22 = 4 °C). The values in the table are a minimum for the average of the highest three test values of four tested samples. (b) Elongation d impact requirements are not specified. Although grades 200-155-1, 1400-1100-1, 230-185, 1600-1300 are primarily used for gear and wear resistance applications, grades 200-5-1 and 1400-1100-1 have applications where some sacrifice in wear resistance is acceptable in order to provide a limited amount of ductility and toughness. (c) Hardness is not ndatory and is shown for information only

ompositions and General Uses for Standard Grades of Ductile Iron

ecification No.	Grade or class	UNC	TC(a)	Typical composition, % Si	Mn	P	S	Description	General uses
TM A395; SME SA395	60-40-18	F32800	3.00 min	2.50 max(b)	...	0.08 max	...	Ferritic; annealed	Pressure-containing parts for use at elevated temperatures
TM A476; SAE MS 5316C	80-60-03	F34100	3.00 min(c)	3.0 max	...	0.08 max	0.05 max	As-cast	Paper mill dryer rolls, at temperatures up to 230 °C (450 °F)
TM A536	60-40-18(d)	F32800						Ferritic; may be annealed	Shock-resistant parts; low-temperature service
	65-45-12(d)	F33100						Mostly ferritic; as-cast or annealed	General service
	80-55-06(d)	F33800						Ferritic/pearlitic; as-cast	General service
	100-70-03(d)	F34800						Mostly pearlitic; may be normalized	Best combination of strength and wear resistance and best response to surface hardening
	120-90-02(d)	F36200						Martensitic; oil quenched and tempered	Highest strength and wear resistance
E J434	D4018(e)	F32800	3.20-4.10	1.80-3.00	0.10-1.00	0.015-0.10	0.005-0.035	Ferritic	Moderately stressed parts requiring good ductility and machinability
	D4512(e)	F33100						Ferritic/pearlitic	Moderately stressed parts requiring moderate machinability
	D5506(e)	F33800						Ferritic/pearlitic	Highly stressed parts requiring good toughness
	D7003(e)	F34800						Pearlitic	Highly stressed parts requiring very good wear resistance and good response to selective hardening
	DQ & T(e)	F30000						Martensitic	Highly stressed parts requiring uniformity of microstructure and close control of properties
E AMS 5315C	Class A	F33101	3.0 min	2.50 max(f)	...	0.08 max	...	Ferritic; annealed	General shipboard service

te: For mechanical properties and typical applications, see an adjoining table. (a) TC, total carbon. (b) The silicon limit may be increased by 0.08%, up to 2.75 Si, for each 0.01% uction in phosphorus content. (c) Carbon equivalent (CE), 3.8-4.5; CE = TC + 0.3 (Si + P). (d) Composition subordinate to mechanical properties; composition range for any ment may be specified by agreement between supplier and purchaser. (e) General composition given under grade D4018 for reference only. Typically, foundries will produce to rower ranges than those shown and will establish different median compositions for different grades. (f) For castings with sections 13 mm (½ in.) and smaller, may have 2.75 Si x with 0.08 P max, or 3.00 Si max with 0.05 P max; for castings with section 50 mm (2 in.) and greater, CE must not exceed 4.3

·chanical Properties and Typical Applications for Standard Grades of Ductile Iron

cification No.	Grade or class	Hardness, HB(a)	Tensile strength, min(b) MPa	Tensile strength, min(b) ksi	Yield strength, min(b) MPa	Yield strength, min(b) ksi	Elongation in 50 mm (2 in.) (min), % (b)	Typical applications
ΓM A395; ASME SA395	60-40-18	143-187	414	60	276	40	18	Valves and fittings for steam and chemical-plant equipment
ΓM A476(c); SAE AMS 5316	80-60-03	201 min	552	80	414	60	3	Paper mill dryer rolls
ΓM A536	60-40-18	...	414	60	276	40	18	Pressure-containing parts such as valve and pump bodies
	65-45-12	...	448	65	310	45	12	Machine components subject to shock and fatigue loads
	80-55-06	...	552	80	379	55	6	Crankshafts, gears, and rollers
	100-70-03	...	689	100	483	70	3	High-strength gears and machine components
	120-90-02	...	827	120	621	90	2	Pinions, gears, rollers, and slides
; J434	D 4018	170 max	414	60	276	40	18	Steering knuckles
	D4512	156-217	448	65	310	45	12	Disk brake calipers
	D5506	187-255	552	80	379	55	6	Crankshafts
	D7003	241-302	689	100	483	70	3	Gears
	DQ&T	(c)	(d)	(d)	(d)	(d)	(d)	Rocker arms
; AMS 5315C	Class A	190 max	414	60	310	45	15	Electric equipment, engine blocks, pumps, housings, gears, valve bodies, clamps, and cylinders

ɛ: For compositions, descriptions, and uses, an adjoining table. (a) Measured at a predetermined location on the casting. (b) Determined using a standard specimen taken from a ɹrately cast test block, as set forth in the applicable specification. (c) Range specified by mutual agreement between producer and purchaser. (d) Value must be compatible with imum hardness specified for production castings

ctile Iron Property Requirements of Various National and International Standards

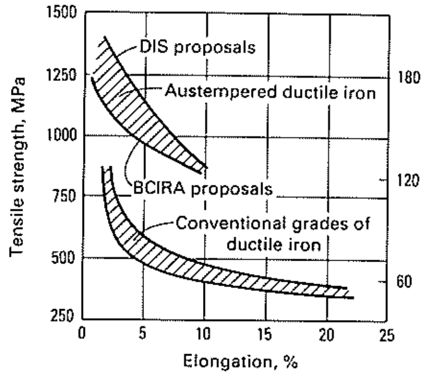
de	Tensile strength MPa	Tensile strength ksi	0.2% offset yield strength MPa	0.2% offset yield strength ksi	Elongation (min, %)	Impact energy Mean(a) J	Impact energy Mean(a) ft · lbf	Impact energy Individual J	Impact energy Individual ft · lbf	Hardness, HB	Structure
Standard 1083 (International)											
·2	800	116	480	70	2	...	...	...	...	248-352	Pearlite or tempered
·2	705	102	420	61	2	...	...	...	...	229-302	Pearlite
3	600	87	370	54	3	...	...	...	...	192-269	Pearlite + ferrite
7	500	73	320	46	7	...	...	...	...	170-241	Ferrite + pearlite
12	400	58	250	36	12	...	...	...	...	<201	Ferrite
17	370	54	230	33	17	13	9.5	11	8.1	<179	Ferrite
ʼM A 536 (United States)											
0-18	414	60	276	40	18	...	...	...	...	...	...
2-10	414	60	290	42	10	...	...	...	...	...	...
5-12	448	65	310	45	12	...	...	...	...	...	...
0-05	485	70	345	50	5	...	...	...	...	...	...
5-06	552	80	379	55	6	...	...	...	...	...	...
0-03	552	80	414	60	3	...	...	...	...	...	...
70-03	690	100	483	70	3	...	...	...	...	...	...
90-02	827	120	621	90	2	...	...	...	...	...	...
; J434 (United States)(b)											
18	414	60	276	40	18	...	...	...	...	170 max	Ferrite
12	448	65	310	45	12	...	...	...	...	156-217	Ferrite + pearlite
06	552	80	379	55	6	...	...	...	...	187-255	Ferrite + pearlite
03	690	100	483	70	3	...	...	...	...	241-302	Pearlite
ξT(c)	...	...	...	...	...	...	...	...	...	...	Martensite

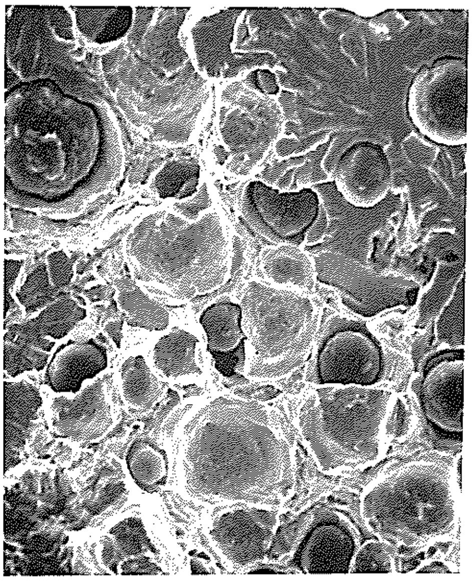
ɬean value from three tests. (b) Specifications for these irons are primarily based on hardness and structure. Mechanical properties are given for information only. (c) Quenched ·empered grade; hardness subject to agreement between supplier and purchaser

ome Tentative Specifications for Austempered Ductile ron

rade	Tensile strength (min) MPa	ksi	0.2% offset yield strength (min) MPa	ksi	Elongation (min), %	Hardness, HB
uctile Iron Society (United States)						
	860	125	550	80	10	269-321
	1035	165	690	100	7	302-363
	1205	175	827	120	4	363-444
	1380	200	965	140	2	388-477
ulzer (Switzerland)						
GG80 BAF	800	116	505	73	8	250-310
GG100	1000	160	705	102	5	280-340
GG120	1200	174	950	138	2	330-390
CIRA (Great Britain)						
50/6	950	138	670	97	6	300-310
050/3	1050	152	780	113	3	345-355
200/1	1200	174	940	136	1	390-400

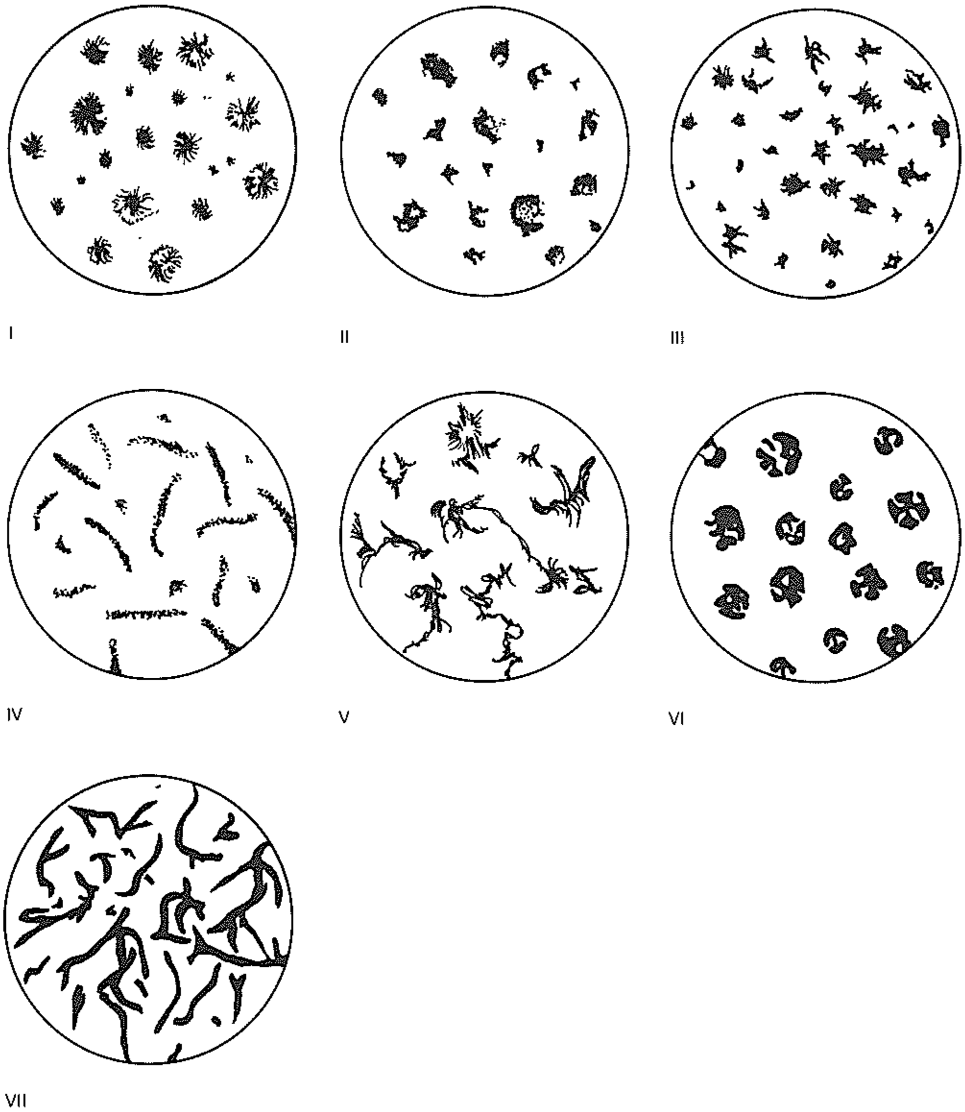
Proposed strength and elongation ranges of austempered ductile iron compared to established criteria for other grades of ductile iron. DIS, Ductile Iron Society; BCIRA, British Cast Iron Research Association





Microstructure. Fractograph showing the brittle fracture of a ductile iron dynamic tear specimen. 355x

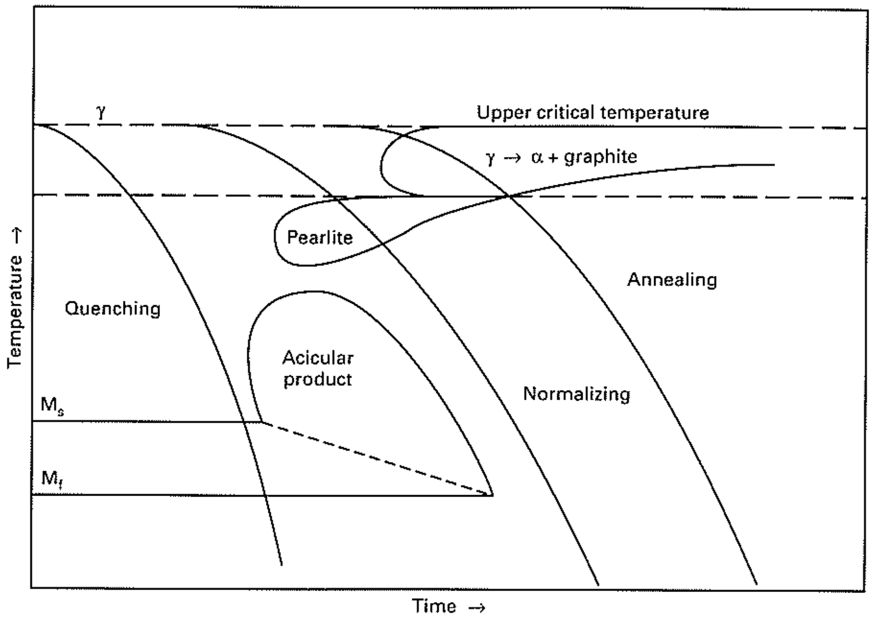
Seven graphite shapes used to classify cast irons



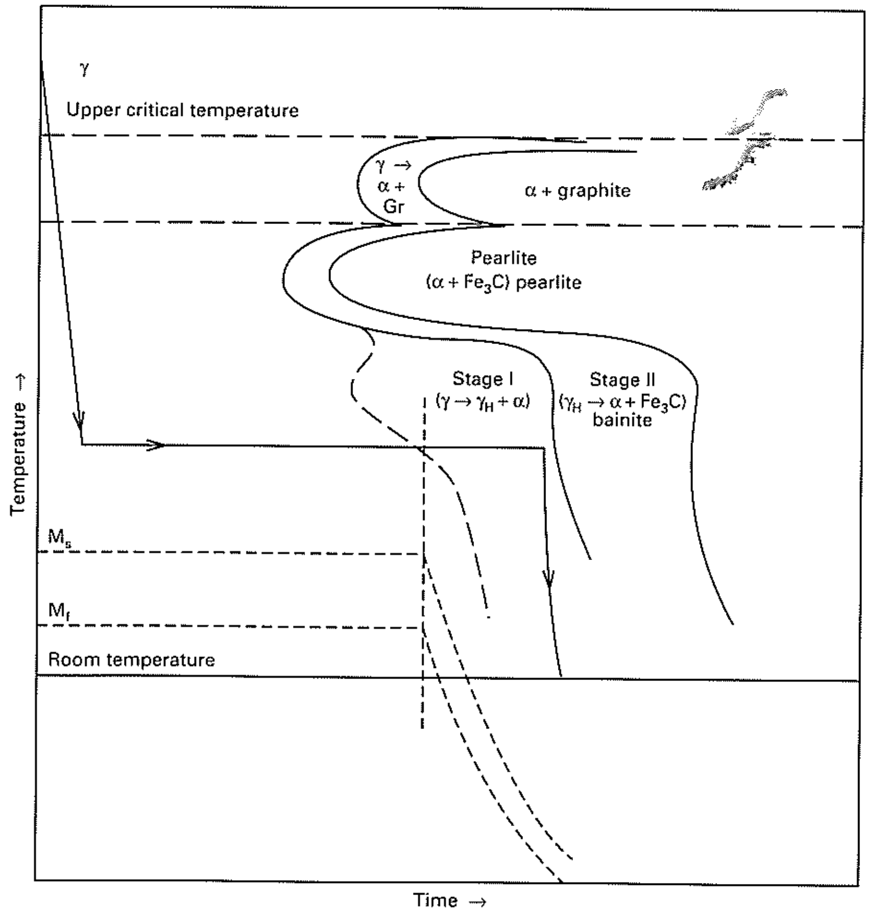
ASTM type(a)	Equivalent ISO form(b)	Description	ASTM type(a)	Equivalent ISO form(b)	Description
I	VI	Nodular (spheroidal) graphite	IV	III	Quasi-flake graphite
II	VI	Nodular (spheroidal) graphite, imperfectly formed	V	II	Crab-form graphite
			VI	V	Irregular or open type nodules
III	IV	Aggregate, or temper carbon	VII(c)	I	Flake graphite

(a) As defined in ASTM A 247. (b) As defined in ISO/R 945-1969 (E). (c) Divided into five subtypes: uniform flakes; rosette grouping; superimposed flake size; interdendritic, random orientation; and interdendritic, preferred orientation

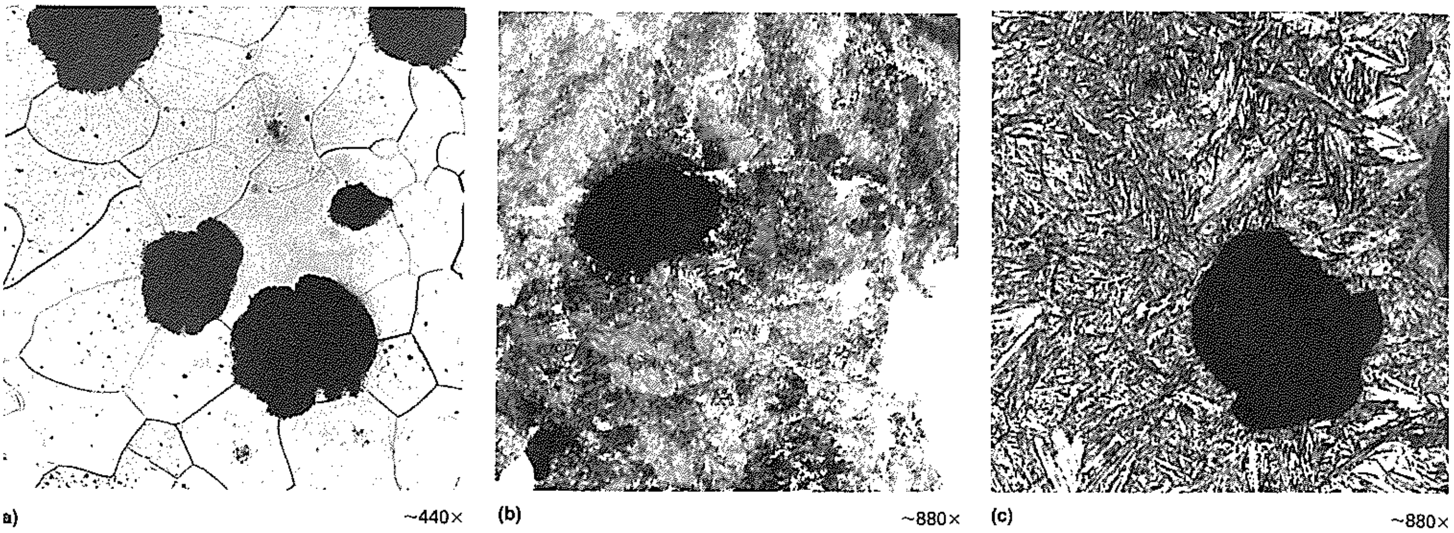
CCT diagram showing annealing, normalizing, and quenching. M_s, martensite start; Mf, martensite finish



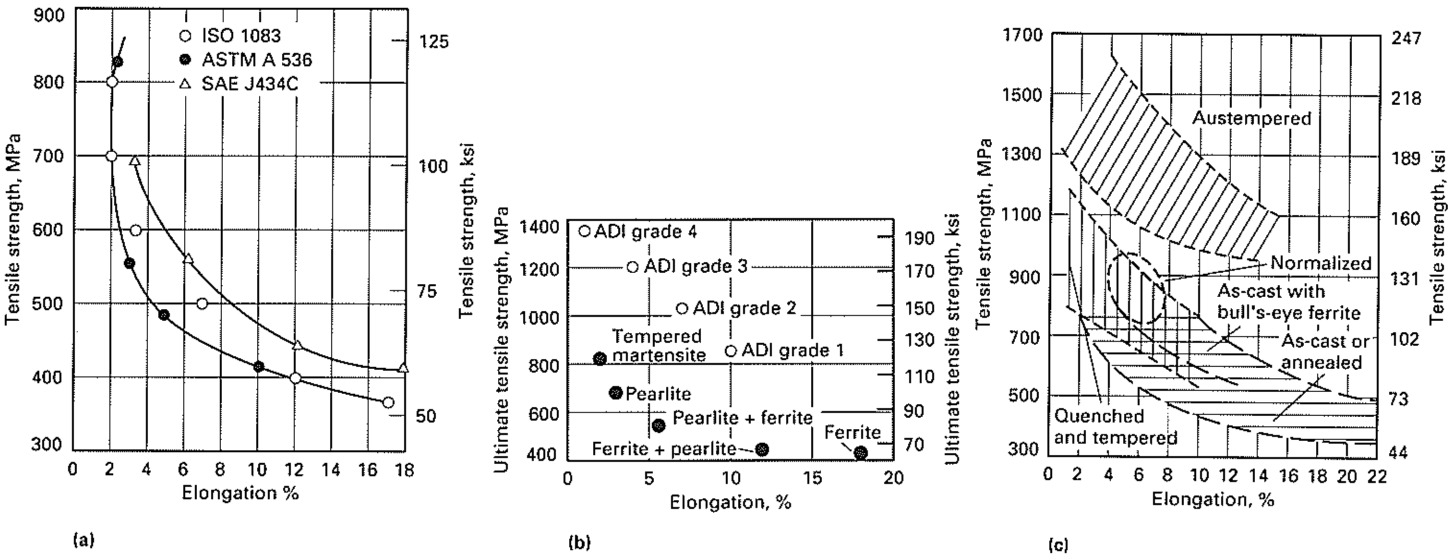
IT diagram of a processing sequence for austempering, with the M_s and M_f decreasing as the γ is enriched with carbon during stage I



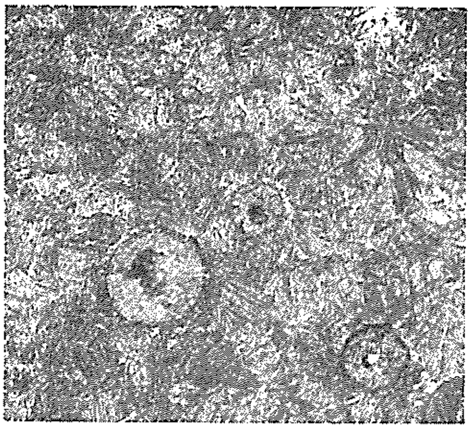
Microstructures. Optical micrographs of ductile iron with (a) a ferritic matrix in an annealed casting, (b) fine pearlitic matrix in a normalized casting, and (c) a martensitic matrix in a quenched casting. Etched in nital; approximate magnifications shown



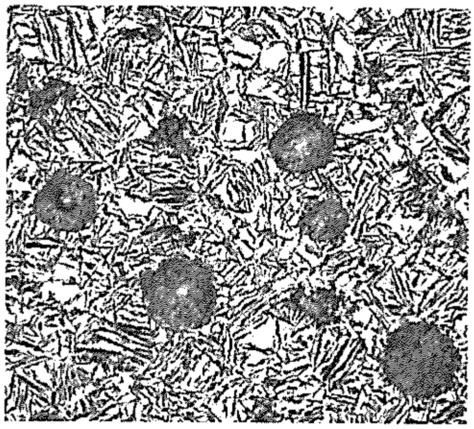
Tensile strength vs elongation of ductile iron. (a) Minimum values given in various standards. (b) Minimum values of austempered ductile iron grades specified in ASTM A 897. (c) Range of tensile strength and elongation values with different heat treatments



Microstructures. Micrographs of ductile iron treated at different austempering temperatures. (a) Ductile iron austempered at 260 °C (500 °F) exhibits a fine acicular structure with the following properties: tensile strength, 1585 MPa (230 ksi); yield strength, 1380 MPa (200 ksi); elongation, 3%; unnotched impact, 54 J (40 ft · lbf); hardness, 475 HB. (b) Same iron as in (a) austempered at 370 °C (700 °F) exhibits a coarse acicular structure with the following properties: tensile strength, 1035 MPa (150 ksi); yield strength, 825 MPa (120 ksi); elongation, 11%; unnotched impact, 130 J (95 ft · lbf); hardness, 321 HB. Both etched with 3% nital. 300×. Source: Applied Process, Inc.

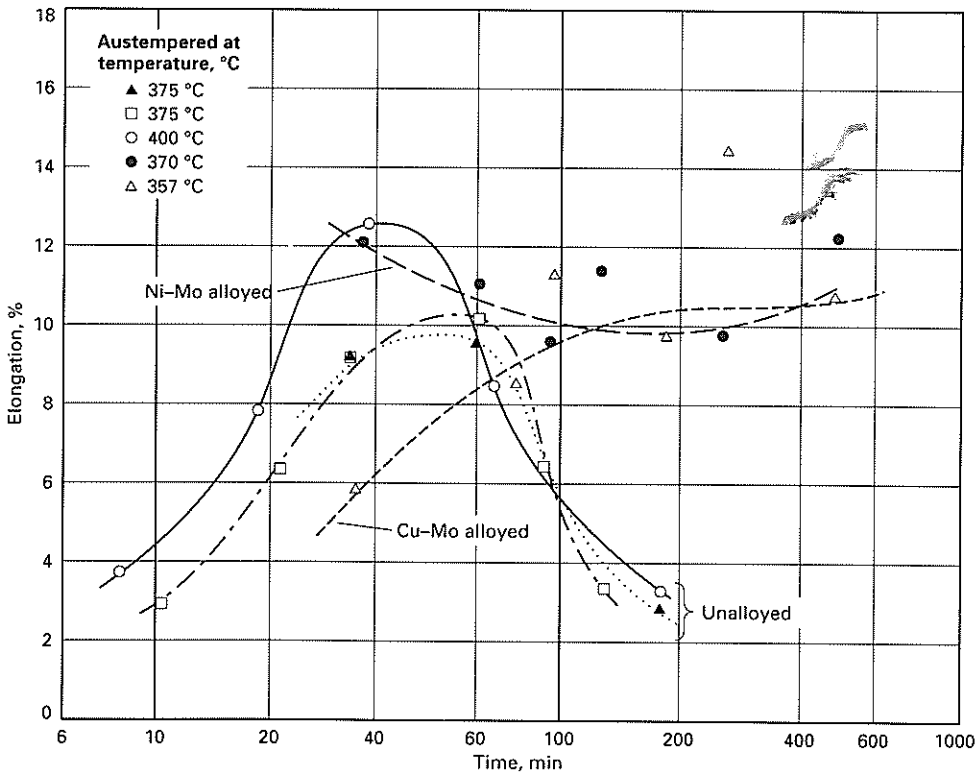


(a)

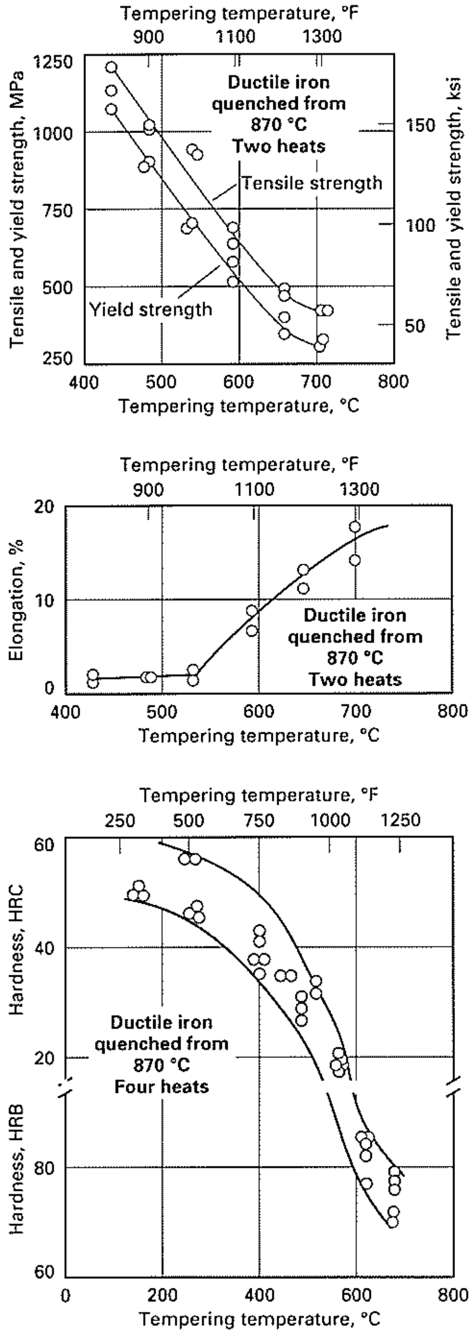


(b)

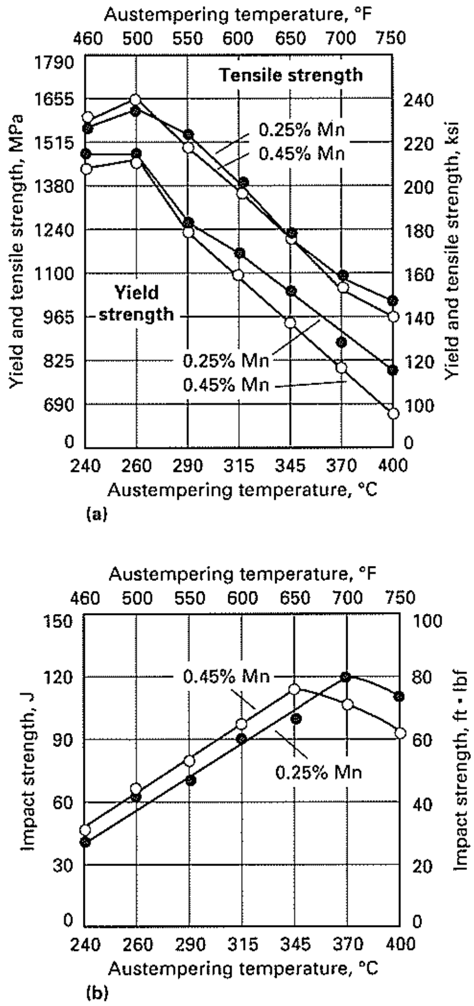
Elongation vs austempering time for a group of ductile iron alloys



Influence of tempering temperature on mechanical properties of ductile iron quenched from 870 °C (1600 °F) and tempered 2 h. Data represent irons from four heats with composition ranges of: 3.52 to 3.68% C, 2.28 to 2.35% Si, 0.02 to 0.04% P, 0.22 to 0.41% Mn, 0.69 to 0.99% Ni, and 0.045 to 0.065% Mg. Data for tensile strength, tensile yield strength, and elongation are for irons (from two of these heats) that contained 0.91 and 0.99% Ni



Effect of austempering temperature on properties of ductile iron. (a) Yield strength and tensile strength vs austempering temperature. (b) Impact strength vs austempering temperature



Heat Treating Malleable Irons

Chemical Composition

Compositions of malleable iron are found in accompanying tables. These irons are limited in two respects: their range of chemical composition and use of alloys.

Chemical compositions usually conform to the following ranges:

Element	Composition, %	
	Ferritic	Pearlitic
Total carbon	2.2-2.9	2.0-2.9
Silicon	0.9-1.9	0.9-1.9
Manganese	0.2-0.6	0.2-1.3
Sulfur	0.02-0.2	0.05-0.2
Phosphorus	0.02-0.2	0.02-0.2

Alloying elements. Small amounts of chromium (0.01 to 0.03%), boron (0.0020%), copper (approximately 1.0%), and molybdenum (0.35 to 0.5%) are sometimes present.

Carbon content. This element is not allowed to drop below a minimum value in the interest of mechanical quality and annealability. Reason: decreasing carbon content reduces the fluidity of molten iron and reduces annealability. In addition, maximum carbon content is limited because of the requirement that castings must be white as cast.

Silicon content. Again, content is limited—in this instance, to ensure proper annealing during a short-cycle, high-production annealing process and to avoid the formation of primary graphite (known as mottle) during the solidification of white iron.

Manganese and sulfur contents. These elements are balanced to ensure that all sulfur is combined with manganese and that only a safe, minimum quantity of excess manganese is present in the iron. Any excess of sulfur or manganese retards annealing in the second stage, which adds to annealing costs.

Chromium content. This value is kept low because of the carbide-stabilizing effect of this element and because it retards both first stage and second stage annealing reactions.

Mottle is a mixture of gray iron and white iron, which produces a speckled appearance. The condition is particularly detrimental to the mechanical properties of annealed castings, both ferritic and pearlitic types. Control is obtained by maintaining a balance of carbon and silicon contents.

How malleable is made. Both ferritic and pearlitic malleable irons are produced by annealing white iron of controlled composition. Annealing is an essential part of the manufacturing process.

Different microstructures (ferritic, tempered pearlitic, and tempered martensitic, or bainitic) are produced by variations in heat treatment. The feature common to all malleable irons is the presence of uniformly dispersed and irregularly shaped graphite nodules in a given microstructure. The nodules, known as temper carbon, are formed by annealing white cast iron. This initial anneal is followed by additional heat treatments that produce specific microstructures.

Characteristics of Malleable Iron

The matrix microstructure is the dominant factor influencing mechanical properties. Mechanical properties relate well to the hardness levels of different microstructures. The softer ferritic matrix provides maximum ductility with lower strength, while increasing pearlite content increases hardness and strength, but ductility is reduced. Martensite provides still higher hardness and strength, but with further declines in ductility. Mechanical properties of pearlitic and martensitic grades are clearly related to hardness.

Properties of malleable iron castings, grades of malleable based on hardness, and grades specified on the basis of tensile properties are listed in accompanying tables.

Two basic types of malleable are available: blackheart and whiteheart. The former is the only type produced in North America and is the most widely used grade throughout the world. Whiteheart is the older type, and is essentially decarburized white iron, produced in a long heat treating process.

Malleable iron, like ductile iron, has considerable ductility and toughness because of its combination of nodular graphite and a low-carbon metallic matrix. Thus both malleable and ductile are suitable choices for some applications calling for good ductility and toughness. In this instance, the deciding factors are economy and availability, rather than comparative properties.

The advantage goes to ductile iron when sections are too thick to permit the solidification of white iron over 100% of the section.

Another advantage of ductile iron, when low solidification shrinkage is needed.

Malleable is preferred:

- For thin section casting
- For parts that are to be pierced, coined, or cold formed
- For parts requiring maximum machinability
- For parts requiring good resistance to impact at low temperatures
- For parts requiring resistance to wear (applies only to martensitic malleable iron)

Both malleable and ductile iron provide:

- High resistance to corrosion
- Excellent machinability
- Good magnetic permeability
- Low magnetic retention—for magnetic clutches and brakes

Other desirable properties of malleable: good fatigue strength and damping capacity make this iron useful for highly stressed parts that see extended service.

Other considerations. After heat treatment, ferritic or pearlitic castings are cleaned by shotblasting. Gates are removed by shearing or grinding, and, where necessary, castings are coined or punched.

Close dimensional tolerances can be held with ferritic grades and the lower hardness types of pearlitic malleable, both of which are easily straightened in dies. The harder pearlitic irons are more difficult to press because of their higher yield strength and a greater tendency toward springback after die pressing. However, even the strongest pearlitic grades can be straightened.

Heat Treating Malleable Irons

Like medium carbon steel, malleable can be heat treated to a wide variety f mechanical properties.

In addition to mill heat treating processes, pearlitic malleable can be electively surface hardened with induction heating and quenching or flame eating and quenching to develop high hardness in heat-affected surfaces. aser and electron beam processes have been used to get similar results.

Malleable is also carburized, carbonitrided, and nitrided to add wear sistance to surfaces. Austempering has been used in specialized applica- ons.

Pearlitic malleable can also be hardened and tempered, martempered and mpered, and treated to produce both upper and lower bainite. The effect f tempering temperature and time on the hardness of ferritic and pearlitic ons is shown in an accompanying table.

Heat Treating Ferritic Malleable

The microstructure of this iron is shown in an accompanying figure. A itisfactory structure consists of temper carbon in a matrix of ferrite.

Annealing. A two-stage cycle is required. The first stage converts imary carbides to temper carbon; the second converts carbon dissolved austenite at the first stage annealing temperature to temper carbon and rrite.

After first stage annealing, castings are cooled as rapidly as practical to 40 to 760 °C (1365 to 1400 °F) in preparation for second stage annealing. ast cooling requires 1 to 6 h, depending on the equipment.

Castings are then cooled slowly at a rate of approximately 3 to 10 °C (5 20 °F) per h. During cooling, carbon in the austenite is converted to aphite and deposited on particles of temper carbon. The result is a fully rritic matrix.

Hardness can be considered an approximate indicator that the ferritizing ineal was complete. Hardness of ferritic malleable almost always ranges om 110 to 156 HB, and is influenced by total carbon and silicon contents.

Mechanical properties

The most important properties for design purposes are tensile strength, eld strength, modulus of elasticity, fatigue strength, impact strength, tigue toughness, and elevated temperature properties.

Also of interest are resistance to corrosion, weldability, brazeability, and solderability. Other properties:

- **Tensile properties.** Usually measured on unmachined test bars. See accompanying table for tensile properties.
- **Fatigue limit.** That of unnotched specimens is about 50 to 60% of tensile strength. Notch radius generally has little effect on fatigue strength, but fatigue strength drops with increasing notch depth.
- **Modulus of elasticity.** This value in tension is approximately 170 GPa (25×10^6 psi). In comparison, the ranges are 150 to 170 GPa (22×10^6 to 25×10^6 psi); the value in torsion ranges from 65 to 75 GPa (9.5×10^6 to 11×10^6 psi).
- **Fracture toughness.** Notch tests such as the Charpy V-notch are conducted over a range of temperatures to establish toughness behavior and the temperature range of transition from ductile to brittle fraction. Brittle fractures are most likely to occur at high strain rates, at low temperatures, and with high restraint on metal deformation.
- **Elevated temperature properties.** Short term, high temperature tensile properties typically show no sign of change to 370 °C (700 °F).
- **Corrosion resistance.** This property in ferritic malleable is improved by the addition of copper (usually about 1%) in certain applications.
- **Welding and brazing.** Welding of ferritic iron almost always produces brittle white iron in the weld zone and the heat-affected zone immediately adjacent to the weld zone. In some cases, welding with a cast iron electrode may produce a brittle, gray iron weld zone.

Welding usually is not recommended unless castings are subsequently annealed to convert carbide to temper carbon and ferrite. However, ferritic can be fusion welded to steel without a requirement for subsequent annealing if a completely decarburized zone as deep as the normal heat affected zone is produced at the faying surface of the malleable iron part before welding.

Ferritic iron can be silver brazed and silver-tin soldered.

Heat Treating Pearlitic and Martensitic Malleable Iron

Both grades can be produced to a wide range of mechanical properties, epending on heat treatment, alloying, and melting practice.

Lower strength pearlitics often are produced by air cooling castings after ie first stage anneal; while the higher strength pearlitic/martensitic grades e made by liquid quenching after the first stage anneal.

With suitable heat treating facilities, air cooling or liquid quenching after ie first stage anneal generally is the most economical way of making earlitic or martensitic/pearlitic irons. The alternative is to reheat ferritic roduced in two-stage annealing to the austenitic temperature, then uenching.

Also, lower strength pearlitics can be made by alloying and a two-stage inealing process.

Heat Treatment of Pearlitic Malleable

The first stage anneal is the same as that for ferritic iron. After this, the rocess is different. Some foundries slow cool castings to approximately 70 °C (1600 °F). During cooling, combined carbon is reduced to approxi- iately 0.75%. Castings are then air cooled. Air cooling is accelerated by i air blast to avoid the formation of ferrite envelopes around temper carbon particles and to produce a fine pearlitic matrix. Castings are then tempered to specifications, or they are reheated to reaustenitize at approximately 870 °C (1600 °F), oil quenched, and tempered to specifications. Large foundries usually skip the reaustenitizing step, and quench castings in oil directly from the first-stage annealing furnace after stabilizing the temperature at 845 to 870 °C (1555 to 1600 °F).

Heat Treating Pearlitic-Martensitic Irons

These high strength grades usually are produced by liquid quenching and tempering. The most economical procedure is to direct quench after first stage annealing. Castings are cooled in the furnace to the quenching temperature of 845 to 870 °C (1555 to 1600 °F) and held 15 to 30 min to homogenize the matrix. Castings are then quenched in agitated oil to develop a matrix microstructure of martensite, having a hardness of 415 to 601 HB. Finally, castings are tempered at an appropriate temperature between 590 to 725 °C (1095 to 1335 °F) to develop specific mechanical properties.

Rehardened and tempered malleable iron can also be produced from fully annealed ferritic iron with a slight variation in the heat treatment used for rested-annealed (air quenched) malleable. The matrix of fully annealed rritic is essentially carbon free, but the iron can be recarburized by heating 840 to 870 °C (1545 to 1600 °F) for 1 h.

Tempering times of 2 h or more after air cooling or liquid quenching are eded for uniformity. Control of final hardness is precise. Processing mitations are about the same as those for the heat treatment of medium or gh carbon steels, especially when specifications call for hardnesses of 11 to 321 HB. Control limits of ±0.2 mm Brinnel diameter can be aintained with ease.

Mechanical properties of pearlitic and martensitic iron vary in a substanılly linear relationship with brittle hardness. In the low hardness range, operties of air quenched and tempered pearlitic are essentially the same those of oil quenched and tempered martensitic malleable iron.

At high hardnesses, oil quenched and tempered malleable has a higher eld strength and more elongation than air quenched and tempered malleıle iron.

Oil quenched and tempered pearlitic is produced commercially to hardsses as high as 321 HB, while the maximum hardness of high production, r quenched and tempered pearlitic malleable is approximately 255 HB. nsile properties of pearlitic normally are measured on machined test bars.

Compressive strength is seldom determined, because failure in compreson is rare.

Shear and torsional strength. Shear strength of ferritic malleable is proximately 80% of tensile strength; for pearlitic, it ranges 70 to 90% of nsile.

Ultimate torsional strength of ferritic malleable is approximately 90% of timate tensile strength. Yield strength in torsion is 75 to 80% of ultimate nsile strength. Torsional strengths of pearlitic grades are about equal to or ghtly less than the tensile strength of the material. Yield strengths in rsion vary from 70 to 75% of tensile yield strength.

Modulus of elasticity of pearlitic in tension is 176 to 193 GPa (25.5×10^6 28.0×10^6 psi).

Fracture toughness: results of Charpy V-notch tests on pearlitic are esented in an accompanying figure.

Studies of this property have been limited.

Properties at elevated temperatures: generally room temperature tensile engths are related to hardness, while tensiles above approximately 450 (840 °F) exhibit asymptotic behavior.

Unnotched fatigue limits of tempered pearlitic malleable (air cooled or l quenched) are approximately 40 to 50% of tensile strength. Tempered artensitic malleable irons (oil quenched) have an unnotched fatigue limit approximately 35 to 45% of tensile strength.

Wear resistance: both pearlitic and martensitic grades have excellent wear resistance.

Welding: both are difficult to weld because temperatures generated in the process can cause the formation of a brittle layer of graphite-free white iron. However, both types of iron can be welded if the surface to welded has been heavily decarburized.

Brazing: malleable iron can be brazed with various commercial processes.

Damping capacity: malleable irons perform well in long term service where parts are highly stressed. Reason: because of a combination of good damping capacity and fatigue strength.

Bainitic Heat Treatment of Pearlitic Malleable

Both upper and lower bainite can be formed in pearlitic with a marked increase in tensile strength and hardness—but there is a loss in ductility.

A pearlitic with a composition of 2.6 C, 1.4 Si, 0.5 Mn, 0.11 S, for example, was treated in this manner: it was annealed at 930 °C (1705 °F) for 16 h, air quenched, and tempered at 680 °C (1255 °F) for 4 h.

Properties developed were: an ultimate tensile strength of 650 MPa (94.2 ksi), a yield strength of 460 MPa (66.5 ksi), and a 3.4% elongation at 900 °C (1650 °F).

The same iron austenitized at 900 °C (1650 °F) in molten salt for 1 h, quenched in molten salt at 295 °C (565 °F) for 3 h, and air cooled developed an ultimate strength of 995 MPa (144.2 ksi) and an elongation of 1% at 388 HB.

Selective Surface Hardening. Pearlitic is surface hardened by induction heating and quenching, or by flame heating and quenching to develop high hardness in the heat affected area. In general, little difficulty is encountered in obtaining hardnesses in the range of 55 to 60 HRC. Depth of penetration is controlled by the rate of heating and surface temperature of the workpiece.

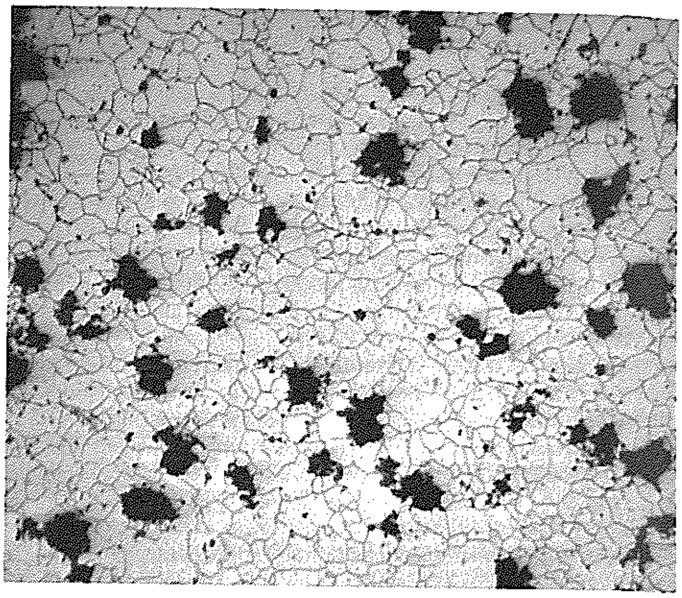
Maximum hardness in the matrix of a properly hardened pearlitic casting is 67 HRC. Generally, a casting with this hardness has an average hardness of approximately 62 HRC, as measured by a standard Rockwell tester.

REFERENCES

1. Article on malleable iron, Vol 1, *ASM Handbook*
2. L.R. Jenkins, Heat Treating of Malleable Iron, Vol 4, *ASM Handbook*

Microstructure. Structure of as-cast malleable white iron showing a mixture of pearlite and eutectic carbides. 400×

Microstructure. Structure of annealed ferritic malleable iron showing temper carbon in ferrite. 100×



Properties of Malleable Iron Castings

Specification No.	Class or grade	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Hardness, HB	Elongation(a), %
Ferritic							
ASTM A47 and A338, ANSI G48.1, FED QQ-1-666c	32510	345	50	224	32	156 max	10
	35018	365	53	241	35	156 max	18
ASTM A197	...	276	40	207	30	156 max	5
Pearlitic and martensitic							
ASTM A220, ANSI G48.2, MIL-I-11444B	40010	414	60	276	40	149-197	10
	45008	448	65	310	45	156-197	8
	45006	448	65	310	45	156-207	6
	50005	483	70	345	50	179-229	5
	60004	552	80	414	60	197-241	4
	70003	586	85	483	70	217-269	3
	80002	655	95	552	80	241-285	2
	90001	724	105	621	90	269-321	1
Automotive							
ASTM A602, SAE J158	M3210(b)	345	50	224	32	156 max	10
	M4504(c)	448	65	310	45	163-217	4
	M5003(c)	517	75	345	50	187-241	3
	M5503(d)	517	75	379	55	187-241	3
	M7002(d)	621	90	483	70	229-269	2
	M8501(d)	724	105	586	85	269-302	1

(a) Minimum in 50 mm (2 in.). (b) Annealed. (c) Air quenched and tempered. (d) Liquid quenched and tempered

Grades of Malleable Iron Specified According to Hardness per ASTM A 602 and SAE J158

Grade	Specified hardness, HB	Heat treatment	Microstructure	Typical applications
M 3210	156 max	Annealed	Ferritic	For low-stress parts requiring good machinability: steering-gear housings, carriers, and mounting brackets
M 4504	163-217	Air quenched and tempered	Ferrite and tempered pearlite(a)	Compressor crankshafts and hubs
M 5003	187-241	Air quenched and tempered	Ferrite and tempered pearlite(a)	For selective hardening: planet carriers, transmission gears, and differential cases
M 5503	187-241	Liquid quenched and tempered	Tempered martensite	For machinability and improved response to induction hardening
M 7002	229-269	Liquid quenched and tempered	Tempered martensite	For high-strength parts: connecting rods and universal-joint yokes
M 8501	269-302	Liquid quenched and tempered	Tempered martensite	For high strength plus good wear resistance: certain gears

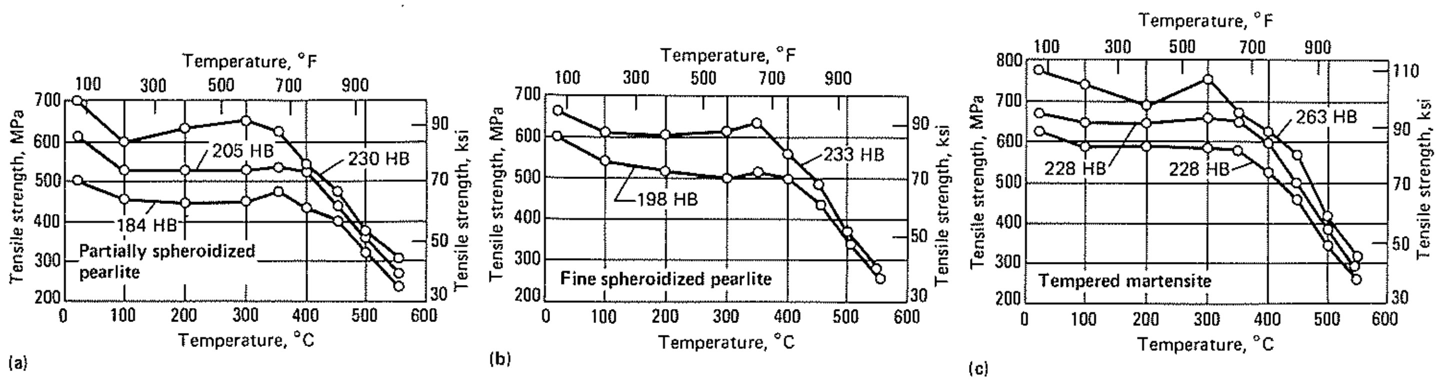
(a) May be all tempered martensite for some applications

Grades of Malleable Iron Specified According to Minimum Tensile Properties

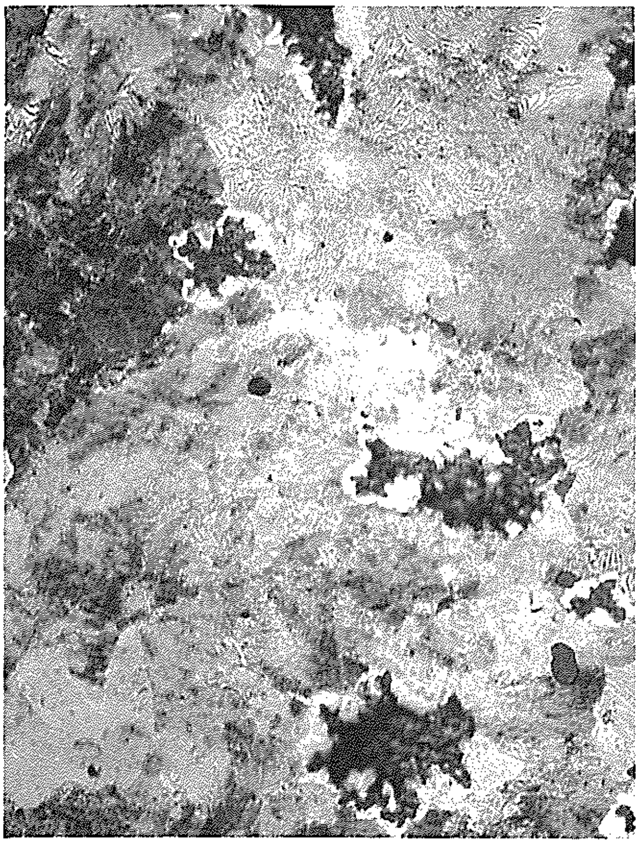
Specification No.	Class or grade(a)	ASTM metric equivalent class(b)	Microstructure	Typical applications
Ferritic				
ASTM A 47(c), ANSI G 48.1, FED QQ-1-666c	32510 35018	22010 24018	Temper carbon and ferrite	General engineering service at normal and elevated temperatures for good machinability and excellent shock resistance
ASTM A 338	(d)	...	Temper carbon and ferrite	Flanges, pipe fittings, and valve parts for railroad, marine, and other heavy-duty service to 345 °C (650 °F)
ASTM A 197, ANSI G49.1	(e)	...	Free of primary graphite	Pipe fittings and valve parts for pressure service
Pearlitic and martensitic				
ASTM A 220(c), ANSI G48.2, MIL-I-11444B	40010 45008 45006 50005 60004 70003 80002 90001	280M10 310M8 310M6 340M5 410M4 480M3 560M2 620M1	Temper carbon in necessary matrix without primary cementite or graphite	General engineering service at normal and elevated temperatures. Dimensional tolerance range for castings is stipulated

(a) The first three digits of the grade designation indicate the minimum yield strength (×100 psi), and the last two digits indicate minimum elongation (%). (b) ASTM specifications designated by footnote (c) provide a metric equivalent class where the first three digits indicate minimum yield strength in MPa. (c) Specifications with a suffix "M" utilize the metric equivalent class designation. (d) Zinc-coated malleable iron specified per ASTM A 47. (e) Cupola ferritic malleable iron

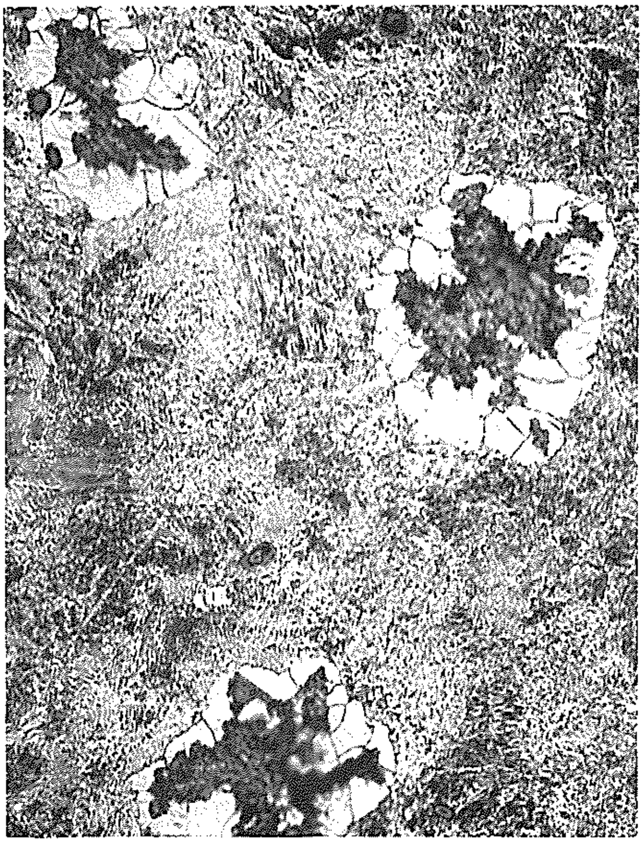
Short-term elevated-temperature tensile strengths of (a) partially spheroidized pearlitic malleable irons produced by air cooling after the temper carbon anneal, (b) finely spheroidized pearlitic malleable irons produced by oil quenching after the temper carbon anneal, and (c) oil-quenched and tempered martensitic malleable irons. The two martensitic malleable irons with hardnesses of 228 HB were reheated (reaustenitized) after the temper carbon anneal [18 h soak at 950 °C (1740 °F)] and then oil quenched. The 263 HB iron was oil quenched from 840 °C (1545 °F) after an anneal of 9.5 h at 950 °C (1740 °F). After oil quenching, all three martensitic irons were tempered



Microstructures. Structure of air-cooled pearlitic malleable iron. (a) Slowly air cooled. 400×. (b) Cooled in an air blast. 400×

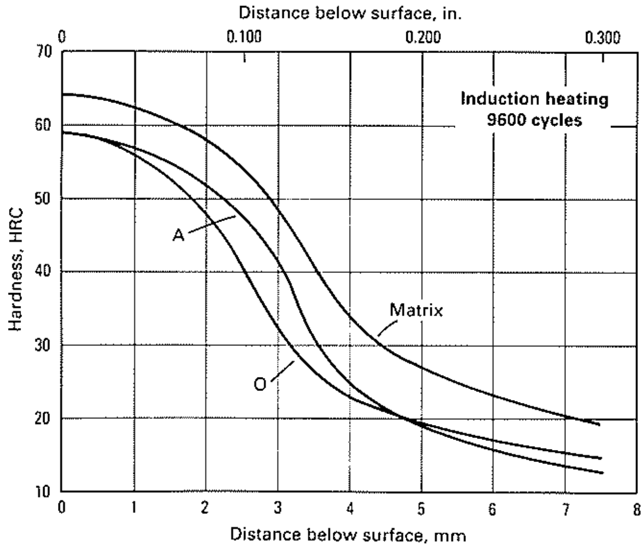


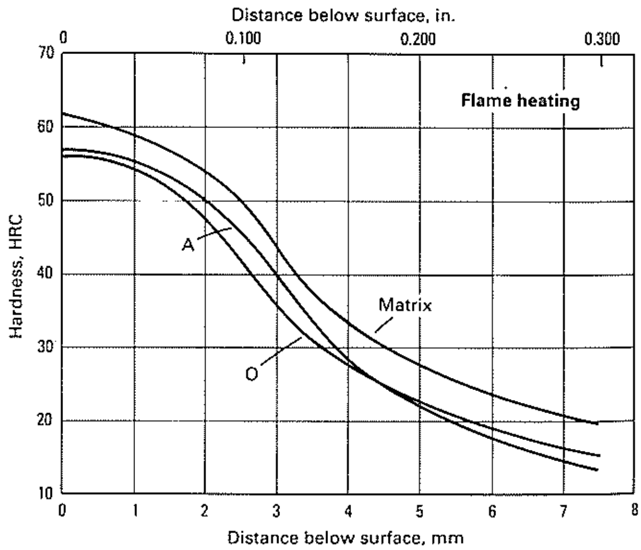
(a)



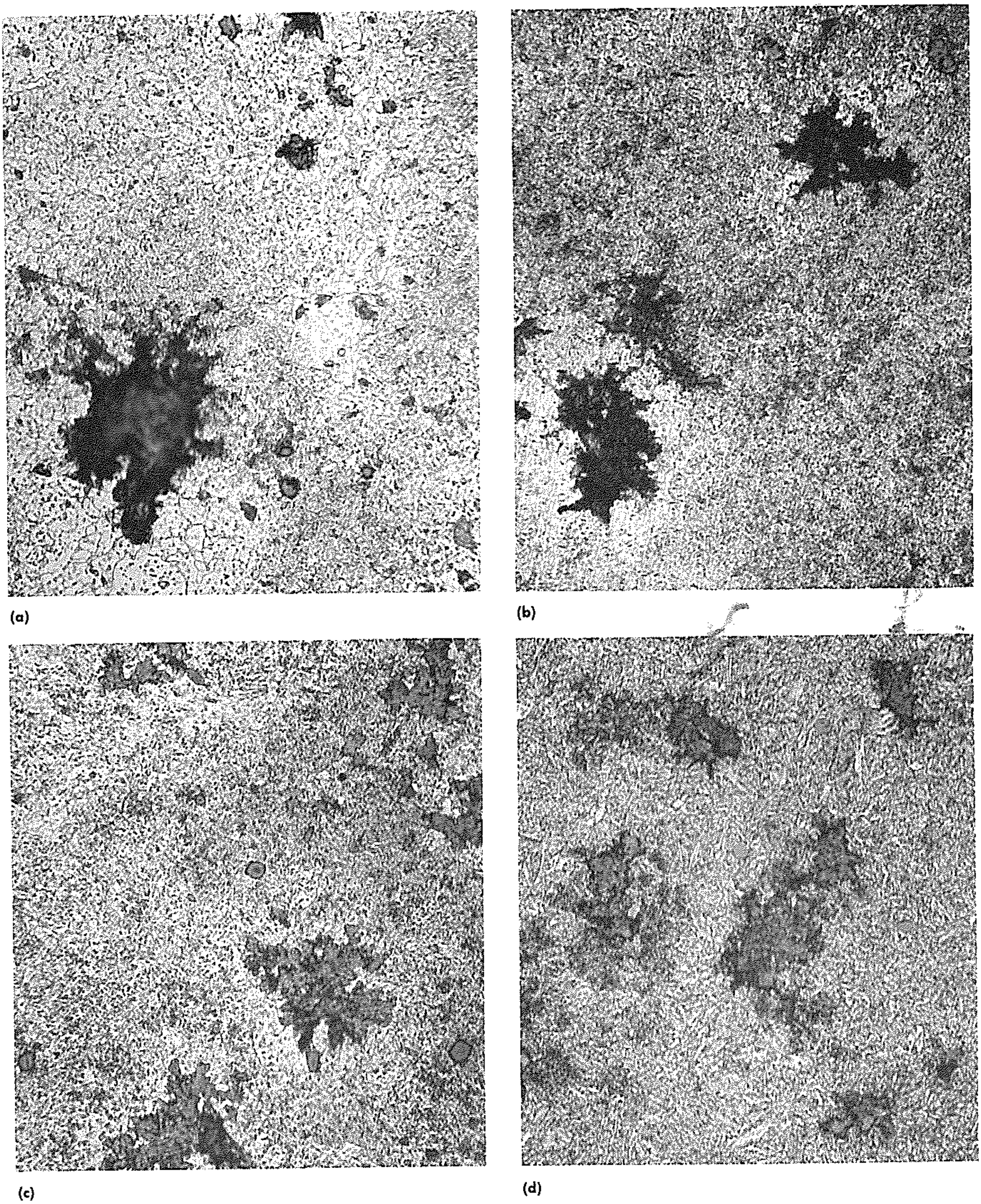
(b)

Hardness vs depth for surface-hardened pearlitic malleable irons. Curves labeled "Matrix" show hardness of the matrix, converted from microhardness tests. O, oil quenched and tempered to 207 HB before surface hardening; A, air cooled and tempered to 207 HB before surface hardening

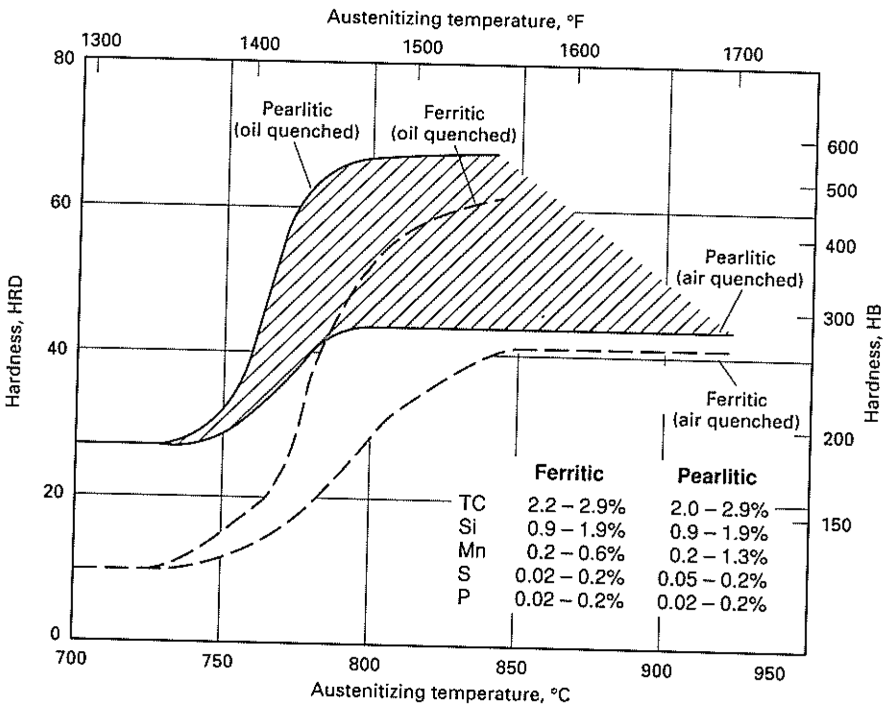




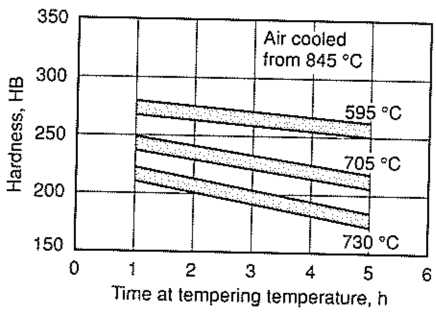
Microstructures. Structure of oil-quenched and tempered martensitic malleable iron. (a) 163 HB. 500×. (b) 179 HB. 500×. (c) 207 HB. 500×. (d) 229 HB. 500×

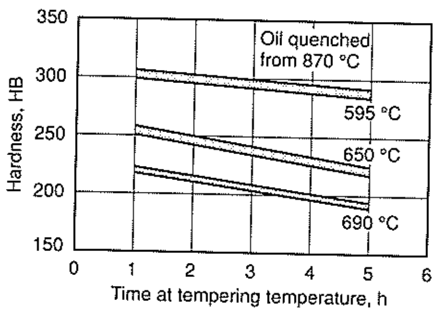


Effects of austenitizing temperature and quenching medium on hardness of as-quenched malleable iron. The listed composition limits for ferritic and pearlitic malleable iron are general limits given in the *Iron Castings Handbook* 1981. In practice, manganese content is 0.2 to 0.45% Mn for the ferritic class and less than 0.6% Mn for the pearlitic class

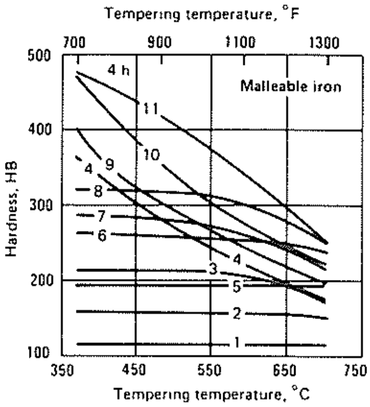


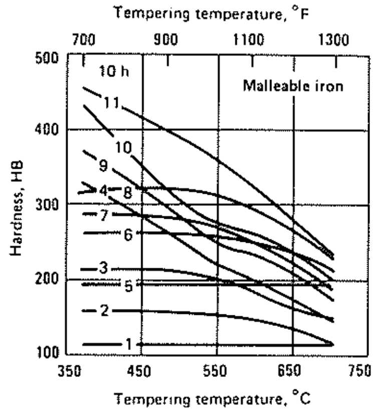
Influence of time and tempering temperature on room-temperature hardness of pearlitic malleable iron. Composition: 2.35 to 2.45% C, 1.45 to 1.55% Si, 0.03% P, 0.06 to 0.15% S, 0.38 to 0.50 % Mn, and less than 0.003% Cr





Effect of tempering temperature and time on the hardness of ferritic and pearlitic malleable irons in the as-received and reheated-and-quenched conditions





Iron	Material	Composition, % TC	Si	S	Mn	Mo	Alloying and prior heat treatment	Hardness, HB
1	Standard (ferritic) grade 32510	2.40	1.80	0.072	0.30	. . .	Unalloyed; fully malleablized	116
2	Pearlitic malleable iron, grade 45007	2.40	1.80	0.072	0.30	. . .	Unalloyed; air quenched from 925 °C (1700 °F), tempered 8 h at 695 °C (1280 °F)	156
3	Pearlitic malleable iron, grade 60003	2.40	1.80	0.072	0.30	. . .	Unalloyed; oil quenched from 870 °C (1600 °F), tempered 3 h at 650 °C (1200 °F)	212
4	Oil-quenched malleable iron	2.40	1.80	0.072	0.30	. . .	Unalloyed; oil quenched from 870 °C (1600 °F), not tempered	444
5	Pearlitic malleable iron, grade 45010	2.40	1.80	0.076	0.90	. . .	Alloyed (Mn); air quenched from 940 °C (1720 °F), tempered 34 h at 715 °C (1320 °F)	192
6	Pearlitic malleable iron, grade 80002	2.40	1.80	0.072	0.90	0.45	Alloyed (Mn and Mo); air quenched from 940 °C (1720 °F), tempered 12 h at 620 °C (1150 °F)	262
7	Air-quenched alloyed malleable iron	2.40	1.80	0.079	0.90	. . .	Alloyed (Mn); air quenched from 925 °C (1700 °F), not tempered	285
8	Air-quenched alloyed malleable iron	2.40	1.80	0.076	1.10	. . .	Alloyed (Mn); air quenched from 925 °C (1700 °F), not tempered	321
9	Oil-quenched alloyed malleable iron	2.40	1.80	0.079	0.90	. . .	Alloyed (Mn); oil quenched from 830 °C (1525 °F), not tempered	514
10	Oil-quenched alloyed malleable iron	2.40	1.80	0.076	1.10	. . .	Alloyed (Mn); oil quenched from 830 °C (1525 °F), not tempered	578
11	Air-quenched alloyed malleable iron	2.40	1.80	0.072	0.90	0.45	Alloyed (Mn and Mo); air quenched from 940 °C (1720 °F), not tempered	514

Heat Treating P/M Tool Steels

Chemical Compositions

Commercial compositions of high speed tool steels, cold work die steels, and hot work die steels are presented in an accompanying table.

Characteristics

Powder metallurgy versions of high speed steel tools have significantly better toughness and grindability than their conventionally produced counterparts.

Highly resulfurized grades offer improved machinability.

Other grades difficult to produce conventionally are readily made with the P/M process.

Still other grades (superhigh speed steels such as CPM Rex 20) are available only as P/M grades.

A distinguishing feature of P/M tool steels is the uniform distribution and small size of primary carbides. The same is true of sulfide inclusions in resulfurized grades. Microstructures of P/M and conventionally produced high speed steel are compared in an accompanying figure.

Heat Treating P/M Tool Steels

Proper heat treatment of tool steels is essential for developing their properties. This is especially true of high-speed and high-alloy materials. Improper heat treatment of these steels can result in a tool with greatly reduced properties or even one that is unusable. Powder metallurgy tool steels utilize the same basic heat treatments as their conventional counterparts, but they tend to respond more rapidly and with better predictability to heat treatment because of their more uniform microstructure and finer carbide size. The basic heat treatments used include preheating, austenitizing, quenching, and tempering. However, optimum heat-treating temperatures may vary somewhat, even if chemical compositions are identical.

The following procedures are specific to ASP high-speed tool steels, but are generally applicable to all P/M high-speed tool steels. Deviations from these practices may be needed for some specific alloys and applications; in such cases, the recommendations by the manufacturer should be followed. The basic heat treatment steps are:

- *Annealing:* Heat to 850 to 900 °C (1560 to 1650 °F). Slow cool to 700 °C (1290 °F) at 10 °C (20 °F) per h. Typical annealed hardness values for ASP 23 are approximately 26 HRC max, 32 HRC for ASP 30, and 36 HRC for ASP 60
- *Stress relieving (before hardening):* Hold for approximately 2 h at 600 to 700 °C (1110 to 1290 °F). Slow cool to 500 °C (930 °F) in furnace
- *Hardening:* Preheat in two steps, first at 450 to 500 °C (840 to 930 °F) and then at 850 to 900 °C (1560 to 1650 °F). Austenitize at 1050 to 1180 °C (1920 to 2155 °F) and quench, preferably in neutral salt baths. Cool to hand warmth
- *Tempering:* Raise temperature to 560 °C (1040 °F) or higher. Repeat two or three times for at least 1 h at full temperature. Cool to room temperature between tempers

The hardnesses of three P/M high-speed tool steels after hardening and tempering are shown in an adjoining Figure.

Three types of distortion are experienced metallurgically during heat treatment:

- Normal volume change due to phase transformations in the steel
- Variations in volume change in different parts of the tool due to the segregation in the steel
- Distortion due to residual stress caused by machining or nonuniform heating and cooling during heat treatment

Powder metallurgy grades, however, differ significantly from conventionally manufactured high-speed tool steels. Dimensional changes are more uniform in all directions. Because P/M high-speed tool steels are segregation free, variations in dimensional change are smaller. Therefore, the dimensional change that occurs during hardening can be predicted more accurately. Conventionally processed high-speed tool steels go out-of-round in a four-cornered pattern. The extent of distortion during heat treatment depends on the type and degree of segregation. In P/M high-speed tool steels, anisotropy is smaller, and out-of-roundness occurs in a close, circular pattern.

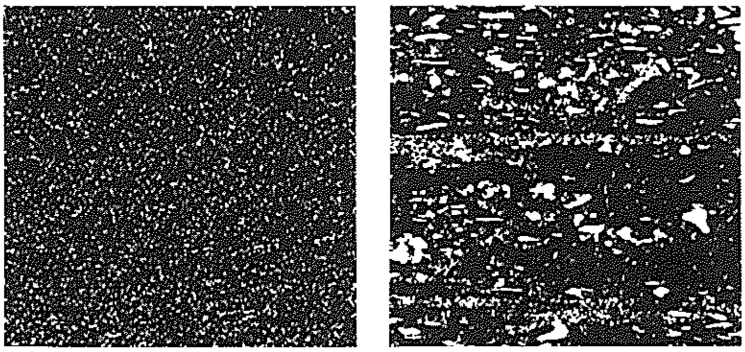
REFERENCE

1. K.E. Pinnow, W. Stasko, P/M Tool Steels, Vol 1, *ASM Handbook*

Commercial P/M Tool Steel Compositions

Trade name	AISI designation	Constituent elements, %								Hardness, HRC
		C	Cr	W	Mo	V	Co	S	Other	
High-speed tool steels(a)										
ASP 23	M3	1.28	4.20	6.40	5.00	3.10	...	...	...	65-67
ASP 30	...	1.28	4.20	6.40	5.00	3.10	8.5	...	...	66-68
ASP 60	...	2.30	4.00	6.50	7.00	6.50	10.50	...	...	67-69
CPM Rex M2HCHS	M2	1.00	4.15	6.40	5.00	2.00	...	0.27	...	64-66
CPM Rex M3HCHS	M3	1.30	4.00	6.25	5.00	3.00	...	0.27	...	65-67
CPM Rex M4	M4	1.35	4.25	5.75	4.50	4.00	...	0.06	...	64-66
CPM Rex M4HS	M4	1.35	4.25	5.75	4.50	4.00	...	0.22	...	64-66
CPM Rex M35HCHS	M35	1.00	4.15	6.00	5.00	2.00	5.0	0.27	...	65-67
CPM Rex M42	M42	1.10	3.75	1.50	9.50	1.15	8.0	...	...	66-68
CPM Rex 45	...	1.30	4.00	6.25	5.00	3.00	8.25	0.03	...	66-68
CPM Rex 45HS	...	1.30	4.00	6.25	5.00	3.00	8.25	0.22	...	66-68
CPM Rex 20	M62	1.30	3.75	6.25	10.50	2.00	...	...	...	66-68
CPM Rex 25	M61	1.80	4.00	12.50	6.50	5.00	...	...	...	67-69
CPM Rex T15	T15	1.55	4.00	12.25	...	5.00	5.0	0.06	...	65-67
CPM Rex T15HS	T15	1.55	4.00	12.25	...	5.00	5.0	0.22	...	65-67
CPM Rex 76	M48	1.50	3.75	10.0	5.25	3.10	9.00	0.06	...	67-69
CPM Rex 76HS	M48	1.50	3.75	10.0	5.25	3.10	9.00	0.22	...	67-69
HAP 10	...	1.35	5.0	3.0	6.0	3.8	...	...	...	64-66
HAP 40	...	1.30	4.0	6.0	5.0	3.0	8.0	...	...	...
HAP 50	...	1.50	4.0	8.0	6.0	4.0	8.0	...	...	...
HAP 60	...	2.00	4.0	10.0	4.0	7.0	12.0	...	...	...
HAP 70	...	2.00	4.0	12.0	10.0	4.5	12.0	...	...	...
KHA 33N	...	0.95	4.0	6.0	6.0	3.5	...	...	0.60N	65-66
Cold-work tool steels										
CPM 9V	...	1.78	5.25	...	1.30	9.00	...	0.03	...	53-55
CPM 10V	All	2.45	5.25	...	1.30	9.75	...	0.07	...	60-62
CPM 440V	...	2.15	17.50	...	0.50	5.75	...	...	...	57-59
Vanadis 4	...	1.50	8.00	...	1.50	4.00	...	...	...	59-63
Hot-work tool steels										
CPM H13	H13	0.40	5.00	...	1.30	1.05	...	...	...	42-48
CPM H19	H19	0.40	4.25	4.25	0.40	2.10	4.25	...	...	44-52
CPM H19V	...	0.80	4.25	4.25	0.40	4.00	4.25	...	...	44-56

(a) HCHS, high carbon, high sulfur; HS, high sulfur



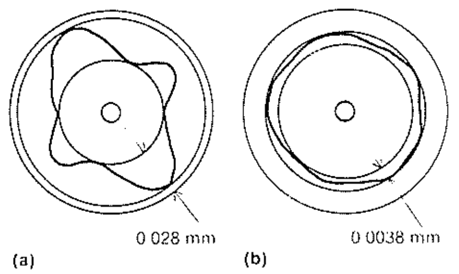
Microstructures. Microstructures of high-speed tool steels. Left: CPM T15. Right: Conventional T15. Carbide segregation and its detrimental effects are eliminated with the CPM process, regardless of the size of the products. Source: Crucible Materials Corporation

Austenitizing Temperatures of ASP 23 Steel

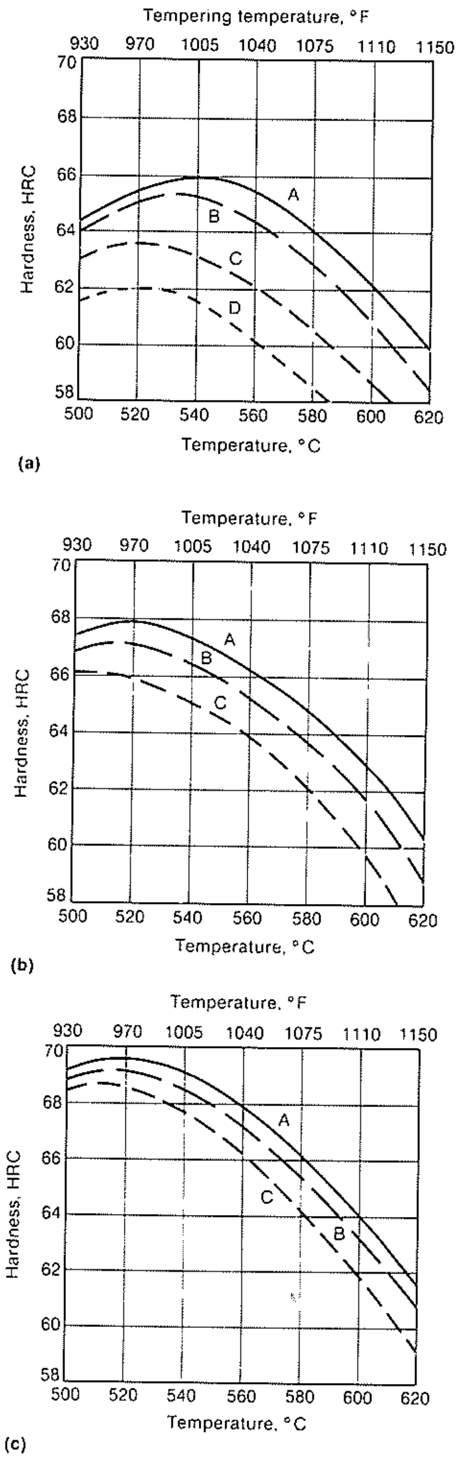
Hardness, HRC(a)	Temperature °C	Temperature °F	Salt bath(b) min/mm	Salt bath(b) min/in.	Other furnace, min(c)
58	1000	1830	0.59	15	30
60	1050	1925	0.47	12	25
62	1100	2010	0.39	10	20
64	1140	2085	0.31	8	15
66	1180	2155	0.24	6	10

(a) After triple temper at 560 °C (1040 °F); hardness values may vary by ±1%. (b) Total immersion time after preheating. (c) Holding time in minutes after tool has reached full temperature

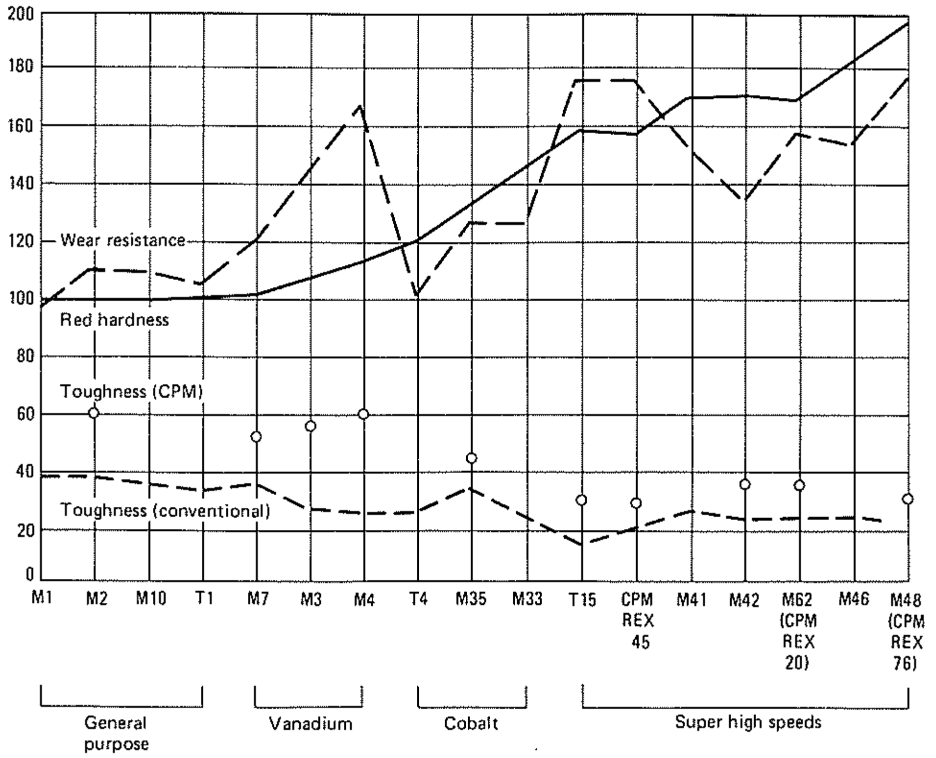
Out-of-roundness measurements on test disks after hardening and tempering. Test disks machined from 102 mm (4 in.) diam bars. (a) AISI M2. (b) ASP 30



Hardness of ASP steels after hardening and tempering a 25 mm (1 in.) diam specimen three times for 1 h. (a) ASP 23. (b) ASP 30. (c) ASP 60, cooled in salt bath. Hardening temperatures for the curves are: A, 1180 °C (2155 °F); B, 1150 °C (2100 °F); C, 1100 °C (2010 °F); D, 1050 °C (1920 °F)



Relative wear resistance, red (hot) hardness, and toughness of CPM and conventional high-speed tool steels. Source: Crucible Materials Corporation



Heat Treating P/M Stainless Steel

Chemical Compositions

Properties and compositions of compacting grade, stainless steel powders are shown in a accompanying table.

Characteristics of P/M Stainless

Compositions are held to tighter tolerances than those for AISI grade wrought stainless steels. Low carbon and high nickel content in austenitic grades of powder contribute to good compressibility. Austenitics are the most widely used grades, accounting for about one-third of total usage.

Alloyed powders are characterized by their irregular shape (see Figure).

In comparison with low alloy, ferrous powders, stainless steel powders require higher compacting pressures in partsmaking, and their strength before sintering (green strength) is lower—about half that of P/M iron.

In commercial practice, compacting pressures range from 550 to 830 MPa (40 to 60 tsi).

Lubricants used in compacting powders, such as stearic acid, increase green strength to some extent, and generally lower the compactability of powders.

Powders are formed into parts (also called preforms at this stage) in dies. Carbide dies are used because highly alloyed powders are inherently harder than pure metals such as iron or copper.

Sintering of Stainless Powders

This is the most critical step in processing. During sintering, lubricants nust be removed from parts and powder particles must be bonded together, o give parts the density and associated mechanical properties required in a given application.

Average sintering temperatures range from 1120 to 1150 °C (2050 to 2100 °F). Temperatures are increased up to 1315 °C (2400 °F) and higher when improvements in mechanical properties and corrosion resistance are needed.

Equipment: up to operating temperatures of approximately 1150 °C 2100 °F) continuous, mesh belt furnaces do the job. At higher temperaures, manual, automatic pusher, walking beam, or vacuum furnaces are ised.

Atmospheres used are dissociated ammonia, nitrogen-based atmoseheres, and hydrogen. Vacuum furnaces are an alternative.

Sintering Process

Green compacts usually are presintered in air or nitrogen at 425 to 540 C (795 to 1000 °F) to volatilize and burn off pressing lubricant. If emperatures are higher, a protective atmosphere is required. Lubricant iust be removed, because it can cause carburization of the alloy in sinterig; carburization reduces the machinability and corrosion resistance of ustenitic alloys.

Martensitic alloys that contain carbon must be presintered in nitrogen.

Sintering atmospheres

Dissociated ammonia is the most widely used. A dew point of –45 to –50 C (–50 to –60 °F) is required to prevent oxidation.

However, dissociated ammonia is getting competition from nitrogenised atmospheres that contain as little as 3% hydrogen, because of the sing price of dissociated ammonia, which contains 75% hydrogen.

Hydrogen is seldom used commercially because of its high cost.

Use of vacuum is the principal alternative to both dissociated ammonia and nitrogen-based atmospheres. The process is described as partial pressure sintering. Conventional, cold wall vacuum furnaces are used.

In vacuum furnace practice, chromium evaporates if furnace pressure falls below the elemental vapor pressure, and resistance to corrosion is significantly reduced. Chromium content can be virtually depleted in a typical vacuum sintering cycle if the vacuum level is not properly controlled.

Control is provided by backfilling the furnace with a suitable gas to a partial pressure above the vapor pressure of any of the elements in the alloy. A gas pressure of 27 to 67 Pa (200 to 500 Hg) is typical for sintering at 1315 °C (2400 °F).

With argon as the backfill gas, mechanical properties are similar to those obtained when hydrogen is used. With nitrogen, sintered properties are similar to those obtained with dissociated ammonia.

Sintering Cycles

Tensile strength increases with sintering temperature and time, but yield strength drops. After surface oxides are reduced in the initial stage of sintering, powder particles bond together by solid state diffusion.

A high degree of dimensional change (shrinkage) takes place when sintering is at higher temperatures, especially in hydrogen. Longer sintering times increase all tensile properties and shrinkage as well.

Cooling Rates. Regardless of the sintering atmosphere, cooling rate has a profound effect on the properties of sintered austenitic stainless. Typically used rates of cooling provide the best combination of strength and ductility; and when dissociated ammonia is used, nitrogen is also present.

With extremely slow cooling, precipitation occurs preferentially at grain boundaries. The result is a noticeable increase in strength and loss in ductility, even when precipitation is minimal.

Carbide precipitation is detrimental to machinability. Precipitation at grain boundaries is reduced when cooling rates are normal. The result here is lower strength but higher ductility. Rapid cooling, i.e., water quenching, suppresses the precipitation of carbides and nitrides, which produces maximum ductility.

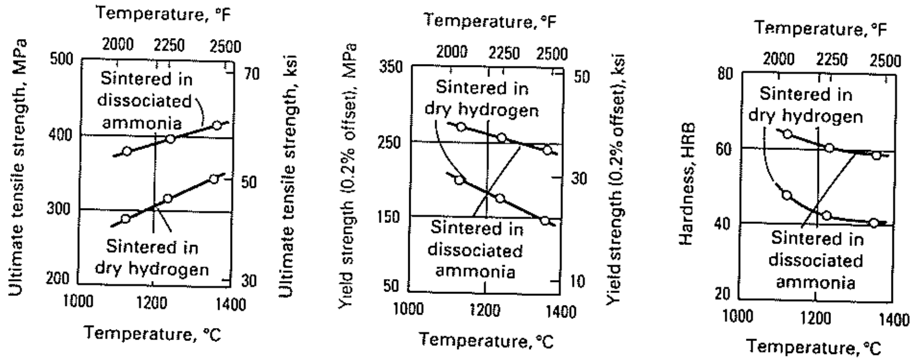
The cooling rate effect in vacuum sintering is largely controlled by the atmosphere in which parts are cooled. With a nitrogen backfill, properties are similar to those obtained by sintering in dissociated ammonia. With argon, properties are similar to those obtained with hydrogen.

Control of Carbon Content. Austenitic grades are made with less than 0.03% carbon. Maintaining this level after sintering, meaning no carbon pickup, ensures maximum corrosion resistance, weldability, and machinability.

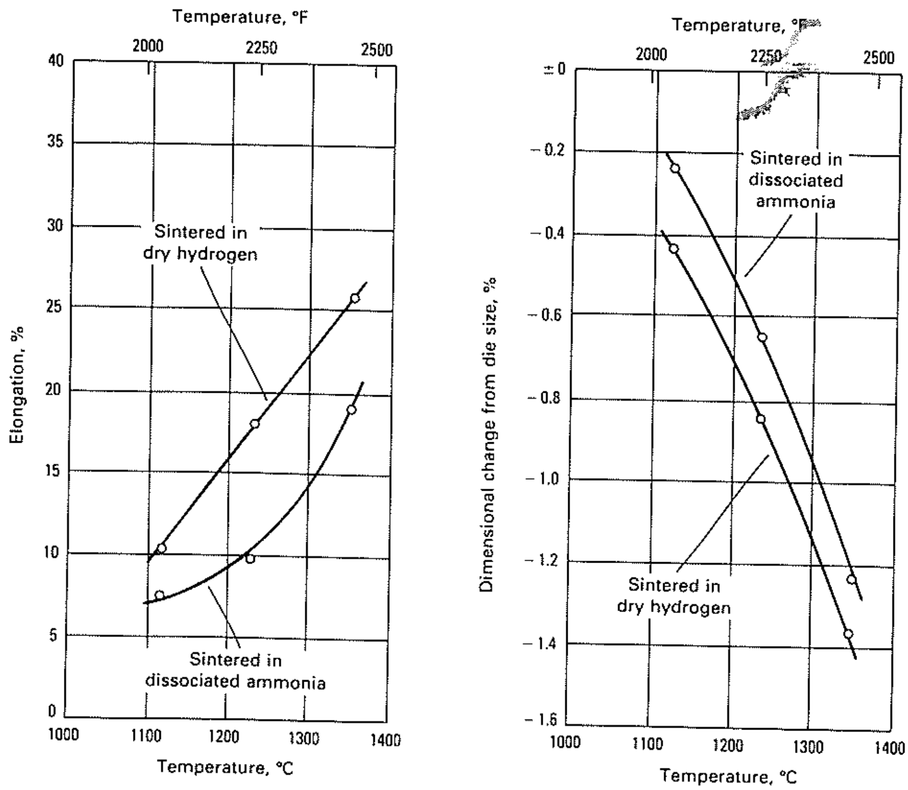
REFERENCE

1. R.W. Stevenson, P/M Stainless Steel, Vol 7, *ASM Handbook*

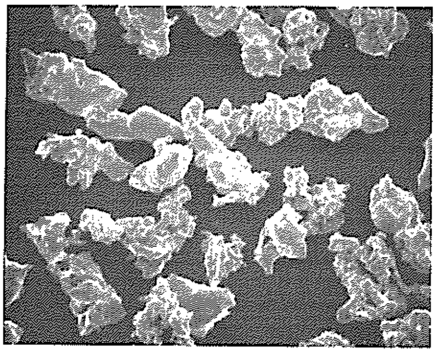
Effect of Sintering Temperature of Tensile and Yield Strengths and Apparent Hardness of Type 316L Stainless Steel. Pressed to 6.85 g/cm³ and sintered for 30 min in various atmospheres



Effect of Sintering Temperature on Elongation and Dimensional Change During Sintering of Type 316L Stainless Steel. Pressed to 6.85 g/cm³ and sintered for 30 min in various atmospheres



Microstructure. Scanning electron micrograph of water-atomized type 304L stainless steel (−100 mesh). Magnification: 150×



Influence of Sintering Atmosphere on Mechanical Properties of Type 316L Pressed to 6.85 g/cm^3

Property	Sintered in dissociated ammonia	Sintered in hydrogen
Ultimate tensile strength, MPa (psi)	365.4 (53 000)	288.2 (41 800 psi)
Yield strength, MPa (psi)	274.4 (39 800)	183.4 (26 600 psi)
Elongation in 25 mm (1 in.), %	7.0	10.9
Apparent hardness, HRB	67	47

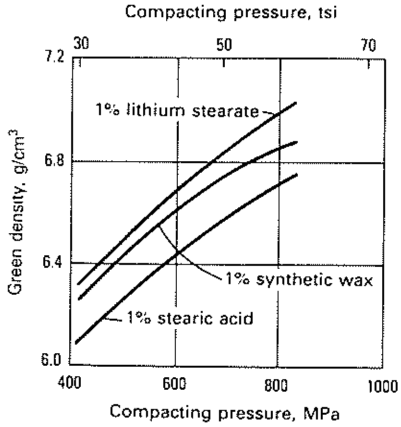
Note: Compacts sintered for 30 min at 1120 °C (2050 °F)

Compositions and Properties of Stainless Steel Compacting-Grade Powders

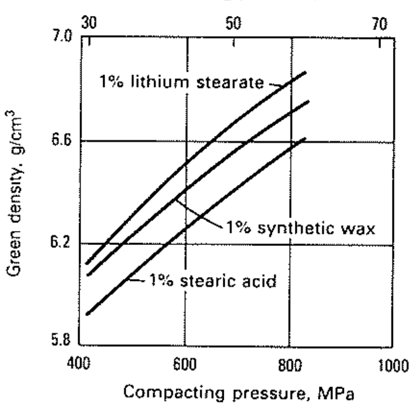
	303L(a)	304L	316L	830(b)	410L	434L
Chemical analysis, %						
Chromium	17.5	18.5	16.5	20.5	12.0	17.0
Nickel	12.5	11.5	13.5	30.0	...	...
Molybdenum	...	...	2.1	2.5	...	1.0
Manganese	0.2	0.2	0.2	0.2	0.5	0.2
Silicon	0.7	0.8	0.7	1.0	0.8	0.8
Carbon	0.02	0.02	0.02 (max)	0.02	0.02	0.02
Iron	rem	rem	rem	rem	rem	rem
Physical properties						
Apparent density, g/cm^3	3.1	2.7	2.7	2.8	2.9	2.8
Flow rate, s/50 g	26	30	30	30	28	29
Screen analysis, %						
+100 mesh	1	1	1	1	1	1
−100 + 150 mesh	7	12	11	9	14	11
−150 + 200 mesh	13	20	18	14	20	17
−200 + 325 mesh	24	25	26	27	26	27
−325 mesh	55	42	44	49	39	44

Note: Type 830 is used for the manufacture of P/M parts where superior corrosion resistance is of primary consideration. Parts made from type 830 exhibit improved resistance to oxidizing media and sulfuric acid. This grade is not recommended for conditions involving unstable chlorides. (a) 0.2% sulfur added for machinability. (b) 3.5% copper also present

Compactibility of Stainless Steel Powders. (a) Type 316L austenitic stainless steel. (b) Type 410L martensitic stainless steel

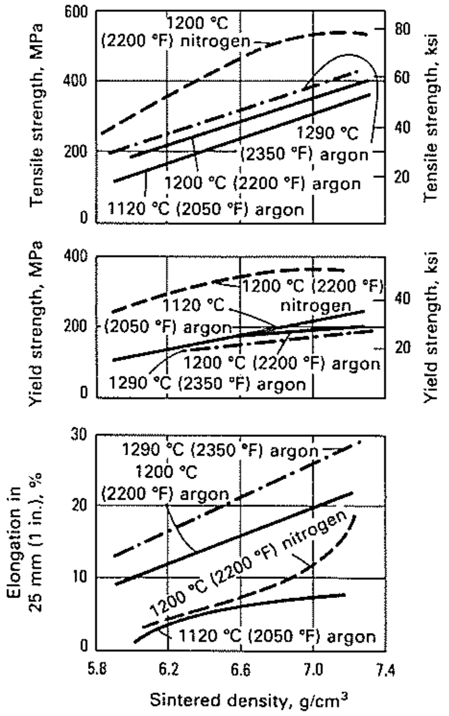


(a)

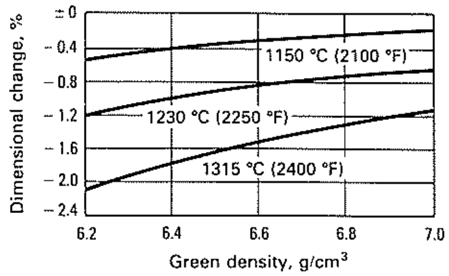


(b)

Tensile Properties of Standard Type 316L Stainless Steel Metal Powder Industries Federation Tensile Bars. Bars sintered in vacuum for 2 h using argon and nitrogen as backfilling gases. A partial pressure of 400 μm mercury was used to prevent vaporization of chromium



Dimensional Changes for Type 304L Stainless Steel. Dimensional changes were determined on transverse-rupture bars sintered for 45 min in −40 °C (−40 °F) dew point dissociated ammonia and were calculated from die size



Properties of Sintered Type 410L Stainless Steel

Processing treatment	Graphite added, %	Sintering atmosphere(a)	Tempering temperature °C	Tempering temperature °F	Tensile strength MPa	Tensile strength ksi	Apparent hardness, HRB
As sintered and cooled in water-jacketed zone of furnace	0	Dissociated ammonia	...	...	724	105	102
	0.10	Dissociated ammonia	205	400	683	99	103
	0	Hydrogen	...	...	393	57	68
	0.10	Hydrogen	175	350	710	103	95
Reheated in dissociated ammonia and oil quenched from 950 °C (1750 °F)	0	Dissociated ammonia	205	400	627	91	106
	0.10	Dissociated ammonia	220	430	703	102	102
	0	Hydrogen	...	...	752	109	106
	0.10	Hydrogen	220	430	717	104	105
Reheated in hydrogen and oil quenched from 950 °C (1750 °F)	0	Dissociated ammonia	205	400	731	106	104
	0.10	Dissociated ammonia	205	400	745	108	104
	0	Hydrogen	205	400	641	93	95
	0.10	Hydrogen	220	430	800	116	101

(a) Sintered for 30 min at 1120 °C (2050 °F)

Heat Treating of P/M Steel Parts

Chemical compositions

Tables accompanying this text provide compositions and applications of a variety of ferrous P/M materials, typical mechanical properties, and other practical information such as the green density of different iron powders and typical mechanical properties of forged P/M alloys.

Characteristics of P/M Parts

With some exceptions these materials are treated in much the same manner as their cast or forged counterparts. Exceptions stem primarily from the inherent porosity of P/M parts. Examples include:

- Depth of hardening depends largely on porosity and alloy content. The latter must be determined precisely, because of its effect on the heat treating process. Additions of chromium and molybdenum, for instance, increase hardenability
- Response to hardening also depends on combined carbon content, not necessarily total carbon, and the amount of carbon that dissolves in the austenite. Sintering time and temperature are also important. If too little combined carbon (excessive graphite) is present, the condition can be compensated for by using higher austenitizing temperatures to dissolve most or all of the graphite. A caveat: too much cementite can be formed, making parts excessively brittle after heat treatment
- Problems are encountered in testing for hardness because of the presence of porosity and free graphite. Indentation readings indicate lower than actual hardness values. One reason is that free graphite does not indicate hardness when measured by the indentation method. Porosity is the primary cause of error. As porosity is reduced, differences between indicated and actual hardness become smaller.

Recommended practice is to:

- Evaluate hardness of heat treated samples with microhardness testing
- Follow up with a suitable indentation method, such as Rockwell A, to establish an acceptable range of observed hardness
- After doing the above, conventional hardness testing may be used as a quality control tool, but continued monitoring with microhardness testing is advised

Forging P/M Steel Parts

Properties are upgraded significantly by reducing porosity with forging and repressing processes. Both are discussed later in this article.

Recommended Heat Treating Practices

Austenitizing Process

Generally, P/M compacts are less homogeneous than their rolled or forged counterparts. To get complete austenitization, higher temperatures or longer times at temperature are required. The following austenitizing temperatures are recommended:

Combined C %	Temperature °C	Temperature °F
0.25	915	1680
0.35	900	1650
0.45	885	1625
0.55	870	1600
0.65	860	1580

Times usually run about 50% longer than those for treating wrought parts. When alloying elements are present, both temperature and time are slightly higher.

A variety of batch and continuous type furnaces are used in austenitizing.

Austenitizing atmospheres. In through hardening, parts normally are heated in a gaseous atmosphere, such as that provided by an endothermic generator. Any nitrogen-based atmosphere may be used, as long as its carbon potential is controlled to match the carbon content of the workpiece. Vacuum atmospheres are also used.

Heating in molten salt is not recommended, even when parts have maximum density. Parts are difficult to wash after heating in molten salt, and any salts left in pores cause immediate corrosion.

Quenching austenitized parts. Parts have a greater tendency toward cracking than their wrought counterparts.

Aqueous quenchants are used, but oil is preferred because it provides a less drastic quench. Fast oils expedite quenching to maximum hardness. Aqueous quenchants (water and brine, water and caustic, plain water, and polymer quenchants) are used to obtain full hardness in quenching plain carbon steel parts with sections greater than approximately 5 mm (0.2 in.). In using these quenchants, however, parts can crack, and aqueous media can cause corrosion.

Parts with thicker sections should contain sufficient amounts of alloying elements, such as nickel, manganese, and/or chromium.

Tempering P/M Parts

All austenitized and quenched parts should be tempered immediately after quenching.

In tempering, forced air, convection-type furnaces are preferred. Use of salt or molten metal is not recommended.

Tempering temperatures should be at least 150 °C (300 °F). Higher temperatures may be used, but loss of some hardness is a tradeoff.

Steam Treating Process

This process is frequently used in conjunction with tempering as a protective atmosphere at temperatures up to approximately 540 °C (1000 °F). Serendipitous benefits are byproducts: an oxide coating (usually bluish) is developed on surfaces, which serves as a finish that improves resistance to wear and corrosion, and improves appearance as well.

Still another benefit is realized: in the treatment, ferrous-ferritic oxide forms in pores and tends to close them. Entry of contaminants into pores is minimized or eliminated, and resistance to hydraulic pressures is improved.

Little adjunct equipment is needed to convert a forced air, tempering furnace for steam treating.

Recommended Processing Sequence for Steam Treating

- Load degreased parts in a cold or nearly cold furnace in baskets, making sure parts are separated
- After closing furnace, set it at 370 °C (700 °F)
- Introduce steam at full pressure when furnace temperature reaches 345 °C (655 °F)
- Purge furnace chamber with steam for 15 min when temperature reaches 370 °C (700 °F)
- Adjust and maintain furnace pressure at a slightly positive pressure for an additional 15 min
- Heat load to 540 °C (1000 °F) and hold 1.5 h with steam on
- Cool charge to 290 °C (555 °F)
- Remove parts from furnace after steam is turned off
- When parts cool to 290 °C (555 °F) they can be quenched in mineral oil to improve appearance and resistance to corrosion

Case Hardening

A clear case-core relationship can be obtained only when parts have a density of at least 7.2 g/cm^3. Various case hardening methods are used, but success with a given process tends to depend on the application. Processes discussed here are gas and pack carburizing, carbonitriding, nitrocarburizing, and gas nitriding.

Carburizing

Parts with combined carbon content around 0.10 to 0.20% and free of graphite can be carburized by the conventional gas or pack methods.

Liquid carburizing is not recommended—it is difficult to remove salt from pores by washing.

Pack carburizing is not economical in large volume production of small parts, and the method is seldom used.

Gas carburizing is the more practical, though seldom used, process. Part density and composition are the important considerations.

Porosity in low density parts poses a problem: carburizing gases penetrate pores, and it is not possible to get a distinct case. Carbon penetration may be so deep that thin sections of parts may be brittle.

In addition, conventional gas carburizing does not increase hardenability, meaning that plain carbon steels must be quenched in an aqueous medium, and cracking is possible, especially if carbon penetration is excessive.

Case depth depends on time and temperature. Results that can be expected with high density parts are comparable to those in carburizing wrought parts.

Carbonitriding Process

This process does not present the diffusion problem in carburizing that is associated with porosity. In carbonitriding at 790 to 845 °C (1455 to 1555 °F) the problem is avoided. Lower rates of diffusion allow closer control of case depth and adequate buildup of carbon in the case. File hard cases with a microhardness equal to 60 HRC and a predominately martensitic structure are consistently obtained. Typical case depths range from 0.08 to 0.30 mm (0.003 to 0.12 in.). Case depths of copper-infiltrated parts approach those of wrought parts.

Typically, the process, in comparison with gas carburizing, is carried out at a lower temperature, i.e., 55 °C (130 °F) lower and a shorter time, i.e., a half hour or more. Nitrogen diffuses into steel surfaces simultaneously with the carbon.

Applications. Carbonitriding is widely used in case hardening parts made of ferrous powders. Sintered densities vary from approximately 6.5 g/cm^3 up to approximately 7.9 g/cm^3. Parts may be infiltrated with copper prior to carbonitriding. The process is extremely effective in case hardening to densities of 7.2 g/cm^3, and is reasonably effective in treating parts with lower densities.

Equipment. Batch-type, shaker hearth, and belt-type continuous are well-suited to the process. A typical furnace is shown in an accompanying figure.

Process. The processing cycle, including gas composition, is critical. Ammonia content, usually 10%, increases hardenability and affects dimensional stability, often a critical economic consideration in evaluating the feasibility of making parts with the P/M process. Of equal importance are control of temperature and the quenching medium selected.

Tempering. Generally, temperatures are higher than those used in tempering similar wrought parts. If temperatures above 205 °C (400 °F) are required, parts should be cleaned with ultrasonic degreasing. Pores containing oil can pose a fire hazard, but at temperatures normally used, oil is removed in the tempering process.

Hardness testing. Because cases are very thin, hardness can't be determined with common indentation methods. File testing is the primary method for routine evaluation. Microhardness is used to determine actual hardness.

Nitrocarburizing Process

Salt bath and gaseous ferritic processes are available. The former, however, is not well suited to the P/M process.

The gaseous process is a nitrogen and carbon system, like the carbonitriding process. The difference is that in gaseous nitrocarburizing, temperatures are completely within the ferritic phase field. Carbonitriding is in the austenitic range. The temperature in nitrocarburizing is typically approximately 570 °C (1060 °F), which is slightly under that for carbonitriding.

The primary objective in gaseous nitrocarburizing is to produce a thin layer of iron carbonitride and nitrides (the white layer, or compound zone), and an underlying diffusion zone containing dissolved nitrogen and iron (or alloy) nitrides.

White layer provides resistance to galling, corrosion, and wear. The diffusion zone significantly improves fatigue properties of carbon and low alloy P/M parts.

Process. Typically, sealed quench batch furnaces are used, and are of the same design as those for gas carburizing and carbonitriding. Furnace operating temperatures are low enough to maintain workpieces in the ferritic condition.

Atmosphere composition can vary with the process. For example, in one process equal amounts of ammonia and endothermic gas are used, while in another, the atmosphere consists of 35% ammonia and 65% refined exothermic gas (AGA Type 301), which is nominally 97% nitrogen, and may be enriched by a hydrocarbon gas such as methane or propane.

Time cycles usually range from 1 to 5 h, but cycles of no more than 1 h usually are recommended because deep penetration (into pores) can cause excessive embrittlement.

Quenching. Optimum results are obtained with oil quenching from the processing temperature.

Final word: because cases are extremely thin, usage of the process should be confined to finished parts. No stock is removed after nitrocarburizing.

Gas Nitriding

Applications of this process are extremely limited for several reasons:

- As in gas carburizing, cycles are long and nitriding gas penetrates deeply into pores. The condition is difficult to control, and often results in excessive embrittlement
- Carbon content should be maintained within 0.30 to 0.50%
- Alloying elements that form hard, stable nitrides must be present. Both chromium and aluminum promote nitride formation

Process. For optimum results, treatment should be initiated by austenitizing, quenching, and tempering parts. Success requires a microstructure of tempered martensite. Next, parts must be finished or thoroughly cleaned to produce the surface required for nitriding.

Annealing Process

This process is used to improve the machinability of forged P/M parts. Otherwise, its application is limited.

Generally, forged parts are treated at temperatures appropriate for their combined carbon content, followed by cooling as rapidly as possible to approximately 705 °C (1300 °F) for 1/2 to 2 h.

Optimum austenitizing temperatures for annealing plain carbon-iron compacts depend on combined carbon contents as follows:

Combined C %	Temperature °C	Temperature °F
).20	900	1650
).30	885	1625
).40	870	1600
).50	860	1580

Repressing Sintered Parts

Repressing at room temperature has a number of advantages:

- Density and hardness are increased
- Mechanical and physical properties are improved
- Parts are held close to final dimensions—the amount of material deformation is greater than that possible with sizing because forces are greater

Forging P/M Parts

Unsintered, presintered, and sintered parts are forged (or hot formed). The concept: a porous preform is densified by hot forging with a single blow in a heated, totally enclosed die. Virtually no flash is produced.

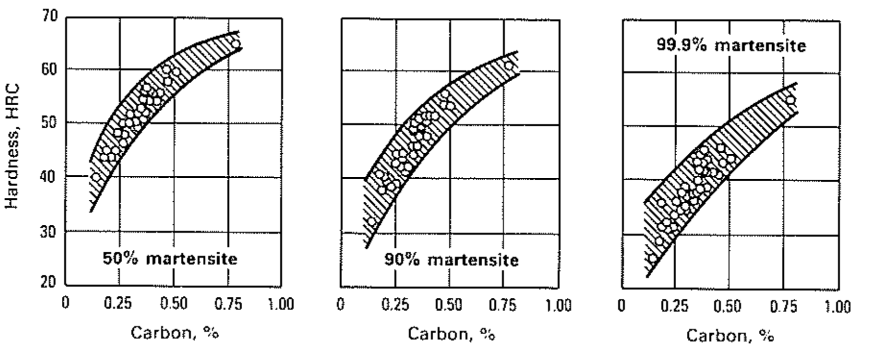
Sintered preforms can be forged directly from the sintering furnace; or stabilized at lower temperatures and forged; or cooled to room temperature, reheated, and forged.

Heat treating practices are the same as those for conventionally processed materials similar in composition. Common heat treat treatments include carburizing and quenching and tempering.

REFERENCES

1. H.E. Boyer, Secondary Operations on P/M Parts and Products, Vol 7, *ASM Handbook*
2. L.F. Pease III, Mechanical Properties of P/M Materials, Vol 7, *ASM Handbook*; Ferrous Powder Metallurgy Materials, Vol 1, *ASM Handbook*
3. ASM Metals Reference Book, Third Edition, ASM International

Relation of Carbon Content and Percentage Martensite to Rockwell C Hardness



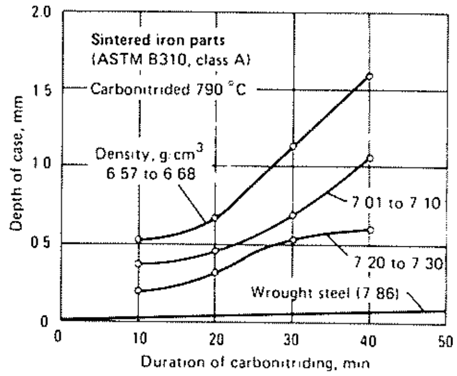
/alues of Case Depth Calculated by the Harris Equation

'ime (t), h	870 °C (1600 °F) mm	870 °C (1600 °F) in.	900 °C (1650 °F) mm	900 °C (1650 °F) in.	925 °C (1700 °F) mm	925 °C (1700 °F) in.
	0.64	0.025	0.76	0.030	0.89	0.035
	0.89	0.035	1.07	0.042	1.27	0.050
	1.27	0.050	1.52	0.060	1.80	0.071
2	1.55	0.061	1.85	0.073	2.21	0.087
6	1.80	0.071	2.13	0.084	2.54	0.100
0	2.01	0.079	2.39	0.094	2.84	0.112
4	2.18	0.086	2.62	0.103	3.10	0.122
0	2.46	0.097	2.95	0.116	3.48	0.137
5	2.74	0.108	3.20	0.126	3.81	0.150

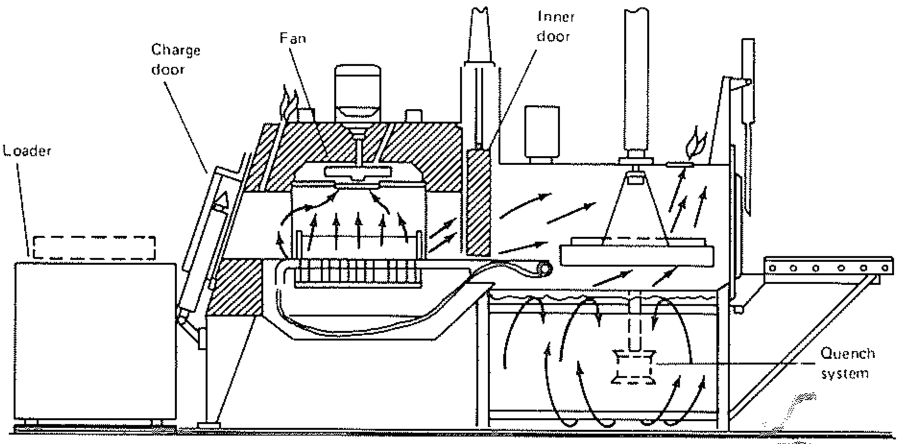
Case depth(a), after carburizing at the temperatures shown.

ı) Case depth: mm = $0.635\sqrt{t}$ (case depth: in. = $0.025\sqrt{t}$) for 925 °C (1700 °F); $0.533\sqrt{t}$ ($0.021\sqrt{t}$) for 900 °C (1650 °F); $0.457\sqrt{t}$ ($0.018\sqrt{t}$) for 870 °C (1600 °F). For normal ɪrburizing (saturated austenite at the steel surface while at temperature)

Case Depth vs Time for Carbonitriding P/M Parts



Typical Furnace for Gaseous Nitrocarburizing



ypical Compositions of Ferrous P/M Structural Materials

laterial	Designation(a) MPIF	ASTM	SAE	MPIF composition limits and ranges(b), % C	Ni	Cu	Fe
/M iron	F-0000	B 310, class A	853, class 1	0.3 max	...	...	97.7-100
/M steel	F-0005	B 310, class B	853, class 2	0.3-0.6	...	...	97.4-99.7
	F-0008	B 310, class C	853, class 3	0.6-1.0	...	...	97.0-99.1
/M copper iron	FC-0200	...	...	0.3 max	...	1.5-3.9	93.8-98.5
/M copper steel	FC-0205	...	...	0.3-0.6	...	1.5-3.9	93.5-98.2
	FC-0208	B 426, grade 1	864, grade 1, class 3	0.6-1.0	...	1.5-3.9	93.1-97.9
	FC-0505	...	...	0.3-0.6	...	4.0-6.0	91.4-95.7
	FC-0508	B 426, grade 2	864, grade 2, class 3	0.6-1.0	...	4.0-6.0	91.0-95.4
	FC-0808	B 426, grade 3	864, grade 3, class 3	0.6-1.0	...	6.0-11.0	86.0-93.4
	...	B 426, grade 4	864, grade 4, class 3	0.6-0.9	...	18.0-22.0	75.1 min
/M iron-copper	FC-1000	B 222; B 439, grade 3	862	0.3 max	...	9.5-10.5	87.2-90.5
/M iron-nickel	FN-0200	B 484, grade 1, class A	...	0.3 max	1.0-3.0	2.5 max	92.2-99.0
/M nickel steel	FN-0205	B 484, grade 1, class B	...	0.3-0.6	1.0-3.0	2.5 max	91.9-98.7
	FN-0208	B 484, grade 1, class C	...	0.6-0.9	1.0-3.0	2.5 max	91.6-98.4
/M iron-nickel	FN-0400	B 484, grade 2, class A	...	0.3 max	3.0-5.5	2.0 max	90.2-97.0
/M nickel steel	FN-0405	B 484, grade 2, class B	...	0.3-0.6	3.0-5.5	2.0 max	89.9-96.7
	FN-0408	B 484, grade 2, class C	...	0.6-0.9	3.0-5.5	2.0 max	89.6-96.4
/M iron-nickel	FN-0700	B 484, grade 3, class A	...	0.3 max	6.0-8.0	2.0 max	87.7-94.0
/M nickel steel	FN-0705	B 484, grade 3, class B	...	0.3-0.6	6.0-8.0	2.0 max	87.4-93.7
	FN-0708	B 484, grade 3, class C	...	0.6-0.9	6.0-8.0	2.0 max	87.1-93.4
/M infiltrated steel	FX-1005	...	...	0.3-0.6	...	8.0-14.9	80.5-91.7
	FX-1008	...	...	0.6-1.0	...	8.0-14.9	80.1-91.4
	FX-2000	B 303, class A	870	0.3 max	...	15.0-25.0	70.7-85.0
	FX-2005	B 303, class B	...	0.3-0.6	...	15.0-25.0	70.4-84.7
	FX-2008	B 303, class C	872	0.6-1.0	...	15.0-25.0	70.0-84.4

ı) Designations listed are nearest comparable designations; ranges and limits may vary slightly between comparable designations. (b) MPIF standards require that the total amount f all other elements be less than 2.0%, except that the total amount of other elements must be less than 4.0% in infiltrated steels

Typical Mechanical Properties of Ferrous P/M Materials

Designation	MPIF density suffix(a)	Condition(b)	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation in 25 mm (1 in.), %	Fatigue strength MPa	Fatigue strength ksi	Impact energy(c) J	Impact energy(c) ft · lb	Apparent hardness	Elastic modulus GPa	Elastic modulus 10^6 psi
F-0000	N	AS	110	16	75	11	2.0	40	6(d)	4.1	3.0	10 HRH	70	10.5
	P	AS	130	19	95	14	2.5	50	7(d)	6.1	4.5	70 HRH	90	13
	R	AS	165	24	110	16	5	60	9(d)	13	9.5	80 HRH	110	16
	S	AS	205	30	150	22	9	80	11(d)	20	15	15 HRB	130	19
	T	AS	275	40	180	26	15	105	15(d)	34	25	30 HRB	160	23
F-0005	N	AS	125	18	105	15	1.0	45	7(d)	3.4	2.5	5 HRB	70	10.5
	P	AS	170	25	140	20	1.5	65	10(d)	4.7	3.5	20 HRB	90	13
	R	AS	220	32	160	23	2.5	85	12(d)	6.8	5.0	45 HRB	110	16
		HT	415	60	395	57	0.5	155	23(d)	...	...	100 HRB	110	16
	S	AS	295	43	195	28	3.5	110	16(d)	12	9.0	60 HRB	130	19
		HT	550	80	515	75	0.5	210	30(d)	...	...	25 HRC	130	19
F-0008	N	AS	200	29	170	25	0.5	75	11(d)	2.7	2.0	35 HRB	70	10.5
		HT	290	42	...	...	<0.5	110	16(d)	...	...	90 HRB	70	10.5
	P	AS	240	35	205	30	1.0	90	13(d)	4.1	3.0	50 HRB	90	13
		HT	400	58	...	...	<0.5	150	22(d)	...	...	100 HRB	90	13
	R	AS	290	42	250	36	1.5	110	14(d)	4.7	3.5	65 HRB	110	16
		HT	510	74	...	...	<0.5	195	28(d)	...	...	25 HRC	110	16
	S	AS	395	57	275	40	2.5	150	22(d)	9.5	7.0	75 HRB	130	19
		HT	650	94	625	91	<0.5	245	36(d)	...	...	30 HRC	130	19
FC-0200	P	AS	160	23	115	17	2.5	60	9(d)	7.5	5.5	80 HRH	90	13
	R	AS	205	30	145	21	4	80	11(d)	9.5	7.0	15 HRB	110	16
	S	AS	255	37	160	23	7	95	14(d)	23	17	30 HRB	130	19
FC-0205	P	AS	275	40	235	34	1.0	105	15(d)	4.7	3.5	35 HRB	90	13
	R	AS	345	50	260	38	1.5	130	19(d)	7.5	5.5	60 HRB	110	16
		HT	585	85	560	81	<0.5	220	31(d)	...	...	30 HRC	110	16
	S	AS	425	62	310	45	3.0	160	24(d)	13	9.5	75 HRB	130	19
		HT	690	100	655	95	<0.5	260	38(d)	...	...	35 HRC	130	19
FC-0208	N	AS	225	33	205	30	<0.5	85	13(d)	3.4	2.5	45 HRB	70	10.5
		HT	295	43	...	...	<0.5	110	16(d)	...	...	95 HRB	70	10.5
	P	AS	310	45	280	41	<0.5	115	17(d)	4.1	3.0	50 HRB	90	13
		HT	380	55	...	...	<0.5	145	21(d)	...	...	25 HRC	90	13
	R	AS	415	60	330	48	1.0	155	23(d)	6.8	5.0	70 HRB	110	16
		HT	550	80	...	...	<0.5	210	30(d)	...	...	35 HRC	110	16
	S	AS	550	80	395	57	1.5	210	30(d)	11	8.0	80 HRB	130	19
		HT	690	100	655	95	<0.5	260	38(d)	...	...	40 HRC	130	19
FC-0505	N	AS	240	35	205	30	0.5	90	13(d)	4.1	3.0	50 HRB	70	10.5
	P	AS	345	50	290	42	1.0	130	19(d)	6.1	4.5	60 HRB	90	13
	R	AS	455	66	380	55	1.5	170	25(d)	6.8	5.0	75 HRB	116	16
FC-0508	N	AS	330	48	295	43	<0.5	125	18(d)	4.1	3.0	60 HRB	70	10.5
	P	AS	425	62	395	57	1.0	160	24(d)	4.7	3.5	65 HRB	90	13
		HT	480	70	480	70	<0.5	185	27(d)	...	...	30 HRC	90	13
	R	AS	515	75	480	70	1.0	195	29(d)	6.1	4.5	85 HRB	116	16
FC-0808	N	AS	250	36	...	...	<0.5	...	...	...	...	55 HRB	...	...
FC-1000	N	AS	205	30	...	...	0.5	...	...	...	...	70 HRF	...	...
FN-0200	R	AS	195	28	125	18	4	75	11	19	14	38 HRB	115	17
	S	AS	260	38	170	25	7	105	15	43	32	42 HRB	145	21
	T	AS	310	45	205	30	11	125	18	68	50	51 HRB	160	23
FN-0205	R	AS	255	37	160	23	3.0	105	15	14	10	50 HRB	115	17
		HT	565	82	450	65	0.5	225	33	8.1	6	32 HRC	115	17
	S	SS	345	50	215	31	3.5	140	20	24	18	70 HRB	145	21
		HT	760	110	605	88	1.0	305	44	22	16	42 HRC	145	21
	T	SS	420	61	255	37	4.5	165	24	43	32	85 HRB	160	23
		HT	925	134	725	105	2.0	370	54	38	28	46 HRC	160	23
FN-0208	R	AS	330	48	205	30	2.0	130	19	11	8	62 HRB	115	17
		HT	690	100	650	94	0.5	275	40	8.1	6	34 HRC	115	17
	S	AS	450	65	280	41	3.0	180	26	19	14	79 HRB	145	21
		HT	930	135	880	128	0.5	370	54	16	12	45 HRC	145	21
	T	AS	545	79	345	50	3.5	220	32	30	22	87 HRB	160	23
		HT	1105	160	1070	155	0.5	415	60	24	18	47 HRC	160	23
FN-0400	R	AS	250	36	150	22	5	95	14	22	16	40 HRB	115	17
	S	AS	340	49	205	30	6	140	20	47	35	60 HRB	145	21
	T	AS	400	58	250	36	6.5	160	23	68	50	67 HRB	160	23
FN-0405	R	AS	310	45	180	26	3.0	125	18	14	10	63 HRB	115	17
		HT	770	112	650	94	0.5	310	45	8.1	6	27 HRC	115	17

(continued)

(a) For density range. (b) AS, as sintered; SS, sintered and sized; HT, heat treated, typically austenitized at 870 °C (1600 °F), oil quenched and tempered 1 h at 200 °C (400 °F). (c) Unnotched Charpy test. (d) Estimated as 38% of tensile strength. (e) X indicates infiltrated steel

Typical Mechanical Properties of Ferrous P/M Materials (continued)

Designation	MPIF density suffix(a)	Condition(b)	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation in 25 mm (1 in.), %	Fatigue strength MPa	Fatigue strength ksi	Impact energy(c) J	Impact energy(c) ft · lb	Apparent hardness	Elastic modulus GPa	Elastic modulus 10^6 psi
FN-0405 (continued)	S	AS	425	62	240	35	4.5	165	24	20	15	72 HRB	145	21
		HT	1060	154	880	128	1.0	415	60	14	10	39 HRC	145	21
	T	AS	510	74	295	43	6.0	205	30	41	30	80 HRB	160	23
		HT	1240	180	1060	154	1.5	450	65	19	14	44 HRC	160	23
FN-0408	R	AS	395	57	290	42	1.5	160	23	8.1	6	72 HRB	115	17
	S	AS	530	77	390	57	3.0	215	31	14	10	88 HRB	145	21
	T	AS	640	93	470	68	4.5	255	37	22	16	95 HRB	160	23
FN-0700	R	AS	560	52	205	30	2.5	145	21	16	12	60 HRB	115	17
	S	AS	490	71	275	40	4	195	28	28	21	72 HRB	145	21
	T	AS	585	85	330	48	6	240	34	35	26	83 HRB	160	23
FN-0705	R	AS	370	54	240	35	2.0	150	22	12	9	69 HRB	115	17
		HT	705	102	550	80	0.5	280	41	11	8	24 HRC	115	17
	S	AS	525	76	330	48	3.5	205	30	23	17	83 HRB	145	21
		HT	965	140	760	110	1.0	385	56	20	15	38 HRC	145	21
	T	AS	620	90	390	57	5.0	250	36	33	24	90 HRB	160	23
		HT	1160	168	895	130	1.5	500	65	27	20	40 HRC	160	23
FN-0708(e)	R	AS	395	57	280	41	1.5	160	23	8	6	75 HRB	115	17
	S	AS	550	80	380	55	2.5	220	32	16	12	88 HRB	145	21
	T	AS	655	95	455	66	3.0	260	38	22	16	96 HRB	160	23
FX-1005(e)	T	AS	570	83	440	64	4.0	...	...	19	14	75 HRB	135	20
		HT	830	120	740	107	1.0	...	...	9.5	7.0	35 HRC	135	20
FX-1008(e)	T	AS	620	90	515	75	2.5	...	...	16	12	80 HRB	135	20
		HT	895	130	725	105	60.5	...	...	9.5	7.0	40 HRC	135	20
FX-2000(e)	T	AS	450	65	...	...	1.0	...	...	20	15	60 HRB	...	...
FX-2005(e)	T	AS	515	75	345	50	1.5	...	...	12.9	9.5	75 HRB	125	18
		HT	790	115	655	95	<0.5	...	...	8.1	6.0	30 HRC	125	18
FX-2008(e)	T	AS	585	85	515	75	1.0	...	...	14	10	80 HRB	125	18
		HT	860	125	740	107	<0.5	...	...	6.8	5.0	42 HRC	125	18

(a) For density range. (b) AS, as sintered; SS, sintered and sized; HT, heat treated, typically austenitized at 870 °C (1600 °F), oil quenched and tempered 1 h at 200 °C (400 °F). (c) Unnotched Charpy test. (d) Estimated as 38% of tensile strength. (e) X indicates infiltrated steel

Typical Density Designations and Ranges of Ferrous P/M Materials

Density of pure iron is 7.87 g/cm^3.

Designation: MPIF density suffix	Designation: ASTM type(a)	Designation: SAE type	Density, g/cm^3
N	I	1(b)	Less than 6.0
P	II	2	6.0 to 6.4
R	III	3	6.4 to 6.8
S	IV	4	6.8 to 7.2
T	V(c)	5(c)	7.2 to 7.6
U	...	...	7.6 to 8.0

(a) ASTM B 426 only; different density ranges used in ASTM B 310 and B 484. (b) Density range of 5.6 to 6.0 g/cm^3 is specified. (c) Minimum density of 7.2 g/cm^3 is specified

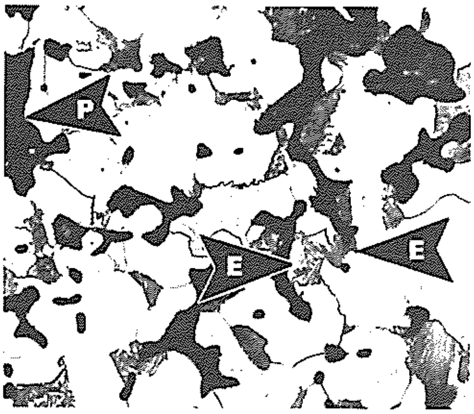
Effects of Density on Elastic Modulus, Poisson's Ratio, and Coefficient of Thermal Expansion of P/M Steels

MPIF density suffix(a)	Density, g/cm^3	Elastic modulus GPa	Elastic modulus 10^6 psi	Poisson's ratio	Coefficient of thermal expansion, 10^{-6}/K
N	5.6-6.0	72	10.5	0.18	8.1
P	6.0-6.4	90	13	0.20	8.7
R	6.4-6.8	110	16	0.21	9.2
S	6.8-7.2	130	19	0.23	9.8
T	7.2-7.6	160	23	0.26	10.4
Theoretical	7.86	205	30	0.28	11-12

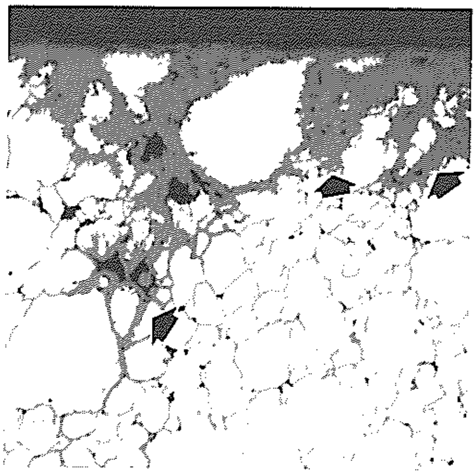
Effects of Steam Treating on Density and Apparent Hardness of Ferrous P/M Materials

MPIF designation	MPIF density suffix(a)	Density, g/cm³ Sintered	Density, g/cm³ Steam treated	Apparent hardness Sintered	Apparent hardness Steam treated
F-0000	N	5.8	6.2	7 HRF	75 HRB
	P	6.2	6.4	32 HRF	61 HRB
	R	6.5	6.6	45 HRF	51 HRB
F0008	M	5.8	6.1	44 HRB	100 HRB
	P	6.2	6.4	58 HRB	98 HRB
	R	6.5	6.6	60 HRB	97 HRB
FC-0700	N	5.7	6.0	14 HRB	73 HRB
	P	6.35	6.5	49 HRB	78 HRB
	R	6.6	6.6	58 HRB	77 HRB
FC-0708	N	5.7	6.0	52 HRB	97 HRB
	P	6.3	6.4	72 HRB	94 HRB
	R	6.6	6.6	79 HRB	93 HRB

Microstructure. Atomized iron powder with 0.3% graphite added to yield 0.1 to 0.2% combined carbon (6.7 g/cm³). Pressed at 410 to 480 MPa (30 to 35 tsi) and sintered 30 min at 1120 °C (2050 °F) in dissociated ammonia. White regions are ferrite. Arrows E surround a colony of eutectoid (pearlite). Arrow P points to a pore. 2% nital. 545×



Microstructure. Surface finger oxides (arrows at upper right) and interparticle oxide networks (arrow near lower left) in a powder forged material

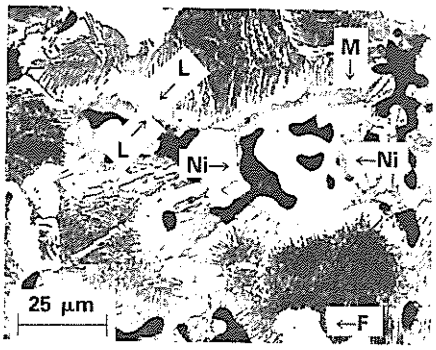


Typical Density Designations and Ranges of Ferrous P/M Materials

Designation: MPIF density suffix	Designation: ASTM type(a)	Designation: SAE type	Density, g/cm³
N	I	1(b)	Less than 6.0
P	II	2	6.0 to 6.4
R	III	3	6.4 to 6.8
S	IV	4	6.8 to 7.2
T	V(c)	5(c)	7.2 to 7.6
U	...	...	7.6 to 8.0

Note: Density of pure iron is 7.87 g/cm³. (a) ASTM B 426 only; different density ranges used in ASTM B 310 and B 484. (b) Density range of 5.6 to 6.0 g/cm³ is specified. (c) Minimum density of 7.2 g/cm³ is specified

Microstructure. Microstructure of sintered Fe-2Ni-0.5C alloy. Sintered for 30 min at 1120 °C (2050 °F). Arrows marked Ni outline nickel-rich particle. Arrow M, martensite or bainite at nickel-rich boundary. Arrows marked L, diffusion layer between nickel and pearlite. This is not unalloyed ferrite. Arrow F, ferrite. 4% nital etched



Minimum and Typical Mechanical Properties of Ferrous P/M Materials

Minimum strength values (in ksi) are specified by the suffix of the material designation code in the first column of the table. Typical values are given in the remaining columns.

Material designation code(a)	Ultimate strength MPa	Ultimate strength ksi	0.2% offset yield strength MPa	0.2% offset yield strength ksi	Elongation in 25 mm (1 in.), %	Elastic modulus GPa	Elastic modulus 10^6 psi	Transverse rupture strength MPa	Transverse rupture strength ksi	Impact energy(b) J	Impact energy(b) ft · lbf	Apparent hardness(c)	Fatigue strength(d) MPa	Fatigue strength(d) ksi
Iron and carbon steel														
F-0000-10(e)	125	18	90	13	1.5	96.5	14.0	248	36	4	3	40 HRF	48	7
F-0000-15(e)	172	25	125	18	2.5	117	17.0	345	50	8	6	60 HRF	70	10
F-0000-20(e)	262	38	172	25	7.0	141	20.5	655	95	47	35	80 HRF	96	14
F-0005-15(e)	165	24	125	18	<1.0	96.5	14.0	330	48	4	3	25 HRB	62	9
F-0005-20(e)	220	32	160	23	1.0	114	16.5	440	64	5.5	4	40 HRB	83	12
F-0005-25(e)	262	38	193	28	1.5	124	18.0	525	76	6.8	5	55 HRB	97	14
F-0005-50HT(f)	415	60	(g)	(g)	<0.5	114	16.5	725	105	4	3	20 HRC(h)	160	23
F-0005-60HT(f)	483	70	(g)	(g)	<0.5	120	17.5	827	120	4.7	3.5	22 HRC(h)	185	27
F-0005-70HT(f)	550	80	(g)	(g)	<0.5	130	19.0	965	140	5.5	4	25 HRC(h)	207	30
F-0008-20(e)	200	29	172	25	<0.5	83	12.0	350	51	3.5	2.5	35 HRB	75	11
F-0008-25(e)	240	35	207	30	<0.5	100	14.5	420	61	4	3	50 HRB	90	13
F-0008-30(e)	290	42	240	35	<1.0	114	16.5	510	74	5.5	4	60 HRB	110	16
F-0008-35(e)	393	57	275	40	1.0	130	19.0	690	100	6.8	5	70 HRB	150	22
F-0008-55HT(f)	448	65	(g)	(g)	<0.5	103	15.0	690	100	4	3	22 HRC(i)	172	25
F-0008-65HT(f)	517	75	(g)	(g)	<0.5	114	16.5	793	115	5.5	4	28 HRC(i)	200	29
F-0008-75HT(f)	585	85	(g)	(g)	<0.5	125	18.0	895	130	6	4.5	32 HRC(i)	220	32
F-0008-85HT(f)	655	95	(g)	(g)	<0.5	135	19.5	1000	145	6.8	5	35 HRC(i)	250	36
Iron-copper and copper steel														
FC-0200-15(e)	172	25	138	20	1.0	90	13.0	310	45	6	4.5	11 HRB	70	10
FC-0200-18(e)	193	28	160	23	1.5	103	15.0	350	51	6.8	5	18 HRB	75	11
FC-0200-21(e)	215	31	180	26	1.5	114	16.5	385	56	7.5	5.5	26 HRB	83	12
FC-0200-24(e)	235	34	200	29	2.0	124	18.0	435	63	8	6	36 HRB	90	13
FC-0205-30(e)	240	35	240	35	<1.0	90	13.0	415	60	<2.7	<2	37 HRB	90	13
FC-0205-35(e)	275	40	275	40	<1.0	103	15.0	517	75	4	3	48 HRB	103	15
FC-0205-40(e)	345	50	310	45	<1.0	117	17.0	655	95	6.8	5	60 HRB	130	19
FC-0205-45(e)	415	60	345	50	<1.0	134	19.5	793	115	11	8	72 HRB	160	23
FC-0205-60HT(f)	483	70	(g)	(g)	<0.5	100	14.5	655	95	3.5	2.5	19 HRC(h)	185	27
FC-0205-70HT(f)	550	80	(g)	(g)	<0.5	110	16.0	758	110	4.7	3.5	25 HRC(h)	207	30
FC-0205-80HT(f)	620	90	(g)	(g)	<0.5	121	17.5	827	120	6	4.5	31 HRC(h)	235	34
FC-0205-90HT(f)	690	100	(g)	(g)	<0.5	131	19.0	930	135	7.5	5.5	36 HRC(h)	262	38
FC-0208-30(e)	240	35	240	35	<1.0	83	12.0	415	60	<2.7	<2	50 HRB	90	13
FC-0208-40(e)	345	50	310	45	<1.0	103	15.0	620	90	2.7	2	61 HRB	130	19
FC-0208-50(e)	415	60	380	55	<1.0	117	17.0	860	125	6.8	5	73 HRB	160	23
FC-0208-60(e)	517	75	448	65	<1.0	138	20.0	1070	155	9.5	7	84 HRB	200	29
FC-0208-50HT(f)	450	65	(g)	(g)	<0.5	96.5	14.0	655	95	3.5	2.5	20 HRC(i)	172	25
FC-0208-65HT(f)	517	75	(g)	(g)	<0.5	107	15.5	760	110	4.7	3.5	27 HRC(i)	200	29
FC-0208-80HT(f)	620	90	(g)	(g)	<0.5	121	17.5	895	130	6	4.5	35 HRC(i)	235	34
FC-0208-95HT(f)	725	105	(g)	(g)	<0.5	134	19.5	1035	150	7.5	5.5	43 HRC(i)	275	40
FC-0505-30(e)	303	44	248	36	<0.5	83	12.0	530	77	4	3	51 HRB	117	17
FC-0505-40(e)	400	58	325	47	<0.5	103	15.0	703	102	6	4.5	62 HRB	152	22
FC-0505-50(e)	490	71	385	56	<1.0	117	17.0	855	124	6.8	5	72 HRB	185	27
FC-0508-40(e)	400	58	345	50	<0.5	86	12.5	690	100	4	3	60 HRB	152	22
FC-0508-50(e)	470	68	415	60	<0.5	103	15.0	827	120	4.7	3.5	68 HRB	180	26
FC-0508-60(e)	565	82	483	70	<1.0	121	17.5	1000	145	6	4.5	80 HRB	215	31
FC-0808-45(e)	380	55	345	50	<0.5	90	13.0	585	85	4	3	65 HRB	145	21
FC-1000-20(e)	207	30	180	26	<1.0	90	13.0	365	53	4.7	3.5	15 HRB	75	11
Iron-nickel and nickel steel														
FN-0200-15(e)	172	25	117	17	1.5	107	15.5	...	...	...	...	...	70	10
FN-0200-20(e)	240	35	172	25	4.0	134	19.5	550	80	26.5	19.5	75 HRF	90	13
FN-0200-25(e)	275	40	205	30	6.5	159	23.0	...	...	...	...	...	105	15
FN-0205-20(e)	275	40	172	25	1.5	107	15.5	450	65	8	6.0	44 HRB	105	15
FN-0205-25(e)	345	50	205	30	2.5	128	18.5	690	100	16.5	12.0	59 HRB	130	19
FN-0205-30(e)	415	60	240	35	4.0	152	22.0	860	125	28.5	21.0	69 HRB	160	23
FN-0205-35(e)	483	70	275	40	5.5	165	24.0	1035	150	46	34.0	78 HRB	185	27
FN-0205-80HT(f)	620	90	(g)	(g)	<0.5	107	15.5	827	120	4.5	3.5	23 HRC(j)	235	34

(continued)

(a) The suffix of the material designation codes represent either the minimum yield strength or the minimum ultimate strength in ksi. For example, the minimum yield strength of F-0000-10 is 10 ksi, while the minimum yield strength of F-0000-15 is 15 ksi. (b) Unnotched Charpy test. (c) Where applicable, the matrix (converted) hardness is also given in the footnotes. (d) Fatigue limit for 10^7 cycles from reverse-bending fatigue tests. (e) The suffix number represents the minimum yield strength (in ksi) for the material in the as-sintered condition. (f) The suffix number for heat-treated (HT) materials represents the minimum ultimate tensile strength in ksi. Tempering temperature for heat-treated materials is 175 °C (350 °F). (g) Yield strength and ultimate tensile strength are approximately the same for heat-treated materials. (h) Or a matrix (converted) hardness of 58 HRC. (i) Or a matrix (converted) hardness of 60 HRC. (j) Or a matrix (converted) hardness of 55 HRC. (k) Or a matrix (converted) hardness of 57 HRC. (l) All data based on single-pass infiltration. (m) Codes for the stainless steel designations: N1, nitrogen alloyed, with good strength and low elongation; N2, nitrogen alloyed, with high strength and medium elongation; L, low carbon, with lower strength and highest elongation; HT, martensitic grade, heat treated, and highest strength

ⅰinimum and Typical Mechanical Properties of Ferrous P/M Materials (continued)

ⅰinimum strength values (in ksi) are specified by the suffix of the material designation code in the first column of the table. Typical values are iven in the remaining columns.

ⅰaterial esignation code(a)	Ultimate strength		0.2% offset yield strength		Elongation in 25 mm (1 in.), %	Elastic modulus		Transverse rupture strength		Impact energy(b)		Apparent hardness(c)	Fatigue strength(d)	
	MPa	ksi	MPa	ksi		GPa	10^6 psi	MPa	ksi	J	ft · lbf		MPa	ksi
ⅰon-nickel and nickel steel (continued)														
N-0205-105HT(f)	827	120	(g)	(g)	<0.5	128	18.5	1100	160	6	4.5	29 HRC(j)	315	46
N-0205-130HT(f)	1000	145	(g)	(g)	<0.5	145	21.0	1310	190	8	6.0	33 HRC(j)	380	55
N-0205-155HT(f)	1100	160	(g)	(g)	<0.5	152	22.0	1480	215	9.5	7.0	36 HRC(j)	420	61
N-0205-180HT(f)	1275	185	(g)	(g)	<0.5	165	24.0	1725	250	13	9.5	40 HRC(j)	480	70
N-0208-30(e)	310	45	240	35	1.5	114	16.5	585	85	7.5	5.5	63 HRB	115	17
N-0208-35(e)	380	55	275	40	1.5	128	18.5	725	105	11	8.0	71 HRB	145	21
N-0208-40(e)	483	70	310	45	2.0	145	21.0	895	130	15	11.0	77 HRB	185	27
N-0208-45(e)	550	80	345	50	2.5	159	23.0	1070	155	21.5	16.0	83 HRB	205	30
N-0208-50(e)	620	90	380	55	3.0	165	24.0	1170	170	28.5	21.0	88 HRB	235	34
N-0208-80HT(f)	620	90	(g)	(g)	<0.5	114	16.5	827	120	5.5	4.0	26 HRC(k)	235	34
N-0208-105HT(f)	827	120	(g)	(g)	<0.5	128	18.5	1035	150	6	4.5	31 HRC(k)	315	46
N-0208-130HT(f)	1000	145	(g)	(g)	<0.5	134	19.5	1275	185	7.5	5.5	35 HRC(k)	380	55
N-0208-155HT(f)	1170	170	(g)	(g)	<0.5	152	22.0	1515	220	9.5	7.0	39 HRC(k)	450	65
N-0208-180HT(f)	1345	195	(g)	(g)	<0.5	165	24.0	1725	250	11	8.0	42 HRC(k)	510	74
N-0405-25(e)	275	40	205	30	<1.0	96.5	14.0	450	65	6	4.5	49 HRB	105	15
N-0405-35(e)	415	60	275	40	3.0	134	19.5	827	120	19.5	14.5	71 HRB	160	23
N-0405-45(e)	620	90	345	50	4.5	165	24.0	1205	175	45.5	33.5	84 HRB	235	34
N-0405-80HT(f)	585	85	(g)	(g)	<0.5	96.5	14.0	793	115	5.5	4.0	19 HRC(j)	220	32
N-0405-105HT(f)	760	110	(g)	(g)	<0.5	121	17.5	1000	145	6.8	5.0	25 HRC(j)	290	42
N-0405-130HT(f)	930	135	(g)	(g)	<0.5	134	19.5	1380	200	8.8	6.5	31 HRC(j)	350	51
N-0405-155HT(f)	1100	160	(g)	(g)	<0.5	159	23.0	1690	245	13	9.5	37 HRC(j)	420	61
N-0405-180HT(f)	1275	185	(g)	(g)	<0.5	165	24.0	1930	280	17.5	13.0	40 HRC(j)	480	70
N-0408-35(e)	310	45	275	40	1.0	100	14.5	517	75	5.5	4.0	67 HRB	115	17
N-0408-45(e)	450	65	345	50	1.0	128	18.5	793	115	10	7.5	78 HRB	170	25
N-0408-55(e)	550	80	415	60	1.0	152	22.0	1035	150	15	11.0	87 HRB	205	30
ⅰw-alloy steel														
-4205-80HT(f)	620	90	(g)	(g)	<0.5	117	17.0	930	135	4.7	3.5	28 HRC(i)	235	34
-4205-100HT(f)	760	110	(g)	(g)	<0.5	130	19.0	1100	160	5.5	4.0	32 HRC(i)	290	42
-4205-120HT(f)	895	130	(g)	(g)	<0.5	150	22.0	1275	185	5.5	4.0	36 HRC(i)	338	49
-4205-140HT(f)	1035	150	(g)	(g)	<0.5	172	25.0	1480	215	6	4.5	39 HRC(i)	393	57
-4605-80HT(f)	585	85	(g)	(g)	<0.5	115	16.5	895	130	4.7	3.5	24 HRC(i)	220	32
-4605-100HT(f)	760	110	(g)	(g)	<0.5	125	18.0	1135	165	6	4.5	29 HRC(i)	290	42
-4605-120HT(f)	895	130	(g)	(g)	<0.5	138	20.0	1345	195	8	6.0	34 HRC(i)	338	49
-4605-140HT(f)	1070	155	(g)	(g)	<0.5	148	21.5	1585	230	9.5	7.0	39 HRC(i)	405	59
pper-infiltrated iron and steel(l)														
-1000-25(e)	350	51	220	32	7.0	110	16.0	910	132	34	25	65 HRB	130	19
-1005-40(E)	530	77	345	50	4.0	110	16.0	1090	158	17.5	13	82 HRB	200	29
-1005-110HT(f)	825	120	(g)	(g)	<0.5	110	16.0	1445	210	9.5	7	38 HRC(j)	315	46
-1008-50(e)	600	87	415	60	3.0	110	16.0	1145	166	13.5	10	89 HRB	225	33
-1008-110HT(f)	825	120	(g)	(g)	<0.5	110	16.0	1305	189	8.8	6.5	43 HRC(h)	315	46
-2000-25(e)	315	46	255	37	3.0	103	15.0	993	144	20	5	66 HRB	115	17
-2005-45(e)	515	75	415	60	1.5	103	15.0	1020	148	10.8	8	85 HRB	200	29
-2005-90HT(f)	690	100	(g)	(g)	<0.5	103	15.0	1180	171	9.5	7	36 HRC(j)	260	38
-2008-60(e)	550	80	483	70	1.0	103	15.0	1075	156	9.5	7	90 HRB	205	30
-2008-90HT(f)	690	100	(g)	(g)	<0.5	103	15.0	1095	159	6.8	5	36 HRC(h)	260	38
inless steel(m)														
303N1-25(e)	270	39	220	32	0.5	...	...	593	86	4.7	3.5	62 HRB	...	...
303N2-35(e)	380	55	290	42	5	...	...	675	98	26	19	63 HRB	...	...
303L-12(e)	270	39	115	17	17.5	...	...	565	82	...	...	21 HRB	...	...
304N1-30(e)	295	43	260	38	0.5	...	...	772	112	5.5	4	61 HRB	...	...
304N2-33(e)	393	57	275	40	10	...	...	875	127	34	25	62 HRB	...	...
304L-13(e)	295	43	125	18	23	...	...	...	...	...	...	...	...	...
316N1-25(e)	283	41	235	34	0.5	...	...	745	108	6.8	5	59 HRB	...	...
316N2-33(e)	415	60	270	39	10	...	...	860	125	38	28	62 HRB	...	...
316L-15(e)	283	41	138	20	18.5	...	...	550	80	47	35	20 HRB	...	...
410-90HT(f)	725	105	(g)	(g)	<0.5	...	...	780	113	3.5	2.5	23 HRC(j)	...	...

ⅰThe suffix of the material designation codes represent either the minimum yield strength or the minimum ultimate strength in ksi. For example, the minimum yield strength of ⅰ00-10 is 10 ksi, while the minimum yield strength of F-0000-15 is 15 ksi. (b) Unnotched Charpy test. (c) Where applicable, the matrix (converted) hardness is also given in the notes. (d) Fatigue limit for 10^7 cycles from reverse-bending fatigue tests. (e) The suffix number represents the minimum yield strength (in ksi) for the material in the as-sintered ⅰdition. (f) The suffix number for heat-treated (HT) materials represents the minimum ultimate tensile strength in ksi. Tempering temperature for heat-treated materials is 175 °C ⅰ°F). (g) Yield strength and ultimate tensile strength are approximately the same for heat-treated materials. (h) Or a matrix (converted) hardness of 58 HRC. (i) Or a matrix (con-ed) hardness of 60 HRC. (j) Or a matrix (converted) hardness of 55 HRC. (k) Or a matrix (converted) hardness of 57 HRC. (l) All data based on single-pass infiltration. (m) Codes ⅰhe stainless steel designations: N1, nitrogen alloyed, with good strength and low elongation; N2, nitrogen alloyed, with high strength and medium elongation; L, low carbon, ⅰlower strength and highest elongation; HT, martensitic grade, heat treated, and highest strength

Precision of Rockwell Apparent Hardness Readings on P/M Parts

All laboratories tested identical coupons. If similar but different coupons were to be compared, variability would be increased, and larger differences between respective readings would be expected.

MPIF material designation	Density, g/cm³	Number of laboratories	Average apparent hardness	Repeatability(a) (95% confidence limits) One reading	Average of six readings	Reproducibility(a) (95% confidence limits) One reading	Average of six readings
ZP-2002	7.92	9	82.5 HRC	1.7	0.7	2.2	0.9
-0000	6.74	9	63.4 HRF	4.0	1.6	4.4	1.8
C-0208	6.63	9	70.8 HRB	4.5	1.8	5.7	2.3
X-2008	7.45	9	86.4 HRB	4.3	1.8	4.9	2.0
L-4605-HT	6.90	8	107.2 HRB(b)	1.9	0.8	3.1	1.3
L-4605-HT	6.90	8	34.6 HRC	2.2	0.9	3.1	1.3
C-0208-HT	6.29	10	97.1 HRB(b)	3.1	1.3	4.4	1.8
C-0208-HT	6.29	10	18.7 HRC	4.2	1.7	5.1	2.1
N-0208-HT	6.89	10	105.3 HRB(b)	2.9	1.2	4.1	1.7
N-0208-HT	6.89	10	30.5 HRC	3.8	1.5	4.6	1.9

(a) Repeatability and reproducibility defined according to ASTM E 691. (b) HRB scale with 1.6 mm (1/16 in.) diam carbide ball indentors

Comparison of Average Mechanical Properties of Steam-Blackened P/M Materials with As-Sintered Properties and Typical Standard 35

Material	Blackening(a)	Ultimate tensile strength MPa	ksi	Average-density ultimate tensile strength MPa	ksi	Elongation in 25 mm (1 in.), %	Transverse rupture strength MPa	ksi	Impact energy(b) J	ft · lbf	0.2% offset yield strength MPa	ksi	Hardness, HRB
-0000	None	138	20.0	42.7	6.20	6.4	330	47.9	5.4	4.0	...	...	37
	Light	154	22.3	45.0	6.52	1.8	367	53.2	2.7	2.0	...	...	88
	Heavy	152	22.1	44.6	6.47	1.2	434	63.0	2.7	2.0	...	...	85
Standard 35	None	124	18.0	...	...	1.5	248	36.0	4.1	3.0	690	10	40 HRF
-0000	None	132	19.1	47.8	6.93	3.7	395	57.3	5.8	4.3	...	...	52
	Light	139	20.2	49.0	7.10	0.6	496	72.0	3.0	2.2	...	...	90
	Heavy	134	19.5	48.8	7.08	0.8	545	79.1	3.0	2.2	...	...	88
Standard 35	None	173	25.1	...	...	2.5	345	50.0	8.1	6.0	103	15	60 HRF
-0008	None	211	30.6	43.2	6.26	1.5	453	65.7	3.6	2.7	...	...	69
	Light	134	19.4	45.6	6.61	0.4	434	63.0	2.3	1.7	...	...	108
	Heavy	116	16.8	45.4	6.59	0.4	450	65.2	2.4	1.8	...	...	106
Standard 35	None	241	35	...	...	<0.5	420	61	4.1	3	170	25	50
-0008	None	272	39.5	46.7	6.78	1.6	665	96.4	4.3	3.2	...	...	87
	Light	192	27.9	48.0	6.96	0.3	656	95.1	3.0	2.2	...	...	110
	Heavy	193	28.0	48.1	6.97	0.8	752	109	3.1	2.3	...	...	108
Standard 35	None	345	50.0	...	...	<1.0	600	87.0	6.1	4.5	220	32	65
-0208	None	331	48.0	43.2	6.27	1.2	684	99.2	4.7	3.5	...	...	87
	Light	208	30.2	45.1	6.54	0.4	606	87.9	2.7	2.0	...	...	112
	Heavy	205	29.8	44.9	6.51	0.7	738	107	2.7	2.0	...	...	110
Standard 35	None	345	50	...	...	<1.0	620	90	2.7	2.0	275	40	61
-208	None	461	66.8	47.2	6.85	1.7	952	138	8.8	6.5	...	...	95
	Light	405	58.8	48.5	7.03	1.2	924	134	5.8	4.3	...	...	111
	Heavy	383	55.5	47.6	6.9	0.3	1040	151	5.7	4.2	...	...	108
Standard 35	None	434	63	...	...	<1.0	903	131	7.5	5.5	360	52	75

(a) None, as sintered; Light blackening, 2 h exposure in 538 °C (1000 °F) steam; heavy blackening, 4 h exposure in 538 °C (1000 °F) steam. Unnotched Charpy test at room temperature

Applications of Ferrous P/M Materials

Material and specification designation	MPIF density suffix	Condition	Application
P/M iron F-0000-N through T: 0.3 C max	N	As sintered	Structural (lightly loaded gears); magnetic (motor pole pieces); self-lubricating bearings; structural wear-resisting (small levers and cams) as carbonitrided
	P	As sintered	
	R	As sintered	
	S	As sintered	
	T	As sintered	
P/M steel F-0005-N through T: 0.3 to 0.6 C	N	As sintered	Structural (moderately loaded gears, levers, cams); structural (moderately loaded gears, levers, and cams requiring wear resistance) as heat treated
	P	As sintered	
	R	As sintered	
		Heat treated	
	S	As sintered	
		Heat treated	
P/M steel F-0008-N through T: 0.6 to 1.0 C	N	As sintered	Structural (moderately loaded gears, levers, cams); structural (moderately loaded gears, levers, and cams requiring wear resistance) as heat treated
		Heat treated	
	P	As sintered	
		Heat treated	
	R	As sintered	
		Heat treated	
	S	As sintered	
		Heat treated	
P/M copper iron FC-0200-P through S: 1.5 to 3.9 Cu, 0.3 C max	P	As sintered	Bearings or mechanical components
	R	As sintered	Mechanical components
	S	As sintered	
P/M copper steel FC-0205-P through S: 1.5 to 3.9 Cu, 0.3 to 0.6 C	P	As sintered	Bearings or mechanical components
	R	Heat treated	Mechanical components
		As sintered	
	S	Heat treated	
P/M copper steel FC-0208-N through S: 1.5 to 3.9 Cu, 0.6 to 1.0 C	N	As sintered	Bearings or mechanical components
		Heat treated	Mechanical components
	P	As sintered	
		Heat treated	
	R	As sintered	
		Heat treated	
	S	As sintered	
		Heat treated	
P/M copper steel FC-0505-N through S: 4.0 to 6.0 Cu, 0.3 to 0.6 C	N	As sintered	
		Heat treated(a)	
	P	As sintered	
		Heat treated(a)	
	R	As sintered	
		Heat treated(a)	
P/M copper steel FC-0508-N through R: 4.0 to 6.0 Cu, 0.6 to 1.0 C	N	As sintered	Mechanical components
		Heat treated(a)	
	P	As sintered	
		Heat treated(a)	
	R	As sintered	
		Heat treated(a)	
P/M copper steel FC-0808-N: 6 to 11 Cu, 0.6 to 1.0 C	N	As sintered	Mechanical components
P/M copper iron FC-1000-N: 9.5 to 10.5 Cu, 0.3 C max	N	As sintered	Bearings or mechanical components
P/M iron-nickel FN-0200-R through T: 1 to 3 Ni, 2.5 Cu max, 0.3 C max	R	As sintered	Mechanical components (can be case hardened)
	S	As sintered	
	T	As sintered	
	R	As sintered	Structural (couplings) as sintered; structural, wear resisting (oil pump gears and heavily loaded support brackets) as heat treated; structural, wear and impact resisting (oil pump gears to 3000 psi and heavily loaded transmission gears)
		Heat treated	
	S	Sintered and sized	
		Heat treated	
	T	Sintered and sized	
		Heat treated	
P/M nickel steel FN-0208-R through T: 1 to 3 Ni, 0.6 to 0.9 C, 2.5 Cu max	R	As sintered	Mechanical components
		Heat treated	
	S	As sintered	
		Heat treated	
	T	As sintered	
		Heat treated	

(continued)

a) Generally heat treated for wear resistance rather than strength

Applications of Ferrous P/M Materials (continued)

Material and specification designation	MPIF density suffix	Condition	Application
P/M iron-nickel FN-0400-R through T: 3 to 5.5 Ni, 0.3 to 0.6 C, 2.0 Cu max	R	As sintered	Mechanical components (can be case hardened)
P/M nickel steel FN-0405-R through T: 3 to 5 Ni, 0.3 to 0.6 C, 2.0 Cu max	R	As sintered Heat treated	Mechanical components
	S	As sintered Heat treated	
	T	As sintered Heat treated	
P/M nickel steel FN-0408-R through T: 3.0 to 5.0 Ni, 0.6 to 0.9 C, 2.0 Cu max	R S T	As sintered As sintered As sintered	Structural, wear resisting, high stress (planetary differential and transmission gears up to 6 hp) as heat treated; structural, wear resisting, high stress and requiring welded assembly (welded assembly of pinion and sprocket) as carbonitrided
P/M iron-nickel FN-0700-R through T: 6 to 8 Ni, 0.3 C max, 2.0 Cu max	R S T	As sintered As sintered As sintered	Mechanical components (can be case hardened)
P/M nickel steel FN-0705-R through T: 6 to 8 Ni, 0.3 to 0.6 C, 2.0 Cu max	R	As sintered Heat treated	Mechanical components
	S	As sintered Heat treated	
	T	As sintered Heat treated	
P/M nickel steel FN-0708-R through T: 6 to 8 Ni, 0.6 to 0.9 C, 2.0 Cu max	R S T	As sintered As sintered As sintered	Mechanical components
P/M infiltrated steel FX-1005-T: 8 to 14.9 Cu, 0.3 to 0.6 C	T	As sintered Heat treated	Mechanical components (special shapes)
FX-1008-T: 8 to 14.9 Cu, 0.6 to 1.0 C	T	As sintered Heat treated	Mechanical components (special shapes)
FX-2000 T: 15 to 25 Cu, 10.3 C max	T	As sintered	Mechanical components
FX-2005-T: 15 to 25 Cu, 0.3 to 0.6 C	T	As sintered Heat treated	Mechanical components
FX-2008-T: 15 to 25 Cu, 0.6 to 1.0 C	T	As sintered Heat treated	Mechanical components
P/M austenitic stainless steel SS-303-P SS-303-R SS-316-P SS-316-R SS-410-N SS-410-P	P R P R N P	As sintered As sintered As sintered As sintered As sintered As sintered	Type 303, mechanical components requiring secondary machining: type 316, structural, corrosion resisting, nonmagnetic (small gears, levers, cams, and other parts for exposure to salt water and specific industrial acids); type 410, structural, corrosion resisting (small gears, levers, cams, and other parts where applications require heat treating for wear resistance)

(a) Generally heat treated for wear resistance rather than strength

Effects of Density on Elastic Modulus, Poisson's Ratio, and Coefficient of Thermal Expansion of Ferrous P/M Materials

MPIF density suffix	Density, g/cm^3	Elastic modulus, GPa	Elastic modulus, 10^6 psi	Poisson's ratio	Coefficient of thermal expansion, 10^{-6}/K
N	5.6 to 6.0	72	10.5	0.18	8.1
P	6.0 to 6.4	90	13	0.20	8.7
R	6.4 to 6.8	110	16	0.21	9.2
S	6.8 to 7.2	130	19	0.23	9.8
T	7.2 to 7.6	160	23	0.26	10.4
Theoretical	7.86	205	30	0.28	11-12

Green Density and Green Strength for Various Types of Iron Powders

Powder	Apparent density, g/cm³	Compaction pressure		Green density, g/cm³	Green strength	
		MPa	tsi		MPa	psi
Sponge(a)	2.4	410	30	6.2	14	2100
		550	40	6.6	22	3200
		690	50	6.8	28	4100
Atomized sponge(b)	2.5	410	30	6.55	13	1900
		550	40	6.8	19	2700
		690	50	7.0	...	...
Reduced(a)	2.5	410	30	6.5	16	2300
		550	40	6.7	21	3000
		690	50	6.9	24	3500
Sponge(a)	2.6	410	30	6.6	19	2700
		550	40	6.8	25	3600
		690	50	7.0	27	3900
Electrolytic(c)	2.6	410	30	6.3	32	4600
		550	40	6.7	43	6200
		690	50	6.95	54	7800

(a) Powders contained 1% zinc stearate blended in. (b) Powder contained 0.75% zinc stearate blended in. (c) Isostatically pressed

Mechanical Properties of Electrolytic Iron Powder Compacts Hot Pressed at 140 MPa (20 ksi)

Temperature		Dwell time at temperature and pressure, s	Tensile strength		Elongation in 25 mm (1 in.), %	Hardness, HB
°C	°F		MPa	ksi		
500	930	50	180	26.2	0	50
		150	176	25.5	0	51
		450	274	39.8	1	63
600	1110	50	254	36.9	0.5	62
		150	281	40.8	1	77
		450	336	48.8	2	80
700	1290	50	330	47.8	1	90
		150	395	57.3	12	95
		450	397	57.5	27	100
780	1435	50	373	54.1	22	101
		150	361	52.4	32	93
		450	365	52.9	37	96

Effect of Hydrogen Chloride on Iron Sintered in Hydrogen

Temperature		Time, min	Atmosphere, % hydrogen chloride	Density, g/cm³	Strength		Elongation %
°C	°F				MPa	ksi	
950	1740	30	0	6.20	131	19	6
		30	1	6.30	159	23	10
		120	0	6.30	138	20	6
		120	1	6.30	159	23	10
1375	2505	30	0	7.00	193	28	11
		30	1	7.20	234	34	20
		120	0	7.50	234	34	17
		120	1	7.80	283	41	25

ypical Mechanical Properties of P/M Forged Low-Alloy Steels

ll materials are in the hardened and tempered condition unless otherwise indicated

aterial	Processing	Ultimate tensile strength, MPa	Ultimate tensile strength, ksi	0.2% yield strength, MPa	0.2% yield strength, ksi	Elongation in 25 mm (1 in.), %	Reduction in area, %	Charpy V-notch impact energy, J	Charpy V-notch impact energy, ft · lb	Hardness	Fracture toughness (K_{Ic}), MPa$\sqrt{m}$	Fracture toughness (K_{Ic}), ksi$\sqrt{in.}$	Density, % of theoretical
-2MCM-0.67C(a)(b)	...	960	139.3	590	86	...	12	...	...	98 HRB	...	...	...
-2MCM-0.67C(a)	...	1900	275.6	1500	218	...	4.5	...	...	49 HRC	...	...	...
20	Sintered at 1315 °C (2400 °F), repressed	701	101.7	616	89.4	14	46	38	28	20-25 HRC	...	...	100
20	Sintered at 1315 °C (2400 °F), repressed	936	135.7	...	...	9	13	39	29	20-25 HRC	...	...	100
30	Gas atomized, –65 mesh	1586	230	1303	189	5	3	10	7.5	46 HRC	49	45	100
40	Gas atomized, –65 mesh	...	...	...	...	...	...	7	5	55 HRC	36	33	100
	Water atomized	...	...	...	...	...	...	7	5	42 HRC	37	34	100
	Sintered at 1200 °C (2190 °F)	1040	150.8	1000	145	20	40	36	26	310-350 HV	...	...	99
-2Ni-0.35C	Mixed elemental powders	938	136	600	87	13	44	...	13	31 HRC	...	...	99
-0.55Ni-0.32Mo-0.47Mn-0.23Cr-0.30C	Sintered at 1200 °C (2190 °F)	1020	147.9	970	141	17	37	46	34	...	...	...	...
-3Cu-0.5C-0.3S	...	873	127	...	...	6.5	...	...	...	274 HV	...	...	99
-9Cu-0.34Mn-0.43Ni-0.65Mo-0.31C	...	1675	245	1410	205	13	31	19	14	49 HRC	...	...	99
-0.35Mn-0.57Mo-1.95Ni-0.5C	...	1200	174	1120	162	10	19	30	22	475 HV	...	...	99
30 modified	Sintered at 1205 °C (2200 °F)	148	215	1331	193	6	10	8	6	42 HRC	...	...	98

MCM is a master alloy containing 20% Mn, 20% Cr, 20% Mo, and 7% C. (b) As-sintered condition

Glossary of Terms Related to Heat Treating

A

$_{cm}$, A_1, A_3, A_4. Same as Ae_{cm}, Ae_1, Ae_3, and Ae_4.

c_{cm}, Ac_1, Ac_3, Ac_4. Defined under *transformation temperature.*

icicular ferrite. A highly substructured nonequiaxed ferrite that forms upon continuous cooling by a mixed diffusion and shear mode of transformation that begins at a temperature transformation range for upper bainite. It is distinguished from bainite in that it has a limited amount of carbon available; thus, there is only a small amount of carbide present.

e_{cm}, Ae_1, Ae_3, Ae_4. Defined under *transformation temperature.*

erated bath nitriding. A type of liquid nitriding in which air is pumped through the molten bath creating agitation and increased chemical activity.

ge hardening. Hardening by aging, usually after rapid cooling or cold working. See also *aging.*

ge softening. Spontaneous decrease of strength and hardness that takes place at room temperature in certain strain hardened alloys, especially those of aluminum.

ging. A change in the properties of certain metals and alloys that occurs at ambient or moderately elevated temperatures after hot working or a heat treatment (quench aging in ferrous alloys, natural or artificial aging in ferrous and nonferrous alloys) or after a cold working operation (strain aging). The change in properties is often, but not always, due to a phase change (precipitation), but never involves a change in chemical composition of the metal or alloy. See also *age hardening, artificial aging, interrupted aging, natural aging, overaging, precipitation hardening, precipitation heat treatment, progressive aging, quench aging, step aging,* and *strain aging.*

ir-hardening steel. A steel containing sufficient carbon and other alloying elements to harden fully during cooling in air or other gaseous mediums from a temperature above its transformation range. The terms should be restricted to steels that are capable of being hardened by cooling in air in fairly large sections, about 2 in. (50 mm) or more in diameter. Same as self-hardening steel.

llotropy. A near synonym for *polymorphism.* Allotropy is generally restricted to describing polymorphic behavior in elements, terminal phases, and alloys whose behavior closely parallels that of the predominant constituent element.

lloy cast iron. A cast iron containing more than 3% alloy content. Alloy cast irons may be a type of *ductile cast iron, gray cast iron,* or *white cast iron.*

lloy steel. Steel containing specified quantities of alloying elements (other than carbon and the commonly accepted amounts of manganese, copper, silicon, sulfur, and phosphorus) within the limits recognized for constructional alloy steels, added to effect changes in mechanical or physical properties.

lpha ferrite. See *ferrite.*

nnealing. A generic term denoting a treatment, consisting of heating to and holding at a suitable temperature followed by cooling at a suitable rate, used primarily to soften metallic materials, but also to simultaneously produce desired changes in other properties or in microstructure. The purpose of such changes may be, but is not confined to: improvement of machinability, facilitation of cold work, improvement of mechanical or electrical properties, and/or increase in stability of dimensions. When the term is used without qualification, full annealing is implied. When applied only for the relief of stress, the process is properly called stress relieving or stress-relief annealing.

In ferrous alloys, annealing usually is done above the upper critical temperature, but the time-temperature cycles vary widely in both maximum temperature attained and in cooling rate employed, depending on composition, material condition, and results desired. When applicable, the following commercial process names should be used: *black annealing, blue annealing, box annealing, bright annealing, cycle annealing, flame annealing, full annealing, graphitizing, intercritical annealing, isothermal annealing, malleablizing, order hardening, process annealing, quench annealing, spheroidizing,* and *subcritical annealing.*

annealing carbon. Fine, apparently amorphous carbon particles formed in white cast iron and certain steels during prolonged annealing. Also called temper carbon.

annealing twin. A twin form in a crystal during recrystallization.

anneal to temper. A final partial anneal that softens a cold worked nonferrous alloy to a specified level of hardness or tensile strength.

Ar_{cm}, Ar_1, Ar_3, Ar_4, Ar', Ar''. Defined under *transformation temperature.*

artificial aging. Aging above room temperature. See also *aging.* Compare with *natural aging.*

athermal transformation. A reaction that proceeds without benefit of thermal fluctuations; that is, thermal activation is not required. In contrast, a reaction that occurs at constant temperature is an *isothermal transformation;* thermal activation is necessary in this case and the reaction proceeds as a function of time.

ausforming. Thermomechanical treatment of steel in the metastable austenitic condition below the recrystallization temperature followed by quenching to obtain martensite and/or bainite.

austempering. A heat treatment for ferrous alloys in which a part is quenched from the austenitizing temperature at a rate fast enough to avoid formation of ferrite or pearlite and then held at a temperature just above M_s until transformation to bainite is complete. Although designated as bainite in both austempered steel and austempered ductile iron (ADI), austempered steel consists of two phase mixtures containing ferrite and carbide, while austempered ductile iron consists of two phase mixtures containing ferrite and austenite.

austenite. A solid solution of one or more elements in face-centered cubic iron. Unless otherwise designated (such as nickel austenite), the solute is generally assumed to be carbon.

austenitic grain size. The size attained by the grains of steel when heated to the austenitic region; may be revealed by appropriate etching of cross sections after cooling to room temperature.

austenitizing. Forming austenite by heating a ferrous alloy into the transformation range (partial austenitizing) or above the transformation range (complete austenitizing). When used without qualification, the term implies complete austenitizing.

B

bainite. A metastable aggregate of *ferrite* and *cementite* resulting from the transformation of austenite at temperatures below the pearlite range but above M_s. Upper bainite, which is an aggregate that contains parallel lath-shape units of ferrite and produces the so-called "feathery" appearance in optical (light) microscopy (Fig. 1), is formed above approximately 350 °C (660 °F). Lower bainite, which has an acicular appearance similar to tempered martensite (Fig. 2), is formed below approximately 350 °C (660 °F).

bainitic hardening. Quench-hardening treatment resulting principally in the formation of *bainite.*

batch furnace. A furnace used to heat treat a single load at a time. Batch-type furnaces are necessary for large parts such as heavy forgings

Fig. 1 Upper bainite in a 4360 steel specimen

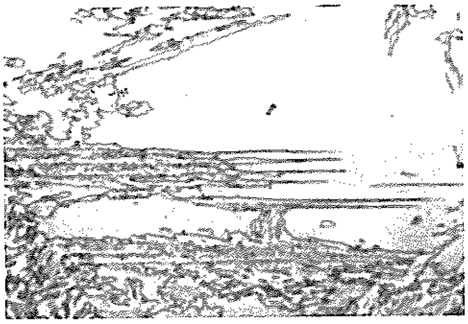
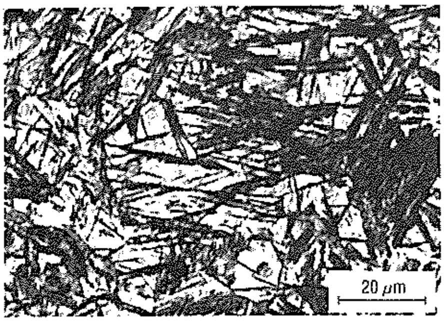


Fig. 2 Lower bainite (dark plates) in a 4150 steel specimen



and are preferred for complex alloy grades requiring long cycles. See also *car furnace* and *horizontal batch furnace*.

belt furnace. A continuous-type furnace which uses a mesh-type or cast-link belt to carry parts through the furnace.

black annealing. Box annealing or pot annealing ferrous alloy sheet, strip, wire to impart a black color to the oxidized surface. See *box annealing*.

black oxide. A black finish on a metal produced by immersing it in hot oxidizing salts or salt solutions.

blank carburizing. Simulating the carburizing operation without introducing carbon. This is usually accomplished by using an inert material in place of the carburizing agent, or by applying a suitable protective coating to the ferrous alloy.

blank nitriding. Simulating the nitriding operation without introducing nitrogen. This is usually accomplished by using an inert material in place of the nitriding agent or by applying a suitable protective coating to the ferrous alloy.

blue annealing. Heating hot-rolled ferrous sheet in an open furnace to a temperature within the transformation range and then cooling in air, in order to soften the metal. The formation of a bluish oxide on the surface is incidental.

blue brittleness. Brittleness exhibited by some steels after being heated to some temperature within the range of about 205 to 370 °C (400 to 700 °F), particularly if the steel is worked at the elevated temperature. Killed steels are virtually free of this kind of brittleness. See also *killed steel*.

bluing. Subjecting the scale-free surface of a ferrous alloy to the action of air, steam, or other agents at a suitable temperature, thus forming a thin blue film of oxide and improving the appearance and resistance to corrosion. Note: This term is ordinarily applied to sheet, strip, or finished parts. It is used also to denote the heating of springs after fabrication to improve their properties.

boriding. Thermochemical treatment involving the enrichment of the surface layer of an object with borides. This surface-hardening process is performed below the Ac_1 temperature.

boronizing. See *boriding*.

box annealing. Annealing a metal or alloy in a sealed container under conditions that minimize oxidation. In box annealing a ferrous alloy, the charge is usually heated slowly to a temperature below the transformation range, but sometimes above or within it, and is then cooled slowly; this process is also called close annealing or pot annealing. See *black annealing*.

breaks. Creases or ridges usually in "untempered" or in aged material where the yield point has been exceeded.

bright annealing. Annealing in a protective medium to prevent discoloration of the bright surface.

bright nitriding. Nitriding in a protective medium to prevent discoloration of the bright surface. Compare with *blank nitriding*.

brine quenching. A quench in which brine (salt water-chlorides, carbonates, and cyanides) is the quenching medium. The salt addition improves the efficiency of water at the vapor phase or hot stage of the quenching process.

Brinell hardness test. A test for determining the hardness of a material by forcing a hard steel or carbide ball of specified diameter into it under a specified load. The result is expressed as the Brinell hardness number, which is the value obtained by dividing the applied load in kilograms by the surface area of the resulting impression in square millimeters.

brittle fracture. Separation of a solid accompanied by little or no macroscopic plastic deformation. Typically, brittle fracture occurs by rapid crack propagation with less expenditure of energy than for *ductile fracture*. Brittle tensile fractures have a bright, granular appearance and exhibit little or no necking (Fig. 3).

burning. (1) Permanently damaging a metal or alloy by heating to cause either incipient melting or intergranular oxidation. See *overheating, grain-boundary liquation*. (2) In grinding, getting the work hot enough to cause discoloration or to change the microstructure by tempering or hardening.

C

calorizing. Imparting resistance to oxidation to an iron or steel surface by heating in aluminum powder at 800 to 1000 °C (1470 to 1830 °F).

capped steel. A type of steel similar to rimmed steel, usually cast in a bottle-top ingot mold, in which the application of a mechanical or a chemical cap renders the rimming action incomplete by causing the top metal to solidify (Fig. 4). The surface condition of capped steel is much like that of rimmed steel, but certain other characteristics are intermediate between those of *rimmed steel* and those of *semi-killed steel*.

carbonitriding. A case hardening process in which a suitable ferrous material is heated above the lower transformation temperature in a gaseous atmosphere of such composition as to cause simultaneous absorption of carbon and nitrogen by the surface and, by diffusion, create a concentration gradient. The process is completed by cooling at a rate that produces the desired properties in the workpiece.

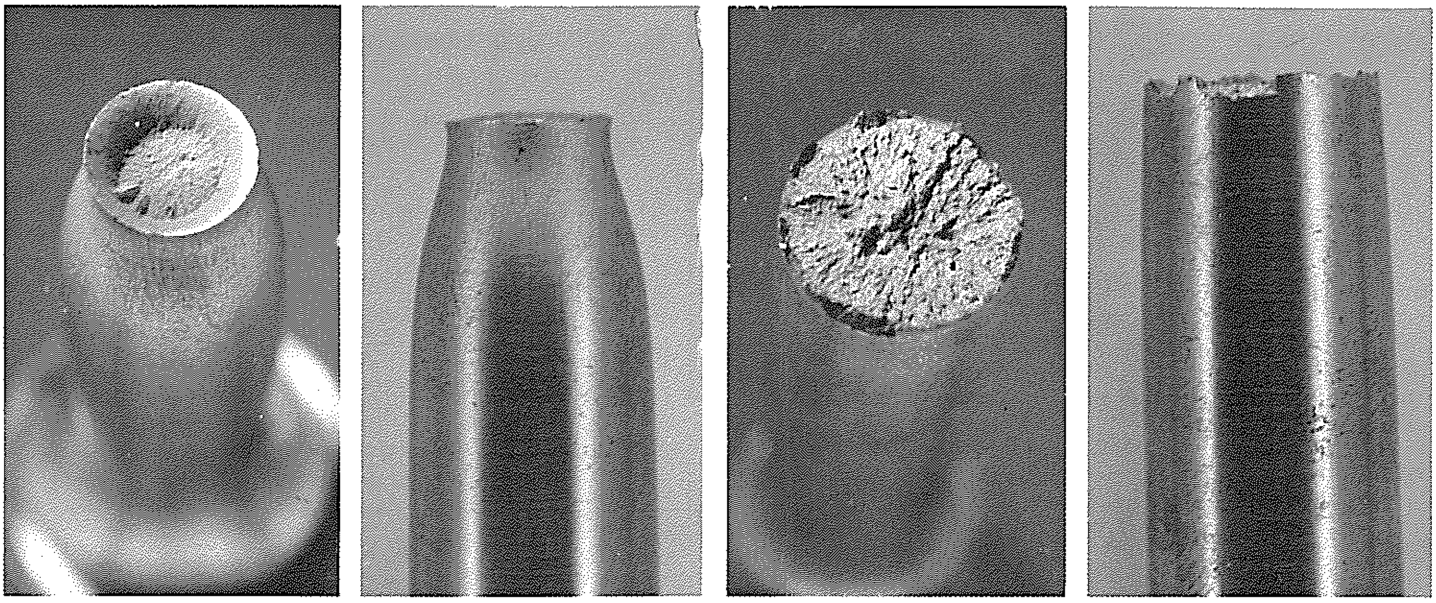
carbonization. Conversion of an organic substance into elemental carbon. (Should not be confused with car*bur*ization.)

carbon potential. A measure of the ability of an environment containing active carbon to alter or maintain, under prescribed conditions, the carbon level of the steel. Note: In any particular environment, the carbon level attained will depend on such factors as temperature, time, and steel composition.

carbon restoration. Replacing the carbon lost in the surface layer from previous processing by carburizing this layer to substantially the original carbon level. Sometimes called recarburizing.

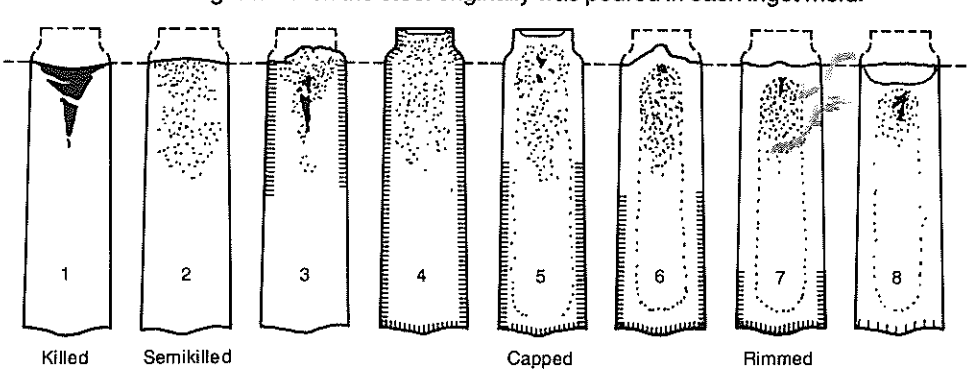
carbon steel. Steel having no specified minimum quantity for any alloying elements—other than the commonly accepted amounts of manganese (≤1.65%), silicon (≤0.60%), and copper (≤0.60%)—and containing only an incidental amount of any element other than carbon, silicon, manganese, copper, sulfur, and phosphorus. Low-carbon steels contain up to 0.30% C, medium-carbon steels contain from 0.30 to 0.60% C, and high-carbon steels contain from 0.60 to 1.00% C.

Fig. 3 Macroscopic appearance of ductile (a and b) and brittle (c and d) tensile fractures



(a) (b) (c) (d)

Fig. 4 Eight typical conditions of commercial steel ingots, cast in identical bottle-top molds, in relation to the degree of suppression of gas evolution. The dotted line indicates the height to which the steel originally was poured in each ingot mold.



rburizing. Absorption and diffusion of carbon into solid ferrous alloys by heating, to a temperature usually above Ac_3, in contact with a suitable carbonaceous material. A form of *case hardening* that produces a carbon gradient extending inward from the surface, enabling the surface layer to be hardened either by quenching directly from the carburizing temperature or by cooling to room temperature, then reaustenitizing and quenching.

rburizing flame. A gas flame that will introduce carbon into some heated metals, as during a gas welding operation. A carburizing flame is a *reducing flame,* but a reducing flame is not necessarily a carburizing flame.

r furnace. A batch-type furnace using a car on rails to enter and leave the furnace area. Car furnaces are used for lower stress relieving ranges.

se. That portion of a ferrous alloy, extending inward from the surface, whose composition has been altered so that it can be case hardened. Typically considered to be the portion of the alloy (a) whose composition has been measurably altered from the original composition, (b) that appears dark on an etched cross section, or (c) that has a hardness, after hardening, equal to or greater than a specified value. Contrast with *core.*

case hardening. A generic term covering several processes applicable to steel that change the chemical composition of the surface layer by absorption of carbon, nitrogen, or a mixture of the two and, by diffusion, create a concentration gradient. The processes commonly used are carburizing and quench hardening; cyaniding; nitriding; and carbonitriding. The use of the applicable specific process name is preferred.

cast iron. A generic term for a large family of cast ferrous alloys in which the carbon content exceeds the solubility of carbon in austenite at the eutectic temperature. Most cast irons contain at least 2% carbon, plus silicon and sulfur, and may not contain other alloying elements. For the various forms—*gray cast iron, white cast iron, ductile cast iron, compacted graphite cast iron,* and *malleable cast iron*—the word "cast" is often left out, resulting in "gray iron," "white iron," "ductile iron," "compacted graphite iron," and "malleable iron," respectively.

caustic quenching. Quenching with aqueous solutions of 5 to 10% sodium hydroxide (NaOH).

CCT diagram. See *continuous cooling transformation diagram.*

cementation. The introduction of one or more elements into the outer portion of a metal object by means of diffusion at high temperature.

Fig. 5 White cast iron containing massive cementite (white) and pearlite (dark). 500×

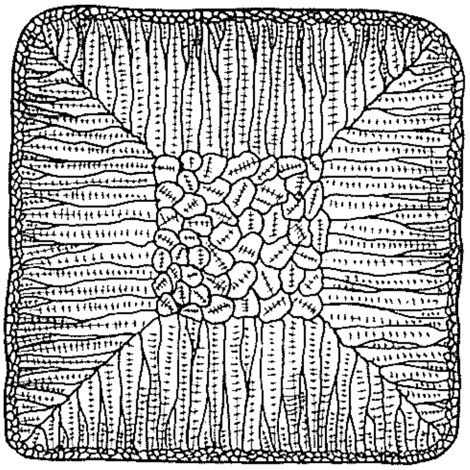


Fig. 6 Schematic cross section of a steel ingot showing typical columnar structure

cementite. A hard, brittle compound of iron and carbon, known chemically as iron carbide and having the approximate chemical formula Fe_3C. It is characterized by an orthorhombic crystal structure. When it occurs as a phase in steel, the chemical composition will be altered by the presence of manganese and other carbide-forming elements. The highest cementite contents are observed in white cast irons (Fig. 5).

checks. Numerous, very fine cracks in a coating or at the surface of a metal part. Checks may appear during processing or during service and are most often associated with thermal treatment or thermal cycling. Also called check marks, checking, heat checks.

close annealing. Same as *box annealing*.

coalescence. (1) The union of particles of a dispersed phase into larger units, usually effected at temperatures below the fusion point. (2) Growth of grains at the expense of the remainder by absorption or the growth of a phase or particle at the expense of the remainder by absorption or reprecipitation.

coarsening. An increase in the grain size, usually, but not necessarily, by *grain growth*.

coherent precipitate. A crystalline precipitate that forms from solid solution with an orientation that maintains continuity between the crystal lattice of the precipitate and the lattice of the matrix, usually accompanied by some strain in both lattices. Because the lattices fit at the interface between precipitate and matrix, there is no discernible phase boundary.

cold die quenching. A quench utilizing cold, flat, or shaped dies to extract heat from a part. Cold die quenching is slow, expensive, and is limited to smaller parts with large surface areas.

cold dry die quenching. Same as *cold die quenching*.

cold treatment. Treatment carried out after quenching to transform retained austenite into martensite, involving cooling and holding at a temperature below ambient.

columnar structure. A coarse structure of parallel elongated grains formed by unidirectional growth, most often observed in castings (Fig. 6), but sometimes in structures resulting from diffusional growth accompanied by a solid-state transformation.

combined carbon. The part of the total carbon in steel or cast iron that is present as other than *free carbon*.

compacted graphite cast iron. A cast iron having a graphite shape between the flake form typical of gray iron and the spherical form of ductile iron. Also known as CG iron or vermicular iron. See also the figures accompanying the terms *ductile cast iron* and *gray cast iron*.

conditioning heat treatment. A preliminary heat treatment used to prepare a material for desired reaction to a subsequent heat treatment. For the term to be meaningful, the exact heat treatment must be specified.

congruent transformation. An isothermal or isobaric phase change in which both of the phases concerned have the same composition throughout the process.

constitution diagram. See *phase diagram*.

continuous cooling transformation (CCT) diagram. Set of curves drawn using logarithmic time and linear temperature as coordinates, which define for each cooling curve the beginning and end of the transformation of the initial phase (Fig. 7).

continuous precipitation. Precipitation from a supersaturated solid solution in which the precipitate particles grow by long-range diffusion without recrystallization of the matrix. Continuous precipitates grow from nuclei distributed more or less uniformly throughout the matrix. They usually are randomly oriented, but may form a *Widmanstätten structure*. Also called general precipitation. Compare with *discontinuous precipitation* and *localized precipitation*.

continuous-type furnace. A furnace used for heat treating materials that progress continuously through the furnace, entering one door and being discharged from another. See also *belt furnace, direct-fired tunnel-type furnace, rotary retort furnace*, and *shaker-hearth furnace*.

controlled cooling. Cooling from an elevated temperature in a predetermined manner, to avoid hardening, cracking, or internal damage, or to produce desired microstructure or mechanical properties.

cooling curve. A curve showing the relation between time and temperature during the cooling of a material. It is used to find the temperature at which phase changes occur.

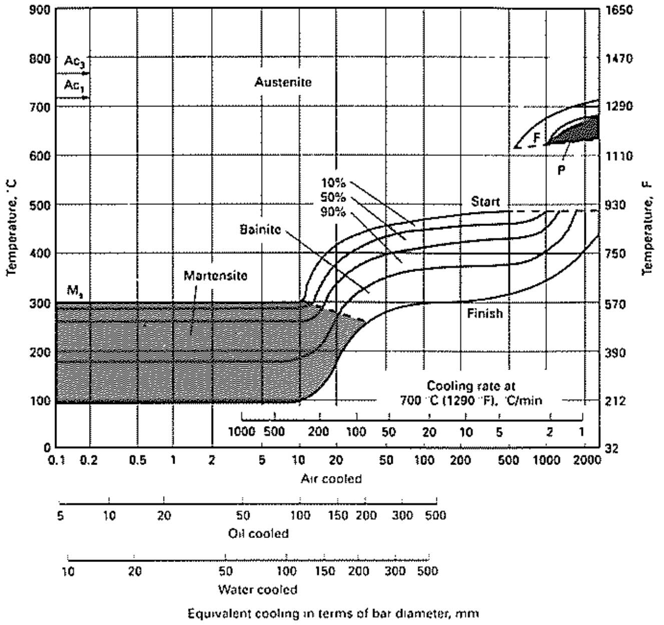
cooling stresses. Residual stresses resulting from nonuniform distribution of temperature during cooling.

core. In a ferrous alloy prepared for *case hardening*, that portion of the alloy that is not part of the *case*. Typically considered to be the portion that (a) appears light on an etched cross section, (b) has an essentially unaltered chemical composition, or (c) has a hardness, after hardening, less than a specified value.

critical cooling rate. The rate of continuous cooling required to prevent undesirable transformation. For steel, it is the minimum rate at which austenite must be continuously cooled to suppress transformations above the M_s temperature.

critical diameter. Diameter of the bar that can be fully hardened with 50% martensite at its center.

ig. 7 CCT diagram for an alloy steel with 0.40% C, 1.50% Ni, .20% Cr, and 0.30% Mo, plotted as a function of bar diameter



tical point. (1) The temperature or pressure at which a change in crystal structure, phase, or physical properties occurs. Same as *transformation temperature*. (2) In an equilibrium diagram, that specific value of composition, temperature, and pressure, or combinations thereof, at which the phases of a heterogeneous system are in equilibrium.

tical strain. The strain just sufficient to cause *recrystallization;* because the strain is small, usually only a few percent, recrystallization takes place from only a few nuclei, which produces a recrystallized structure consisting of very large grains.

tical temperature. (1) Synonymous with *critical point* if the pressure is constant. (2) The temperature above which the vapor phase cannot be condensed to liquid by an increase in pressure.

tical temperature ranges. Synonymous with *transformation ranges*, which is the preferred term.

'ogenic treatment. See *cold treatment*.

iniding. A case-hardening process in which a ferrous material is heated above the lower transformation range in a molten salt containing cyanide to cause simultaneous absorption of carbon and nitrogen at the surface and, by diffusion, create a concentration gradient. Quench hardening completes the process.

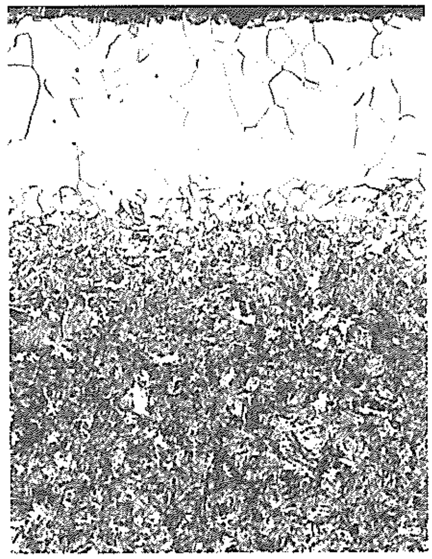
:le annealing. An annealing process employing a predetermined and closely controlled time-temperature cycle to produce specific properties or microstructures.

ad soft. A *temper* of nonferrous alloys and some ferrous alloys corresponding to the condition of minimum hardness and tensile strength produced by *full annealing*.

calescence. A phenomenon, associated with the transformation of alpha iron to gamma iron on the heating (superheating) of iron or steel, revealed by the darkening of the metal surface owing to the sudden decrease in temperature caused by the fast absorption of the latent heat of transformation. Contrast with *recalescence*.

carburization. Loss of carbon from the surface layer of a carbon-containing alloy due to reaction with one or more chemical substances in a medium that contacts the surface (Fig. 8).

Fig. 8 Decarburization of a spring steel



degrees of freedom. The number of independent variables (such as temperature, pressure, or concentration within the phases present) that may be altered at will without causing a phase change in an alloy system at equilibrium; or the number of such variables that must be fixed arbitrarily to define the system completely.

delta ferrite. See *ferrite*.

dew point. The temperature and pressure at which a gas begins to condense to a liquid.

dew point analyzer. An atmosphere monitoring device that measures the partial pressure of water vapor in an atmosphere.

differential heating. Heating that intentionally produces a temperature gradient within an object such that, after cooling, a desired stress distribution or variation in properties is present within the object.

diffusion. (1) Spreading of a constituent in a gas, liquid, or solid, tending to make the composition of all parts uniform. (2) The spontaneous movement of atoms or molecules to new sites within a material.

diffusion coefficient. A factor of proportionality representing the amount of substance diffusing across a unit area through a unit concentration gradient in unit time.

dilatometer. An instrument for measuring the linear expansion or contraction in a metal resulting from changes in such factors as temperature and *allotropy*.

direct-fired tunnel-type furnace. A continuous-type furnace where the work is conveyed through a tunnel-type heating zone, and the parts are hung on hooks or fixtures to minimize distortion.

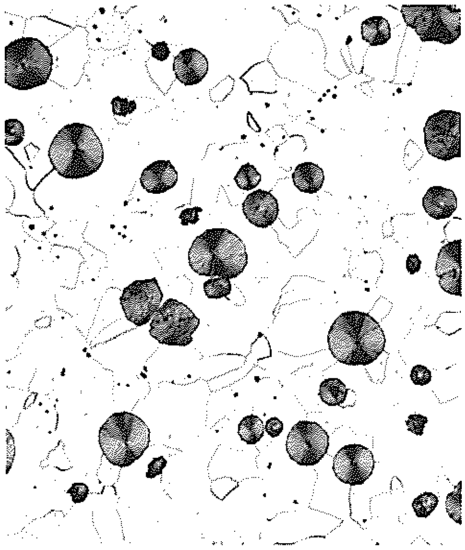
direct quenching. (1) Quenching carburized parts directly from the carburizing operation. (2) Also used for quenching pearlitic malleable parts directly from the malleablizing operation.

discontinuous precipitation. Precipitation from a supersaturated solid solution in which the precipitate particles grow by short-range diffusion, accompanied by recrystallization of the matrix in the region of precipitation. Discontinuous precipitates grow into the matrix from nuclei near grain boundaries, forming cells of alternate lamellae of precipitate and depleted (and recrystallized) matrix. Often referred to as cellular or nodular precipitation. Compare with *continuous precipitation* and *localized precipitation*.

dissociation. As applied to heterogeneous equilibria, the transformation of one phase into two or more new phases of different composition. Compare with *order-disorder transformation*.

double aging. Employment of two different aging treatments to control the type of precipitate formed from a supersaturated matrix in order to obtain the desired properties. The first aging treatment, sometimes

Fig. 9 Microstructure of annealed ductile iron. Note spheroidal shape of graphite nodules. 100×



referred to as intermediate or stabilizing, is usually carried out at higher temperature than the second.

double tempering. A treatment in which a quench-hardened ferrous metal is subjected to two complete tempering cycles, usually at substantially the same temperature, for the purpose of ensuring completion of the tempering reaction and promoting stability of the resulting microstructure.

drawing. A misnomer for *tempering*.

dry cyaniding. (obsolete) Same as *carbonitriding*.

ductile cast iron. A cast iron that has been treated while molten with an element such as magnesium or cerium to induce the formation of free graphite as nodules or spherulites (Fig. 9), which imparts a measurable degree of ductility to the cast metal. Also known as nodular cast iron, spherulitic graphite cast iron, and SG iron.

ductile fracture. Fracture characterized by tearing of metal accompanied by appreciable gross plastic deformation and expenditure of considerable energy. Contrast with *brittle fracture* (see also the figure accompanying *brittle fracture*).

ductility. The ability of a material to deform plastically without fracturing, measured by elongation or reduction of area in a tensile test, by height of cupping in an Erichsen test, or by other means.

E

475 °C (885 °F) embrittlement. *Embrittlement* of stainless steels upon extended exposure to temperatures between 400 and 510 °C (750 and 950 °F). This type of embrittlement is caused by fine, chromium-rich precipitates that segregate at grain boundaries; time at temperature directly influences the amount of segregation. Grain-boundary segregation of the chromium-rich precipitates increases strength and hardness, decreases ductility and toughness, and changes corrosion resistance. This type of embrittlement can be reversed by heating above the precipitation range.

elastic limit. The maximum stress that a material is capable of sustaining without any permanent strain (deformation) remaining upon complete release of the stress.

electron-beam heat treating. A selective surface hardening process that rapidly heats a surface by direct bombardment with an accelerated stream of electrons.

embrittlement. The severe loss of *ductility* or *toughness* or both, of a material, usually a metal or alloy. Many forms of embrittlement can lead to *brittle fracture*. Many forms can occur during thermal treatment or elevated-temperature service (thermally induced embrittlement). Some of these forms of embrittlement, which affect steels, include *blue brittleness, 885 °F (475 °C) embrittlement, quench-age embrittlement, sigma-phase embrittlement, strain-age embrittlement, temper embrittlement, tempered martensite embrittlement,* and *thermal embrittlement.* In addition, steels can be embrittled by environmental conditions (environmentally assisted embrittlement).

enantiotropy. The relation of crystal forms of the same substance in which one form is stable above a certain temperature and the other form stable below that temperature. Ferrite and austenite are enantiotropic in ferrous alloys, for example.

end-quench hardenability test. A laboratory procedure for determining the hardenability of a steel or other ferrous alloy; widely referred to as the *Jominy test.* Hardenability is determined by heating a standard specimen above the upper critical temperature, placing the hot specimen in a fixture so that a stream of cold water impinges on one end (Fig. 10a), and, after cooling to room temperature is completed, measuring the hardness near the surface of the specimen at regularly spaced intervals along its length. The data are normally plotted as hardness versus distance from the quenched end (Fig. 10b).

equilibrium diagram. A graphical representation of the temperature, pressure, and composition limits of phase fields in an alloy system as they exist under conditions of complete equilibrium. In metal systems, pressure is usually considered constant.

eutectic. (1) An isothermal reversible reaction in which a liquid solution is converted into two or more intimately mixed solids on cooling, the number of solids formed being the same as the number of components in the system. (2) An alloy having the composition indicated by the eutectic point on an equilibrium diagram. (3) An alloy structure of intermixed solid constituents formed by a eutectic reaction.

eutectic carbide. Carbide formed during freezing as one of the mutually insoluble phases participating in the eutectic reaction of ferrous alloys.

eutectic melting. Melting of localized microscopic areas whose composition corresponds to that of the eutectic in the system.

eutectoid. (1) An isothermal reversible reaction in which a solid solution is converted into two or more intimately mixed solids on cooling, the number of solids formed being the same as the number of components in the system. (2) An alloy having the composition indicated by the eutectoid point on an equilibrium diagram. (3) An alloy structure of intermixed solid constituents formed by a eutectoid reaction.

extra hard. A *temper* of some ferrous alloys characterized by tensile strength and hardness about one-third of the way from *full hard* to *extra spring temper.*

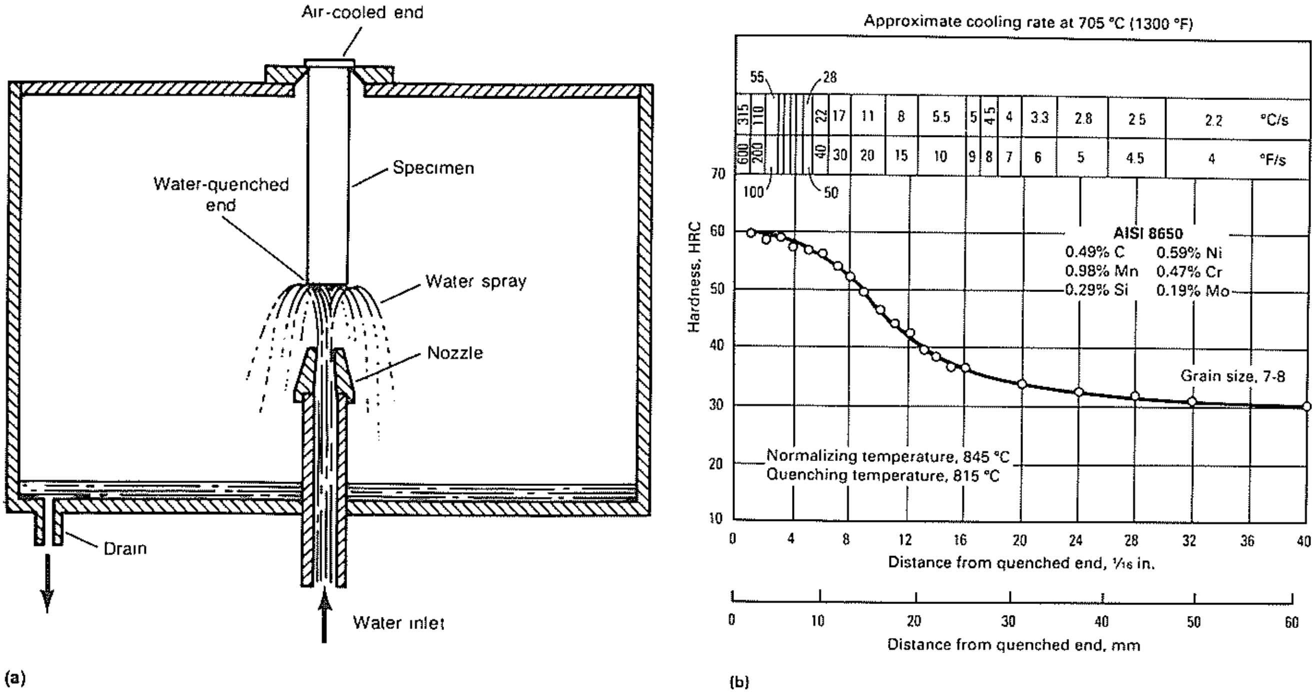
extra spring. A *temper* of some ferrous alloys corresponding approximately to a cold-worked state above *full hard* beyond which further cold work will not measurably increase the strength and hardness.

F

ferrite. (1) A solid solution of one or more elements in body-centered cubic iron. Unless otherwise designated (for instance, as chromium ferrite), the solute is generally assumed to be carbon. On some equilibrium diagrams, there are two ferrite regions separated by an austenite area. The lower area is alpha ferrite; the upper, delta ferrite. If there is no designation, alpha ferrite is assumed. (2) An essentially carbon-free solid solution in which alpha iron is the solvent, and which is characterized by a body-centered cubic crystal structure. Fully ferritic steels are only obtained when the carbon content is quite low. The most obvious microstructural features in such metals are the ferrite grain boundaries (Fig. 11).

ferritizing anneal. A treatment given as-cast gray or ductile (nodular) iron to produce an essentially ferritic matrix. For the term to be meaningful,

. **10** Jominy end-quench apparatus (a) and method for presenting end-quench hardenability data (b)



: final microstructure desired or the time-temperature cycle used must specified.

ınnealing. An imprecise term used to denote the last anneal given to onferrous alloy prior to shipment.

annealing. A *subcritical annealing* treatment applied to cold-rked low- or medium-carbon steel. Finish annealing, which is a npromise treatment, lowers residual stresses, thereby minimizing the ‹ of distortion in machining while retaining most of the benefits to chinability contributed by cold working. Compare with *final anneal-*.

ing temperature. The temperature at which hot working is com-ted.

ing. The placing of parts to be heat treated in a constraining or niconstraining apparatus to avoid heat-related distortions. See also *king.*

graphite. Graphitic carbon, in the form of platelets, occurring in the :rostructure of *gray cast iron* (Fig. 12).

annealing. Annealing in which the heat is applied directly by a ne.

hardening. A process for hardening the surfaces of hardenable ous alloys in which an intense flame is used to heat the surface layers ›ve the upper transformation temperature, whereupon the workpiece mmediately quenched.

straightening. Correcting distortion in metal structures by localized ting with a gas flame.

ed-bed heating. Heating carried out in a medium of solid particles pended in a flow of gas.

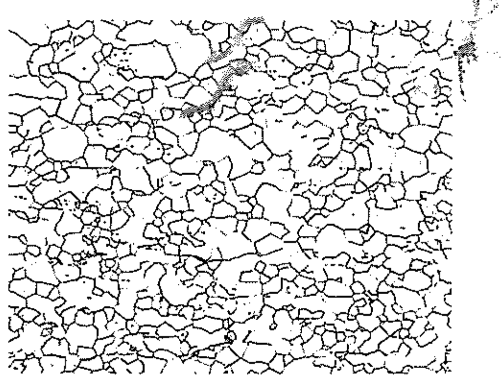
enching. Quenching in a fine vapor or mist.

-air quench. A quench utilizing blasts of compressed air against ıtively small parts such as a gear.

ırbon. The part of the total carbon in steel or cast iron that is present lemental form as graphite or temper carbon. Contrast with *combined bon.*

rrite. (1) Ferrite that is formed directly from the decomposition of ›oeutectoid austenite during cooling, without the simultaneous for-:ion of cementite. (2) Ferrite formed into separate grains and not mately associated with carbides as in pearlite. Also proeutectoid ite.

Fig. 11 Low-carbon ferritic steel etched to reveal ferrite grain boundaries. 100×



freezing range. That temperature range between liquidus and solidus temperatures in which molten and solid constituents coexist.

full annealing. An imprecise term that denotes an annealing cycle to produce minimum strength and hardness. For the term to be meaningful, the composition and starting condition of the material and the time-temperature cycle used must be stated.

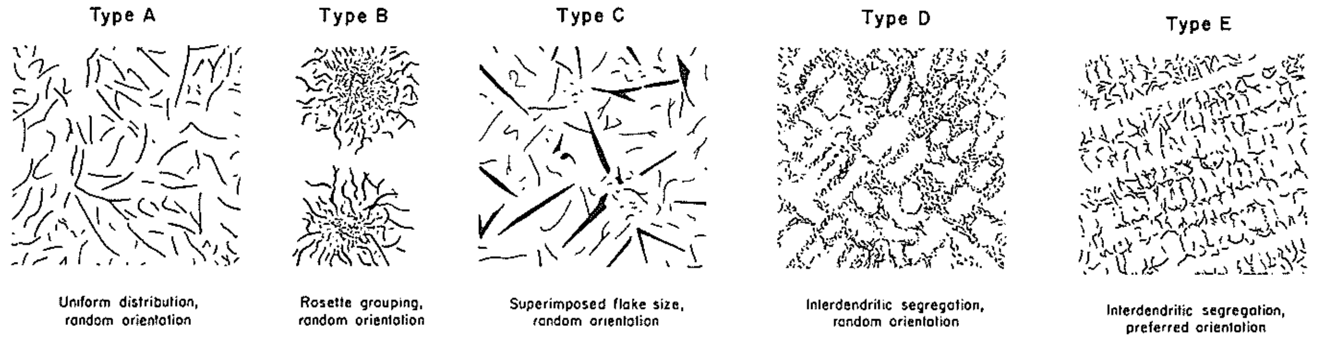
full hard. A *temper* of some ferrous alloys corresponding approximately to a cold-worked state beyond which the material can no longer be formed by bending. In specifications, a full hard temper is commonly defined in terms of minimum hardness or minimum tensile strength (or, alternatively, a range of hardness or strength) corresponding to a specific percentage of cold reduction following a full anneal.

G

gamma iron. The face-centered cubic form of pure iron, stable from 910 to 1400 °C (1670 to 2550 °F).

gas cyaniding. A misnomer for *carbonitriding.*

Fig. 12 Types of graphite flakes in gray iron (per ASTM)



grain-boundary liquation. An advanced stage of overheating in which material in the region of austenitic grain boundaries melts. Also termed *burning*.

grain coarsening. A heat treatment that produces excessively large austenitic grains.

grain growth. An increase in the average size of the grains in polycrystalline metal, usually as a result of heating at elevated temperature.

grain refiner. A material added to a molten metal to induce a finer-than-normal grain size in the final structure.

grain size. For metals, a measure of the areas or volumes of grains in a polycrystalline material, usually expressed as an average when the individual sizes are fairly uniform. In metals containing two or more phases, the grain size refers to that of the matrix unless otherwise specified. Grain sizes are reported in terms of number of grains per unit area or volume, average diameter, or as a grain-size number derived from area measurements.

graphitic carbon. Free carbon in steel or cast iron. See also *graphitization*.

graphitization. Formation of graphite in iron or steel. Where graphite is formed during solidification, the phenomenon is called primary graphitization; where formed later by heat treatment, secondary graphitization.

graphitizing. Annealing a ferrous alloy in such a way that some or all of the carbon is precipitated as graphite.

gray cast iron. A *cast iron* that gives a gray fracture due to the presence of *flake graphite*. Often called gray iron.

Grossmann chart. A chart describing the ability of a quenching medium to extract heat from a hot steel workpiece in comparison to still water.

Grossmann number (*H*). A ratio describing the ability of a quenching medium to extract heat from a hot steel workpiece in comparison to still water defined by the following equation:

$$H = h/2k$$

where h is the heat transfer coefficient and k is the conductivity of the metal.

Guinier-Preston (G-P) zone. A small precipitation domain in a supersaturated metallic solid solution. A G-P zone has no well-defined crystalline structure of its own and contains an abnormally high concentration of solute atoms. The formation of G-P zones constitutes the first stage of precipitation and is usually accompanied by a change in properties of the solid solution in which they occur.

H

half hard. A *temper* of some ferrous alloys characterized by tensile strength about midway between that of *dead soft* and *full hard* tempers.

hardenability. The relative ability of a ferrous alloy to form martensite when quenched from a temperature above the upper critical temperature. Hardenability is commonly measured as the distance below a quenched surface where the metal exhibits a specific hardness (50 HRC, for example) or a specific percentage of martensite in the microstructure.

hardening. Increasing hardness by suitable treatment, usually involving heating and cooling. When applicable, the following more specific terms should be used: *age hardening, flame hardening, induction hardening, laser hardening, precipitation hardening,* and *quench hardening*.

hardness. Resistance of metal to plastic deformation, usually by indentation. However, the term may also refer to stiffness or temper, or to resistance to scratching, abrasion, or cutting. Indentation hardness may be measured by various hardness tests, such as *Brinell, Rockwell, Knoop*, and *Vickers*.

hardness profile. Hardness as a function of distance from a fixed reference point (usually from the surface).

hard temper. Same as *full hard* temper.

heat checks. See *checks*.

heat tinting. Coloration of a metal surface through oxidation by heating to reveal details of the microstructure.

heat-treatable alloy. An alloy that can be hardened by heat treatment.

heat-treating film. A thin coating or film, usually an oxide, formed on the surface of metals during heat treatment.

heat treatment. Heating and cooling a solid metal or alloy in such a way as to obtain desired conditions or properties.

holding. The portion of the thermal cycle during which the temperature of the object is maintained constant.

holding temperature. The constant temperature at which the object is maintained.

holding time. Time for which the temperature of the object is maintained constant.

homogeneous carburizing. Use of a carburizing process to convert a low-carbon ferrous alloy to one of uniform and higher carbon content throughout the section.

homogenizing. Holding at high temperature to eliminate or decrease chemical segregation by diffusion.

horizontal batch furnace. A versatile batch-type furnace that can give light or deep case depths, and because the parts are not exposed to air, horizontal batch furnaces can give surfaces almost entirely free of oxides.

hot quenching. An imprecise term used to cover a variety of quenching procedures in which a quenching medium is maintained at a prescribed temperature above 70 °C (160 °F).

hot-wire analyzer. An electrical atmosphere analysis device that is based on the fact that the electrical resistivity of steel is a linear function of carbon content over a range from 0.05% C to saturation. The device measures the carbon potential of furnace atmospheres (typically). This term is not to be confused with the *hot-wire test* which measures heat extraction rates.

hot-wire test. Method used to test heat extraction rates of various quenchants. Faster heat-extracting quenchants will permit more electric current to pass through a standard wire because it is cooled more quickly. Compare with *hot-wire analyzer.*

hypereutectic alloy. In an alloy system exhibiting a eutectic, any alloy whose composition has an excess of alloying element compared with the eutectic composition, and whose equilibrium microstructure contains some eutectic structure.

hypereutectoid alloy. In an alloy system exhibiting a eutectoid, any alloy whose composition has an excess of alloying element compared with the eutectoid composition, and whose equilibrium microstructure contains some eutectoid structure.

hypoeutectic alloy. In an alloy system exhibiting a eutectic, any alloy whose composition has an excess of base metal compared with the eutectic composition, and whose equilibrium microstructure contains some eutectic structure.

hypoeutectoid alloy. In an alloy system exhibiting a eutectoid, any alloy whose composition has an excess of base metal compared with the eutectoid composition, and whose equilibrium microstructure contains some eutectoid structure.

Fig. 13 Internally heat salt bath furnace with immersed electrodes

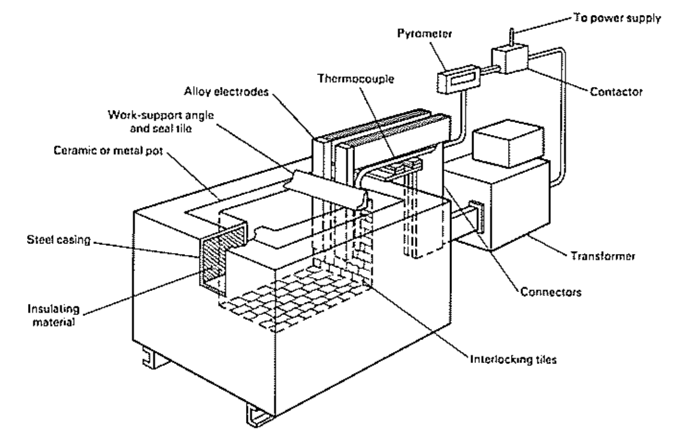
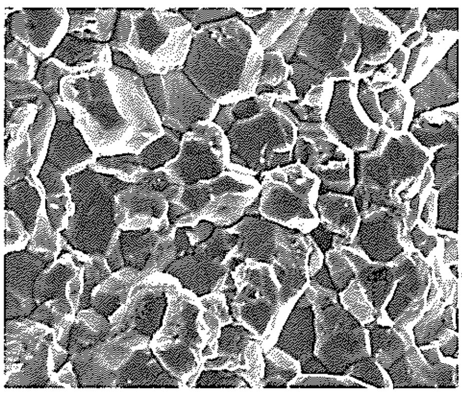


Fig. 14 Intergranular fracture of a maraging steel



I

ideal critical diameter (D_I). Under an ideal quench condition, the bar diameter that has 50% martensite at the center of the bar when the surface is cooled at an infinitely rapid rate (that is, when $H = \infty$, where H is the quench severity factor or *Grossmann number*).

immersed-electrode furnaces. A furnace used for liquid carburizing of parts by heating molten salt baths with the use of electrodes immersed in the liquid (Fig. 13). See also *submerged-electrode furnace.*

impact tube. Same as *Pitot tube.*

induction hardening. A surface-hardening process in which only the surface layer of a suitable ferrous workpiece is heated by electromagnetic induction to above the upper critical temperature and immediately quenched.

induction heating. Heating by combined electrical resistance and hysteresis losses induced by subjecting a metal to the varying magnetic field surrounding a coil carrying alternating current.

induction tempering. Tempering of steel using low-frequency electrical *induction heating.*

infrared analyzer. An atmosphere-monitoring device that measures a gas (usually carbon monoxide, carbon dioxide, and methane) presence based on specific wavelength absorption of infrared energy.

intense quenching. Quenching in which the quenching medium is cooling the part at a rate at least two and a half times faster than still water. See also *Grossmann chart.*

intercritical annealing. Any annealing treatment that involves heating to, and holding at, a temperature between the upper and lower critical temperatures to obtain partial austenitization, followed by either slow cooling or holding at a temperature below the lower critical temperature.

intergranular. Between crystals or grains. Also called intercrystalline. Contrast with *transgranular.*

intergranular cracking. Cracking or fracturing that occurs between the grains or crystals in a polycrystalline aggregate. Also called intercrystalline cracking. Contrast with *transgranular cracking.*

intergranular fracture. Brittle fracture of a polycrystalline material in which the fracture is between the grains, or crystals, that form the material (Fig. 14). Also called intercrystalline fracture. Contrast with *transgranular fracture.*

intermediate annealing. Annealing wrought metals at one or more stages during manufacture and before final treatment.

interrupted aging. Aging at two or more temperatures, by steps, and cooling to room temperature after each step. See also *aging,* and compare with *progressive aging* and *step aging.*

interrupted quenching. A quenching procedure in which the workpiece is removed from the first quench at a temperature substantially higher than that of the quenchant and is then subjected to a second quenching system having a different cooling rate than the first.

interval test. Method used to test heat extraction rates of various quenchants. This test measures the increase in temperature of a quenchant when a standard bar of metal is quenched for five seconds. Faster quenchants will exhibit greater temperature increases.

ion carburizing. A method of surface hardening in which carbon ions are diffused into a workpiece in a vacuum through the use of high-voltage electrical energy. Synonymous with plasma carburizing or glow-discharge carburizing.

ion nitriding. A method of surface hardening in which nitrogen ions are diffused into a workpiece in a vacuum through the use of high-voltage electrical energy. Synonymous with plasma nitriding or glow-discharge nitriding.

isothermal annealing. Austenitizing a ferrous alloy and then cooling to and holding at a temperature at which austenite transforms to a relatively soft ferrite carbide aggregate.

isothermal transformation. A change in phase that takes place at a constant temperature. The time required for transformation to be completed, and in some instances the time delay before transformation begins, depends on the amount of supercooling below (or superheating above) the equilibrium temperature for the same transformation.

isothermal transformation (IT) diagram. (1) Set of curves drawn using logarithmic time and linear temperature as coordinates, which define for each level of temperature the beginning and end of the transformation

Fig. 15 Isothermal transformation diagram for a steel with 0.39% C, 0.86% Mn, 0.72% Cr, and 0.97% Ni. The upper C-shape curves describe transformation to pearlite; the low C-shape curves to bainite

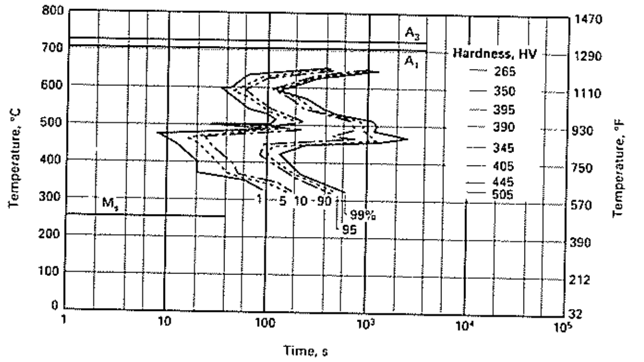
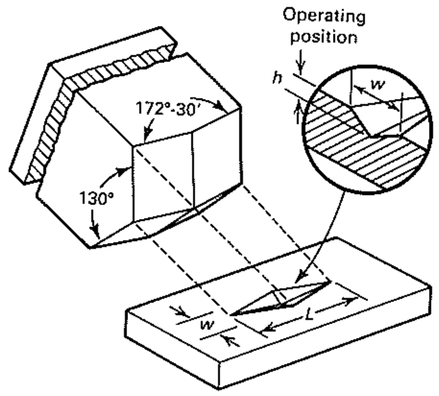


Fig. 16 Pyramidal Knoop indenter and resulting indention in the workpiece



of the initial phase under isothermal conditions. (2) A diagram that shows the isothermal time required for transformation of austenite to begin and to finish as a function of temperature (Fig. 15). Same as time-temperature-transformation (TTT) diagram or S-curve.

J

Jominy test. See *end-quench hardenability test.*

K

killed steel. Steel treated with a strong deoxidizing agent such as silicon or aluminum in order to reduce the oxygen content to such a level that no reaction occurs between carbon and oxygen during solidification. See also the figure accompanying the term *capped steel.*

kish. Free graphite that forms in molten hypereutectic cast iron as it cools. In castings, the kish may segregate toward the cope surface, where it lodges at or immediately beneath the casting surface.

Knoop hardness test. An indentation hardness test using calibrated machines to force a rhombic-based pyramidal diamond indenter having specified edge angles, under specified conditions, into the surface of the material under test and to measure the long diagonal after removal of the load (Fig. 16).

L

laser hardening. A surface-hardening process which uses a laser to quickly heat a surface. Heat conduction into the interior of the part will quickly cool the surface, leaving a shallow martensitic layer.

latent heat. Thermal energy absorbed or released when a substance undergoes a phase change.

lath martensite. Martensite formed partly in steels containing less than approximately 1.0% carbon and solely in steels containing less than approximately 0.5% carbon as parallel arrays of packets of lath-shape units 0.1 to 0.3 μm thick (Fig. 17).

ledeburite. The eutectic of the iron-carbon system, the constituents being austenite and cementite. The austenite decomposes into ferrite and cementite on cooling below the Ar_1.

Leidenfrost phenomenon. Slow cooling rates associated with a hot vapor blanket that surrounds a part being quenched in a liquid medium such as water. The gaseous vapor envelope acts as an insulator, thus slowing the cooling rate.

Fig. 17 Lath martensite in a water-quenched 0.20% C steel. 500×

liquation temperature. The lowest temperature at which partial melting can occur in an alloy that exhibits the greatest possible degree of segregation.

liquid carburizing. Surface hardening of steel by immersion into a molten bath consisting of cyanides and other salts.

liquid nitriding. A method of surface hardening in which molten nitrogen-bearing, fused-salt baths containing both cyanides and cyanates are exposed to parts at subcritical temperatures.

liquid nitrocarburizing. A nitrocarburizing process (where both carbon and nitrogen are absorbed into the surface) utilizing molten liquid salt baths below the lower critical temperature.

liquid spray quench. Same as *spray quenching.*

localized precipitation. Precipitation from a supersaturated solid solution similar to *continuous precipitation,* except that the precipitate particles form at preferred locations, such as along slip planes, grain boundaries, or incoherent twin boundaries.

M

magnetic quenchometer test. Method used to test heat extraction rates of various quenchants. The test works by utilizing the change in magnetic properties of metals at their Curie point—the temperature above which metals lose their magnetism.

malleable cast iron. A *cast iron* made by prolonged annealing of white cast iron in which decarburization of graphitization, or both, take place to eliminate some or all of the cementite. The graphite is in the form of temper carbon. If decarburization is the predominant reaction, the product will exhibit a light fracture surface, hence, "whiteheart malleable," otherwise, the fracture surface will be dark, hence, "blackheart malleable." Ferritic malleable has a predominantly ferritic matrix; pearlitic malleable may contain pearlitic, spheroidite, or tempered martensite depending on heat treatment and desired hardness.

malleablizing. Annealing white cast iron in such a way that some or all of the combined carbon is transformed to graphite or, in some instances, part of the carbon is removed completely.

maraging. A precipitation-hardening treatment applied to a special group of high-nickel-content (12 to 18 wt% Ni) iron-base alloys (maraging steels) to precipitate one or more intermetallic compounds in a matrix of essentially carbon-free martensite.

marquenching. See *martempering.*

martempering. (1) A hardening procedure in which an austenitized ferrous workpiece is quenched into an appropriate medium whose temperature is maintained substantially at the M_s of the workpiece, held in the medium until its temperature is uniform throughout—but not long enough to permit bainite to form—and then cooled in air. The treatment is frequently followed by tempering. (2) When the process is applied to carburized material, the controlling M_s temperature is that of the case. This variation of the process is frequently called marquenching.

martensite. A generic term for microstructures formed by diffusionless phase transformation in which the parent and product phases have a specific crystallographic relationship. Martensite is characterized by an acicular pattern in the microstructure in both ferrous and nonferrous alloys. In alloys where the solute atoms occupy interstitial positions in the martensitic lattice (such as carbon in iron), the structure is hard and highly strained; but where the solute atoms occupy substitutional positions (such as nickel in iron), the martensite is soft and ductile. The amount of high-temperature phase that transforms to martensite on cooling depends to a large extent on the lowest temperature attained, there being a rather distinct beginning temperature (M_s) and a temperature at which the transformation is essentially complete (M_f). See also *lath martensite*, *plate martensite*, and *tempered martensite*.

martensite range. The temperature interval between M_s and M_f.

martensitic transformation. A reaction that takes place in some metals on cooling, with the formation of an acicular structure called *martensite.*

McQuaid-Ehn test. A test to reveal grain size after heating into the austenitic temperature range. Eight standard McQuaid-Ehn grain sizes rate the structure, No. 8 being finest, No. 1 coarsest.

M_f temperature. For any alloy system, the temperature at which martensite formation on cooling is essentially finished. See *transformation temperature* for the definition applicable to ferrous alloys.

microhardness. The hardness of a material as determined by forcing an indenter such as a Vickers or Knoop indenter into the surface of a material under very light load; usually, the indentations are so small that they must be measured with a microscope. Capable of determining hardnesses of different microconstituents within a structure, or of measuring steep hardness gradients such as those encountered in case hardening. See also *Knoop hardness test* and *Vickers hardness test.*

microscopic stresses. Residual stresses that vary from tension to compression in a distance (presumably approximating the grain size) that is small compared with the gage length in ordinary strain measurements. They are not detectable by dissection methods, but can sometimes be measured from line shift or line broadening in an x-ray diffraction pattern.

microsegregation. Segregation within a grain, crystal, or small particle.

mill scale. The heavy oxide layer formed during hot fabrication or heat treatment of metals.

monotropism. The ability of a solid to exist in two or more forms (crystal structures), but in which one form is the stable modification at all temperatures and pressures. Ferrite and martensite are a monotropic pair below Ac_1 in steels, for example. May also be spelled monotrophism.

M_s temperature. For any alloy system, the temperature at which martensite starts to form on cooling. See *transformation temperature* for the definition applicable to ferrous alloys.

N

natural aging. Spontaneous aging of a supersaturated solid solution at room temperature. See also *aging,* and compare with *artificial aging.*

neutral flame. A gas flame in which there is no excess of either fuel or oxygen in the inner flame. Oxygen from ambient air is used to complete the combustion of CO_2 and H_2 produced in the inner flame.

neutralization number. An ASTM number given to quenching oils that reflects the oil's tendency towards oxidation and sludging. See also *saponification number.*

nitriding. Introducing nitrogen into the surface layer of a solid ferrous alloy by holding at a suitable temperature (below Ac_1 for ferritic steels) in contact with a nitrogenous material, usually ammonia or molten cyanide of appropriate composition. Quenching is not required to produce a hard case. See also *aerated bath nitriding, bright nitriding,* and *liquid nitriding.*

nitrocarburizing. Any of several processes in which both nitrogen and carbon are absorbed into the surface layers of a ferrous material at temperatures below the lower critical temperature and, by diffusion, create a concentration gradient. Nitrocarburizing is done mainly to provide an antiscuffing surface layer and to improve fatigue resistance. Compare with *carbonitriding.*

normalizing. Heating a ferrous alloy to a suitable temperature above the transformation range and then cooling in air to a temperature substantially below the transformation range.

nucleation. The initiation of a phase transformation at discrete sites, the new phase growing on nuclei. See *nucleus.*

nucleus. The first structurally stable particle capable of initiating recrystallization of a phase or the growth of a new phase, and possessing an interface with the parent matrix. The term is also applied to a foreign particle that initiates such action.

O

oil hardening. Quench-hardening treatment involving cooling in oil.

oil quenching. Hardening of carbon steel in an oil bath. Oils are categorized as conventional, fast, *martempering,* or *hot quenching.*

optical pyrometer. An instrument for measuring the temperature of heated material by comparing the intensity of light emitted with a known intensity of an incandescent lamp filament.

order-disorder transformation. A phase change among two solid solutions having the same crystal structure, but in which the atoms of one phase (disordered) are randomly distributed; in the other, the different kinds of atoms occur in a regular sequence upon the crystal lattice, that is, in an ordered arrangement. Compare with *dissociation.*

order hardening. A low-temperature *annealing* treatment that permits short-range ordering of solute atoms within a matrix, which greatly impedes dislocation motion.

Orsat analyzer. An atmosphere analysis device in which gases are absorbed selectively (volumetric basis) by passing them through a series of preselected solvents.

overaging. Aging under conditions of time and temperature greater than those required to obtain maximum change in a certain property, so that the property is altered in the direction of the initial value. See also *aging.*

overheating. Heating a metal or alloy to such a high temperature that its properties are impaired. When the original properties cannot be restored by further heat treating, by mechanical working, or by a combination of working and heat treating, the overheating is known as *burning.*

oxidation. (1) A reaction in which there is an increase in valence resulting from a loss of electrons. (2) A corrosion reaction in which the corroded metal forms an oxide; usually applied to reaction with a gas containing elemental oxygen, such as air.

oxidized surface (on steel). Surface having a thin, tightly adhering, oxidized skin (from straw to blue in color), extending in from the edge of a coil or sheet. Sometimes called annealing border.

oxidizing agent. A compound that causes oxidation, thereby itself becoming reduced.

oxidizing flame. A gas flame produced with excess oxygen in the inner flame.

oxygen probe. An atmosphere-monitoring device that electronically measures the difference between the partial pressure of oxygen in a furnace or furnace supply atmosphere and the external air.

P

pack carburizing. A method of surface hardening of steel in which parts are packed in a steel box with the carburizing compound and heated to elevated temperatures.

pack nitriding. A method of surface hardening of steel in which parts are packed in a steel box with the nitriding compound and heated to elevated temperatures.

partial annealing. An imprecise term used to denote a treatment given cold-worked material to reduce the strength to a controlled level or to effect stress relief. To be meaningful, the type of material, the degree of cold work, and the time-temperature schedule must be stated.

patenting. In wiremaking, a heat treatment applied to medium-carbon or high-carbon steel before the drawing of wire or between drafts. This process consists of heating to a temperature above the transformation range and then cooling to a temperature below Ae_1 in air or in a bath of molten lead or salt.

pearlite. A metastable lamellar aggregate of ferrite and cementite resulting from the transformation of austenite at temperatures above the bainite range (Fig. 18).

phase diagram. A graphical representation of the temperature and composition limits of phase fields in an alloy system as they actually exist under the specific conditions of heating or cooling (Fig. 19). A phase diagram may be an equilibrium diagram, an approximation to an equilibrium diagram, or a representation of metastable conditions or phases. Synonymous with constitution diagram. Compare with *equilibrium diagram.*

Pirani gage. An instrument used to measure the pressure inside a vacuum chamber. The gage measures electrical resistance in a wire filament which will change in temperature depending on atmospheric pressure.

Pilot tube. An instrument that measures the stagnation pressure of a flowing fluid, consisting of an open tube pointing into the fluid and connected to a pressure-indicating device. Also known as impact tube.

plasma carburizing. Same as *ion carburizing.*

plasma nitriding. Same as *ion nitriding.*

plastic deformation. The permanent (inelastic) distortion of metals under applied stresses that strain the material beyond its *elastic limit.*

plate martensite. Martensite formed partly in steel containing more than approximately 0.5% carbon and solely in steel containing more than approximately 1.0% carbon that appears as lenticular-shape plates (crystals) (Fig. 20).

polymorphism. The property of a chemical substance crystallizing into two or more forms having different structures, such as diamond and graphite.

postheating. Heating weldments immediately after welding, for tempering, for stress relieving, or for providing a controlled rate of cooling to prevent formation of a hard or brittle structure.

postweld heat treatment. Any heat treatment that follows the welding operation.

pot annealing. Same as *box annealing.*

Fig. 18 Pearlite structure in a high-carbon (0.75% C) steel. The cementite lamellae are white; the ferrite is dark. 500×

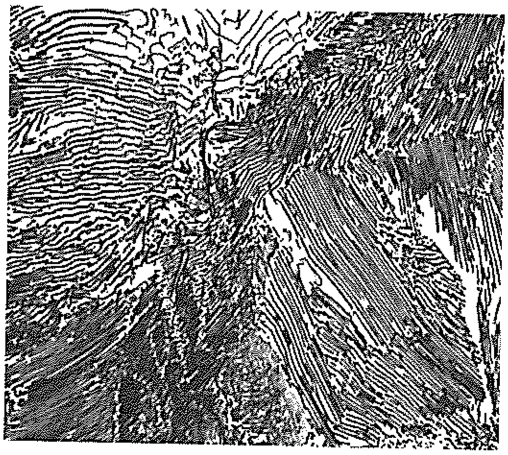
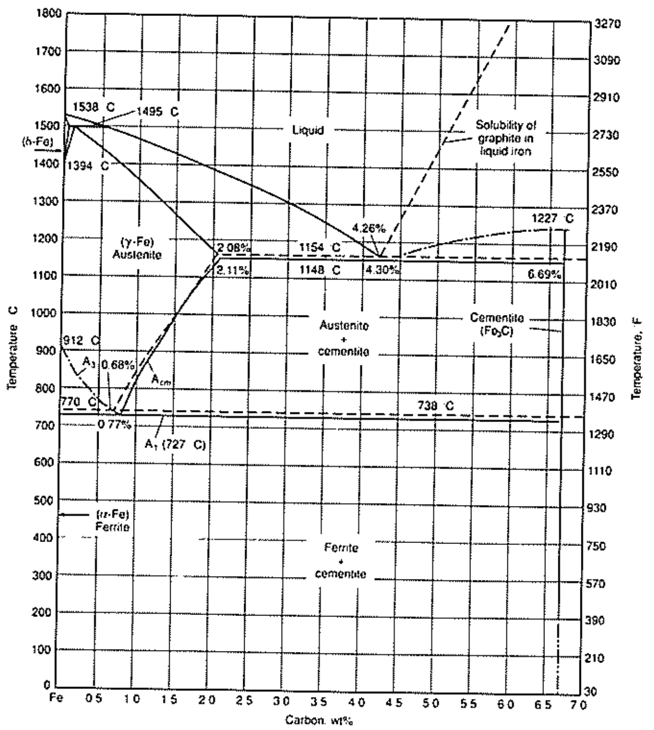


Fig. 19 Iron-carbon phase diagram up to 6.67% C. Solid lines indicate Fe-Fe_3C diagram; dashed lines indicate iron-graphite diagram

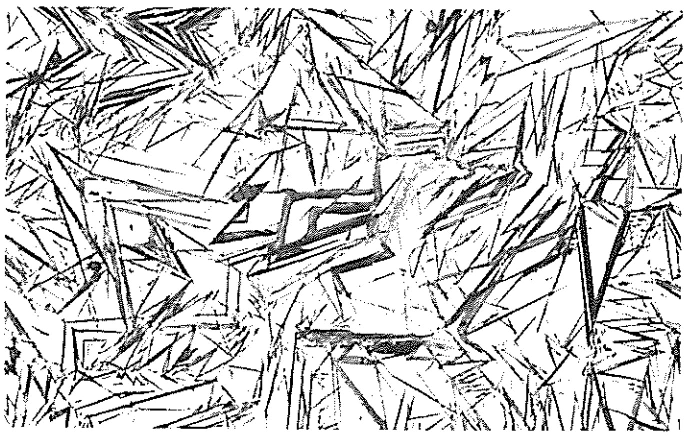


precipitation hardening. Hardening caused by the precipitation of a constituent from a supersaturated solid solution. See also *age hardening* and *aging.*

precipitation heat treatment. *Artificial aging* in which a constituent precipitates from a supersaturated solid solution.

preheating. Heating before some further thermal or mechanical treatment. For tool steel, heating to an intermediate temperature immediately before final austenitizing. For some nonferrous alloys, heating to a high temperature for a long time, to homogenize the structure before working. In welding and related processes, heating to an intermediate tem-

Fig. 20 Plate martensite in an Fe-1.4C alloy. 200×



perature for a short time immediately before welding, brazing, soldering, cutting, or thermal spraying.

press quenching. A quench in which hot dies are pressed and aligned with a part before the quenching process begins. Then the part is placed in contact with a quenching medium in a controlled manner. This process avoids part distortion.

process annealing. An imprecise term denoting various treatments used to improve workability. For the term to be meaningful, the condition of the material and the time-temperature cycle used must be stated.

progressive aging. Aging by increasing the temperature in steps or continuously during the aging cycle. See also *aging* and compare with *interrupted aging* and *step aging.*

pseudocarburizing. See *blank carburizing.*

pseudonitriding. See *blank nitriding.*

pusher furnace. A type of continuous furnace in which parts to be heated are periodically charged into the furnace in containers, which are pushed along the hearth against a line of previously charged containers thus advancing the containers toward the discharge end of the furnace, where they are removed.

pyrometer. A device for measuring temperatures above the range of liquid thermometers.

Q

quarter hard. A *temper* of some ferrous alloys characterized by tensile strength about midway between that of *dead soft* and *half hard* tempers.

quench-age embrittlement. *Embrittlement* of low-carbon steels resulting from precipitation of solute carbon at existing dislocations and from precipitation hardening of the steel caused by differences in ferrite at different temperatures. Quench-age embrittlement usually is caused by rapid cooling of the steel from temperatures slightly below Ac_1 (the temperature at which austenite begins to form), and can be minimized by quenching from lower temperatures.

quench aging. Aging induced by rapid cooling after *solution heat treatment.*

quench annealing. Annealing an austenitic ferrous alloy by *solution heat treatment* followed by rapid quenching.

quench cracking. Fracture of a metal during quenching from elevated temperature. Most frequently observed in hardened carbon steel, alloy steel, or tool steel parts of high hardness and low toughness. Cracks often emanate from fillets, holes, corners, or other stress raisers and result from high stresses due to the volume changes accompanying transformation to martensite.

quench hardening. In ferrous alloys, hardening by austenitizing and then cooling at a rate such that a substantial amount of austenite transforms to martensite.

quenching. Rapid cooling. When applicable, the following more specific terms should be used: *brine quenching, caustic quenching, cold quenching, forced-air quenching, intense quenching, oil quenching, press quenching, spray quenching, direct quenching, fog quenching, hot quenching, interrupted quenching, selective quenching, time quenching,* and *water quenching.*

R

racking. A term used to describe the placing of parts to be heat treated on a rack or tray. This is done to keep parts in a proper position to avoid heat-related distortions and to keep the parts separated. See *fixturing.*

recalescence. A phenomenon, associated with the transformation of gamma iron to alpha iron on the cooling (supercooling) of iron or steel, revealed by the brightening (reglowing) of the metal surface owing to the sudden increase in temperature caused by the fast liberation of the latent heat of transformation. Contrast with *decalescence.*

recarburize. (1) To increase the carbon content of molten cast iron or steel by adding carbonaceous material, high-carbon pig iron, or a high-carbon alloy. (2) To carburize a metal part to return surface carbon lost in processing; also known as carbon restoration.

recovery. Reduction or removal of work-hardening effects, without motion of large-angle grain boundaries.

recrystallization. (1) The formation of a new, strain-free structure from that existing in cold-worked metal, usually accomplished by heating. (2) The change from one crystal structure to another, as occurs on heating or cooling through a critical temperature.

recrystallization annealing. Annealing cold-worked metal to produce a new grain structure without phase change.

recrystallization temperature. The approximate minimum temperature at which complete recrystallization of a cold-worked metal occurs within a specified time.

recuperator. Equipment for transferring heat from gaseous products of combustion to incoming air or fuel. The incoming material passes through pipes surrounded by a chamber through which the outgoing gases pass.

reducing flame. A gas flame produced with excess fuel in the inner flame.

refractory. (1) A material of very high melting point with properties that make it suitable for such uses as furnace linings and kiln construction. (2) The quality of resisting heat.

regenerator. Same as *recuperator* except the gaseous products or combustion heat brick checkerwork in a chamber connected to the exhaust side of the furnace while the incoming air and fuel are being heated by the brick checkerwork in a second chamber, connected to the entrance side. At intervals, the gas flow is reversed so that incoming air and fuel contact hot checkerwork while that in the second chamber is being reheated by exhaust gases.

residual stress. An internal stress not depending on external forces resulting from such factors as cold working, phase changes, or temperature gradients.

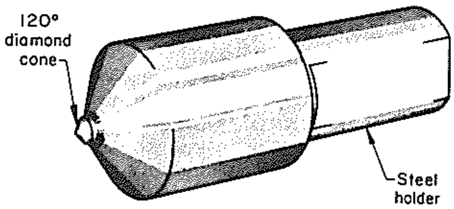
retort. A vessel used for distillation of volatile materials, as in separation of some metals and in destructive distillation of coal.

reverberatory furnace. A furnace with a shallow hearth, usually nonregenerative, having a roof that deflects the flame and radiates heat toward the hearth or the surface of the charge.

rimmed steel. A low-carbon steel containing sufficient iron oxide to give a continuous evolution of carbon monoxide while the ingot is solidifying, resulting in a case or rim of metal virtually free of voids. Sheet and strip products made from rimmed steel ingots have very good surface quality. See also the figure accompanying the term *capped steel.*

Rockwell hardness test. An indentation hardness test based on the depth of penetration, under constant load, as a measure of hardness. Either a

Fig. 21 Diamond-cone Brale indenter used in Rockwell hardness testing (shown at about 2×)



120° diamond cone with a slightly rounded point (Fig. 21) or a 1.6 or 3.2 mm (1/16 or 1/8 in.) diam steel ball is used as the indenter.

rotary retort furnace. A continuous-type furnace in which the work advances by means of an internal spiral, which gives good control of the retention time within the heated chamber.

S

salt bath heat treatment. Heat treatment carried out in a bath of molten salt.

saponification number. A number given to quenching oils that reflects the oils' amount of compounding with fatty materials, which thereby helps evaluate the condition of these oils in service. See also *neutralization number.*

selective heating. Intentionally heating only certain portions of a workpiece.

selective quenching. Quenching only certain portions of an object.

self-hardening steel. See preferred term, *air-hardening steel.*

semikilled steel. Steel that is incompletely deoxidized and contains sufficient dissolved oxygen to react with the carbon to form carbon monoxide and thus offset solidification shrinkage. See also the figure accompanying the term *capped steel.*

sensitization. In austenitic stainless steels, the precipitation of chromium carbides, usually at grain boundaries, on exposure to temperatures of about 540 to 845 °C (about 1000 to 1550 °F), leaving the grain boundaries depleted of chromium and therefore susceptible to preferential attack by a corroding (oxidizing) medium.

severity of quench. Ability of quenching medium to extract heat from a hot steel workpiece; expressed in terms of the *Grossmann number (H).*

shaker-hearth furnace. A continuous-type furnace that uses a reciprocating shaker motion to move the parts along the hearth.

shell hardening. A surface-hardening process in which a suitable steel workpiece, when heated through and quench hardened, develops a martensitic layer or shell that closely follows the contour of the piece and surrounds a core of essentially pearlitic transformation product. This result is accomplished by a proper balance among section size, steel hardenability, and severity of quench.

shim. A thin piece of material placed between two surfaces to obtain a proper fit, adjustment, or alignment. The piece can also be analyzed to measure furnace carbon potential (that is, because while in the furnace it will quickly carburize to a level equal to the furnace carbon potential).

sigma phase. A hard, brittle, nonmagnetic intermediate phase with a tetragonal crystal structure, containing 30 atoms per unit cell, space group $P4_2/mnm$, occurring in many binary and ternary alloys of the transition elements. The composition of this phase in the various systems is not the same, and the phase usually exhibits a wide range in homogeneity. Alloying with a third transition element usually enlarges the field of homogeneity and extends it deep into the ternary section.

sigma-phase embrittlement. *Embrittlement* of iron-chromium alloys (most notably austenitic stainless steels) caused by precipitation at grain boundaries of the hard, brittle intermetallic *sigma phase* during long periods of exposure to temperatures between approximately 565 and 980 °C (1050 and 1800 °F). Sigma-phase embrittlement results in severe loss in *toughness* and *ductility* and can make the embrittled material structure susceptible to intergranular corrosion. See also *sensitization.*

siliconizing. Diffusing silicon into solid metal, usually steel, at an elevated temperature.

sintering. The bonding of adjacent surfaces in a mass of particles by molecular or atomic attraction on heating at high temperatures below the melting temperature of any constituent in the material. Sintering strengthens a powder mass and normally produces densification and, in powdered metals, recrystallization.

slack quenching. The incomplete hardening of steel due to quenching from the austenitizing temperature at a rate slower than the critical cooling rate for the particular steel, resulting in the formation of one or more transformation products in addition to martensite.

slot furnace. A common batch furnace where stock is charged and removed through a slot or opening.

snap temper. A precautionary interim stress-relieving treatment applied to high-hardenability steels immediately after quenching to prevent cracking because of delay in tempering them at the prescribed higher temperature.

soaking. Prolonged holding at a selected temperature to effect homogenization of structure or composition.

soft temper. Same as *dead soft* temper.

solid solution. A single, solid, homogeneous crystalline phase containing two or more chemical species.

solution heat treatment. Heating an alloy to a suitable temperature, holding at that temperature long enough to cause one or more constituents to enter into solid solution, and then cooling rapidly enough to hold these constituents in solution.

sorbite. (obsolete) A fine mixture of ferrite and cementite produced either by regulating the rate of cooling of steel or by tempering steel after hardening. The first type is very fine pearlite difficult to resolve under the microscope; the second type is tempered martensite.

spalling. A chipping or flaking of a surface due to any kind of improper heat treatment.

spinodal hardening. See *aging.*

spheroidal graphite (SG) iron. Same as *ductile cast iron.*

spheroidite. An aggregate of iron or alloy carbides of essentially spherical shape dispersed throughout a matrix of ferrite.

spheroidized structure. A microstructure consisting of a matrix containing spheroidal particles of another constituent (Fig. 22).

spheroidizing. Heating and cooling to produce a spheroidal or globular form of carbide in steel. Spheroidizing methods frequently used are:

1. Prolonged holding at a temperature just below Ae_1
2. Heating and cooling alternately between temperatures that are just above and just below Ae_1
3. Heating to a temperature above Ae_1 or Ae_2 and then cooling very slowly in the furnace or holding at a temperature just below Ae_1
4. Cooling at a suitable rate from the minimum temperature at which all carbide is dissolved, to prevent the reformation of a carbide network, and then reheating in accordance with method 1 or 2 above. (Applicable to hypereutectoid steel containing a carbide network.)

spinodal structure. A fine homogeneous mixture of two phases that form by the growth of composition waves in a solid solution during suitable heat treatment (Fig. 23). The phases of a spinodal structure differ in composition from each other and from the parent phase but have the same crystal structure as the parent phase.

spray quenching. A quenching process using spray nozzles to spray water or other liquids on a part. The quench rate is controlled by the velocity and volume of liquid per unit area per unit of time of impingement.

spring temper. A *temper* of some ferrous alloys characterized by tensile strength and hardness about two-thirds of the way from *full hard* to *extra spring* temper.

stabilizing treatment. (1) Before finishing to final dimensions, repeatedly heating a ferrous part to or slightly above its normal operating tempera-

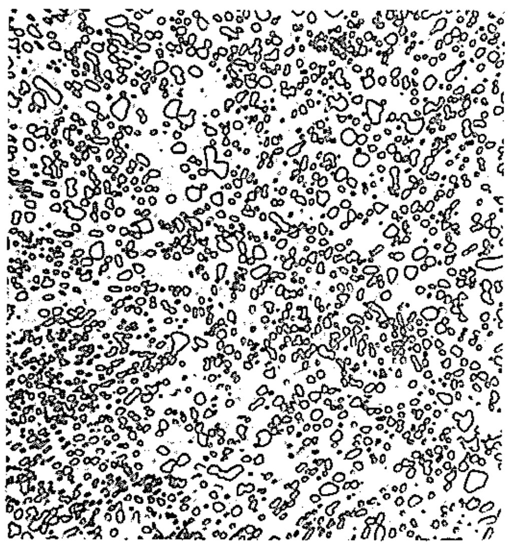


Fig. 22 Spheroidized cementite in AISI W2 tool steel. 1000×

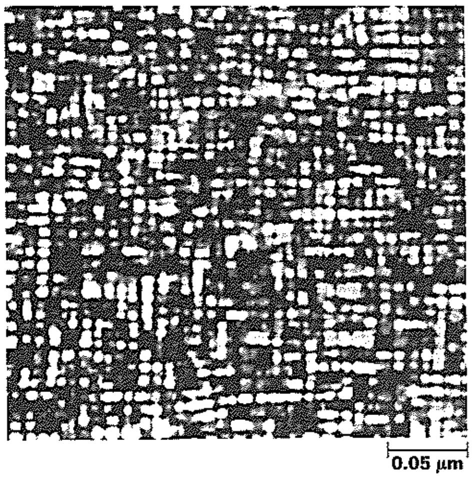


Fig. 23 Spinodal structure in an Fe-25Be (at.%) alloy that was aged 2 h at 400 °C (750 °F). The bright phase is the beryllium-enriched structure; the dark phase is the iron-rich structure. Transmission electron micrograph. 200,000×

ture and then cooling to room temperature to ensure dimensional stability in service. (2) Transforming retained austenite in quenched hardenable steels, usually by *cold treatment.* (3) Heating a solution-treated stabilized grade of austenitic stainless steel to 870 to 900 °C (1600 to 1650 °F) to precipitate all carbon as TiC, NbC, or TaC so that *sensitization* is avoided to subsequent exposure to elevated temperature.

stainless steel. A group of iron-base alloys containing at least approximately 10.5% chromium that achieve their stainless characteristics through the formation of an invisible and adherent chromium-rich oxide surface film.

statistical process control. The application of statistical techniques for measuring and analyzing the variation in processes.

statistical quality control. The application of statistical techniques for measuring and improving the quality of processes and products (includes statistical process control, diagnostic tools, sampling plans, and other statistical techniques).

Stead's brittleness. A condition of brittleness that causes transcrystalline fracture in the coarse grain structure that results from prolonged annealing of thin sheets of low-carbon steel previously rolled at a temperature below about 705 °C (1300 °F). The fracture usually occurs at about 45° to the direction of rolling.

step aging. Aging at two or more temperatures, by steps, without cooling to room temperature after each step. See *aging*, and compare with *interrupted aging* and *progressive aging.*

strain-age embrittlement. A loss in ductility accompanied by an increase in hardness and strength that occurs when low-carbon steel (especially *rimmed* or *capped steel*) is aged following plastic deformation. The degree of embrittlement is a function of aging time and temperature, occurring in a matter of minutes at about 200 °C (400 °F) but requiring a few hours to a year at room temperature.

strain aging. Aging following plastic deformation.

stress equalizing. A low-temperature heat treatment used to balance stresses in cold-worked material without an appreciable decrease in the mechanical strength produced by cold working.

stress relieving. Heating to a suitable temperature, holding long enough to reduce residual stresses, and then cooling slowly enough to minimize the development of new residual stresses.

subcritical annealing. A process anneal performed on ferrous alloys at a temperature below Ac_1. See also *process annealing.*

submerged-electrode furnace. A furnace used for liquid carburizing of parts by heating molten salt baths with the use of electrodes submerged in the ceramic lining (Fig. 24). See also *immersed-electrode furnace.*

supercooling. Cooling below the temperature at which an equilibrium phase transformation can take place, without actually obtaining the transformation.

superheating. Heating above the temperature at which an equilibrium phase transformation should occur without actually obtaining the transformation.

surface hardening. A generic term covering several processes applicable to a suitable ferrous alloy that produces, by quench hardening only, a surface layer that is harder or more wear resistant than the core. There is no significant alteration of the chemical composition of the surface layer. The processes commonly used are *induction hardening, flame hardening, and shell hardening.* Use of the applicable specific process name is preferred.

T

temper. (1) In heat treatment, reheating hardened steel or hardened cast iron to some temperature below the eutectoid temperature for the purpose of decreasing hardness and increasing toughness. The process also is sometimes applied to normalized steel. (2) In tool steels, temper is sometimes used, but inadvisedly, to denote the carbon content.

temper carbon. Clusters of finely divided graphite, such as that found in *malleable cast iron*, that are formed as a result of decomposition cementite, for example, by heating *white cast iron* above the ferrite-austenite transformation temperature and holding at these temperatures for a considerable period of time. Also known as *annealing carbon.*

temper color. A thin, tightly adhering oxide skin that forms when steel is tempered at a low temperature, or for a short time, in air or a mildly oxidizing atmosphere. The color, which ranges from straw to blue depending on the thickness of the oxide skin, varies with both tempering time and temperature (Fig. 25).

tempered martensite. The decomposition products that result from heating martensite below the ferrite-austenite transformation.

tempered martensite embrittlement. *Embrittlement* of ultrahigh-strength steels caused by tempering in the temperature range of 205 to 400 °C (400 to 750 °F); also called 350 °C or 500 °F embrittlement. Tempered martensite embrittlement is thought to result from the combined effects of cementite precipitation on prior-austenite grain boundaries or interlath boundaries and the segregation of impurities at prior-austenite grain boundaries. It differs from *temper embrittlement* in the strength of the

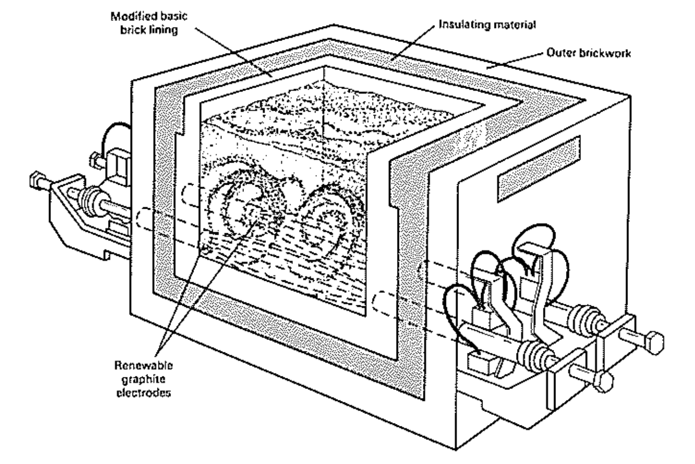


Fig. 24 Internally heated salt bath furnace with submerged electrodes

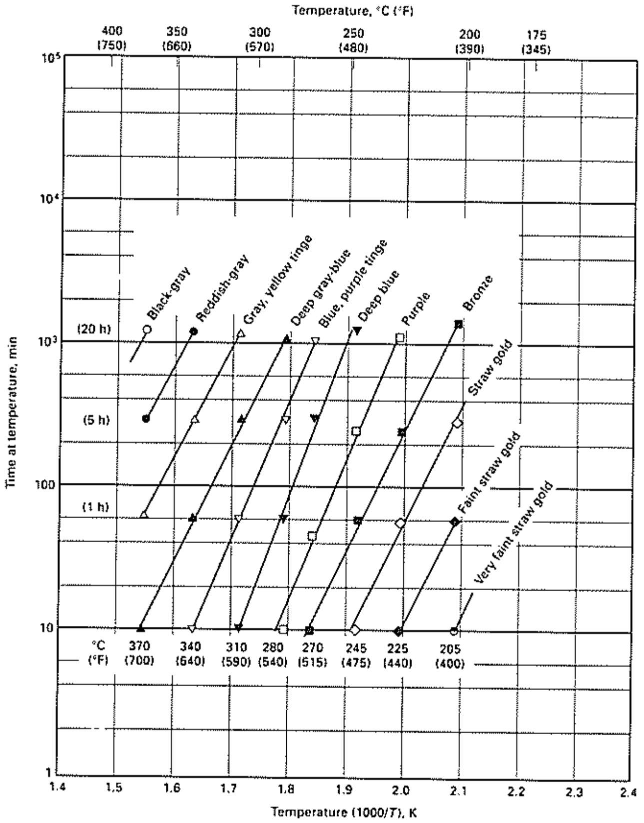


Fig. 25 Temper colors after heating 1035 steel in circulating air (atmospheric pressure)

material and the temperature exposure range. In temper embrittlement, the steel is usually tempered at a relatively high temperature, producing lower strength and hardness, and embrittlement occurs during slow cooling after tempering and during service at temperatures within the embrittlement range. In tempered martensite embrittlement, the steel is tempered within the embrittlement range, and service exposure is usually at room temperature.

temper embrittlement. *Embrittlement* of alloy steels caused by holding within or cooling slowly through a temperature range (generally 300 to 600 °C, or 570 to 1110 °F) just below the transformation range. Embrittlement is the result of the segregation at grain boundaries of impurities such as arsenic, antimony, phosphorus, and tin; it is usually manifested as an upward shift in ductile-to-brittle transition temperature. Temper embrittlement can be reversed by retempering above the critical temperature range, then cooling rapidly. See also *transition temperature* and compare with *tempered martensite embrittlement.*

hermal analysis. A method for determining transformations in a metal by noting the temperatures at which thermal arrests occur. These arrests are manifested by changes in slope of the plotted or mechanically traced heating and cooling curves. When such data are secured under nearly equilibrium conditions of heating and cooling, the method is commonly used for determining certain critical temperatures required for the construction of equilibrium diagrams.

hermal electromotive force. The electromotive force generated in a circuit containing two dissimilar metals when one junction is at a temperature different from that of the other. See also *thermocouple.*

hermal fatigue. Fracture resulting from the presence of temperature gradients that vary with time in such a manner as to produce cyclic stresses in a structure.

hermal shock. The development of a steep temperature gradient and accompanying high stresses within a structure.

hermal stresses. Stresses in metal resulting from nonuniform temperature distribution.

hermochemical treatment. Heat treatment carried out in a medium suitably chosen to produce a change in the chemical composition of the object by exchange with the medium.

hermocouple. A device for measuring temperatures, consisting of lengths of two dissimilar metals or alloys that are electrically joined at one end and connected to a voltage-measuring instrument at the other end. When one junction is hotter than the other, a thermal electromotive force is produced that is roughly proportional to the difference in temperature between the hot and cold junctions.

ıermomechanical working. A general term covering a variety of processes combining controlled thermal and deformation treatments to obtain specific properties. Same as thermal-mechanical treatment.

three-quarters hard. A *temper* of some ferrous alloys characterized by tensile strength and hardness about midway between those of *half hard* and *full hard* tempers.

time quenching. A term used to describe a quench in which the cooling rate of the part being quenched must be changed abruptly at some time during the cooling cycle.

time-temperature-transformation (TTT) diagram. See *isothermal transformation (IT) diagram.*

total carbon. The sum of the free and combined carbon (including carbon in solution) in a ferrous alloy.

toughness. The ability of a metal to absorb energy and deform plastically before fracturing.

transcrystalline. See *transgranular.*

transformation hardening. Heat treatment comprising austenitization followed by cooling under conditions such that the austenite transforms more or less completely into martensite and possibly into bainite.

transformation-induced plasticity. A phenomenon, occurring chiefly in certain highly alloyed steels that have been heat treated to produce metastable austenite or metastable austenite plus martensite, whereby, on subsequent deformation, part of the austenite undergoes strain-induced transformation to martensite. Steels capable of transforming in this manner, commonly referred to as TRIP steels, are highly plastic after heat treatment, but exhibit a very high rate of strain hardening and thus have high tensile and yield strengths after plastic deformation at temperatures between about 20 and 500 °C (70 and 930 °F). Cooling to -195 °C (-320 °F) may or may not be required to complete the transformation to martensite. Tempering usually is done following transformation.

transformation ranges. Those ranges of temperature within which a phase forms during heating and transforms during cooling. The two ranges are distinct, sometimes overlapping but never coinciding. The limiting

Fig. 26 Diamond pyramid indenter used for the Vickers hardness test and resulting indentation in the workpiece

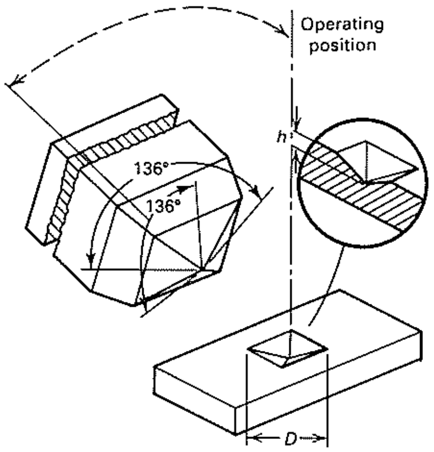
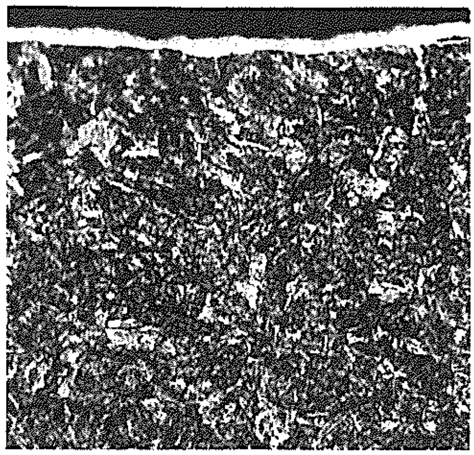


Fig. 27 White layer in a gas-nitrided 4140 steel specimen



temperatures of the ranges depend on the composition of the alloy and on the rate of change of temperature, particularly during cooling. See also *transformation temperature.*

transformation temperature. The temperature at which a change in phase occurs. The term is sometimes used to denote the limiting temperature of a transformation range. The following symbols are used for iron and steels.

Ac_{cm}. In hypereutectoid steel, the temperature at which the solution of cementite in austenite is completed during heating.

Ac_1. The temperature at which austenite begins to form during heating.

Ac_3. The temperature at which transformation of ferrite to austenite is completed during heating.

Ac_4. The temperature at which austenite transforms to delta ferrite during heating.

Ae_{cm}, Ae_1, Ae_3, Ae_4. The temperatures of phase changes at equilibrium.

Ar_{cm}. In hypereutectoid steel, the temperature at which precipitation of cementite starts during cooling.

Ar_1. The temperature at which transformation of austenite to ferrite or to ferrite plus cementite is completed during cooling.

Ar_3. The temperature at which austenite begins to transform to ferrite during cooling.

Ar_4. The temperature at which delta ferrite transforms to austenite during cooling.

Ar'. The temperature at which transformation of austenite to pearlite starts during cooling.

M_f. The temperature at which transformation of austenite to martensite finishes during cooling.

M_s, (or Ar''). The temperature at which transformation of austenite to martensite starts during cooling.

Note: All these changes except the formation of martensite occur at lower temperatures during cooling than during heating, and depend on the rate of change of temperature.

transgranular. Through or across crystals or grains. Also called intracrystalline or transcrystalline.

transgranular cracking. Cracking or fracturing that occurs through or across a crystal or grain. Also called transcrystalline cracking. Contrast with *intergranular cracking.*

transgranular fracture. Fracture through or across the crystals or grains of a metal. Also called transcrystalline fracture or intracrystalline fracture. Contrast with *intergranular fracture.*

transition temperature. (1) An arbitrarily defined temperature that lies within the temperature range in which metal fracture characteristics (as usually determined by tests of notched specimens) change rapidly, such as the ductile-to-brittle transition temperature (DBTT). The DBTT can be assessed in several ways, the most common being the temperature for 50% ductile and 50% brittle fracture (50% fracture appearance transition temperature, or FATT), or the lowest temperature at which the fracture is 100% ductile (100% fibrous criterion). The DBTT is commonly associated with temper embrittlement. (2) Sometimes used to denote an arbitrarily defined temperature within a range in which the ductility changes rapidly with temperature.

TRIP steel. A commercial steel product exhibiting *transformation-induced plasticity.*

troostite. (obsolete) A previously unresolvable rapidly etching fine aggregate of carbide and ferrite produced either by tempering martensite at low temperature or by quenching a steel at a rate slower than the critical cooling rate. Preferred terminology for the first product is tempered martensite; for the latter, fine pearlite.

U

undercooling. Same as *supercooling.*

V

vacuum annealing. Annealing carried out at subatmospheric pressure.

vacuum carburizing. A high-temperature gas carburizing process using furnace pressures between 7 and 55 kPa during the carburizing portion of the cycle.

vacuum furnace. A furnace using low atmospheric pressures instead of a protective gas atmosphere like most heat-treating furnaces. Vacuum furnaces are categorized as hot wall or cold wall, depending on the location of the heating and insulating components.

vacuum nitrocarburizing. A subatmospheric nitrocarburizing process using a basic atmosphere of 50% ammonia/50% methane, containing controlled oxygen additions of up to 2%.

Vickers hardness test. A microindentation hardness test employing a 136° diamond pyramid indenter (Fig. 26) and variable loads, enabling the use of one hardness scale for all ranges of hardness—from soft lead to cemented tungsten carbide. Also known as the diamond pyramid hardness test.

W

walking-beam furnace. A continuous-type furnace consisting of two sets of rails, one stationary and the other movable, that lift and advance parts inside the hearth. With this system, the moving rails lift the work from the stationary rails, move it forward, and then lower it back onto stationary rails. The moving rails then return to the starting position and repeat the process to advance the parts again.

water quenching. A quench in which water is the quenching medium. The major disadvantage of water quenching is its poor efficiency at the beginning or hot stage of the quenching process.

white cast iron. A *cast iron* that is essentially free of graphite, and most of the carbon content is present as separate grains of hard cementite. White iron exhibits a white, crystalline fracture surface because fracture occurs along the iron carbide platelets. See also the figure accompanying the term *cementite*.

white layer. Compound layer that forms in steels as a result of the *nitriding* process (Fig. 27).

Widmanstätten structure. A structure characterized by a geometrical pattern resulting from the formation of a new phase along certain crystallographic planes of the parent solid solution (Fig. 28). The orientation of the lattice in the new phase is related crystallographically to the orientation of the lattice in the parent phase. The structure was originally observed in meteorites, but is readily produced in many alloys—ferrous and nonferrous—by appropriate heat treatment.

Fig. 28 Widmanstätten platelets of ferrite nucleated at prior austenite grain boundaries and within grains in a 1541 steel forging. 330×

Common Units for Converting From the English to the Metric (SI) System

The International System of Units (SI for short) is a modernized version of the metric system. It is built upon seven base units and two supplementary units. Derived units are related to base and supplementary units by formulas in the right-hand column. Symbols for units with specific names are given in parentheses. The information supplied in this Data Sheet, adapted from the revised *Metric Practice Guide,* Standard E380 ASTM, includes a selected list of factors for converting U. S. customary units to SI units.

Metric Units and Conversion Factors

Quantity	Unit	Formula
Base units		
length	metre (m)	...
mass	kilogram (kg)	...
time	second (s)	...
electric current	ampere (A)	...
thermodynamic temperature	kelvin (K)	...
amount of substance	mole (mol)	...
luminous intensity	candela (cd)	...
Supplementary units		
plane angle	radian (rad)	...
solid angle	steradian (sr)	...
Derived units		
acceleration	metre per second squared	m/s^2
activity (of a radioactive source)	disintegration per second	(disintegration)/s
angular acceleration	radian per second squared	rad/s^2
angular velocity	radian per second	rad/s
area	square metre	m^2
density	kilogram per cubic metre	kg/m^3
electric capacitance	farad (F)	A · s/V
electric conductance	siemens (S)	A/V
electric field strength	volt per metre	V/m
electric inductance	henry (H)	V · s/A
electric potential difference	volt (V)	W/A
electric resistance	ohm (Ω)	V/A
electromotive force	volt (V)	W/A
energy	joule (J)	N · m
entropy	joule per kelvin	J/K
force	newton (N)	$kg \cdot m/s^2$
frequency	hertz (Hz)	(cycle)/s
illuminance	lux (lx)	lm/m^2
luminance	candela per square metre	cd/m^2
luminous flux	lumen (lm)	cd · sr
magnetic field strength	ampere per metre	A/m
magnetic flux	weber (Wb)	V · s
magnetic flux density	tesla (T)	Wb/m^2
magnetomotive force	ampere (A)	—
power	watt (W)	J/s
pressure	pascal (Pa)	N/m^2
quantity of electricity	coulomb (C)	A · s
quantity of heat	joule (J)	N · m
radiant intensity	watt per steradian	W/sr
specific heat	joule per kilogram-kelvin	J/kg · K
stress	pascal (Pa)	N/m^2
thermal conductivity	watt per metre-kelvin	W/m · K
velocity	metre per second	m/s
viscosity, dynamic	pascal-second	Pa · s
viscosity, kinematic	square metre per second	m^2/s
voltage	volt (V)	W/A
volume	cubic metre	m^3
wavenumber	reciprocal metre	(wave)/m
work	joule (J)	N · m

Metric Conversion Factors

To convert from	To	Multiply by
atmosphere (760 mm Hg)	Pa	$1.013\ 25 \times 10^5$
Btu (International Table)	J	$1.055\ 056 \times 10^3$
Btu (International Table)/hour	W	$2.930\ 711 \times 10^{-1}$
calorie (International Table)	J	4.186 800(a)
centipoise	Pa · s	$1.000\ 000(a) \times 10^{-3}$
centistoke	m^2/s	$1.000\ 000(a) \times 10^{-6}$
circular mil	m^2	$5.067\ 075 \times 10^{-10}$
degree Fahrenheit	°C	tC = (tF − 32)/1.8
foot	m	$3.048\ 000(a) \times 10^{-1}$
$foot^2$	m^2	$9.290\ 304(a) \times 10^{-2}$
$foot^3$	m^3	$2.831\ 685 \times 10^{-2}$
foot-pound-force	J	1.355 818
foot-pound-force/minute	W	$2.259\ 697 \times 10^{-2}$
$foot/second^2$	m/s^2	$3.048\ 000(a) \times 10^{-1}$
gallon (U.S. liquid)	m^3	$3.785\ 412 \times 10^{-3}$
horsepower (electric)	W	$7.460\ 000(a) \times 10^2$
inch	m	$2.540\ 000(a) \times 10^{-2}$
$inch^2$	m^2	$6.451\ 600(a) \times 10^{-4}$
$inch^3$	m^3	$1.638\ 706 \times 10^{-5}$
inch of mercury (60 F)	Pa	$3.376\ 85 \times 10^3$
inch of water (60 F)	Pa	$2.488\ 4 \times 10^2$
$kilogram\text{-}force/centimetre^2$	Pa	$9.806\ 650(a) \times 10^4$
kip (1000 lbf)	N	$4.448\ 222 \times 10^3$
$kip/inch^2$ (ksi)	Pa	$6.894\ 757 \times 10^6$
ounce (U.S. fluid)	m^3	$2.957\ 353 \times 10^{-5}$
ounce-force (avoirdupois)	N	$2.780\ 139 \times 10^{-1}$
ounce-mass (avoirdupois)	kg	$2.834\ 952 \times 10^{-2}$
$ounce\text{-}mass/ft^2$	kg/m^2	$3.051\ 52 \times 10^{-1}$
$ounce\text{-}mass/yard^2$	kg/m^2	$3.390\ 575 \times 10^{-2}$
pint (U.S. liquid)	m^3	$4.731\ 765 \times 10^{-4}$
pound-force (lbf avoirdupois)	N	4.448 222
pound-mass (lbm avoirdupois)	kg	$4.535\ 924 \times 10^{-1}$
$pound\text{-}force/inch^2$ (psi)	Pa	$6.894\ 757 \times 10^3$
$pound\text{-}mass/inch^3$	kg/m^3	$2.767\ 990 \times 10^4$
$pound\text{-}mass/foot^3$	kg/m^3	$1.601\ 846 \times 10$
quart (U.S. liquid)	m^3	$9.463\ 529 \times 10^{-4}$
ton (short, 2000 lbm)	kg	$9.071\ 847 \times 10^2$
torr (mm-Hg)	Pa	$1.333\ 22 \times 10^2$
watt-hour	J	$3.600\ 000(a) \times 10^3$
yard	m	$9.144\ 000(a) \times 10^{-1}$
$yard^2$	m^2	$8.361\ 274 \times 10^{-1}$
$yard^3$	m^3	$7.645\ 549 \times 10^{-1}$

(a) Exact

Multiplication Factors

Multiplication factors	Prefix	SI symbol
$1\ 000\ 000\ 000\ 000 = 10^{12}$	tera	T
$1\ 000\ 000\ 000 = 10^9$	giga	G
$1\ 000\ 000 = 10^6$	mega	M
$1\ 000 = 10^3$	kilo	k
$100 = 10^2$	hecto(a)	h
$10 = 10^1$	deka(a)	da
$0.1 = 10^{-1}$	deci(a)	d
$0.01 = 10^{-2}$	centi(a)	c
$0.001 = 10^{-3}$	milli	m
$0.000\ 001 = 10^{-6}$	micro	μ
$0.000\ 000\ 001 = 10^{-9}$	nano	n
$0.000\ 000\ 000\ 001 = 10^{-12}$	pico	p
$0.000\ 000\ 000\ 000\ 001 = 10^{-15}$	femto	f
$0.000\ 000\ 000\ 000\ 000\ 001 = 10^{-18}$	atto	a

(a) To be avoided where possible

Cross Reference to Steels

The following index was developed to help the Heat Treat cross-index chemically similar specifications. The specifications are listed alpha-numerically by country of origin. It is recommended that this index serve only as a guide. Any determination of the true equivalence of any two alloys should only be made after careful comparison of their chemical compositions. For further information on the chemical compositions and mechanical properties of the alloys listed in this index the reader may find it useful to consult such publications as the *Worldwide Guide to Equivalent Irons and Steels*, ASM, 1993 and *Woldman's Engineering Alloys, 8th Edition*, ASM, 1994.

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Germany

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1.1625	W1	518
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1.1663	W1	518
1.167	1541H	249
1.1673	W1	518
1.1744	W1	518
1.1750	W1	518
1.1820	W1	518
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1.2206	O6	539
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1.2235	L2	574
.2241	L2	574
.2242	L2	574
.2243	L2	574
.2311	P20	585
.2328	P20	585
.2330	P20	585
.2330	P6	584
.2341	P4	581
.2343	H11	591
.2344	H13	600
.2363	A2	544
.2365	H10	589
.2367	H10	589
DIN		
1.2369	M50 (Carpenter VIM-VAR M-50 H5S)	669
1.2378	D7	572
1.2379	D2	560
1.2414	O7	542
1.2419	O7	542
1.2436	D3	566
1.2436	D4	568
1.2442	O7	542
1.2510	O1	533
1.2516	O7	542
1.2519	O7	542
1.2542	S1	524
1.2550	S1	524
1.2567	H14	605
1.2581	H21	609
1.2581	H22	612
1.2601	D2	560
1.2606	A8	555
1.2606	H12	597
1.2625	H23	614
1.2678	H19	607
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1.2735	P6	584
1.2745	P6	584
1.2823	S5	528
1.2833	W2	522
1.2842	O2	537
1.2880	D5	570
1.2884	D3	566
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1.3245	M41	661
1.3246	M41	661
1.3247	M42	662
1.3247	M46	666
1.3247	M47	667
1.3249	M30	657
1.3249	M33	658
1.3249	M34	659
1.3255	T4	629
1.3257	T6	632
1.3265	T5	631
1.3340	M2	642
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1.3554	M2	642
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1.4005	416	772
1.4006	410	765
1.4016	430	760
1.4021	420	775
1.4024	403	763
1.4057	431	779
1.4104	430F	761
1.4112	440B	782
1.4113	434	761
1.4125	440C	783
1.4301	304	733
1.4303	305	739
1.4303	308	740
1.4305	303	731
1.4306	304L	735
1.4310	301	728
1.4401	316	746
DIN		
1.4404	316L	748
1.4438	317L	751
1.4449	317	751
1.4512	409	760
1.4541	321	752
1.4546	348	756
1.4550	347	755
1.4568	17-7PH	799
1.4828	309	741
1.4833	309S	742
1.4841	310	743
1.4841	314	745
1.4935	422	777
1.4980	A-286	805
1.5069	1340H	271
1.5523	15B21H	228
1.5527	15B41H	252
1.5713	P3	581
1.6523	8617	439
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QQ-S-763	414	770
QQ-S-763	420	775
QQ-S-763	429	760
QQ-S-763	430	760
QQ-S-763	440A	781
QQ-S-763	440B	782
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QQ-S-766	310	743
QQ-S-766	316	746
QQ-S-766	316L	748
QQ-S-766	321	752
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QQ-S-766	348	756
QQ-S-766	420	775
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QQ-W-423	316	746
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G94301	94B30	507
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H10450	1045H	184
H13300	1330H	265
H13350	1335H	268
H13400	1340H	271
H13450	1345H	274
H15211	15B21H	228
H15220	1522H	231
H15240	1524H	234
H15260	1526H	238
H15351	15B35H	244
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H15371	15B37H	247
H15410	1541H	249
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H15621	15B62H	260
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H40320	4032H	286
H40370	4037H	289
H40420	4042H	293
H40470	4047H	297
H41180	4118H	303
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H41370	4137H	316
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H41450	4145H	329
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H41610	4161H	337
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H50461	50B46H	390
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