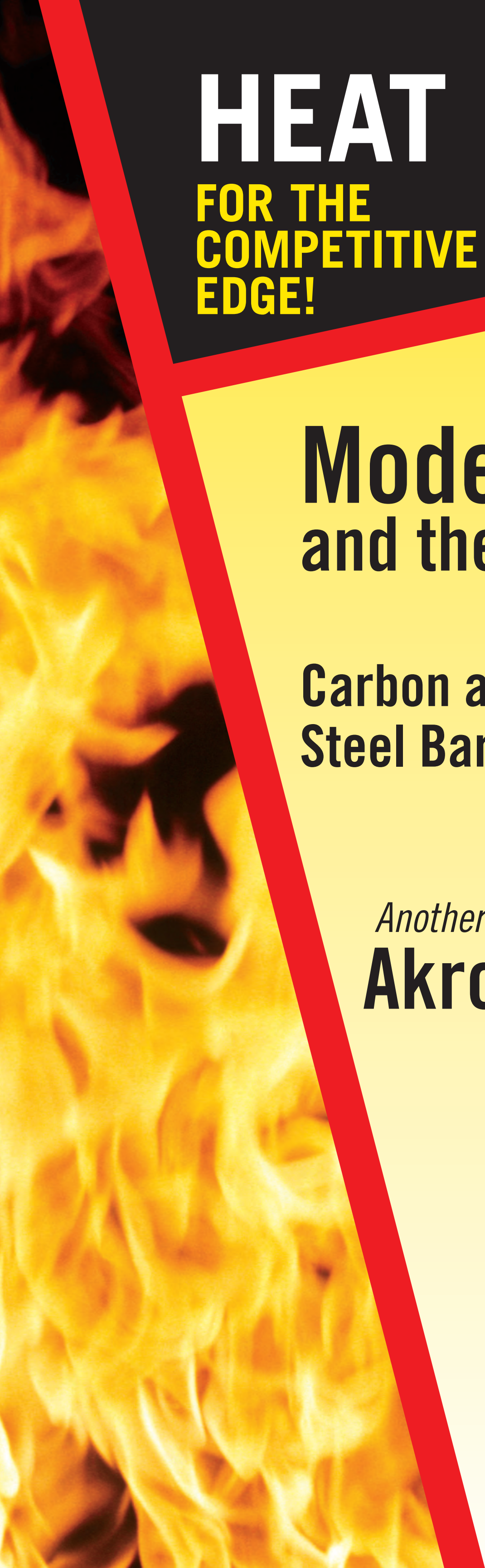

HEAT TREATING

FOR THE COMPETITIVE EDGE!

Modern Steels
and their properties

Carbon and Alloy
Steel Bars and Rods

Another Customer Service of

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Since 1943

Combining Art & Science
for Solutions that Work

To Our Customers and Friends:

Akron Steel Treating Company and Summit Heat Treating Company have been in the metal heat treating business since 1943. Our experience in heat treating has taught us many things about the art and the science of metal treating. Our belief is the more we know about each other's process and product needs, the better able we are to meet those needs. **Good communication is the foundation of good quality.** For several years, we have offered plant tours and free Seminars, "Heat Treating for the Non-Heat Treater," in an effort to foster good communication with our Customers.

It is the intent of this booklet (compiled originally by Bethlehem Steel) to help our Customers to know more about the materials we work with, their properties and their applications. Although the information is believed to be correct, it is by no means a complete guide to heat treating. AST and Summit DO NOT WARRANT the correctness of the information nor its application to a particular product. This information is provided without cost to our Customers and does not create any EXPRESS OR IMPLIED WARRANTIES; AST and Summit are not liable for CONSEQUENTIAL DAMAGES and all work accepted or performed by AST and Summit is done pursuant to the Metal Treating Institute Statement of Limited Liability, a copy of which is on the reverse side of this page.

Thank you for your interest in our services. We look forward to serving your metal treating and black oxiding needs.

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Combining Art & Science for Solutions that Work

Contents

MODERN STEELMAKING

Steel is essentially a combination of iron and carbon, the carbon content of common grades ranging from a few hundredths to about one per cent. All steels also contain varying amounts of other elements, principally manganese, phosphorus, sulfur, and silicon, which are always present if only in trace amounts. The presence and amounts of these and some 20 other alloying elements, which are added in various combinations as desired, determine to a great extent the ultimate properties and characteristics of the particular steel.

Raw Materials

The principal raw materials of the steel industry are iron ore, iron and steel scrap, coal, and limestone. Iron ore is a natural combination of iron oxides and other materials, such as silicon and phosphorus. Until recently, the industry's main sources of iron were the high-grade ores, containing from 55 to 65 per cent iron, which were mined and sent directly to the steel plants. Today, the most available domestic iron ore is taconite, which contains a lesser amount of iron, making its use uneconomical without some kind of beneficiation, a process in which the material is upgraded and formed into high-iron-bearing pellets. Nearly one-half of the iron ore produced on this continent is now used in this pellet form.

A second source of iron is scrap. Most of this comes from the steel plant itself; only about two-thirds of the steel produced by steel plants is shipped as product, the remainder being discarded during processing and returned to the furnaces as scrap. Other scrap, if needed, comes from outside the plant from such sources as old automobiles, worn out railway cars and rails, obsolete machinery, and cuttings from metalworking shops.

Coal is converted into coke, gas, and chemicals in the coke ovens. The coke is used in the blast furnace as a fuel and reducing agent, the gas is burned in heating units, and the chemicals are processed into various organic materials.

Limestone is employed as a flux in both the blast furnace and steelmaking furnace where it serves to remove impurities from the melt. It is used either as crushed stone direct from the quarry or, after calcining, as burnt lime.

Blast Furnace

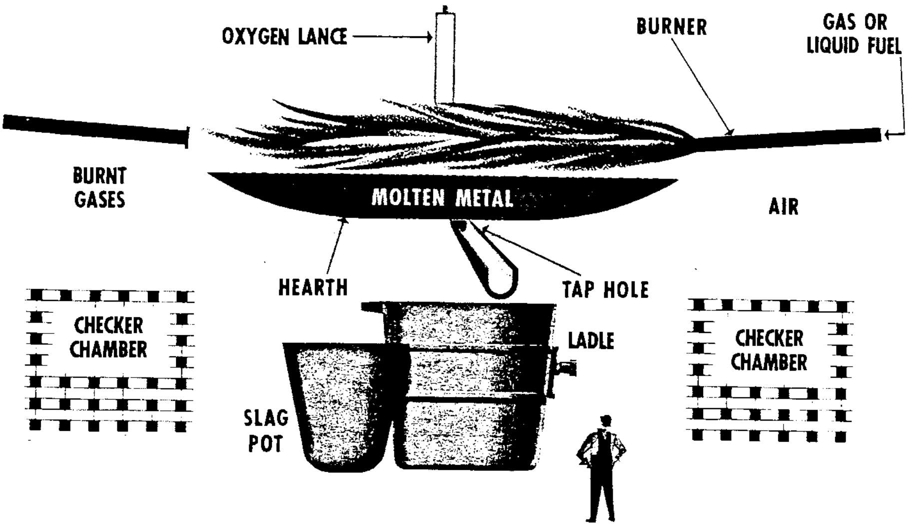
The principal charging material used in making steel is molten pig iron, the product of the blast furnace. To produce it, iron ore, coke, and limestone are charged into the top of the furnace. A continuous blast of preheated air, introduced near the bottom of the furnace, reacts with the coke to form carbon monoxide gas which then combines with the oxygen in the iron oxides, thereby reducing them to metallic iron. The molten iron is tapped into a ladle for transportation to the steel producing unit.

Pig iron contains considerable amounts of carbon, manganese, phosphorus, sulfur, and silicon. In the solid form, it is hard and brittle and therefore unsuitable for applications where ductility is important.

Steelmaking Methods

Steelmaking may be described as the process of refining pig iron or ferrous scrap by removing the undesirable elements from the melt and then adding the desired elements in predetermined amounts. These additions are often the same elements which were originally removed, the difference being that the elements present in the final steel product are in the proper proportion to produce the desired properties.

The open-hearth, the basic oxygen, and the electric-arc processes account for nearly all the steel tonnage produced in this country today. The open-hearth furnace was the nation's major source of steel until 1969, when this role was assumed by the relatively new basic oxygen process. Together, these two methods account for over 80 per cent of the steel made in America. The remainder is made up of electric furnace steels.



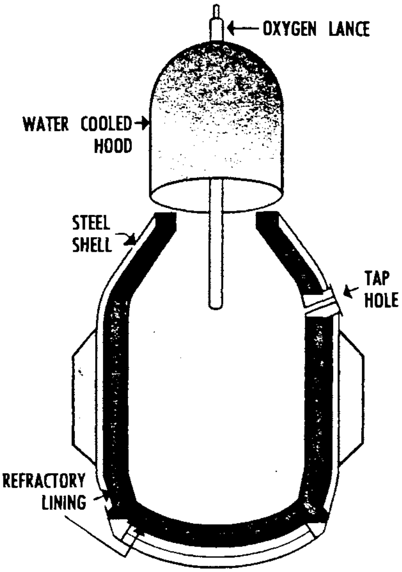
Simplified cutaway diagram of a typical open-hearth furnace, equipped with oxygen lance. Oxygen may be injected through one or more lances.

OPEN-HEARTH FURNACE. The open-hearth furnace has the ability to produce steels in a wide range of compositions. The process can be closely controlled, yielding steels of high quality from charges which need be only nominally restrictive in their analyses. Most modern open-hearth furnaces are lined with a chemically basic material, such as magnesite, and use a basic refining slag. Furnace capacities range from 100 to 500 tons per melt, or heat, each heat requiring from 4 to 10 hours of furnace time.

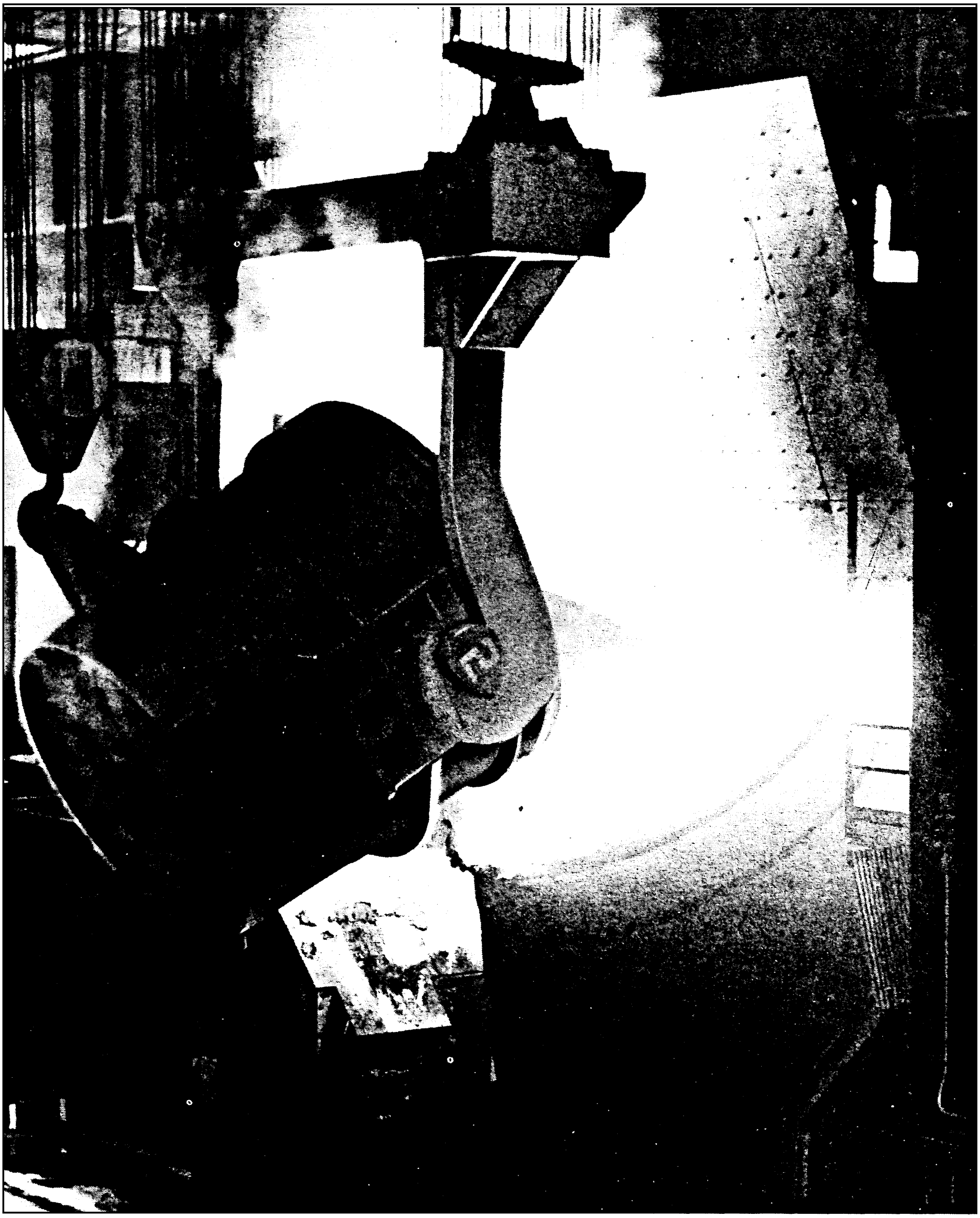
To begin the process, the basic open-hearth furnace is charged with scrap, limestone, and iron ore. This initial charge lies on an "open" hearth, where it is melted by exposure to flames sweeping over its surface. The pig iron, which may constitute as much as 75 per cent of the charge, is added in the molten state after the scrap is partially melted. During the subsequent refining of the heat—a process which is frequently accelerated by the introduction of oxygen through roof lances—nearly all of the manganese, phosphorus, and silicon are oxidized and retained by the slag, which floats on the heavier molten metal. Appreciable percentages of sulfur can also be taken into the slag.

The heat is allowed to react until its carbon content has been reduced by oxidation to approximately that desired in the finished steel. The furnace is then tapped, allowing the molten metal to flow into a ladle. To obtain the desired analysis, appropriate quantities of needed elements, usually in the form of ferroalloys, are added to the heat as it pours into the ladle, or, in the case of some elements, added to the furnace just prior to tapping. A deoxidizer, such as aluminum or ferrosilicon, is also normally added to control the amount of gas evolved during solidification (see p. 12). The heat is then usually poured into ingot molds where it solidifies into steel ingots.

BASIC OXYGEN FURNACE. The "BOF" involves the same chemical reactions as the open-hearth, but uses gaseous oxygen as the oxidizing agent to increase the speed of these reactions and thereby reduce the time of the refining process. Although the advantages of the use of oxygen were obvious to steelmakers a hundred years ago, only in recent years has the pure gas become commercially available in the vast quantities required to make the BOF feasible. Heats of steel as large as 300 tons can be made in less than an hour, several times faster than the average open-hearth can operate. The steel is of excellent quality, equivalent to open-hearth steel in every respect.



During the charging and tapping of the BOF, the oxygen lance is raised and the vessel is tilted.



The basic oxygen furnace, a closed-bottom, refractory-lined vessel, is charged with molten pig iron and scrap. During the oxygen blow, burnt lime and fluorspar, which form the slag, are charged into the furnace. A high-velocity stream of oxygen is directed down onto the charge through a water-cooled lance, causing the rapid oxidation of carbon, manganese, and silicon in the melt. These reactions provide the heat required for scrap melting, slag formation, and refining. Additions of deoxidizers and any required alloying elements are made as the steel is tapped from the vessel into the ladle. It is then usually poured into ingot molds, as with other steelmaking processes.

In keeping with the industry's trend to use the most advanced technologies, the entire process is usually controlled by a computer. From data on the analysis and weights of the charge materials and of melt samplings, the computer quickly determines the precise amounts of the additive elements needed, as well as the cycle time required for the refining operation.

ELECTRIC-ARC FURNACE. Special steels, such as the high-alloy, stainless, and tool steels, are normally made in electric-arc furnaces. The primary advantage of this type furnace is that it permits the extremely close control of temperature, heat analysis, and refining conditions required in the production of these complex steels. As another advantage, these furnaces can be operated efficiently on a cold metal charge, thereby eliminating the need for blast furnaces and associated facilities. For this reason, electric furnaces are today being used with increasing frequency for the production of standard carbon and alloy steels.

The furnace proper is round or elliptical, with carbon or graphite electrodes extending through the roof. In operation, the electrodes are lowered to a point near the charge, which is melted by the heat of the electricity arcing between the electrodes and the charge. When the charge of carefully selected steel scrap is about 70 per cent molten, iron ore and burnt lime are added. Alloying elements are added during a later stage of the refining process. Some 3 to 7 hours are required for each heat, depending mostly on the type of steel being produced. Furnace capacity can vary from a few hundred pounds to 200 tons or more.

Tapping a 50-ton, tilting electric-arc furnace.

Slag practice is geared to the economies of refining steels for different levels of quality. The standard carbon and alloy steels may be refined under a single slag to meet product requirements. Where cleanliness or a specific chemical analysis is the prime consideration, a double-slag practice may be used. The first of these is an oxidizing slag, used to remove some unwanted elements, principally phosphorus and some of the sulfur. This is discarded during the refining process and replaced by a reducing slag which serves to prevent excessive oxidation of the melt, thus enhancing cleanliness and the recovery of alloying additions of oxidizable elements. A further reduction in sulfur is also accomplished during this stage.

The Steel Ingot

The cross section of most ingots is square or rectangular with rounded corners and corrugated sides. Some round-corrugated ingots are produced, but have a limited usage. All ingot molds are tapered to facilitate removal of the ingot, which may be poured big-end-up or big-end-down depending on the type of steel and ultimate product.

All steel is subject to variation in internal characteristics as a result of natural phenomena which occur as the metal solidifies in the mold. The shrinkage which occurs in cooling may cause a central cavity known as "pipe" in the upper part of the ingot. The extent of the piping is dependent upon the type of steel involved, as well as the size and design of the ingot mold itself. Pipe is eliminated by sufficient cropping during rolling.

Another condition present in all ingots to some degree is nonuniformity of chemical composition, or segregation. Certain elements tend to concentrate slightly in the remaining molten metal as ingot solidification progresses. As a result, the top center portion of the ingot which solidifies last will contain appreciably greater percentages of these elements than indicated by the average composition of the ingot. Of the normal elements found in steels, carbon, phosphorus, and sulfur are most prone to segregate. The degree of segregation is influenced by the type of steel, pouring temperature, and ingot size. It will also vary within the ingot, and according to the tendency of the individual element to segregate.

Types of Steel

In most steelmaking processes the primary reaction involved is the combination of carbon and oxygen to form a gas. If the oxygen available for this reaction is not removed prior to or during pouring (by the addition of ferrosilicon or some other deoxidizer), the gaseous products continue to evolve during solidification. Proper control of the amount of gas evolved during solidification determines the type of steel. If no gas is evolved, the steel is termed "killed" because it lies quietly in the molds. Increasing degrees of gas evolution characterize semi-killed, capped, or rimmed steel.

RIMMED STEELS are only slightly deoxidized, thereby allowing a brisk effervescence, or evolution of gas to occur as the metal begins to solidify. The gas is produced by a reaction between the carbon and oxygen in the molten steel which occurs at the boundary between the solidified metal and the remaining molten metal. As a result, the outer skin, or "rim" of the ingot is practically free of carbon. The rimming action may be stopped mechanically or chemically after a desired period, or it may be allowed to continue until the action subsides and the ingot top freezes over, thereby ending all gas evolution. The center portion of the ingot, which solidifies after the rimming ceases, has a fairly pronounced tendency to segregate, as discussed above.

The low-carbon surface layer of rimmed steel is very ductile. Proper control of the rimming action will result in a very sound surface in subsequent rolling. Consequently, rimmed grades are particularly adaptable to applications involving cold forming, and where surface is of prime importance.

The presence of appreciable percentages of carbon or manganese will serve to decrease the oxygen available for the rimming action. If the carbon is above .25% and the manganese over .60%, the action is very sluggish or non-existent. If a rim is formed, it will be quite thin and porous. As a result, the cold-forming properties and surface quality are seriously impaired. It is therefore standard practice to specify rimmed steel only for grades with lower percentages of these elements.

KILLED STEELS are strongly deoxidized and are characterized by a relatively high degree of uniformity in composition and properties. The metal shrinks during solidification, thereby forming a cavity, or "pipe", in the uppermost portion of the ingot. Generally, these grades are poured in big-end-up molds. A refractory hot-top is placed on the mold before pouring and filled with metal after the ingot is poured. The pipe formed will be confined to the hot-top section of the ingot, which is removed by cropping during subsequent rolling. The most severely segregated areas of the ingot will also be eliminated by this cropping.

While killed steels are more uniform in composition and properties than any other type, they are nevertheless susceptible to some degree of segregation. As in the other grades, the top center portion of the ingot will exhibit greater segregation than the balance of the ingot.

The uniformity of killed steel renders it most suitable for applications involving such operations as hot-forging, cold extrusion, carburizing, and thermal treatment.

SEMI-KILLED STEELS are intermediate in deoxidation between rimmed and killed grades. Sufficient oxygen is retained so that its evolution counteracts the shrinkage on solidification, but there is no rimming action. Consequently, the composition is more uniform than in rimmed steel, but there is a greater possibility of segregation than in killed steel. Semi-killed steels are used where neither the surface and cold-forming characteristics of rimmed steel nor the greater uniformity of killed steels are essential requirements.

CAPPED STEELS are much the same as rimmed steels except that the duration of the rimming action is curtailed. A deoxidizer is usually added during the pouring of the ingot, with the result that a sufficient amount of gas is entrapped in the solidifying steel to cause the metal to rise in the mold. With the bottle-top mold generally used, action is stopped when the rising metal contacts a heavy metal cap placed on the mold after pouring. A similar effect can be obtained chemically by adding ferrosilicon or aluminum to the ingot top after the ingot has rimmed for the desired time. Action will be stopped and rapid freezing of the ingot top follows.

Capped steels have a thin low-carbon rim which imparts the surface and cold-forming characteristics of rimmed steel. The remainder of the cross section approaches the degree of uniformity typical of semi-killed steels. This combination of properties has resulted in a great increase in the use of capped steels in recent years, primarily for cold forming.

Strand Casting

In traditional steelmaking, molten steel is poured into molds to form ingots. The ingots are removed from the molds, reheated, and rolled into semi-finished products—blooms, billets, or slabs.

Strand casting bypasses the operations between molten steel and the semi-finished product. Molten steel is poured at a regulated rate via a tundish into the top of an oscillating water-cooled mold with a cross-sectional size corresponding to that of the desired bloom, billet or slab. As the molten metal begins to freeze along the mold walls, it forms a shell that permits the gradual withdrawal of the strand product from the bottom of the mold into a water-spray chamber where solidification is completed. With the straight-type mold, the descending solidified product may be cut into suitable lengths while still vertical, or bent into the horizontal position by a series of rolls and then cut to length. With the curved-type mold, the solidified strand is roller-straightened after emerging from the cooling chamber, and then cut to length. In both cases, the cut lengths are then reheated and rolled into finished product as in the conventional manner.

Vacuum Treatment

Liquid steel contains measurable amounts of dissolved gases, principally oxygen, hydrogen, and nitrogen. For the great majority of applications, the effect of these gases on the properties of the solidified steel is insignificant and may be safely ignored. Some of the more critical applications, however, require steels with an exceptionally high degree of structural uniformity, internal soundness, or some other quality which may be impaired by the effects of uncontrolled amounts of dissolved gases. In such cases, certain steelmaking and deoxidation practices are specified to reduce and control the amounts of various gases in the steel. Supplementary vacuum treatment may also be used. This additional procedure of exposing the molten steel to a vacuum during the melting or refining process may be justified in order to achieve one or more of several results:

- Reduced hydrogen, thereby reducing tendency to flaking and embrittlement, and minimizing time for slow cooling of primary mill products.
- Reduced oxygen, thereby improving microcleanliness.
- Improved recovery and distribution of alloying and other additive elements.
- Closer control of composition.
- Higher and more uniform transverse ductility, improved fatigue resistance and elevated-temperature characteristics.
- Exceptionally low carbon content, normally unattainable with conventional refining practices.

Hydrogen removal by vacuum degassing is regularly specified for a variety of steels. Reducing the amount of this gas to levels where it can no longer cause flaking is of particular importance where the steel is to be used in large sections, such as for heavy forgings.

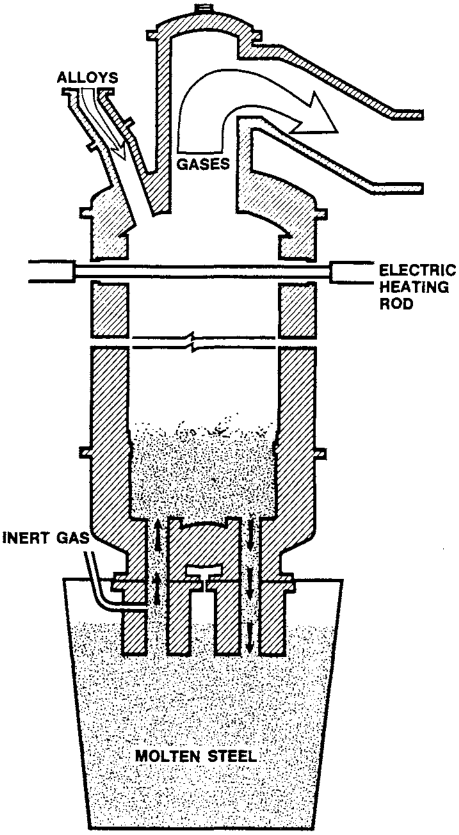
The control of dissolved oxygen, however, is a more complex undertaking because of this element's great chemical activity. It can exist in solution as free oxygen or as a soluble non-metallic oxide; it can combine with carbon to form gaseous oxides; it can be present as complex oxides in steelmaking slags and refractories. As a consequence, deoxidation and other metallurgical procedures performed during refining must be carefully coordinated to assure a final steel product which will meet the specification requirements.

Conventional deoxidation at atmospheric pressure is normally accomplished by adding suitable metallic deoxidizers, such as silicon or aluminum, to the molten steel. The deoxidizers combine with dissolved oxygen to form silicates and oxides, which are largely retained in the solidified steel in the form of non-metallic inclusions. To minimize such inclusions, vacuum treatment is often specified. This is conducted in conjunction with the use of a metallic deoxidizer, and is most effective when the deoxidizer is added late in the vacuum-treatment cycle. Such practice is known as "vacuum carbon deoxidation" because the vacuum environment causes the dissolved oxygen to react with the bath carbon to form carbon monoxide gas, which is removed from the chamber by the pumping system. With most of the oxygen thus removed, the amounts of metallic deoxidizers required for final deoxidation is minimized, and a cleaner steel results.

Where the ultimate in cleanliness is required, steel can be melted as well as refined under vacuum. The vacuum induction melting, the consumable arc remelting, and the electroslag processes are all used in the production of certain specialty steels. These processes, however—particularly when used in combination—are expensive and are generally specified only for steels needed for the most critical applications.

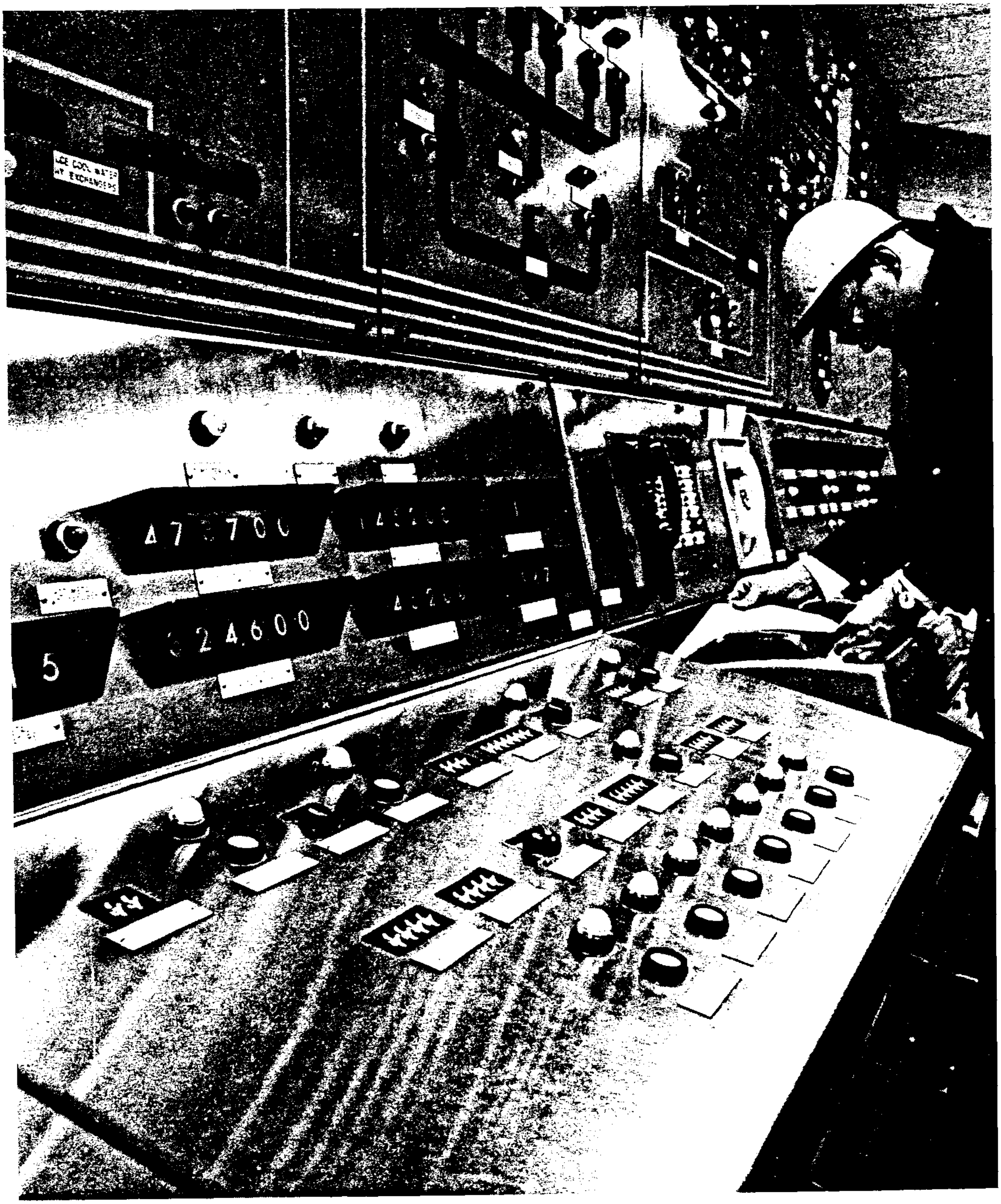
There are three principal commercial processes used for vacuum treatment of steels produced by standard steelmaking methods:

(1) STREAM DEGASSING. In this process, molten steel from the furnace is tapped into a ladle from which it is poured into a vacuum chamber containing either 1) an ingot mold for subsequent direct processing of the steel into heavy forgings, or 2) a second ladle from which the steel is cast into smaller ingots for processing into semi-finished and bar products. As the liquid stream enters the chamber, the low pressure causes the steel to break up into droplets, facilitating the release of its gases into the chamber from which they are exhausted.



(2) CONTINUOUS CIRCULATION DEGASSING. Here, a ladle containing molten steel is moved beneath a suspended vacuum vessel, which is essentially a chamber wherein the degassing or deoxidizing process occurs. When the vessel is lowered, its two refractory tubes are immersed in the steel. The chamber is then opened to a vacuum and inert gas is bubbled into one tube. This gas creates a density differential between the two tubes, thus allowing atmospheric pressure to move the molten metal up through one tube into the chamber and down through the other back into the ladle. Circulation is continued until the steel is degassed to the degree desired.

(3) LADLE DEGASSING. In this process, a ladle of molten steel is placed in a large tank which is then covered and sealed. Pumps exhaust the air from the tank and maintain the vacuum throughout the degassing operation. To expose the maximum amount of steel directly to the vacuum, the melt is usually stirred by electrical induction or agitated by argon gas introduced through orifices near the bottom of the ladle.



Nerve center for basic oxygen steelmaking is the computer room on the charging floor.

CARBON AND ALLOY STEELS

In commercial practice, carbon and alloy steels have some common characteristics, and differentiation between them is arbitrary to a degree. Both contain carbon, manganese, and usually silicon in varying percentages. Both can have copper and boron as specified additions. A steel qualifies as a carbon steel when its manganese content is limited to 1.65% max, silicon to .60% max, and copper to .60% max; with the exception of deoxidizers and boron when specified, no other alloying element is intentionally added. Alloy steels comprise not only those grades which exceed the above limits, but also any grade to which any element other than those mentioned above is added for the purpose of achieving a specific alloying effect.

The alloy steels discussed in this edition of Modern Steels are limited to the "constructional alloy steels," or those which depend on thermal treatment for the development of properties required for specific applications. Other important categories of alloy steels, such as high-strength, low-alloy steels (which are alloyed for the purpose of increasing strength in the as-rolled or normalized condition), corrosion- and heat-resisting steels, and tool steels, are discussed in other Bethlehem Steel Corporation publications, obtainable on request.

Effects of Chemical Elements

The effects of the commonly specified chemical elements on the properties of hot-rolled carbon and alloy bars are discussed here by considering the various elements individually. In practice, however, the effect of any particular element will often depend on the quantities of other elements also present in the steel. For example, the total effect of a combination of alloying elements on the hardenability of a steel is usually greater than the sum of their individual contributions. This type of interrelation should be taken into account whenever a change in a specified analysis is evaluated.

CARBON is the principal hardening element in steel, with each additional increment of carbon increasing the hardness and tensile strength of the steel in the as-rolled or normalized condition. As the carbon content increases above approximately .85%, the resulting increase in strength and hardness is proportionately less than it is for the lower carbon ranges. Upon quenching, the maximum attainable hardness also increases with increasing carbon, but above a content of .60%, the rate of increase is very small.

Conversely, a steel's ductility and weldability decreases as its carbon content is increased. The effect of carbon on machinability is discussed on page 171.

Carbon has a moderate tendency to segregate within the ingot, and because of its significant effect on properties, such segregation is frequently of greater importance than the segregation of other elements in the steel.

MANGANESE is present in all commercial steels, and contributes significantly to a steel's strength and hardness in much the same manner, but to a lesser extent, than does carbon. Its effectiveness depends largely upon, and is directly proportional to, the carbon content of the steel. Another important characteristic of this element is its ability to decrease the critical cooling rate during hardening, thereby increasing the steel's hardenability. Its effect in this respect is greater than that of any of the other commonly used alloying elements.

Manganese is an active deoxidizer, and shows less tendency to segregate within the ingot than do most other elements. Its presence in a steel is also highly beneficial to surface quality in that it tends to combine with sulfur, thereby minimizing the formation of iron sulfide, the causative factor of hot-shortness, or susceptibility to cracking and tearing at rolling temperatures.

PHOSPHORUS is generally considered an impurity except where its beneficial effect on machinability and resistance to atmospheric corrosion is desired. While phosphorus increases strength and hardness to about the same degree as carbon, it also tends to decrease ductility and toughness, or impact strength, particularly for steel in the quenched and tempered condition. The phosphorus content of most steels is therefore kept below specified maxima, which range up to .04 per cent.

In the free-machining steels, however, specified phosphorus content may run as high as .12%. This is attained by adding phosphorus to the ladle, commonly termed rephosphorizing. For a discussion of the effect of phosphorus on machinability, see page 169.

SULFUR is generally considered an undesirable element except where machinability is an important consideration (see page 169). Whereas sulfides in steel act as effective chip-breakers to improve machinability, they also serve to decrease transverse ductility and impact strength. Moreover, increasing sulfur impairs weldability and has an adverse effect on surface quality. Steels with the higher sulfur contents—and particularly those with .15 to .25% carbon—require appreciable surface preparation during processing. Extra discard of these steels at the mill may also be necessary to minimize the amount of segregated steel in the finished product, inasmuch as sulfur, like phosphorus, shows a strong tendency to segregate within the ingot.

SILICON is one of the principal deoxidizers used in the manufacture of both carbon and alloy steels, and depending on the type of steel, can be present in varying amounts up to .35% as a result of deoxidation. It is used in greater amounts in some steels, such as the silico-manganese steels, where its effects tend to complement those of manganese to produce unusually high strength combined with good ductility and shock-resistance in the quenched and tempered condition. In these larger quantities, however, silicon has an adverse effect on machinability, and increases the steel's susceptibility to decarburization and graphitization.

NICKEL is one of the fundamental steel-alloying elements. When present in appreciable amounts, it provides improved toughness, particularly at low temperatures; simplified and more economical thermal treatment; increased hardenability; less distortion in quenching; and improved corrosion resistance.

Nickel lowers the critical temperatures of steel, widens the temperature range for effective quenching and tempering, and retards the decomposition of austenite. In addition, nickel does not form carbides or other compounds which might be difficult to dissolve during heating for austenitizing. All these factors contribute to easier and more successful thermal treatment. This relative insensitivity to variations in quenching conditions provides insurance against costly failures to attain the desired properties, particularly where the furnace is not equipped for precision control.

CHROMIUM is used in constructional alloy steels primarily to increase hardenability, provide improved abrasion-resistance, and to promote carburization. Of the common alloying elements, chromium is surpassed only by manganese and molybdenum in its effect on hardenability.

Chromium forms the most stable carbide of any of the more common alloying elements, giving to high-carbon chromium steels exceptional wear-resistance. And because its carbide is relatively stable at elevated temperatures, chromium is frequently added to steels used for high temperature applications.

A chromium content of 3.99% has been established as the maximum limit applicable to constructional alloy steels. Contents above this level place steels in the category of heat-resisting or stainless steels.

MOLYBDENUM exhibits a greater effect on hardenability per unit added than any other commonly specified alloying element except manganese. It is a non-oxidizing element, making it highly useful in the melting of steels where close hardenability control is desired.

Molybdenum is unique in the degree to which it increases the high-temperature tensile and creep strengths of steel. Its use also reduces a steel's susceptibility to temper brittleness.

VANADIUM improves the strength and toughness of thermally treated steels, primarily because of its ability to inhibit grain-growth over a fairly broad quenching range. It is a strong carbide-former and its carbides are quite stable. Hardenability of medium-carbon steels is increased with a minimum effect upon grain size with vanadium additions of about .04 to .05%; above this content, the hardenability effect per unit added decreases with normal quenching temperatures due to the formation of insoluble carbides. However, the hardenability can be increased with the higher vanadium contents by increasing the austenitizing temperatures.

COPPER is added to steel primarily to improve the steel's resistance to corrosion. In the usual amounts of from .20 to .50%, the copper addition does not significantly affect the mechanical properties. Copper oxidizes at the surface of steel products during heating and rolling, the oxide forming at the grain boundaries and causing a hot-shortness which adversely affects surface quality.

BORON has the unique ability to increase the hardenability of steel when added in amounts as small as .0005%. This effect on hardenability is most pronounced at the lower carbon levels, diminishing with increasing carbon content to where, as the eutectoid composition is approached, the effect becomes negligible. Because boron is ineffective when it is allowed to combine with oxygen or nitrogen, its use is limited to aluminum-killed steels.

Unlike many other elements, boron does not increase the ferrite strength of steel. Boron additions, therefore, promote improved machinability and formability at a particular level of hardenability. It will also intensify the hardenability effects of other alloys, and in some instances, decrease costs by making possible a reduction of total alloy content.

LEAD does not alloy with steel. Instead, as added in pellet form during teeming of the ingot, it is retained in its elemental state as a fine dispersion within the steel's structure. Lead additions have no significant effect on the room temperature mechanical properties of any steel; yet, when present in the usual range of .15 to .35%, the lead additive enhances the steel's machining characteristics to a marked degree.

Although lead can be added to any steel, its use to date has been most significant with the free-machining carbon grades. Added to a base composition which has been resulfurized, rephosphorized, and nitrogen-treated, lead helps these steels achieve the optimum in machinability (see page 170).

NITROGEN is inherently present in all steels, but usually only in small amounts which produce no observable effect. Present in amounts above about .004%, however, nitrogen will combine with certain other elements to precipitate as a nitride. This increases the steel's hardness and tensile and yield strengths while reducing its ductility and toughness. Such effect is similar to that of phosphorus, and is highly beneficial to the machining performance of the steel (see page 169).

ALUMINUM is used in steel principally to control grain size (see page 81) and to achieve deoxidation. Aluminum-killed steels exhibit a high order of fracture toughness.

A specialized use of aluminum is in nitriding steels (see page 67). When such steels containing .95 to 1.30% aluminum are heated in a nitrogenous medium, they achieve a thin case containing aluminum nitride. This stable compound imparts a high surface hardness and exceptional wear resistance to the steels involved.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AISI and SAE Standard Grades and Ranges

The following tables list the ladle chemical ranges and limits in per cent for those grades of carbon and alloy steel bars, blooms, billets, slabs, and rods designated as standard by AISI (American Iron and Steel Institute) and/or SAE (Society of Automotive Engineers), and in effect as of the printing date of this book. The tables are not intended to be a listing of the steels which are produced or offered for sale by Bethlehem Steel Corporation.

Accompanying these tables are tables on product analysis tolerances and ladle chemical ranges and limits for both carbon and alloy steels.

CARBON STEELS

NONRESULFURIZED

(Manganese 1.00 per cent maximum)

AISI/SAE Number	C	Mn	P Max	S Max
1005*	.06 max	.35 max	.040	.050
1006*	.08 max	.25/ .40	.040	.050
1008	.10 max	.30/ .50	.040	.050
1010	.08/.13	.30/ .60	.040	.050
1011†	.08/.13	.60/ .90	.040	.050
1012	.10/.15	.30/ .60	.040	.050
1013†	.11/.16	.50/ .80	.040	.050
1015	.13/.18	.30/ .60	.040	.050
1016	.13/.18	.60/ .90	.040	.050
1017	.15/.20	.30/ .60	.040	.050
1018	.15/.20	.60/ .90	.040	.050
1019	.15/.20	.70/1.00	.040	.050
1020	.18/.23	.30/ .60	.040	.050
1021	.18/.23	.60/ .90	.040	.050
1022	.18/.23	.70/1.00	.040	.050
1023	.20/.25	.30/ .60	.040	.050
1025	.22/.28	.30/ .60	.040	.050
1026	.22/.28	.60/ .90	.040	.050
1029	.25/.31	.60/ .90	.040	.050
1030	.28/.34	.60/ .90	.040	.050
1035	.32/.38	.60/ .90	.040	.050
1037	.32/.38	.70/1.00	.040	.050
1038	.35/.42	.60/ .90	.040	.050
1039	.37/.44	.70/1.00	.040	.050
1040	.37/.44	.60/ .90	.040	.050
1042	.40/.47	.60/ .90	.040	.050
1043	.40/.47	.70/1.00	.040	.050
1044	.43/.50	.30/ .60	.040	.050
1045	.43/.50	.60/ .90	.040	.050
1046	.43/.50	.70/1.00	.040	.050
1049	.46/.53	.60/ .90	.040	.050

AISI/SAE Number	C	Mn	P Max	S Max
1050	.48/ .55	.60/ .90	.040	.050
1053	.48/ .55	.70/1.00	.040	.050
1055	.50/ .60	.60/ .90	.040	.050
1059*	.55/ .65	.50/ .80	.040	.050
1060	.55/ .65	.60/ .90	.040	.050
1064†	.60/ .70	.50/ .80	.040	.050
1065†	.60/ .70	.60/ .90	.040	.050
1069†	.65/ .75	.40/ .70	.040	.050
1070	.65/ .75	.60/ .90	.040	.050
1074†	.70/ .80	.50/ .80	.040	.050
1075†	.70/ .80	.40/ .70	.040	.050
1078	.72/ .85	.30/ .60	.040	.050
1080	.75/ .88	.60/ .90	.040	.050
1084	.80/ .93	.60/ .90	.040	.050
1085†	.80/ .93	.70/1.00	.040	.050
1086*	.80/ .93	.30/ .50	.040	.050
1090	.85/ .98	.60/ .90	.040	.050
1095	.90/1.03	.30/ .50	.040	.050

*Standard grades for wire rods and wire only. †SAE only

NOTE: In the case of certain qualities, the foregoing standard steels are ordinarily furnished to lower phosphorus and lower sulfur maxima.

BARS AND SEMI-FINISHED

Silicon. When silicon ranges or limits are required, the values shown in the table for Ladle Chemical Ranges and Limits apply.

RODS

Silicon. When silicon is required, the following ranges and limits are commonly used for nonresulfurized carbon steels:

0.10 per cent maximum	0.10 to 0.20 per cent	0.20 to 0.40 per cent
0.07 to 0.15 per cent	0.15 to 0.30 per cent	0.30 to 0.60 per cent

ALL PRODUCTS

Boron. Standard killed carbon steels may be produced with a boron addition to improve hardenability. Such steels can be expected to contain 0.0005 per cent minimum boron. These steels are identified by inserting the letter "B" between the second and third numerals of the AISI number, e.g., 10B46.

Lead. Standard carbon steels can be produced to a lead range of 0.15 to 0.35 per cent to improve machinability. Such steels are identified by inserting the letter "L" between the second and third numerals of the AISI number, e.g., 10L45.

Copper. When copper is required, 0.20 per cent minimum is generally used.

CARBON STEELS

NONRESULFURIZED

(Manganese maximum over 1.00 per cent)

AISI/SAE Number	**C**	**Mn**	**P** Max	**S** Max
1513	.10/.16	1.10/1.40	.040	.050
1522	.18/.24	1.10/1.40	.040	.050
1524	.19/.25	1.35/1.65	.040	.050
1526	.22/.29	1.10/1.40	.040	.050
1527	.22/.29	1.20/1.50	.040	.050
1541	.36/.44	1.35/1.65	.040	.050
1548	.44/.52	1.10/1.40	.040	.050
1551	.45/.56	.85/1.15	.040	.050
1552	.47/.55	1.20/1.50	.040	.050
1561	.55/.65	.75/1.05	.040	.050
1566	.60/.71	.85/1.15	.040	.050

NOTE: In the case of certain qualities, the foregoing standard steels are ordinarily furnished to lower phosphorus and lower sulfur maxima.

NOTE: Addenda to table "Carbon Steels, Nonresulfurized (Manganese 1.00 per cent maximum)," p. 27, in reference to Silicon, Boron, Lead, and Copper, also apply to table above.

CARBON STEELS

RESULFURIZED

AISI/SAE Number	C	Mn	P Max	S
1110	.08/.13	.30/ .60	.040	.08/.13
1117	.14/.20	1.00/1.30	.040	.08/.13
1118	.14/.20	1.30/1.60	.040	.08/.13
1137	.32/.39	1.35/1.65	.040	.08/.13
1139	.35/.43	1.35/.165	.040	.13/.20
1140	.37/.44	.70/1.00	.040	.08/.13
1141	.37/.45	1.35/1.65	.040	.08/.13
1144	.40/.48	1.35/1.65	.040	.24/.33
1146	.42/.49	.70/1.00	.040	.08/.13
1151	.48/.55	.70/1.00	.040	.08/.13

BARS AND SEMI-FINISHED

Silicon. When silicon ranges and limits are required, the values shown in the table for Ladle Chemical Ranges and Limits apply.

RODS

Silicon. When silicon is required, the following ranges and limits are commonly used:

Standard Steel Designations	Silicon Ranges or Limits, per cent
Up to 1110 incl	0.10 max
1116 and over	0.10 max; or 0.10 to 0.20; or 0.15 to 0.30

ALL PRODUCTS

Lead. See note on lead, p. 27.

CARBON STEELS

REPHOSPHORIZED AND RESULFURIZED

AISI/SAE Number	C	Mn	P	S	Pb
1211	.13 max	.60/ .90	.07/.12	.10/.15	—
1212	.13 max	.70/1.00	.07/.12	.16/.23	—
1213	.13 max	.70/1.00	.07/.12	.24/.33	—
12L14	.15 max	.85/1.15	.04/.09	.26/.35	.15/.35
1215	.09 max	.75/1.05	.04/.09	.26/.35	—

Silicon. It is not common practice to produce these steels to specified limits for silicon because of its adverse effect on machinability.

Nitrogen. These grades are normally nitrogen treated unless otherwise specified.

Lead. See note on lead, p. 27.

BETHLEHEM FREE-MACHINING CARBON STEELS

Name	C	Mn	P	S	Pb
Beth-Led	.09 max	.70/1.00	.07/.12	.26/.35	.15/.35
Beth-Led B	.15 max	.85/1.35	.04/.09	.40 min	.15/.35
1213-B	.09 max	.70/1.00	.07/.12	.26/.35	—

Silicon. It is not common practice to produce these steels to specified limits for silicon because of its adverse effect on machinability.

Nitrogen. Beth-Led and 1213-B are nitrogen treated.

CARBON STEELS

"M" Series

AISI Number	C	Mn	P Max	S Max
M1008	.10 max	.25/.60	.04	.05
M1010	.07/.14	.25/.60	.04	.05
M1012	.09/.16	.25/.60	.04	.05
M1015	.12/.19	.25/.60	.04	.05
M1017	.14/.21	.25/.60	.04	.05
M1020	.17/.24	.25/.60	.04	.05
M1023	.19/.27	.25/.60	.04	.05
M1025	.20/.30	.25/.60	.04	.05
M1031	.26/.36	.25/.60	.04	.05
M1044	.40/.50	.25/.60	.04	.05

NOTE: Standard ranges and limits do not apply to "M"-Series steels.
NOTE: These modified steels are available in the indicated analyses only.

CARBON H-STEELS

AISI/SAE Number	**C**	**Mn**	**P** Max	**S** Max	**Si**
1038 H	.34/.43	.50/1.00	.040	.050	.15/.30
1045 H	.42/.51	.50/1.00	.040	.050	.15/.30
1522 H	.17/.25	1.00/1.50	.040	.050	.15/.30
1524 H	.18/.26	1.25/1.75*	.040	.050	.15/.30
1526 H	.21/.30	1.00/1.50	.040	.050	.15/.30
1541 H	.35/.45	1.25/1.75*	.040	.050	.15/.30

CARBON BORON H-STEELS

These steels can be expected to contain 0.0005 to 0.003% boron.

AISI/SAE Number	**C**	**Mn**	**P** Max	**S** Max	**Si**
15B21 H	.17/.24	.70/1.20	.040	.050	.15/.30
15B35 H	.31/.39	.70/1.20	.040	.050	.15/.30
15B37 H	.30/.39	1.00/1.50	.040	.050	.15/.30
15B41 H	.35/.45	1.25/1.75*	.040	.050	.15/.30
15B48 H	.43/.53	1.00/1.50	.040	.050	.15/.30
15B62 H	.54/.67	1.00/1.50	.040	.050	.40/.60

*Standard H-Steels with 1.75 per cent maximum manganese are classified as carbon steels.

NOTE: In the case of certain qualities, the foregoing standard steels are ordinarily furnished to lower phosphorus and lower sulfur maxima.

SEE ALSO: Note on Lead, page 27; and Note 1, page 39.

CARBON STEELS

LADLE CHEMICAL RANGES AND LIMITS

Bars, Blooms, Billets, Slabs, and Rods

Element	When maximum of specified element is, per cent	Range, per cent
Carbon (*Note 2*)	To 0.12 incl	—
	Over 0.12 to 0.25 incl	0.05
	Over 0.25 to 0.40 incl	0.06
	Over 0.40 to 0.55 incl	0.07
	Over 0.55 to 0.80 incl	0.10
	Over 0.80	0.13
Manganese	To 0.40 incl	0.15
	Over 0.40 to 0.50 incl	0.20
	Over 0.50 to 1.65 incl	0.30
Phosphorus	To 0.040 incl	—
	Over 0.040 to 0.08 incl	0.03
	Over 0.08 to 0.13 incl	0.05
Sulfur	To 0.050 incl	—
	Over 0.050 to 0.09 incl	0.03
	Over 0.09 to 0.15 incl	0.05
	Over 0.15 to 0.23 incl	0.07
	Over 0.23 to 0.35 incl	0.09
Silicon (*Note 3*)	To 0.10 incl	—
	Over 0.10 to 0.15 incl	0.08
	Over 0.15 to 0.20 incl	0.10
	Over 0.20 to 0.30 incl	0.15
	Over 0.30 to 0.60 incl	0.20
Copper	When copper is required, 0.20 minimum is generally used.	
Lead (*Note 4*)	When lead is required, a range of 0.15/0.35 is generally used.	
Boron	When boron treatment is specified for killed carbon steels, a boron content of 0.0005 to 0.003 per cent can be expected.	

NOTE 1. In the case of certain qualities, lower phosphorus and lower sulfur maxima are ordinarily furnished.

NOTE 2. *Carbon.* The carbon ranges shown in the column headed "Range" apply when the specified maximum limit for manganese does not exceed 1.10 per cent. When the maximum manganese limit exceeds 1.10 per cent, add 0.01 to the carbon ranges shown above.

NOTE 3. *Silicon.* It is not common practice to produce a rephosphorized and resulfurized carbon steel to specified limits for silicon because of its adverse effect on machinability.

NOTE 4. *Lead* is reported only as a range (generally 0.15 to 0.35 per cent) since it is added to the ladle stream as the steel is being poured.

CARBON STEELS

PRODUCT ANALYSIS TOLERANCES

Bars, Blooms, Billets, Slabs, and Rods

Element	Limit, or Maximum of Specified Range, per cent	Tolerance Over the Maximum Limit or Under the Minimum Limit, per cent			
		To 100 sq in. incl	Over 100 to 200 sq in. incl	Over 200 to 400 sq in. incl	Over 400 to 800 sq in. incl
Carbon	To 0.25 incl	0.02	0.03	0.04	0.05
	Over 0.25 to 0.55 incl	0.03	0.04	0.05	0.06
	Over 0.55	0.04	0.05	0.06	0.07
Manganese	To 0.90 incl	0.03	0.04	0.06	0.07
	Over 0.90 to 1.65 incl	0.06	0.06	0.07	0.08
Phosphorus	Over maximum only, to 0.040 incl	0.008	0.008	0.010	0.015
Sulfur	Over maximum only	0.008	0.010	0.010	0.015
Silicon	To 0.35 incl	0.02	0.02	0.03	0.04
	Over 0.35 to 0.60 incl	0.05	—	—	—
Copper	Under minimum only	0.02	0.03	—	—
Lead	Over *and* under 0.15 to 0.35 incl	0.03	0.03	—	—
Boron	Not subject to product analysis tolerances.				

NOTE 1. Rimmed or capped steels are characterized by a lack of uniformity in their chemical composition, especially for the elements carbon, phosphorus, and sulfur, and for this reason product analysis tolerances are not technologically appropriate for those elements.

NOTE 2. In all types of steel, because of the degree to which phosphorus and sulfur segregate, product analysis tolerances for those elements are not technologically appropriate for rephosphorized or resulfurized steels.

ALLOY STEELS

AISI/SAE Number	C	Mn	Ni	Cr	Mo	Other Elements
1330	.28/.33	1.60/1.90	—	—	—	—
1335	.33/.38	1.60/1.90	—	—	—	—
1340	.38/.43	1.60/1.90	—	—	—	—
1345	.43/.48	1.60/1.90	—	—	—	—
4012††	.09/.14	.75/1.00	—	—	.15/.25	—
4023	.20/.25	.70/ .90	—	—	.20/.30	—
4024	.20/.25	.70/ .90	—	—	.20/.30	S .035/.050
4027	.25/.30	.70/ .90	—	—	.20/.30	—
4028	.25/.30	.70/ .90	—	—	.20/.30	.035/.050
4032††	.30/.35	.70/ .90	—	—	.20/.30	—
4037	.35/.40	.70/ .90	—	—	.20/.30	—
4042††	.40/.45	.70/ .90	—	—	.20/.30	—
4047	.45/.50	.70/ .90	—	—	.20/.30	—
4118	.18/.23	.70/ .90	—	.40/ .60	.08/.15	—
4130	.28/.33	.40/ .60	—	.80/1.10	.15/.25	—
4135††	.33/.38	.70/ .90	—	.80/1.10	.15/.25	—
4137	.35/.40	.70/ .90	—	.80/1.10	.15/.25	—
4140	.38/.43	.75/1.00	—	.80/1.10	.15/.25	—
4142	.40/.45	.75/1.00	—	.80/1.10	.15/.25	—
4145	.43/.48	.75/1.00	—	.80/1.10	.15/.25	—
4147	.45/.50	.75/1.00	—	.80/1.10	.15/.25	—
4150	.48/.53	.75/1.00	—	.80/1.10	.15/.25	—
4161	.56/.64	.75/1.00	—	.70/ .90	.25/.35	—
4320	.17/.22	.45/ .65	1.65/2.00	.40/ .60	.20/.30	—
4340	.38/.43	.60/ .80	1.65/2.00	.70/ .90	.20/.30	—
E4340	.38/.43	.65/ .85	1.65/2.00	.70/ .90	.20/.30	—
4419††	.18/.23	.45/ .65	—	—	.45/.60	—
4422††	.20/.25	.70/ .90	—	—	.35/.45	—
4427††	.24/.29	.70/ .90	—	—	.35/.45	—
4615	.13/.18	.45/ .65	1.65/2.00	—	.20/.30	—
4617††	.15/.20	.45/ .65	1.65/2.00	—	.20/.30	—
4620	.17/.22	.45/ .65	1.65/2.00	—	.20/.30	—
4621††	.18/.23	.70/ .90	1.65/2.00	—	.20/.30	—
4626	.24/.29	.45/ .65	.70/1.00	—	.15/.25	—
4718††	.16/.21	.70/ .90	.90/1.20	.35/ .55	.30/.40	—
4720	.17/.22	.50/ .70	.90/1.20	.35/ .55	.15/.25	—
4815	.13/.18	.40/ .60	3.25/3.75	—	.20/.30	—
4817	.15/.20	.40/ .60	3.25/3.75	—	.20/.30	—
4820	.18/.23	.50/ .70	3.25/3.75	—	.20/.30	—

††SAE only

AISI/SAE Number	C	Mn	Ni	Cr	Mo	Other Elements
5015††	.12/ .17	.30/ .50	—	.30/ .50	—	—
5046††	.43/ .48	.75/1.00	—	.20/ .35	—	—
5060††	.56/ .64	.75/1.00	—	.40/ .60	—	—
5115††	.13/ .18	.70/ .90	—	.70/ .90	—	—
5120	.17/ .22	.70/ .90	—	.70/ .90	—	—
5130	.28/ .33	.70/ .90	—	.80/1.10	—	—
5132	.30/ .35	.60/ .80	—	.75/1.00	—	—
5135	.33/ .38	.60/ .80	—	.80/1.05	—	—
5140	.38/ .43	.70/ .90	—	.70/ .90	—	—
5145††	.43/ .48	.70/ .90	—	.70/ .90	—	—
5147††	.46/ .51	.70/ .95	—	.85/1.15	—	—
5150	.48/ .53	.70/ .90	—	.70/ .90	—	—
5155	.51/ .59	.70/ .90	—	.70/ .90	—	—
5160	.56/ .64	.75/1.00	—	.70/ .90	—	—
50100††	.98/1.10	.25/ .45	—	.40/ .60	—	—
E51100	.98/1.10	.25/ .45	—	.90/1.15	—	—
E52100	.98/1.10	.25/ .45	—	1.30/1.60	—	—
						V
6118	.16/ .21	.50/ .70	—	.50/ .70	—	.10/.15
6150	.48/ .53	.70/ .90	—	.80/1.10	—	.15 min
8115††	.13/ .18	.70/ .90	.20/.40	.30/ .50	.08/.15	—
8615	.13/ .18	.70/ .90	.40/.70	.40/ .60	.15/.25	—
8617	.15/ .20	.70/ .90	.40/.70	.40/ .60	.15/.25	—
8620	.18/ .23	.70/ .90	.40/.70	.40/ .60	.15/.25	—
8622	.20/ .25	.70/ .90	.40/.70	.40/ .60	.15/.25	—
8625	.23/ .28	.70/ .90	.40/.70	.40/ .60	.15/.25	—
8627	.25/ .30	.70/ .90	.40/.70	.40/ .60	.15/.25	—
8630	.28/ .33	.70/ .90	.40/.70	.40/ .60	.15/.25	—
8637	.35/ .40	.75/1.00	.40/.70	.40/ .60	.15/.25	—
8640	.38/ .43	.75/1.00	.40/.70	.40/ .60	.15/.25	—
8642	.40/ .45	.75/1.00	.40/.70	.40/ .60	.15/.25	—
8645	.43/ .48	.75/1.00	.40/.70	.40/ .60	.15/.25	—
8650††	.48/ .53	.75/1.00	.40/.70	.40/ .60	.15/.25	—
8655	.51/ .59	.75/1.00	.40/.70	.40/ .60	.15/.25	—
8660††	.56/ .64	.75/1.00	.40/.70	.40/ .60	.15/.25	—
8720	.18/ .23	.70/ .90	.40/.70	.40/ .60	.20/.30	—
8740	.38/ .43	.75/1.00	.40/.70	.40/ .60	.20/.30	—
8822	.20/ .25	.75/1.00	.40/.70	.40/ .60	.30/.40	—
						Si
9254††	.51/ .59	.60/ .80	—	.60/ .80	—	1.20/1.60
9255††	.51/ .59	.70/ .95	—	—	—	1.80/2.20
9260	.56/ .64	.75/1.00	—	—	—	1.80/2.20
9310††	.08/ .13	.45/ .65	3.00/3.50	1.00/1.40	.08/.15	—

††SAE only

(See Notes, page 39)

ALLOY H-STEELS

AISI/SAE Number	C	Mn	Ni	Cr	Mo	Other Elements
1330 H	.27/.33	1.45/2.05	—	—	—	—
1335 H	.32/.38	1.45/2.05	—	—	—	—
1340 H	.37/.44	1.45/2.05	—	—	—	—
1345 H	.42/.49	1.45/2.05	—	—	—	—
4027 H	.24/.30	.60/1.00	—	—	.20/.30	—
4028 H	.24/.30	.60/1.00	—	—	.20/.30	S .035/.050
4032 H††	.29/.35	.60/1.00	—	—	.20/.30	—
4037 H	.34/.41	.60/1.00	—	—	.20/.30	—
4042 H††	.39/.46	.60/1.00	—	—	.20/.30	—
4047 H	.44/.51	.60/1.00	—	—	.20/.30	—
4118 H	.17/.23	.60/1.00	—	.30/ .70	.08/.15	—
4130 H	.27/.33	.30/ .70	—	.75/1.20	.15/.25	—
4135 H††	.32/.38	.60/1.00	—	.75/1.20	.15/.25	—
4137 H	.34/.41	.60/1.00	—	.75/1.20	.15/.25	—
4140 H	.37/.44	.65/1.10	—	.75/1.20	.15/.25	—
4142 H	.39/.46	.65/1.10	—	.75/1.20	.15/.25	—
4145 H	.42/.49	.65/1.10	—	.75/1.20	.15/.25	—
4147 H	.44/.51	.65/1.10	—	.75/1.20	.15/.25	—
4150 H	.47/.54	.65/1.10	—	.75/1.20	.15/.25	—
4161 H	.55/.65	.65/1.10	—	.60/ .95	.25/.35	—
4320 H	.17/.23	.40/ .70	1.55/2.00	.35/ .65	.20/.30	—
4340 H	.37/.44	.55/ .90	1.55/2.00	.65/ .95	.20/.30	—
E4340 H	.37/.44	.60/ .95	1.55/2.00	.65/ .95	.20/.30	—
4419 H††	.17/.23	.35/ .75	—	—	.45/.60	—
4620 H	.17/.23	.35/ .75	1.55/2.00	—	.20/.30	—
4621 H††	.17/.23	.60/1.00	1.55/2.00	—	.20/.30	—
4626 H†	.23/.29	.40/ .70	.65/1.05	—	.15/.25	—
4718 H††	.15/.21	.60/ .95	.85/1.25	.30/ .60	.30/.40	—
4720 H	.17/.23	.45/ .75	.85/1.25	.30/ .60	.15/.25	—
4815 H	.12/.18	.30/ .70	3.20/3.80	—	.20/.30	—
4817 H	.14/.20	.30/ .70	3.20/3.80	—	.20/.30	—
4820 H	.17/.23	.40/ .80	3.20/3.80	—	.20/.30	—

†AISI only ††SAE only

AISI/SAE Number	C	Mn	Ni	Cr	Mo	Other Elements
5046 H††	.43/.50	.65/1.10	—	.13/ .43	—	—
5120 H	.17/.23	.60/1.00	—	.60/1.00	—	—
5130 H	.27/.33	.60/1.00	—	.75/1.20	—	—
5132 H	.29/.35	.50/ .90	—	.65/1.10	—	—
5135 H	.32/.38	.50/ .90	—	.70/1.15	—	—
5140 H	.37/.44	.60/1.00	—	.60/1.00	—	—
5145 H††	.42/.49	.60/1.00	—	.60/1.00	—	—
5147 H††	.45/.52	.60/1.05	—	.80/1.25	—	—
5150 H	.47/.54	.60/1.00	—	.60/1.00	—	—
5155 H	.50/.60	.60/1.00	—	.60/1.00	—	—
5160 H	.55/.65	.65/1.10	—	.60/1.00	—	—
						V
6118 H	.15/.21	.40/ .80	—	.40/ .80	—	.10/.15
6150 H	.47/.54	.60/1.00	—	.75/1.20	—	.15 min
8617 H	.14/.20	.60/ .95	.35/.75	.35/ .65	.15/.25	—
8620 H	.17/.23	.60/ .95	.35/.75	.35/ .65	.15/.25	—
8622 H	.19/.25	.60/ .95	.35/.75	.35/ .65	.15/.25	—
8625 H	.22/.28	.60/ .95	.35/.75	.35/ .65	.15/.25	—
8627 H	.24/.30	.60/ .95	.35/.75	.35/ .65	.15/.25	—
8630 H	.27/.33	.60/ .95	.35/.75	.35/ .65	.15/.25	—
8637 H	.34/.41	.70/1.05	.35/.75	.35/ .65	.15/.25	—
8640 H	.37/.44	.70/1.05	.35/.75	.35/ .65	.15/.25	—
8642 H	.39/.46	.70/1.05	.35/.75	.35/ .65	.15/.25	—
8645 H	.42/.49	.70/1.05	.35/.75	.35/ .65	.15/.25	—
8650 H††	.47/.54	.70/1.05	.35/.75	.35/ .65	.15/.25	—
8655 H	.50/.60	.70/1.05	.35/.75	.35/ .65	.15/.25	—
8660 H††	.55/.65	.70/1.05	.35/.75	.35/ .65	.15/.25	—
8720 H	.17/.23	.60/ .95	.35/.75	.35/ .65	.20/.30	—
8740 H	.37/.44	.70/1.05	.35/.75	.35/ .65	.20/.30	—
8822 H	.19/.25	.70/1.05	.35/.75	.35/ .65	.30/.40	—
						Si
9260 H	.55/.65	.65/1.10	—	—	—	1.70/2.20
9310 H††	.07/.13	.40/ .70	2.95/3.55	1.00/1.45	.08/.15	—

††SAE only

(See Notes, page 39)

ALLOY BORON STEELS

These steels can be expected to contain 0.0005 to 0.003% boron.

AISI/SAE Number	C	Mn	Ni	Cr	Mo
50B40[††]	.38/.43	.75/1.00	—	.40/.60	—
50B44	.43/.48	.75/1.00	—	.40/.60	—
50B46	.44/.49	.75/1.00	—	.20/.35	—
50B50	.48/.53	.75/1.00	—	.40/.60	—
50B60	.56/.64	.75/1.00	—	.40/.60	—
51B60	.56/.64	.75/1.00	—	.70/.90	—
81B45	.43/.48	.75/1.00	.20/.40	.35/.55	.08/.15
86B45[††]	.43/.48	.75/1.00	.40/.70	.40/.60	.15/.25
94B15[††]	.13/.18	.75/1.00	.30/.60	.30/.50	.08/.15
94B17	.15/.20	.75/1.00	.30/.60	.30/.50	.08/.15
94B30	.28/.33	.75/1.00	.30/.60	.30/.50	.08/.15

[††] SAE only

(See Notes, page 39)

ALLOY BORON H-STEELS

These steels can be expected to have 0.0005% min boron content.

AISI/SAE Number	C	Mn	Ni	Cr	Mo
50B40 H[††]	.37/.44	.65/1.10	—	.30/ .70	—
50B44 H	.42/.49	.65/1.10	—	.30/ .70	—
50B46 H	.43/.50	.65/1.10	—	.13/ .43	—
50B50 H	.47/.54	.65/1.10	—	.30/ .70	—
50B60 H	.55/.65	.65/1.10	—	.30/ .70	—
51B60 H	.55/.65	.65/1.10	—	.60/1.00	—
81B45 H	.42/.49	.70/1.05	.15/.45	30/ .60	.08/.15
86B30 H	.27/.33	.60/ .95	.35/.75	.35/ .65	.15/.25
86B45 H[††]	.42/.49	.70/1.05	.35/.75	.35/ .65	.15/.25
94B15 H[††]	.12/.18	.70/1.05	.25/.65	.25/ .55	.08/.15
94B17 H	.14/.20	.70/1.05	.25/.65	.25/ .55	.08/.15
94B30 H	.27/.33	.70/1.05	.25/.65	.25/ .55	.08/.15

[††] SAE only

(See Notes, page 39)

NOTES ON ALLOY TABLES

1. Grades shown with prefix letter E are made only by the basic electric furnace process. All others are normally manufactured by the basic open hearth or basic oxygen processes, but may be manufactured by the basic electric furnace process with adjustments in phosphorus and sulfur.

2. The phosphorus and sulfur limitations for each process are as follows:

	Maximum, per cent	
	P	S
Basic electric	0.025	0.025
Basic open hearth or basic oxygen	0.035	0.040
Acid electric or acid open hearth	0.050	0.050

3. Minimum silicon limit for acid open hearth or acid electric furnace alloy steel is .15 per cent.

4. Small quantities of certain elements are present in alloy steels, but are not specified or required. These elements are considered as incidental and may be present in the following maximum percentages: copper, .35; nickel, .25; chromium, .20; molybdenum, .06.

5. The listing of minimum and maximum sulfur content indicates a resulfurized steel.

6. Standard alloy steels can be produced to a lead range of .15/.35 per cent to improve machinability.

7. Silicon range for all standard alloy steels except where noted is .15/.30 per cent.

ALLOY STEELS

LADLE CHEMICAL RANGES AND LIMITS

Bars, Blooms, Billets, Slabs, and Rods

Element	When maximum of specified element is, per cent	Range, per cent		Maximum limit, per cent*
		Open hearth or basic oxygen steel	Electric furnace steel	
Carbon	To 0.55 incl	0.05	0.05	
	Over 0.55 to 0.70 incl	0.08	0.07	
	Over 0.70 to 0.80 incl	0.10	0.09	
	Over 0.80 to 0.95 incl	0.12	0.11	
	Over 0.95 to 1.35 incl	0.13	0.12	
Manganese	To 0.60 incl	0.20	0.15	
	Over 0.60 to 0.90 incl	0.20	0.20	
	Over 0.90 to 1.05 incl	0.25	0.25	
	Over 1.05 to 1.90 incl	0.30	0.30	
	Over 1.90 to 2.10 incl	0.40	0.35	
Phosphorus	Basic open hearth or basic oxygen steel (Note 5)			0.035
	Acid open hearth steel			0.050
	Basic electric furnace steel			0.025
	Acid electric furnace steel			0.050
Sulfur	To 0.050 incl	0.015	0.015	
	Over 0.050 to 0.07 incl	0.02	0.02	
	Over 0.07 to 0.10 incl	0.04	0.04	
	Over 0.10 to 0.14 incl	0.05	0.05	
	Basic open hearth or basic oxygen steel (Note 5)			0.040
	Acid open hearth steel			0.050
	Basic electric furnace steel			0.025
	Acid electric furnace steel			0.050
Silicon	To 0.15 incl	0.08	0.08	
	Over 0.15 to 0.20 incl	0.10	0.10	
	Over 0.20 to 0.40 incl	0.15	0.15	
	Over 0.40 to 0.60 incl	0.20	0.20	
	Over 0.60 to 1.00 incl	0.30	0.30	
	Over 1.00 to 2.20 incl	0.40	0.35	
	Acid steels (Note 1)			
Nickel	To 0.50 incl	0.20	0.20	
	Over 0.50 to 1.50 incl	0.30	0.30	
	Over 1.50 to 2.00 incl	0.35	0.35	
	Over 2.00 to 3.00 incl	0.40	0.40	
	Over 3.00 to 5.30 incl	0.50	0.50	
	Over 5.30 to 10.00 incl	1.00	1.00	

*Applies to only nonrephosphorized and nonresulfurized steels.

Element	When maximum of specified element is, per cent	Range, per cent	
		Open hearth or basic oxygen steel	Electric furnace steel
Chromium	To 0.40 incl	0.15	0.15
	Over 0.40 to 0.90 incl	0.20	0.20
	Over 0.90 to 1.05 incl	0.25	0.25
	Over 1.05 to 1.60 incl	0.30	0.30
	Over 1.60 to 1.75 incl	**	0.35
	Over 1.75 to 2.10 incl	**	0.40
	Over 2.10 to 3.99 incl	**	0.50
Molybdenum	To 0.10 incl	0.05	0.05
	Over 0.10 to 0.20 incl	0.07	0.07
	Over 0.20 to 0.50 incl	0.10	0.10
	Over 0.50 to 0.80 incl	0.15	0.15
	Over 0.80 to 1.15 incl	0.20	0.20
Tungsten	To 0.50 incl	0.20	0.20
	Over 0.50 to 1.00 incl	0.30	0.30
	Over 1.00 to 2.00 incl	0.50	0.50
	Over 2.00 to 4.00 incl	0.60	0.60
Vanadium	To 0.25 incl	0.05	0.05
	Over 0.25 to 0.50 incl	0.10	0.10
Aluminum	Up to 0.10 incl	0.05	0.05
	Over 0.10 to 0.20 incl	0.10	0.10
	Over 0.20 to 0.30 incl	0.15	0.15
	Over 0.30 to 0.80 incl	0.25	0.25
	Over 0.80 to 1.30 incl	0.35	0.35
	Over 1.30 to 1.80 incl	0.45	0.45
Copper	To 0.60 incl	0.20	0.20
	Over 0.60 to 1.50 incl	0.30	0.30
	Over 1.50 to 2.00 incl	0.35	0.35

**Not normally produced in open hearth or basic oxygen furnaces.

NOTE 1. Minimum silicon limit for acid open hearth or acid electric furnace alloy steels is 0.15 per cent.

NOTE 2. Boron steels can be expected to have 0.0005 per cent minimum boron content.

NOTE 3. Alloy steels can be produced with a lead range of 0.15/0.35. A ladle analysis for lead is not determinable, since lead is added to the ladle stream while each ingot is poured.

NOTE 4. The chemical ranges and limits of alloy steels are produced to product analysis tolerances shown in Table on p. 42.

NOTE 5. In the case of certain qualities, lower phosphorous and lower sulphur maxima are ordinarily furnished.

ALLOY STEELS

PRODUCT ANALYSIS TOLERANCES

Bars, Blooms, Billets, Slabs, and Rods

		Tolerance Over the Maximum Limit or Under the Minimum Limit, per cent			
Element	Limit, or Maximum of Specified Range, per cent	To 100 sq in. incl	Over 100 to 200 sq in. incl	Over 200 to 400 sq in. incl	Over 400 to 800 sq in. incl
Carbon	To 0.30 incl	0.01	0.02	0.03	0.04
	Over 0.30 to 0.75 incl	0.02	0.03	0.04	0.05
	Over 0.75	0.03	0.04	0.05	0.06
Manganese	To 0.90 incl	0.03	0.04	0.05	0.06
	Over 0.90 to 2.10 incl	0.04	0.05	0.06	0.07
Phosphorus	Over max only	0.005	0.010	0.010	0.010
Sulfur	Over max only*	0.005	0.010	0.010	0.010
Silicon	To 0.40 incl	0.02	0.02	0.03	0.04
	Over 0.40 to 2.20 incl	0.05	0.06	0.06	0.07
Nickel	To 1.00 incl	0.03	0.03	0.03	0.03
	Over 1.00 to 2.00 incl	0.05	0.05	0.05	0.05
	Over 2.00 to 5.30 incl	0.07	0.07	0.07	0.07
	Over 5.30 to 10.00 incl	0.10	0.10	0.10	0.10
Chromium	To 0.90 incl	0.03	0.04	0.04	0.05
	Over 0.90 to 2.10 incl	0.05	0.06	0.06	0.07
	Over 2.10 to 3.99 incl	0.10	0.10	0.12	0.14
Molybdenum	To 0.20 incl	0.01	0.01	0.02	0.03
	Over 0.20 to 0.40 incl	0.02	0.03	0.03	0.04
	Over 0.40 to 1.15 incl	0.03	0.04	0.05	0.06
Vanadium	To 0.10 incl	0.01	0.01	0.01	0.01
	Over 0.10 to 0.25 incl	0.02	0.02	0.02	0.02
	Over 0.25 to 0.50 incl	0.03	0.03	0.03	0.03
	Min value specified, check under min limit†	0.01	0.01	0.01	0.01
Tungsten	To 1.00 incl	0.04	0.05	0.05	0.06
	Over 1.00 to 4.00 incl	0.08	0.09	0.10	0.12
Aluminum**	Up to 0.10 incl	0.03	—	—	—
	Over 0.10 to 0.20 incl	0.04	—	—	—
	Over 0.20 to 0.30 incl	0.05	—	—	—
	Over 0.30 to 0.80 incl	0.07	—	—	—
	Over 0.80 to 1.80 incl	0.10	—	—	—
Lead**	0.15 to 0.35 incl	0.03***	—	—	—
Copper**	To 1.00 incl	0.03	—	—	—
	Over 1.00 to 2.00 incl	0.05	—	—	—
Titanium** Columbium**	To 0.10 incl	0.01***	—	—	—
Zirconium**	To 0.15 incl	0.03	—	—	—
Nitrogen**	To 0.30 incl	0.005	—	—	—

†If the minimum of the range is 0.01%, the under tolerance is 0.005%.

*Sulfur over 0.060 per cent is not subject to product analysis.

**Tolerances shown apply only to 100 sq in. or less.

***Tolerance is over *and* under.

NOTE: Boron is not subject to product analysis tolerances.

HARDENABILITY OF STEEL

Hardenability is a term used to designate that property of steel which determines the depth and distribution of hardness induced by quenching from the austenitizing temperature. Whereas the as-quenched surface hardness of a steel part is dependent primarily on carbon content and cooling rate, the *depth* to which a certain hardness level is maintained with given quenching conditions is a function of its hardenability. Hardenability is largely determined by the percentage of alloying elements present in the steel. Austenitic grain size, time and temperature during austenitizing, and prior microstructure also can have significant effects.

Since hardenability is determined by standard procedures as described below, it is constant for a given composition, whereas hardness will vary with the cooling rate. Thus, for a given composition, the hardness obtained at any location in a part will depend not only on carbon content and hardenability but also on the size and configuration of the part and the quenchant and quenching conditions used.

The hardenability required for a particular part depends on many factors, including size, design, and service stresses. For highly stressed parts, particularly those loaded principally in tension, the best combination of strength and toughness is attained by through-hardening to a martensitic structure followed by adequate tempering. Quenching such parts to a minimum of 80% martensite is generally considered adequate. Carbon steel can be used for thin sections, but as section size increases, alloy steels of increasing hardenability are required. Where only moderate stresses are involved, quenching to a minimum of 50% martensite is sometimes appropriate.

In order to satisfy the stress loading requirements of a particular application, a carbon or alloy steel having the required hardenability must be selected. Grades suitable for highly stressed parts are listed on page 60 according to the section sizes in which the properties shown can be attained by oil or water quenching to 80% martensite. Grades for moderately stressed parts (quenched to 50% martensite) are listed on pages 58 and 59. The usual practice is to select the most economical grade which can consistently meet the desired properties. These tables should be used as a guide only, in view of the many variables which can exist in production heat-treating. Further, these tables are of only nominal use when the part must exhibit special properties which can be obtained only by composition (see Effects of Elements, page 19).

There are many applications where through-hardening is not necessary, or even desirable. For example, for parts which are stressed principally at or near the surface, or in which wear-resistance or resistance to shock loading are primary considerations, shallow-hardening steels or surface hardening treatments, as discussed below, may be appropriate.

End-Quench Hardenability Testing

The most commonly used method of determining hardenability is the end-quench test developed by Jominy and Boegehold[1]. In conducting the test, a 1-inch-round specimen 4 inches long is first normalized to eliminate the variable of prior microstructure, then heated uniformly to a standard austenitizing temperature. The specimen is removed from the furnace, placed in a jig, and immediately end-quenched by a jet of water maintained at room temperature. The water contacts the end-face of the specimen without wetting the sides, and quenching is continued until the entire specimen has cooled. Longitudinal flat surfaces are ground on opposite sides of the quenched specimen, and Rockwell C scale readings are taken at 16th-inch intervals for the first inch from the quenched end, and at greater intervals beyond that point until a hardness level of HRC 20 or a distance of 2 inches from the quenched end is reached. A hardenability curve is usually plotted using Rockwell C readings as ordinates and distances from the quenched end as abscissas. Representative data have been accumulated for a variety of standard grades and are published by SAE and AISI as H-bands. These show graphically and in tabular form the high and low limits applicable to each grade. Steels specified to these limits are designated as H-grades. Limits for standard H-grades are listed on pages 51-57.

Since only the end of the specimen is quenched in this test, it is obvious that the cooling rate along the surface of the specimen decreases as the distance from the quenched end increases. Experiments

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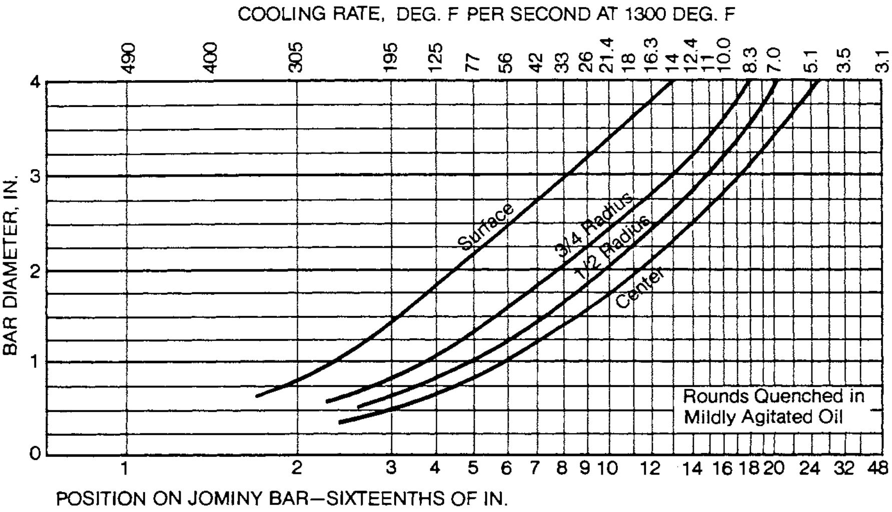
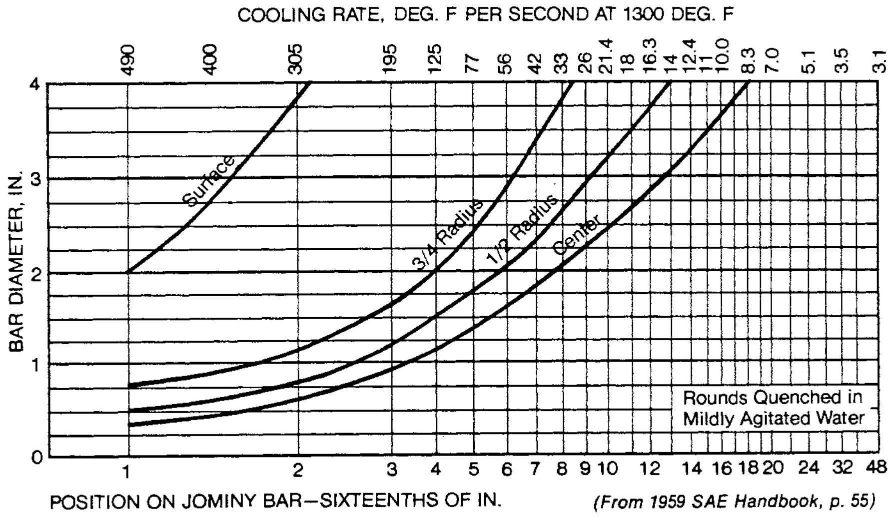
[1] For a complete description of this test, see the SAE Handbook J406, or ASTM Designation A255.





(From 1959 SAE Handbook, p. 55)

have confirmed that the cooling rate at a given point along the bar can be correlated with the cooling rate at various locations in rounds of various sizes. The graphs above show this correlation for surface, ¾ radius, ½ radius, and center locations for rounds up to 4 inches in diameter quenched in mildly agitated oil and in mildly agitated water. Similar data are shown at the top of each H-band as published by SAE and AISI. These values are not absolute, but are useful in determining the grades which may achieve a particular hardness at a specified location in a given section.

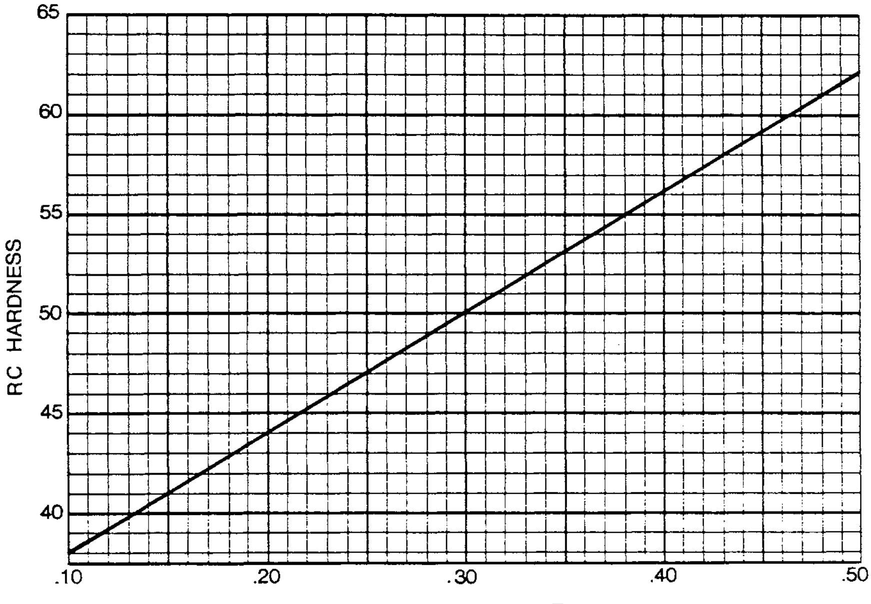
Calculation of End-Quench Hardenability Based on Analysis

It is sometimes desirable to predict the end-quench hardenability curve of a proposed analysis or of a commercial steel not available for testing. The method[1] described here affords a reasonably accurate means of calculating hardness at any Jominy location on a section of steel of known analysis and grain size.

To illustrate this method, consider a heat of 8640 having a grain size of No. 8 at the quenching temperature and the analysis shown in step II, below.

STEP I. Determine the initial hardness (IH). This is the hardness at 1/16 inch on the end-quench specimen and is a function of the carbon content as illustrated by the graph below. The IH for .39% carbon is HRC 55.5.

INITIAL HARDNESS (IH)
(RC Hardness at 1/16 in. from Quenched End)



(Courtesy of AISI)

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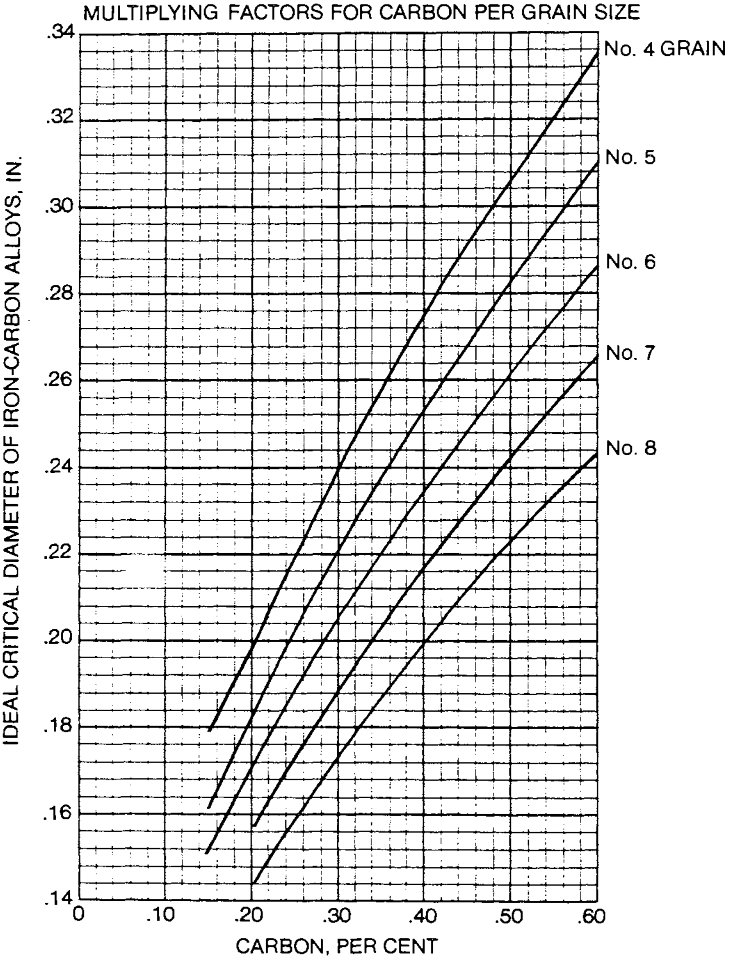
[1] Based on the work of M. A. Grossman, AIME, February 1942, and J. Field, Metal Progress, March 1943.

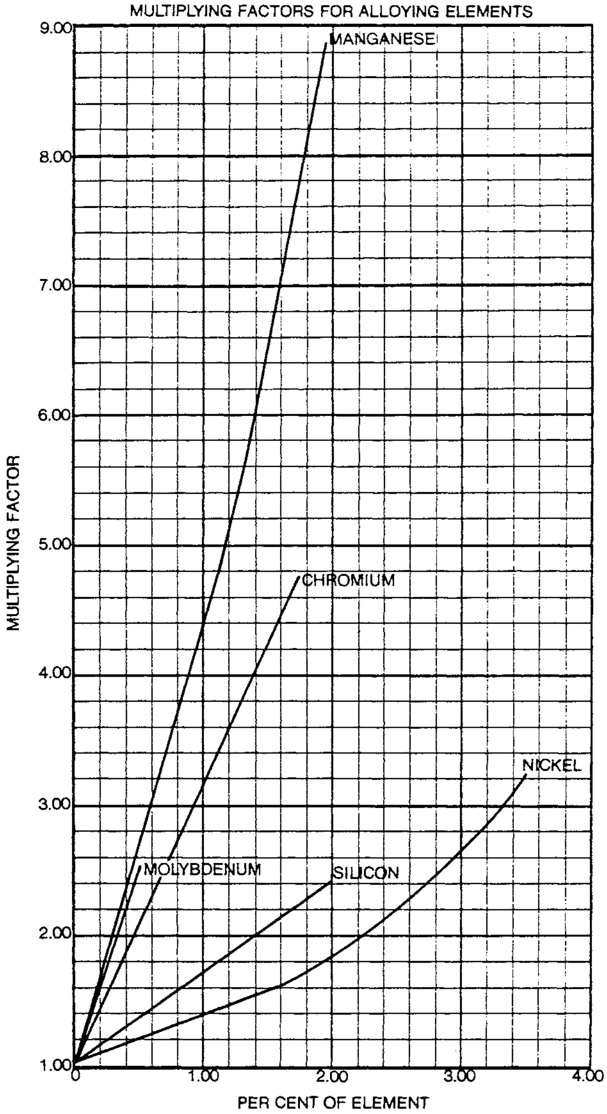
STEP II. Calculate the ideal critical diameter (DI). This is the diameter of the largest round of the given analysis which will harden to 50% martensite at the center during an ideal quench. The DI is the product of the multiplying factors representing each element.

From the graphs below and on page 48, find the multiplying factors for carbon at No. 8 grain size, and for the other elements:

	C	Mn	Si	Ni	Cr	Mo
Heat Analysis(%)	.39	.91	.25	.54	.56	.20
Multiplying Factor	.195	4.03	1.18	1.20	2.21	1.60

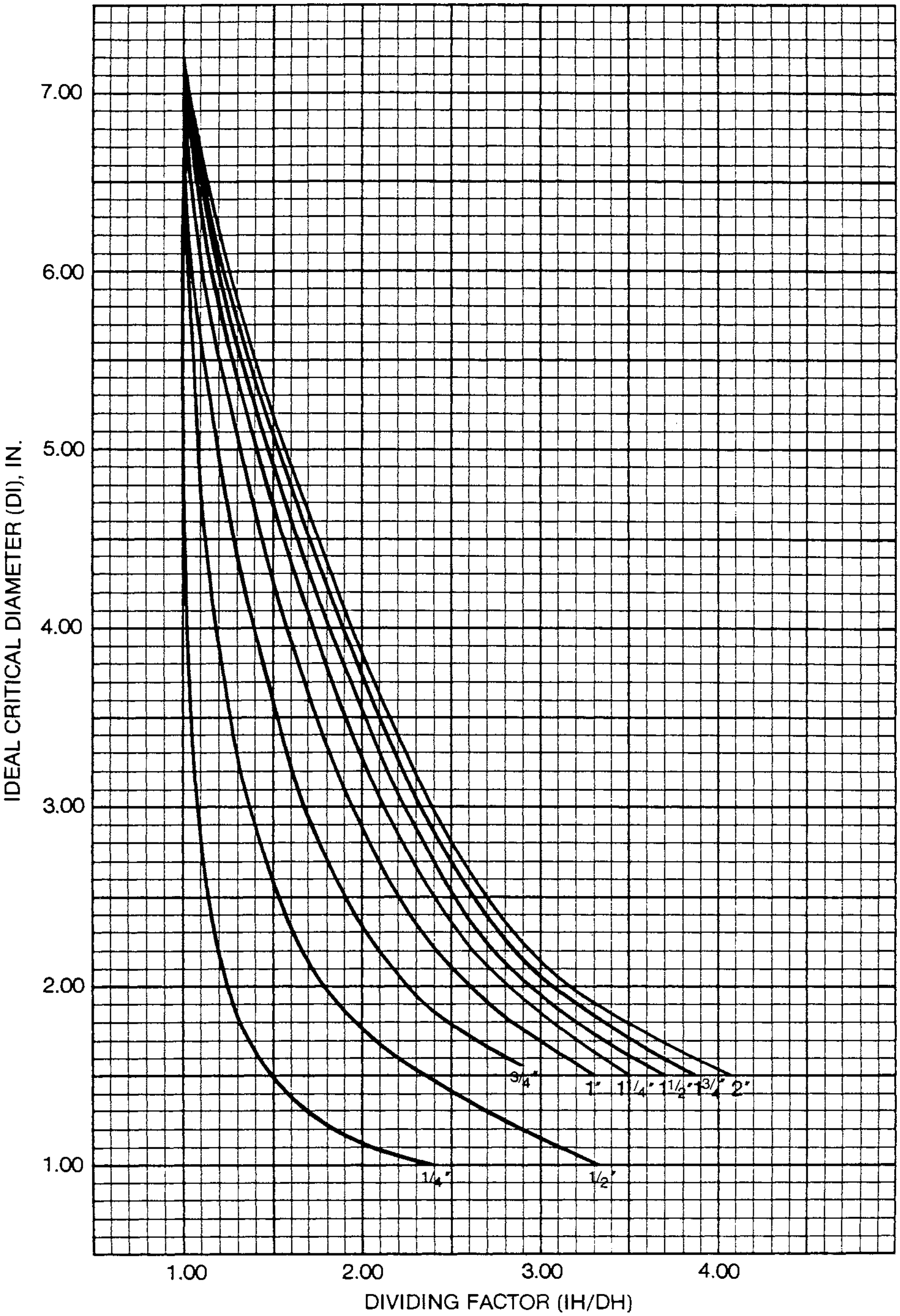
The product of these factors is 3.93 DI.





STEP III. Determine the IH/DH ratios corresponding to each Jominy distance for a DI of 3.93. The IH/DH ratio is based on the observation that with a DI 7.30 or greater, an end-quench curve approximating a straight line out to 2 inches is obtained, and that a DI less than 7.30 will produce a falling curve. The drop in hardness at any point on the curve may be conveniently expressed as a ratio of the maximum hardness attainable (IH) to the hardness actually obtained (DH). The IH/DH ratios, or dividing factors, are plotted on page 49.

RELATION BETWEEN DI AND DIVIDING FACTORS
FOR VARIOUS DISTANCES FROM QUENCHED END



STEP IV. Calculate the Rockwell C hardness for each distance by dividing the IH (55.5) by each respective dividing factor:

Distance, in.	Dividing Factor	Calculated HRC
1/16	—	55.5
1/4	1.03	54
1/2	1.21	46
3/4	1.41	39.5
1	1.61	34.5
1 1/4	1.75	32
1 1/2	1.84	30
1 3/4	1.92	29
2	1.96	28.5

HARDENABILITY LIMITS

The following tables show maximum and minimum hardenability limits for carbon and alloy H-steels from the latest published data of AISI. These values are rounded off to the nearest Rockwell C hardness unit, and are to be used for specification purposes.

For steels which may have been designated as H-steels after the publishing date of this handbook, refer to the latest issues of the applicable AISI Carbon and Alloy Steel Products Manuals.

End-Quench Hardenability Limits

"J" Distance Sixteenths of an inch	1038 H		1045 H		1522 H		1524 H		1526 H		1541 H	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	58	51	62	55	50	41	51	42	53	44	60	53
2	55	34	59	42	47	32	48	38	49	38	59	50
3	49	26	52	31	45	22	45	29	46	26	57	44
4	37	23	38	28	39	20	39	22	39	21	55	38
5	30	22	33	26	34		35		33		52	32
6	28	21	32	25	30		32		30		48	27
7	27		31	25	27		29		27		44	25
8	26		30	24			27		26		39	23
9							26		24			
10	25		29	22			25		24		33	22
11												
12	24		28	21			23		23		32	21
13												
14	23		27	20			22				31	20
15												
16	21		26								30	
18												
20												
22												
24												
26												
28												
30												
32												

End-Quench Hardenability Limits (Cont'd)

"J" Distance Sixteenths of an inch	15B21H		15B35 H		15B37 H		15B41 H		15B48 H		15B62 H	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	48	41	58	51	58	50	60	53	63	56		60
2	47	40	56	50	56	50	59	52	62	56		60
3	46	38	55	49	55	49	59	52	62	55		60
4	44	30	54	48	54	48	58	51	61	54		60
5	40	20	53	39	53	43	58	51	60	53	65	59
6	35		51	28	52	37	57	50	59	52	65	58
7	27		47	24	51	33	57	49	58	42	64	57
8	20		41	22	50	26	56	48	57	37	64	52
9							55	44	56	31	64	43
10			30	20	45	22	55	37	55	30	63	39
11							54	32	53	29	63	37
12			27		40	21	53	28	51	28	63	35
13							52	26	48	27	62	35
14			26		33	20	51	25	45	27	62	34
15							50	25	41	26	61	33
16			25		29		49	24	38	26	60	33
18							46	23	34	25	58	32
20			24		27		42	22	32	24	54	31
22							39	21	31	23	48	30
24			22		25		36	21	30	22	43	30
26							34	20	29	21	40	29
28			20		23		33		29	20	37	28
30							31		28		35	27
32							31		28		34	26

"J" Distance Sixteenths of an inch	1330 H		1335 H		1340 H		1345 H		4027 H 4028 H		4037 H	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	56	49	58	51	60	53	63	56	52	45	59	52
2	56	47	57	49	60	52	63	56	50	40	57	49
3	55	44	56	47	59	51	62	55	46	31	54	42
4	53	40	55	44	58	49	61	54	40	25	51	35
5	52	35	54	38	57	46	61	51	34	22	45	30
6	50	31	52	34	56	40	60	44	30	20	38	26
7	48	28	50	31	55	35	60	38	28		34	23
8	45	26	48	29	54	33	59	35	26		32	22
9	43	25	46	27	52	31	58	33	25		30	21
10	42	23	44	26	51	29	57	32	25		29	20
11	40	22	42	25	50	28	56	31	24		28	
12	39	21	41	24	48	27	55	30	23		27	
13	38	20	40	23	46	26	54	29	23		26	
14	37		39	22	44	25	53	29	22		26	
15	36		38	22	42	25	52	28	22		26	
16	35		37	21	41	24	51	28	21		25	
18	34		35	20	39	23	49	27	21		25	
20	33		34		38	23	48	27	20		25	
22	32		33		37	22	47	26			25	
24	31		32		36	22	46	26			24	
26	31		31		35	21	45	25			24	
28	31		31		35	21	45	25			24	
30	30		30		34	20	45	24			23	
32	30		30		34	20	45	24			23	

"J" Distance Sixteenths of an inch	4047 H		4118 H		4130 H		4137 H		4140 H		4142 H	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	64	57	48	41	56	49	59	52	60	53	62	55
2	62	55	46	36	55	46	59	51	60	53	62	55
3	60	50	41	27	53	42	58	50	60	52	62	54
4	58	42	35	23	52	38	58	49	59	51	61	53
5	55	35	31	20	49	34	57	49	59	51	61	53
6	52	32	28		47	31	57	48	58	50	61	52
7	47	30	27		44	29	56	45	58	48	60	51
8	43	28	25		42	27	55	43	57	47	60	50
9	40	28	24		40	26	55	40	57	44	60	49
10	38	27	23		38	26	54	39	56	42	59	47
11	37	26	22		36	25	53	37	56	40	59	46
12	35	26	21		35	25	52	36	55	39	58	44
13	34	25	21		34	24	51	35	55	38	58	42
14	33	25	20		34	24	50	34	54	37	57	41
15	33	25			33	23	49	33	54	36	57	40
16	32	25			33	23	48	33	53	35	56	39
18	31	24			32	22	46	32	52	34	55	37
20	30	24			32	21	45	31	51	33	54	36
22	30	23			32	20	44	30	49	33	53	35
24	30	23			31		43	30	48	32	53	34
26	30	22			31		42	30	47	32	52	34
28	29	22			30		42	29	46	31	51	34
30	29	21			30		41	29	45	31	51	33
32	29	21			29		41	29	44	30	50	33

"J" Distance Sixteenths of an inch	4145 H		4147 H		4150 H		4161 H		4320 H		4340 H	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	63	56	64	57	65	59	65	60	48	41	60	53
2	63	55	64	57	65	59	65	60	47	38	60	53
3	62	55	64	56	65	59	65	60	45	35	60	53
4	62	54	64	56	65	58	65	60	43	32	60	53
5	62	53	63	55	65	58	65	60	41	29	60	53
6	61	53	63	55	65	57	65	60	38	27	60	53
7	61	52	63	55	65	57	65	60	36	25	60	53
8	61	52	63	54	64	56	65	60	34	23	60	52
9	60	51	63	54	64	56	65	59	33	22	60	52
10	60	50	62	53	64	55	65	59	31	21	60	52
11	60	49	62	52	64	54	65	59	30	20	59	51
12	59	48	62	51	63	53	64	59	29	20	59	51
13	59	46	61	49	63	51	64	58	28		59	50
14	59	45	61	48	62	50	64	58	27		58	49
15	58	43	60	46	62	48	64	57	27		58	49
16	58	42	60	45	62	47	64	56	26		58	48
18	57	40	59	42	61	45	64	55	25		58	47
20	57	38	59	40	60	43	63	53	25		57	46
22	56	37	58	39	59	41	63	50	24		57	45
24	55	36	57	38	59	40	63	48	24		57	44
26	55	35	57	37	58	39	63	45	24		57	43
28	55	35	57	37	58	38	63	43	24		56	42
30	55	34	56	37	58	38	63	42	24		56	41
32	54	34	56	36	58	38	63	41	24		56	40

End-Quench Hardenability Limits (Cont'd)

"J" Distance Sixteenths of an inch	E4340 H		4419 H		4620 H		4621 H		4626 H		4718 H	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	60	53	48	40	48	41	48	41	51	45	47	40
2	60	53	45	33	45	35	47	38	48	36	47	40
3	60	53	41	27	42	27	46	34	41	29	45	38
4	60	53	34	23	39	24	44	30	33	24	43	33
5	60	53	30	21	34	21	41	27	29	21	40	29
6	60	53	28	20	31		37	25	27		37	27
7	60	53	27		29		34	23	25		35	25
8	60	53	25		27		32	22	24		33	24
9	60	53	25		26		30	20	23		32	23
10	60	53	24		25		28		22		31	22
11	60	53	24		24		27		22		30	22
12	60	53	23		23		26		21		29	21
13	60	52	23		22		26		21		29	21
14	59	52	22		22		25		20		28	21
15	59	52	22		22		25				27	20
16	59	51	21		21		24				27	20
18	58	51	21		21		24				27	
20	58	50	20		20		23				26	
22	58	49					23				26	
24	57	48					22				25	
26	57	47					22				25	
28	57	46					22				24	
30	57	45					21				24	
32	57	44					21				24	

"J" Distance Sixteenths of an inch	4720 H		4815 H		4817 H		4820 H		5120 H		5130 H	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	48	41	45	38	46	39	48	41	48	40	56	49
2	47	39	44	37	46	38	48	40	46	34	55	46
3	43	31	44	34	45	35	47	39	41	28	53	42
4	39	27	42	30	44	32	46	38	36	23	51	39
5	35	23	41	27	42	29	45	34	33	20	49	35
6	32	21	39	24	41	27	43	31	30		47	32
7	29		37	22	39	25	42	29	28		45	30
8	28		35	21	37	23	40	27	27		42	28
9	27		33	20	35	22	39	26	25		40	26
10	26		31		33	21	37	25	24		38	25
11	25		30		32	20	36	24	23		37	23
12	24		29		31	20	35	23	22		36	22
13	24		28		30		34	22	21		35	21
14	23		28		29		33	22	21		34	20
15	23		27		28		32	21	20		34	
16	22		27		28		31	21			33	
18	21		26		27		29	20			32	
20	21		25		26		28	20			31	
22	21		24		25		28				30	
24	20		24		25		27				29	
26			24		25		27				27	
28			23		25		26				26	
30			23		24		26				25	
32			23		24		25				24	

"J" Distance Sixteenths of an inch	5132 H		5135 H		5140 H		5145 H		5147 H		5150 H	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	57	50	58	51	60	53	63	56	64	57	65	59
2	56	47	57	49	59	52	62	55	64	56	65	58
3	54	43	56	47	58	50	61	53	63	55	64	57
4	52	40	55	43	57	48	60	51	62	54	63	56
5	50	35	54	38	56	43	59	48	62	53	62	53
6	48	32	52	35	54	38	58	42	61	52	61	49
7	45	29	50	32	52	35	57	38	61	49	60	42
8	42	27	47	30	50	33	56	35	60	45	59	38
9	40	25	45	28	48	31	55	33	60	40	58	36
10	38	24	43	27	46	30	53	32	59	37	56	34
11	37	23	41	25	45	29	52	31	59	35	55	33
12	36	22	40	24	43	28	50	30	58	34	53	32
13	35	21	39	23	42	27	48	30	58	33	51	31
14	34	20	38	22	40	27	47	29	57	32	50	31
15	34		37	21	39	26	45	28	57	32	48	30
16	33		37	21	38	25	44	28	56	31	47	30
18	32		36	20	37	24	42	26	55	30	45	29
20	31		35		36	23	41	25	54	29	43	28
22	30		34		35	21	39	24	53	27	42	27
24	29		33		34	20	38	23	52	26	41	26
26	28		32		34		37	22	51	25	40	25
28	27		32		33		37	21	50	24	39	24
30	26		31		33		36		49	22	39	23
32	25		30		32		35		48	21	38	22

"J" Distance Sixteenths of an inch	5155 H		5160 H		6118 H		6150 H		8617 H		8620 H	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1		60		60	46	39	65	59	46	39	48	41
2	65	59		60	44	36	65	58	44	33	47	37
3	64	58		60	38	28	64	57	41	27	44	32
4	64	57	65	59	33	24	64	56	38	24	41	27
5	63	55	65	58	30	22	63	55	34	20	37	23
6	63	52	64	56	28	20	63	53	31		34	21
7	62	47	64	52	27		62	50	28		32	
8	62	41	63	47	26		61	47	27		30	
9	61	37	62	42	26		61	43	26		29	
10	60	36	61	39	25		60	41	25		28	
11	59	35	60	37	25		59	39	24		27	
12	57	34	59	36	24		58	38	23		26	
13	55	34	58	35	24		57	37	23		25	
14	52	33	56	35	23		55	36	22		25	
15	51	33	54	34	23		54	35	22		24	
16	49	32	52	34	22		52	35	21		24	
18	47	31	48	33	22		50	34	21		23	
20	45	31	47	32	21		48	32	20		23	
22	44	30	46	31	21		47	31			23	
24	43	29	45	30	20		46	30			23	
26	42	28	44	29			45	29			23	
28	41	27	43	28			44	27			22	
30	41	26	43	28			43	26			22	
32	40	25	42	27			42	25			22	

End-Quench Hardenability Limits (Cont'd)

"J" Distance Sixteenths of an inch	8622 H		8625 H		8627 H		8630 H		8637 H		8640 H	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	50	43	52	45	54	47	56	49	59	52	60	53
2	49	39	51	41	52	43	55	46	58	51	60	53
3	47	34	48	36	50	38	54	43	58	50	60	52
4	44	30	46	32	48	35	52	39	57	48	59	51
5	40	26	43	29	45	32	50	35	56	45	59	49
6	37	24	40	27	43	29	47	32	55	42	58	46
7	34	22	37	25	40	27	44	29	54	39	57	42
8	32	20	35	23	38	26	41	28	53	36	55	39
9	31		33	22	36	24	39	27	51	34	54	36
10	30		32	21	34	24	37	26	49	32	52	34
11	29		31	20	33	23	35	25	47	31	50	32
12	28		30		32	22	34	24	46	30	49	31
13	27		29		31	21	33	23	44	29	47	30
14	26		28		30	21	33	22	43	28	45	29
15	26		28		30	20	32	22	41	27	44	28
16	25		27		29	20	31	21	40	26	42	28
18	25		27		28		30	21	39	25	41	26
20	24		26		28		30	20	37	25	39	26
22	24		26		28		29	20	36	24	38	25
24	24		26		27		29		36	24	38	25
26	24		26		27		29		35	24	37	24
28	24		25		27		29		35	24	37	24
30	24		25		27		29		35	23	37	24
32	24		25		27		29		35	23	37	24

"J" Distance Sixteenths of an inch	8642 H		8645 H		8655 H		8720 H		8740 H		8822 H	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	62	55	63	56		60	48	41	60	53	50	43
2	62	54	63	56		59	47	38	60	53	49	42
3	62	53	63	55		59	45	35	60	52	48	39
4	61	52	63	54		58	42	30	60	51	46	33
5	61	50	62	52		57	38	26	59	49	43	29
6	60	48	61	50		56	35	24	58	46	40	27
7	59	45	61	48		55	33	22	57	43	37	25
8	58	42	60	45		54	31	21	56	40	35	24
9	57	39	59	41		52	30	20	55	37	34	24
10	55	37	58	39	65	49	29		53	35	33	23
11	54	34	56	37	65	46	28		52	34	32	23
12	52	33	55	35	64	43	27		50	32	31	22
13	50	32	54	34	64	41	26		49	31	31	22
14	49	31	52	33	63	40	26		48	31	30	22
15	48	30	51	32	63	39	25		46	30	30	21
16	46	29	49	31	62	38	25		45	29	29	21
18	44	28	47	30	61	37	24		43	28	29	20
20	42	28	45	29	60	35	24		42	28	28	
22	41	27	43	28	59	34	23		41	27	27	
24	40	27	42	28	58	34	23		40	27	27	
26	40	26	42	27	57	33	23		39	27	27	
28	39	26	41	27	56	33	23		39	27	27	
30	39	26	41	27	55	32	22		38	26	27	
32	39	26	41	27	53	32	22		38	26	27	

"J" Distance Sixteenths of an inch	9260 H		50B44 H		50B46 H		50B50 H		50B60 H		51B60 H	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1		60	63	56	63	56	65	59		60		60
2		60	63	56	62	54	65	59		60		60
3	65	57	62	55	61	52	64	58		60		60
4	64	53	62	55	60	50	64	57		60		60
5	63	46	61	54	59	41	63	56		60		60
6	62	41	61	52	58	32	63	55		59		59
7	60	38	60	48	57	31	62	52		57		58
8	58	36	60	43	56	30	62	47	65	53		57
9	55	36	59	38	54	29	61	42	65	47		54
10	52	35	58	34	51	28	60	37	64	42		50
11	49	34	57	31	47	27	60	35	64	39		44
12	47	34	56	30	43	26	59	33	64	37	65	41
13	45	33	54	29	40	26	58	32	63	36	65	40
14	43	33	52	29	38	25	57	31	63	35	64	39
15	42	32	50	28	37	25	56	30	63	34	64	38
16	40	32	48	27	36	24	54	29	62	34	63	37
18	38	31	44	26	35	23	50	28	60	33	61	36
20	37	31	40	24	34	22	47	27	58	31	59	34
22	36	30	38	23	33	21	44	26	55	30	57	33
24	36	30	37	21	32	20	41	25	53	29	55	31
26	35	29	36	20	31		39	24	51	28	53	30
28	35	29	35		30		38	22	49	27	51	28
30	35	28	34		29		37	21	47	26	49	27
32	34	28	33		28		36	20	44	25	47	25

"J" Distance Sixteenths of an inch	81B45 H		94B17 H		94B30 H							
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	63	56	46	39	56	49						
2	63	56	46	39	56	49						
3	63	56	45	38	55	48						
4	63	56	45	37	55	48						
5	63	55	44	34	54	47						
6	63	54	43	29	54	46						
7	62	53	42	26	53	44						
8	62	51	41	24	53	42						
9	61	48	40	23	52	39						
10	60	44	38	21	52	37						
11	60	41	36	20	51	34						
12	59	39	34		51	32						
13	58	38	33		50	30						
14	57	37	32		49	29						
15	57	36	31		48	28						
16	56	35	30		46	27						
18	55	34	28		44	25						
20	53	32	27		42	24						
22	52	31	26		40	23						
24	50	30	25		38	23						
26	49	29	24		37	22						
28	47	28	24		35	21						
30	45	28	23		34	21						
32	43	27	23		34	20						

Mechanical properties obtainable with steels for

MODERATELY STRESSED PARTS
OIL QUENCH

Yield strength, psi	Hardness after temper, RC	Hardness after quenching 50% martensite, min	Round Sections						
			To ½ in.	Over ½ in. to 1 in.	Over 1 in. to 1½ in.	Over 1½ in. to 2 in.	Over 2 in. to 2½ in.	Over 2½ in. to 3 in.	Over 3 in. to 3½ in.
			Quenched to 50% Martensite						
			Full radius to center		At ½ radius		At ¾ radius		
			Jominy Reference Point						
			3-1/2/16	6/16	7-1/2/16	10/16	10-1/2/16	13/16	15/16
90,000 to 125,000	23 to 30	42	1330H 4130H 5132H	8637H	3140H 8740H	4140H			
Over 125,000 to 150,000	30 to 36	44	1335H 4042H 5135H	3140H 4135H 8640H 8740H	4137H 6150H 8642H 8645H 8742H		4142H	4145H	4337H 86B45 9850
Over 150,000 to 170,000	36 to 41	48	1340H 3140H 4047H 4135H 50B40 5140H 8637H	4137H 4140H 5150H 8642H 8645H 8742H	4142H 50B50 5147H		4145H 8655H 9840	4147H 4337H 81B45 86B45	4340H
Over 170,000 to 185,000	41 to 46	51	4063H 4140H 50B44 5145H 5150H 8640H 8642H 8740H 8742H 9260H	4142H 4337H 50B50 5147H 6150H	4145H 50B60 81B45 8650H 8655H 9260H		4147H 4340H 51B60 81B45 86B45 8660H	4150H 9850	
Over 185,000	46 min	55	4150H 5160H 8655H 9262H	50B60	8660H				

Mechanical properties obtainable with steels for

MODERATELY STRESSED PARTS
WATER QUENCH

Yield strength, psi	Hardness after temper, RC	Hardness after quenching 50% martensite, min	Round Sections						
			To ½ in.	Over ½ in. to 1 in.	Over 1 in. to 1½ in.	Over 1½ in. to 2 in.	Over 2 in. to 2½ in.	Over 2½ in. to 3 in.	Over 3 in. to 3½ in.
			Quenched to 50% Martensite						
			Full radius to center		At ½ radius		At ¾ radius		
			Jominy Reference Point						
			1-1/2/16	3/16	4/16	6/16	5/16	6-1/2/16	7-1/2/16
90,000 to 125,000	23 to 30	42	1040	1330H 4037H 4130H 5130H 5132H 8630H			1340H 4135H 8637H		3140H 8640H 8740H
Over 125,000 to 150,000	30 to 36	44	1036 1045 1330H 4130H 8630H		1335H 5135H		1340H 3140H 5140H 5145H 8637H	4135H 5150H 8640H 8740H	4137H 4140H 50B40 6150H 8642H 8645H 8742H
Over 150,000 to 170,000	36 to 41	48	1335H 4037H 5135H	4042H 50B40	1340H 4135H 50B40 5140H 8637H		4137H 50B40 5145H 8640H 8740H	4140H 50B44 6150H 8645H 8742H	50B50 5147H 9262H

NOTE: Parts made of steel with a carbon content of .33% or higher should not be water quenched without careful exploration for quench cracking.

Mechanical properties obtainable with steels for

HIGHLY STRESSED PARTS—OIL QUENCH

Yield strength, psi	Hardness after temper, RC	Hardness after quenching 80% martensite, min	Round Sections						
			To ½ in.	Over ½ in. to 1 in.	Over 1 in. to 1½ in.	Over 1½ in. to 2 in.	Over 2 in. to 2½ in.	Over 2½ in. to 3 in.	Over 3 in. to 3½ in.
			Quenched to 80% Martensite						
			Full radius to center		At ½ radius		At ¾ radius		
			Jominy Reference Point						
			3-1/2/16	6/16	7-1/2/16	10/16	10-1/2/16	13/16	15/16
90,000 to 125,000	23 to 30	42	1330H 4130H 5132H						
Over 125,000 to 150,000	30 to 36	44	1335H 5135H	3140H 4135H 50B40 8640H 8740H	4137H	4142H 81B45		9840	4337H 86B45 9850
Over 150,000 to 170,000	36 to 41	48	1340H 5140H 3140H 8637H 4047H 4135H 50B40	4137H 8642H 8645H 8742H	4140H		4145H 9840	4147 4147H 4337H 81B45 86B45	4340H
Over 170,000 to 185,000	41 to 46	51	4063H 8640H 4140H 8642H 50B44 8740H 50B50 8742H 5145H 9260H 5150H	50B50 5147H 5160H 6150H 9262H	4142H 8650H 4145H 8655H 4337H 50B60 81B45	51B60 8660H	4147H 4340H 81B45 86B45	4150H 9850	
Over 185,000	46 min	55	4150H 8655H 50B60 9262H 5160H		8660H				

WATER QUENCH

			Jominy Reference Point						
			1-1/2/16	3/16	4/16	6/16	5/16	6-1/2/16	7-1/2/16
90,000 to 125,000	23 to 30	42		1330H 4130H 5130H 5132H 8630H					
Over 125,000 to 150,000	30 to 36	44	1330H 5132H 4130H 8630H 5130H	5132H			1340H 3140H 50B40 8637H	4135H	4137H

NOTE: Parts made of steel with a carbon content of .33% or higher should not be water quenched without careful exploration for quench cracking.

THERMAL TREATMENT OF STEEL

The versatility of steel is attributable in large measure to its response to a variety of thermal treatments. While a major percentage of steel is used in the as-rolled condition, thermal treatment greatly broadens the spectrum of properties attainable. Treatments fall into two general categories: (1), those which increase the strength, hardness and toughness by virtue of rapid cooling from above the transformation range, and (2), those which decrease hardness and promote uniformity by slow cooling from above the transformation range, or by prolonged heating within or below the transformation range, followed by slow cooling. The first category can involve through-hardening by quenching and tempering, or a variety of specialized treatments undertaken to enhance hardness of the surface to a controlled depth. The second category encompasses normalizing and various types of annealing, the purpose of which may be to improve machinability, toughness, or cold forming characteristics, or to relieve stresses and restore ductility after a processing which has involved some form of cold deformation.

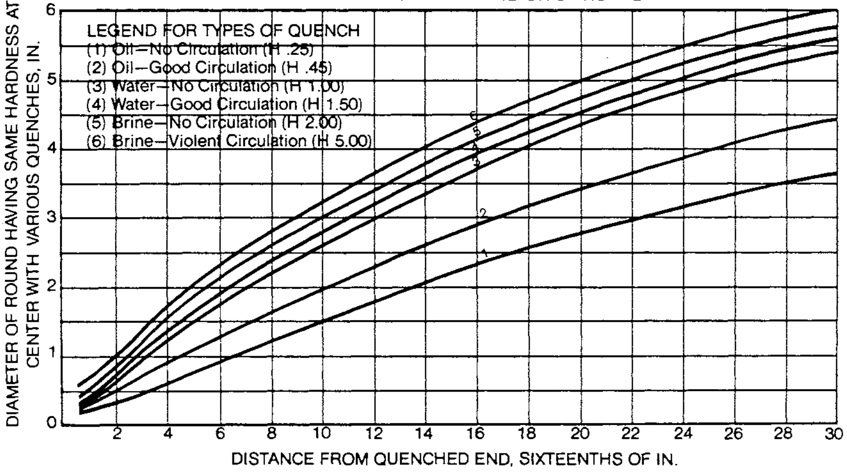
Conventional Quenching and Tempering

As discussed in the previous section, the best combination of strength and toughness is usually obtained by suitably tempering a quenched microstructure consisting of a minimum of 80% martensite throughout the cross section. Steels of suitable hardenability attain this martensitic structure when liquid-quenched from their austenitizing temperatures. Those used most frequently for quenched and tempered parts contain from .30 to .60% carbon, although the carbon specification for any particular application must be determined by the surface hardness and overall strength level required. The hardenability necessary to attain the desired through hardening is a function of the section size and the quenching parameters (see graph, page 62).

Plain carbon steels with low manganese content can be through-hardened only in very thin sections when a mild quench is used. With higher manganese carbon grades, or more drastic quenches, somewhat heavier sections can be quenched effectively. For sections beyond the hardening capability of carbon steels, carbon-boron or alloy steels are required.

QUENCHING MEDIA. As indicated above, the mechanical properties obtained in a quenched part are primarily dependent upon the hardenability of the steel as determined by its chemical composition and by the rate at which it is cooled from the austenitizing temperature. Once the desired cooling rate has been determined, a variety of factors must be considered before the method of achieving that rate can be specified. A part with a specific mass will cool at a rate determined by its temperature in relation to that of the quenching medium, by the characteristics of that medium, and by the quenching conditions used. Furthermore, the cooling rate developed in a particular quenching facility will depend on the volume of the quenching medium as well as its temperature, specific heat, viscosity, and degree of agitation. Careful selection of the quenching medium is essential. For example, use of a drastic quench will make possible the development of a given set of properties in a steel of a specific hardenability. However, size and design of the part, or the steel composition itself, may be such that a drastic quench will cause quench cracks or distortion. Under these conditions, overall economy as well as safety will best be served by using a quenchant with less cooling capacity and a steel of greater hardenability.

RELATION BETWEEN DISTANCE ON STANDARD END-QUENCH TEST AND DIAMETER OF ROUND



The most common quenching media are water and various mineral oils. In most quenching facilities, water is maintained at a temperature of about 65 F. As the water temperature increases, or as the amount of agitation during the quench decreases, there is an increasing tendency for an envelope of steam to form around the part. Because this envelope interferes with the flow of water around the part, it reduces the water's effective cooling capacity. A brine of 5 to 10% sodium chloride has a lower tendency than plain water to form an envelope, and therefore provides a more effective quench. Sodium hydroxide solutions are even more effective. The brine and sodium hydroxide solutions are generally used on very shallow-hardening steels to attain high surface hardness while retaining a ductile core.

Quenching oils providing a wide variety of cooling rates are available commercially. These are characterized by relative stability and chemical inactivity with respect to hot steel, high flash point, and little change in cooling capacity with normal variation in temperature. Most production quenching facilities incorporate cooling coils to maintain the oil bath at a reasonably constant temperature, and provide for sufficient agitation to minimize localized effects of vapor envelopes formed during quenching.

Regardless of the quenching medium used, it is of utmost importance to temper parts immediately after the quenching operation. Delay in tempering greatly increases the risk of cracking, since the as-quenched part is in a highly stressed condition.

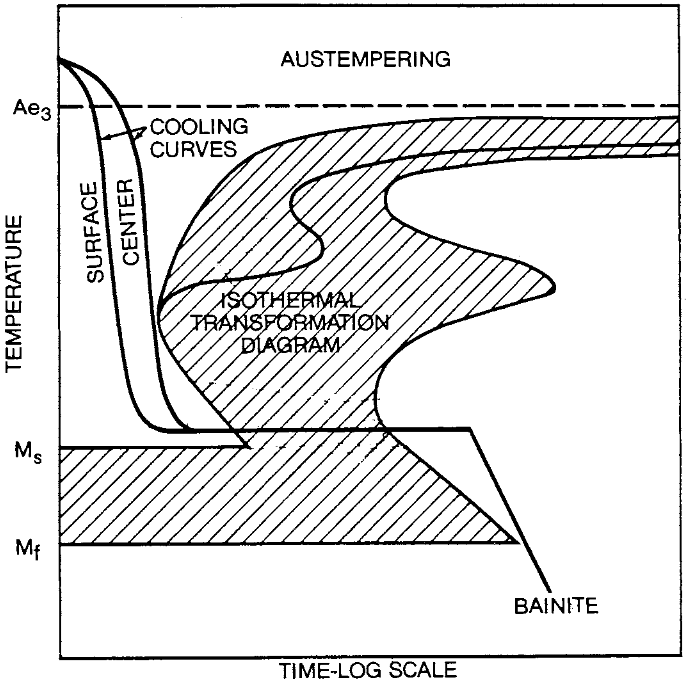
Isothermal Treatments

The preceding sections are concerned with hardening of steel by quenching, using a medium which is at or near room temperature. Another approach to the thermal treatment of steels involves isothermal transformation, accomplished by quenching in a medium held at a constant temperature. For a given steel it may be shown by means of a series of test specimens quenched in media at various temperatures that the time required for the beginning and for the completion of transformation varies considerably. By plotting the various quenching bath temperatures against the time interval required for inception and completion of transformation (on a logarithmic scale) the so-called "S" curve, or TTT (time-temperature-transformation) curve is produced.

It is not within the scope of this book to engage in a lengthy technical discussion of these curves. Some features of the curves have received rather widespread application and will be presented in the following sections. These applications involve both annealing and hardening.

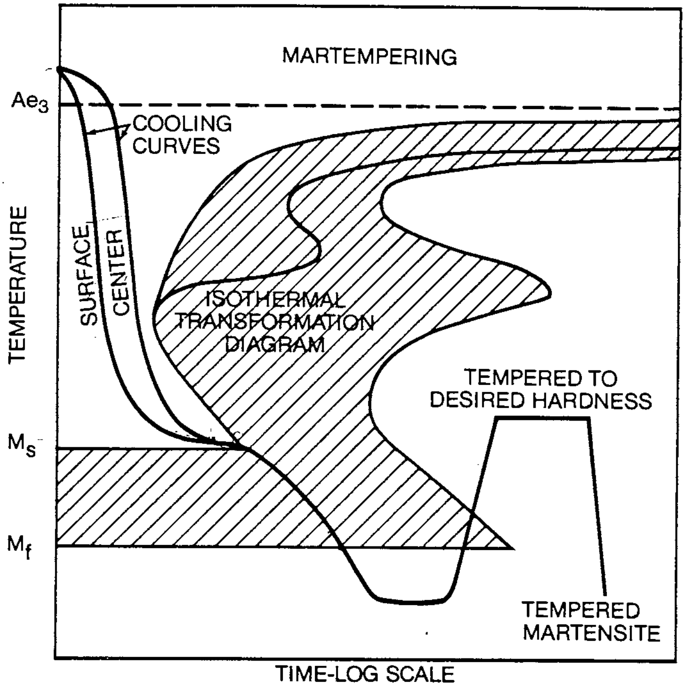
Each steel has a temperature range in which transformation takes place quite rapidly. This occurs at a fairly elevated temperature, and that section of the transformation curve is often referred to as the nose of the curve. Above or below this rapid transformation range, the times required for the critical changes are considerably greater. In order to harden steel it is necessary to quench at such a rate that transformation at the higher temperatures is avoided. If the bath temperature is below approximately 400 F, martensite will form. The highest temperature at which martensite will start to form is termed the M_s temperature. The M_f temperature is the highest temperature at which the transformation can be considered complete. If the quenching bath temperature is above the M_s temperature, other microstructures are formed, as discussed below.

Quenching at a temperature above that of the nose of the curve results in a soft structure after completion of transformation and subsequent cooling to room temperature. (See Annealing, page 71.)



AUSTEMPERING is a hardening treatment which consists of quenching in a molten salt bath maintained somewhat above the M_S temperature, and holding until transformation is complete. The product formed is termed lower bainite and is somewhat softer than martensite.

The advantage of austempering is the high degree of freedom it provides from distortion and quenching cracks. Higher hardenability material must be used, however, to insure against transformation occurring at the nose of the curve, since cooling rates in molten salt baths may be lower than in the oil or water used in conventional quenching. The transformation rate of the higher hardenability steels is quite slow in the temperature range involved, and therefore, austempering has the disadvantage of requiring more time than other quenching methods, even though it is not followed by a tempering treatment.



MARTEMPERING involves quenching from the normal austenitizing temperature in a molten salt bath maintained at approximately the M_S temperature. The part is held at this temperature for a period of time sufficient to allow equalization of temperature within the part, but not long enough to permit any transformation to occur. The material is then removed from the bath and allowed to cool in air through the martensite range, followed by the customary tempering treatment to obtain the desired mechanical properties.

Like austempering, martempering tends to minimize distortion and quench cracking, since the high stresses typical of conventional quenching are avoided. The two processes also share the characteristic of requiring higher hardenability steels than those suitable for conventional quenching, as mentioned above. However, martempering compares favorably with full quenching as far as time is concerned, since the material need only be held for temperature equalization.

Surface Hardening Treatments

A variety of applications require high hardness or strength primarily at the surface; for example, instances involving wear or torsional loading. Service stresses are frequently complex, necessitating not only a hard, wear-resistant surface, but also core strength and toughness to withstand tensile or impact stresses and fatigue. Treatments required to achieve these properties involve two general types of processes: those in which the chemical composition of the surface is altered prior to quenching and tempering; and those in which only the surface layer is hardened by the heating and quenching process employed. The first category includes carburizing, cyaniding, carbo-nitriding, and nitriding. The most common processes included in the second category are flame hardening and induction hardening.

CARBURIZING. In this process, carbon is diffused into the surface of the part to a controlled depth by heating in a carbonaceous medium. The resultant depth of carburization, commonly referred to as case depth, depends on the carbon potential of the medium used and the time and temperature of the carburizing treatment. The steels most suitable for carburizing are those with sufficiently low carbon contents (usually below .30%) to enhance toughness. The actual carbon level, as well as the necessary hardenability and the type of quench, is determined by the section size and the desired core hardness.

There are three types of carburizing in general use:

LIQUID CARBURIZING involves heating in barium cyanide or sodium cyanide at temperatures ranging from 1550 to

1750 F. The temperature and the time at temperature are adjusted to obtain various case depths, usually up to .03 inch, although greater depths are possible. The case absorbs some nitrogen in addition to carbon, thus enhancing surface hardness.

GAS CARBURIZING involves heating in a gas of controlled carbon potential such that the steel surface absorbs carbon. Case depths in the range of .01 to .04 inch are common, the depth again depending on temperature and time. Carbon level in the case can be controlled where advantageous.

PACK CARBURIZING consists of sealing the parts in a gas-tight container together with solid carbonaceous material and heating for eight hours or more to develop case depths in excess of .04 inch. This method is particularly suitable for producing deep cases of .06 inch and over.

With any of the above methods, the part may be quenched after the carburizing cycle without reheating, or it may be air-cooled followed by reheating to the austenitizing temperature prior to quenching. The recommended carburizing temperatures and quenching treatments published by SAE are listed on pages 74-76.

The depth of case may be varied to suit the conditions of loading in service. For simple wear applications a very thin case may suffice. Under conditions of severe loading which would tend to collapse the case, greater case depth and higher core hardness are required.

Frequently, service characteristics require that only selective areas of a part be hardened. Such selective hardening can be accomplished in various ways. The most common method is by copper plating the non-wear surfaces, or by coating them with one of several available commercial pastes, thereby allowing the carbon to penetrate only the exposed areas. A second method is by carburizing the entire part and then removing the case in the selected areas by machining or grinding. A localized hardening treatment after carburizing is another method sometimes used.

NITRIDING consists of heating at a temperature of 900 to 1150 F in an atmosphere of ammonia gas and dissociated ammonia for an extended period of time, depending on the case depth desired. A thin, very hard case results from the formation of nitrides. Special compositions containing the strong nitride-forming elements (usually aluminum, chromium, and molybdenum) are used. The major advantages of this process are that parts can be machined prior to nitriding, and that during such treatment, they exhibit desirable dimensional stability with little distortion. Where required to develop core properties, parts are quenched and tempered prior to final machining. Nitrided parts have exceptional wear resistance with little tendency to gall and seize, and are therefore particularly serviceable in applications involving metal-to-metal wear. They also have high resistance to fatigue plus improved corrosion resistance.

CYANIDING involves heating in a bath of sodium cyanide to a temperature slightly above the transformation range to obtain a thin case of high hardness, followed by quenching. This results in a hard, somewhat brittle case (because of the presence of nitrides) backed by a fine-grained tough core. Parts have superior wear resistance, approaching that of a nitrided case.

CARBO-NITRIDING is similar to cyaniding except that the absorption of carbon and nitrogen is accomplished by heating in a gaseous atmosphere containing hydrocarbons and ammonia. Case depths range from .003 to .025 inch. Case composition depends on the atmosphere, temperature, time, and steel composition. Temperatures of 1425 to 1625 F are used for parts to be quenched, while lower temperatures (1200 to 1450 F) may be used where a liquid quench is not required.

FLAME HARDENING involves rapid heating with a direct high-temperature gas flame, such that the surface layer of the part is heated above the transformation range, followed by cooling at a rate which will accomplish the desired hardening. Heating and cooling cycles must be precisely controlled to attain the desired depth of hardening consistently. Steels for flame hardening are usually in the range of .30 to .60% carbon, with hardenability appropriate for the depth to be hardened and the quenchant used. Various quenching media are used, and usually sprayed on the surface at a short distance behind the heating flame. Immediate tempering is required to avoid cracking caused by residual stresses, and may be accomplished by conventional furnace tempering or flame tempering processes, depending on part size and economic considerations.

INDUCTION HARDENING. In recent years considerable quantities of steel have been heated for hardening by electrical induction. As optimum results from this type of thermal treatment involve metallurgical considerations somewhat unique for the process, an explanation of the fundamental principles and metallurgical aspects follows.

When high frequency alternating current is sent through a coil or inductor, a magnetic field is developed in the coil. If an electrical conductor, such as a steel part, is placed in this field, it will be heated by induced energy. Heating results primarily from the resistance of the part to the flow of currents created by the induced voltage (viz., eddy current losses) and also from hysteresis losses caused by the rapidly alternating magnetic field if the part is magnetic. Thus, most plain carbon and alloy steels heat most rapidly below the Curie temperature (approximately the upper critical temperature) where they are ferromagnetic, and less rapidly above this temperature.

With conventional induction-heating generators, the heat is developed primarily on the surface of the part. The total depth of heating depends upon the frequency of the alternating current passing through the coil, the rate at which heat is conducted from the surface to the interior, and the length of the heating cycle. Thus, the process is capable either of surface (or case) hardening to various controlled depths, or of through hardening. Surface hardening is normally accomplished with frequencies of 10,000 to 500,000 cycles per second using high power and short heating cycles, while lower frequencies and long heating cycles are preferred for through heating by induction.

Quenching is usually accomplished with a water spray introduced at the proper time by a quench ring or through the inductor block or coil. In some instances, however, oil quenching is successfully employed by dropping the pieces into a bath of oil after they reach the hardening temperature.

From the metallurgical standpoint, induction heating and conventional heating vary primarily in the time allowed for metallurgical reactions. Heating by induction is very rapid and zero time is normally provided at the hardening temperature prior to quenching. The very short austenitizing times which result may have a significant influence on the metallurgical results and often make it necessary to give special attention to the selection of the steel, the microstructure prior to heating, and the hardening temperature.

Plain medium carbon steels are preferred for induction surface hardening, although the free machining grades 1141 and 1144 are frequently used. Alloy steels can also be successfully induction hardened, although it is often necessary to increase the hardening temperature to provide alloy solution in steels containing carbide-forming elements, e.g., 4340 and 4150. Alloy steels may be required if a very deep case or through hardening is necessary. The steels tabulated below are typical of those which have been satisfactorily hardened by induction heating. Since steels containing higher carbon than those shown are also successfully induction hardened, the list should be considered indicative rather than inclusive.

Plain Carbon	Free Machining	Alloy	Surface Hardness after Quenching
1040	1141	4140 4340 8740	HRC 52 Min
1045	1144	4145 8645	HRC 56 Min
1050		4150 5150 6150	HRC 60 Min

This tabulation also provides minimum hardnesses to be expected on the surface of parts surface-hardened by induction heating and quenching. These values are considered conservative minima. While the hardness in induction heating is a function of the carbon content as in conventional heating, higher hardness values for a given carbon content have often been observed for induction surface-hardened parts. The increment of added hardness may be as much as 5 HRC points for steels of .30% carbon, and decreases with the carbon content.

Microstructures which show a fine uniform distribution of ferrite and carbide respond most rapidly to induction heating and are necessary where shallow case depths are required. Thus quenched and tempered or normalized structures provide optimum results, while annealed, hot-rolled, or spheroidized structures which may contain considerable amounts of massive free ferrite will require a longer heating cycle.

Conventional hardening temperatures can generally be used when induction heating plain carbon grades and alloy steels containing non-carbide-forming elements. With alloy steels containing carbide-forming elements such as chromium, molybdenum, and vanadium, however, the hardening temperature must be increased if the normal influence of the alloying elements is desired. Increased hardening temperatures do not increase the austenitic grain size since grain growth is inhibited by the undissolved carbides. In general, steels heated to conventional hardening temperatures by induction show a similar or somewhat finer grain size than steels heated in the furnace for hardening.

It is, of course, essential to remove any decarburized surface by machining or grinding prior to induction hardening if maximum surface hardness is desired.

Normalizing and Annealing

Preceding discussions have been concerned with the principles and techniques of hardening and strengthening of steels by various processes which involve some form of quenching and tempering. Another important type of thermal treatment has as its purpose either a softening of the steel or the development of a more uniform microstructure prior to further processing.

NORMALIZING involves heating to a temperature of about 100 to 150 F above the upper critical temperature, followed by cooling in still air. The uniformly fine-grained pearlitic structure which normally results enhances the uniformity of mechanical properties, and for certain grades, improves machinability. Notch toughness in particular is much better than that experienced in the as-rolled condition. For large sections, and where freedom from residual stresses or lower hardness is desired, the normalizing treatment may be followed by a stress-relief treatment (see below). Normalizing is also frequently used as a conditioning treatment prior to quenching and tempering. The purpose is to facilitate austenitizing, particularly in grades containing strong carbide-forming elements.

ANNEALING consists of a heating cycle, a holding period, and a controlled cooling cycle. As discussed below, various types of annealing are used for various purposes, such as to relieve stresses, to soften the steel, to improve formability, or to develop a particular microstructure conducive to optimum machinability or cold formability.

STRESS RELIEF ANNEAL. This treatment consists of heating to a temperature approaching the lower transformation temperature (Ac_1), holding for a sufficient time to achieve temperature uniformity throughout the part, and then cooling to ambient temperature. Its usual purpose is to relieve residual stresses induced by normalizing, welding, machining, or straightening or cold deformation of any kind. A similar treatment is sometimes used to facilitate cold-shearing of as-rolled material. If the steel has undergone a considerable amount of prior cold work, this annealing treatment will cause the ferrite in the microstructure to recrystallize; otherwise, little change in structure will result. A degree of softening and improved ductility may be experienced, depending on the temperature and time involved.

SUB-CRITICAL ANNEAL. This treatment differs from stress-relieving primarily in that it requires a longer holding period at the annealing temperature. and that the furnace charge is then slow-cooled at a controlled rate. The purpose of this type anneal is to soften the steel, usually in preparation for subsequent cold deformation. The treatment does not allow consistent control of microstructures, inasmuch as the carbide tends to spheroidize to a degree which depends on prior structure and on the temperature, time, and cooling rates involved.

SOLUTION, OR FULL ANNEAL. This treatment involves heating to a temperature above the transformation range, followed by controlled cooling to a temperature substantially below that range. A predominantly lamellar microstructure is normally obtained, with some variation dependent upon the rate of cooling through the transformation range and the degree of homogenization of the carbides prior to cooling. This treatment softens the steel, but its principal use is to improve the machinability of medium carbon steels.

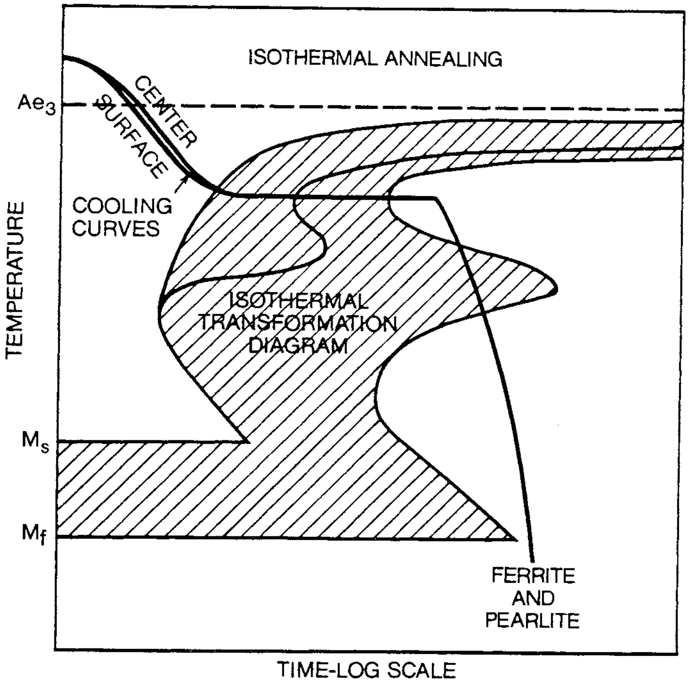
SPHEROIDIZE ANNEAL. The purpose of this type of annealing is to achieve a spheroidal or globular form of the carbides, primarily to provide optimum cold forming characteristics. A spheroidized structure is also desirable for machinability in high carbon steels. Several methods are used to develop this condition:

(1) Heating to a temperature between the upper and lower transformation temperatures and cooling very slowly in the furnace to below the transformation range.

(2) Heating as in (1), then cooling rapidly to a temperature just below the transformation range and holding for a prolonged period (see Isothermal Anneal).

(3) Heating to a temperature just below the Ac_1, holding for an extended length of time, then slow cooling.

(4) Alternate repetitive heating to a temperature within, and to a temperature slightly below the transformation range.



ISOTHERMAL ANNEAL. This process makes use of the principles discussed under Isothermal Treatments (page 63) and is effective in obtaining either a lamellar or a spheroidized structure. If a lamellar pearlitic structure is desired, the work is austenitized above the upper transformation temperature, then cooled to, and held at a temperature at or above the nose of the S-curve. Transformation at the nose of the curve will be more rapid, but will result in finer pearlite and a higher hardness than transformation at higher temperatures.

To obtain a spheroidized structure, a lower austenitizing temperature is used so that some carbide remains undissolved. Cooling and transformation as for the pearlitic anneal above will result in a spheroidized structure.

By accelerating the cooling to the transformation temperature and also the cooling subsequent to transformation, appreciable time savings can be realized as compared with that required for conventional annealing practices.

SAE Typical Thermal Treatments

ALLOY STEELS—Carburizing Grades

SAE Number[a]	Pretreatments			Carburizing[e] Temp, F	Cooling Method	Reheat Temp, F	Quenching Medium	Tempering[f] Temp, F
	Normalize[b]	Normalize and Temper[c]	Cycle Anneal[d]					
4012 4023 4024 4027 4028 4032 4118	Yes	–	–	1650-1700	Quench in oil[g]	–	–	250-350
4320	Yes	–	Yes	1650-1700	Quench in oil[g] Cool slowly	– 1525-1550[i]	– Oil	250-350
4419 4422 4427	Yes	–	Yes	1650-1700	Quench in oil[g]	–	–	250-350
4615 4617 4620 4621 4626 4718	Yes	–	Yes	1650-1700	Quench in oil[g] Cool slowly Quench in oil	– 1500-1550[i] 1500-1550[h]	– Oil Oil	250-350
4720	Yes	–	Yes	1650-1700	Quench in oil	1500-1550[h]	Oil	250-350
4815 4817 4820	–	Yes	Yes	1650-1700	Quench in oil[g] Cool slowly Quench in oil	– 1475-1525[i] 1475-1525[h]	– Oil Oil	250-325
5015 5115 5120	Yes	–	–	1650-1700	Quench in oil[g]	–	–	250-350
6118	Yes	–	–	1650	Quench in oil[g]	–	–	325

SAE Number[a]	Pretreatments			Carburizing[e] Temp, F	Cooling Method	Reheat Temp, F	Quenching Medium	Tempering[f] Temp, F
	Normalize[b]	Normalize and Temper[c]	Cycle Anneal[d]					
8115 8615 8617	Yes	—	—	1650-1700	Quench in oil[g]	—	—	250-350
					Cool slowly	1550-1600[i]	Oil	
					Quench in oil	1550-1600[h]	Oil	
8620 8622 8625 8627 8720 8822	Yes	—	Yes	1650-1700	Quench in oil[g]	—	—	250-350
					Cool slowly	1550-1600[i]	Oil	
					Quench in oil	1550-1600[h]	Oil	
9310	—	Yes	—	1600-1700	Quench in oil	1450-1525[h]	Oil	250-325
					Cool slowly	1450-1525[i]	Oil	
94B15 94B17	Yes	—	—	1650-1700	Quench in oil[g]	—	—	250-350

[a] These steels are fine grain. Heat treatments are not necessarily correct for coarse grain.

[b] Normalizing temperature should be at least as high as the carburizing temperature followed by air cooling.

[c] After normalizing, reheat to temperature of 1100-1200 F and hold at temperature approximately 1 hr per in. of maximum section or 4 hr minimum time.

[d] Where cycle annealing is desired, heat to at least as high as the carburizing temperature, hold for uniformity, cool rapidly to 1000-1250 F, hold 1 to 3 hr, then air cool or furnace cool to obtain a structure suitable for machining and finish.

[e] It is general practice to reduce carburizing temperatures to approximately 1550 F before quenching to minimize distortion and retained austenite. For 4800 series steels, the carburizing temperature is reduced to approximately 1500 F before quenching.

[f] Temperatures higher than those shown are used in some instances where application requires.

[g] This treatment is most commonly used and generally produces a minimum of distortion.

[h] This treatment is used where the maximum grain refinement is required and/or where parts are subsequently ground on critical dimensions. A combination of good case and core properties is secured with somewhat greater distortion than is obtained by a single quench from the carburizing treatment.

[i] In this treatment the parts are slowly cooled, preferably under a protective atmosphere. They are then reheated and oil quenched. A tempering operation follows as required. This treatment is used when machining must be done between carburizing and hardening or when facilities for quenching from the carburizing cycle are not available. Distortion is at least equal to that obtained by a single quench from the carburizing cycle, as described in note e.

SAE Typical Thermal Treatments

CARBON STEELS—Carburizing Grades

SAE Number	Carburizing Temp, F	Cooling Method	Reheat Temp, F	Cooling Medium	Carbo-nitriding Temp, F	Cooling Medium
1010	—	—	—	—	1450-1650	Oil
1015	—	—	—	—		
1016	1650-1700	Water or Caustic	—	—	1450-1650	Oil
1018 1019 1020 1022 1026 1030	1650-1700	Water or Caustic	1450	Water or Caustic[a]	1450-1650	Oil
1109	1650-1700	Water or Oil	1400-1450	Water or Caustic[a]	—	—
1117	1650-1700	Water or Oil	1450-1600	Water or Caustic[a]	1450-1650	Oil
1118	1650-1700	Oil	1450-1600	Oil	—[b]	—
1513 1518 1522 1524 1525 1526 1527	1650-1700	Oil	1450	Oil	—[b]	—

NOTE: Normalizing is generally unnecessary for fulfilling either dimensional or machinability requirements of parts made from the above grades. Where dimension is of vital importance, normalizing temperatures of at least 50 F above the carburizing temperatures are sometimes required to minimize distortion.

NOTE: Tempering temperatures are usually 250-400 F, but higher temperatures may be used when permitted by the hardness specification for the finished parts.

[a] 3% sodium hydroxide.

[b] The higher manganese steels such as 1118 and the 1500 series are not usually carbonitrided. If carbonitriding is performed, care must be taken to limit the nitrogen content because high nitrogen will increase their tendency to retain austenite.

SAE Typical Thermal Treatments

CARBON STEELS

Water and Oil Hardening Grades

SAE Number	Normalizing Temp, F	Annealing Temp, F	Hardening Temp, F	Quenching Medium
1030	–	–	1575-1600	Water or Caustic
1035	–	–	1550-1600	Water or Caustic
1037 1038[a] 1039[a] 1040[a]	–	–	1525-1575	Water or Caustic
1042 1043[a] 1045[a] 1046[a]	–	–	1500-1550	Water or Caustic
1050[a] 1053	1600-1700	–	1500-1550	Water or Caustic
1060	1600-1700	1400-1500	1575-1625	Oil
1074	1550-1650	1400-1500	1575-1625	Oil
1080 1084 1085 1090	1550-1650	1400-1500[b]	1575-1625	Oil[c]
1095	1550-1650	1400-1500[b]	1575-1625	Water and Oil
1137	–	–	1550-1600	Oil
1141	–	1400-1500	1500-1550	Oil
1144	1600-1700	1400-1500	1500-1550	Oil
1145 1146	– –	– –	1475-1500	Water or Oil
1151	1600-1700	–	1475-1500	Water or Oil
1536	1600-1700	–	1500-1550	Water or Oil
1541	1600-1700	1400-1500	1500-1550	Water or Oil
1548 1552	1600-1700	–	1500-1550	Oil
1566	1600-1700	–	1575-1625	Oil

NOTE: When tempering is required, temperature should be selected to effect desired hardness.

[a] These grades are commonly used for parts where induction hardening is employed, although all steels from 1030 up may be induction hardened.

[b] Spheroidal structures are often required for machining purposes and should be cooled very slowly or be isothermally transformed to produce the desired structure.

[c] May be water or brine quenched by special techniques such as partial immersion or time quenched; otherwise, they are subject to quench cracking.

SAE Typical Thermal Treatments

ALLOY STEELS—Directly Hardenable Grades

SAE Number[a]	Normalizing Temp, F	Annealing[d] Temp, F	Hardening[e] Temp, F	Quenching Medium
1330	1600-1700[b]	1550-1650	1525-1575	Water or Oil
1335 1340 1345	1600-1700[b]	1550-1650	1500-1550	Oil
4037 4042	–	1500-1575	1525-1575	Oil
4047	–	1450-1550	1500-1575	Oil
4130	1600-1700[b]	1450-1550	1500-1600	Water or Oil
4135 4137 4140 4142	–	1450-1550	1550-1600	Oil
4145 4147 4150	–	1450-1550	1500-1550	Oil
4161	–	1450-1550	1550-1550	Oil[f]
4340	1600-1700[b]	1450-1550	1500-1550	Oil[c]
50B40 50B44 5046 50B46	1600-1700[b]	1500-1600	1500-1550	Oil
50B50 5060 50B60	1600-1700[b]	1500-1600	1475-1550	Oil
5130 5132	1600-1700[b]	1450-1550	1525-1575	Water, Caustic or Oil
5135 5140 5145	1600-1700[b]	1500-1600	1500-1550	Oil

SAE Number[a]	Normalizing Temp, F	Annealing[d] Temp, F	Hardening[e] Temp, F	Quenching Medium
5147 5150 5155 5160 51B60	1600-1700[b]	1500-1600	1475-1550	Oil
50100 51100 52100	–	1350-1450	1425-1475 1500-1600	Water Oil
6150	–	1550-1650	1550-1625	Oil
81B45	1600-1700[b]	1550-1650	1500-1575	Oil
8630	1600-1700[b]	1450-1550	1525-1600	Water or Oil
8637 8640	–	1500-1600	1525-1575	Oil
8642 8645 86B45 8650	–	1500-1600	1500-1575	Oil
8655 8660	–	1500-1600	1475-1550	Oil
8740	–	1500-1600	1525-1575	Oil
9254 9255 9260	–	–	1500-1650	Oil
94B30	1600-1700[b]	1450-1550	1550-1625	Oil

NOTE. When tempering is required, temperature should be selected to effect desired hardness. See footnotes c and f.

[a] These steels are fine grain.

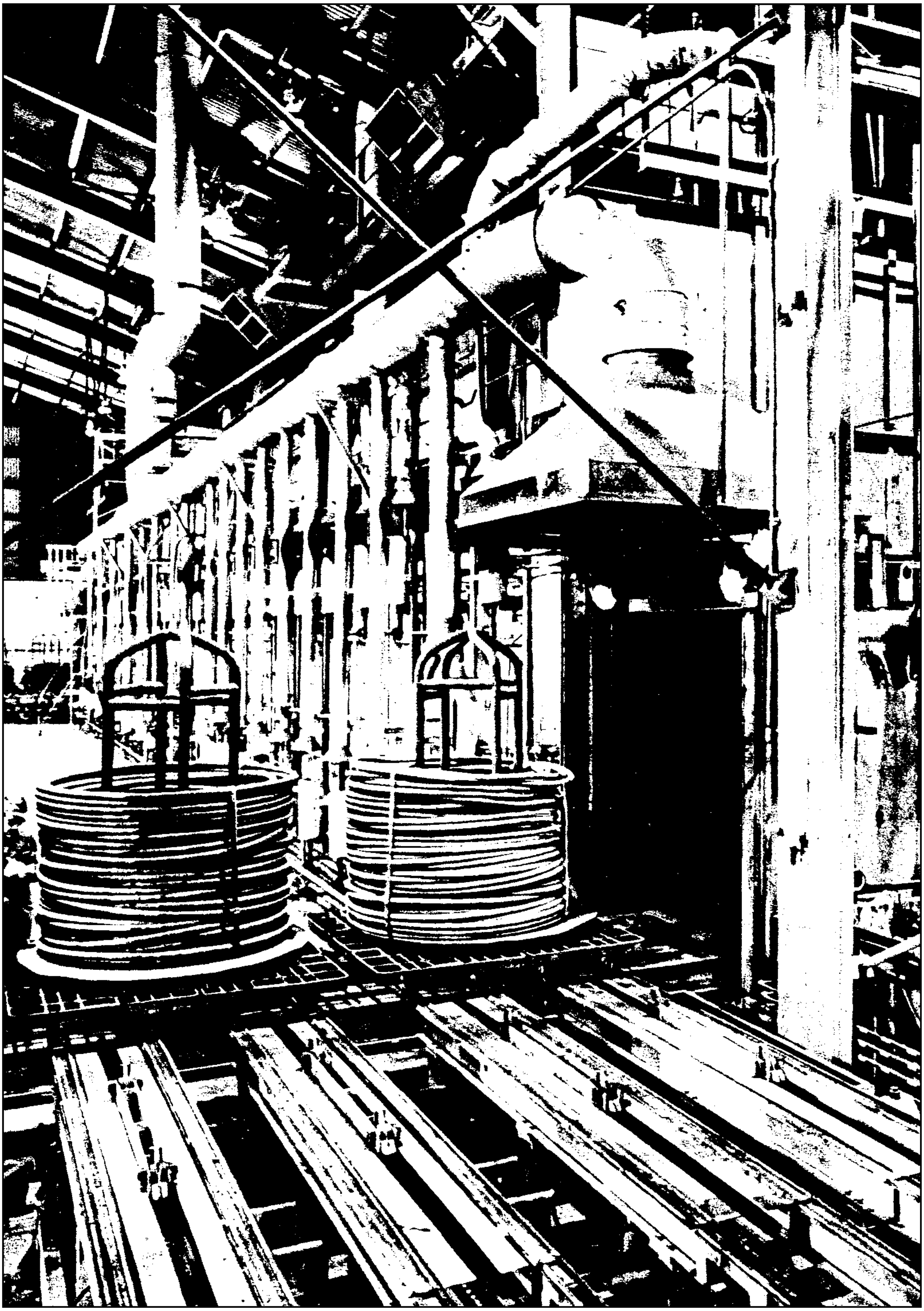
[b] These steels should be either normalized or annealed for optimum machinability.

[c] Temper at 1100-1225 F.

[d] The specific annealing cycle is dependent upon the alloy content of the steel, the type of subsequent machining operations, and desired surface finish.

[e] Frequently, these steels, with the exception of 4340, 50100, 51100, and 52100, are hardened and tempered to a final machinable hardness without preliminary thermal treatment.

[f] Temper above 700 F.



GRAIN SIZE

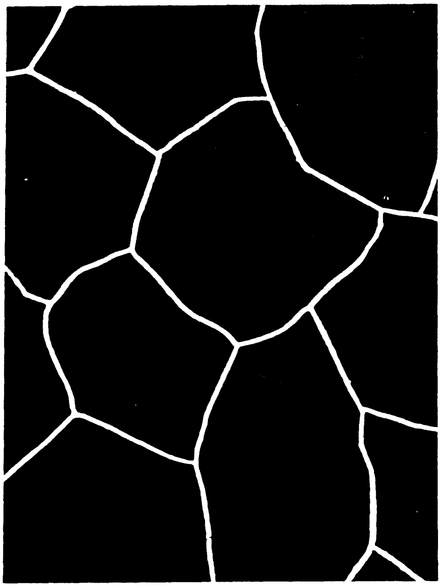
Grain size, as considered within the scope of this publication, is the austenitic grain size. As any carbon or alloy steel is heated to a temperature just above the upper critical temperature, it transforms to austenite of uniformly fine grain size. On heating to progressively higher temperatures, coarsening of the austenite grains eventually will occur. The temperature at which this occurs is dependent to some extent on the composition of the steel, but is influenced primarily by the type and degree of deoxidation used in the steelmaking process. Time at temperature also influences the degree of coarsening. Deoxidizers such as aluminum, and alloying elements such as vanadium, titanium, and columbium, inhibit grain growth, thereby increasing the temperature at which coarsening of the austenitic grains occurs. Aluminum is most commonly used for grain size control because of its low cost and dependability.

For steels used in the quenched and tempered condition, a fine grain size at the quenching temperature is almost always preferred, because fine austenitic grain size is conducive to good ductility and toughness. Coarse grain size enhances hardenability, but also increases the tendency of the steel to crack during thermal treatment.

When austenitic grain size is specified, the generally accepted method of determining it is the McQuaid-Ehn test[1] This test consists of carburizing a specimen at 1700 F, followed by slow cooling to develop a carbide network at the grain boundaries. The specimen is polished and etched, and then compared at 100 diameters magnification with a standard (pages 82-83). Since it is impossible to produce steels of a single grain size, a range of grain size numbers is usually reported. For specification purposes, a steel is considered fine grained if it is predominantly 5 to 8 inclusive, and coarse grained if it is predominantly 1 to 5 inclusive. These requirements are usually considered fulfilled if 70% of the grains examined fall within these ranges.

Steels which are fine grained at 1700 F will be fine grained at a lower quenching temperature. A steel which exhibits coarse grain size at 1700 F, is usually fine grained at conventional quenching temperatures, but this cannot be guaranteed. Consequently, fine grain size (McQuaid-Ehn) is usually specified for applications involving hardening by thermal treatment.

[1] A detailed discussion of the McQuaid-Ehn test and of other methods for determining grain size can be found in ASTM Specification E112.



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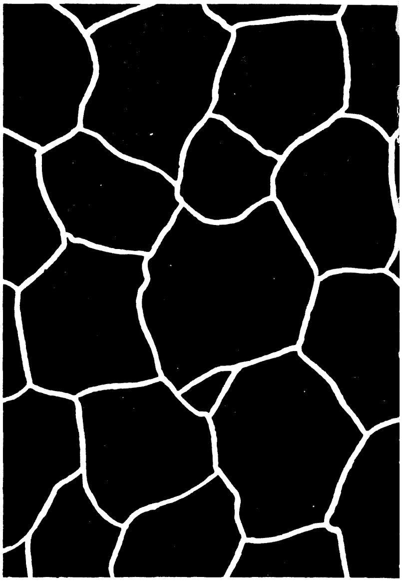

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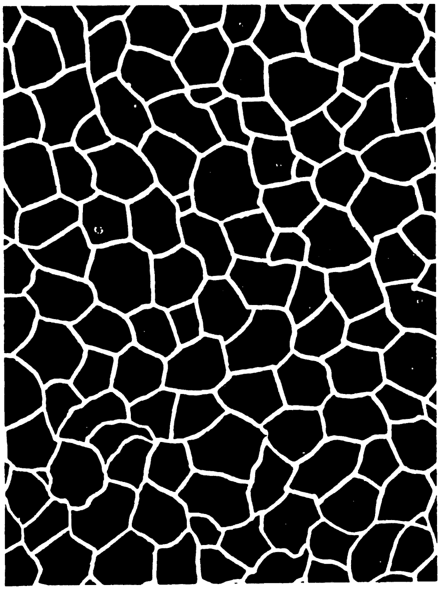

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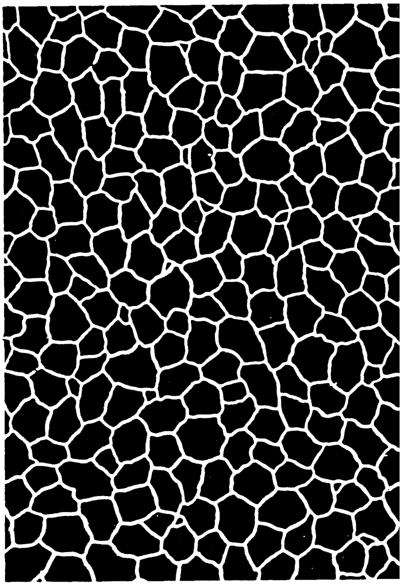

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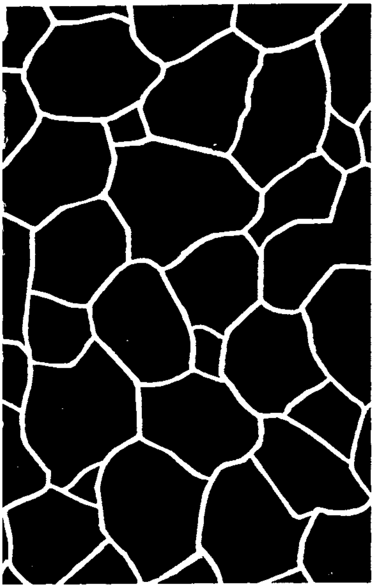

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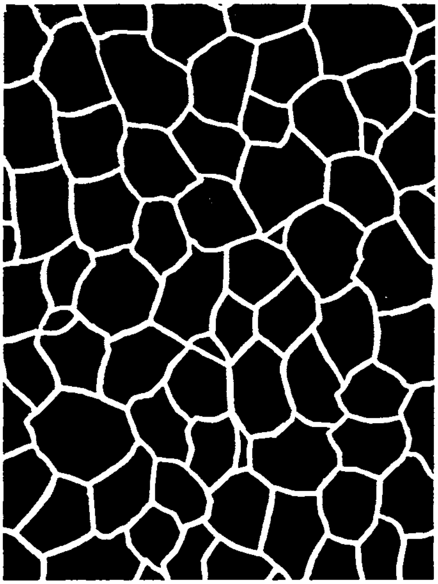

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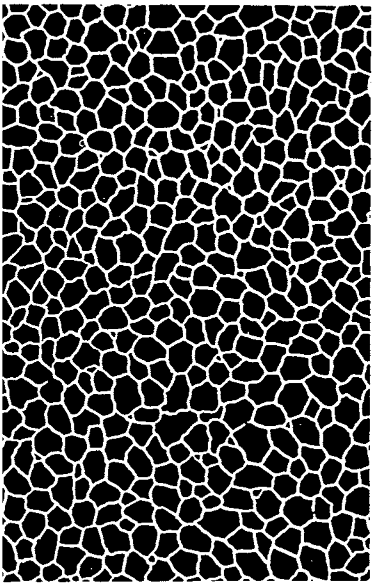

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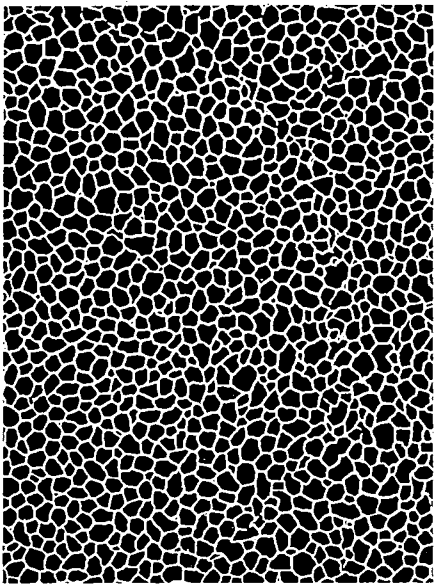


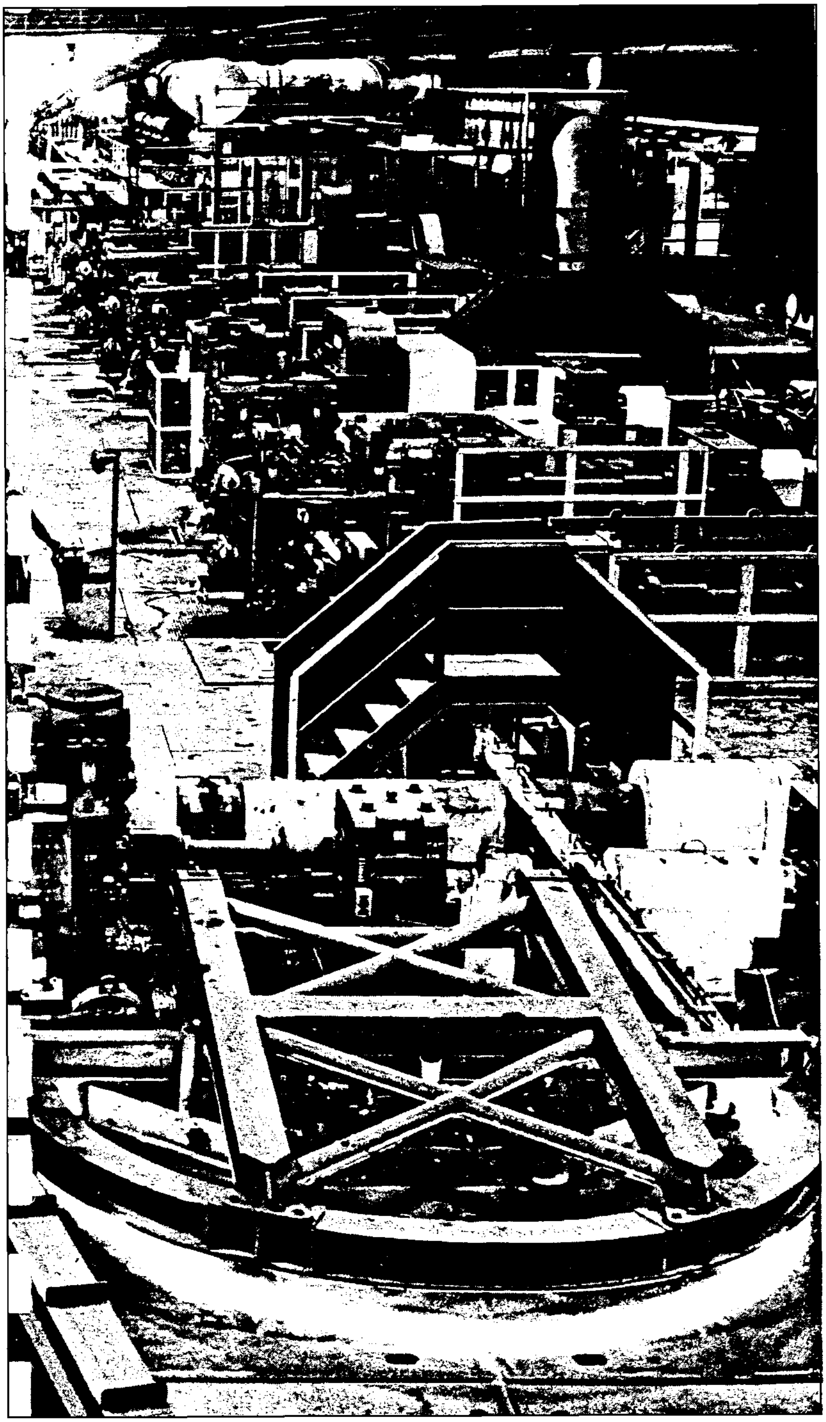
8

MECHANICAL PROPERTIES

of Carbon and Alloy Steels

The mechanical properties of a number of common carbon and alloy steels are given on the following pages. The data were obtained by testing single heats of the compositions indicated, and may be used as a guide in selecting grades for specific applications. However, it should be kept in mind that every grade of steel is furnished to a range of composition, and that the resultant heat-to-heat variations in the percentages of individual elements present in any grade can cause significant differences in the properties obtainable by thermal treatment. Similarly, section size and thermal treatment parameters markedly influence the properties which can be developed in any particular part. Hence, the mechanical properties given in this section should not be considered as maximum, minimum, or average values for a particular application of the grades involved.

CARBON STEEL
CARBURIZING GRADES



1015

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Grain Size
Grade	.13/.18	.30/.60	.040 Max	.050 Max	—	
Ladle	.15	.53	.018	.031	.17	6-8

Critical Points, F: Ac_1 1390 Ac_3 1560 Ar_3 1510 Ar_1 1390

SINGLE QUENCH AND TEMPER

Carburized at 1675 F for 8 hours; pot-cooled; reheated to 1425 F; water-quenched; tempered at 350 F.

1-in. Round Treated Case Depth .048 in. Case Hardness HRC 62

MASS EFFECT

Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1600 F, furnace-cooled 30 F per hour to 1340 F, cooled in air.)					
1	56,000	41,250	37.0	69.7	111
Normalized (Heated to 1700 F, cooled in air.)					
½	63,250	48,000	38.6	71.0	126
1	61,500	47,000	37.0	69.6	121
2	60,000	44,500	37.5	69.2	116
4	59,250	41,800	36.5	67.8	116
Mock-Carburized at 1675 F for 8 hours; reheated to 1425 F; quenched in water; tempered at 350 F.					
½	106,250	60,000	15.0	32.9	217
1	75,500	44,000	30.0	69.0	156
2	70,750	41,375	32.0	70.4	131
4	67,250	39,000	30.5	69.5	121

As-quenched Hardness (water)

Size Round	Surface	½ Radius	Center
½	HRC 36.5	HRC 23	HRC 22
1	HRB 99	HRB 91	HRB 90
2	HRB 98	HRB 84	HRB 82
4	HRB 97	HRB 80	HRB 78

1020

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Grain Size
Grade	.18/.23	.30/.60	.040 Max	.050 Max	—	
Ladle	.19	.48	.012	.022	.18	6-8

Critical Points, F: Ac_1 1350 Ac_3 1540 Ar_3 1470 Ar_1 1340

SINGLE QUENCH AND TEMPER

Carburized at 1675 F for 8 hours; pot-cooled; reheated to 1425 F; water-quenched; tempered at 350 F.

1-in. Round Treated Case Depth .046 in. Case Hardness HRC 62

MASS EFFECT

	Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
As-Rolled	1	68,500	55,750	32.0	66.5	137
Annealed (Heated to 1600 F, furnace-cooled 30 F per hour to 1290 F, cooled in air.)						
	1	57,250	42,750	36.5	66.0	111
Normalized (Heated to 1700 F, cooled in air.)						
	½	64,500	50,250	39.3	69.1	131
	1	64,000	50,250	35.8	67.9	131
	2	63,500	46,250	35.5	65.5	126
	4	60,000	40,750	36.0	66.6	121
Mock-Carburized at 1675 F for 8 hours; reheated to 1425 F; quenched in water; tempered at 350 F.						
	½	129,000	72,000	11.4	29.4	255
	1	87,000	54,000	23.0	64.2	179
	2	75,500	43,750	31.3	67.9	156
	4	71,250	42,000	33.0	67.6	143

As-quenched Hardness (water)

Size Round	Surface	½ Radius	Center
½	HRC 40.5	HRC 30	HRC 28
1	HRC 29.5	HRB 96	HRB 93
2	HRB 95	HRB 85	HRB 83
4	HRB 94	HRB 78	HRB 77

1022

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Grain Size
Grade	.18/.23	.70/1.00	.040 Max	.050 Max	—	
Ladle	.22	.82	.016	.023	.20	6-8

Critical Points, F: Ac_1 1360 Ac_3 1530 Ar_3 1440 Ar_1 1300

SINGLE QUENCH AND TEMPER

Carburized at 1675 F for 8 hours; pot-cooled; reheated to 1425 F; water-quenched; tempered at 350 F.

1-in. Round Treated Case Depth .046 in. Case Hardness HRC 62

MASS EFFECT

	Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
As-Rolled	1	70,250	52,250	33.0	65.2	137
Annealed (Heated to 1600 F, furnace-cooled 30 F per hour to 1250 F, cooled in air.)						
	1	65,250	46,000	35.0	63.6	137
Normalized (Heated to 1700 F, cooled in air.)						
	½	70,500	53,000	35.7	68.3	143
	1	70,000	52,000	34.0	67.5	143
	2	68,750	48,000	34.0	66.6	137
	4	67,250	45,000	33.8	63.9	131
Mock-Carburized at 1675 F for 8 hours; reheated to 1425 F; quenched in water; tempered at 350 F.						
	½	135,000	75,000	13.6	24.3	262
	1	89,000	55,000	25.5	57.3	179
	2	82,000	50,250	30.0	69.6	163
	4	74,000	42,500	32.5	71.6	149

As-quenched Hardness (water)

Size Round	Surface	½ Radius	Center
½	HRC 45	HRC 29	HRC 27
1	HRC 41	HRB 95	HRB 92
2	HRC 38	HRB 88	HRB 84
4	HRC 34	HRB 84	HRB 81

1117

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Grain Size
Grade	.14/.20	1.00/1.30	.040 Max	.08/.13	—	
Ladle	.19	1.10	.015	.084	.11	2-4

Critical Points, F: Ac_1 1345 Ac_3 1540 Ar_3 1450 Ar_1 1340

SINGLE QUENCH AND TEMPER

Carburized at 1700 F for 8 hours; pot-cooled; reheated to 1450 F; water-quenched; tempered at 350 F.

1-in. Round Treated Case Depth .045 in. Case Hardness HRC 65

MASS EFFECT

	Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
As-Rolled	1	69,750	49,500	33.5	61.1	149
Annealed (Heated to 1575 F, furnace-cooled 30 F per hour to 1290 F, cooled in air.)						
	1	62,250	40,500	32.8	58.0	121
Normalized (Heated to 1650 F, cooled in air.)						
	½	69,750	45,000	34.3	61.0	143
	1	67,750	44,000	33.5	63.8	137
	2	67,000	41,500	33.5	64.7	137
	4	63,750	35,000	34.3	64.7	126
Mock-Carburized at 1700 F for 8 hours; reheated to 1450 F; quenched in water; tempered at 350 F.						
	½	124,750	66,500	9.7	18.4	235
	1	89,500	50,500	22.3	48.8	183
	2	78,000	47,750	26.3	65.7	156
	4	74,750	42,750	27.3	62.6	149

As-quenched Hardness (water)

Size Round	Surface	½ Radius	Center
½	HRC 42	HRC 34.5	HRC 29.5
1	HRC 37	HRB 96	HRB 93
2	HRC 33	HRB 90	HRB 86
4	HRC 32	HRB 83	HRB 81

1118

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Grain Size
Grade	.14/.20	1.30/1.60	.040 Max	.08/.13	—	
Ladle	.20	1.34	.017	.08	.09	90% 3-5 10% 2

Critical Points, F: Ac_1 1330 Ac_3 1515 Ar_3 1385 Ar_1 1175

SINGLE QUENCH AND TEMPER

Carburized at 1700 F for 8 hours; pot-cooled; reheated to 1450 F; water-quenched; tempered at 350 F.

1-in. Round Treated Case Depth .065 in. Case Hardness HRC 61

MASS EFFECT

	Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
As-Rolled	1	70,500	51,500	32.3	63.0	143
Annealed (Heated to 1450 F, furnace-cooled 30 F per hour to 1125 F, cooled in air.)						
	1	65,250	41,250	34.5	66.8	131
Normalized (Heated to 1700 F, cooled in air.)						
	½	72,750	47,800	33.3	62.8	156
	1	69,250	46,250	33.5	65.9	143
	2	68,500	43,250	33.0	67.7	137
	4	66,250	37,750	34.0	67.4	131
Mock-Carburized at 1700 F for 8 hours; reheated to 1450 F; quenched in water; tempered at 350 F.						
	½	144,500	90,000	13.2	30.8	285
	1	102,500	59,250	19.0	48.9	207
	2	82,250	47,875	27.3	65.5	167
	4	77,000	45,000	31.0	67.4	156

As-quenched Hardness (water)

Size Round	Surface	½ Radius	Center
½	HRC 43	HRC 36	HRC 33
1	HRC 36	HRB 99	HRB 96.5
2	HRC 34	HRB 91	HRB 87
4	HRC 32	HRB 84	HRB 82

CARBON STEEL WATER- AND OIL-HARDENING GRADES

It will be noted in the properties charts that the hardness values listed are frequently incompatible with the tensile strength shown for the same tempering temperatures. These carbon steels are comparatively shallow hardening; and hardness tests made on the surface of a quenched and tempered bar will not be equivalent to the tensile strength obtained on a .505-in. specimen machined from the center of the same bar.

94	1030
96	1040
100	1050
104	1060
106	1080
108	1095
112	1137
116	1141
118	1144

1030 Water-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Grain Size
Grade	.28/.34	.60/.90	.040 Max	.050 Max	—	
Ladle	.31	.65	.023	.026	.14	5-7

Critical Points, F: Ac_1 1350 Ac_3 1485 Ar_3 1395 Ar_1 1250

MASS EFFECT

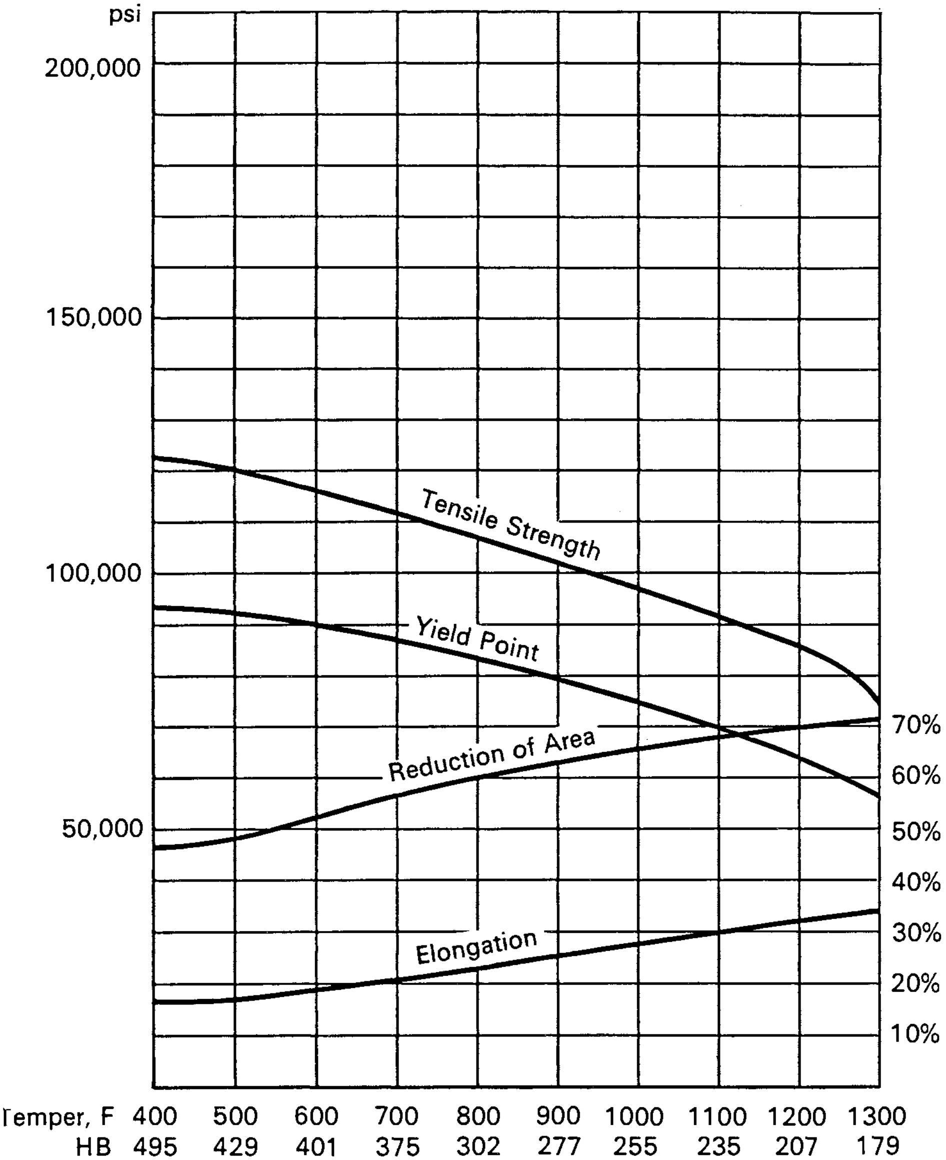
Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1550 F, furnace-cooled 20 F per hour to 1200 F, cooled in air.)					
1	67,250	49,500	31.2	57.9	126
Normalized (Heated to 1700 F, cooled in air.)					
½	77,500	50,000	32.1	61.1	156
1	75,500	50,000	32.0	60.8	149
2	74,000	49,500	29.5	58.9	137
4	72,500	47,250	29.7	56.2	137
Water-quenched from 1600 F, tempered at **1000** F.					
½	91,500	75,000	28.2	58.0	187
1	88,000	68,500	28.0	68.6	179
2	86,500	63,750	28.2	65.8	170
4	80,750	54,750	32.0	68.2	163
Water-quenched from 1600 F, tempered at **1100** F.					
½	88,500	64,000	28.9	69.7	179
1	85,250	63,000	29.0	70.8	170
2	83,750	57,250	29.0	69.1	167
4	80,500	54,500	32.0	68.5	163
Water-quenched from 1600 F, tempered at **1200** F.					
½	85,500	62,000	29.9	70.5	174
1	84,500	61,500	28.5	71.4	170
2	80,000	56,750	30.2	70.9	156
4	74,500	49,500	34.2	71.0	149

As-quenched Hardness (water)

Size Round	Surface	½ Radius	Center
½	HRC 50	HRC 50	HRC 23
1	HRC 46	HRC 23	HRC 21
2	HRC 30	HRB 93	HRB 90
4	HRB 97	HRB 88	HRB 85

Water-quenched 1030

Treatment: Normalized at 1700 F; reheated to 1600 F; quenched in water, 1-in. Round Treated; .505-in. Round Tested. As-quenched HB 514.



1040 Oil-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Grain Size
Grade	.37/.44	.60/.90	.040 Max	.050 Max	—	
Ladle	.39	.71	.019	.036	.15	5-7

Critical Points, F: Ac_1 1340 Ac_3 1445 Ar_3 1350 Ar_1 1250

MASS EFFECT

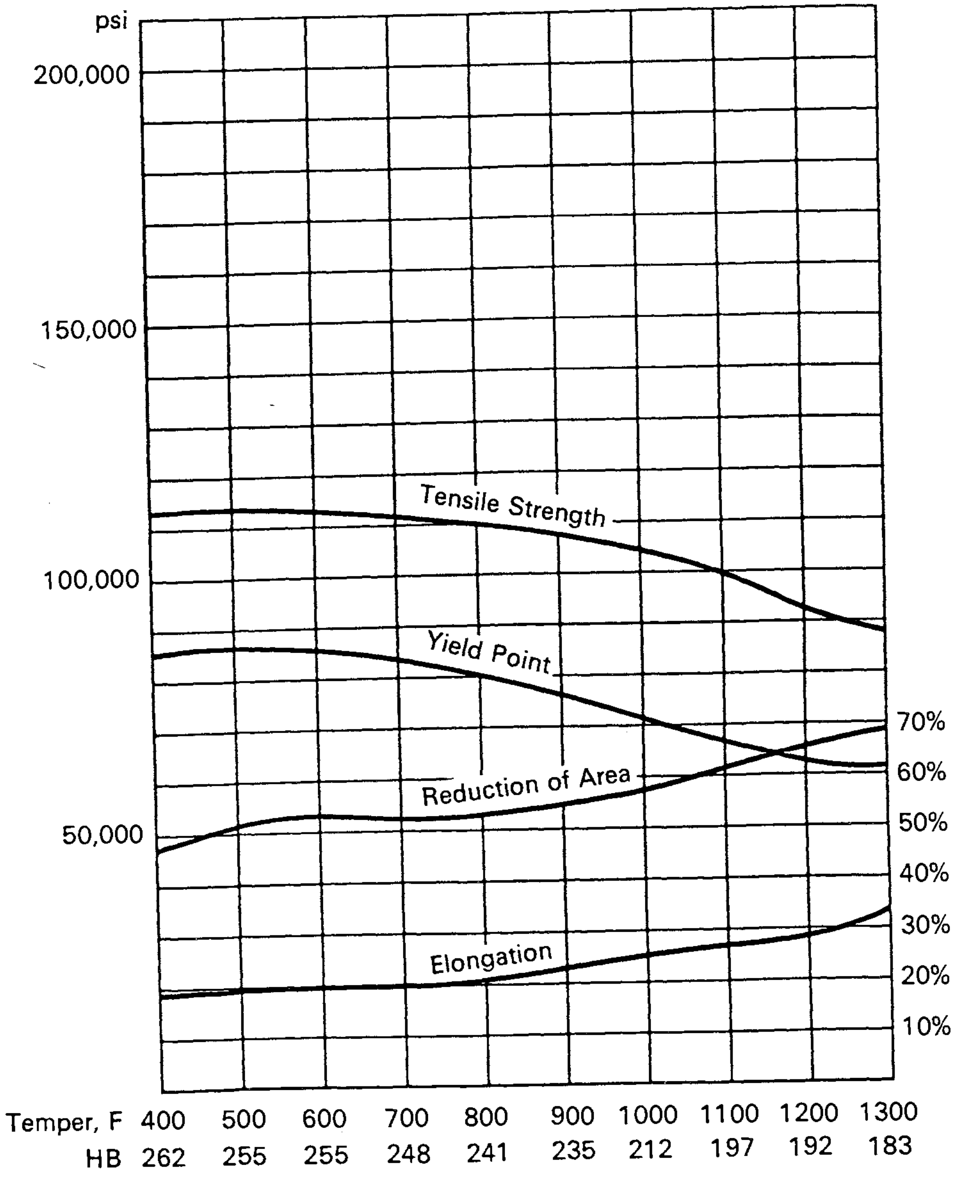
Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1450 F, furnace-cooled 20 F per hour to 1200 F, cooled in air.)					
1	75,250	51,250	30.2	57.2	149
Normalized (Heated to 1650 F, cooled in air.)					
½	88,250	58,500	30.0	56.5	183
1	85,500	54,250	28.0	54.9	170
2	84,250	53,000	28.0	53.3	167
4	83,500	49,250	27.0	51.8	167
Oil-quenched from 1575 F, tempered at **1000** F.					
½	104,750	72,500	27.0	62.0	217
1	96,250	68,000	26.5	61.1	197
2	92,250	59,750	27.0	59.7	187
4	90,000	57,500	27.0	60.3	179
Oil-quenched from 1575 F, tempered at **1100** F.					
½	100,500	69,500	27.0	65.2	207
1	91,500	64,250	28.2	63.5	187
2	86,750	56,875	28.0	62.5	174
4	82,750	52,250	30.0	61.6	170
Oil-quenched from 1575 F, tempered at **1200** F.					
½	95,000	66,625	28.9	65.4	197
1	85,250	60,250	30.0	67.4	170
2	82,500	54,500	31.0	66.4	167
4	78,750	50,000	31.2	64.5	156

As-quenched Hardness (oil)

Size Round	Surface	½ Radius	Center
½	HRC 28	HRC 22	HRC 21
1	HRC 23	HRC 21	HRC 18
2	HRB 93	HRB 92	HRB 91
4	HRB 91	HRB 91	HRB 89

Oil-quenched 1040

Treatment: Normalized at 1650 F; reheated to 1575 F; quenched in oil.
1-in. Round Treated; .505-in. Round Tested. As-quenched HB 269.



1040 Water-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Grain Size
Grade	.37/.44	.60/.90	.040 Max	.050 Max	—	
Ladle	.39	.71	.019	.036	.15	5-7

Critical Points, F: Ac_1 1340 Ac_3 1445 Ar_3 1350 Ar_1 1250

MASS EFFECT

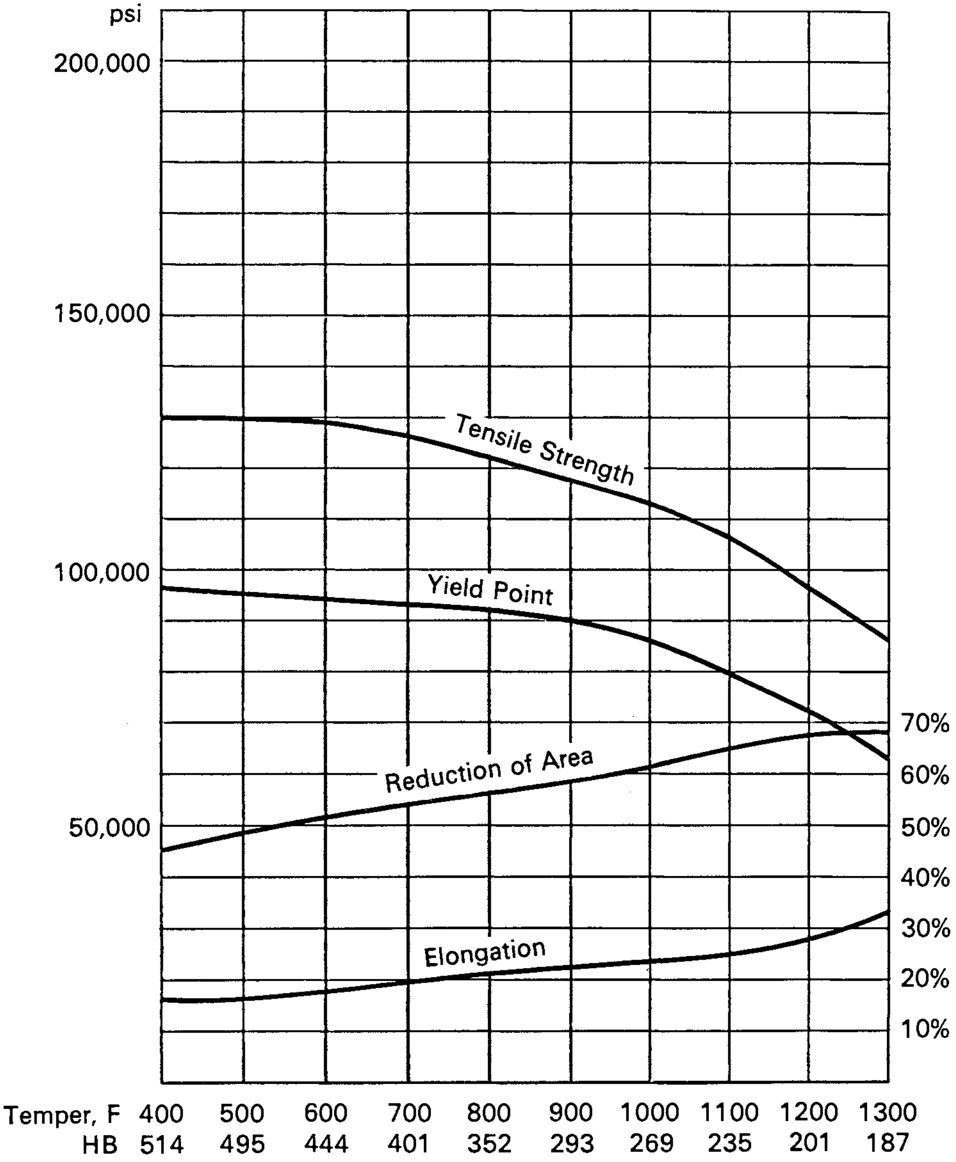
Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Water-quenched from 1550 F, tempered at **1000** F.					
½	109,000	81,500	23.8	61.5	223
1	107,750	78,500	23.2	62.6	217
2	101,750	69,500	24.7	63.6	207
4	99,000	63,826	24.7	60.2	201
Water-quenched from 1550 F, tempered at **1100** F.					
½	101,250	71,000	26.4	65.2	212
1	100,000	69,500	26.0	65.0	207
2	95,000	68,000	29.0	69.2	197
4	94,250	59,125	27.0	63.4	192
Water-quenched from 1550 F, tempered at **1200** F.					
½	96,000	69,000	27.7	66.6	201
1	93,500	68,000	27.0	67.9	197
2	89,000	59,875	28.7	69.0	183
4	85,000	54,750	30.2	67.2	170

As-quenched Hardness (water)

Size Round	Surface	½ Radius	Center
½	HRC 54	HRC 53	HRC 53
1	HRC 50	HRC 22	HRC 18
2	HRC 50	HRB 97	HRB 95
4	HRB 98	HRB 96	HRB 95

Water-quenched 1040

Treatment: Normalized at 1650 F; reheated to 1550 F; quenched in water.
1-in. Round Treated; .505-in. Round Tested. As-quenched HB 534.



1050 Oil-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Grain Size
Grade	.48/.55	.60/.90	.040 Max	.050 Max	—	
Ladle	.54	.69	.012	.030	.19	5-7

Critical Points, F: Ac_1 1340 Ac_3 1420 Ar_3 1320 Ar_1 1250

MASS EFFECT

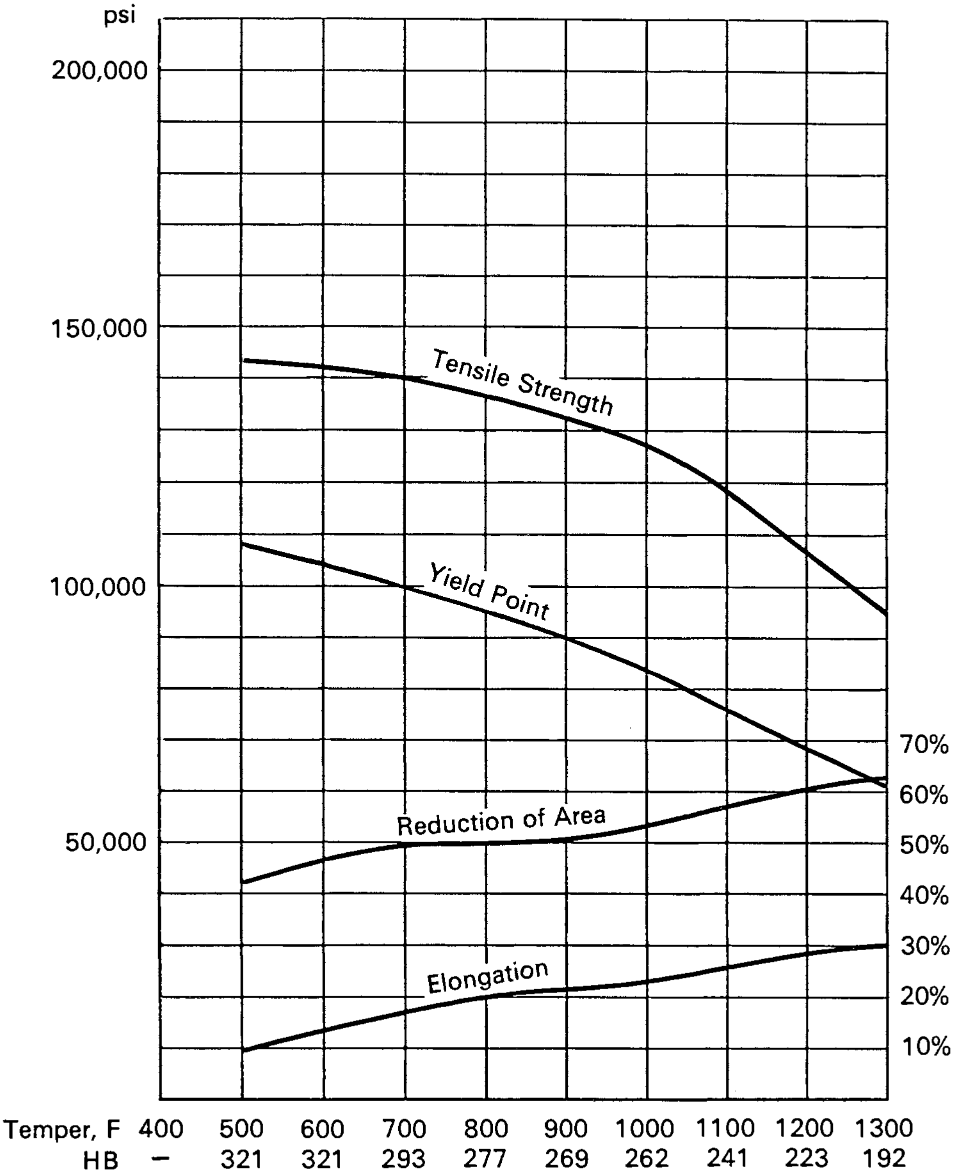
Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1450 F, furnace-cooled 20 F per hour to 1200 F, cooled in air.)					
1	92,250	53,000	23.7	39.9	187
Normalized (Heated to 1650 F, cooled in air.)					
½	111,500	62,500	21.5	45.1	223
1	108,500	62,000	20.0	39.4	217
2	106,250	58,325	20.0	38.8	212
4	100,000	56,000	21.7	41.6	201
Oil-quenched from 1550 F, tempered at **1000** F.					
½	132,500	87,500	20.7	52.9	262
1	123,500	76,000	20.2	53.3	248
2	122,500	74,875	19.7	51.4	248
4	121,000	69,000	19.7	48.0	241
Oil-quenched from 1550 F, tempered at **1100** F.					
½	122,000	81,000	22.8	58.1	248
1	114,000	70,500	23.5	57.6	223
2	112,000	68,000	23.0	55.6	223
4	101,000	58,750	25.2	54.5	207
Oil-quenched from 1550 F, tempered at **1200** F.					
½	112,500	74,000	24.6	61.8	229
1	106,000	64,250	24.7	60.5	217
2	105,000	64,000	25.0	59.1	217
4	96,750	55,750	25.5	56.6	197

As-quenched Hardness (oil)

Size Round	Surface	½ Radius	Center
½	HRC 57	HRC 37	HRC 34
1	HRC 33	HRC 30	HRC 26
2	HRC 27	HRC 25	HRC 21
4	HRB 98	HRB 95	HRB 91

Oil-quenched 1050

Treatment: Normalized at 1650 F; reheated to 1550 F; quenched in oil.
1-in. Round Treated; .505-in. Round Tested. As-quenched HB 321.



1050 Water-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Grain Size
Grade	.48/.55	.60/.90	.040 Max	.050 Max	—	
Ladle	.54	.69	.012	.030	.19	5-7

Critical Points, F: Ac_1 1340 Ac_3 1420 Ar_3 1320 Ar_1 1250

MASS EFFECT

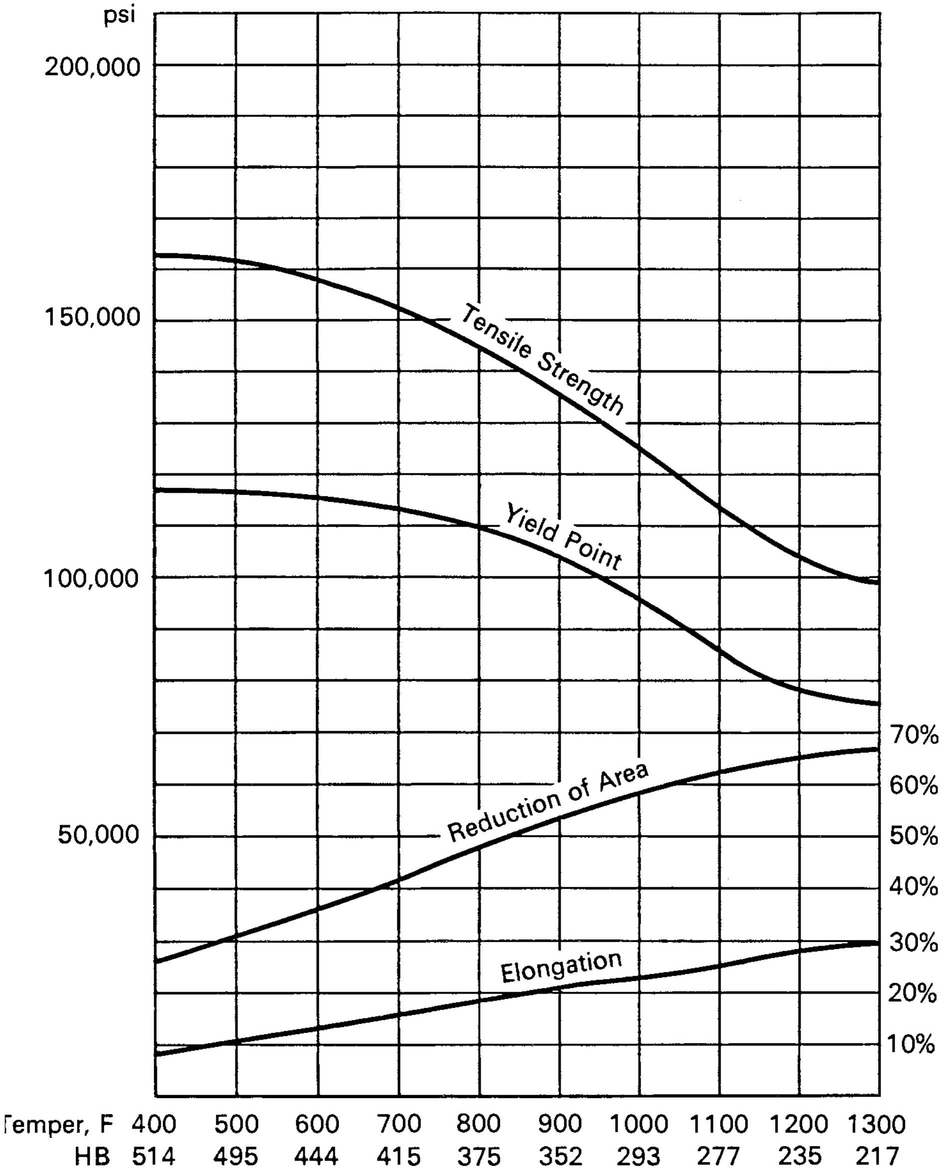
Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Water-quenched from 1525 F, tempered at **1000** F.					
½	134,000	99,000	20.0	54.4	269
1	131,250	92,250	20.0	55.2	262
2	129,500	84,125	20.7	56.6	255
4	122,750	78,250	21.5	55.3	248
Water-quenched from 1525 F, tempered at **1100** F.					
½	119,000	88,000	21.7	59.9	241
1	118,000	80,000	22.5	59.9	241
2	117,250	78,750	23.0	61.0	235
4	112,250	68,250	23.7	55.5	229
Water-quenched from 1525 F, tempered at **1200** F.					
½	110,000	86,000	24.8	60.6	229
1	109,000	76,500	23.7	61.2	229
2	107,750	68,500	24.7	61.0	223
4	104,500	65,250	25.2	60.8	217

As-quenched Hardness (water)

Size Round	Surface	½ Radius	Center
½	HRC 64	HRC 59	HRC 57
1	HRC 60	HRC 35	HRC 33
2	HRC 50	HRC 32	HRC 26
4	HRC 33	HRC 27	HRC 20

Water-quenched 1050

Treatment: Normalized at 1650 F; reheated to 1525 F; quenched in water.
1-in. Round Treated; .505-in. Round Tested. As-quenched HB 601.



1060 Oil-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Grain Size
Grade	.55/.65	.60/.90	.040 Max	.050 Max	—	
Ladle	.60	.66	.016	.046	.17	90% 5-7 10% 1-3

Critical Points, F: Ac$_1$ 1355 Ac$_3$ 1400 Ar$_3$ 1300 Ar$_1$ 1250

MASS EFFECT

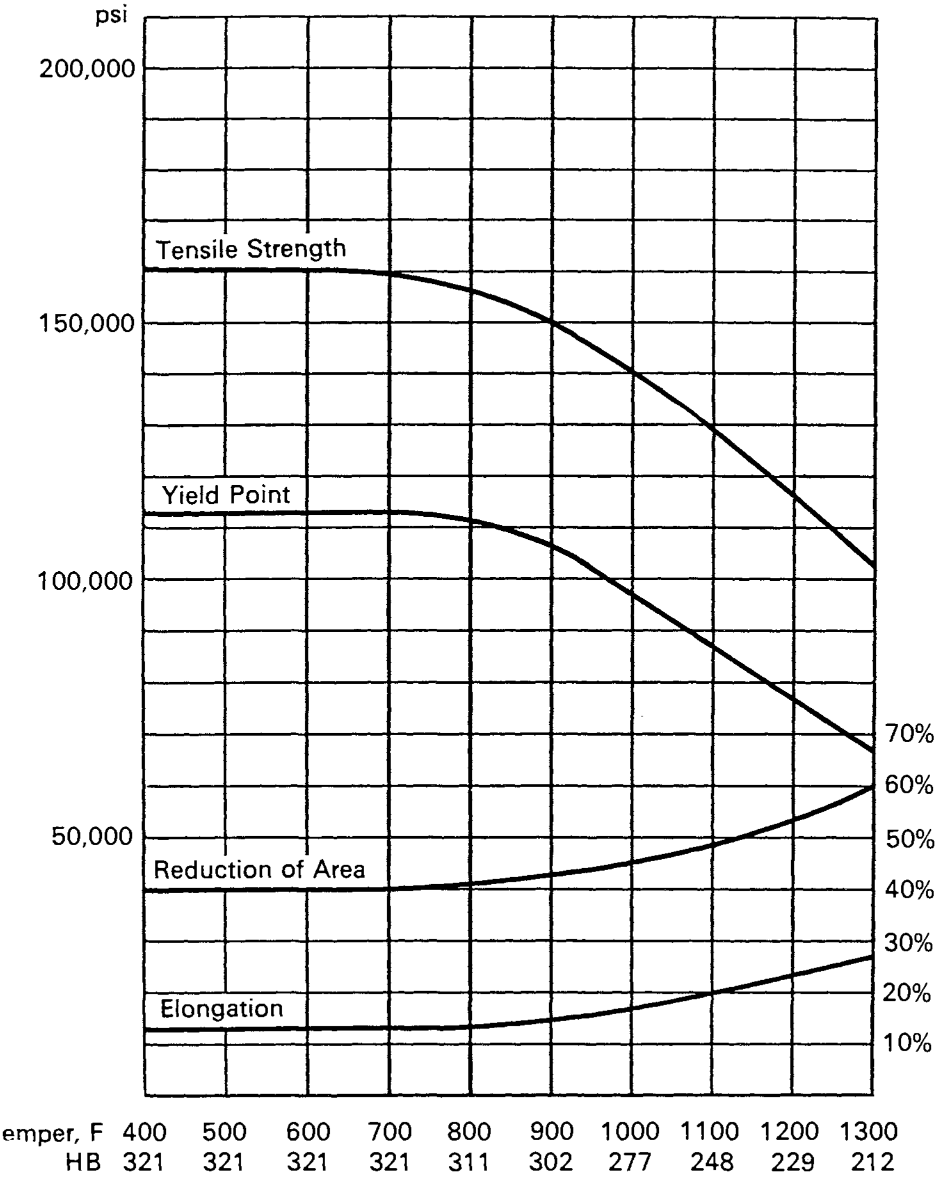
Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1450 F, furnace-cooled 20 F per hour to 1200 F, cooled in air.)					
1	90,750	54,000	22.5	38.2	179
Normalized (Heated to 1650 F, cooled in air.)					
½	113,000	62,000	20.4	40.6	229
1	112,500	61,000	18.0	37.2	229
2	110,000	57,500	17.7	34.0	223
4	108,250	51,250	18.0	31.3	223
Oil-quenched from 1550 F, tempered at **900** F.					
½	149,000	98,250	15.1	46.0	302
1	145,500	93,000	16.2	44.0	293
2	142,750	89,500	16.5	46.2	285
4	134,750	75,250	18.2	44.8	269
Oil-quenched from 1550 F, tempered at **1000** F.					
½	139,500	92,000	19.6	52.1	277
1	136,500	85,750	17.7	48.0	269
2	133,000	79,250	18.5	50.3	262
4	124,500	66,250	20.0	48.0	248
Oil-quenched from 1550 F, tempered at **1100** F.					
½	131,500	82,500	20.7	53.5	262
1	127,750	79,000	20.0	51.7	255
2	125,250	76,500	20.2	53.3	248
4	118,750	62,000	21.5	49.4	241

As-quenched Hardness (oil)

Size Round	Surface	½ Radius	Center
½	HRC 59	HRC 37	HRC 35
1	HRC 34	HRC 32	HRC 30
2	HRC 30.5	HRC 27.5	HRC 25
4	HRC 29	HRC 26	HRC 24

Oil-quenched 1060

Treatment: Normalized at 1650 F; reheated to 1550 F; quenched in oil.
1-in. Round Treated; .505-in. Round Tested. As-quenched HB 321.



1080 Oil-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Grain Size
Grade	.75/.88	.60/.90	.040 Max	.050 Max	—	
Ladle	.85	.76	.012	.027	.13	80% 5-7 20% 1-4

Critical Points, F: Ac_1 1350 Ac_3 1370 Ar_3 1280 Ar_1 1250

MASS EFFECT

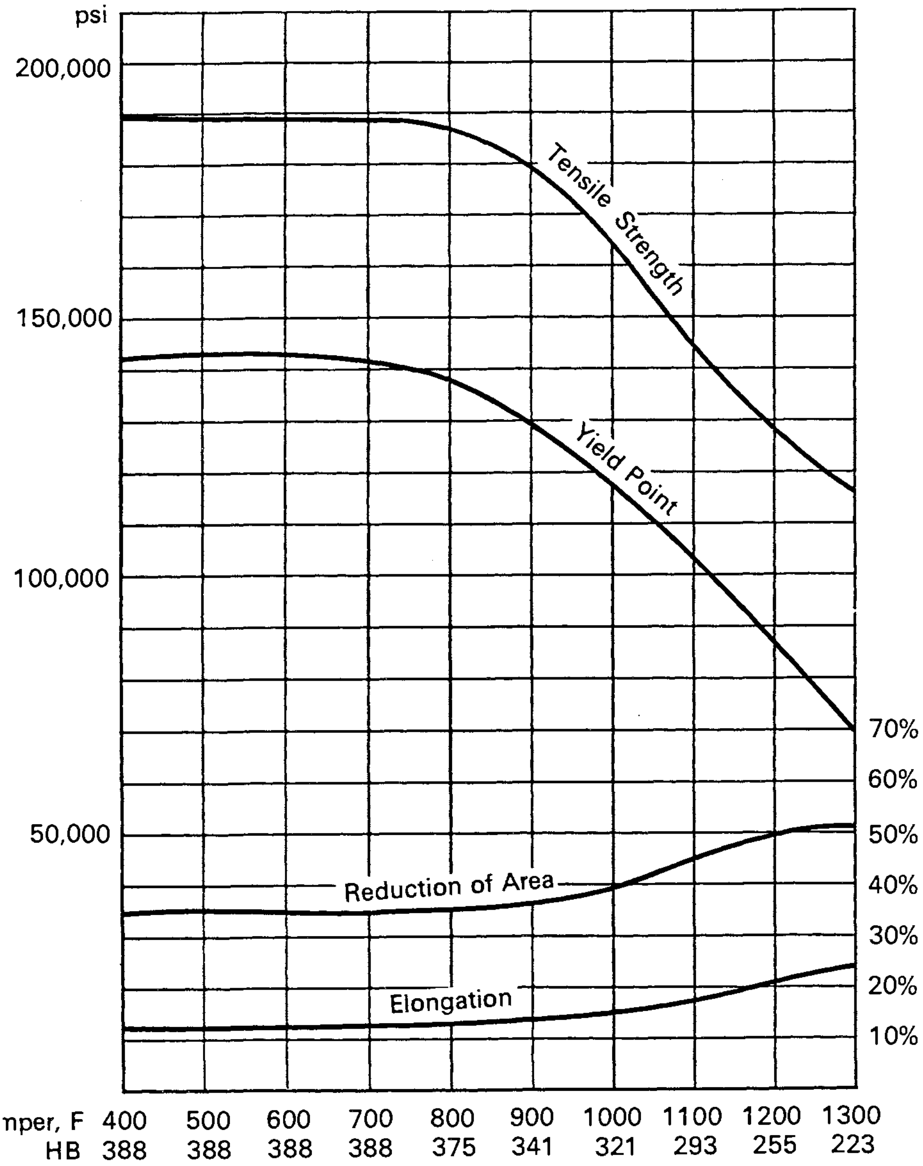
Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1450 F, furnace-cooled 20 F per hour to 1200 F, cooled in air.)					
1	89,250	54,500	24.7	45.0	174
Normalized (Heated to 1650 F, cooled in air.)					
½	150,500	80,500	12.4	27.7	293
1	146,500	76,000	11.0	20.6	293
2	141,000	70,000	10.7	17.0	285
4	134,750	64,500	10.7	15.5	269
Oil-quenched from 1500 F, tempered at **900** F.					
½	184,000	125,500	12.1	34.4	363
1	181,500	112,500	13.0	35.8	352
2	180,000	110,000	12.7	37.3	352
4	171,250	104,000	11.7	28.6	341
Oil-quenched from 1500 F, tempered at **1000** F.					
½	169,000	121,500	15.0	38.6	341
1	166,000	103,500	15.0	37.6	331
2	163,500	102,625	15.2	38.0	321
4	157,000	89,750	11.5	24.4	311
Oil-quenched from 1500 F, tempered at **1100** F.					
½	152,000	107,000	17.0	43.6	302
1	150,000	97,000	16.5	40.3	302
2	140,250	87,500	17.7	42.2	277
4	134,500	75,000	15.7	33.1	269

As-quenched Hardness (oil)

Size Round	Surface	½ Radius	Center
½	HRC 60	HRC 43	HRC 40
1	HRC 45	HRC 42	HRC 39
2	HRC 43	HRC 40	HRC 37
4	HRC 39	HRC 37	HRC 32

Oil-quenched 1080

Treatment: Normalized at 1650 F; reheated to 1500 F; quenched in oil.
1-in. Round Treated; .505-in. Round Tested. As-quenched HB 388.



1095 Oil-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Grain Size
Grade	.90/1.03	.30/.50	.040 Max	.050 Max	—	
Ladle	.96	.40	.012	.029	.20	50% 5-7 50% 1-4

Critical Points, F: Ac_1 1350 Ac_3 1365 Ar_3 1320 Ar_1 1265

MASS EFFECT

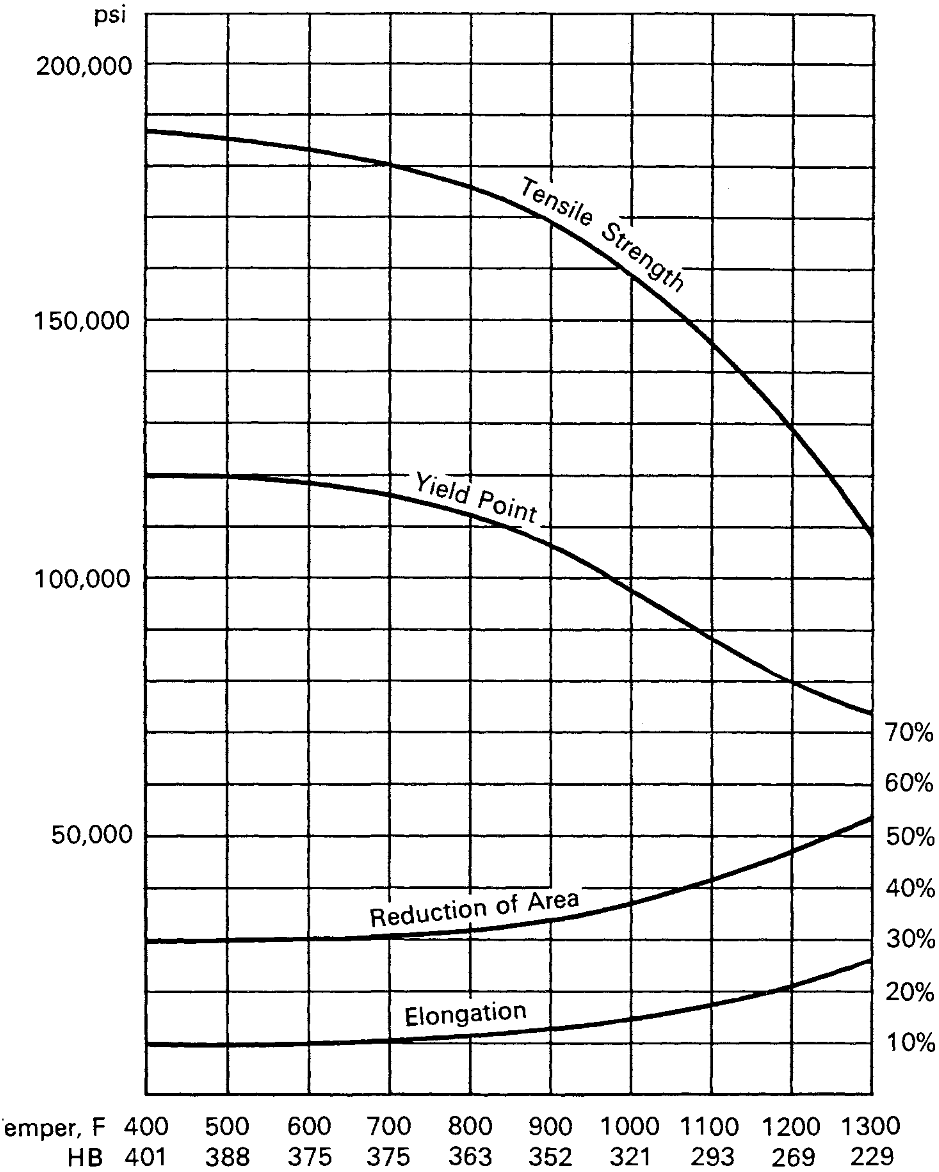
Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1450 F, furnace-cooled 20 F per hour to 1215 F, cooled in air.)					
1	95,250	55,000	13.0	20.6	192
Normalized (Heated to 1650 F, cooled in air.)					
½	151,000	80,500	12.3	27.7	302
1	147,000	72,500	9.5	13.5	293
2	132,500	58,000	9.2	13.4	269
4	128,250	57,250	10.0	13.9	255
Oil-quenched from 1475 F, tempered at **900** F.					
½	184,000	116,000	12.8	35.5	363
1	175,750	102,250	10.0	23.4	352
2	167,750	98,250	12.0	29.8	331
4	165,000	93,000	12.2	17.3	331
Oil-quenched from 1475 F, tempered at **1000** F.					
½	166,500	101,500	15.7	40.0	331
1	159,750	95,250	13.2	32.4	321
2	151,000	92,500	13.7	31.4	311
4	148,000	80,000	11.7	22.1	302
Oil-quenched from 1475 F, tempered at **1100** F.					
½	142,000	87,000	17.4	42.8	293
1	139,750	79,000	17.2	38.8	277
2	134,500	77,250	18.7	43.4	269
4	130,000	65,750	17.2	34.4	262

As-quenched Hardness (oil)

Size Round	Surface	½ Radius	Center
½	HRC 60	HRC 44	HRC 41
1	HRC 46	HRC 42	HRC 40
2	HRC 43	HRC 40	HRC 37
4	HRC 40	HRC 37	HRC 30

Oil-quenched **1095**

Treatment: Normalized at 1650 F; reheated to 1475 F; quenched in oil.
1-in. Round Treated; .505-in. Round Tested. As-quenched HB 401.



1095 Water-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Grain Size
Grade	.90/1.03	.30/.50	.040 Max	.050 Max	—	
Ladle	.96	.40	.012	.029	.20	50% 5-7 50% 1-4

Critical Points, F: Ac$_1$ 1350 Ac$_3$ 1365 Ar$_3$ 1320 Ar$_1$ 1265

MASS EFFECT

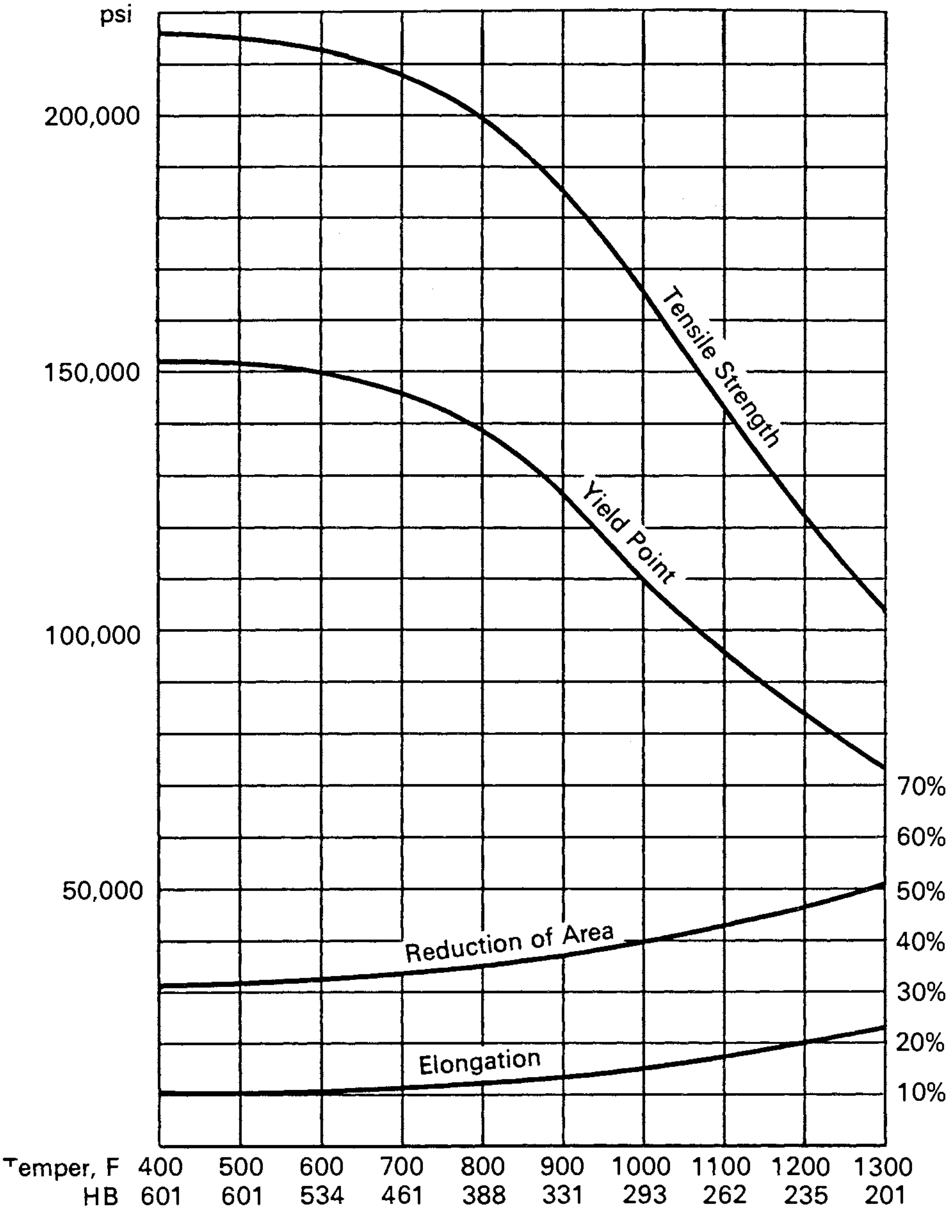
Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Water-quenched from 1450 F, tempered at **900** F.					
½	191,500	135,500	12.3	31.7	375
1	182,000	121,000	13.0	37.3	363
2	179,750	113,000	12.7	33.8	352
4	167,250	94,500	12.5	31.4	331
Water-quenched from 1450 F, tempered at **1000** F.					
½	172,000	111,000	12.4	44.1	321
1	165,000	102,500	16.0	41.4	311
2	154,750	98,500	15.7	39.1	302
4	150,000	81,000	15.7	35.3	285
Water-quenched from 1450 F, tempered at **1100** F.					
½	144,000	99,000	17.2	44.9	293
1	143,000	96,500	16.7	43.7	293
2	140,000	90,000	17.5	43.6	285
4	131,250	78,000	18.7	41.1	262

As-quenched Hardness (water)

Size Round	Surface	½ Radius	Center
½	HRC 65	HRC 55	HRC 48
1	HRC 64	HRC 46	HRC 44
2	HRC 63	HRC 43	HRC 40
4	HRC 63	HRC 38	HRC 30

Water-quenched 1095

Treatment: Normalized at 1650 F; reheated to 1450 F; quenched in water.
1-in. Round Treated; .505-in. Round Tested. As-quenched HB 601.



1137 Oil-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Grain Size
Grade	.32/.39	1.35/1.65	.040 Max	.08/.13	—	
Ladle	.37	1.40	.015	.08	.17	1-4

Critical Points, F: Ac_1 1330 Ac_3 1450 Ar_3 1310 Ar_1 1180

MASS EFFECT

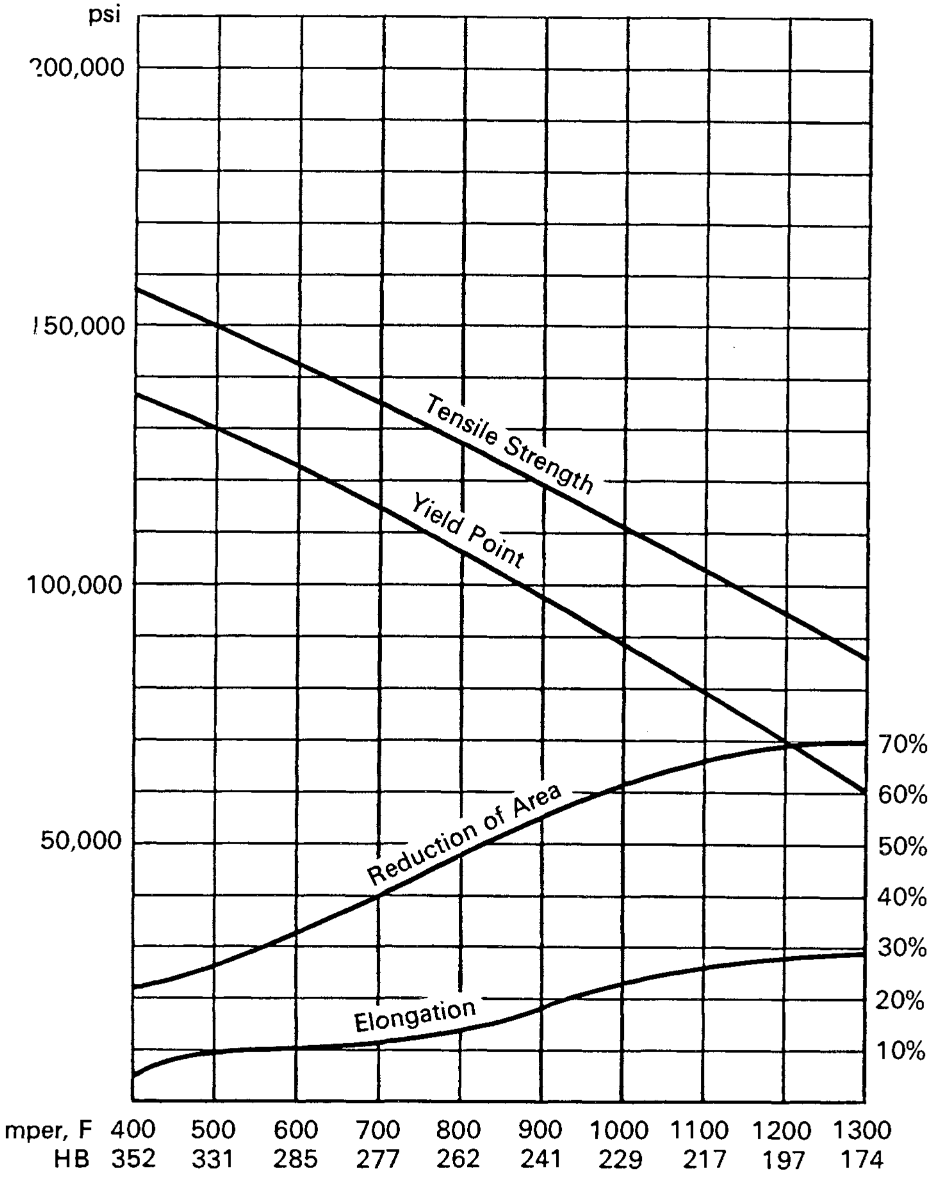
Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1450 F, furnace-cooled 20 F per hour to 1130 F, cooled in air.)					
1	84,750	50,000	26.8	53.9	174
Normalized (Heated to 1650 F, cooled in air.)					
½	98,000	58,500	25.0	58.5	201
1	97,000	57,500	22.5	48.5	197
2	96,000	49,000	21.8	51.6	197
4	94,000	48,000	23.3	51.0	192
Oil-quenched from 1575 F, tempered at **1000** F.					
½	127,500	100,000	18.2	55.8	255
1	108,000	75,750	21.3	56.0	223
2	105,000	63,000	23.0	56.2	217
4	100,500	58,750	22.3	55.5	201
Oil-quenched from 1575 F, tempered at **1100** F.					
½	112,500	90,000	21.8	61.0	229
1	100,750	68,750	23.5	60.1	207
2	98,000	61,500	23.0	57.8	207
4	95,250	57,000	24.5	59.5	192
Oil-quenched from 1575 F, tempered at **1200** F.					
½	104,000	80,500	24.6	63.6	217
1	97,750	68,750	23.5	60.8	201
2	97,000	57,250	25.0	64.1	197
4	94,500	56,000	24.0	61.1	192

As-quenched Hardness (oil)

Size Round	Surface	½ Radius	Center
½	HRC 48	HRC 43	HRC 42
1	HRC 34	HRC 28	HRC 23
2	HRC 28	HRC 22	HRC 18
4	HRC 21	HRC 18	HRC 16

Oil-quenched 1137

Treatment: Normalized at 1650 F; reheated to 1575 F; quenched in oil.
1-in. Round Treated; .505-in. Round Tested. As-quenched HB 363.



1137 Water-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Grain Size
Grade	.32/.39	1.35/1.65	.040 Max	.08/.13	—	
Ladle	.37	1.40	.015	.08	.17	1-4

Critical Points, F: Ac_1 1330 Ac_3 1450 Ar_3 1310 Ar_1 1180

MASS EFFECT

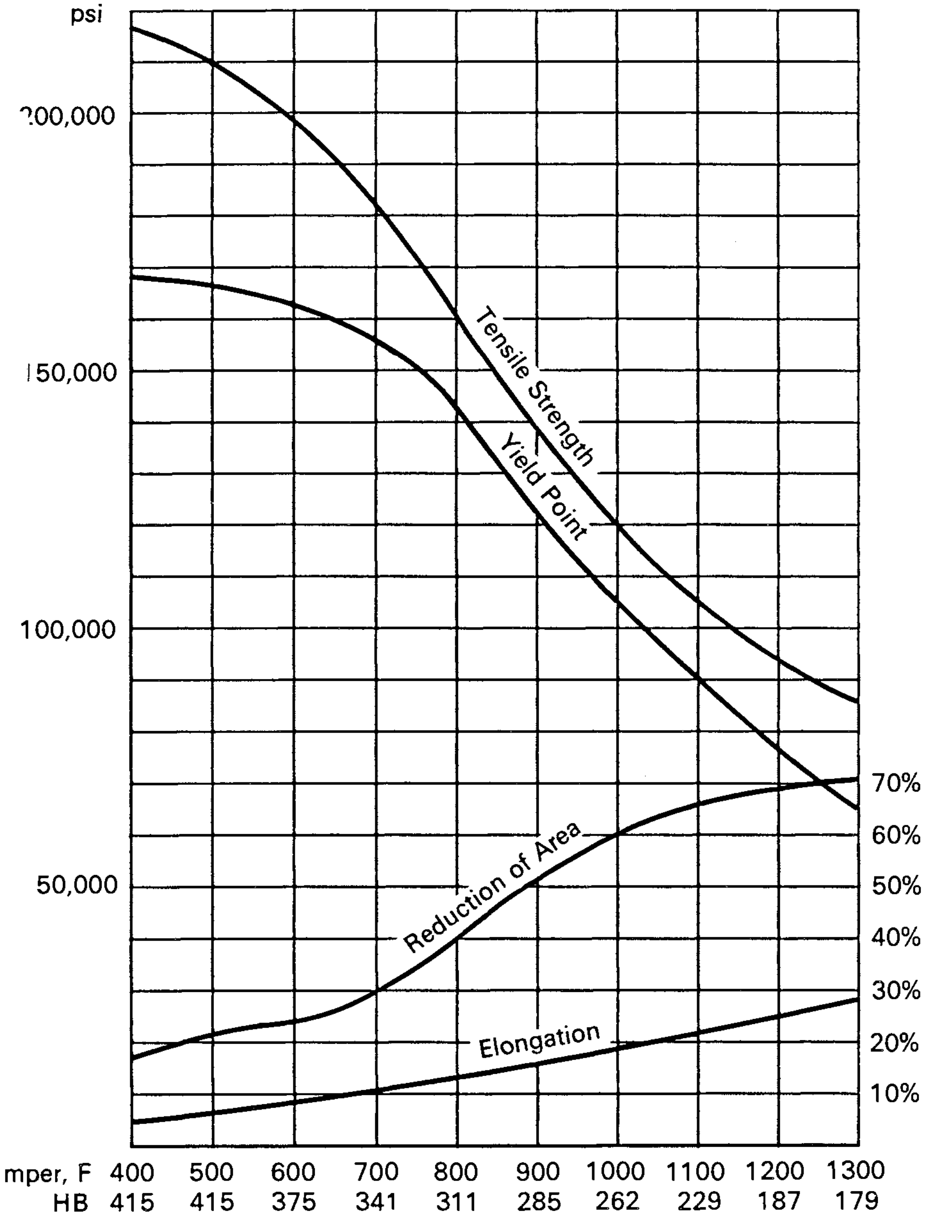
Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Water-quenched from 1550 F, tempered at **1000** F.					
½	129,500	112,000	17.1	51.3	262
1	122,000	98,000	16.9	51.2	248
2	110,000	71,250	20.8	56.1	229
4	108,000	69,000	20.3	52.1	223
Water-quenched from 1550 F, tempered at **1100** F.					
½	112,500	95,000	21.4	57.6	229
1	107,750	87,750	21.0	59.2	223
2	105,250	76,000	22.0	61.7	217
4	97,750	61,250	23.5	60.9	201
Water-quenched from 1550 F, tempered at **1200** F.					
½	105,000	89,000	23.9	61.2	223
1	102,500	81,750	22.3	58.8	217
2	97,500	67,000	24.0	64.1	201
4	95,500	60,000	24.0	63.5	197

As-quenched Hardness (water)

Size Round	Surface	½ Radius	Center
½	HRC 57	HRC 53	HRC 50
1	HRC 56	HRC 50	HRC 45
2	HRC 52	HRC 35	HRC 24
4	HRC 48	HRC 23	HRC 20

Water-quenched 1137

Treatment: Normalized at 1650 F; reheated to 1550 F; quenched in water.
1-in. Round Treated; .505-in. Round Tested. As-quenched HB 415.



1141 Oil-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Grain Size
Grade	.37/.45	1.35/1.65	.040 Max	.08/.13	—	
Ladle	.39	1.58	.02	.08	.19	90% 2-4 10% 5

Critical Points, F: Ac_1 1330 Ac_3 1435 Ar_3 1230 Ar_1 1190

MASS EFFECT

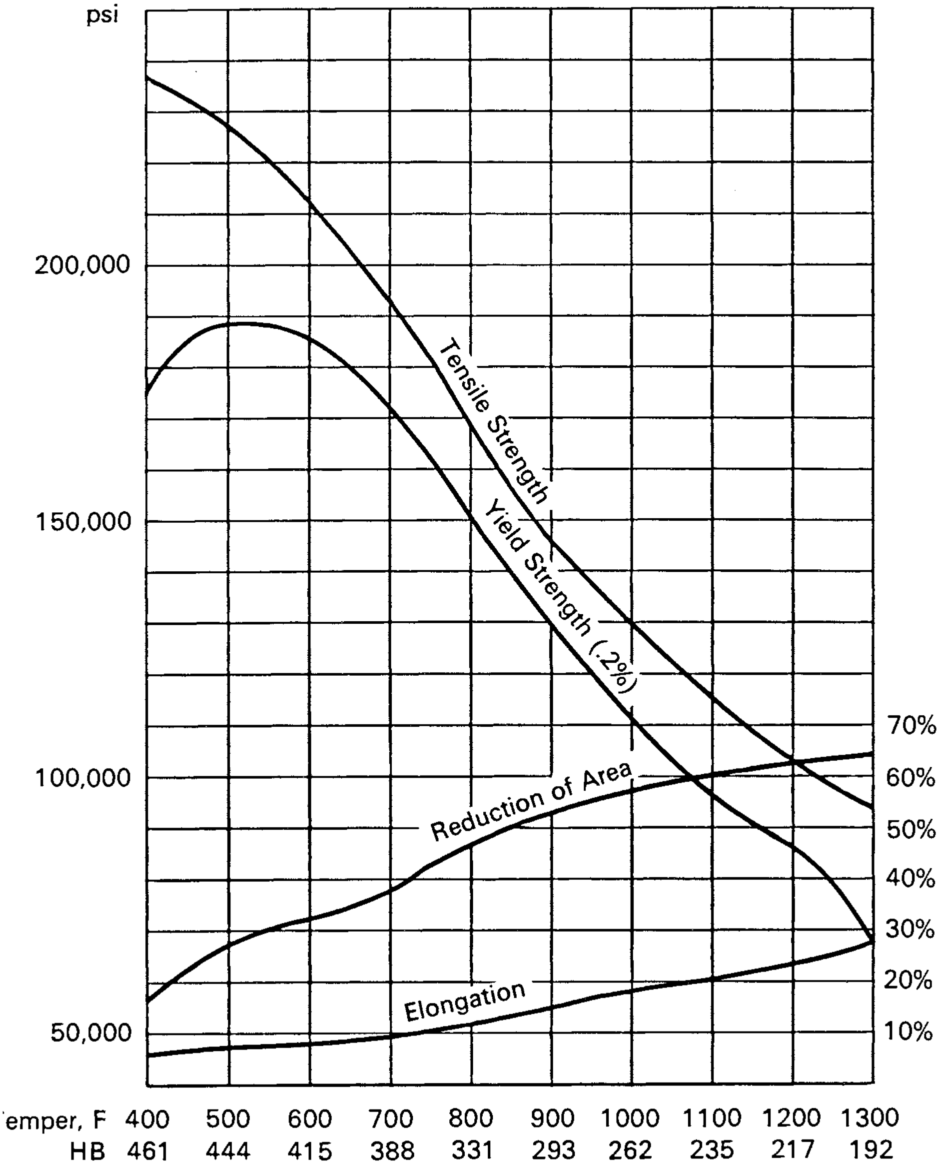
Size Round in.	Tensile Strength psi	Yield Strength (.2% Offset) psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1500 F, furnace-cooled 20 F per hour to 900 F, cooled in air.)					
1	86,800	51,200	25.5	49.3	163
Normalized (Heated to 1650 F, cooled in air.)					
½	105,800	62,300	22.7	57.8	207
1	102,500	58,750	22.7	55.5	201
2	101,200	57,000	22.5	55.8	201
4	100,500	55,000	21.7	49.3	201
Oil-quenched from 1500 F, tempered at **1000** F.					
½	129,500	110,200	18.7	57.1	262
1	110,200	75,300	23.5	58.7	229
2	108,500	74,700	21.8	57.2	217
4	107,200	66,800	20.8	54.3	212
Oil-quenched from 1500 F, tempered at **1100** F.					
½	116,200	95,700	20.7	60.6	235
1	103,000	69,800	23.8	62.2	207
2	101,000	68,700	24.0	62.5	201
4	100,000	61,300	23.5	59.1	197
Oil-quenched from 1500 F, tempered at **1200** F.					
½	105,200	87,400	23.5	63.8	217
1	96,300	69,600	24.8	64.1	197
2	95,800	65,300	25.2	65.1	192
4	95,200	60,300	25.2	63.0	183

As-quenched Hardness (oil)

Size Round	Surface	½ Radius	Center
½	HRC 52	HRC 49	HRC 46
1	HRC 48	HRC 43	HRC 38
2	HRC 36	HRC 28	HRC 22
4	HRC 27	HRC 22	HRC 18

Oil-quenched 1141

Treatment: Normalized at 1575 F; reheated to 1500 F; quenched in oil. .530-in. Round Treated; .505-in. Round Tested. As-quenched HB 495.



1144 Oil-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Grain Size
Grade	.40/.48	1.35/1.65	.040 Max	.24/.33	—	
Ladle	.46	1.37	.019	.24	.05	75% 1-4 25% 5-6

Critical Points, F: Ac_1 1335 Ac_3 1400 Ar_3 1285 Ar_1 1200

MASS EFFECT

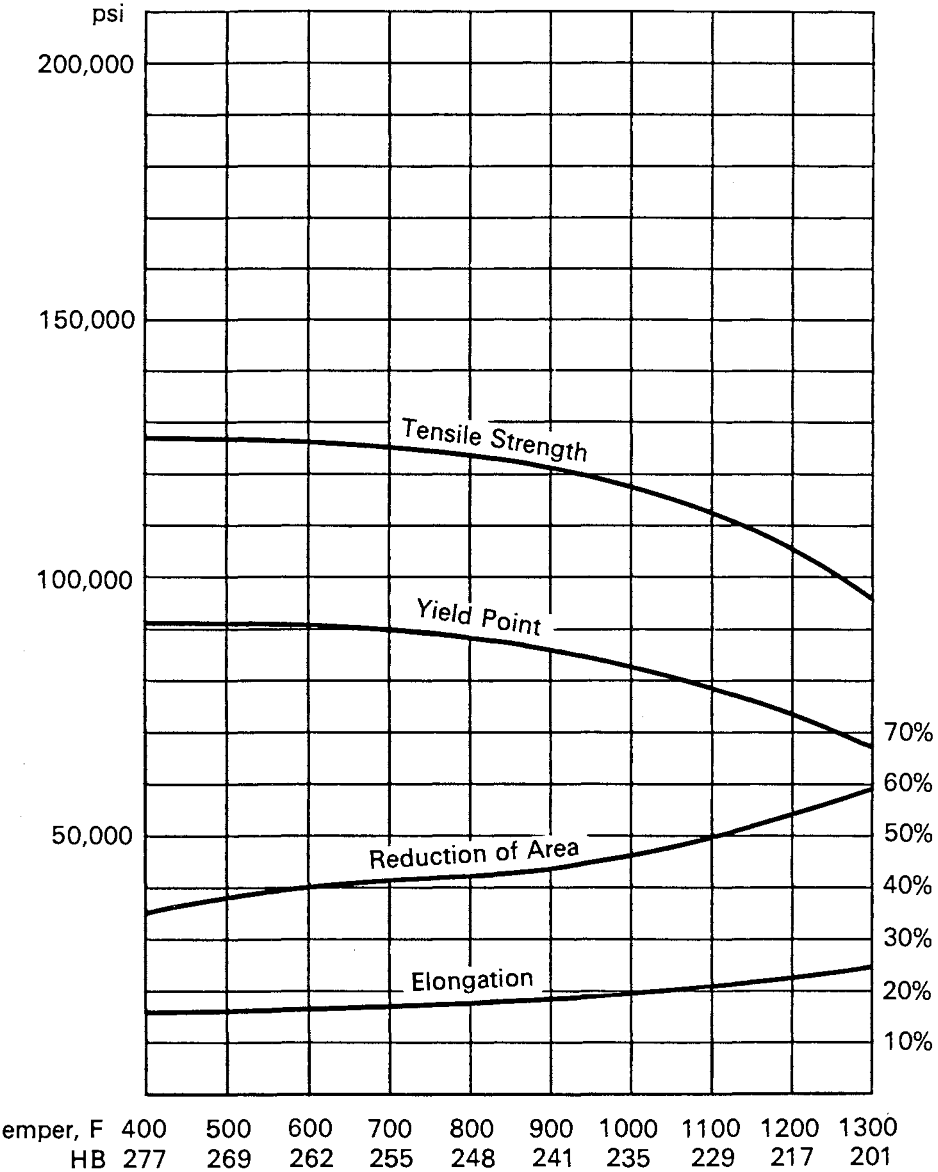
Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1450 F, furnace-cooled 20 F per hour to 1150 F, cooled in air.)					
1	84,750	50,250	24.8	41.3	167
Normalized (Heated to 1650 F, cooled in air.)					
½	98,000	60,500	24.6	51.0	201
1	96,750	58,000	21.0	40.4	197
2	95,500	54,000	21.5	45.0	192
4	94,250	52,500	21.5	42.7	192
Oil-quenched from 1550 F, tempered at **1000** F.					
½	113,500	79,000	20.4	52.1	235
1	108,500	72,750	19.3	46.0	223
2	105,000	67,750	20.5	49.6	212
4	101,750	63,000	21.5	50.0	207
Oil-quenched from 1550 F, tempered at **1100** F.					
½	104,000	71,250	20.7	51.2	217
1	102,750	68,000	21.5	51.4	212
2	101,000	65,000	23.3	56.5	207
4	94,250	57,750	23.8	54.4	192
Oil-quenched from 1550 F, tempered at **1200** F.					
½	97,500	69,000	23.2	55.2	201
1	97,000	68,000	23.0	52.4	201
2	94,000	61,500	24.0	57.7	192
4	89,000	54,000	25.8	57.7	183

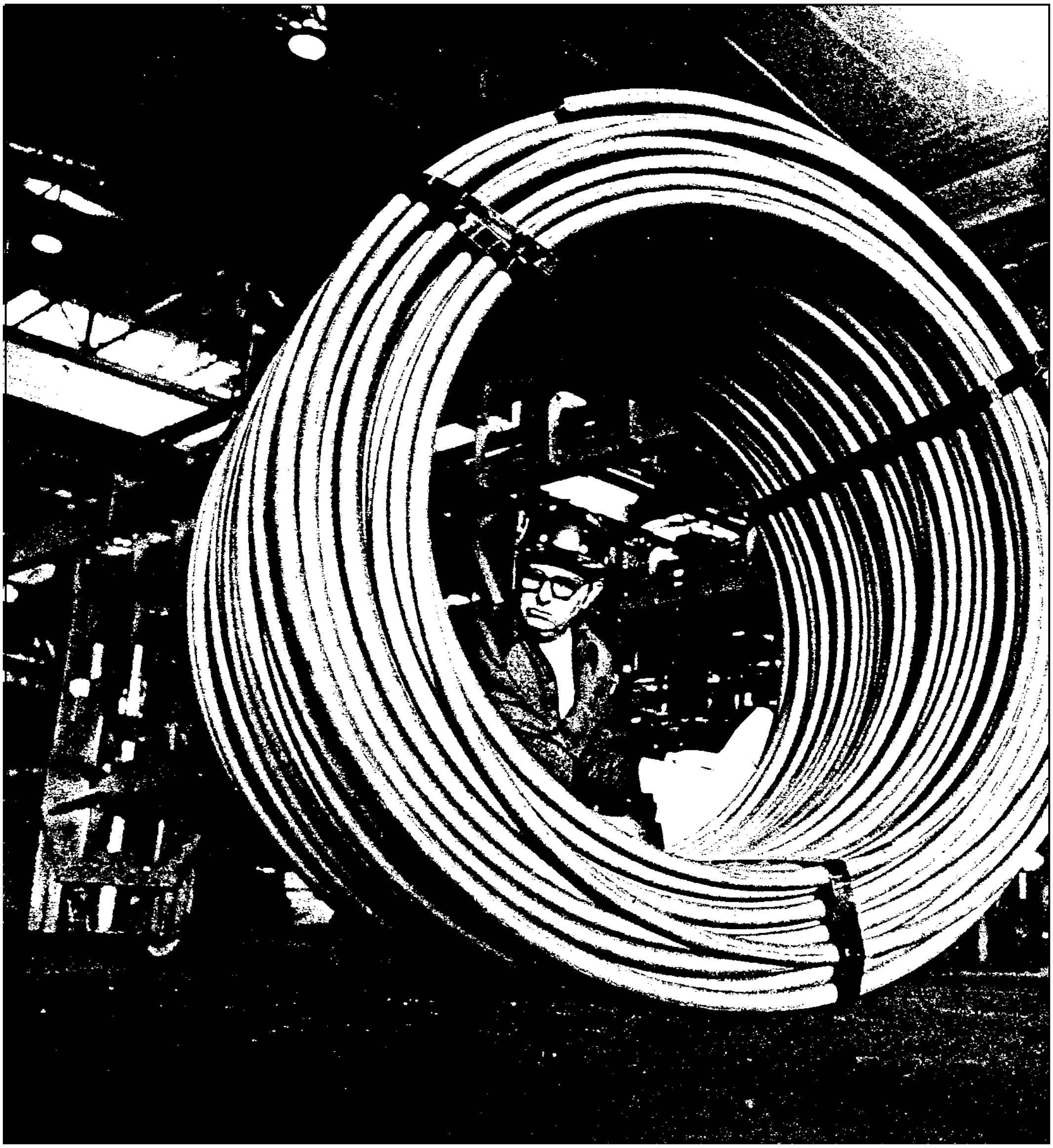
As-quenched Hardness (oil)

Size Round	Surface	½ Radius	Center
½	HRC 39	HRC 32	HRC 28
1	HRC 36	HRC 29	HRC 24
2	HRC 30	HRC 27	HRC 22
4	HRC 27	HRB 98	HRB 97

Oil-quenched **1144**

Treatment: Normalized at 1650 F; reheated to 1550 F; quenched in oil.
1-in. Round Treated; .505-in. Round Tested. As-quenched HB 285.





ALLOY STEEL CARBURIZING GRADES

4118

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Grade	.18/.23	.70/.90	—	—	.20/.35	—	.40/.60	.08/.15	
Ladle	.21	.80	.008	.007	.27	.16	.52	.08	6-8

MASS EFFECT

Size Round in.	Tensile Strength psi	Yield Strength (.2% Offset) psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1600 F; furnace-cooled 20 F per hour to 1150 F; cooled in air.)					
1	75,000	53,000	33.0	63.7	137
Normalized (Heated to 1670 F; cooled in air.)					
.565	85,000	57,000	31.5	70.1	170
1	84,500	56,000	32.0	71.0	156
2	77,500	54,500	34.0	74.4	143
4	75,500	49,500	34.0	71.2	137
Mock-Carburized at 1700 F for 8 hours; reheated to 1525 F; quenched in oil; tempered at **300** F.					
.565	143,000	93,500	17.5	41.3	293
1	119,000	64,500	21.0	37.5	241
2	97,000	46,000	26.5	56.3	201
4	93,000	43,500	28.0	61.3	192
Mock-Carburized at 1700 F for 8 hours; reheated to 1525 F; quenched in oil; tempered at **450** F.					
.565	138,000	89,500	17.5	41.9	277
1	115,000	64,000	22.0	49.0	235
2	93,500	45,500	28.0	62.0	192
4	89,500	43,000	28.5	63.5	187

As-quenched Hardness (oil)

Size Round	Surface	½ Radius	Center
.565	HRC 33	HRC 33	HRC 33
1	HRC 22	HRC 20	HRC 20
2	HRB 88	HRB 88	HRB 87
4	HRB 87	HRB 87	HRB 85

4118

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Ladle	.21	.80	.008	.007	.27	.16	.52	.08	6-8

Critical Points, F: Ac_1 1380 Ac_3 1520 Ar_3 1430 Ar_1 1260

.565-in. Round Treated; .505-in. Round Tested

CASE		CORE PROPERTIES				
Hardness HRC	Depth in.	Tensile Strength psi	Yield Strength (.2% Offset) psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB

Recommended Practice for Maximum Case Hardness

Direct quench from pot: 1) Carburized at 1700 F for 8 hours; 2) quenched in agitated oil; 3) tempered at **300** F.

61	.063	177,500	131,000	9.0	42.3	352

Single-quench and temper—for good case and core properties: 1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1525 F; 4) quenched in agitated oil; 5) tempered at **300** F.

62	.047	143,000	93,500	17.5	41.3	293

Double-quench and temper—for maximum refinement of case and core: 1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1525 F; 4) quenched in agitated oil; 5) reheated to 1475 F; 6) quenched in agitated oil; 7) tempered at **300** F.

62	.047	126,000	63,500	21.0	42.4	241

Recommended Practice for Maximum Core Toughness

Direct quench from pot: 1) Carburized at 1700 F for 8 hours; 2) quenched in agitated oil; 3) tempered at **450** F.

57	.063	177,000	130,000	13.0	48.0	341

Single-quench and temper—for good case and core properties: 1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1525 F; 4) quenched in agitated oil; 5) tempered at **450** F.

56	.047	138,000	89,500	17.5	41.9	277

Double-quench and temper—for maximum refinement of case and core: 1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1525 F; 4) quenched in agitated oil; 5) reheated to 1475 F; 6) quenched in agitated oil; 7) tempered at **450** F.

56	.047	120,000	63,000	22.0	48.9	229

4320

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Grade	.17/.22	.45/.65	—	—	.20/.35	1.65/2.00	.40/.60	.20/.30	
Ladle	.20	.59	.021	.018	.25	1.77	.47	.23	6-8

MASS EFFECT

Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1560 F; furnace-cooled 30 F per hour to 790 F; cooled in air.)					
1	84,000	61,625	29.0	58.4	163
Normalized (Heated to 1640 F; cooled in air.)					
½	121,500	74,375	23.9	54.3	248
1	115,000	67,250	20.8	50.7	235
2	102,500	58,750	23.3	59.2	212
4	102,000	57,000	22.3	54.7	201
Mock-Carburized at 1700 F for 8 hours; reheated to 1500 F; quenched in oil; tempered at **300** F.					
½	212,000	163,250	11.8	45.5	415
1	152,500	107,250	17.0	51.0	302
2	132,500	86,000	22.5	56.4	255
4	119,750	75,250	24.0	57.1	248
Mock-Carburized at 1700 F for 8 hours; reheated to 1500 F; quenched in oil; tempered at **450** F.					
½	187,500	149,500	13.9	52.8	388
1	148,750	105,000	17.8	55.2	285
2	129,750	85,000	20.8	63.8	255
4	118,000	75,000	22.5	51.9	241

As-quenched Hardness (oil)

Size Round	Surface	½ Radius	Center
½	HRC 44.5	HRC 44.5	HRC 44.5
1	HRC 39	HRC 37	HRC 36
2	HRC 35	HRC 30	HRC 27
4	HRC 25	HRC 24	HRC 24

4320

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Ladle	.20	.59	.021	.018	.25	1.77	.47	.23	6-8

Critical Points, F: Ac_1 1350 Ac_3 1485 Ar_3 1330 Ar_1 840

.565-in. Round Treated; .505-in. Round Tested

CASE		CORE PROPERTIES				
Hardness HRC	Depth in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Recommended Practice for Maximum Case Hardness						
Direct quench from pot: 1) Carburized at 1700 F for 8 hours; 2) quenched in agitated oil; 3) tempered at **300** F.						
60.5	.060	217,000	159,500	13.0	50.1	429
Single-quench and temper—for good case and core properties: 1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1500 F; 4) quenched in agitated oil; 5) tempered at **300** F.						
62.5	.075	218,250	178,000	13.5	48.2	429
Double-quench and temper—for maximum refinement of case and core: 1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1500 F; 4) quenched in agitated oil; 5) reheated to 1425 F; 6) quenched in agitated oil; 7) tempered at **300** F.						
62	.075	151,750	97,000	19.5	49.4	302
Recommended Practice for Maximum Core Toughness						
Direct quench from pot: 1) Carburized at 1700 F for 8 hours; 2) quenched in agitated oil; 3) tempered at **450** F.						
58.5	.060	215,500	158,750	12.5	49.4	415
Single-quench and temper—for good case and core properties: 1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1500 F; 4) quenched in agitated oil; 5) tempered at **450** F.						
59	.075	211,500	173,000	12.5	50.9	415
Double-quench and temper—for maximum refinement of case and core: 1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1500 F; 4) quenched in agitated oil; 5) reheated to 1425 F; 6) quenched in agitated oil; 7) tempered at **450** F.						
59	.075	145,750	94,500	21.8	56.3	293

4419

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Grade	.18/.23	.45/.65	—	—	.20/.35	—	—	.45/.60	
Ladle	.18	.57	.010	.029	.28	.03	.01	.52	6-8

MASS EFFECT

Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1675 F; furnace-cooled 20 F per hour to 900 F; cooled in air.)					
1	64,750	48,000	31.2	62.8	121
Normalized (Heated to 1750 F; cooled in air.)					
½*	77,500	52,250	33.2	69.9	149
1	75,250	51,000	32.5	69.4	143
2	72,250	50,000	30.8	64.9	143
4	72,750	47,750	30.0	60.8	143
Mock-Carburized at 1700 F for 8 hours; reheated to 1550 F; quenched in oil; tempered at **300** F.					
½*	103,250	65,250	24.3	60.3	217
1	97,250	62,750	24.2	66.4	201
2	96,000	60,250	25.3	64.7	201
4	86,000	53,250	27.7	66.3	179
Mock-Carburized at 1700 F for 8 hours; reheated to 1550 F; quenched in oil; tempered at **450** F.					
½*	102,750	62,500	24.8	63.6	212
1	94,250	58,750	25.0	68.6	197
2	92,500	58,000	26.2	68.2	192
4	83,500	48,500	27.0	67.1	170

As-quenched Hardness (oil)

Size Round	Surface	½ Radius	Center
½	HRB 96	HRB 95	HRB 93
1	HRB 94	HRB 93	HRB 89
2	HRB 94	HRB 92	HRB 88
4	HRB 93	HRB 90	HRB 82

*Treated as .565 in. Rd.

4419

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Ladle	.18	.57	.010	.029	.28	.03	.01	.52	6-8

Critical Points, F: Ac_1 1380 Ac_3 1600 Ar_3 1510 Ar_1 1420

.565-in. Round Treated; .505-in. Round Tested

CASE		CORE PROPERTIES				
Hardness HRC	Depth in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB

Recommended Practice for Maximum Case Hardness

Direct quench from pot: 1) Carburized at 1700 F for 8 hours; 2) quenched in agitated oil; 3) tempered at **300** F.

64	.054	120,500	88,250	19.7	64.7	241

Single-quench and temper—for good case and core properties:
1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1550 F; 4) quenched in agitated oil; 5) tempered at **300** F.

65	.062	103,250	65,250	24.3	60.3	217

Double-quench and temper—for maximum refinement of case and core:
1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1575 F; 4) quenched in agitated oil; 5) reheated to 1525 F; 6) quenched in agitated oil; 7) tempered at **300** F.

66	.070	106,500	54,750	21.7	49.7	217

Recommended Practice for Maximum Core Toughness

Direct quench from pot: 1) Carburized at 1700 F for 8 hours; 2) quenched in agitated oil; 3) tempered at **450** F.

59	.054	118,500	86,500	18.8	67.0	235

Single-quench and temper—for good case and core properties:
1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1550 F; 4) quenched in agitated oil; 5) tempered at **450** F.

60.5	.062	102,750	62,500	24.8	63.6	212

Double-quench and temper—for maximum refinement of case and core:
1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1575 F; 4) quenched in agitated oil; 5) reheated to 1525 F; 6) quenched in agitated oil; 7) tempered at **450** F.

61	.070	98,500	54,500	23.4	59.7	201

4620

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Grade	.17/.22	.45/.65	—	—	.20/.35	1.65/2.00	—	.20/.30	
Ladle	.17	.52	.017	.016	.26	1.81	.10	.21	6-8

MASS EFFECT

Annealed (Heated to 1575 F; furnace-cooled 30 F per hour to 900 F; cooled in air.)

Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
1	74,250	54,000	31.3	60.3	149

Normalized (Heated to 1650 F; cooled in air.)

Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
½	87,250	54,750	30.7	68.0	192
1	83,250	53,125	29.0	66.7	174
2	80,500	53,000	29.5	67.1	167
4	77,000	51,750	30.5	65.2	163

Mock-Carburized at 1700 F for 8 hours; reheated to 1500 F; quenched in oil; tempered at **300** F.

Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
½	127,000	89,500	20.0	59.8	255
1	98,000	67,000	25.8	70.0	197
2	96,500	65,250	27.0	69.7	192
4	84,750	52,500	29.5	69.2	170

Mock-Carburized at 1700 F for 8 hours; reheated to 1500 F; quenched in oil; tempered at **450** F.

Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
½	117,500	81,000	21.4	65.3	241
1	98,000	66,250	27.5	68.9	192
2	95,750	62,000	26.8	69.2	187
4	84,500	52,750	29.8	70.3	170

As-quenched Hardness (oil)

Size Round	Surface	½ Radius	Center
½	HRC 40	HRC 32	HRC 31
1	HRC 27	HRB 99	HRB 97
2	HRC 24	HRB 94	HRB 91
4	HRB 96	HRB 91	HRB 88

4620

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Ladle	.17	.52	.017	.016	.26	1.81	.10	.21	6-8

Critical Points, F: Ac_1 1300 Ac_3 1490 Ar_3 1335 Ar_1 1220

.565-in. Round Treated; .505-in. Round Tested

CASE CORE PROPERTIES

Hardness HRC	Depth in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB

Recommended Practice for Maximum Case Hardness

Direct quench from pot: 1) Carburized at 1700 F for 8 hours; 2) quenched in agitated oil; 3) tempered at **300** F.

60.5	.075	148,250	116,500	17.0	55.7	311

Single-quench and temper—for good case and core properties:
1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1500 F; 4) quenched in agitated oil; 5) tempered at **300** F.

62.5	.075	119,250	83,500	19.5	59.4	277

Double-quench and temper—for maximum refinement of case and core:
1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1525 F; 4) quenched in agitated oil; 5) reheated to 1475 F; 6) quenched in agitated oil; 7) tempered at **300** F.

62	.060	122,000	77,250	22.0	55.7	248

Recommended Practice for Maximum Core Toughness

Direct quench from pot: 1) Carburized at 1700 F for 8 hours; 2) quenched in agitated oil; 3) tempered at **450** F.

58.5	.060	147,500	115,750	16.8	57.9	302

Single-quench and temper—for good case and core properties:
1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1500 F; 4) quenched in agitated oil; 5) tempered at **450** F.

59	.065	115,500	80,750	20.5	63.6	248

Double-quench and temper—for maximum refinement of case and core:
1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1525 F; 4) quenched in agitated oil; 5) reheated to 1475 F; 6) quenched in agitated oil; 7) tempered at **450** F.

59	.060	115,250	77,000	22.5	62.1	235

4820

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Grade	.18/.23	.50/.70	—	—	.20/.35	3.25/3.75	—	.20/.30	
Ladle	.20	.61	.027	.016	.29	3.47	.07	.22	6-8

MASS EFFECT

Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1500 F; furnace-cooled 30 F per hour to 500 F; cooled in air.)					
1	98,750	67,250	22.3	58.8	197
Normalized (Heated to 1580 F; cooled in air.)					
½	112,500	72,500	26.0	57.8	235
1	109,500	70,250	24.0	59.2	229
2	107,250	69,000	23.0	59.8	223
4	103,500	68,000	22.0	58.4	212
Mock-Carburized at 1700 F for 8 hours; reheated to 1475 F; quenched in oil; tempered at **300** F.					
½	209,000	172,750	14.2	54.3	401
1	169,500	126,500	15.0	51.0	352
2	135,500	93,250	19.8	56.3	277
4	118,750	81,000	23.0	59.4	241
Mock-Carburized at 1700 F for 8 hours; reheated to 1475 F; quenched in oil; tempered at **450** F.					
½	205,000	170,000	13.2	52.3	388
1	163,250	120,500	15.5	53.1	331
2	130,000	92,500	19.0	62.7	269
4	117,000	80,000	21.0	63.8	235

As-quenched Hardness (oil)

Size Round	Surface	½ Radius	Center
½	HRC 45	HRC 45	HRC 44
1	HRC 43	HRC 39	HRC 37
2	HRC 36	HRC 31	HRC 27
4	HRC 27	HRC 24	HRC 24

4820

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Ladle	.21	.51	.021	.018	.21	3.49	.18	.24	

Critical Points, F: Ac_1 1310 Ac_3 1440 Ar_3 1215 Ar_1 780 6-8

.565-in. Round Treated; .505-in. Round Tested

CASE		CORE PROPERTIES				
Hardness HRC	Depth in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB

Recommended Practice for Maximum Case Hardness

Direct quench from pot: 1) Carburized at 1700 F for 8 hours; 2) quenched in agitated oil; 3) tempered at **300** F.

60	.039	205,000	165,500	13.3	53.3	415

Single-quench and temper—for good case and core properties:
1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1475 F; 4) quenched in agitated oil; 5) tempered at **300** F.

61	.047	207,500	167,000	13.8	52.2	415

Double-quench and temper—for maximum refinement of case and core:
1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1500 F; 4) quenched in agitated oil; 5) reheated to 1450 F; 6) quenched in agitated oil; 7) tempered at **300** F.

60	.047	204,500	165,500	13.8	52.4	415

Recommended Practice for Maximum Core Toughness

Direct quench from pot: 1) Carburized at 1700 F for 8 hours; 2) quenched in agitated oil; 3) tempered at **450** F.

56	.039	200,500	170,000	12.8	53.0	401

Single-quench and temper—for good case and core properties:
1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1475 F; 4) quenched in agitated oil; 5) tempered at **450** F.

57.5	.047	205,000	184,500	13.0	53.3	415

Double-quench and temper—for maximum refinement of case and core:
1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1500 F; 4) quenched in agitated oil; 5) reheated to 1450 F; 6) quenched in agitated oil; 7) tempered at **450** F.

56.5	.047	196,500	171,500	13.0	53.4	401

8620

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Grade	.18/.23	.70/.90	—	—	.20/.35	.40/.70	.40/.60	.15/.25	90% 7-8
Ladle	.23	.81	.025	.016	.28	.56	.43	.19	10% 4

MASS EFFECT

Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1600 F; furnace-cooled 30 F per hour to 1150 F; cooled in air.)					
1	77,750	55,875	31.3	62.1	149
Normalized (Heated to 1675 F; cooled in air.)					
½	96,500	54,250	26.3	62.5	197
1	91,750	51,750	26.3	59.7	183
2	87,250	51,500	27.8	62.1	179
4	81,750	51,500	28.5	62.3	163
Mock-Carburized at 1700 F for 8 hours; reheated to 1550 F; quenched in oil; tempered at **300** F.					
½	199,500	157,000	13.2	49.4	388
1	126,750	83,750	20.8	52.7	255
2	117,250	73,000	23.0	57.8	235
4	98,500	57,750	24.3	57.6	207
Mock-Carburized at 1700 F for 8 hours; reheated to 1550 F; quenched in oil; tempered at **450** F.					
½	178,500	139,500	14.6	53.9	352
1	124,250	80,750	19.5	54.2	248
2	114,500	72,250	22.0	59.0	229
4	98,000	55,500	25.5	57.8	201

As-quenched Hardness (oil)

Size Round	Surface	½ Radius	Center
½	HRC 43	HRC 43	HRC 43
1	HRC 29	HRC 27	HRC 25
2	HRC 23	HRC 22	HRB 97
4	HRC 22	HRB 95	HRB 93

8620

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Ladle	.23	.81	.025	.016	.28	.56	.43	.19	90% 7-8 10% 4

Critical Points, F: Ac_1 1380 Ac_3 1520 Ar_3 1400 Ar_1 1200

.565-in. Round Treated; .505-in. Round Tested

CASE		CORE PROPERTIES				
Hardness HRC	Depth in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB

Recommended Practice for Maximum Case Hardness

Direct quench from pot: 1) Carburized at 1700 F for 8 hours; 2) quenched in agitated oil; 3) tempered at **300** F.

63	.056	192,000	150,250	12.5	49.4	388

Single-quench and temper—for good case and core properties: 1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1550 F; 4) quenched in agitated oil; 5) tempered at **300** F.

64	.075	188,500	149,750	11.5	51.6	388

Double-quench and temper—for maximum refinement of case and core: 1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1550 F; 4) quenched in agitated oil; 5) reheated to 1475 F; 6) quenched in agitated oil; 7) tempered at **300** F.

64	.070	133,000	83,000	20.0	56.8	269

Recommended Practice for Maximum Core Toughness

Direct quench from pot: 1) Carburized at 1700 F for 8 hours; 2) quenched in agitated oil; 3) tempered at **450** F.

58	.050	181,250	134,250	12.8	50.6	352

Single-quench and temper—for good case and core properties: 1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1550 F; 4) quenched in agitated oil; 5) tempered at **450** F.

61	.076	167,750	120,750	14.3	53.2	341

Double-quench and temper—for maximum refinement of case and core: 1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1550 F; 4) quenched in agitated oil; 5) reheated to 1475 F; 6) quenched in agitated oil; 7) tempered at **450** F.

61	.070	130,250	77,250	22.5	51.7	262

E9310

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Grade	.08/.13	.45/.65	—	—	.20/.35	3.00/3.50	1.00/1.40	.08/.15	
Ladle	.09	.57	.012	.010	.32	3.11	1.23	.13	80% 5 20% 2-4

MASS EFFECT

Annealed (Heated to 1550 F; furnace-cooled 30 F per hour to 760 F; cooled in air.)

Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
1	119,000	63,750	17.3	42.1	241

Normalized (Heated to 1630 F; cooled in air.)

Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
½	133,000	87,750	20.0	63.7	285
1	131,500	82,750	18.8	58.1	269
2	131,250	82,000	19.5	60.5	262
4	125,250	81,750	19.5	61.7	255

Mock-Carburized at 1700 F for 8 hours; reheated to 1450 F; quenched in oil; tempered at **300** F.

Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
½	178,750	143,000	15.7	58.9	363
1	159,000	122,750	15.5	57.5	321
2	145,250	108,000	18.5	66.7	293
4	136,000	94,750	19.0	62.3	277

Mock-Carburized at 1700 F for 8 hours; reheated to 1450 F; quenched in oil; tempered at **450** F.

Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
½	178,250	141,500	15.0	60.3	363
1	157,500	123,000	16.0	61.7	321
2	143,500	105,500	17.8	68.1	293
4	131,500	96,500	20.5	67.0	269

As-quenched Hardness (oil)

Size Round	Surface	½ Radius	Center
½	HRC 40	HRC 40	HRC 38
1	HRC 40	HRC 38	HRC 37
2	HRC 38	HRC 35	HRC 32
4	HRC 31	HRC 30	HRC 29

E9310

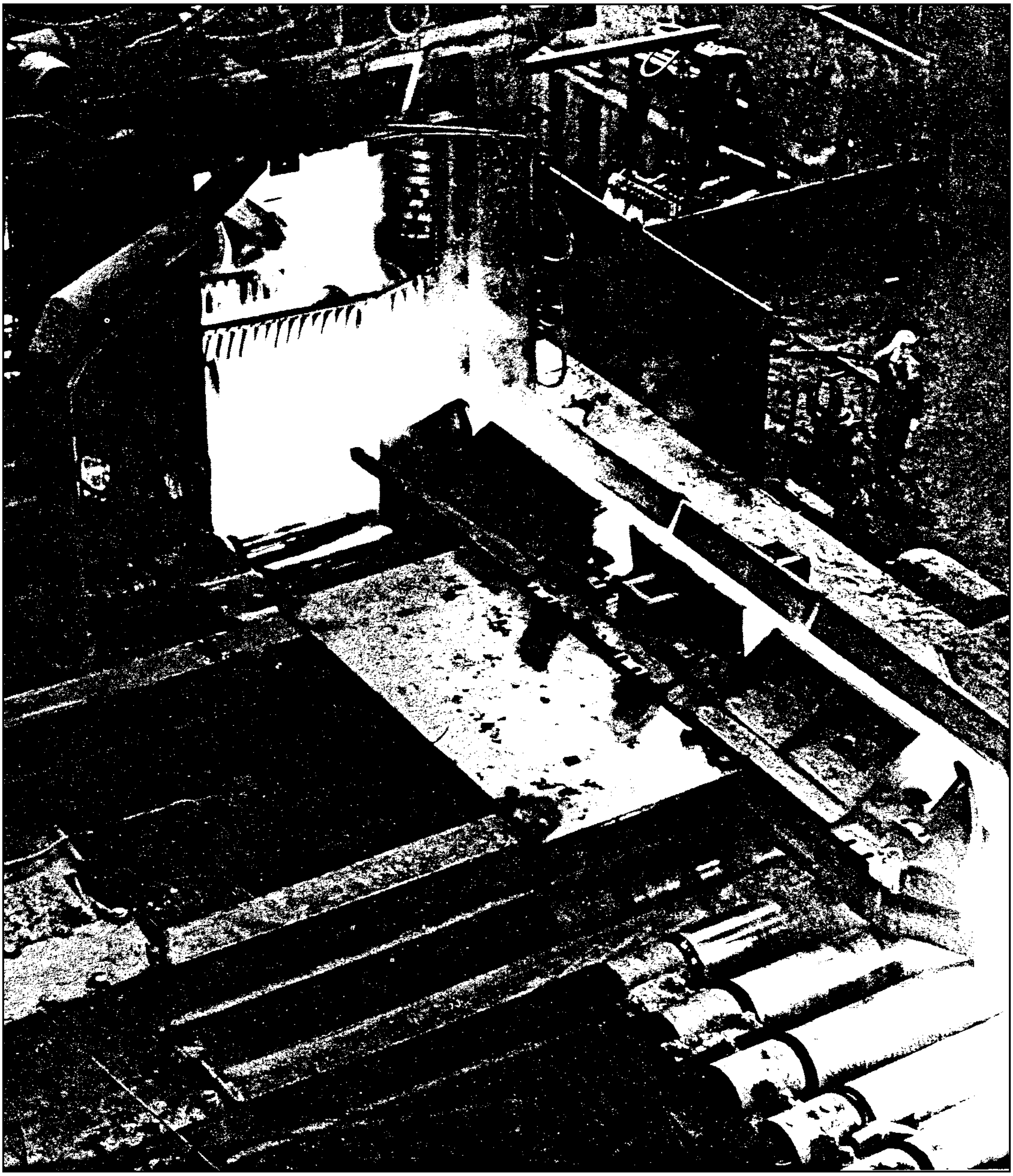
SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Ladle	11.	.53	.013	.014	.29	3.19	1.23	.11	5-7

Critical Points, F: Ac_1 1350 Ac_3 1480 Ar_3 1210 Ar_1 810

.565-in. Round Treated; .505-in. Round Tested

CASE		CORE PROPERTIES				
Hardness HRC	Depth in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Recommended Practice for Maximum Case Hardness						
Direct quench from pot: 1) Carburized at 1700 F for 8 hours; 2) quenched in agitated oil; 3) tempered at **300** F.						
59.5	.039	179,500	144,000	15.3	59.1	375
Single-quench and temper—for good case and core properties: 1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1450 F; 4) quenched in agitated oil; 5) tempered at **300** F.						
62	.047	173,000	135,000	15.5	60.0	363
Double-quench and temper—for maximum refinement of case and core: 1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1475 F; 4) quenched in agitated oil; 5) reheated to 1425 F; 6) quenched in agitated oil; 7) tempered at **300** F.						
60.5	.055	174,500	139,000	15.3	62.1	363
Recommended Practice for Maximum Core Toughness						
Direct quench from pot: 1) Carburized at 1700 F for 8 hours; 2) quenched in agitated oil; 3) tempered at **450** F.						
54.5	.039	178,000	146,500	15.0	59.7	363
Single-quench and temper—for good case and core properties: 1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1450 F; 4) quenched in agitated oil; 5) tempered at **450** F.						
59.5	.047	168,000	137,500	15.5	60.0	341
Double-quench and temper—for maximum refinement of case and core: 1) Carburized at 1700 F for 8 hours; 2) pot-cooled; 3) reheated to 1475 F; 4) quenched in agitated oil; 5) reheated to 1425 F; 6) quenched in agitated oil; 7) tempered at **450** F.						
58	.055	169,500	138,000	14.8	61.8	352



ALLOY STEEL WATER-HARDENING GRADES

4027 Water-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Grade	.25/.30	.70/.90	—	—	.20/.35	—	—	.20/.30	
Ladle	.27	.75	.014	.033	.28	.05	.07	.22	5-7

MASS EFFECT

Size Round in.	Tensile Strength psi	Yield Strength (.2% Offset) psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1585 F, furnace-cooled 20 F per hour to 800 F, cooled in air.)					
1	75,000	47,250	30.0	52.9	143
Normalized (Heated to 1660 F, cooled in air.)					
.565	94,500	61,500	25.5	60.2	179
1	93,250	61,250	25.8	60.2	179
2	85,500	55,750	27.7	57.1	163
4	81,750	51,250	28.3	55.9	156
Water-quenched from 1585 F, tempered at **900** F.					
.565	156,500	143,250	15.8	58.4	321
1	150,000	133,000	16.0	57.8	311
2	114,500	89,000	22.0	66.6	229
4	101,000	77,500	25.0	68.3	201
Water-quenched from 1585 F, tempered at **1000** F.					
.565	144,000	130,500	17.7	61.3	302
1	139,250	122,250	18.8	60.1	285
2	111,000	85,000	23.7	67.2	223
4	100,000	73,750	25.2	67.4	201
Water-quenched from 1585 F, tempered at **1100** F.					
.565	130,250	115,750	20.0	64.5	262
1	114,250	93,250	23.0	67.6	229
2	104,250	80,000	24.8	68.3	212
4	95,000	71,000	26.6	68.0	192

As-quenched Hardness (water)

Size Round	Surface	½ Radius	Center
.565	HRC 50	HRC 50	HRC 50
1	HRC 50	HRC 47	HRC 44
2	HRC 47	HRC 27	HRC 27
4	HRB 83	HRB 77	HRB 75

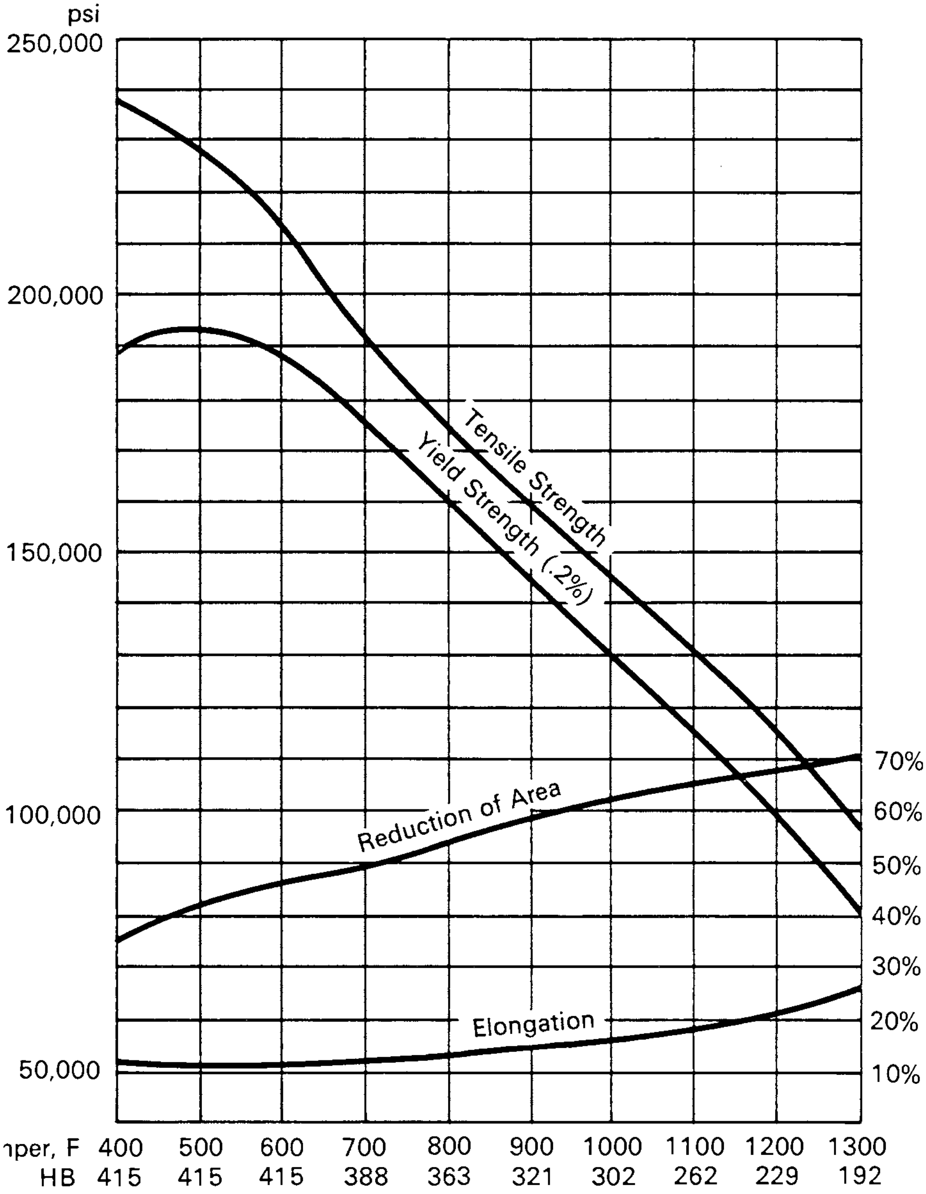
Water-quenched **4027**

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Ladle	.27	.75	.014	.033	.28	.05	.07	.22	5-7

Critical Points, F: Ac_1 1370 Ac_3 1510 Ar_3 1410 Ar_1 1320

Treatment: Normalized at 1660 F; reheated to 1585 F; quenched in water.
.565-in. Round Treated; .505-in. Round Tested. As-quenched HB 477.



4130 Water-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Grade	.28/.33	.40/.60	—	—	.20/.35	—	.80/1.10	.15/.25	
Ladle	.30	.48	.015	.015	.20	.12	.91	.20	6-8

MASS EFFECT

Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1585 F, furnace-cooled 20 F per hour to 1255 F, cooled in air.)					
1	81,250	52,250	28.2	55.6	156
Normalized (Heated to 1600 F, cooled in air.)					
½	106,500	67,000	25.1	59.6	217
1	97,000	63,250	25.5	59.5	197
2	89,000	61,750	28.2	65.4	167
4	88,750	57,750	27.0	61.2	163
Water-quenched from 1575 F, tempered at **900** F.					
½	166,500	161,000	16.4	61.0	331
1	161,000	137,500	14.7	54.4	321
2	132,750	110,250	19.0	63.0	269
4	121,500	95,000	20.5	63.6	241
Water-quenched from 1575 F, tempered at **1000** F.					
½	151,000	142,500	18.1	63.9	302
1	144,500	129,500	18.5	61.8	293
2	121,750	98,750	21.2	66.3	241
4	116,000	91,500	21.5	63.5	235
Water-quenched from 1575 F, tempered at **1100** F.					
½	133,000	122,500	20.7	69.0	269
1	128,000	113,250	21.2	67.5	262
2	114,500	91,500	21.7	67.7	229
4	101,500	77,500	24.5	69.2	197

As-quenched Hardness (water)

Size Round	Surface	½ Radius	Center
½	HRC 51	HRC 50	HRC 50
1	HRC 51	HRC 50	HRC 44
2	HRC 47	HRC 32	HRC 31
4	HRC 45.5	HRC 25	HRC 24.5

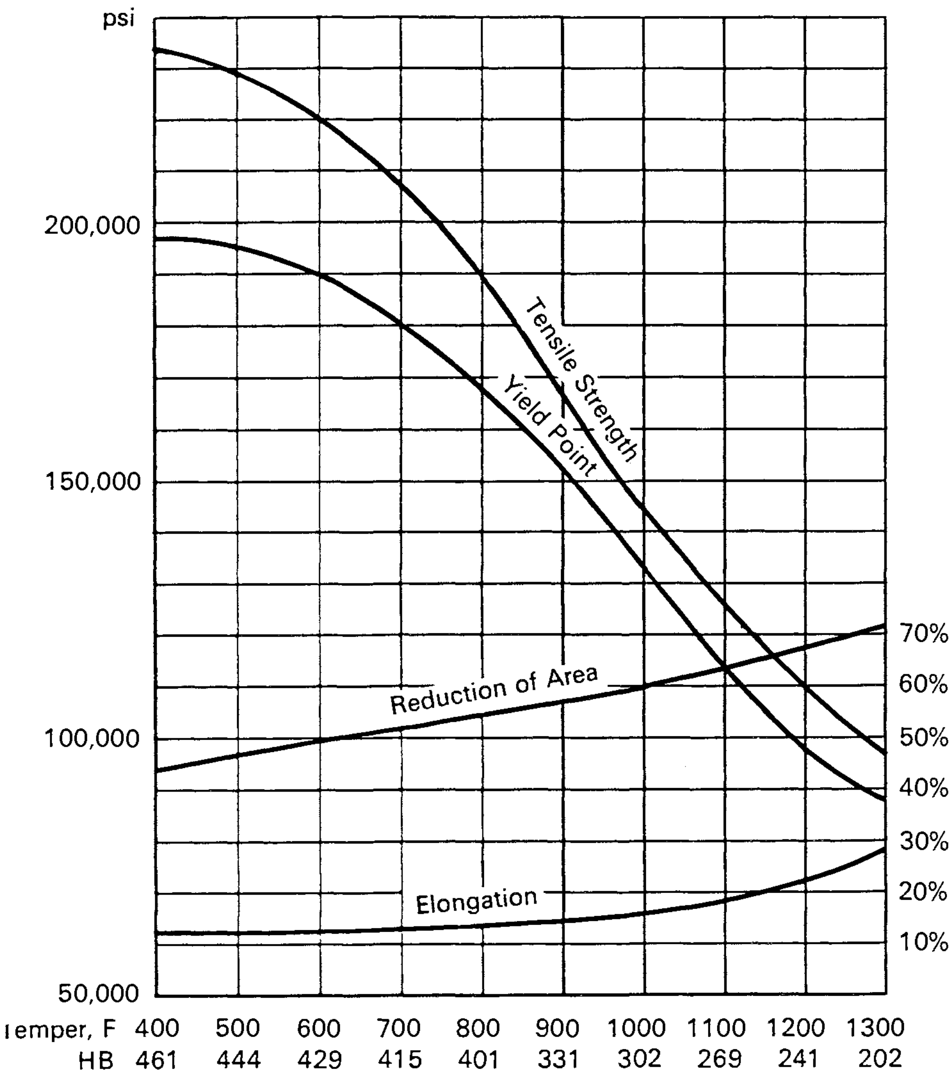
Water-quenched **4130**

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Ladle	.30	.48	.015	.015	.20	.12	.91	.20	6-8

Critical Points, F: Ac$_1$ 1400 Ac$_3$ 1510 Ar$_3$ 1400 Ar$_1$ 1305

Treatment: Normalized at 1600 F; reheated to 1575 F; quenched in water.
.530-in. Round Treated; 505-in. Round Tested. As-quenched HB 495.



8630 Water-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Grade	.28/.33	.70/.90	—	—	.20/.35	.40/.70	.40/.60	.15/.25	
Ladle	.29	.85	.012	.021	.25	.62	.44	.19	6-8

MASS EFFECT

Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1550 F, furnace-cooled 20 F per hour to 1155 F, cooled in air.)					
1	81,750	54,000	29.0	58.9	156
Normalized (Heated to 1600 F, cooled in air.)					
½	95,000	61,750	25.2	60.2	201
1	94,250	62,250	23.5	53.5	187
2	93,000	62,000	26.2	59.2	187
4	92,500	56,250	24.5	57.3	187
Water-quenched from 1550 F, tempered at **900** F.					
½	152,250	150,500	16.4	59.4	302
1	146,750	131,750	16.2	56.5	293
2	129,750	107,250	19.2	63.7	269
4	113,000	86,000	21.2	64.7	235
Water-quenched from 1550 F, tempered at **1000** F.					
½	139,250	132,500	18.9	58.1	285
1	134,750	123,000	18.7	59.6	269
2	120,250	100,000	21.2	65.6	235
4	107,250	82,500	23.0	63.0	217
Water-quenched from 1550 F, tempered at **1100** F.					
½	134,500	132,000	19.2	61.0	269
1	118,000	101,250	18.7	58.2	241
2	111,250	89,000	22.5	68.6	223
4	96,000	72,250	25.5	68.1	197

As-quenched Hardness (water)

Size Round	Surface	½ Radius	Center
½	HRC 52	HRC 49	HRC 47
1	HRC 52	HRC 48	HRC 43
2	HRC 51	HRC 31	HRC 30
4	HRC 47	HRC 25	HRC 22

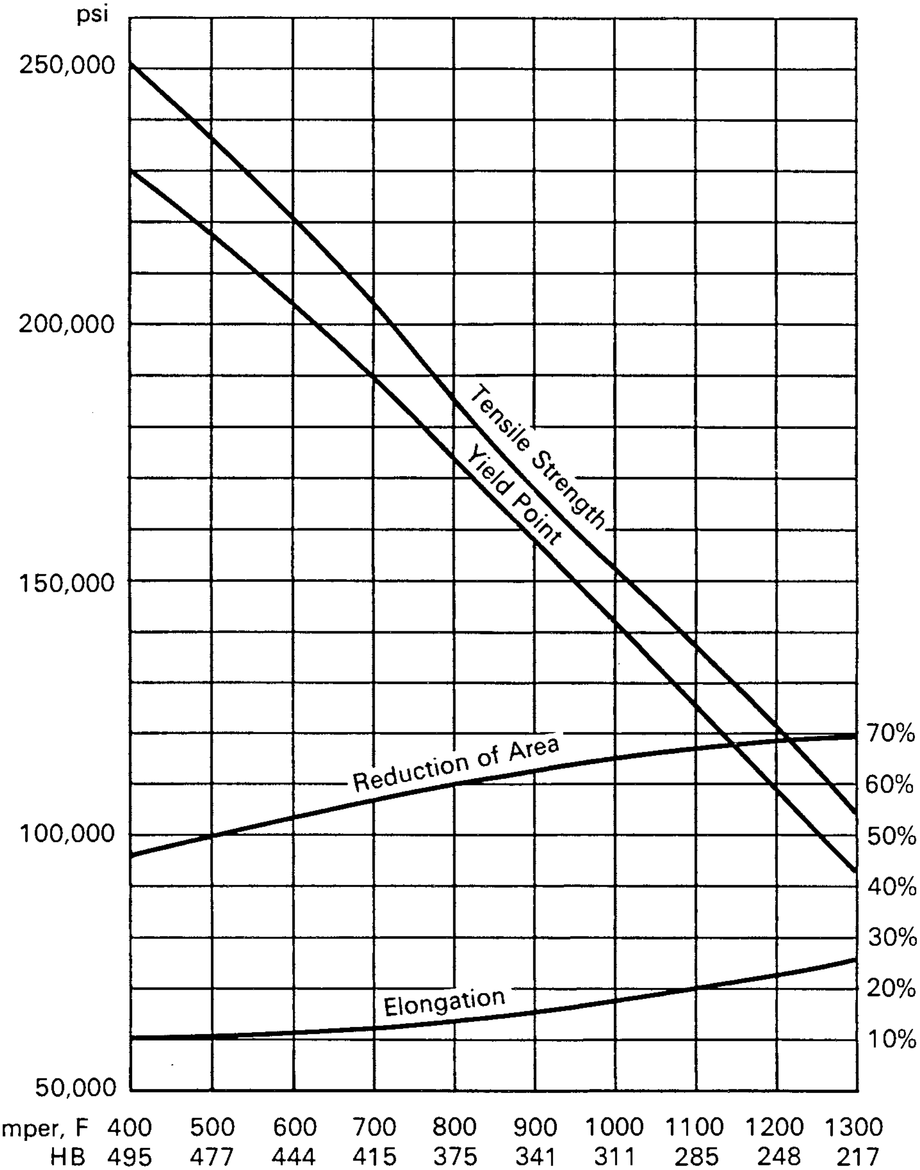
Water-quenched **8630**

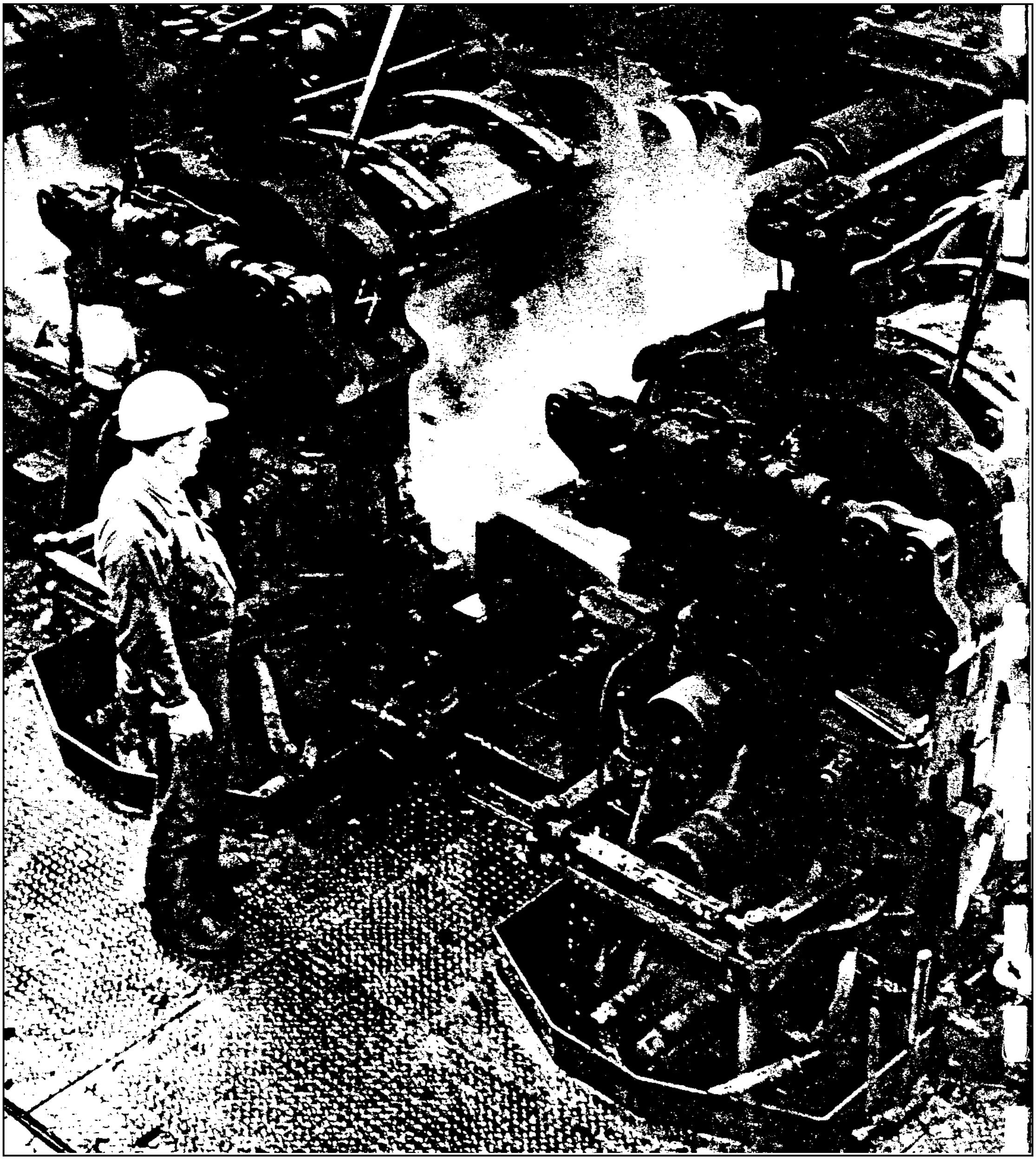
SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Ladle	.30	.80	.018	.024	.27	.65	.48	.18	6-8

Critical Points, F: Ac_1 1365 Ac_3 1465 Ar_3 1335 Ar_1 1205

Treatment: Normalized at 1600 F; reheated to 1550 F; quenched in water.
.530-in. Round Treated; .505-in. Round Tested. As-quenched HB 534.





ALLOY STEEL OIL-HARDENING GRADES

1340 Oil-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Grade	.38/.43	1.60/1.90	—	—	.20/.35	—	—	—	
Ladle	.40	1.77	.027	.016	.25	.10	.12	.01	6-8

MASS EFFECT

Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1475 F, furnace-cooled 20 F per hour to 1110 F, cooled in air.)					
1	102,000	63,250	25.5	57.3	207
Normalized (Heated to 1600 F, cooled in air.)					
½	132,000	81,500	20.0	51.0	269
1	121,250	81,000	22.0	62.9	248
2	120,000	76,250	23.5	61.0	235
4	120,000	72,250	21.7	59.2	235
Oil-quenched from 1525 F, tempered at **1000** F.					
½	142,500	131,500	18.8	55.2	285
1	137,750	121,000	19.2	57.4	285
2	120,500	84,250	21.2	60.7	248
4	116,500	83,000	21.7	57.9	241
Oil-quenched from 1525 F, tempered at **1100** F.					
½	127,000	118,000	21.0	57.9	255
1	118,000	98,250	21.7	60.1	241
2	108,750	82,250	24.7	64.3	217
4	103,250	71,000	25.5	64.5	217
Oil-quenched from 1525 F, tempered at **1200** F.					
½	118,500	108,500	22.1	59.5	241
1	112,000	96,000	23.2	62.4	229
2	105,750	79,500	25.5	66.2	217
4	102,250	72,000	26.0	64.8	212

As-quenched Hardness (oil)

Size Round	Surface	½ Radius	Center
½	HRC 58	HRC 57	HRC 57
1	HRC 57	HRC 56	HRC 50
2	HRC 39	HRC 34	HRC 32
4	HRC 32	HRC 30	HRC 26

Oil-quenched 1340

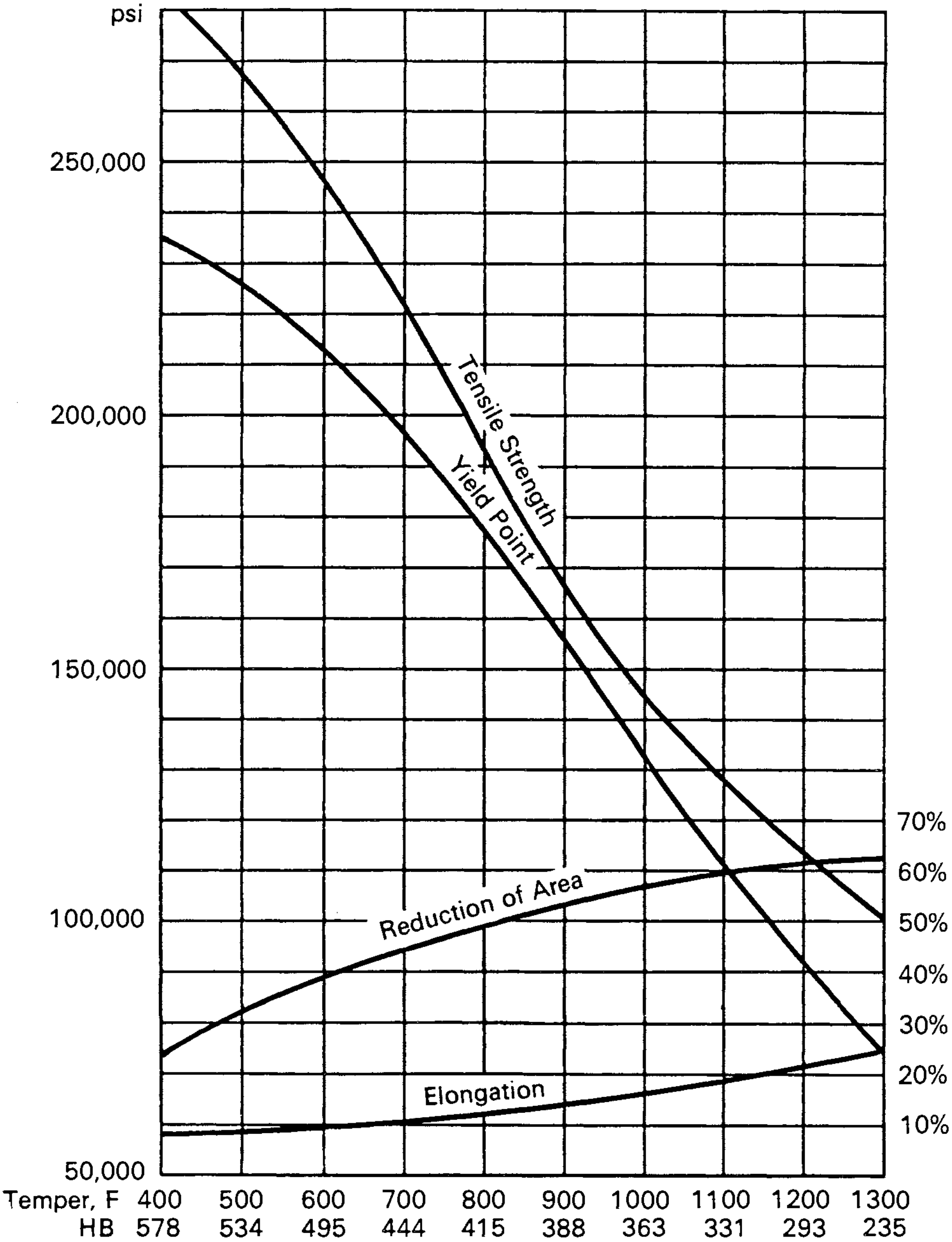
SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Ladle	.43	1.70	.015	.039	.23	.03	.02	—	6-8

Critical Points, F: Ac_1 1340 Ac_3 1420 Ar_3 1195 Ar_1 1160

Treatment: Normalized at 1600 F; reheated to 1525 F; quenched in agitated oil.

.565-in. Round Treated; .505-in. Round Tested. As-quenched HB 601.



4140 Oil-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Grade	.38/.43	.75/1.00	—	—	.20/.35	—	.80/1.10	.15/.25	
Ladle	.40	.83	.012	.009	.26	.11	.94	.21	7-8

MASS EFFECT

Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1500 F, furnace-cooled 20 F per hour to 1230 F, cooled in air.)					
1	95,000	60,500	25.7	56.9	197
Normalized (Heated to 1600 F, cooled in air.)					
½	148,500	98,500	17.8	48.2	302
1	148,000	95,000	17.7	46.8	302
2	140,750	91,750	16.5	48.1	285
4	117,500	69,500	22.2	57.4	241
Oil-quenched from 1550 F, tempered at **1000** F.					
½	171,500	161,000	15.4	55.7	341
1	156,000	143,250	15.5	56.9	311
2	139,750	115,750	17.5	59.8	285
4	127,750	99,250	19.2	60.4	277
Oil-quenched from 1550 F, tempered at **1100** F.					
½	157,500	148,750	18.1	59.4	321
1	140,250	135,000	19.5	62.3	285
2	127,500	102,750	21.7	65.0	262
4	116,750	87,000	21.5	62.1	235
Oil-quenched from 1550 F, tempered at **1200** F.					
½	136,500	128,750	19.9	62.3	277
1	132,750	122,500	21.0	65.0	269
2	121,500	98,250	23.2	65.8	241
4	112,500	83,500	23.2	64.9	229

As-quenched Hardness (oil)

Size Round	Surface	½ Radius	Center
½	HRC 57	HRC 56	HRC 55
1	HRC 55	HRC 55	HRC 50
2	HRC 49	HRC 43	HRC 38
4	HRC 36	HRC 34.5	HRC 34

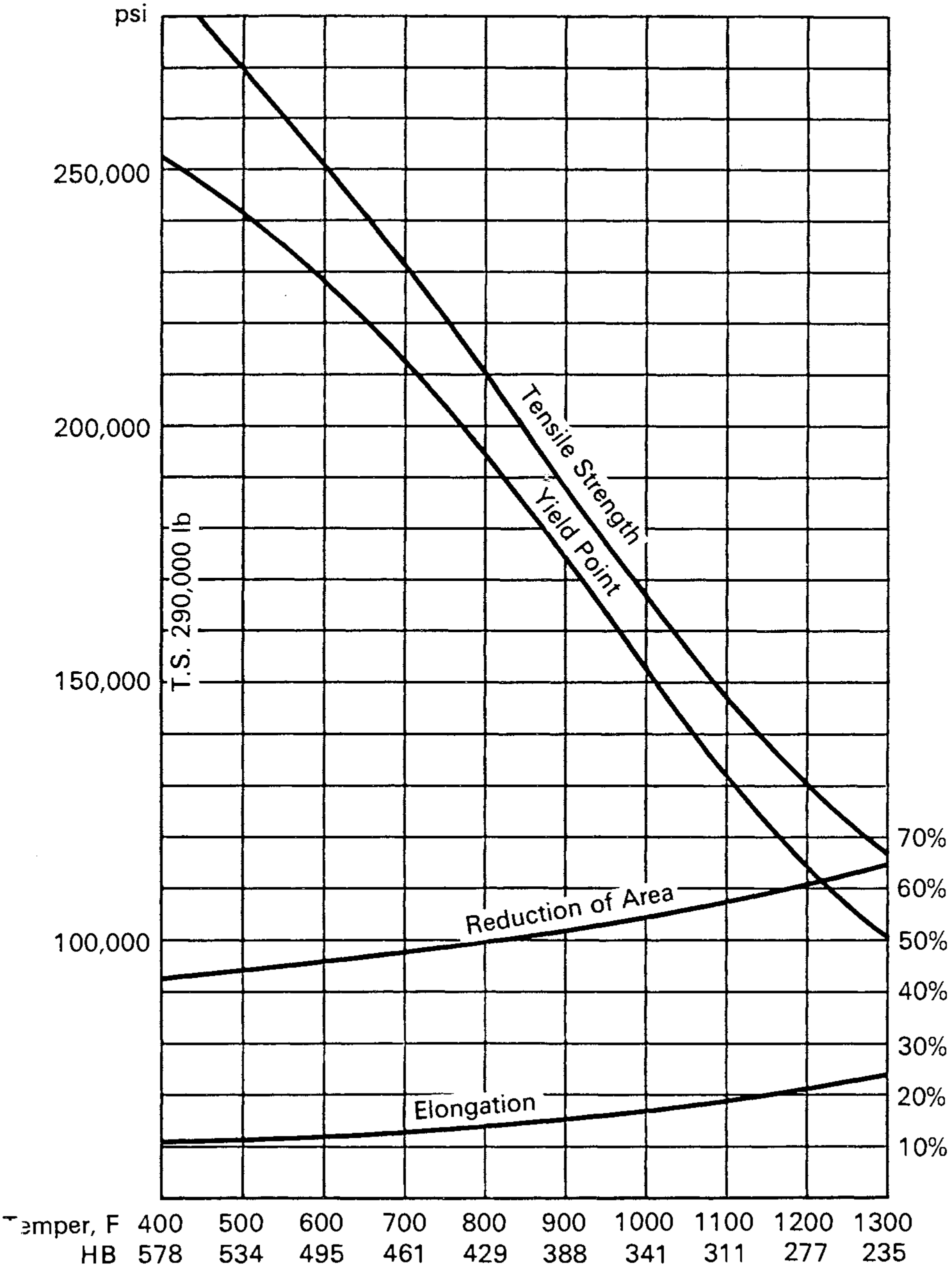
Oil-quenched 4140

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Ladle	.41	.85	.024	.031	.20	.12	1.01	.24	6-8

Critical Points, F: Ac$_1$ 1395 Ac$_3$ 1450 Ar$_3$ 1330 Ar$_1$ 1280

Treatment: Normalized at 1600 F; reheated to 1550 F; quenched in agitated oil.
.530-in. Round Treated; .505-in. Round Tested. As-quenched HB 601.



4340 Oil-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Grade	.38/.43	.60/.80	—	—	.20/.35	1.65/2.00	.70/.90	.20/.30	
Ladle	.40	.68	.020	.013	.28	1.87	.74	.25	7-8

MASS EFFECT

Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1490 F, furnace-cooled 20 F per hour to 670 F, cooled in air.)					
1	108,000	68,500	22.0	49.9	217
Normalized (Heated to 1600 F, cooled in air.)					
½	209,500	141,000	12.1	35.3	388
1	185,500	125,000	12.2	36.3	363
2	176,750	114,500	13.5	37.3	341
4	161,000	103,000	13.2	36.0	321
Oil-quenched from 1475, tempered at **1000** F.					
½	182,000	169,000	13.7	45.0	363
1	175,000	166,000	14.2	45.9	352
2	170,000	159,500	16.0	54.8	341
4	164,750	145,250	15.5	53.4	331
Oil-quenched from 1475 F, tempered at **1100** F.					
½	165,750	162,000	17.1	57.0	331
1	164,750	159,000	16.5	54.1	331
2	147,250	139,250	19.0	60.4	293
4	133,750	114,500	19.7	60.7	269
Oil-quenched from 1475 F, tempered at **1200** F.					
½	145,000	135,500	20.0	59.3	285
1	139,000	128,000	20.0	59.7	277
2	134,750	121,000	20.5	62.5	269
4	124,000	105,750	21.7	63.0	255

As-quenched Hardness (oil)

Size Round	Surface	½ Radius	Center
½	HRC 58	HRC 58	HRC 56
1	HRC 57	HRC 57	HRC 56
2	HRC 56	HRC 55	HRC 54
4	HRC 53	HRC 49	HRC 47

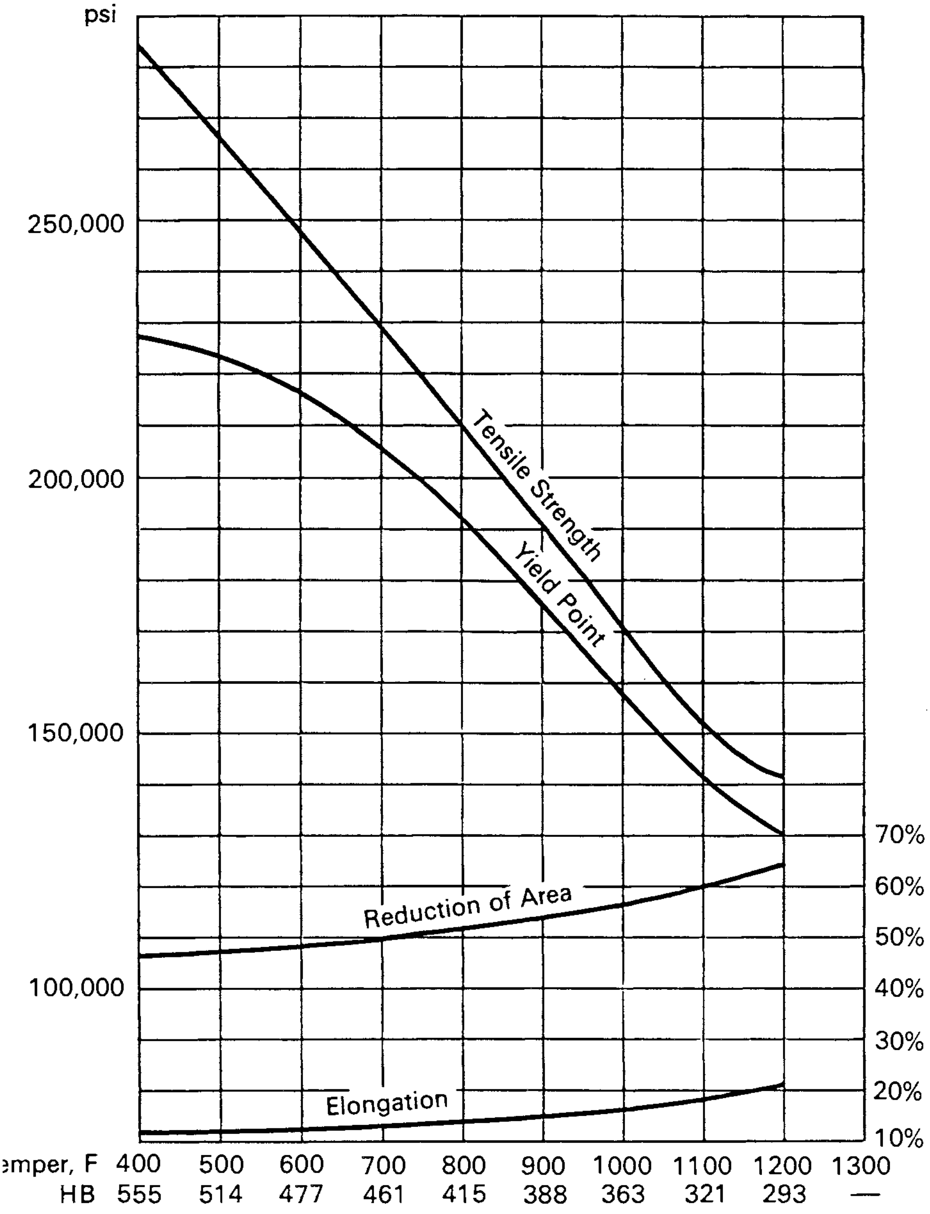
Oil-quenched 4340

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Ladle	.41	.67	.023	.018	.26	1.77	.78	.26	6-8

Critical Points, F: Ac_1 1350 Ac_3 1415 Ar_3 890 Ar_1 720

Treatment: Normalized at 1600 F; reheated to 1475 F; quenched in agitated oil.
.530-in. Round Treated; .505-in. Round Tested. As-quenched HB 601.



5140 Oil-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Grade	.38/.43	.70/.90	—	—	.20/.35	—	.70/.90	—	
Ladle	.43	.78	.020	.033	.22	.06	.74	.01	6-8

MASS EFFECT

Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1525 F, furnace-cooled 20 F per hour to 1200 F, cooled in air.)					
1	83,000	42,500	28.6	57.3	167
Normalized (Heated to 1600 F, cooled in air.)					
½	120,000	75,500	22.0	62.3	235
1	115,000	68,500	22.7	59.2	229
2	113,000	65,500	21.8	55.8	223
4	111,400	60,375	21.6	52.3	217
Oil-quenched from 1550 F, tempered at **1000** F.					
½	146,750	131,500	17.8	57.1	302
1	141,000	121,500	18.5	58.9	293
2	128,000	100,500	19.7	59.1	255
4	125,000	81,500	20.2	55.4	248
Oil-quenched from 1550 F, tempered at **1100** F.					
½	130,500	113,000	20.2	61.4	269
1	127,250	105,000	20.5	61.7	262
2	118,000	89,000	22.0	63.2	241
4	115,500	73,500	22.1	59.0	235
Oil-quenched from 1550 F, tempered at **1200** F.					
½	120,000	102,000	22.2	63.4	241
1	117,000	94,500	22.5	63.5	235
2	109,500	81,500	24.5	67.1	223
4	106,000	68,000	24.6	63.1	217

As-quenched Hardness (oil)

Size Round	Surface	½ Radius	Center
½	HRC 57	HRC 57	HRC 56
1	HRC 53	HRC 48	HRC 45
2	HRC 46	HRC 38	HRC 35
4	HRC 35	HRC 29	HRC 20

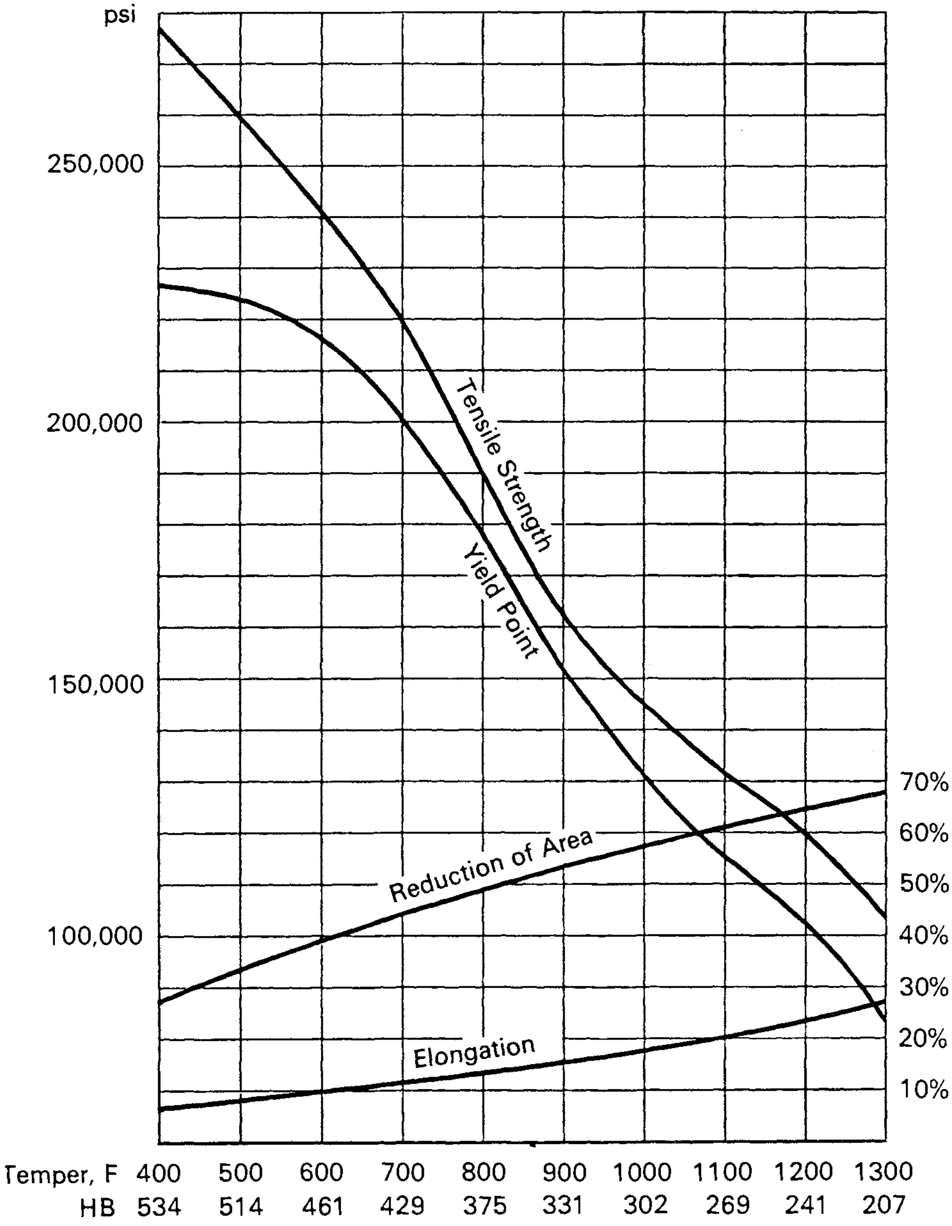
Oil-quenched 5140

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Ladle	.43	.78	.020	.033	.22	.06	.74	.01	6-8

Critical Points, F: Ac_1 1370 Ac_3 1440 Ar_3 1320 Ar_1 1260

Treatment: Normalized at 1600 F; reheated to 1550 F; quenched in agitated oil.
.530-in. Round Treated; .505-in. Round Tested. As-quenched HB 601.



8740 Oil-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Grade	.38/.43	.75/1.00	—	—	.20/.35	.40/.70	.40/.60	.20/.30	
Ladle	.41	.90	.016	.010	.25	.63	.53	.29	7-8

MASS EFFECT

Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1500 F, furnace-cooled 20 F per hour to 1100 F, cooled in air.)					
1	100,750	60,250	22.2	46.4	201
Normalized (Heated to 1600 F, cooled in air.)					
½	135,500	89,500	16.0	47.1	269
1	134,750	88,000	16.0	47.9	269
2	132,000	87,500	16.7	50.1	262
4	132,000	87,000	15.5	46.1	255
Oil-quenched from 1525 F, tempered at **1000** F.					
½	179,000	165,000	13.5	47.4	352
1	178,500	164,250	16.0	53.0	352
2	170,750	153,500	15.7	52.8	331
4	138,750	108,500	18.0	55.6	277
Oil-quenched from 1525 F, tempered at **1100** F.					
½	153,500	139,500	17.4	55.1	311
1	149,250	134,500	18.2	59.9	302
2	142,500	122,500	18.5	62.0	277
4	123,750	96,750	20.5	59.8	248
Oil-quenched from 1525 F, tempered at **1200** F.					
½	140,000	127,250	19.9	60.7	285
1	138,000	123,000	20.0	60.7	285
2	127,250	105,750	21.5	65.4	255
4	115,500	88,250	22.7	62.9	229

As-quenched Hardness (oil)

Size Round	Surface	½ Radius	Center
½	HRC 57	HRC 56	HRC 55
1	HRC 56	HRC 55	HRC 54
2	HRC 52	HRC 49	HRC 45
4	HRC 42	HRC 37	HRC 36

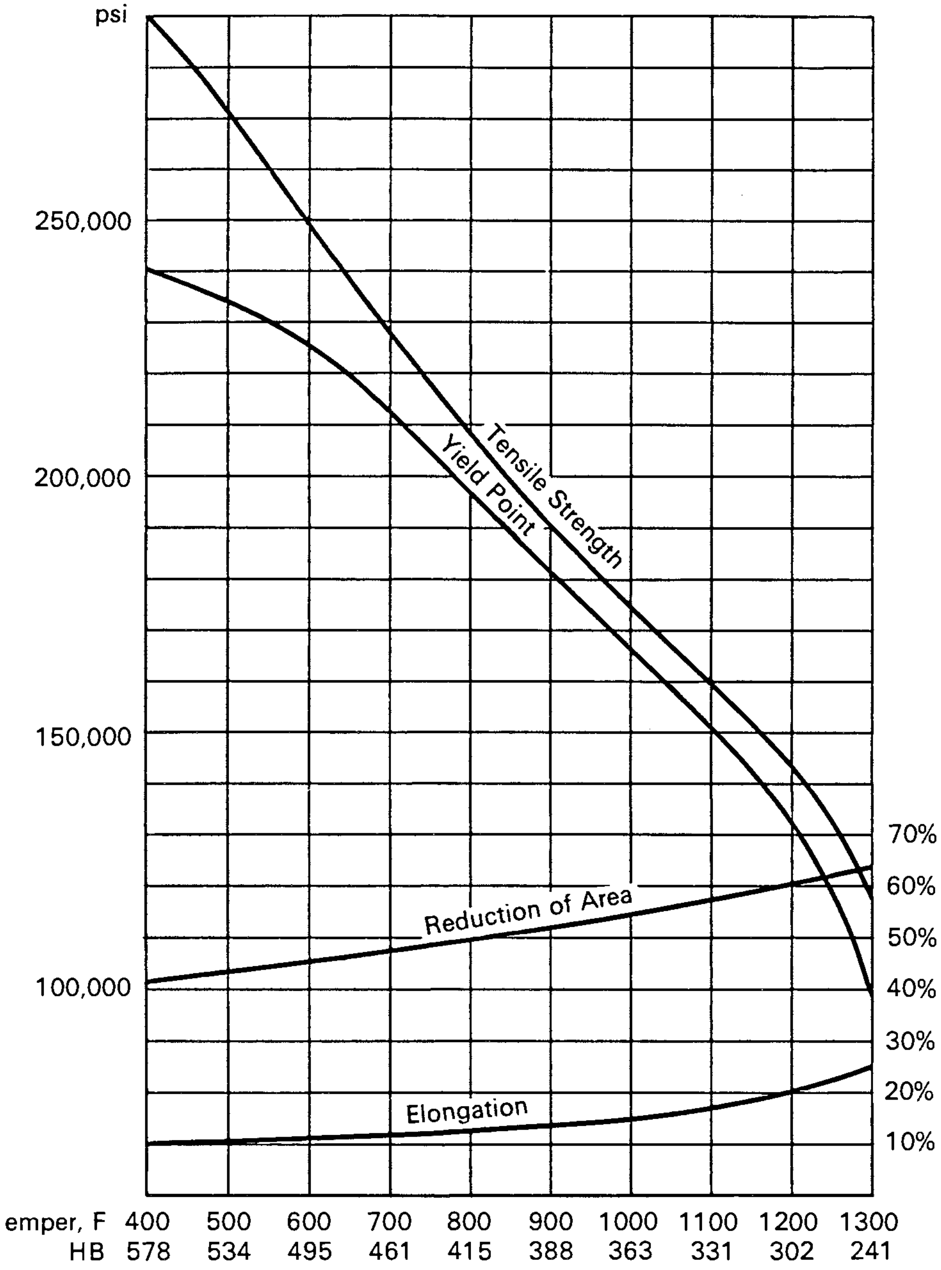
Oil-quenched 8740

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Ladle	.39	1.00	.012	.017	.25	.53	.52	.28	6-8

Critical Points, F: Ac_1 1370 Ac_3 1435 Ar_3 1265 Ar_1 1160

Treatment: Normalized at 1600 F; reheated to 1525 F; quenched in agitated oil.
.565-in. Round Treated; .505-in. Round Tested. As-quenched HB 601.



4150 Oil-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Grade	.48/.53	.75/1.00	—	—	.20/.35	—	.80/1.10	.15/.25	
Ladle	.51	.89	.018	.017	.27	.12	.87	.18	95% 7-8 5% 5

MASS EFFECT

Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1525 F, furnace-cooled 20 F per hour to 1190 F, cooled in air.)					
1	105,750	55,000	20.2	40.2	197
Normalized (Heated to 1600 F, cooled in air.)					
½	194,000	129,500	10.0	24.8	375
1	167,500	106,500	11.7	30.8	321
2	158,750	104,000	13.5	40.6	311
4	146,000	91,750	19.5	56.5	293
Oil-quenched from 1525 F, tempered at **1000** F.					
½	189,500	176,250	13.5	47.2	375
1	175,250	159,500	14.0	46.5	352
2	168,750	151,000	15.5	51.0	341
4	158,750	127,750	15.0	46.7	311
Oil-quenched from 1525 F, tempered at **1100** F.					
½	170,000	155,500	14.6	45.5	341
1	165,500	150,000	15.7	51.1	331
2	150,250	131,500	18.7	56.4	302
4	132,500	98,250	20.0	57.5	269
Oil-quenched from 1525 F, tempered at **1200** F.					
½	148,000	137,250	17.4	53.3	302
1	141,000	127,500	18.7	55.7	285
2	134,750	118,250	20.5	60.0	269
4	124,000	91,000	21.5	61.4	255

As-quenched Hardness (oil)

Size Round	Surface	½ Radius	Center
½	HRC 64	HRC 64	HRC 63
1	HRC 62	HRC 62	HRC 62
2	HRC 58	HRC 57	HRC 56
4	HRC 47	HRC 43	HRC 42

Oil-quenched 4150

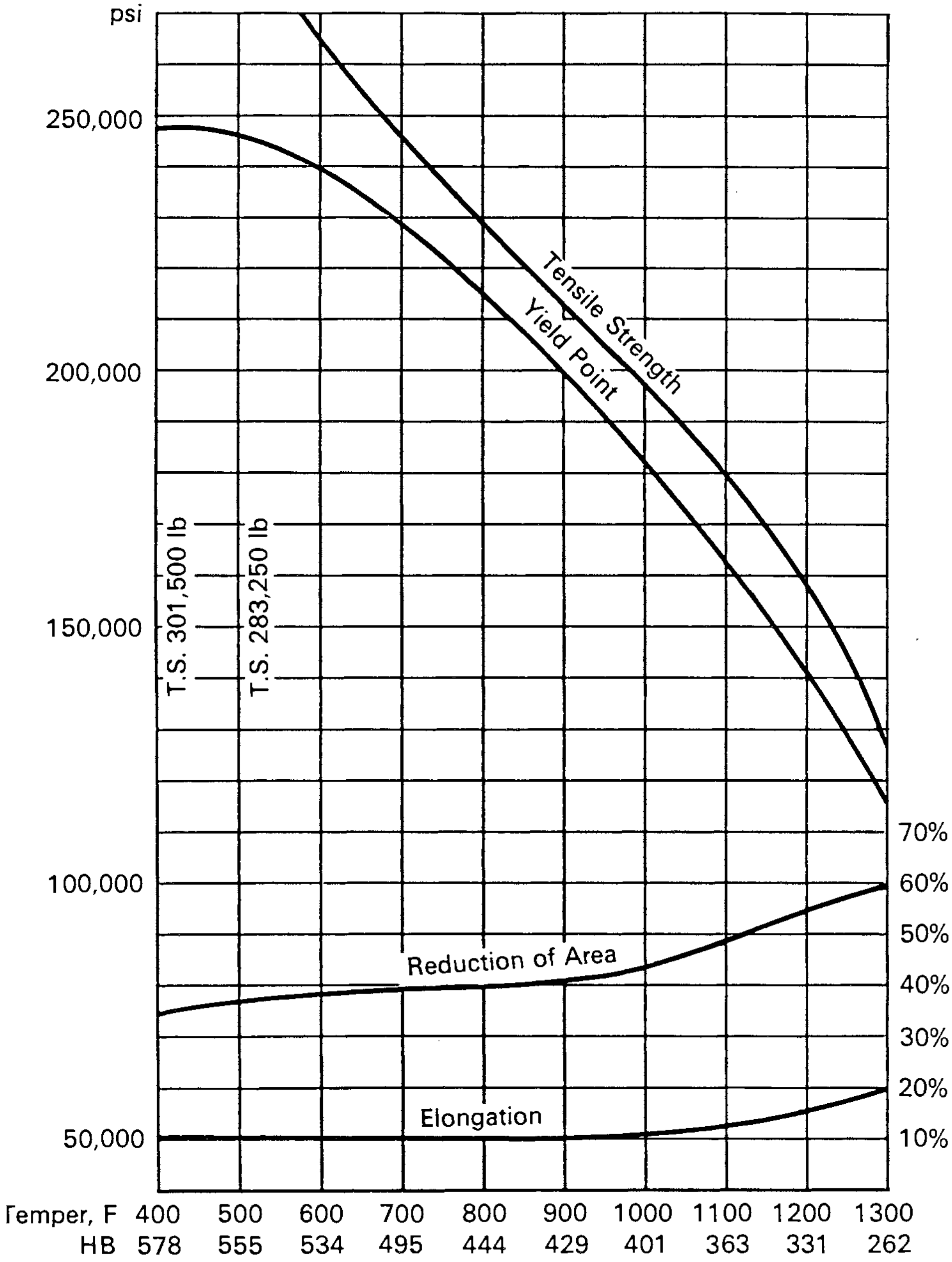
SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Ladle	.50	.76	.015	.012	.21	.20	.95	.21	90% 7-8

Critical Points, F: Ac$_1$ 1390 Ac$_3$ 1450 Ar$_3$ 1290 Ar$_1$ 1245

Treatment: Normalized at 1600 F; reheated to 1525 F; quenched in agitated oil.

.530-in. Round Treated; .505-in. Round Tested. As-quenched HB 656.



5150 Oil-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Grade	.48/.53	.70/.90	—	—	.20/.35	—	.70/.90	—	
Ladle	.49	.75	.018	.018	.25	.11	.80	.05	7-8

MASS EFFECT

Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1520 F, furnace-cooled 20 F per hour to 1190 F, cooled in air.)					
1	98,000	51,750	22.0	43.7	197
Normalized (Heated to 1600 F, cooled in air.)					
½	131,000	81,500	21.0	60.6	262
1	126,250	76,750	20.7	58.7	255
2	123,000	72,500	20.0	53.3	248
4	122,000	63,000	18.2	48.2	241
Oil-quenched from 1525 F, tempered at **1000** F.					
½	158,750	145,250	16.4	52.9	311
1	153,000	131,750	17.0	54.1	302
2	132,000	96,750	18.5	55.5	255
4	125,000	85,750	20.0	57.5	248
Oil-quenched from 1525 F, tempered at **1100** F.					
½	144,000	131,000	19.2	55.2	285
1	137,000	115,250	20.2	59.5	277
2	126,750	87,250	20.0	58.8	255
4	120,000	80,500	19.7	56.4	241
Oil-quenched from 1525 F, tempered at **1200** F.					
½	135,500	121,000	21.7	59.7	269
1	128,000	108,000	21.2	61.9	255
2	118,750	88,500	22.7	63.0	241
4	115,000	75,500	21.5	60.8	235

As-quenched Hardness (oil)

Size Round	Surface	½ Radius	Center
½	HRC 60	HRC 60	HRC 59
1	HRC 59	HRC 52	HRC 50
2	HRC 55	HRC 44	HRC 40
4	HRC 37	HRC 31	HRC 29

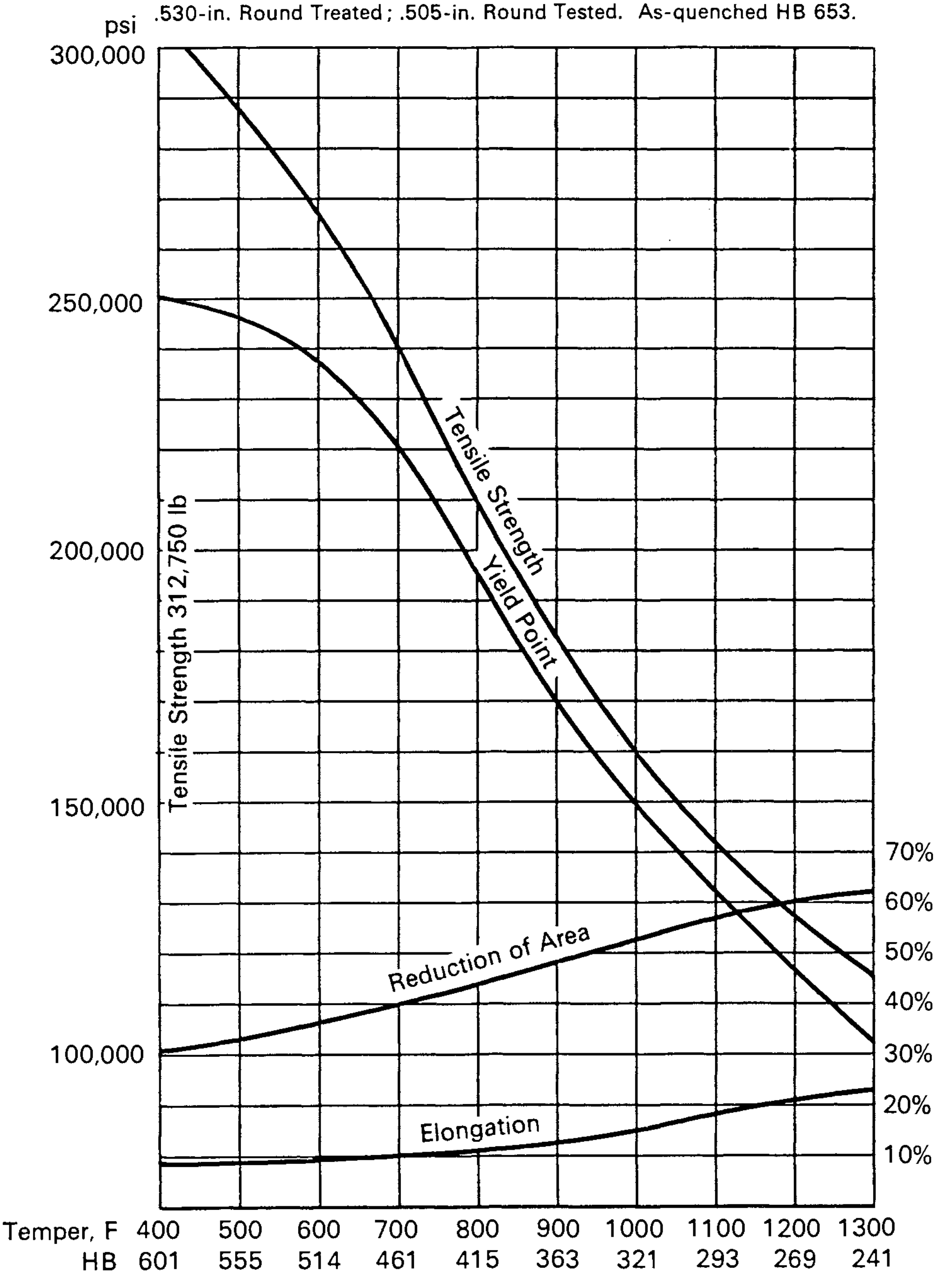
Oil-quenched **5150**

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Ladle	.49	.75	.018	.018	.25	.11	.80	.05	7-8

Critical Points, F: Ac_1 1345 Ac_3 1445 Ar_3 1310 Ar_1 1240

Treatment: Normalized at 1600 F; reheated to 1525 F; quenched in oil.
.530-in. Round Treated; .505-in. Round Tested. As-quenched HB 653.



6150 Oil-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	V	Grain Size
Grade	.48/.53	.70/.90	—	—	.20/.35	—	.80/1.10	—	.15 min	
Ladle	.51	.80	.014	.015	.35	.11	.95	.01	.18	70% 5-6 30% 2-4

MASS EFFECT

Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1500 F, furnace-cooled 20 F per hour to 1240 F, cooled in air.)					
1	96,750	59,750	23.0	48.4	197
Normalized (Heated to 1600 F, cooled in air.)					
½	141,250	93,000	20.6	63.0	285
1	136,250	89,250	21.8	61.0	269
2	129,750	75,250	20.7	56.5	262
4	128,000	67,000	18.2	49.6	255
Oil-quenched from 1550 F, tempered at **1000** F.					
½	179,500	177,750	14.6	49.4	363
1	173,500	167,750	14.5	48.2	352
2	166,000	145,250	14.5	46.7	331
4	151,500	127,000	16.0	48.7	302
Oil-quenched from 1550 F, tempered at **1100** F.					
½	160,000	158,500	16.4	52.3	321
1	158,250	150,500	16.0	53.2	311
2	148,250	131,750	17.7	55.2	293
4	130,000	108,500	19.0	55.4	262
Oil-quenched from 1550 F, tempered at **1200** F.					
½	147,000	141,500	17.8	53.9	293
1	141,250	129,500	18.7	56.3	293
2	133,750	116,500	19.5	57.4	269
4	121,500	94,500	21.0	59.7	241

As-quenched Hardness (oil)

Size Round	Surface	½ Radius	Center
½	HRC 61	HRC 60	HRC 60
1	HRC 60	HRC 58	HRC 57
2	HRC 54	HRC 47	HRC 44
4	HRC 42	HRC 36	HRC 35

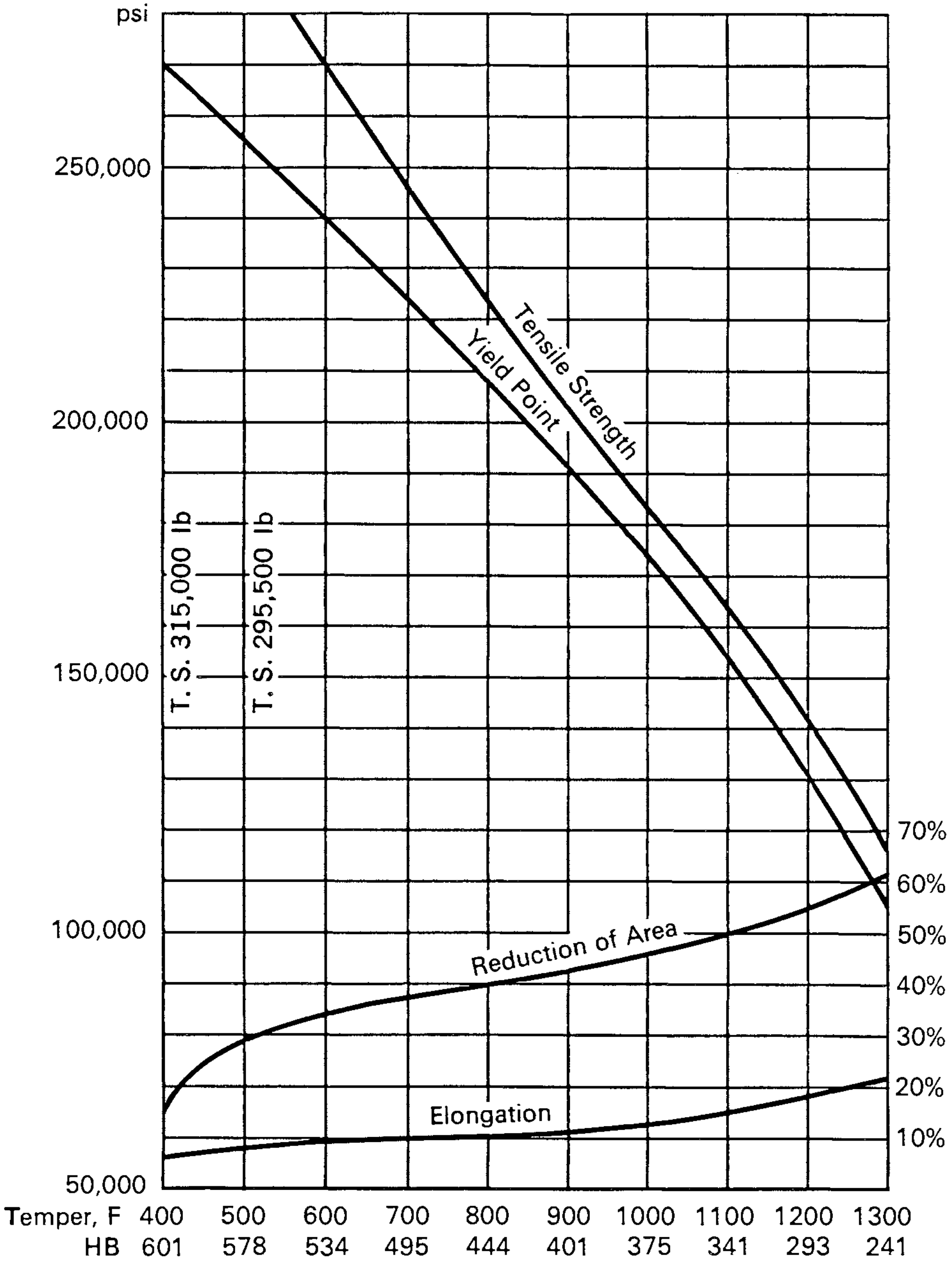
Oil-quenched 6150

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	V	Grain Size
Ladle	.49	.78	.012	.016	.29	.18	1.00	.05	.17	6-8

Critical Points, F: Ac₁ 1395 Ac₃ 1445 Ar₃ 1315 Ar₁ 1290

Treatment: Normalized at 1600 F; reheated to 1550 F; quenched in agitated oil. .565-in. Round Treated; .505-in. Round Tested. As-quenched HB 627.



8650 Oil-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Grade	.48/.53	.75/1.00	—	—	.20/.35	.40/.70	.40/.60	.15/.25	
Ladle	.48	.86	.020	.016	.31	.58	.53	.24	6-8

MASS EFFECT

Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1465 F, furnace-cooled 20 F per hour to 860 F, cooled in air.)					
1	103,750	56,000	22.5	46.4	212
Normalized (Heated to 1600 F, cooled in air.)					
½	182,000	131,250	10.3	25.3	363
1	148,500	99,750	14.0	40.4	302
2	144,250	95,750	15.5	44.8	293
4	139,250	93,250	15.0	40.5	285
Oil-quenched from 1475 F, tempered at **1000** F.					
½	177,500	168,750	14.6	48.2	363
1	172,500	159,750	14.5	49.1	352
2	165,250	148,500	17.0	55.6	331
4	143,250	113,000	18.7	54.9	285
Oil-quenched from 1475 F, tempered at **1100** F.					
½	154,500	151,000	17.8	54.9	321
1	153,500	142,750	17.7	57.3	311
2	145,000	131,000	20.0	61.0	293
4	126,250	98,500	22.0	61.2	255
Oil-quenched from 1475 F, tempered at **1200** F.					
½	148,000	137,000	18.5	54.8	293
1	141,000	132,000	19.5	59.8	285
2	135,250	121,000	21.2	62.3	277
4	121,750	94,000	22.5	59.8	241

As-quenched Hardness (oil)

Size Round	Surface	½ Radius	Center
½	HRC 61	HRC 61	HRC 61
1	HRC 58	HRC 58	HRC 57
2	HRC 53	HRC 53	HRC 52
4	HRC 42	HRC 39	HRC 38

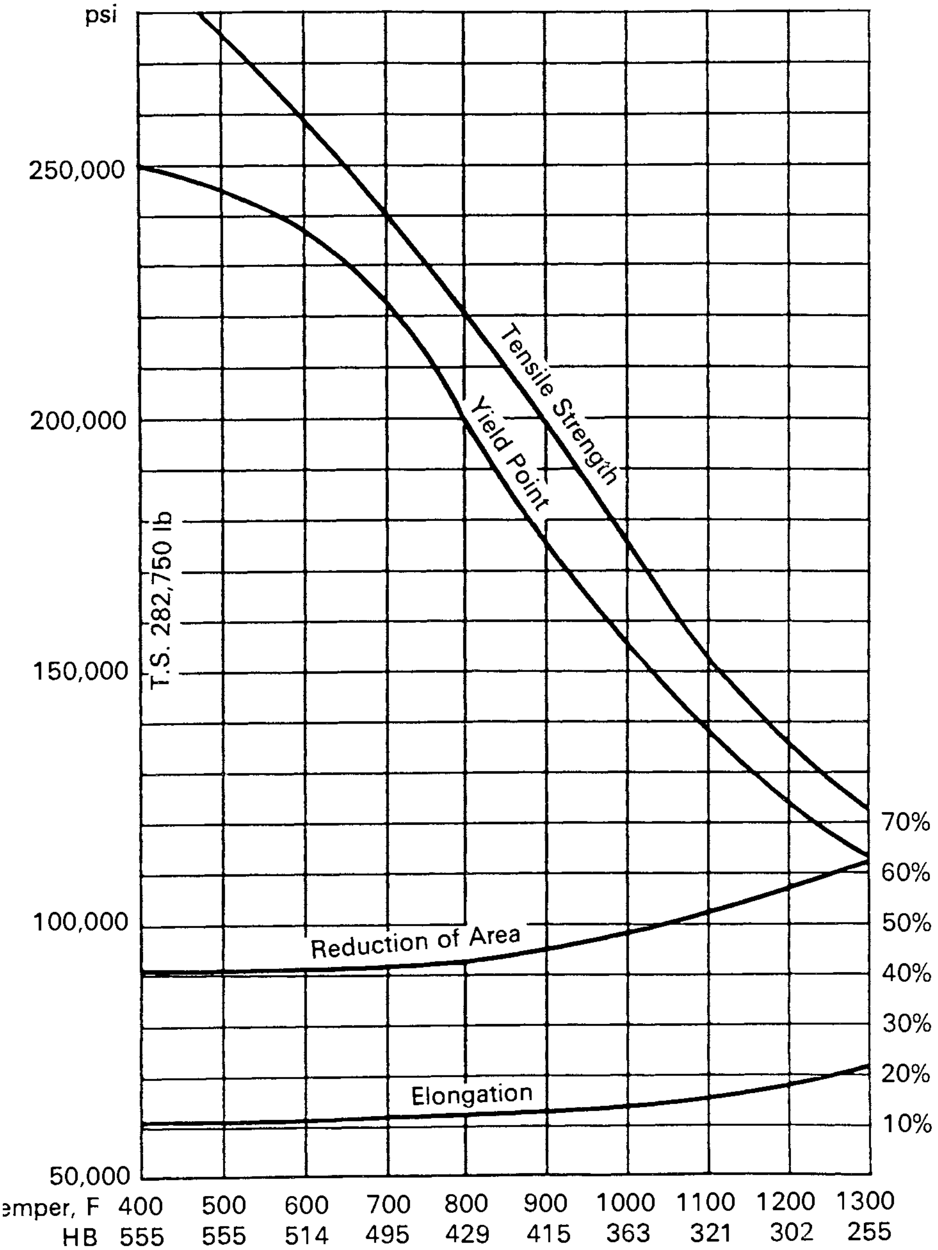
Oil-quenched 8650

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Ladle	.51	.80	.018	.019	.24	.53	.52	.25	6-8

Critical Points, F: Ac_1 1325 Ac_3 1390 Ar_3 1230 Ar_1 910

Treatment: Normalized at 1600 F; reheated to 1475 F; quenched in agitated oil.
.530-in. Round Treated; .505-in. Round Tested. As-quenched HB 638.



9255 Oil-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Grade	.51/.59	.70/.95	—	—	1.80/2.20	—	—	—	
Ladle	.52	.75	.024	.016	2.20	.07	.12	.01	6-8

MASS EFFECT

Size Round in.	Tensile Strength psi	Yield Point psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1550 F, furnace-cooled 20 F per hour to 1220 F, cooled in air.)					
1	112,750	70,500	21.7	41.1	229
Normalized (Heated to 1650 F, cooled in air.)					
½	137,500	85,250	20.0	45.5	277
1	135,250	84,000	19.7	43.4	269
2	135,000	82,000	19.5	39.5	269
4	133,000	79,500	18.7	36.1	269
Oil-quenched from 1625 F, tempered at **1000** F.					
½	170,000	146,500	14.9	40.0	331
1	164,250	133,750	16.7	38.3	321
2	154,750	102,500	18.0	45.6	302
4	149,000	94,000	19.2	43.7	293
Oil-quenched from 1625 F, tempered at **1100** F.					
½	155,000	132,250	18.1	45.3	302
1	150,000	118,000	19.2	44.8	293
2	145,500	91,750	20.0	48.7	293
4	137,000	83,000	21.0	46.0	277
Oil-quenched from 1625 F, tempered at **1200** F.					
½	144,750	123,000	21.0	50.4	285
1	138,000	106,500	21.2	48.2	277
2	137,500	87,250	21.0	50.7	277
4	132,250	81,750	21.7	48.3	262

As-quenched Hardness (oil)

Size Round	Surface	½ Radius	Center
½	HRC 61	HRC 59	HRC 58
1	HRC 57	HRC 55	HRC 48
2	HRC 52	HRC 37	HRC 33
4	HRC 35.5	HRC 31.5	HRC 27.5

Oil-quenched **9255**

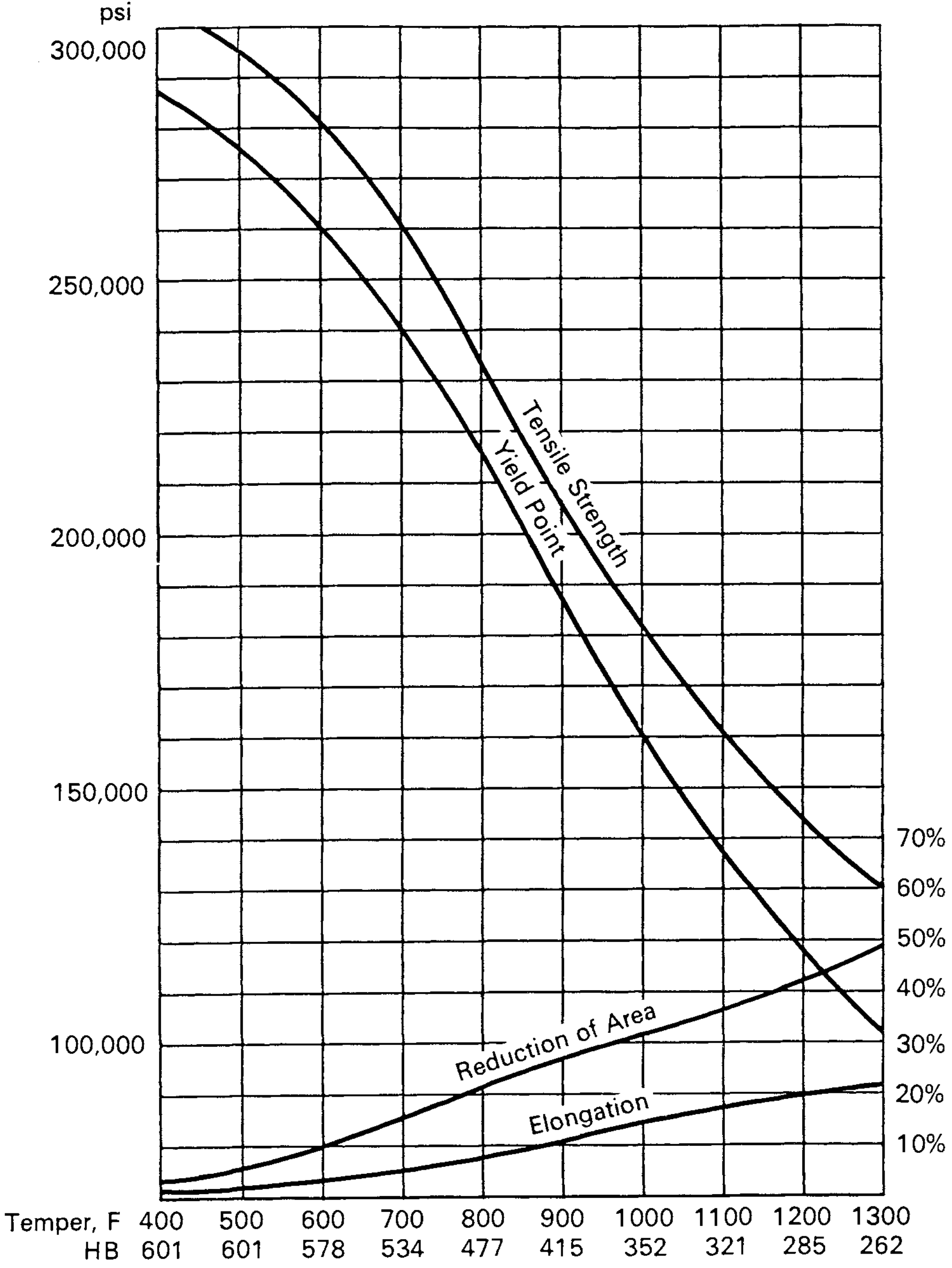
SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Ladle	.58	.78	.020	.024	2.00	.08	.08	—	6-8

Critical Points, F: Ac_1 1410 Ac_3 1480 Ar_3 1330 Ar_1 1270

Treatment: Normalized at 1650 F; reheated to 1625 F; quenched in agitated oil.

1-in. Round Treated; .505-in. Round Tested. As-quenched HB 653.



5160 Oil-quenched

SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Grade	.56/.64	.75/1.00	—	—	.20/.30	—	.70/.90	—	
Ladle	.62	.84	.010	.034	.24	.04	.74	.01	6-8

MASS EFFECT

Size Round in.	Tensile Strength psi	Yield Strength (.2% Offset) psi	Elongation % 2 in.	Reduction of Area, %	Hardness HB
Annealed (Heated to 1495 F, furnace-cooled 20 F per hour to 900 F, cooled in air.)					
1	104,750	40,000	17.2	30.6	197
Normalized (Heated to 1575 F, cooled in air.)					
½	149,000	93,750	18.2	50.7	285
1	138,750	77,000	17.5	44.8	269
2	133,750	73,500	16.0	39.0	262
4	133,500	70,250	14.8	34.2	255
Oil-quenched from 1525 F, tempered at **1000** F.					
½	170,500	155,250	14.2	45.1	341
1	165,500	145,500	14.5	45.7	341
2	154,250	102,250	17.8	51.2	293
4	140,500	101,750	18.5	52.0	285
Oil-quenched from 1525 F, tempered at **1100** F.					
½	152,250	134,000	16.6	50.6	302
1	145,250	126,000	18.0	53.6	302
2	135,250	91,750	20.0	54.6	277
4	129,250	89,250	21.2	57.0	262
Oil-quenched from 1525 F, tempered at **1200** F.					
½	133,000	115,250	19.8	55.5	269
1	128,750	110,750	20.7	55.6	262
2	113,250	84,000	21.8	57.5	248
4	120,500	77,750	22.8	60.8	241

As-quenched Hardness (oil)

Size Round	Surface	½ Radius	Center
½	HRC 63	HRC 62	HRC 62
1	HRC 62	HRC 61	HRC 60
2	HRC 53	HRC 46	HRC 43
4	HRC 40	HRC 32	HRC 29

Oil-quenched 5160

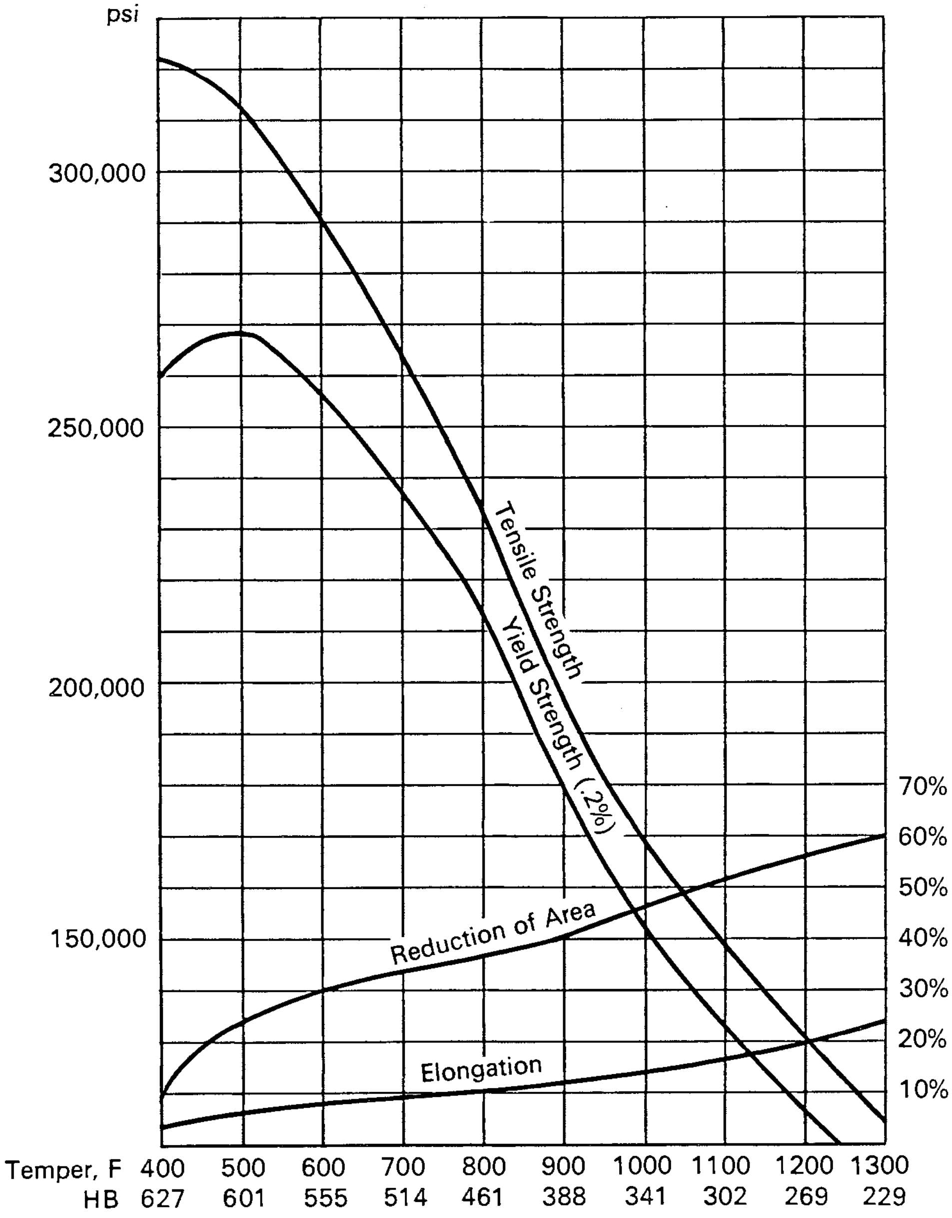
SINGLE HEAT RESULTS

	C	Mn	P	S	Si	Ni	Cr	Mo	Grain Size
Ladle	.62	.84	.010	.034	.24	.04	.74	.01	6-8

Critical Points, F: Ac_1 1380 Ac_3 1420 Ar_3 1310 Ar_1 1280

Treatment: Normalized at 1575 F; reheated to 1525 F; quenched in oil.

.530-in. Round Treated; .505-in. Round Tested. As-quenched HB 682.



MACHINABILITY OF STEEL[1]

Among the many practical methods of shaping steel, machining is perhaps the most widely employed, both alone and in conjunction with such other methods as forging, extrusion, and cold-heading.

The term, *machinability,* is most often used to describe the performance of metals in machining. By its simplest definition, it is the ability to be cut by an appropriate tool; but notwithstanding the simplicity, there appear to be no fundamental units by which this ability can be measured. Machining performance is therefore generally expressed in relative terms which compare the response of one material to that of a standard in a similar machining operation and employing similar performance criteria.

Machinability Testing

Over a period of many years, Bethlehem has conducted almost continuous machinability studies involving hundreds of tests run on multiple-spindle automatic bar machines of the types commonly used in industry. This approach has clearly shown that the machining performances of different steels can be truly compared only when the production conditions for each steel satisfy two basic similarity requirements:

1) The *level of product quality* with respect to surface finish and dimensions must be *similar* among the steels being evaluated;

2) The *duration of average tool life* must also be *similar* to that of the other steels being evaluated. Six to eight hours of actual running time is the preferable duration.

Under these conditions, machinability can be rated by comparing either the maximum production rates achieved with each steel, or the cutting speeds used to attain these rates. Historically, the cutting-speed method of rating has been more commonly employed; yet, this method does not include the equally important effect of tool feed rate on production. As a consequence, it can overlook the contributions of some elements, notably nitrogen and phosphorus, which augment production by permitting the use of higher feed rates. This

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[1] A more detailed discussion of this subject is contained in the Bethlehem Steel booklet, "Machinability of Steel," available on request.

problem is avoided when machinability comparisons are based on maximum production rates consistent with the basic similarity requirements, inasmuch as this method automatically considers both cutting speed and tool feed rate.

Free-cutting steels, comprising the 1200 and 1100 series, find their greatest application in the manufacture of parts requiring extensive machining into shapes of varying complexity on automatic bar machines. Within the composition ranges of the 1200 series, the elements which most affect machining performance are sulfur, phosphorus, nitrogen, lead, and selenium; in the 1100 series, sulfur and carbon are major variables, with manganese exerting a secondary but significant influence.

Sulfur

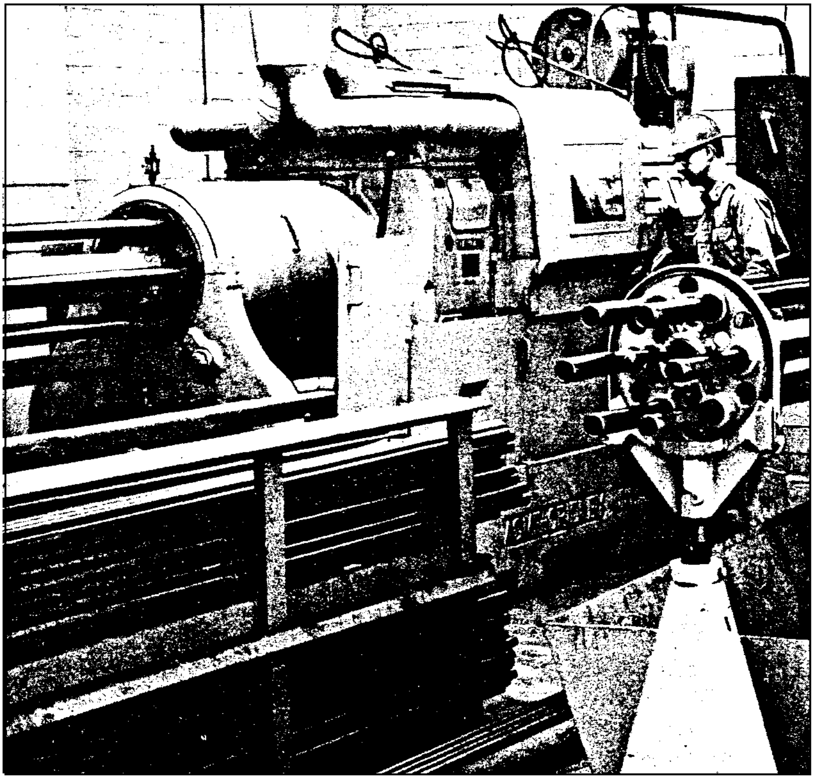
Increasing sulfur improves machining performance at all carbon levels in both alloy and plain carbon grades. Small increases in sulfur up to .05/.06% markedly improve the machinability of a nonresulfurized base. For increases above this level, machinability improves at a lower rate. In the case of the 1200 and 1100 series steels, the rate of improvement caused by increasing sulfur is somewhat higher in steels with the lower carbon contents.

Phosphorus and Nitrogen

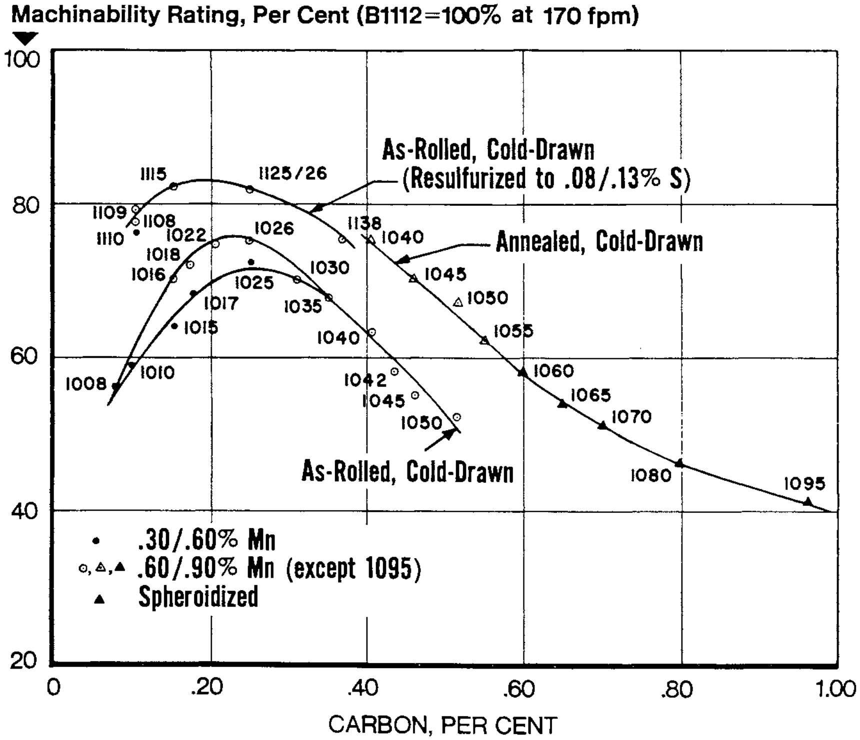
One of the distinguishing features of the very free-cutting grades is their ability to be machined at higher production rates while maintaining the desired finish on the product. But even in these grades, the quality of the machined surface varies with composition. Phosphorus and nitrogen can be added to free-machining grades of steel to enhance machining performance. Both increase hardness and tensile strength, particularly in the cold-drawn condition. Actual tests as described above have established that the machinability of the 1200 series steels, as measured by relative production rates for equal part quality and tool life, is markedly improved by increasing phosphorus content to within the range of .07/.12%. Further improvement is realized when nitrogen content is increased to a level of about .010%. The ability to use higher speeds and feeds with increasing phosphorus and nitrogen contents (within the stated limits) is related to the decreased size and more controllable behavior of the built-up-edge on the cutting tools. This control of the built-up-edge results in an improvement of surface finish.

Lead Additions

The machining performance of steel is considerably improved by the addition of lead (see page 23) in the usual specification range of .15/.35%. Lead lubricates the cutting edge of the tool and permits an increase in cutting speed and feed and an improvement in surface finish quality without an attendant decrease in tool life. As a result, lead additions can be expected to improve production rates —in screw-machine operations in particular—by some 20 to 40 per cent.



EFFECT OF CARBON AND MANGANESE ON MACHINABILITY



Carbon and Manganese

Plain carbon steels with very low carbon contents tend to be tough and gummy in machining operations. Increases in carbon and manganese increase the strength and hardness of steel and result in improved surface finish and chip character. For carbon contents up to .20/.25%, this results in improved machinability for both hot-rolled and cold-drawn steels. As the carbon is increased above this level, however, hardness increases to the point where tool life is adversely affected, leading to a decrease in the machinability rating.

The graph above illustrates this effect by plotting machinability ratings for a series of grades with increasing carbon contents at two manganese levels. Note also how the machinability ratings of 1040, 1045, and 1050 were significantly improved by annealing.

Most carbon steels below .35% carbon are machined in the as-rolled or as-rolled, cold-drawn condition. Higher carbon grades are frequently annealed to improve machinability, particularly when they are to be cold-drawn prior to machining.

Alloy Steels

The commonly used alloying elements increase the as-rolled strength and hardness in comparison with a plain carbon steel of equivalent carbon content. The intensity of this effect on hardness differs for the various elements; but in all cases, hardness increases with increasing percentages of the element. In the as-rolled condition, the leaner alloys machine more like their plain carbon counterparts than do the more highly alloyed types. For example, 4023 behaves about the same as 1022 or 1026 under the cutting tool, whereas the more highly alloyed 8620 has about the same machinability as the higher-carbon 1040. Accordingly, it is common practice to thermally treat alloy bars prior to cold-drawing and machining.

Normalizing is sometimes used for the lower carbon grades, but annealing is more frequently used because it results in lower hardness. Optimum microstructure varies with the per cent of pearlite typical of the composition involved, and to a degree, with the parameters of the machining operation itself. In general, a lamellar annealed structure is preferred in the low and medium carbon ranges, or up to the carbon level of about .40/.50% which corresponds to approximately 90% pearlite, depending on both carbon and alloy content. Above that carbon level, a spheroidized structure is usually preferred because it improves tool life, although at some sacrifice of surface finish. Where machined finish is of paramount importance in these higher carbon grades, it is sometimes desirable to use a lamellar structure and accept a somewhat shorter tool life. For certain machining operations, a compromise structure consisting of lamellar pearlite with some spheroidized carbides may be desirable. Since alloying elements increase the percentage of pearlite in the microstructure of a given carbon level over that typical of plain carbon steels, determination of the optimum microstructure must take into consideration the carbon level and the alloy content.

NONDESTRUCTIVE EXAMINATION

Nondestructive tests are effective for the inspection of the surface or internal quality of steel products, supplementing or replacing visual methods of inspection. In general, for bar and billet testing, ultrasonic methods are used for internal inspection, and magnetic particle and eddy current methods for the inspection of surface.

Ultrasonic Testing

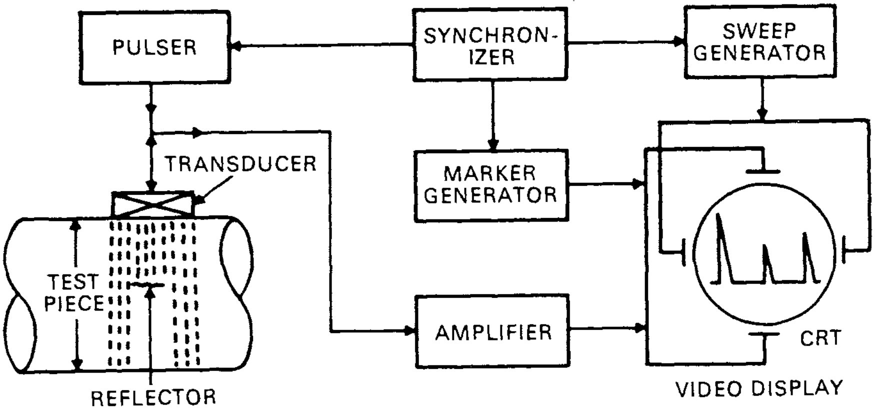
Ultrasonic testing is based upon ultra-sound, or sound which is pitched too high (above 20,000 cps) for the human ear to detect. Pulses of this sound energy are sent into a section of a material, such as a steel bar, and are reflected from the boundaries of the section as well as from internal discontinuities. The reflected pulses are received and portrayed on a cathode ray tube, and the image interpreted with respect to the strength of the returning pulse and the time lapse between its generation and reception.

With proper calibration of the test equipment, the location, size, shape and orientation of discontinuities within the steel can be estimated. Two basic calibration methods are used to provide standards for the test against which the received signals can be compared. In one, the standard is provided by signals from a reference reflector, such as a notch or hole in a test block. In the second, the standard is derived from the signal reflected from the far side of the steel section. Some discontinuities are not good reflectors, but can be detected by their shadowing effect which results in a partial or total loss of this back reflection signal.

PULSE ECHO ULTRASONIC SYSTEM. Ultrasonic test systems are based upon the behavior of piezoelectric material which, when excited electrically, is caused to vibrate mechanically with ultrasonic energy. Conversely, an electrical voltage is generated when this material, or crystal, is vibrated. The holder containing the crystal and its associated electrical components is called a transducer, or search unit, and is one of the major elements of the test system. Another essential part of the overall unit is the electronic package which functions as the control center. This instrument generates a brief power output, or pulse, that excites the crystal. It also receives and amplifies the voltage generated as a result of reflected sound vibrating the crystal.

Both the exciting pulse and any echoes are displayed on a cathode ray tube. Since sound travels at a constant speed in a specific material under constant conditions, distance within a material is a function of time. Thus, distance (time) is represented on the horizontal axis of the tube, and signal amplitudes (exciting pulse and echoes) on the vertical axis. The magnitude of the echo will depend upon several external factors including the operating frequency, which is usually between 1 and 10 MHz (1MHz=1 million cycles per second), the amount of beam dispersion, the surface condition and internal metallurgical structure of the steel, the amount of hot or cold working of the steel, temperatures, and variables associated with transducer and instrument characteristics. With these variables relatively constant, the reflected signal amplitude will be dependent upon the following material characteristics:

- the area of the reflector, which may be a discontinuity or boundary, its shape and orientation to the ultrasonic path, plus its roughness;

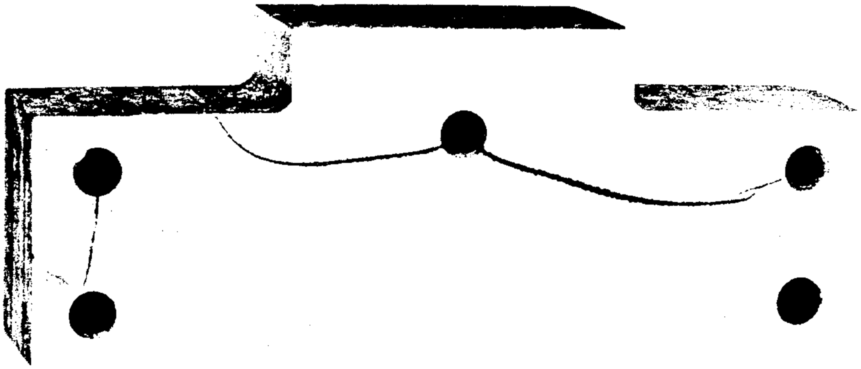


Pulse-echo ultrasonic system.

- the distance of the reflector from the search unit;
- the acoustic impedance of the reflector.

It should be noted that the ultrasonic vibrations are normally directed into the test piece through a suitable coupling medium such as water, glycerin, or oil to prevent the high energy losses that would occur in air transmission.

Electromagnetic Test Methods



Magnetic particle indications of quench cracks.

In a ferromagnetic material that has been magnetized, the normal lines of magnetic force are distrupted by discontinuities within the otherwise homogenous microstructure of the material, thus causing localized force gradients. Fine magnetic particles are attracted to these field gradients; and so provide a measure of the geometry and extent of the discontinuity.

Many variations of magnetic particle testing are employed in practice depending upon the type of anticipated discontinuity and its location. Results are affected by the type of current used (a.c. or d.c.) and its magnitude and duration, the direction of magnetization, and the wet or dry condition of the indicating particles.

For bars and billets, circular magnetization is most frequently used to facilitate the detection of longitudinal discontinuities such as laps or seams. This type of field is created when the current is passed longitudinally through the material itself. Discontinuities at right angles to the bar length would need to be detected by longitudinal magnetization produced by passing current through a coil encircling the material being tested.

This testing method is useful in detecting primary discontinuities, such as non-metallic inclusions and porosity, as well as fabricating discontinuities, such as laps, bursts, cracks and seams.

EDDY CURRENT TESTING. Eddy current testing is a non-contact means of testing bars, rods or tubes for surface flaws at production speeds. It is based upon the interaction between alternating current flow in metallic materials and the reactive magnetic fields thus produced, and on the detection of variations in these fields as caused by structural discontinuities in the material under test.

There are two basic variations of the eddy current test. In one, the material being tested is passed lengthwise through an electrical coil assembly consisting of an inducing coil positioned between two sensing coils that respectively produce an eddy current flow in the steel and detect variations in the induced reactive fields. This test mode provides detection capability oriented essentially for discontinuities at right angles to the long axis of the bar. In the other method, a small pair of coils, an inductor and a sensor, is rotated circumferentially about the bar. With the fields thus generated, discontinuities which are oriented parallel to the bar axis can be detected.

Certain variables, such as test signal frequency, probe spacing between the coils and the work, and the surface condition of the bar can have an important influence on test results. Variations attributable to differing magnetic characteristics of the steel itself can be minimized by magnetic field saturation.

USEFUL DATA

Bethlehem produces tool steels in all popular sections, sizes, and types.

TOOL STEELS

Identification and Type Classification

The percentages of the elements shown for each type are only for identification purposes and are not to be considered as the means of the composition ranges of the elements.

AISI Type	Bethlehem Grade Name	Identifying Elements, per cent						
		C	Mn	Si	W	Mo	Cr	Other
WATER-HARDENING TOOL STEELS								
W1	X, XCL, XX	.60/1.40 *	—	—	—	—	—	—
W2	Best, Superior	.60/1.40 *	—	—	—	—	—	.25V
W5	—	1.10	—	—	—	—	.50	—
*Other carbon contents may be available.								
COLD-WORK TOOL STEELS								
Oil-Hardening Types								
O1	BTR	.90	1.00	—	.50	—	.50	—
O2	—	.90	1.60	—	—	—	—	—
O6	O-6	1.45	.80	1.00	—	.25	—	—
O7	67 Tap	1.20	—	—	1.75	—	.75	—
Medium Alloy Air-Hardening Types								
A2	A-H5	1.00	—	—	—	1.00	5.00	—
A3	—	1.25	—	—	—	1.00	5.00	1.00V
A4	Air-4	1.00	2.00	—	—	1.00	1.00	—
A6	—	.70	2.00	—	—	1.25	1.00	—
A7	A-7	2.25	—	—	1.00†	1.00	5.25	4.75V
A8	Cromo-W55	.55	—	—	1.25	1.25	5.00	—
A9	—	.50	—	—	—	1.40	5.00	1.00V 1.50Ni
A10	—	1.35	1.80	1.25	—	1.50	—	1.80Ni
—	A-HT	1.00	—	—	1.05	1.10	3.00	.25V 1.00Ti
†Optional								
High Carbon—High Chromium Types								
D2	Lehigh H	1.50	—	—	—	1.00	12.00	1.00V
D3	Lehigh S	2.25	—	—	—	—	12.00	—
D4	—	2.25	—	—	—	1.00	12.00	—
D5	—	1.50	—	—	—	1.00	12.00	3.00Co
D7	—	2.35	—	—	—	1.00	12.00	4.00V
SHOCK-RESISTING TOOL STEELS								
S1	67 Chisel	.50	—	—	2.50	—	1.50	—
S2	Imperial	.50	—	1.00	—	.50	—	—
S5	Omega	.55	.80	2.00	—	.40	—	—
S6	—	.45	1.40	2.25	—	.40	1.50	—
S7	Bearcat	.50	—	—	—	1.40	3.25	—

AISI Type	Bethlehem Grade Name	Identifying Elements, per cent							
		C	Mn	Si	W	Mo	Cr	V	Co
		HOT-WORK TOOL STEELS							
		Chromium Types							
H10	—	.40	—	—	—	2.50	3.25	.40	—
H11	Cromo-V	.35	—	—	—	1.50	5.00	.40	—
H12	Cromo-W	.35	—	—	1.50	1.50	5.00	.40	—
H13	Cromo-High V	.35	—	—	—	1.50	5.00	1.00	—
H14	—	.40	—	—	5.00	—	5.00	—	—
H19	—	.40	—	—	4.25	—	4.25	2.00	4.25
—	Cromo-N	.26	.95	1.00	.90	1.00	11.00	.50	.10N 1.00Ni
		Tungsten Types							
H21	57 HW	.35	—	—	9.00	—	3.50	—	—
H22	—	.35	—	—	11.00	—	2.00	—	—
H23	—	.30	—	—	12.00	—	12.00	—	—
H24	57 Special	.45	—	—	15.00	—	3.00	—	—
H25	—	.25	—	—	15.00	—	4.00	—	—
H26	Special HS-55	.50	—	—	18.00	—	4.00	1.00	—
		Molybdenum Types							
H43	HW8	.55	—	—	—	8.00	4.00	2.00	—
		HIGH-SPEED TOOL STEELS							
		Tungsten Types							
T1	T-1	.75*	—	—	18.00	—	4.00	1.00	—
T2	—	.80	—	—	18.00	—	4.00	2.00	—
T4	—	.75	—	—	18.00	—	4.00	1.00	5.00
T5	—	.80	—	—	18.00	—	4.00	2.00	8.00
T6	—	.80	—	—	20.00	—	4.50	1.50	12.00
T8	—	.75	—	—	14.00	—	4.00	2.00	5.00
T15	—	1.50	—	—	12.00	—	4.00	5.00	5.00
		Molybdenum Types							
M1	M-1	.85*	—	—	1.50	8.50	4.00	1.00	—
M2	M-2	.85/1.00*	—	—	6.00	5.00	4.00	2.00	—
M3	(Class 1)	1.05	—	—	6.00	5.00	4.00	2.40	—
M3	(Class 2)	1.20	—	—	6.00	5.00	4.00	3.00	—
M4	M-4	1.30	—	—	5.50	4.50	4.00	4.00	—
M6	—	.80	—	—	4.00	5.00	4.00	1.50	12.00
M7	M-7	1.00	—	—	1.75	8.75	4.00	2.00	—
M10	M-10	.85/1.00*	—	—	—	8.00	4.00	2.00	—
M30	—	.80	—	—	2.00	8.00	4.00	1.25	5.00
M33	—	.90	—	—	1.50	9.50	4.00	1.15	8.00
M34	—	.90	—	—	2.00	8.00	4.00	2.00	8.00
M36	—	.80	—	—	6.00	5.00	4.00	2.00	8.00
M41	—	1.10	—	—	6.75	3.75	4.25	2.00	5.00
M42	—	1.10	—	—	1.50	9.50	3.75	1.15	8.00
M43	—	1.20	—	—	2.75	8.00	3.75	1.60	8.25
M44	—	1.15	—	—	5.25	6.25	4.25	2.00	12.00
M46	—	1.25	—	—	2.00	8.25	4.00	3.20	8.25
M47	—	1.10	—	—	1.50	9.50	3.75	1.25	5.00

*Other carbon contents may be available.

TOOL STEELS (Cont'd)

AISI Type	Bethlehem Grade Name	Identifying Elements, per cent							
		C	Mn	Si	W	Mo	Cr	Ni	Other
		PLASTIC-MOLD STEELS							
P2	Duramold B	.07	—	—	—	.20	2.00	.50	—
P3	Duramold Ni-Cr	.10	—	—	—	—	.60	1.25	—
P4	Duramold A	.07	—	—	—	.75	5.00	—	—
P5	—	.10	—	—	—	—	2.25	—	—
P6	Duramold N	.10	—	—	—	—	1.50	3.50	—
P20	P-20	.35	—	—	—	.40	1.70	—	—
P21	—	.20	—	—	—	—	—	4.00	1.20Al
—	Lustre-Die	.50	1.00	.30	—	.25	1.10	—	—
		SPECIAL-PURPOSE TOOL STEELS **Low Alloy Types**							
L2	Tough M	.50/ 1.10 *	—	—	—	—	1.00	—	.20V
L6	Bethalloy	.70	—	—	—	.25†	.75	1.50	—

*Other carbon contents may be available. †Optional.

OTHER SPECIAL-PURPOSE TOOL STEELS

Bethlehem Name Grade	Identifying Elements, per cent						
	C	Mn	Si	W	Mo	Cr	Cu
Brake Die	.51	1.00	—	—	.20	.95	—
Non-Tempering	.35	.70	.25	.50	.35	.85	.30
Lehigh L	1.00	—	—	—	1.00	12.00	—
71 Alloy	.55	.80	2.00	—	—	—	—
Bearing Standard	1.00	—	—	—	—	1.25	—

NITRIDING STEELS

Type	Identifying Elements, per cent						
	C	Mn	Si	Mo	Cr	Ni	Al	S
Nitriding 135 (Type G)	.30/ .40	.40/ .70	.20/ .40	.15/ .25	.90/ 1.40	—	.85/ 1.20	—
Nitriding 135 Mod. (Aircraft Spec.)	.38/ .45	.40/ .70	.20/ .40	.30/ .45	1.40/ 1.80	—	.85/ 1.20	—
Nitriding N (3.5% Ni)	.20/ .27	.40/ .70	.20/ .40	.20/ .30	1.00/ 1.30	3.25/ 3.75	.85/ 1.20	—
Nitriding EZ (Type G with S)	.30/ .40	.50/ 1.10	.20/ .40	.15/ .25	1.00/ 1.50	—	.85/ 1.20	.08/ .13

HARDNESS CONVERSION TABLE

Brinell		Rockwell		Tensile Strength, 1000 psi Approx.	Brinell		Rockwell		Tensile Strength, 1000 psi Approx.
Indent. Diam., mm	No.*	B	C		Indent. Diam., mm	No.*	B	C	
2.25	745		65.3		3.75	262	(103.0)	26.6	127
2.30	712		—		3.80	255	(102.0)	25.4	123
2.35	682		61.7		3.85	248	(101.0)	24.2	120
2.40	653		60.0		3.90	241	100.0	22.8	116
2.45	627		58.7		3.95	235	99.0	21.7	114
2.50	601		57.3		4.00	229	98.2	20.5	111
2.55	578		56.0		4.05	223	97.3	(18.8)	—
2.60	555		54.7	298	4.10	217	96.4	(17.5)	105
2.65	534		53.5	288	4.15	212	95.5	(16.0)	102
2.70	514		52.1	274	4.20	207	94.6	(15.2)	100
2.75	495		51.6	269	4.25	201	93.8	(13.8)	98
2.80	477		50.3	258	4.30	197	92.8	(12.7)	95
2.85	461		48.8	244	4.35	192	91.9	(11.5)	93
2.90	444		47.2	231	4.40	187	90.7	(10.0)	90
2.95	429		45.7	219	4.45	183	90.0	(9.0)	89
3.00	415		44.5	212	4.50	179	89.0	(8.0)	87
3.05	401		43.1	202	4.55	174	87.8	(6.4)	85
3.10	388		41.8	193	4.60	170	86.8	(5.4)	83
3.15	375		40.4	184	4.65	167	86.0	(4.4)	81
3.20	363		39.1	177	4.70	163	85.0	(3.3)	79
3.25	352	(110.0)	37.9	171	4.80	156	82.9	(0.9)	76
3.30	341	(109.0)	36.6	164	4.90	149	80.8		73
3.35	331	(108.5)	35.5	159	5.00	143	78.7		71
3.40	321	(108.0)	34.3	154	5.10	137	76.4		67
3.45	311	(107.5)	33.1	149	5.20	131	74.0		65
3.50	302	(107.0)	32.1	146	5.30	126	72.0		63
3.55	293	(106.0)	30.9	141	5.40	121	69.8		60
3.60	285	(105.5)	29.9	138	5.50	116	67.6		58
3.65	277	(104.5)	28.8	134	5.60	111	65.7		56
3.70	269	(104.0)	27.6	130					

NOTE: This is a condensation of Table 2, Report J417b, SAE 1971 Handbook. Values in ( ) are beyond normal range, and are presented for information only.

*Values above 500 are for tungsten carbide ball; below 500 for standard ball.

TEMPERATURE CONVERSION TABLE

—459.4 to 0			0 to 100						100 to 1000					
C	C F	F	C	C F	F	C	C F	F	C	C F	F	C	C F	F
—273	*—459.4*		—17.8	*0*	32	10.0	*50*	122.0	38	*100*	212	260	*500*	932
—268	*—450*		—17.2	*1*	33.8	10.6	*51*	123.8	43	*110*	230	266	*510*	950
—262	*—440*		—16.7	*2*	35.6	11.1	*52*	125.6	49	*120*	248	271	*520*	968
—257	*—430*		—16.1	*3*	37.4	11.7	*53*	127.4	54	*130*	266	277	*530*	986
—251	*—420*		—15.6	*4*	39.2	12.2	*54*	129.2	60	*140*	284	282	*540*	1004
—246	*—410*		—15.0	*5*	41.0	12.8	*55*	131.0	66	*150*	302	288	*550*	1022
—240	*—400*		—14.4	*6*	42.8	13.3	*56*	132.8	71	*160*	320	293	*560*	1040
—234	*—390*		—13.9	*7*	44.6	13.9	*57*	134.6	77	*170*	338	299	*570*	1058
—229	*—380*		—13.3	*8*	46.4	14.4	*58*	136.4	82	*180*	356	304	*580*	1076
—223	*—370*		—12.8	*9*	48.2	15.0	*59*	138.2	88	*190*	374	310	*590*	1094
—218	*—360*		—12.2	*10*	50.0	15.6	*60*	140.0	93	*200*	392	316	*600*	1112
—212	*—350*		—11.7	*11*	51.8	16.1	*61*	141.8	99	*210*	410	321	*610*	1130
—207	*—340*		—11.1	*12*	53.6	16.7	*62*	143.6	100	*212*	413.6	327	*620*	1148
—201	*—330*		—10.6	*13*	55.4	17.2	*63*	145.4	104	*220*	428	332	*630*	1166
—196	*—320*		—10.0	*14*	57.2	17.8	*64*	147.2	110	*230*	446	338	*640*	1184
—190	*—310*		— 9.4	*15*	59.0	18.3	*65*	149.0	116	*240*	464	343	*650*	1202
—184	*—300*		— 8.9	*16*	60.8	18.9	*66*	150.8	121	*250*	482	349	*660*	1220
—179	*—290*		— 8.3	*17*	62.6	19.4	*67*	152.6	127	*260*	500	354	*670*	1238
—173	*—280*		— 7.8	*18*	64.4	20.0	*68*	154.4	132	*270*	518	360	*680*	1256
—169	*—273*	—459.4	— 7.2	*19*	66.2	20.6	*69*	156.2	138	*280*	536	366	*690*	1274
—168	*—270*	—454	— 6.7	*20*	68.0	21.1	*70*	158.0	143	*290*	554	371	*700*	1292
—162	*—260*	—436	— 6.1	*21*	69.8	21.7	*71*	159.8	149	*300*	572	377	*710*	1310
—157	*—250*	—418	— 5.6	*22*	71.6	22.2	*72*	161.6	154	*310*	590	382	*720*	1328
—151	*—240*	—400	— 5.0	*23*	73.4	22.8	*73*	163.4	160	*320*	608	388	*730*	1346
—146	*—230*	—382	— 4.4	*24*	75.2	23.3	*74*	165.2	166	*330*	626	393	*740*	1364
—140	*—220*	—364	— 3.9	*25*	77.0	23.9	*75*	167.0	171	*340*	644	399	*750*	1382
—134	*—210*	—346	— 3.3	*26*	78.8	24.4	*76*	168.8	177	*350*	662	404	*760*	1400
—129	*—200*	—328	— 2.8	*27*	80.6	25.0	*77*	170.6	182	*360*	680	410	*770*	1418
—123	*—190*	—310	— 2.2	*28*	82.4	25.6	*78*	172.4	188	*370*	698	416	*780*	1436
—118	*—180*	—292	— 1.7	*29*	84.2	26.1	*79*	174.2	193	*380*	716	421	*790*	1454
—112	*—170*	—274	— 1.1	*30*	86.0	26.7	*80*	176.0	199	*390*	734	427	*800*	1472
—107	*—160*	—256	— .6	*31*	87.8	27.2	*81*	177.8	204	*400*	752	432	*810*	1490
—101	*—150*	—238	0	*32*	89.6	27.8	*82*	179.6	210	*410*	770	438	*820*	1508
— 96	*—140*	—220	.6	*33*	91.4	28.3	*83*	181.4	216	*420*	788	443	*830*	1526
— 90	*—130*	—202	1.1	*34*	93.2	28.9	*84*	183.2	221	*430*	806	449	*840*	1544
— 84	*—120*	—184	1.7	*35*	95.0	29.4	*85*	185.0	227	*440*	824	454	*850*	1562
— 79	*—110*	—166	2.2	*36*	96.8	30.0	*86*	186.8	232	*450*	842	460	*860*	1580
— 73	*—100*	—148	2.8	*37*	98.6	30.6	*87*	188.6	238	*460*	860	466	*870*	1598
— 68	*— 90*	—130	3.3	*38*	100.4	31.1	*88*	190.4	243	*470*	878	471	*880*	1616
— 62	*— 80*	—112	3.9	*39*	102.2	31.7	*89*	192.2	249	*480*	896	477	*890*	1634
— 57	*— 70*	— 94	4.4	*40*	104.0	32.2	*90*	194.0	254	*490*	914	482	*900*	1652
— 51	*— 60*	— 76	5.0	*41*	105.8	32.8	*91*	195.8				488	*910*	1670
— 46	*— 50*	— 58	5.6	*42*	107.6	33.3	*92*	197.6				493	*920*	1688
— 40	*— 40*	— 40	6.1	*43*	109.4	33.9	*93*	199.4				499	*930*	1706
— 34	*— 30*	— 22	6.7	*44*	111.2	34.4	*94*	201.2				504	*940*	1724
— 29	*— 20*	— 4	7.2	*45*	113.0	35.0	*95*	203.0				510	*950*	1742
— 23	*— 10*	14	7.8	*46*	114.8	35.6	*96*	204.8				516	*960*	1760
— 17.8	*0*	32	8.3	*47*	116.6	36.1	*97*	206.6				521	*970*	1778
			8.9	*48*	118.4	36.7	*98*	208.4				527	*980*	1796
			9.4	*49*	120.2	37.2	*99*	210.2				532	*990*	1814
						37.8	*100*	212.0				538	*1000*	1832

Look up reading in middle column. If in degrees Centigrade, read Fahrenheit equivalent ir right hand column ; if in Fahrenheit degrees, read Centigrade equivalent in left hand column.

1000 to 2000						2000 to 3000					
C	C F	F	C	C F	F	C	C F	F	C	C F	F
538	*1000*	1832	816	*1500*	2732	1093	*2000*	3632	1371	*2500*	4532
543	*1010*	1850	821	*1510*	2750	1099	*2010*	3650	1377	*2510*	4550
549	*1020*	1868	827	*1520*	2768	1104	*2020*	3668	1382	*2520*	4568
554	*1030*	1886	832	*1530*	2786	1110	*2030*	3686	1388	*2530*	4586
560	*1040*	1904	838	*1540*	2804	1116	*2040*	3704	1393	*2540*	4604
566	*1050*	1922	843	*1550*	2822	1121	*2050*	3722	1399	*2550*	4622
571	*1060*	1940	849	*1560*	2840	1127	*2060*	3740	1404	*2560*	4640
577	*1070*	1958	854	*1570*	2858	1132	*2070*	3758	1410	*2570*	4658
582	*1080*	1976	860	*1580*	2876	1138	*2080*	3776	1416	*2580*	4676
588	*1090*	1994	866	*1590*	2894	1143	*2090*	3794	1421	*2590*	4694
593	*1100*	2012	871	*1600*	2912	1149	*2100*	3812	1427	*2600*	4712
599	*1110*	2030	877	*1610*	2930	1154	*2110*	3830	1432	*2610*	4730
604	*1120*	2048	882	*1620*	2948	1160	*2120*	3848	1438	*2620*	4748
610	*1130*	2066	888	*1630*	2966	1166	*2130*	3866	1443	*2630*	4766
616	*1140*	2084	893	*1640*	2984	1171	*2140*	3884	1449	*2640*	4784
621	*1150*	2102	899	*1650*	3002	1177	*2150*	3902	1454	*2650*	4802
627	*1160*	2120	904	*1660*	3020	1182	*2160*	3920	1460	*2660*	4820
632	*1170*	2138	910	*1670*	3038	1188	*2170*	3938	1466	*2670*	4838
638	*1180*	2156	916	*1680*	3056	1193	*2180*	3956	1471	*2680*	4856
643	*1190*	2174	921	*1690*	3074	1199	*2190*	3974	1477	*2690*	4874
649	*1200*	2192	927	*1700*	3092	1204	*2200*	3992	1482	*2700*	4892
654	*1210*	2210	932	*1710*	3110	1210	*2210*	4010	1488	*2710*	4910
660	*1220*	2228	938	*1720*	3128	1216	*2220*	4028	1493	*2720*	4928
666	*1230*	2246	943	*1730*	3146	1221	*2230*	4046	1499	*2730*	4946
671	*1240*	2264	949	*1740*	3164	1227	*2240*	4064	1504	*2740*	4964
677	*1250*	2282	954	*1750*	3182	1232	*2250*	4082	1510	*2750*	4982
682	*1260*	2300	960	*1760*	3200	1238	*2260*	4100	1516	*2760*	5000
688	*1270*	2318	966	*1770*	3218	1243	*2270*	4118	1521	*2770*	5018
693	*1280*	2336	971	*1780*	3236	1249	*2280*	4136	1527	*2780*	5036
699	*1290*	2354	977	*1790*	3254	1254	*2290*	4154	1532	*2790*	5054
704	*1300*	2372	982	*1800*	3272	1260	*2300*	4172	1538	*2800*	5072
710	*1310*	2390	988	*1810*	3290	1266	*2310*	4190	1543	*2810*	5090
716	*1320*	2408	993	*1820*	3308	1271	*2320*	4208	1549	*2820*	5108
721	*1330*	2426	999	*1830*	3326	1277	*2330*	4226	1554	*2830*	5126
727	*1340*	2444	1004	*1840*	3344	1282	*2340*	4244	1560	*2840*	5144
732	*1350*	2462	1010	*1850*	3362	1288	*2350*	4262	1566	*2850*	5162
738	*1360*	2480	1016	*1860*	3380	1293	*2360*	4280	1571	*2860*	5180
743	*1370*	2498	1021	*1870*	3398	1299	*2370*	4298	1577	*2870*	5198
749	*1380*	2516	1027	*1880*	3416	1304	*2380*	4316	1582	*2880*	5216
754	*1390*	2534	1032	*1890*	3434	1310	*2390*	4334	1588	*2890*	5234
760	*1400*	2552	1038	*1900*	3452	1316	*2400*	4352	1593	*2900*	5252
766	*1410*	2570	1043	*1910*	3470	1321	*2410*	4370	1599	*2910*	5270
771	*1420*	2588	1049	*1920*	3488	1327	*2420*	4388	1604	*2920*	5288
777	*1430*	2606	1054	*1930*	3506	1332	*2430*	4406	1610	*2930*	5306
782	*1440*	2624	1060	*1940*	3524	1338	*2440*	4424	1616	*2940*	5324
788	*1450*	2642	1066	*1950*	3542	1343	*2450*	4442	1621	*2950*	5342
793	*1460*	2660	1071	*1960*	3560	1349	*2460*	4460	1627	*2960*	5360
799	*1470*	2678	1077	*1970*	3578	1354	*2470*	4478	1632	*2970*	5378
804	*1480*	2696	1082	*1980*	3596	1360	*2480*	4496	1638	*2980*	5396
810	*1490*	2714	1088	*1990*	3614	1366	*2490*	4514	1643	*2990*	5414
			1093	*2000*	3632				1649	*3000*	5432

Look up reading in middle column. If in degrees Centigrade, read Fahrenheit equivalent in right hand column; if in degrees Fahrenheit, read Centigrade equivalent in left hand column.

INCH/MILLIMETER EQUIVALENTS

Fraction	Decimal	Millimeters	Fraction	Decimal	Millimeters
1/64	.015625	0.39688	33/64	.515625	13.09690
1/32	.03125	0.79375	17/32	.53125	13.49378
3/64	.046875	1.19063	35/64	.546875	13.89065
1/16	.0625	1.58750	9/16	.5625	14.28753
5/64	.078125	1.98438	37/64	.578125	14.68440
3/32	.09375	2.38125	19/32	.59375	15.08128
7/64	.109375	2.77813	39/64	.609375	15.47816
1/8	.125	3.17501	5/8	.625	15.87503
9/64	.140625	3.57188	41/64	.640625	16.27191
5/32	.15625	3.96876	21/32	.65625	16.66878
11/64	.171875	4.36563	43/64	.671875	17.06566
3/16	.1875	4.76251	11/16	.6875	17.46253
13/64	.203125	5.15939	45/64	.703125	17.85941
7/32	.21875	5.55626	23/32	.71875	18.25629
15/64	.234375	5.95314	47/64	.734375	18.65316
1/4	.25	6.35001	3/4	.75	19.05004
17/64	.265625	6.74689	49/64	.765625	19.44691
9/32	.28125	7.14376	25/32	.78125	19.84379
19/64	.296875	7.54064	51/64	.796875	20.24067
5/16	.3125	7.93752	13/16	.8125	20.63754
21/64	.328125	8.33439	53/64	.828125	21.03442
11/32	.34375	8.73127	27/32	.84375	21.43129
23/64	.359375	9.12814	55/64	.859375	21.82817
3/8	.375	9.52502	7/8	.875	22.22504
25/64	.390625	9.92189	57/64	.890625	22.62192
13/32	.40625	10.31877	29/32	.90625	23.01880
27/64	.421875	10.71565	59/64	.921875	23.41567
7/16	.4375	11.11252	15/16	.9375	23.81255
29/64	.453125	11.50940	61/64	.953125	24.20942
15/32	.46875	11.90627	31/32	.96875	24.60630
31/64	.484375	12.30315	63/64	.984375	25.00318
1/2	.5	12.70003	1	1.	25.40005

METRIC EQUIVALENTS FOR WEIGHTS

1 ounce Avoirdupois (oz) = 28.3495 gm
1 pound (lb) (16 oz) = 453.6 gm
1 b per in. = 178.6 gm per cm
1 b per in.^{2} = 70.31 gm per cm^2
1 lb per in.^{3} = 27.68 gm per cm^3
1 b per ft = 1.4882 kg per m
1 b per ft^2 = 4.8824 kg per m^2
1 lb per ft^3 = 16.0184 kg per m^3
1 et ton (NT) (2,000 lb) = 907.19 kg

1 gram (gm) = 0.0022 lb
1 gm per cm = 0.0056 lb per in.
1 gm per cm^2 = 0.0142 lb per in.^{2}
1 gm per cm^3 = 0.0361 lb per in.^{3}
1 ilogram (kg) (1,000 gm) = 2.2046 lb
1 kg per m = 0.67197 lb per ft
1 kg per m^2 = 0.2048 lb per ft^2
1 kg per m^3 = 0.0624 lb per ft^3
1 metric ton (1,000 kg) = 1.1023 NT

METRIC EQUIVALENTS FOR MEASURES

1 inch (in.) = 2.54 cm
1 square inch (in.^{2}) = 6.4516 cm^2
1 cubic inch (in.^{3}) = 16.3872 cm^3
1 foot (ft) (12 in.) = 30.48 cm
1 square foot (ft^2) = 929.03 cm^2 = 0.0929 m^2
1 cubic foot (ft^3) = 28,317 cm^3 = 0.0283 m^3
1 yard (yd) (3 ft) = 91.44 cm = 0.9144 m
1 square yard (yd^2) = 0.8361 m^2
1 cubic yard (yd^3) = 0.7646 m^3
1 mile (5,280 ft, or 1,760 yd) =1,609.344 m = 1.6093 km

1 millimeter (mm) = 0.03937 in.
1 square mm (mm^2) = 0.0015 in.^{2}
1 centimeter (cm) (10 mm) = 0.3937 in.
1 square cm (cm^2) = 0.1549 in.^{2}
1 cubic cm (cm^3) = 0.0610 in.^{3}
1 meter (m) (100 cm) = 39.37 in. = 3.2808 ft = 1.0936 yd
1 square meter (m^2) = 10.7639 ft^2 = 1.196 yd^2
1 cubic meter (m^3) = 35.314 ft^3 = 1.3079 yd^3
1 kilometer (km) (1,000 m) = 3,280.83 ft = 1,093.61 yd = 0.6214 mile

WEIGHTS AND AREAS OF SQUARE AND ROUND STEEL BARS

Size or Diam in.	Weight, lb per ft		Area, sq in.	
	Square ■	Round ●	Square □	Round ○
1/16	.013	.010	.0039	.0031
5/64	.021	.016	.0061	.0048
3/32	.030	.023	.0088	.0069
7/64	.041	.032	.0120	.0094
1/8	.053	.042	.0156	.0123
9/64	.067	.053	.0198	.0155
5/32	.083	.065	.0244	.0192
11/64	.100	.079	.0295	.0232
3/16	.120	.094	.0352	.0276
13/64	.140	.110	.0413	.0324
7/32	.163	.128	.0479	.0376
15/64	.187	.147	.0549	.0431
1/4	.212	.167	.0625	.0491
17/64	.240	.188	.0706	.0554
9/32	.269	.211	.0791	.0621
19/64	.300	.235	.0881	.0692
5/16	.332	.261	.0977	.0767
21/64	.366	.288	.1077	.0846
11/32	.402	.316	.1182	.0928
23/64	.439	.345	.1292	.1014
3/8	.478	.376	.1406	.1104
25/64	.519	.407	.1526	.1198
13/32	.561	.441	.1650	.1296
27/64	.605	.475	.1780	.1398
7/16	.651	.511	.1914	.1503
29/64	.698	.548	.2053	.1613
15/32	.747	.587	.2197	.1726
31/64	.798	.627	.2346	.1843
1/2	.850	.668	.2500	.1963
33/64	.904	.710	.2659	.2088
17/32	.960	.754	.2822	.2217
35/64	1.017	.799	.2991	.2349
9/16	1.076	.845	.3164	.2485
37/64	1.136	.893	.3342	.2625
19/32	1.199	.941	.3525	.2769
39/64	1.263	.992	.3713	.2916
5/8	1.328	1.043	.3906	.3068
41/64	1.395	1.096	.4104	.3223
21/32	1.464	1.150	.4307	.3382
43/64	1.535	1.205	.4514	.3545
11/16	1.607	1.262	.4727	.3712
45/64	1.681	1.320	.4944	.3883
23/32	1.756	1.379	.5166	.4057
47/64	1.834	1.440	.5393	.4236
3/4	1.913	1.502	.5625	.4418
49/64	1.993	1.565	.5862	.4604
25/32	2.075	1.630	.6103	.4794
51/64	2.159	1.696	.6350	.4987
13/16	2.245	1.763	.6602	.5185
53/64	2.332	1.831	.6858	.5386
27/32	2.420	1.901	.7119	.5591
55/64	2.511	1.972	.7385	.5800
7/8	2.603	2.044	.7656	.6013
57/64	2.697	2.118	.7932	.6230
29/32	2.792	2.193	.8213	.6450
59/64	2.889	2.270	.8498	.6675
15/16	2.988	2.347	.8789	.6903
61/64	3.089	2.426	.9084	.7135
31/32	3.191	2.506	.9385	.7371
63/64	3.294	2.587	.9689	.7610
1	3.400	2.670	1.0000	.7854
1/32	3.616	2.840	1.0635	.8353
1/16	3.838	3.014	1.1289	.8866
3/32	4.067	3.194	1.1963	.9396
1/8	4.303	3.379	1.2656	.9940
5/32	4.545	3.570	1.3369	1.0500
3/16	4.795	3.766	1.4102	1.1075
7/32	5.050	3.966	1.4853	1.1666
1/4	5.312	4.173	1.5625	1.2272
9/32	5.581	4.384	1.6416	1.2893
5/16	5.857	4.600	1.7227	1.3530
11/32	6.139	4.822	1.8056	1.4182
3/8	6.428	5.049	1.8906	1.4849
13/32	6.724	5.281	1.9775	1.5532
7/16	7.026	5.518	2.0664	1.6230
15/32	7.334	5.761	2.1572	1.6943
1/2	7.650	6.008	2.2500	1.7671
17/32	7.972	6.261	2.3447	1.8415
9/16	8.301	6.520	2.4414	1.9175
19/32	8.636	6.783	2.5400	1.9949
5/8	8.978	7.051	2.6406	2.0739
21/32	9.327	7.325	2.7431	2.1545
11/16	9.682	7.604	2.8477	2.2365
23/32	10.044	7.889	2.9541	2.3202
3/4	10.413	8.178	3.0625	2.4053
25/32	10.788	8.473	3.1728	2.4920
13/16	11.170	8.773	3.2852	2.5802
27/32	11.558	9.078	3.3994	2.6699
7/8	11.953	9.388	3.5156	2.7612
29/32	12.355	9.704	3.6337	2.8540
15/16	12.763	10.024	3.7539	2.9483
31/32	13.178	10.350	3.8760	3.0442

Size or Diam in.	Weight, lb per ft		Area, sq in.	
	Square ■	Round ●	Square □	Round ○
2	13.600	10.681	4.0000	3.1416
¹⁄₁₆	14.463	11.359	4.2539	3.3410
⅛	15.353	12.058	4.5156	3.5466
³⁄₁₆	16.270	12.778	4.7852	3.7583
¼	17.213	13.519	5.0625	3.9761
⁵⁄₁₆	18.182	14.280	5.3477	4.2000
⅜	19.178	15.062	5.6406	4.4301
⁷⁄₁₆	20.201	15.866	5.9414	4.6664
½	21.250	16.690	6.2500	4.9087
⁹⁄₁₆	22.326	17.535	6.5664	5.1572
⅝	23.428	18.400	6.8906	5.4119
¹¹⁄₁₆	24.557	19.287	7.2227	5.6727
¾	25.713	20.195	7.5625	5.9396
¹³⁄₁₆	26.895	21.123	7.9102	6.2126
⅞	28.103	22.072	8.2656	6.4918
¹⁵⁄₁₆	29.338	23.042	8.6289	6.7771
3	30.600	24.033	9.0000	7.0686
¹⁄₁₆	31.888	25.045	9.3789	7.3662
⅛	33.203	26.078	9.7656	7.6699
³⁄₁₆	34.545	27.131	10.160	7.9798
¼	35.913	28.206	10.563	8.2958
⁵⁄₁₆	37.307	29.301	10.973	8.6179
⅜	38.728	30.417	11.391	8.9462
⁷⁄₁₆	40.176	31.554	11.816	9.2806
½	41.650	32.712	12.250	9.6211
⁹⁄₁₆	43.151	33.891	12.691	9.9678
⅝	44.678	35.090	13.141	10.321
¹¹⁄₁₆	46.232	36.311	13.598	10.680
¾	47.813	37.552	14.063	11.045
¹³⁄₁₆	49.420	38.814	14.535	11.416
⅞	51.053	40.097	15.016	11.793
¹⁵⁄₁₆	52.713	41.401	15.504	12.177
4	54.400	42.726	16.000	12.566
¹⁄₁₆	56.113	44.071	16.504	12.962
⅛	57.853	45.438	17.016	13.364
³⁄₁₆	59.620	46.825	17.535	13.772
¼	61.413	48.233	18.063	14.186
⁵⁄₁₆	63.232	49.662	18.598	14.607
⅜	65.078	51.112	19.141	15.033
⁷⁄₁₆	66.951	52.583	19.691	15.466
½	68.850	54.075	20.250	15.904
⁹⁄₁₆	70.776	55.587	20.816	16.349
⅝	72.728	57.121	21.391	16.800
¹¹⁄₁₆	74.707	58.675	21.973	17.257
¾	76.713	60.250	22.563	17.721
¹³⁄₁₆	78.745	61.846	23.160	18.190
⅞	80.803	63.463	23.766	18.665
¹⁵⁄₁₆	82.888	65.100	24.379	19.147
5	85.000	66.759	25.000	19.635
¹⁄₁₆	87.138	68.438	25.629	20.129
⅛	89.303	70.139	26.266	20.629
³⁄₁₆	91.495	71.860	26.910	21.135
¼	93.713	73.602	27.563	21.648
⁵⁄₁₆	95.957	75.364	28.223	22.166
⅜	98.228	77.148	28.891	22.691
⁷⁄₁₆	100.53	78.953	29.566	23.221
½	102.85	80.778	30.250	23.758
⁹⁄₁₆	105.20	82.624	30.941	24.301
⅝	107.58	84.492	31.641	24.850
¹¹⁄₁₆	109.98	86.380	32.348	25.406
¾	112.41	88.289	33.063	25.967
¹³⁄₁₆	114.87	90.218	33.785	26.535
⅞	117.35	92.169	34.516	27.109
¹⁵⁄₁₆	119.86	94.140	35.254	27.688
6	122.40	96.133	36.000	28.274
¹⁄₁₆	124.96	98.146	36.754	28.866
⅛	127.55	100.18	37.516	29.465
³⁄₁₆	130.17	102.23	38.285	30.069
¼	132.81	104.31	39.063	30.680
⁵⁄₁₆	135.48	106.41	39.848	31.296
⅜	138.18	108.52	40.641	31.919
⁷⁄₁₆	140.90	110.66	41.441	32.548
½	143.65	112.82	42.250	33.183
⁹⁄₁₆	146.43	115.00	43.066	33.824
⅝	149.23	117.20	43.891	34.472
¹¹⁄₁₆	152.06	119.43	44.723	35.125
¾	154.91	121.67	45.563	35.785
¹³⁄₁₆	157.79	123.93	46.410	36.450
⅞	160.70	126.22	47.266	37.122
¹⁵⁄₁₆	163.64	128.52	48.129	37.800
7	166.60	130.85	49.000	38.485
¹⁄₁₆	169.59	133.19	49.879	39.175
⅛	172.60	135.56	50.766	39.871
³⁄₁₆	175.64	137.95	51.660	40.574
¼	178.71	140.36	52.563	41.282
⁵⁄₁₆	181.81	142.79	53.473	41.997
⅜	184.93	145.24	54.391	42.718
⁷⁄₁₆	188.08	147.71	55.316	43.445
½	191.25	150.21	56.250	44.179
⁹⁄₁₆	194.45	152.72	57.191	44.918
⅝	197.68	155.26	58.141	45.664
¹¹⁄₁₆	200.93	157.81	59.098	46.415
¾	204.21	160.39	60.063	47.173
¹³⁄₁₆	207.52	162.99	61.035	47.937
⅞	210.85	165.60	62.016	48.707
¹⁵⁄₁₆	214.21	168.24	63.004	49.483

WEIGHTS OF SQUARE EDGE FLATS

Pounds per Linear Foot

Width, Inches	Thickness, Inches															
	1/16	1/8	3/16	1/4	5/16	3/8	7/16	1/2	9/16	5/8	11/16	3/4	13/16	7/8	15/16	1
1/4	.053	.106	.159	.213	.266	.319	.372	.425	.478	.531	.584	.638	.691	.744	.797	.850
1/2	.106	.213	.319	.425	.531	.638	.744	.850	.956	1.063	1.169	1.275	1.381	1.488	1.594	1.700
3/4	.159	.319	.478	.638	.797	.956	1.116	1.275	1.434	1.594	1.753	1.913	2.072	2.231	2.391	2.550
1	.213	.425	.638	.850	1.063	1.275	1.488	1.700	1.913	2.125	2.338	2.550	2.763	2.975	3.188	3.400
1 1/4	.266	.531	.797	1.063	1.328	1.594	1.859	2.125	2.391	2.656	2.922	3.188	3.453	3.719	3.984	4.250
1 1/2	.319	.638	.956	1.275	1.594	1.913	2.231	2.550	2.869	3.188	3.506	3.825	4.144	4.463	4.781	5.100
1 3/4	.372	.744	1.116	1.488	1.859	2.231	2.603	2.975	3.347	3.719	4.091	4.463	4.834	5.206	5.578	5.950
2	.425	.850	1.275	1.700	2.125	2.550	2.975	3.400	3.825	4.250	4.675	5.100	5.525	5.950	6.375	6.800
2 1/4	.478	.956	1.434	1.913	2.391	2.869	3.347	3.825	4.303	4.781	5.259	5.738	6.216	6.694	7.172	7.650
2 1/2	.531	1.063	1.594	2.125	2.656	3.188	3.719	4.250	4.781	5.313	5.844	6.375	6.906	7.438	7.969	8.500
2 3/4	.584	1.169	1.753	2.338	2.922	3.503	4.091	4.675	5.259	5.844	6.428	7.013	7.597	8.181	8.766	9.350
3	.638	1.275	1.913	2.550	3.188	3.825	4.463	5.100	5.738	6.375	7.013	7.650	8.288	8.925	9.563	10.20
3 1/4	.691	1.381	2.072	2.763	3.453	4.144	4.834	5.525	6.216	6.906	7.597	8.288	8.978	9.669	10.36	11.05
3 1/2	.744	1.488	2.231	2.975	3.719	4.463	5.206	5.950	6.694	7.438	8.181	8.925	9.669	10.41	11.16	11.90
3 3/4	.797	1.594	2.391	3.188	3.994	4.781	5.578	6.375	7.172	7.969	8.766	9.563	10.36	11.16	11.95	12.75
4	.850	1.700	2.550	3.400	4.250	5.100	5.950	6.800	7.650	8.500	9.350	10.20	11.05	11.90	12.75	13.60
4 1/4	.903	1.806	2.709	3.613	4.516	5.419	6.322	7.225	8.128	9.031	9.934	10.84	11.74	12.64	13.55	14.45
4 1/2	.956	1.913	2.869	3.825	4.781	5.738	6.694	7.650	8.606	9.563	10.52	11.48	12.43	13.39	14.34	15.30
4 3/4	1.009	2.019	3.028	4.038	5.047	6.056	7.066	8.075	9.084	10.09	11.10	12.11	13.12	14.13	15.14	16.15
5	1.063	2.125	3.188	4.250	5.313	6.375	7.438	8.500	9.563	10.63	11.69	12.75	13.81	14.88	15.94	17.00
5 1/4	1.116	2.231	3.347	4.463	5.578	6.694	7.809	8.925	10.04	11.16	12.27	13.39	14.50	15.62	16.73	17.85
5 1/2	1.169	2.338	3.506	4.675	5.844	7.013	8.181	9.350	10.52	11.69	12.86	14.03	15.19	16.36	17.53	18.70
5 3/4	1.222	2.444	3.666	4.888	6.109	7.331	8.553	9.775	11.00	12.22	13.44	14.66	15.88	17.11	18.33	19.55
6	1.275	2.550	3.825	5.100	6.375	7.650	8.925	10.20	11.48	12.75	14.03	15.30	16.58	17.85	19.13	20.40
6 1/4	1.328	2.656	3.984	5.313	6.641	7.969	9.297	10.63	11.95	13.28	14.61	15.94	17.27	18.59	19.92	21.25
6 1/2	1.381	2.763	4.144	5.525	6.906	8.288	9.669	11.05	12.43	13.81	15.19	16.58	17.96	19.34	20.72	22.10
6 3/4	1.434	2.869	4.303	5.738	7.172	8.606	10.04	11.48	12.91	14.34	15.78	17.21	18.65	20.08	21.52	22.95
7	1.488	2.975	4.463	5.950	7.438	8.925	10.41	11.90	13.39	14.88	16.36	17.85	19.34	20.83	22.31	23.80
7 1/4	1.541	3.081	4.622	6.163	7.703	9.244	10.78	12.33	13.87	15.41	16.95	18.49	20.03	21.57	23.11	24.65
7 1/2	1.594	3.188	4.781	6.375	7.969	9.563	11.16	12.75	14.34	15.94	17.53	19.13	20.72	22.31	23.91	25.50
7 3/4	1.647	3.294	4.941	6.588	8.234	9.881	11.53	13.18	14.82	16.47	18.12	19.76	21.41	23.06	24.70	26.35
8	1.700	3.400	5.100	6.800	8.500	10.20	11.90	13.60	15.30	17.00	18.70	20.40	22.10	23.80	25.50	27.20
8 1/4	1.753	3.506	5.259	7.013	8.766	10.52	12.27	14.03	15.78	17.53	19.28	21.04	22.79	24.54	26.30	28.05
8 1/2	1.806	3.613	5.419	7.225	9.031	10.84	12.64	14.45	16.26	18.06	19.87	21.68	23.48	25.29	27.09	28.90
8 3/4	1.859	3.719	5.578	7.438	9.297	11.16	13.02	14.88	16.73	18.59	20.45	22.31	24.17	26.03	27.89	29.75
9	1.913	3.825	5.738	7.650	9.563	11.48	13.39	15.30	17.21	19.13	21.04	22.95	24.86	26.78	28.69	30.60
9 1/4	1.966	3.931	5.897	7.863	9.828	11.79	13.76	15.73	17.69	19.66	21.62	23.59	25.55	27.52	29.48	31.45
9 1/2	2.019	4.038	6.056	8.075	10.09	12.11	14.13	16.15	18.17	20.19	22.21	24.23	26.24	28.26	30.28	32.30
9 3/4	2.072	4.144	6.216	8.238	10.36	12.43	14.50	16.58	18.65	20.72	22.79	24.86	26.93	29.01	31.08	33.15
10	2.125	4.250	6.375	8.500	10.63	12.75	14.88	17.00	19.13	21.25	23.38	25.50	27.63	29.75	31.88	34.00

Width, Inches	Thickness, Inches															
	1¹⁄₁₆	1⅛	1³⁄₁₆	1¼	1⁵⁄₁₆	1⅜	1⁷⁄₁₆	1½	1⁹⁄₁₆	1⅝	1¹¹⁄₁₆	1¾	1¹³⁄₁₆	1⅞	1¹⁵⁄₁₆	2
¼	.903	.956	1.009	1.063	1.116	1.169	1.222	1.275	1.328	1.381	1.434	1.488	1.541	1.594	1.647	1.700
½	1.806	1.913	2.019	2.125	2.231	2.338	2.444	2.550	2.656	2.763	2.869	2.975	3.081	3.188	3.294	3.400
¾	2.709	2.869	3.028	3.188	3.347	3.506	3.666	3.825	3.984	4.144	4.303	4.463	4.622	4.781	4.941	5.100
1	3.613	3.825	4.038	4.250	4.463	4.675	4.888	5.100	5.313	5.525	5.738	5.950	6.163	6.375	6.588	6.800
1¼	4.516	4.781	5.047	5.313	5.578	5.844	6.109	6.375	6.641	6.906	7.172	7.438	7.703	7.969	8.234	8.500
1½	5.419	5.738	6.056	6.375	6.694	7.013	7.331	7.650	7.969	8.288	8.606	8.925	9.244	9.563	9.881	10.20
1¾	6.322	6.694	7.066	7.438	7.809	8.181	8.553	8.925	9.297	9.669	10.04	10.41	10.78	11.16	11.53	11.90
2	7.225	7.650	8.075	8.500	8.925	9.350	9.775	10.20	10.63	11.05	11.48	11.90	12.33	12.75	13.18	13.60
2¼	8.128	8.606	9.084	9.563	10.04	10.52	11.00	11.48	11.95	12.43	12.91	13.39	13.87	14.34	14.82	15.30
2½	9.031	9.563	10.09	10.63	11.16	11.69	12.22	12.75	13.28	13.81	14.34	14.88	15.41	15.94	16.47	17.00
2¾	9.934	10.52	11.10	11.69	12.27	12.86	13.44	14.03	14.61	15.19	15.78	16.36	16.95	17.53	18.12	18.70
3	10.84	11.48	12.11	12.75	13.39	14.03	14.66	15.30	15.94	16.58	17.21	17.85	18.49	19.13	19.76	20.40
3¼	11.74	12.43	13.12	13.81	14.50	15.19	15.88	16.58	17.27	17.96	18.65	19.34	20.03	20.72	21.41	22.10
3½	12.64	13.39	14.13	14.88	15.62	16.36	17.11	17.85	18.59	19.34	20.08	20.83	21.57	22.31	23.06	23.80
3¾	13.55	14.34	15.14	15.94	16.73	17.53	18.33	19.13	19.92	20.72	21.52	22.31	23.11	23.91	24.70	25.50
4	14.45	15.30	16.15	17.00	17.85	18.70	19.55	20.40	21.25	22.10	22.95	23.80	24.65	25.50	26.35	27.20
4¼	15.35	16.26	17.16	18.06	18.97	19.87	20.77	21.68	22.58	23.48	24.38	25.29	26.19	27.09	28.00	28.90
4½	16.26	17.21	18.17	19.13	20.08	21.04	21.99	22 95	23.91	24.86	25.82	26.78	27.73	28.69	29.64	30.60
4¾	17.16	18.17	19.18	20.19	21.20	22.21	23.22	24.23	25.23	26.24	27.25	28.26	29.27	30.28	31.29	32.30
5	18.06	19.13	20.19	21.25	22.31	23.38	24.44	25.50	26.56	27.63	28.69	29.75	30.81	31.88	32.94	34.00
5¼	18.97	20.08	21.20	22.31	23.43	24.54	25.66	26.78	27.89	29.01	30.12	31.24	32.35	33.47	34.58	35.70
5½	19.87	21.04	22.21	23.38	24.54	25.71	26.88	28.05	29.22	30.39	31.56	32.73	33.89	35.06	36.23	37.40
5¾	20.77	21.99	23.22	24.44	25.66	26.88	28.10	29.33	30.55	31.77	32.99	34.21	35.43	36.66	37.88	39.10
6	21.68	22.95	24.23	25.50	26.78	28.05	29.33	30.60	31.88	33.15	34.43	35.70	36.98	38.25	39.53	40.80
6¼	22.58	23.91	25.23	26.56	27.89	29.22	30.55	31.88	33.20	34.53	35.86	37.19	38.52	39.84	41.17	42.50
6½	23.48	24.86	26.24	27.63	29.01	30.39	31.77	33.15	34.53	35.91	37.29	38.68	40.06	41.44	42.82	44.20
6¾	24.38	25.82	27.25	28 69	30.12	31.56	32.99	34.43	35.86	37.29	38.73	40.16	41.60	43.03	44.47	45.90
7	25.29	26.78	28.26	29.75	31.24	32.73	34.21	35.70	37.19	38.68	40.16	41.65	43.14	44.63	46.11	47.60
7¼	26.19	27.73	29.27	30.81	32.35	33.89	35.43	36.98	38.52	40.06	41.60	43.14	44.68	46.22	47.76	49.30
7½	27.09	28.69	30.28	31.88	33.47	35.06	36.66	38.25	39.84	41.44	43.03	44.63	46.22	47.81	49.41	51.00
7¾	28.00	29.64	31.29	32.94	34.58	36.23	37.88	39.53	41.17	42.82	44.47	46.11	47.76	49.41	51.05	52.70
8	28.90	30.60	32.30	34.00	35.70	37.40	39.10	40.80	42.50	44.20	45.90	47.60	49.30	51.00	52.70	54.40
8¼	29.80	31.56	33.31	35.06	36.82	38.57	40.32	42.08	43.83	45.58	47.33	49.09	50.84	52.59	54.35	56.10
8½	30.71	32.51	34.32	36.13	37.93	39.74	41.54	43.35	45.16	46.96	48.77	50.58	52.38	54.19	55.99	57.80
8¾	31.61	33.47	35.33	37.19	39.05	40.91	42.77	44.63	46.48	48.34	50.20	52.06	53.92	55.78	57.64	59.50
9	32.51	34.43	36.34	38.25	40.16	42.08	43.99	45.90	47.81	49.73	51.64	53.55	55.46	57.38	59.29	61.20
9¼	33.42	35.38	37.35	39.31	41.28	43.24	45.21	47.18	49.14	51.11	53.07	55.04	57.00	58.97	60.93	62.90
9½	34.32	36.34	38.36	40.38	42.39	44.41	46.43	48.45	50.47	52.49	54.51	56.53	58.54	60.56	62.58	64.60
9¾	35.22	37.29	39.37	41.44	43.51	45.58	47.65	49.73	51.80	53.87	55.94	58.01	60.08	62.16	64.23	66.30
10	36.13	38.25	40.38	42.50	44.63	46.75	48.88	51.00	53.13	55.25	57.38	59.50	61.63	63.75	65.88	68.00

ROLLING TOLERANCES—INCHES

Hot-Rolled Carbon and Alloy Steel Bars

Rounds, Squares, & Round-Cornered Squares

Specified Sizes	Variation from Size		Out-of-Round or Out-of-Square
	Over	Under	
To 5/16 incl	0.005	0.005	0.008
Over 5/16 to 7/16 incl	0.006	0.006	0.009
Over 7/16 to ⅝ incl	0.007	0.007	0.010
Over ⅝ to ⅞ incl	0.008	0.008	0.012
Over ⅞ to 1 incl	0.009	0.009	0.013
Over 1 to 1⅛ incl	0.010	0.010	0.015
Over 1⅛ to 1¼ incl	0.011	0.011	0.016
Over 1¼ to 1⅜ incl	0.012	0.012	0.018
Over 1⅜ to 1½ incl	0.014	0.014	0.021
Over 1½ to 2 incl	1/64	1/64	0.023
Over 2 to 2½ incl	1/32	0	0.023
Over 2½ to 3½ incl	3/64	0	0.035
Over 3½ to 4½ incl	1/16	0	0.046
Over 4½ to 5½ incl	5/64	0	0.058
Over 5½ to 6½ incl	⅛	0	0.070
Over 6½ to 8¼ incl	5/32	0	0.085
Over 8¼ to 9½ incl	3/16	0	0.100
Over 9½ to 10	¼	0	0.120

NOTE: Out-of-round is the difference between the maximum and minimum diameters of the bar, measured at the same cross section. Out-of-square is the difference in the two dimensions at the same cross section of a square bar between opposite faces.

Hexagons

Specified Sizes between Opposite Sides	Variation from Size		Out-of-Hexagon
	Over	Under	
To ½ incl	0.007	0.007	0.011
Over ½ to 1 incl	0.010	0.010	0.015
Over 1 to 1½ incl	0.021	0.013	0.025
Over 1½ to 2 incl	1/32	1/64	1/32
Over 2 to 2½ incl	3/64	1/64	3/64
Over 2½ to 3½ incl	1/16	1/64	1/16

NOTE: Out-of-hexagon is the greatest difference between any two dimensions at the same cross section between opposite faces.

Square-Edge and Round-Edge Flats

Specified Widths	Variation from Thickness for Thicknesses Given					Variation from Width	
	.203 to ¼, excl	¼ to ½, incl	Over ½ to 1, incl	Over 1 to 2, incl	Over 2	Over	Under
To 1 incl	0.007	0.008	0.010	—	—	1/64	1/64
Over 1 to 2 incl	0.007	0.012	0.015	1/32	—	1/32	1/32
Over 2 to 4 incl	0.008	0.015	0.020	1/32	3/64	1/16	1/32
Over 4 to 6 incl	0.009	0.015	0.020	1/32	3/64	3/32	1/16
Over 6 to 8 incl	0.015*	0.016	0.025	1/32	3/64**	⅛**	3/32**

*Flats over 6 in. in width are not available in thicknesses under 0.230 in.

**Tolerances not applicable to flats over 6 in. in width and over 3 in. in thickness.

GLOSSARY OF STEEL TESTING AND THERMAL TREATING TERMS[1]

A$_C$ TEMPERATURE. See *Transformation Temperature.*

AGING. A time-dependent change in the properties of certain steels that occurs at ambient or moderately elevated temperatures after hot working, after a thermal treatment (quench aging), or after a cold working operation (strain aging).

ANNEALING. A thermal cycle involving heating to, and holding at a suitable temperature and then cooling at a suitable rate, for such purposes as reducing hardness, improving machinability, facilitating cold working, producing a desired microstructure, or obtaining desired mechanical or other properties.

A$_R$ TEMPERATURE. See *Transformation Temperature.*

AUSTEMPERING. A thermal treatment process which involves quenching steel from a temperature above the transformation range in a medium having a rate of heat abstraction high enough to prevent the formation of high-temperature transformation products, and holding the material at a temperature above that of martensite formation until transformation is complete. The product formed is termed lower bainite.

AUSTENITIZING. The process of forming austenite by heating a ferrous alloy into the transformation range (partial austenitizing) or above this range (complete austenitizing).

BAINITE. A decomposition product of austenite consisting of an aggregate of ferrite and carbide. In general, it forms at temperatures lower than those where very fine pearlite forms, and higher than that where martensite begins to form on cooling. Its microstructural appearance is feathery if formed in the upper part of the temperature range; acicular, resembling tempered martensite, if formed in the lower part.

[1] Certain of these definitions have been derived from ASTM Standard E44-75.

BLUE BRITTLENESS. Brittleness occurring in some steels after being heated to within the temperature range of 400 to 700 F, or more especially, after being worked within this range. Killed steels are virtually free from this kind of brittleness.

BRINELL HARDNESS NUMBER (HB). A measure of hardness determined by the Brinell hardness test, in which a hard steel ball under a specific load is forced into the surface of the test material. The number is derived by dividing the applied load by the surface area of the resulting impression.

CARBURIZING. A process in which an austenitized ferrous material is brought into contact with a carbonaceous atmosphere or medium of sufficient carbon potential as to cause absorption of carbon at the surface and, by diffusion, create a concentration gradient. Hardening by quenching follows.

CASE HARDENING. A term descriptive of one or more processes of hardening steel in which the outer portion, or case, is made substantially harder than the inner portion, or core. Most of the processes involve either enriching the surface layer with carbon and/or nitrogen, usually followed by quenching and tempering, or the selective hardening of the surface layer by means of flame or induction hardening.

CEMENTITE. A hard, brittle compound of iron and carbon (Fe_3C), the major form in which carbon occurs in steel.

CONTROLLED COOLING. A process by which steel is cooled from an elevated temperature in a predetermnied manner to avoid hardening, cracking, or internal damage, or to produce desired microstructure or mechanical properties.

CREEP. A time-dependent deformation of steel occurring under conditions of elevated temperature accompanied by stress intensities well within the apparent elastic limit for the temperature involved.

CRITICAL RANGE. Synonymous with *Transformation Range,* which is the preferred term.

DECARBURIZATION. The loss of carbon from the surface of steel as a result of heating in a medium which reacts with the carbon.

DUCTILITY. The ability of a material to deform plastically without fracturing, usually measured by elongation or reduction of area in a tension test, or, for flat products such as sheet, by height of cupping in an Erichsen test.

ELASTIC LIMIT. The greatest stress that a material can withstand without permanent deformation.

ELONGATION. A measure of ductility, determined by the amount of permanent extension achieved by a tension-test specimen, and expressed as a percentage of that specimen's original gage length. (as: 25% in 2 in.).

END-QUENCH HARDENABILITY TEST (JOMINY TEST). A method for determining the hardenability of steel by water-quenching one end of an austenitized cylindrical test specimen and measuring the resulting hardness at specified distances from the quenched end.

ENDURANCE LIMIT. The maximum cyclic stress, usually expressed in pounds per sq in., to which a metal can be subjected for indefinitely long periods without damage or failure. Conventionally established by the rotating-beam fatigue test.

EXTENSOMETER. An instrument capable of measuring small magnitudes of strain occurring in a specimen during a tension test, conventionally used when a stress-strain diagram is to be plotted.

ETCH TEST (MACROETCH). An inspection procedure in which a sample is deep-etched with acid and visually examined for the purpose of evaluating its structural homogeneity.

FERRITE. A crystalline form of alpha iron, one of the two major constituents of steel (cf *Cementite*) in which it acts as the solvent to form solid solutions with such elements as manganese, nickel, silicon, and, to a small degree, carbon.

FLAKES. Internal fissures which may occur in wrought steel product during cooling from hot-forging or rolling. Their occurrence may be minimized by effective control of hydrogen, either in melting or in cooling from hot work.

FLAME HARDENING. A hardening process in which the surface is heated by direct flame impingement and then quenched.

FULL ANNEALING. A thermal treatment for steel with the primary purpose of decreasing hardness. It is accomplished by heating above the transformation range, holding for the proper time interval, and controlled slow cooling to below that range. Subsequent cooling to ambient temperature may be accomplished either in air or in the furnace.

GRAIN SIZE NUMBER. An arbitrary number which is calculated from the average number of individual crystals, or grains, which appear on the etched surface of a specimen at 100 diameters magnification. See page 81.

HARDENABILITY. That property of steel which determines the depth and distribution of hardness induced by quenching.

HARDNESS. The resistance of a material to plastic deformation. Usually measured in steels by the Brinell, Rockwell, or Vickers indentation-hardness test methods (q.v.).

IMPACT TEST. A test for determining the ability of a steel to withstand high-velocity loading, as measured by the energy, in ft-lb, which a notched-bar specimen absorbs upon fracturing.

INDUCTION HARDENING. A quench hardening process in which the heat is generated by electrical induction.

ISOTHERMAL TRANSFORMATION. A change in phase at any constant temperature. Practical application of the principle involved may be found in the isothermal annealing and austempering of steel.

MARTEMPERING. A method of hardening steel. Involves quenching an austenitized ferrous alloy in a medium at a temperature in the upper part of the martensitic range, or slightly above that range, and holding in the medium until the temperature throughout the alloy is substantially uniform. The alloy is then allowed to cool in air through the martensitic range.

MARTENSITE. A microconstituent or structure in hardened steel, characterized by an acicular, or needle-like pattern, and having the maximum hardness of any of the decomposition products of austenite.

MECHANICAL PROPERTIES. Properties which reveal the reactions, elastic and inelastic, of a material to applied forces. Sometimes designated erroneously as "physical properties."

Some common mechanical properties, tests, and units are listed below:

Mechanical Property	Test	Units: Customary (SI metric)
Cold bending	Cold-bend	angular degrees (radians)
Compressive strength	Compression	psi (kPa)
Corrosion-fatigue limit	Corrosion-fatigue	psi (kPa)
Creep strength	Creep	psi (kPa) per time and temperature
Elastic limit	Tension; Compression	psi (kPa)
Elongation	Tension	per cent of a specific specimen gage length
Endurance Limit	Fatigue	psi (kPa)
Hardness	Static: Brinell; Rockwell; Vickers	empirical numbers
	Dynamic: Shore (Scleroscope)	empirical numbers
Impact	Notched-bar impact (Charpy; Izod)	ft-lb (Joule)
Impact, bending	Bend	ft-lb (Joule)
Impact, torsional	Torsion-impact	ft-lb (Joule)
Modulus of rupture	Bend	psi (kPa)
Proof stress	Tension; Compression	psi (kPa)
Proportional limit	Tension; Compression	psi (kPa)
Reduction of area	Tension	per cent
Shear strength	Shear	psi (kPa)
Tensile strength	Tension	psi (kPa)
Torsional strength	Torsion	psi (kPa)
Yield point	Tension	psi (kPa)
Yield strength	Tension	psi (kPa)

MODULUS OF ELASTICITY (YOUNG'S MODULUS). A measure of stiffness, or rigidity, expressed in pounds per sq in. Developed from the ratio of the stress, as applied to a tension test specimen, to the corresponding strain, or elongation of the specimen, and applicable for tensile loads below the elastic limit of the material.

NITRIDING. A surface hardening process in which certain steels are heated to, and held at a temperature below the transformation range in contact with gaseous ammonia or other source of nascent nitrogen in order to effect a transfer of nitrogen to the surface layer of the steel. The nitrogen combines with certain alloying elements, resulting in a thin case of very high hardness. Slow cooling completes the process.

NORMALIZING. A thermal treatment consisting of heating to a suitable temperature above the transformation range and then cooling in still air. Usually employed to improve toughness or machinability, or as a preparation for further heat treatment.

PEARLITE. A microconstituent of iron and steel consisting of a lamellar aggregate of ferrite and cementite.

PHYSICAL PROPERTIES. Properties which pertain to the physics of a material, such as density, electrical conductivity, and coefficient of thermal expansion. Not to be confused with mechanical properties (q.v.).

PROPORTIONAL LIMIT. The maximum stress at which strain remains directly proportional to stress.

QUENCHING AND TEMPERING. A thermal process used to increase the hardness and strength of steel. It consists of austenitizing, then cooling at a rate sufficient to achieve partial or complete transformation to martensite. Tempering should follow immediately, and involves reheating to a temperature below the transformation range and then cooling at any rate desired. Tempering improves ductility and toughness, but reduces the quenched hardness by an amount determined by the tempering temperature used.

REDUCTION OF AREA. A measure of ductility determined by the difference between the original cross-sectional area of a tension test specimen and the area of its smallest cross section at the point of fracture. Expressed as a percentage of the original area.

ROCKWELL HARDNESS (HRB or HRC). A measure of hardness determined by the Rockwell hardness tester, by which a diamond spheroconical penetrator (Rockwell C scale) or a hard steel ball (Rockwell B scale) is forced into the surface of the test material under sequential minor and major loads. The difference between the depths of impressions from the two loads is read directly on the arbitrarily calibrated dial as the Rockwell hardness value.

SPHEROIDIZE ANNEALING (SPHEROIDIZING). A thermal treatment which produces a spheroidal or globular form of carbide in steel. This is the softest condition possible in steel, hence, the treatment is used prior to cold deformation. Spheroidizing also improves machinability in the higher carbon grades.

STRESS RELIEVING. A thermal cycle involving heating to a suitable temperature, usually 1000/1200 F, holding long enough to reduce residual stresses from either cold deformation or thermal treatment, and then cooling slowly enough to minimize the development of new residual stresses.

TEMPER BRITTLENESS. Brittleness that results when certain steels are held within, or are cooled slowly through, a specific range of temperatures below the transformation range. The brittleness is revealed by notched-bar impact tests at or below room temperature.

TEMPERING. See *Quenching and Tempering.*

TENSILE STRENGTH. The maximum tensile stress in pounds per sq in. which a material is capable of sustaining, as developed by a tension test.

TENSION TEST. A test in which a machined or full-section specimen is subjected to a measured axial load sufficient to cause fracture. The usual information derived includes the elastic properties, ultimate tensile strength, and elongation and reduction of area.

THERMAL TREATMENT. Any operation involving the heating and cooling of a metal or alloy in the solid state to obtain desired microstructure or mechanical properties. This definition excludes heating for the sole purpose of hot working.

TRANSFORMATION RANGES. Those ranges of temperatures within which austenite forms during heating, and transforms during cooling.

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 symbols of primary interest for iron and steels are:

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 transformation of ferrite to austenite begins during heating.

Ac_3 —The temperature at which transformation of ferrite to austenite is completed during heating.

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 transformation of austenite to ferrite begins during cooling.

M_s —The temperature at which transformation of austenite to martensite begins during cooling.

M_f —The temperature at which transformation of austenite to martensite is substantially completed 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.

VICKERS HARDNESS (HV). A measure of hardness determined by the Vickers, or Diamond Pyramid Hardness Test, which is similar in principle to the Brinell test, but utilizes a pyramid-shaped diamond penetrator instead of a ball.

YIELD POINT. The minimum stress at which a marked increase in strain occurs without an increase in stress.

YIELD STRENGTH. The stress at which a material exhibits a specified deviation from the proportionality of stress to strain. The deviation is expressed in terms of strain, and in the offset method, usually a strain of 0.2 per cent is specified.

YOUNG'S MODULUS. See *Modulus of Elasticity.*

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