U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

PRODUCTION, HEAT TREATMENT, AND PROPERTIES OF IRON ALLOYS

CIRCULAR C409

BUREAU OF STANDARDS
APR 27 1936
LIBRARY

[illegible] book not to be [illegible] the Library

U. S. DEPARTMENT OF COMMERCE
DANIEL C. ROPER, Secretary
NATIONAL BUREAU OF STANDARDS
LYMAN J. BRIGGS, Director

CIRCULAR OF THE NATIONAL BUREAU OF STANDARDS C409

PRODUCTION, HEAT TREATMENT, AND PROPERTIES OF IRON ALLOYS

By

LOUIS JORDAN

[Issued March 17, 1936]

UNITED STATES
GOVERNMENT PRINTING OFFICE
WASHINGTON : 1936

For sale by the Superintendent of Documents, Washington, D. C. - - - - Price 10 cents

PRODUCTION, HEAT TREATMENT, AND PROPERTIES OF IRON ALLOYS

By Louis Jordan

ABSTRACT

This circular has been prepared in response to continuing requests made to the National Bureau of Standards for a reasonably brief and simplified statement of the principles of the heat treatment of steels, and for similarly simplified statements covering the production and properties of iron alloys in general. This circular gives particular consideration to recently developed theories of the hardening of steel and of the role of special alloying elements in steel.

I. INTRODUCTION

The National Bureau of Standards receives many requests for information on the meaning of terms used in iron and steel metallurgy, methods of heat treating iron and steel, and for simple directions for and explanations of such processes. Sometimes these requests are prompted by the desire to attempt the more simple operations in a home workshop and sometimes by the desire to secure a not too technical and detailed starting point for study and self-education along metallurgical lines. This circular has been designed to answer such inquiries. It describes very briefly the reduction of iron ore, the production and properties of cast irons, the production and fabrication of steels, and also discusses the fundamental principles upon which the heat treatment of steel is based. There are also included brief discussions of the equipment used in heat-treatment processes and the major types and chief characteristic properties of alloy steels.

Acknowledgments for suggestions and aid in the preparation of this circular are due all of the sources listed in section X under the heading "Elementary General Textbooks." Many of the other sources indicated in section X have also been used as the basis for different portions of this circular. Special acknowledgment is made to E. C. Bain and E. S. Davenport, of the United States Steel Corporation. The entire discussion of the fundamental principles of the hardening of steel by quenching and the classification of the characteristic effects of steel alloying elements are based on their several publications on these subjects.

II. EARLY TYPES OF IRON ALLOYS

1. WROUGHT IRON

Wrought iron was the earliest form of manufactured iron that became commercially important. It was originally produced by heating iron ore (iron oxides) with carbon (charcoal) in "puddling" furnaces. The carbon united with the oxides and reduced them at temperatures not quite high enough to melt the metallic iron product. The resulting pasty mass (a "bloom") of mixed iron particles and slag or "cinder", was squeezed and hammered, or rolled, to any desired shape. The final product was metallic iron of rather high purity, throughout which were particles of slag drawn out in the direction of the rolling or forging of the piece. Hence the fibrous structure characteristic of wrought iron.

In recent years a new type of process for making wrought iron has been developed. In this newer process a molten low-carbon steel and a molten slag are prepared in separate furnaces and are then poured one into the other so as to produce a mass of intimately mixed iron and slag quite similar to the product of the older puddling furnace. This wrought iron is known as Aston-process wrought iron.

2. CEMENTATION STEEL

The earliest method of making *steel*—a forgeable iron-carbon alloy that could be hardened by quenching—was by heating bars of wrought iron packed in a crucible with charcoal, the so-called "cementation" process. The wrought iron absorbed carbon (charcoal) without actually melting. The resulting bars, blistered from the gases developed by action of the carbon on the slag fibers, and hence called "blister steel", could be forged, and hardened by heat treatment. *Crucible steels* were originally made by melting bars of blister steel in a clay or clay-graphite crucible, and for many years this type of crucible steel was regarded as the highest quality steel for cutlery. Comparatively little steel is made today by melting in crucibles. When it is done, low-carbon iron is melted directly in crucibles with carbon.

III. REDUCTION OF IRON ORES

1. BLAST FURNACE—PIG IRON

The first step in modern methods for making iron alloys is generally the reduction of iron ore in the blast furnace to produce a brittle cast iron called *pig iron*, containing several percent each of carbon and silicon, possibly 3 to 4 percent of carbon, and 1 to 3 percent of silicon, together with some sulphur, phosphorus, and manganese.

Iron ores are chiefly oxides of iron. Such ore is mixed with carbon (as coke) and limestone and is charged into the top of the shaft of a blast furnace. (See fig. 1.) A blast of air injected near the bottom of the shaft through tuyères supports combustion of the coke. The heat and the reducing gases produced by this combustion bring about reduction of the iron ore to metallic iron and the fluxing of many of the impurities of the ore by the limestone. Slag and liquid iron collect at the bottom of the blast furnace and are periodically removed through the "cinder notch" and the "iron notch", respectively. This iron is either cast into bars ("pigs"), or it may be taken while still liquid to other types of furnaces for refining to steel without being allowed to solidify.

2. OTHER METHODS OF PRODUCING IRON

Frequent attempts have been made to develop "direct reduction" methods for recovering iron from ores. By such methods iron ore is reduced by gases at low temperatures. The resulting product is relatively pure metallic iron, "sponge iron." These processes are direct as compared with the indirect method generally followed of producing first a pig iron and then refining this to a relatively pure iron.

Iron may be deposited by electrolysis from solutions made either by leaching iron ore or by dissolving metallic iron. In the latter case the object is usually the purification of iron. Electrolytic iron is used only to a very limited extent.

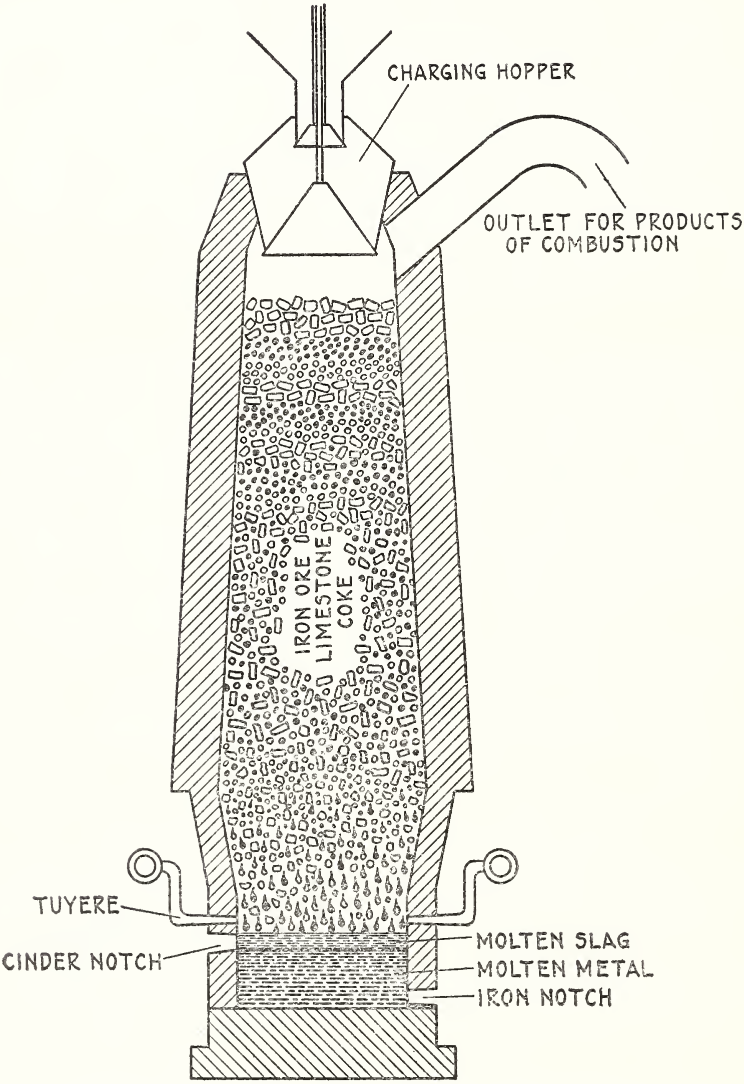

FIGURE 1.—*Diagrammatic section of a blast furnace.*

IV. CAST IRON

Cast irons are alloys of iron which contain 2 or 3 percent of carbon and are not malleable as cast. They melt at a relatively low temperature and are rather easily cast in thin sections or intricate designs. Pig iron from the blast furnace is really one type of cast iron. The other common types of cast iron are gray cast iron, white cast iron, and malleable cast iron.

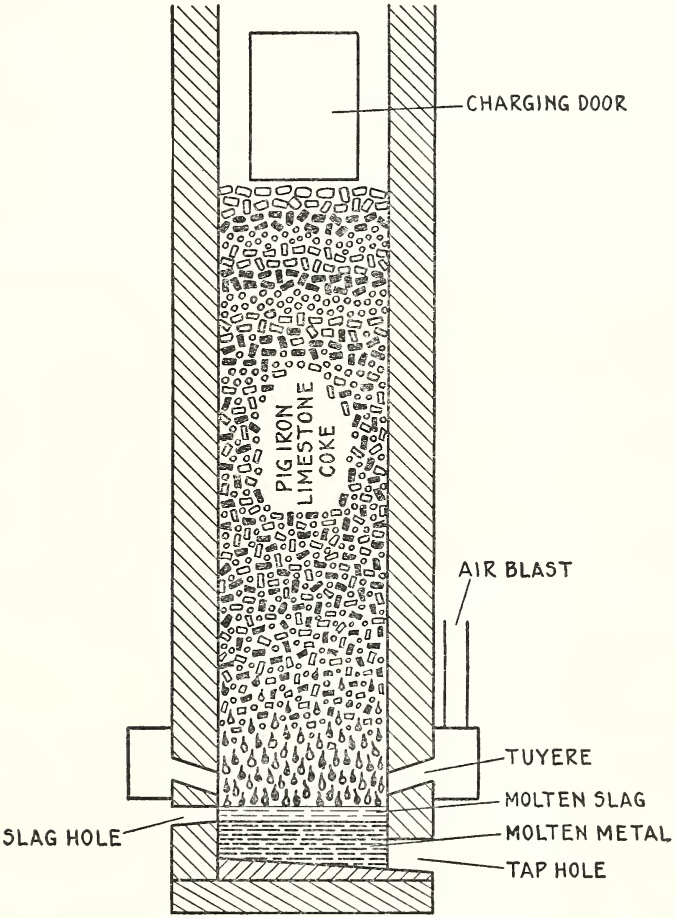

Figure 2.—*Diagrammatic section of a cupola.*

1. GRAY CAST IRON

Gray cast iron is made by melting pig iron, possibly with some scrap iron or steel, in a small shaft furnace called a cupola (fig. 2). Coke and limestone are also added to the cupola with the metal charge. The composition of the cast iron is controlled by selection of the metals used in the charge. Carbon and silicon are the two chief elements to be controlled. Castings are formed by tapping the molten iron from the base of the cupola and pouring it into sand or loam molds, which contain cavities of the size and shape of the desired articles. A mold is formed by packing the sand or loam around patterns and then carefully removing the patterns.

Gray iron is so named because it contains flakes of graphite which give a gray color to a fractured surface. The structure of gray iron as seen by examining a polished specimen under a microscope is indicated in figure 3. The dark elongated particles are the graphite flakes. The material surrounding the graphite flakes may be either rather soft low-carbon iron, (fig. 3, A) or it may be an iron-carbon alloy corresponding to a steel (fig. 3, B). In the latter case the gray iron is said to contain carbon both as graphite and as combined carbon, i. e., combined in the steel-like alloy. A low silicon content in the cast iron permits a greater proportion of the carbon to exist as combined carbon while a high silicon content decreases the combined carbon and increases the free graphite.

Gray cast irons which contain large proportions of combined carbon are harder and stronger than those with very little combined carbon, and are called *high-strength irons*, *high-test irons*, or *pearlitic cast irons*. They have sometimes been called "semisteels", but this term may be misleading and its use is not to be recommended.

2. WHITE CAST IRON

When the silicon content is relatively low, a liquid cast iron can freeze with all the carbon in the combined form. In this condition the iron is very hard and brittle, there are no flakes of graphite, and its fracture is "white"; hence the name, *white cast iron*. By very rapid cooling white iron can also be produced from a liquid iron that normally would form gray iron when cast in sand molds. This is done by putting "chills" in the mold at the places where hard white iron is desired. These chills are frequently heavy plates of iron. "Chilled iron" surfaces are used for resisting abrasion. White iron is also the starting point for the production of malleable iron.

3. MALLEABLE CAST IRON

If white cast iron is packed in sand and either iron ore or mill scale (both are oxides of iron), and is heated for several days at about 800° C (1,500° F), the carbon which was combined carbon in the white iron separates and forms free graphite, but in differently shaped particles from the graphite of gray iron. The free carbon of malleable iron is in small rounded masses or nodules and is called "temper carbon" (fig. 4). The matrix of the malleable iron structure, that is, the material surrounding the temper carbon particles, is rather pure and soft iron. The metal close to the surface of a malleable casting is free from carbon; it has been decarburized during the annealing process. Hence the fractured surface of a malleable casting shows a light colored border and a dark core. This type of malleable iron is called "black heart" malleable iron and is the type produced in this country.

In Europe another type of malleable iron is produced, namely, "white heart" malleable iron in which the carbon of the white-iron casting is almost completely removed by the annealing process, and no dark core remains.

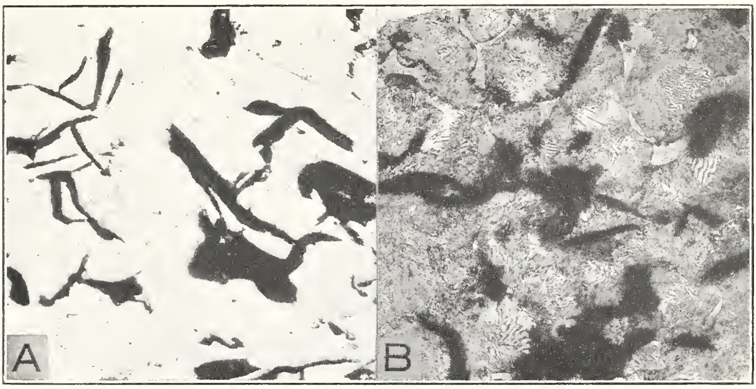

FIGURE 3.—*Microstructure of gray cast iron.*

A, Soft gray cast iron has rather soft, low-carbon iron (white areas) surrounding the graphite flakes (black irregular bands).

B, A high-strength (pearlitic) gray cast iron. The matrix surrounding the graphite flakes is an iron-carbon alloy (pearlite) corresponding to a steel.

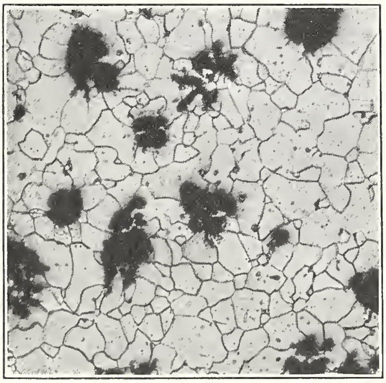

FIGURE 4.—*Microstructure of malleable iron.*

Small nodules of temper carbon in a matrix of rather pure soft iron.

Malleable cast iron is not so malleable, that is, so ductile and capable of being bent without breaking, as is wrought iron and steel, but is distinctly more malleable than other forms of cast iron.

V. PRODUCTION AND MECHANICAL WORKING OF STEEL

1. STEEL-REFINING PROCESSES

It has already been stated that the earliest method of making steel was by the cementation of wrought iron and the melting of the resulting blister steel in crucibles. Present-day production of steel depends on the refining of pig iron in Bessemer converters, or in open-hearth or electric furnaces.

(a) BESSEMER STEEL

The Bessemer converter is somewhat like a large steel barrel lined with refractory brick, with the top open and the bottom pierced with several holes or ports, which are called "tuyères" (fig. 5). In use the converter is tipped on its side, liquid iron from the blast furnace is poured in, and then, with a strong blast of air blowing into the converter through the tuyères in the bottom, the converter is tipped back again to its original nearly upright position. The air then blows through the liquid iron in the bottom of the converter. The oxygen of the air burns the carbon and silicon out of the liquid iron, leaving more nearly pure iron containing only small amounts of carbon, manganese, and silicon with some sulphur and phosphorus. The amounts of carbon, silicon, and manganese necessary to make a steel of the desired composition are added to the molten metal, which is then cast into ingots to be rolled and forged into plates, bars, and other shapes.

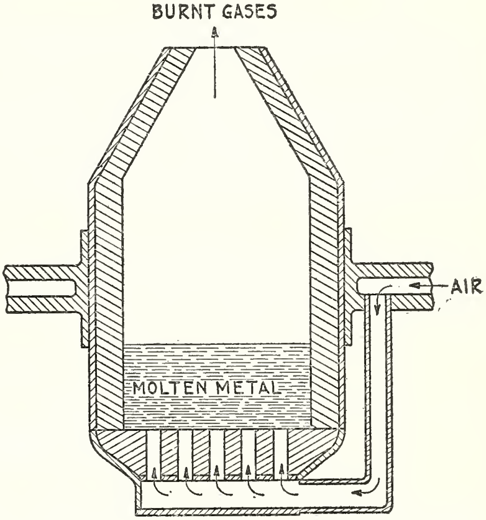

FIGURE 5.—*Diagrammatic section of a Bessemer converter.*

(b) OPEN-HEARTH STEEL

The open-hearth furnace (fig. 6) is essentially a broad, shallow hearth lined with a suitable refractory in which pig iron and scrap steel are melted by flames which burn in the space just above the metal charge. When the pig iron and scrap are melted, a slag of iron silicates is formed and floats as a separate layer on the liquid iron. The chemical composition of this slag is so controlled that the impurities of the underlying liquid iron are oxidized. The oxidation products of these impurities either escape as gases or are dissolved by the slag. After the slag has acted in this manner for a suitable time, the liquid metal under the slag has become an iron alloy containing such proportions of carbon as are desired for the steel, with only small and relatively harmless proportions of the other impurities which were present in the original pig iron. This product is tapped from the open hearth and poured into molds to form steel ingots.

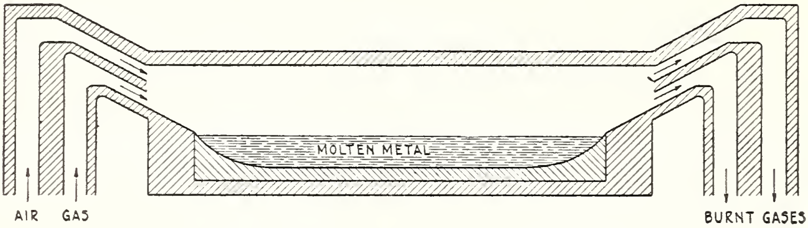

FIGURE 6.—*Diagrammatic section of an open-hearth furnace.*

There are two types of open-hearth furnaces, one lined with a basic refractory such as calcined magnesite (magnesium oxide), the other lined with the acid refractory, silica. Steels made in these two types of furnaces are known as *basic open-hearth steel* and *acid open-hearth steel*, respectively. The refining process of the open hearth, as just described, is characteristic of the basic furnace. Only a little

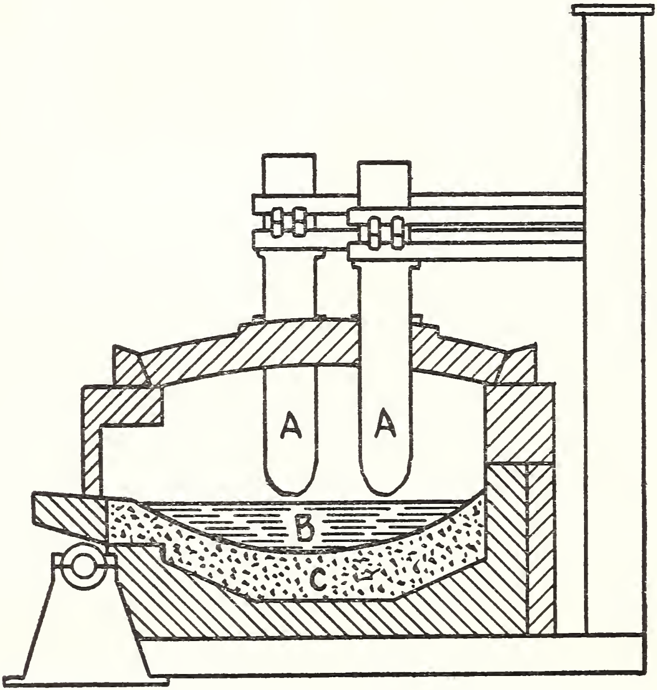

FIGURE 7.—*Diagrammatic section of an electric-steel furnace.*

A A are carbon or graphite electrodes. Arcs between these electrodes and the bath of iron, B, supply the heat. C is the refractory lining.

refining is possible in the acid furnace; accordingly the metal for the charge in the acid furnace must be selected with this in mind.

(c) ELECTRIC-FURNACE STEEL

The electric furnace may be considered as an open-hearth furnace in which the heat is supplied from electric energy rather than by combustion of fuel in the furnace. Heat is produced in electric furnaces for steel refining either by an arc immediately over the furnace hearth (fig. 7) or by electric currents induced in the metal on the hearth. Arc furnaces are the most generally used type, although in recent years induction furnaces have been developing rapidly for special high-grade alloy-steel making.

The refining action of the slag in the electric furnace is frequently quite similar to that in the open-hearth furnace. There is one difference, however, in that it is possible in an electric furnace to heat the charge of steel in an atmosphere in which there is very little or no oxygen, that is, a reducing atmosphere. Under such conditions a strongly reducing slag can be formed on the liquid metal and certain refining reactions take place which are not conveniently carried out in an open-hearth furnace.

There has been in past years a mistaken belief on the part of some that a steel was necessarily of excellent quality simply because it had been made in an electric furnace. The use of electric heating in steel furnaces does not compensate for lack of knowledge and skill in steel making.

2. MECHANICAL WORKING OF STEEL

The chief methods of mechanically working steel are rolling, forging, and drawing.

(a) ROLLING

In rolling steel ingots, the uniformly heated ingot is passed back and forth between heavy iron or steel rolls which can be set closer and closer together as the thickness of the hot steel ingot decreases (fig. 8, A). Ingots may be rolled successively to blooms, "billets", bars, plates, or sheets which, as a rule, become thinner in section in the order named. When the metal going through the rolls is hot, the process is hot rolling and the products are *hot-rolled* steel. If the metal is cold when rolled, it frequently becomes appreciably harder and stiffer, and the rolled surface is smoother and brighter in the resulting *cold-rolled* steel than in the case of hot-rolled steel.

The rolls used in making plates and sheets are termed plain or flat rolls. Grooved rolls are used for rolling certain definite shapes like round or square rods or for rolling such shapes as I beams or railroad rails.

(b) FORGING

The simplest type of forging is hammer forging—the forging practiced by the earliest workers of iron and by the fast vanishing blacksmith of more recent years. Modern forging is done by machines that are, in effect, large hammers or presses (fig. 8, B). Forging is called either hammer forging or press forging, depending on whether the forging press strikes a blow or exerts slow steady application of pressure. Forging often produces better articles of intricate shapes than does rolling. For example, the crankshaft of an automobile or airplane engine would be of very poor quality if made by machining the desired shape from rolled steel, but is much more likely to be satisfactory if it has been forged to the desired shape.

(c) DRAWING

The term "drawing" is used with three different meanings in steel metallurgy: (1) "drawing" a rod or a wire through a tapered hole in a draw plate or die so that the rod or wire is of smaller diameter (and longer) after it has passed through the die; (2) drawing or "deep-drawing" a steel sheet by means of a punch and die to form some cup-shaped article; and (3) as a heat-treating term to designate a heating process employed to lessen the hardness or brittleness of a steel after a hardening heat treatment. Only in the first two meanings does the term designate a method of mechanical working of steel.

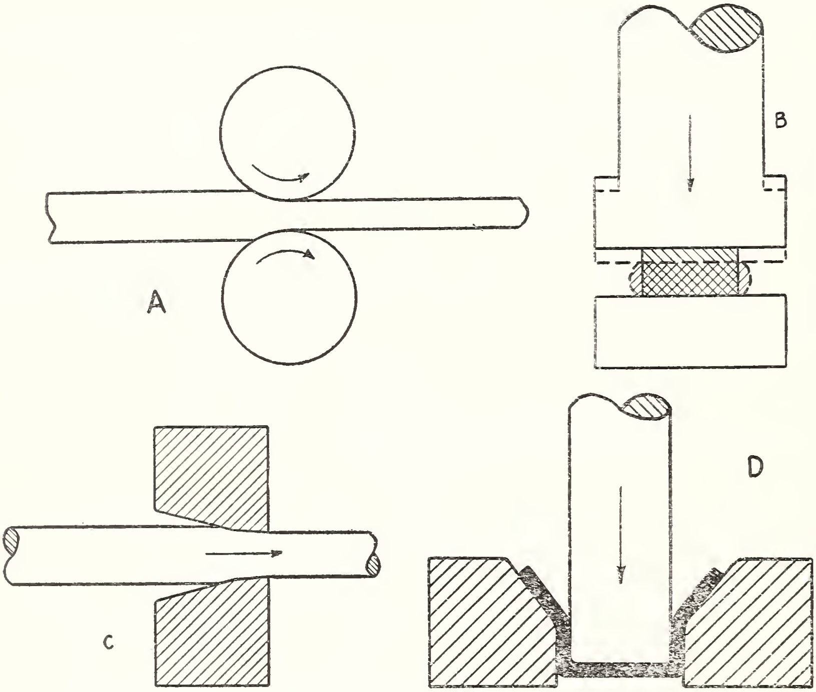

FIGURE 8.—*Methods of mechanical working of steel.*

A, rolling; B, forging; C, drawing rod or wire; and D, deep-drawing.

In the first meaning, drawing is a process used not only to produce rods and wire but also for the production of tubes. Figure 8 (C) shows a rod or wire as it is pulled through the tapered hole in a draw-plate or die. Deep-drawing in its most simple form is illustrated in figure 8 (D) where a cup-shaped article is being formed by a punch forcing a disk of sheet metal into a die.

VI. CONSTITUTION AND STRUCTURE OF STEEL

Steel is an alloy of iron and carbon (containing also other minor constituents or impurities such as manganese, silicon, sulphur, and phosphorus), which is ductile and malleable. Plain carbon steels are essentially iron-carbon alloys containing less than 1.7 percent of carbon. An alloy steel is a carbon steel in which some additional alloying element is present in sufficient proportion to improve some useful property. The carbon in alloy steels may exceed 1.7 percent.

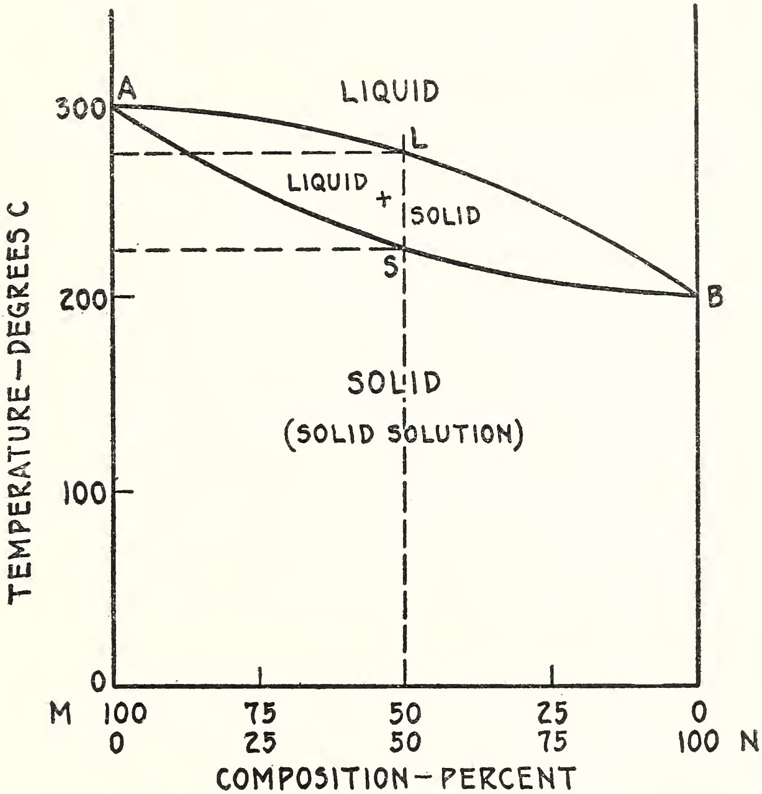

Figure 9.—*Equilibrium diagram typical of solid-solution alloys.*

1. ALLOY DIAGRAMS

The metallurgist depends to a great extent on a very convenient type of diagram to aid him in explaining and remembering the properties, heat treatments, and structures of steels. These diagrams are called "constitutional diagrams", or "equilibrium diagrams." They represent the different *constituents* present in an alloy when that alloy is in its most stable and permanent condition, i. e., *in equilibrium.*

The most simple form of these diagrams is one representing the temperatures at which all the possible alloys of two metals mutually soluble in all proportions begin to melt and begin to freeze. When two such metals, M and N, in the liquid state, are poured together, they mix completely with each other (like water and alcohol), and when such a mixture of M and N freezes, there is but one kind of crystals or grains in the resulting solid, which is called a "solid solution."

A constitutional diagram for two metals of this kind is shown in figure 9. In this figure the vertical scale (the ordinate) represents the temperature and the horizontal scale (the abscissa), the composition of the alloy of the two metals M and N. The diagram shows that the pure metal M (100 percent M) is liquid above 300° C and solid below that temperature. That is, 300° C is the melting point of metal M. Similarly, the diagram shows that metal N melts at 200° C.

If, however, we have an alloy of M and N, it will not melt or freeze completely at any one temperature, but the process of melting or freezing will continue over a range of temperatures. For example, if we have an alloy containing equal parts by weight of M and N (50 percent of each) the state of that alloy (whether solid or liquid) is represented by points along the vertical dotted line at 50 percent M on figure 9. We can tell from this diagram that as we heat such an alloy it will remain solid, for example, at 100° C, also at 200° C. But at about 225° C the vertical dotted line intersects the curved line A S B and the alloy *begins* to melt. As the temperature is increased the melting continues, but some solid remains until a temperature of about 275° C is reached. Here the last of the solid melts, and at temperatures above the line A L B the alloy is completely liquid. On cooling a molten alloy of 50 percent each of M and N, these same changes take place in the reverse order. The line A S B is the "solidus", so-called because it is the boundary of that portion, or field, of the diagram in which all the alloys are entirely solid. The line A L B is the "liquidus", so-called because it is the boundary of the field in which all the alloys are entirely liquid. Between these two boundary lines is the field in which the alloys are part liquid and part solid.

The next type of diagram to be considered is that which represents the alloys of two metals which are mutually soluble in all proportions in the liquid state but have a *limited solid solubility*. This condition is represented by figure 10. The metals P and Q in alloys of all compositions form a homogeneous liquid above C E D in the diagram. In solid alloys, however, Q is in solid solution in P only between the left side of the diagram and the line C M H. Similarly, at the right of the diagram in alloys consisting chiefly of Q, the line D N K represents the greatest amounts of P that can be in solid solution in Q at any temperature. Between M H and N K there are two kinds of crystals or grains in the solid alloys, one type of grain is the solid solution of Q in P (the solid solution of the field at the left), and the other type of grain is the solid solution of P in Q (the solid solution of the field at the right of the diagram).

If we have an alloy of P and Q of the composition represented by the vertical line x x' x'' (which would contain about 95 percent of P, 5 percent of Q) and begin cooling this alloy from the point x, it will begin to freeze at x'. From x' to x'' it will be a mixture of solid and liquid and will progressively freeze until the temperature falls to x'', where it will all become solid. This solid will be a solid solution just as was the case with the solid alloys of M and N in figure 9. If in like manner we cool (along the line *y y′ y″*) an alloy of P and Q containing about 60 percent of P and 40 percent of Q, it will begin to freeze at *y′*, be part liquid and part solid from *y′* to *y″*, and will become entirely solid at *y″*. This solid, however, will be a mixture of two solid solutions and will contain two different kinds of crystals or grains.

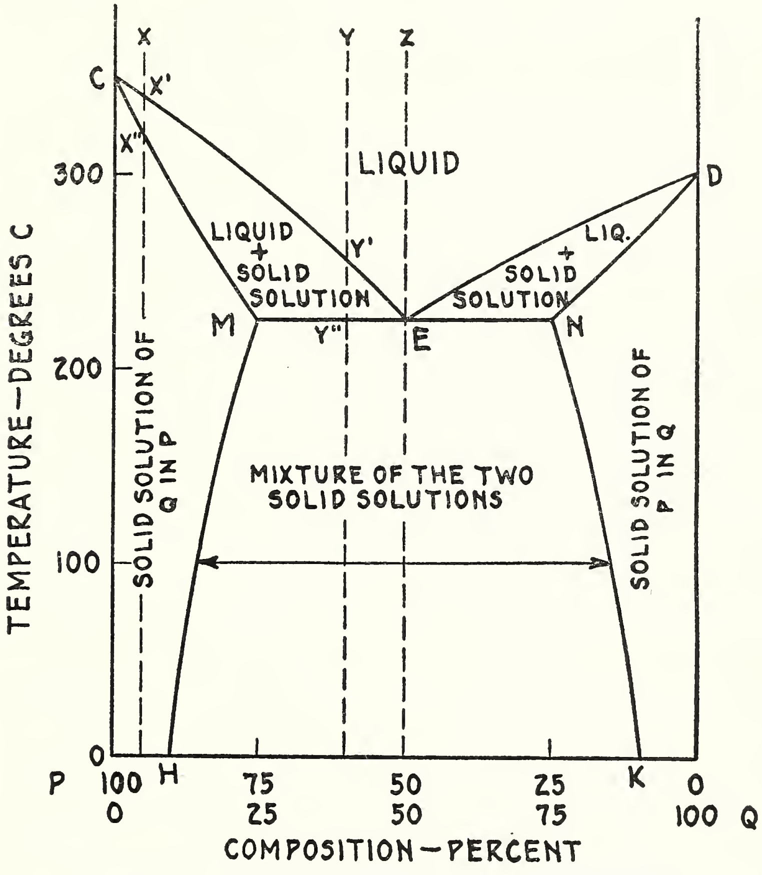

FIGURE 10.—*Equilibrium diagram typical of eutectic alloys.*

An alloy of 50 percent each of P and Q will behave still differently on cooling from *z*. It will freeze at a constant temperature (225° C). In this respect it behaves like a pure metal, but when solidified, it will consist of a mixture of the two solid solutions, Q in P and P in Q. This composition is known as the *eutectic* composition of this alloy system, the point E is the eutectic point, and the line M E N is the eutectic line at the eutectic temperature (225° C). The eutectic composition of any series of alloys is that composition which has the lowest melting point of the series of alloys to which it belongs.

2. IRON-CARBON DIAGRAM (STEEL DIAGRAM)

The diagram which represents the constitution of carbon steels and cast irons at equilibrium is the iron-carbon diagram shown in figure 11.

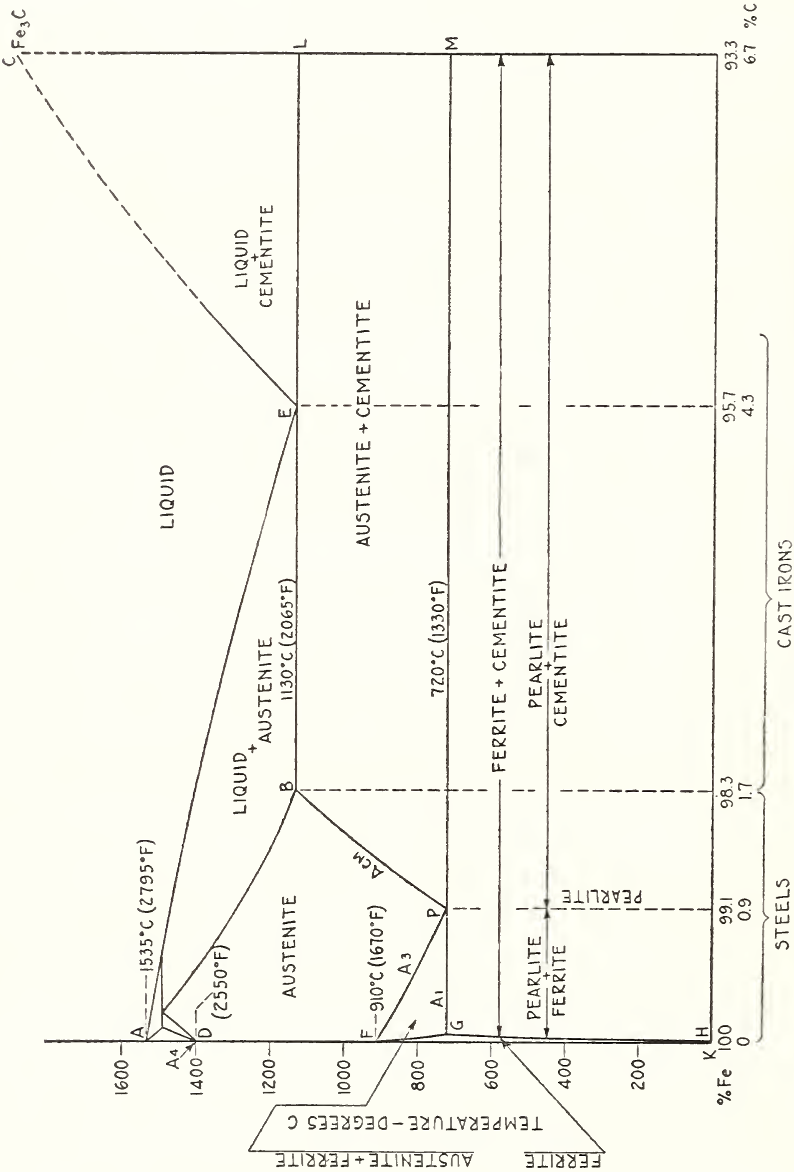

FIGURE 11.—*Iron-carbon diagram.*

This diagram actually represents only a small part of the complete iron-carbon diagram—the high-iron side, from about 93- to 100-percent iron. The right-hand boundary of this diagram represents the iron carbide, Fe_3C, commonly called *cementite.* So this portion of the iron-carbon diagram is a complete diagram of alloys of iron and cementite.

The iron-carbon alloy system has a eutectic at E, about 4.3 percent of carbon. B E L is the eutectic line at a temperature of 1,130° C (2,065° F). In the field directly below the line B E L iron-carbon alloys are a mixture of two types of crystals or grains, namely, the solid solution at the left (austenite) and the carbide (cementite) at the right of the diagram. The field D F P B represents a solid solution of carbon in iron, *austenite.*

The point P resembles the point E in certain respects. Just as point E is the lowest temperature, and the constant temperature, at which the *liquid solutions* of carbon in iron change to a mixture of austenite and cementite, so point P is the lowest temperature, and the constant temperature, at which the *solid solutions* of carbon in iron change to a mixture of *ferrite* (which is simply pure iron) and cementite. The chief difference is that the change at P is from a *solid* solution instead of from a *liquid* solution as at E. When a solid solution is involved, such a point (P) is called a *eutectoid* point.

The eutectic composition of iron-carbon alloys is at about 4.3 percent of carbon; the eutectoid composition at about 0.9 percent of carbon. Steels containing less than about 0.9 percent of carbon are called *hypoeutectoid* (under or less than eutectoid) steels; those containing more than about 0.9 percent of carbon are called *hypereutectoid* (above or more than eutectoid) steels. As a rough approximation, it can be said that the division between steels and cast irons on the basis of carbon content comes at 1.7 percent of carbon. This is the maximum amount of carbon that can be held in solid solution in austenite in a simple iron-carbon alloy (point B, fig. 11).

Another method of defining and distinguishing steels and cast irons is to state that iron-carbon alloys that do not contain the eutectic constituent in their microstructure are steels; those that do contain the eutectic in their microstructure are cast irons.

The portion of figure 11 marked "Cast Irons" represents the constitution of white cast iron, in which the carbon is all combined as cementite and the fracture is white. There is another iron-carbon diagram, the diagram representing iron and graphite as the two alloying elements, which can be used to represent gray cast iron. For the present discussion it is sufficient to say that under certain conditions cast irons freeze with the formation of free graphite and iron when the formation of Fe_3C is indicated in figure 11. Such irons are the gray irons.

That part of figure 11 to the left of the vertical line through B and below the eutectic temperature is the portion of particular interest in the study of steels. This portion is represented on a larger scale in figure 12.

Steels at high temperatures (above the lines F P and P B) are solid solutions of carbon in gamma iron (γ-iron). Gamma iron has its atoms arranged in a face-centered cubic crystal lattice—an atom at each corner of a cube and an atom at the center of each cube face. (See the small diagram under the word "austenite", at top in fig. 12.) Gamma iron can dissolve a very considerable amount of carbon, that is, up to 1.7 percent (point B of figure 12). When pure γ-iron is cooled, it transforms to another kind of iron at 910° C (the so-called A_3 transformation). Below this temperature iron is called alpha iron (α-iron) and has a body-centered cubic crystal lattice—an atom at each

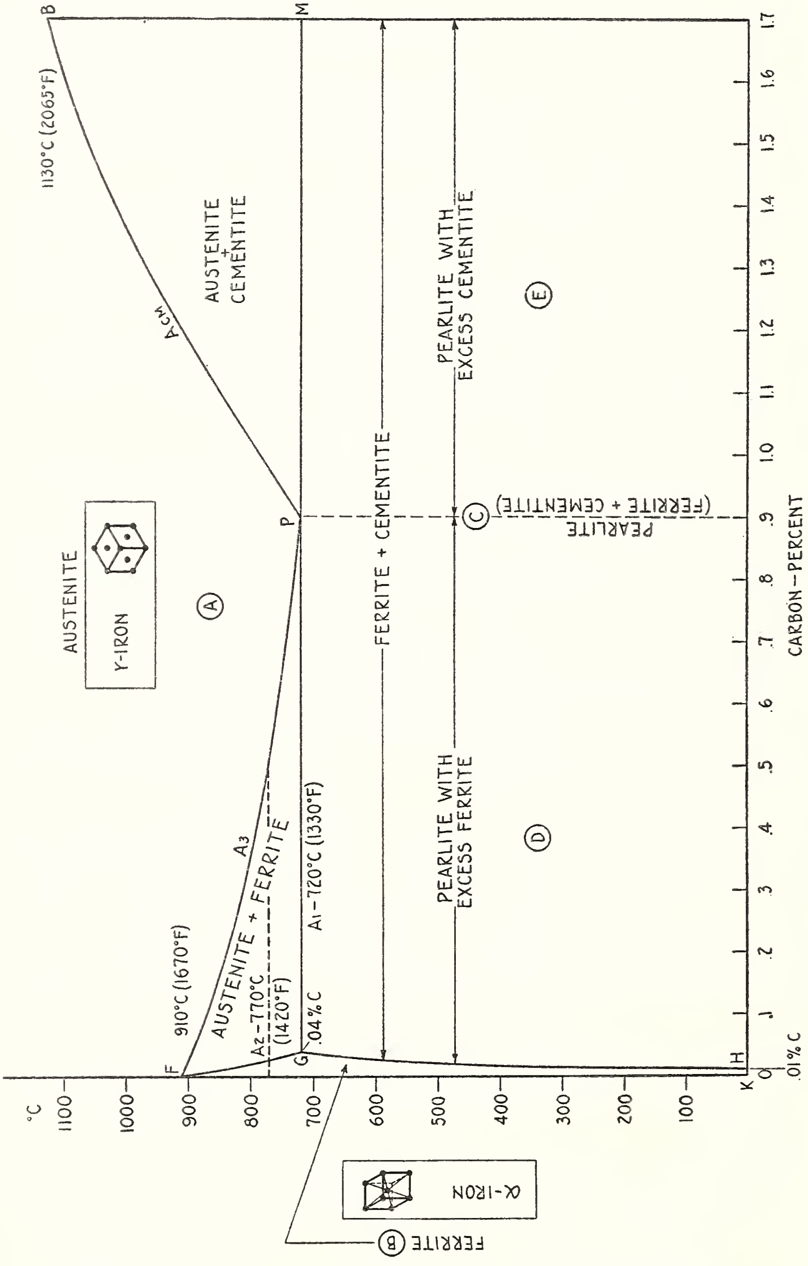

Figure 12.—*Equilibrium diagram for carbon steels.*

corner of a cube and one atom at the center of the cube. (See the small diagram under the word "ferrite", at left, in fig. 12.)

This same change from γ- to α-iron takes place in γ-iron which has carbon in solution, but it occurs at lower temperatures as the carbon content increases (line FPM, fig. 12). Alpha iron can dissolve only a very slight amount of carbon, about .04 percent as a maximum at point G, figure 12. Therefore, when austenite is cooled slowly, most of the carbon originally in solid solution precipitates (as Fe_3C). These are the causes of the various structures typical of slowly cooled carbon steels.

The transformation temperatures indicated by the lines F P, G P, and P M are called "critical temperatures" and the temperature range between F P and G P is called the "critical temperature range."

Figure 13 represents the typical structural constituents of steels. These structures are made visible by polishing a small section of the metal, etching the surface with some suitable chemical that will outline grains and other structures, and then examining the etched surface under a microscope. The number of *diameters* that the structure is magnified by the microscope is indicated with the micrograph usually by such a designation as "× 100", meaning the magnification is 100 diameters.

VII. HEAT TREATMENT OF STEELS

1. DEFINITIONS OF TERMS

Heat treatment and the various operations involved in heat treatment of iron alloys have been defined in the following terms by a committee composed of representatives of the American Society for Testing Materials, the Society of Automotive Engineers, and the American Society for Metals.

Annealing.—A heating and cooling operation of a material in the solid state, usually implying a relatively slow cooling.

NOTE.—Annealing is a comprehensive term. The purpose of such a heat treatment may be:

(a) To remove stresses.
(b) To induce softness.
(c) To alter ductility, toughness, electrical or magnetic characteristics, or other physical properties.
(d) To refine the crystalline structure.
(e) To remove gases.

In annealing the temperature of the operation and the rate of cooling depend upon the material being heat treated and the *purpose* of the treatment.

Certain specific heat treatments coming under the comprehensive term "annealing" are:

Full annealing.—Heating iron-base alloys above the critical-temperature range, holding above that range for a proper period of time, followed by slow cooling through the range.

NOTE.—The annealing temperature is generally about 100° F above the upper limit of the critical-temperature range, and the time of holding is usually not less than one hour for each inch of section of the heaviest objects being treated. The objects being treated are ordinarily allowed to cool slowly in the furnace. They may, however, be removed from the furnace and cooled in some medium which will retard the rate of cooling as compared to unrestricted cooling in air.

Process annealing.—Heating iron-base alloys to a temperature below or close to the lower limit of the critical-temperature range followed by cooling as desired.

NOTE.—This heat treatment is commonly applied in the sheet and wire industries and the temperatures generally used are from 1,020 to 1,200° F.

Normalizing.—Heating iron-base alloys to approximately 100° F above the critical-temperature range followed by cooling to below that range in still air at ordinary temperature.

NOTE.—Normalizing is rarely practiced with hypereutectoid steels because of the coarsening of the grain and the tendency to crystallize cementite at grain boundaries or in needles. However, it may sometimes be necessary to normalize these steels by heating them above the Ac_{cm}[1] line of the iron-carbon diagram.

Patenting.—Heating iron-base alloys above the critical-temperature range followed by cooling to below that range in air or in molten lead maintained at a temperature of about 700° F.

NOTE.—This treatment is applied in the wire industry either as a finishing treatment, or, especially, in the case of eutectoid steel, as a treatment previous to further wire drawing. Its purpose is to produce a sorbitic[2] structure.

Spheroidizing.—Prolonged heating of the iron-base alloys at a temperature in the neighborhood of, but generally slightly below, the critical-temperature range, usually followed by relatively slow cooling.

NOTE.—(a) In the case of small objects of high-carbon steels, the spheroidizing result is achieved more rapidly by prolonged heating to temperatures alternately within and slightly below the critical temperature range.
(b) The object of this heat treatment is to produce a globular condition of the carbide.

Tempering.—(also termed *drawing*)—Reheating iron-base alloys, after hardening, to some temperature below the critical-temperature range, followed by any desired rate of cooling.

NOTE.—(a) Although the terms tempering and drawing are practically synonymous as used in commercial practice, the term tempering is preferred. (b) Tempering, meaning the operation of hardening followed by reheating, is a usage which is illogical and confusing in the present state of the art of heat treating and should be discouraged.

Malleableizing.—Malleableizing is a type of annealing operation with slow cooling whereby the combined carbon in white cast iron is transformed to temper carbon, and in some cases the carbon is entirely removed from the iron.

NOTE.—Temper carbon is free carbon in the form of rounded nodules made up of an aggregate of minute crystals.

Graphitizing.—Graphitizing is a type of annealing for gray cast iron whereby some or all of the combined carbon is transformed to free or graphitic carbon.

Carburizing (Cementation).—Adding carbon to iron-base alloys by heating the metal below its melting point in contact with carbonaceous material.

NOTE.—The term carbonizing used in this sense is incorrect, so its use should be discouraged.

Case.—That portion of a carburized iron-base alloy article in which the carbon content has been substantially increased; also refers to case hardening.

---

[1] The "Ac_{cm} line" corresponds to the line marked simply A_{cm} in figure 12.

[2] A sorbitic structure may be described as an agglomeration of *very fine* carbide and ferrite, showing neither lamellar nor spheroidized carbide particles. The precise definition of sorbite is at present under discussion among metallurgists.

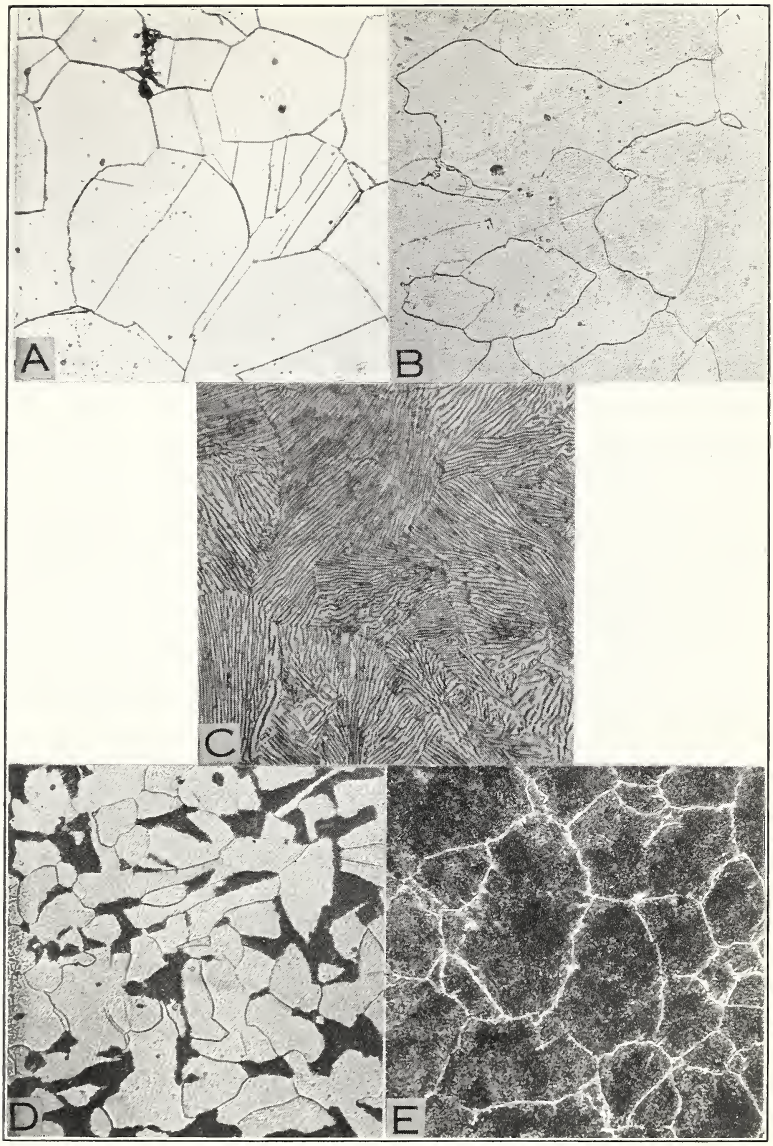

Figure 13.—*Structural constituents of steel.*

A, Austenite. Large grains of a solid solution. All grains of same composition. × 200.

B, Ferrite. Also grains which are all alike in composition. × 100.

C, Pearlite. Two different substances present, ferrite and cementite. They have formed in alternating layers, producing so-called lamellar pearlite. This is closely of eutectoid composition, i. e., 0.9 percent of carbon. × 500.

D, Hypoeutectoid steel. Contains considerably *less than* 0.9 percent of carbon. Structure is therefore a small amount of pearlite (dark areas) with a considerable excess of ferrite (light areas). × 100.

E, Hypereutectoid steel. Contains slightly *more than* 0.9 percent of carbon. Structure is therefore largely pearlite (dark) with a small excess of cementite (light) as a network. × 100.

FIGURE 14.—*Martensite.*

Angular, needle-like structure of hardened steel. × 500.

Case Hardening.—Carburizing, and subsequent hardening by suitable heat treatment, of all or part of the surface portions of a piece of iron-base alloy.

Core.—That portion of a carburized iron-base alloy article in which the carbon content has not been substantially increased; also refers to case hardening.

Also a body of sand or other material placed in a mold to produce a cavity in a casting.

Hardening.—Heating and quenching certain iron-base alloys from a temperature either within or above the critical-temperature range.

Heat treatment.—An operation, or combination of operations, involving the heating and cooling of a metal or alloy in the solid state for the purpose of obtaining certain desirable conditions or properties.

NOTE.—Heating and cooling for the sole purpose of mechanical working are excluded from the meaning of this definition.

Nitriding.—Adding nitrogen to iron-base alloys by heating the metal in contact with ammonia gas or other suitable nitrogenous material.

NOTE.—Nitriding is conducted at a temperature below the iron-carbon critical-temperature range and produces surface hardening of the metal without quenching.

Quenching.—Rapid cooling by immersion.

NOTE.—Immersion may be in liquids, gases, or solids.

The changes taking place in steels during full annealing, process annealing, and normalizing treatments are readily understandable by a study of figure 12. Malleableizing and graphitizing treatments are applied to cast irons in the field indicated in figure 11.

An explanation of the hardening and tempering of steels requires the development of another type of diagram.

2. HARDENING BY QUENCHING

Annealed or slowly cooled steels have the constitution indicated by figure 12 and the structural constituents illustrated in figure 13. At room temperatures such slowly cooled steels consist only of mixtures of ferrite and cementite. Ferrite is relatively soft and, while cementite itself is hard, annealed steels do not develop very great hardness or strength from the relatively coarse particles of cementite that are scattered through the matrix or background of soft ferrite.

If, however, a carbon steel is cooled rapidly, as by quenching in water, from a temperature above the upper critical temperature (above the line F P M, fig. 12), it may become "glass hard", strong but brittle. The angular, needle-like microstructure of such a steel is shown in figure 14. This structural constituent of hardened steels is called martensite. X-ray studies of martensite have shown that its crystal structure is somewhat like that of α-iron, in that its lattice is body-centered. It differs from α-iron, however, in that its lattice is not a perfect cube but has one edge longer than the other two. This "tetragonal" lattice of iron is able to retain in solid solution, or as *very* fine particles, the carbon or cementite that is insoluble in true α-iron, the cubic-lattice α-iron.

In order to understand the conditions that prevail during the quenching of a steel, what takes place during the hardening of steels, and what effects alloys and other factors have in changing the hardening characteristics of steels, we need a diagram that will show the results of cooling iron-carbon alloys at different, relatively fast rates. Figures 11 and 12 represent only iron-carbon alloys that are cooled *slowly*.

Figure 12 shows that a carbon steel containing about 0.9 percent of carbon, when cooled slowly from above the critical temperature (above P), transforms from austenite to pearlite (ferrite+cementite) at the temperature of point P, namely, at 720° C. If we took a specimen of this same steel and cooled it a little more rapidly, we should find that no transformation took place until the temperature had fallen to possibly 650° C. Upon cooling still more rapidly, we

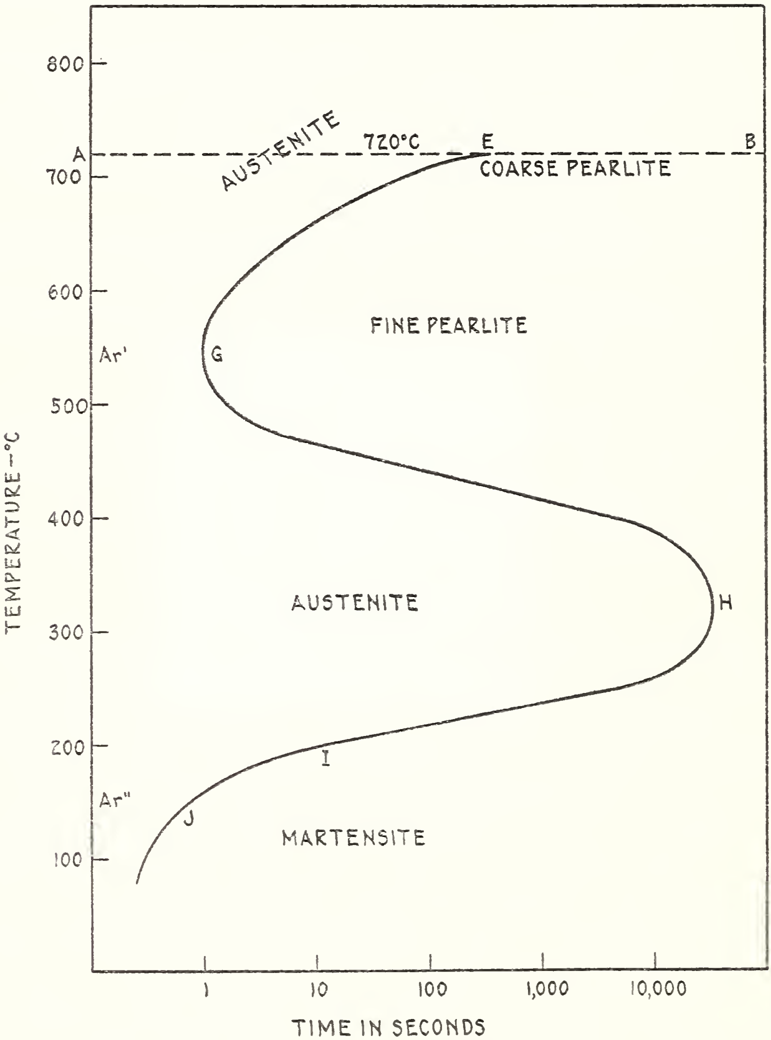

Figure 15.—*Decomposition of austenite at temperatures below the critical temperature.*

might find the temperature of this transformation was still further lowered to between 600 and 550° C and also a second transformation appears at between 200 and 100° C. If we then quenched a specimen of the steel in cold water, we should find no transformation occurred until the steel had cooled to about 100° C. Thus, it is evident that as the rate of cooling the steel is increased, first the temperature of the transformation of γ- to α-iron is progressively lowered, then a second transformation at a much lower temperature appears, and finally, with the fastest rates of cooling (quenching) the high-temperature transformation disappears and only the low-temperature transformation takes place.

The higher temperature transformation is designated as the Ar′ transformation and the lower temperature transformation as the Ar″. The significance of the Ar′ and Ar″ temperatures is conveniently represented by figure 15.

In this figure the S-shaped curve E G H I J represents the time required at any temperature for austenite to begin to decompose. At the temperature of the eutectoid line of the iron-carbon equilibrium diagram (720° C, fig. 12) austenite decomposes on *slow cooling* to form pearlite. This is represented by the point E in figure 15. If this particular austenite is cooled so rapidly to 550° C that no decomposition takes place during the cooling, then the time required for it to begin to decompose at 550° C is *very short.* If this same austenite is cooled very rapidly and without decomposition to about 400° C, then a very long time is required for decomposition to begin at that temperature. Finally, if this austenite is cooled rapidly and without decomposition to about 100° C, it decomposes at that temperature in a very short time and forms martensite. The two temperature ranges of rapid decomposition of austenite are the Ar′ and Ar″ transformation ranges.

Figure 16 shows how the S-shaped curve controls the behavior of steel during rapid cooling or quenching. The curve E F G H I J is the same as the S curve of figure 15 and has the same significance, representing the time required at any temperature for the austenite of a high-carbon steel to begin to decompose.

The four curves all starting at point C just below 800° C, and marked, respectively, "anneal", "slow quench", "fast quench", and "very fast quench", represent the time-temperature relations during different rates of cooling of a high-carbon steel. At temperatures above the line A B (720° C) the steel is austenitic. When such a steel is annealed (cooled very slowly), the austenite changes to coarse pearlite at point E on line E F G, that is, at practically 720° C. The curve marked "slow quench" indicates that the same steel, when cooled more rapidly, suffers no change at 720° C but retains its austenitic condition until it has cooled to point F, where the austenite changes to fine pearlite (also called troostite). This transformation is the Ar′ transformation. The same steel, cooled still more rapidly, along the curve marked "fast quench", reaches the temperature of point G before the Ar′ transformation occurs and any decomposition of austenite takes place. Then only an infinitesimal portion of fine pearlite is formed, while most of the austenite remains stable until the temperature falls to point I. At this relatively very low temperature the remaining austenite decomposes and now forms the extremely hard constituent of quenched steel, martensite. This low-temperature transformation is the Ar″ transformation. At this particular rate of cooling both Ar′ and Ar″ transformations occur in the steel specimen. A specimen quenched still more drastically follows the curve marked "very fast quench", has no Ar′ transformation, retains all its austenite while cooling to point J, and then (at Ar″) transforms to martensite.

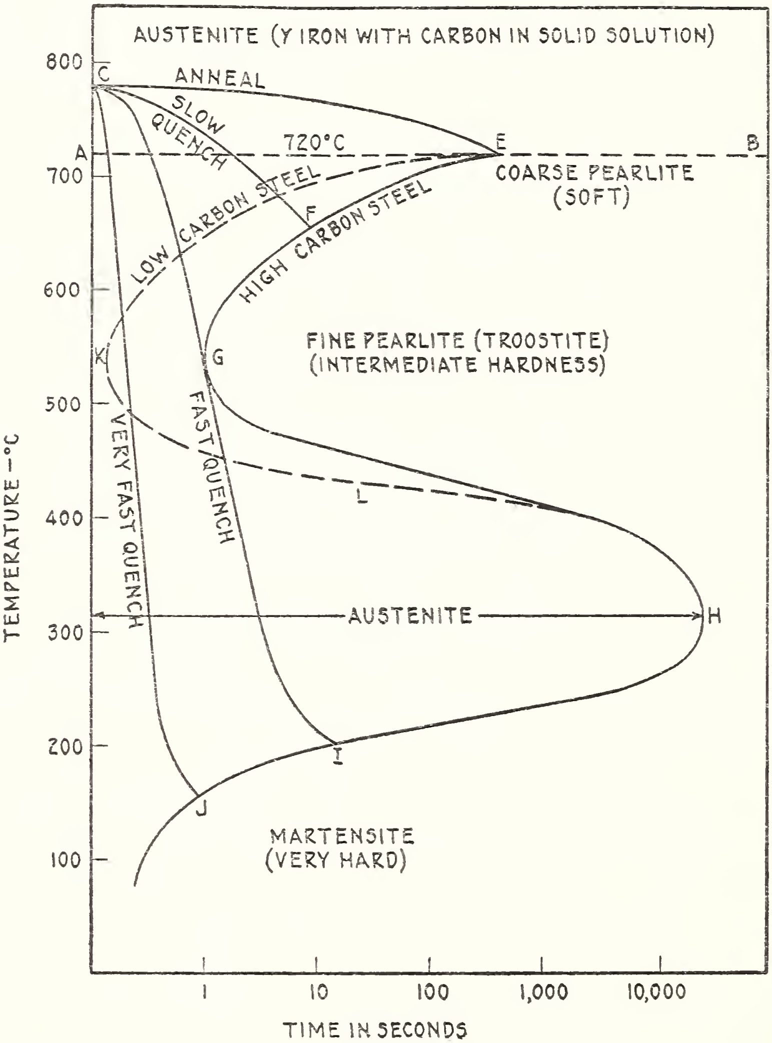

FIGURE 16.—*A quenching diagram for steels.*

The S-shaped curve E F G H I J of figure 16 represents the time required at various temperatures for austenite of a high-carbon steel to decompose; it shows two temperature ranges in which austenite is least stable (decomposes in the shortest times), namely, between 500 and 600° C, the Ar′ temperature range, and between 100 and 200° C, the Ar″ temperature range; it also shows how the product of the decomposition of austenite varies with the temperature at which decomposition takes place. The product of decomposition at temperatures above about 650° C is coarse pearlite and is soft, at 500 to 600° C it is fine pearlite and of intermediate hardness, and at 100 to 200° C it is martensite and is very hard.

The S-curve of figure 16 just discussed in detail represents the behavior of a high carbon steel without any alloying elements. The dotted curve E K L represents the behavior of the austenite of a low-carbon steel. In the Ar′ temperature range the austenite of this low-carbon steel is much less stable than the austenite of the high-carbon steel. It is, therefore, evident that this low-carbon steel must be quenched much more drastically than the high-carbon steel in order to cool its austenite through the Ar′ range without decomposition and enable the steel to harden by transforming to martensite at 200 to 100° C (the Ar′′ range). This corresponds with the fact that low-carbon steels have a low hardenability.

This discussion has been based on the behavior of carbon steels, but the principles apply also to alloy steels that are hardenable by quenching. The specific influences of the various alloying elements in steels will be considered in detail in a subsequent section.

The hardenability of a steel, then, depends on the ease with which its austenite can be cooled through the Ar′ temperature range without decomposition. The further to the left the position of the upper head of the S curve (at K or G, fig. 16), the greater the difficulty in cooling through the Ar′ range without decomposition, and the lower is the hardenability of the steel. Any factor which moves this upper bend of the S curve to the right, such as increasing the carbon content of the steel, increases the hardenability. This influence of carbon (and other factors) on hardenability is reflected in the terms "water-hardening steels" and "oil-hardening steels." The first of these terms is applied to steels such as the low-carbon and low-alloy steels, which require quenching in water for hardening because these S curves are toward the left of figure 16. The second term is applied to steels whose S curves are more to the right in figure 16 and which can therefore be cooled less rapidly, as by quenching in oil, and yet be cooled through the Ar′ range without decomposition of the austenite.

The "critical cooling rate" or "critical quenching rate" of a steel is the slowest rate at which it can be cooled through the Ar′ range without decomposition of the austenite. That is, the critical cooling rate for the high-carbon steel of figure 16 is the slope in the range 600 to 500° C of the temperature-time curve C I which just touches the S curve at G.

3. TEMPERING

Tempering has already been defined as reheating, after hardening, to some temperature below the critical temperature. Reheating a hardened steel gradually softens the martensite, causing it to change at first to true α-iron containing very finely divided particles of cementite (Fe_3C). As tempering continues to higher temperatures, the product becomes softer and softer, resulting in much the same changes in properties as result if austenite is decomposed at higher and higher temperatures along the S curve of figure 16.

Tempering, in general, increases the toughness or the resistance of hardened steel to shocks as the hardness decreases.

4. METHODS OF SURFACE HARDENING

Hardening a steel by quenching is a process that increases hardness to a considerable depth in the steel, possibly hardening the steel article throughout its whole cross section. Frequently methods are used for hardening merely the surface layers of steel, leaving the interior of the steel relatively soft.

(a) CARBURIZING

Carburizing is the most widely used of these surface hardening methods. A low-carbon steel (0.10 to 0.20 percent of carbon), if packed in a box in a mixture of charcoal, barium, calcium, and sodium carbonates, and heated for several hours to about 1,700° F (well above the A_3 line in fig. 12), will absorb considerable amounts of carbon and become, at the surface, a high-carbon steel (more than 0.9 percent of carbon). (See fig. 17.) This method is sometimes called "pack-carburizing." This carburized steel is then cooled and reheated to a temperature which is sufficient to convert the high-carbon case to austenite (just above the line GM, fig. 12) and is quenched. The high-carbon steel at and near the surface is hardened while the low-carbon interior (the core) has not been heated high enough to be changed to austenite (i. e., has been at temperatures far below the line FP, fig. 12) and hardens little or not at all on quenching. The result is a case-hardened steel, with a hard high-carbon surface layer and a relatively soft and tough low-carbon core.

Carburizing mixtures within the following ranges of composition have been used successfully:

Charcoal (%)	40 to 65
Barium carbonate (%)	5 to 16
Calcium carbonate (%)	2 to 7
Sodium carbonate (%)	3 to 12

Carburizing can also be accomplished by heating in an atmosphere of carbon gases, such as illuminating gas.

(b) CYANIDE HARDENING

Cyanide hardening is another method of hardening the surfaces of steel. A low-carbon steel, heated for an hour or two in a bath of molten sodium cyanide (a bath of about 50 percent of cyanide and containing also sodium carbonate and sodium chloride), absorbs both carbon and nitrogen in its surface layers. Subsequent quenching hardens this case in a manner similar to the hardening of the pack-carburized steel. The cyanide case is not as thick as the pack-carburized case and is a little lower in carbon.

(c) NITRIDING

Nitriding is a method of surface hardening developed relatively recently. In this process the steels to be surface hardened (such steel usually containing small amounts of aluminum, chromium, molybdenum, or vanadium) are heated at about 500° C in ammonia gas. The steel absorbs nitrogen at the surface and becomes extremely hard without the necessity of quenching—harder than either a pack-carburized or a cyanide case.

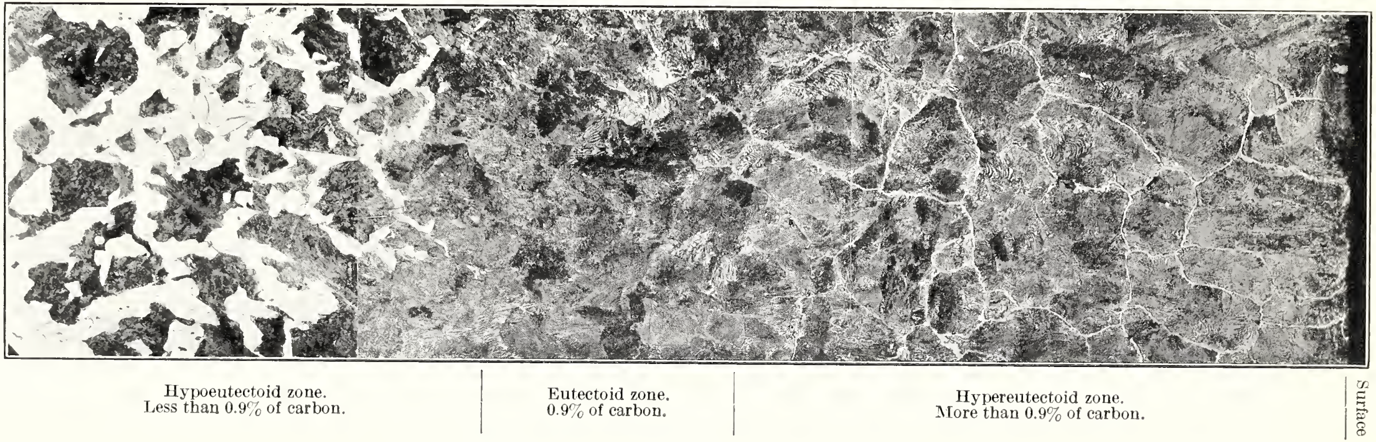

FIGURE 17.—*Structure of a carburized steel.*

This represents the structure of a carburized steel as slowly cooled after carburizing. It has not been hardened. × 75.

VIII. HEAT-TREATING EQUIPMENT

As a rule, satisfactory heat treatment of steel requires, *first*, knowledge of the composition of the steel to be treated; *second*, familiarity with and understanding of the equilibrium diagram (fig. 12) and the quenching diagram (fig. 16) of steels as discussed in the preceding sections (or, in place of this, a knowledge of the recommended treatments for the steel in question as given in textbooks or handbooks of metallurgy); *third*, furnaces that have uniform and readily controlled temperatures; *fourth*, means for accurate measurement of the temperatures of the furnace or of the steel being heated; *fifth*, means for protecting the steel from scaling during heating; and finally, sufficient amounts of suitable quenching media. It is possible for an individual of sufficient experience and skill in the art to do heat treating with only a blacksmith's forge or a torch flame for heating, and a trained eye for judging temperatures by color. But such procedures are not to be recommended to a novice.

1. FURNACES AND FURNACE ATMOSPHERES

Fuel-fired furnaces (gas or oil furnaces) require a supply of compressed air or an air blower for satisfactory application to most heat-treatment operations. They are usually muffle furnaces, that is, the combustion of the fuel takes place outside of the chamber in which the steel pieces are placed for heating. As just mentioned, a hand forge may be used for heat treatments, but the control of rate of heating and of temperature is difficult and uncertain for an operator lacking long experience. Electric-resistance furnaces are very convenient and efficient. The most commonly used electric furnaces are heated by coils or grids of nickel-chromium resistance alloy (much like the alloy wire used in electric toasters and household radiant electric heaters). Such furnaces with the better grades of resistance wire can be operated at temperatures up to about 1,000° C. Recently new types of resistance wire have been developed that are said to permit the use of furnaces at temperatures of about 1,300° C. Another type of electric furnace for temperatures of the order of 1,300° C uses nonmetallic resistor bars containing carbon or carbides.

It is frequently necessary or desirable to protect the steel from surface oxidation (scaling) and loss of carbon from the surface (decarburization) during heating. This protection is sometimes accomplished by packing the steel in sand containing a little crushed charcoal, or by wrapping the steel in a sheet of soft iron and crimping over the edges of the sheet to form a rather tight envelope about the steel piece. Another very convenient method is to keep the furnace full of illuminating gas during heating. The gas escapes around the door and other openings and burns as it reaches the air. Caution must be used in employing gas in this manner as a *mixture* of gas and air will explode if ignited. If the furnace is kept full of gas with no admixture of air, there is no danger of explosion even at very high temperatures. If a furnace is quite gas tight, except around the door, it is possible to protect steel in the furnace by burning gas across the door opening, forming a curtain of burning gas through which no air can reach the hot steel.

Protection from oxidation is also secured by immersing the steel in molten metal or fused salt baths during heat treatment.

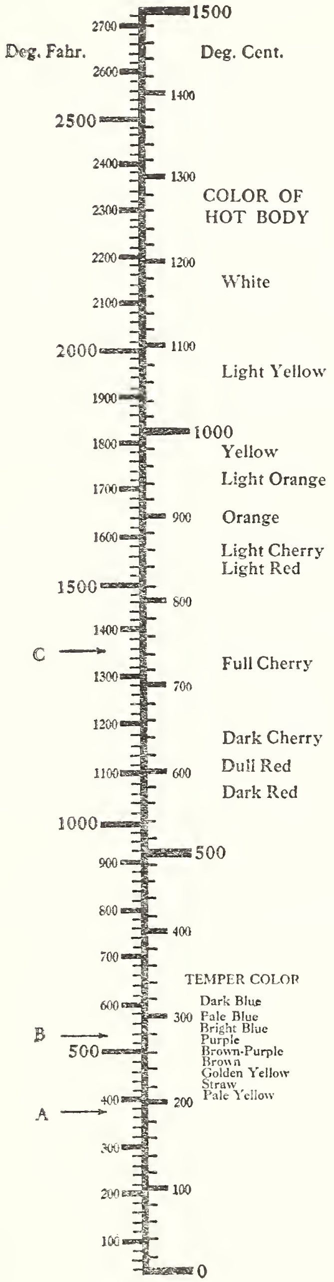

FIGURE 18.—*Temperature chart indicating: (a) Conversion of centigrade to Fahrenheit or vice versa. (b) Color temperature scale for: (1) Hardening-temperature range, (2) tempering-temperature range.*

Fused mixtures of chlorides or chlorides and carbonates are used for high-temperature baths for hardening steel and fused mixtures of nitrates for lower temperature baths for tempering. Baths of high flash-point oils are also used for tempering.

2. TEMPERATURE MEASUREMENT AND CONTROL

Estimating the temperatures in heat treating by the color of the furnace or of the steel requires the least equipment but the greatest amount of skill and experience. Steel begins to appear red when it is heated to about 600° C. As its temperature increases the color changes gradually through various shades of red, to orange, to yellow, and finally to white. A rough approximation of the correspondence between color and temperature is indicated in figure 18.

It is also possible to secure some idea of the temperature of a piece of steel in the range of temperatures used for tempering treatments from the color of the thin oxide films that form on the surface of the steel. The succession of these colors and the approximate temperature they represent are indicated on the lower portion of the scale of figure 18.

All modern efficient heat-treating equipment includes accurate pyrometers for measuring temperatures and also instruments for the automatic control of furnace temperatures. A thermocouple pyrometer consists of two wires of unlike metals or alloys welded together at one end, called the "hot-junction." This hot junction is placed at the point where it is desired to measure the temperature, and the free ends of the two wires, outside the furnace, are attached to an instrument (a potentiometer or a millivoltmeter) which measures the very small electrical potential which is generated by heating the hot junction. The magnitude of this potential generated at the hot junction is proportional to the temperature of the hot junction and thus serves to measure the temperature.

The control of temperature in electric heat-treating furnaces is accomplished by an instrument which increases the heating current in the furnace resistors when a thermocouple, whose hot junction is in the heating chamber of the furnace, indicates a temperature *slightly below* the desired temperature. Conversely, this same thermocouple, if it reads *slightly above* the desired temperature, causes the controller to decrease the current in the heating coils of the furnace.

3. QUENCHING MEDIA

The most commonly used quenching media are water, oil, and aqueous solutions of salts. Quenching media differ in the speed with which they cool a piece of steel from the quenching temperature. For example, the curves CGI, and CJ of figure 16 might represent, respectively, the rate at which a piece of steel is cooled by quenching in oil and in water. Water cools the steel more rapidly than oil. Solutions of caustic soda (sodium hydroxide) or of common salt (sodium chloride) in water quench a steel still more rapidly than water alone.

In figure 16 the cooling of the steel along the curve CGI, by quenching in oil, is just fast enough in the Ar′ range (at point G) to permit the high-carbon steel to harden fully. Oil is, therefore, a suitable quenching medium for this steel and, indeed, is usually to be preferred to a more rapid quench. This is because a more rapid quench, such as along curve CJ by quenching in water, does not make the steel any harder although it is more liable to cause cracking of the steel.

Quenching solutions of strange and unusual compositions are rarely of value. Quenching solutions act only through their ability to cool a steel rapidly. They have no beneficial chemical action on the quenched steel and in themselves impart no unusual properties. Nearly every requirement for quenching media is met satisfactorily by water or by aqueous solutions of inorganic salt, such as common table salt or caustic soda, or by some type of oil.

It must be remembered that the quenching efficiency of any given medium may change appreciably with change in temperature of the solution. This is particularly true of water but less so of oil. For this reason a sufficient quantity of a quenching medium must be used so that the heat of the quenched steel does not cause an excessive increase in the temperature of the quenching medium. As an alternative, and for continuous use, quenching baths may be provided with coils for artificial cooling.

The rate at which a quenching medium cools steel is also influenced by the circulation or agitation of the liquid. Rapid circulation of the liquid increases the cooling power as, for example, the use of a water spray instead of a body of still water for quenching.

The relative cooling rates of various quenching media have been established by comparing them to the cooling rate of still water at 20° C (68° F). If unity (1.00) represents the rate at which still water at 20° C (68° F) cools a piece of steel (quenched from 870° C (1,600° F) at the temperature 720° C (1,325° F), then the relative quenching rates of various quenching media are as shown in table 1, those having a rate greater than 1 are faster than water and those less than 1 are slower than water.

TABLE 1.—*Comparison of speeds of quenching media*

	Relative quenching rate at—		
	20° C (68° F)	60° C (140° F)	99° C (210° F)
Water, still	1.00	0.44	0.07
Water, flowing at 3 ft/sec	1.01	.46	.08
5-percent sodium-chloride solution, still	1.12	.62	--------
5-percent sodium-chloride solution flowing 3 ft/sec	1.14	.72	.14
10-percent sodium-chloride solution flowing 3 ft/sec	1.23	--------	--------
5-percent sodium-hydroxide solution, still	1.17	.78	--------
5-percent sodium-hydroxide solution flowing 3 ft/sec	1.20	.90	.20
10-percent sodium-hydroxide solution flowing 3 ft/sec	1.20	--------	--------
Oils, (various mineral, vegetable, and animal oils and oils especially prepared for quenching steels)	0.15 to .40	--------	--------

IX. PROPERTIES AND USES OF PLAIN CARBON AND ALLOY STEELS

The so-called "plain carbon steels" are the iron-carbon alloys containing up to about 1.7 percent of carbon, as indicated in figure 11, together with small amounts of manganese, silicon, sulphur, and phosphorus. Plain carbon steels containing about 0.10 to 0.20 percent of carbon, sometimes called machinery steel, are often supplied as cold-rolled steel, and are widely used for carburizing. With 0.30 to 0.50 percent of carbon they are often known as forging steels, and may be heat treated to increase their strength and hardness appreciably. Carbon steels, with above about 0.60 percent of carbon, are often classed as tool steels and will be discussed in more detail in a subsequent section on tool steels.

An alloy steel is a carbon steel to which has been added a sufficient proportion of one or more alloying elements (other than carbon) to improve some useful property of the steel. The upper limit of 1.7 percent of carbon does not hold in all cases for alloy steels—some contain over 2 percent of carbon. There are only about a dozen elements that are added to steels as alloying elements. These are nickel, chromium, molybdenum, silicon, manganese, tungsten, vanadium, aluminum, copper, cobalt, titanium, and zirconium.

Steels may be classified on the basis of their special properties or most common uses as follows: (1) structural steels, (2) tool steels, (3) corrosion-resistant steels, (4) steels for high-temperature service, and (5) special-property steels.

1. STRUCTURAL STEELS

These include both plain carbon steels and many low-alloy steels. The classification of these steels that is most widely known and used in this country is that of the Society of Automotive Engineers (SAE). Steels that are in this classification are known as "SAE" steels and are further identified by numbers. These numbers are descriptive of the composition of the steel.

The following description of the SAE steel numbering system and the tables showing the chemical compositions are quoted and extracted from the 1935 SAE Handbook.[3]

---

[3] By permission of the Society of Automotive Engineers, Inc.

A numeral index system is used to identify the compositions of the SAE steels, which makes it possible to use numerals on shop drawings and blueprints that are partially descriptive of the composition of material covered by such numbers. The first digit indicates the type to which the steel belongs; thus 1– indicates a carbon steel, 2– a nickel steel, and 3– a nickel-chromium steel. In the case of the simple alloy steels the second digit generally indicates the approximate percentage of the predominant alloying element. Usually the last two or three digits indicate the average carbon content in points, or hundredths of 1 percent. Thus, 2340 indicates a nickel steel of approximately 3 percent nickel (3.25 to 3.75) and 0.40 percent carbon (0.35 to 0.45); and 71360 indicates a tungsten steel of about 13 percent tungsten (12 to 15) and 0.60 percent carbon (0.50 to 0.70).

In some instances, in order to avoid confusion, it has been found necessary to depart from this system of identifying the approximate alloy composition of a steel by varying the second and third digits of the number. An instance of such departure is the steel numbers selected for several of the corrosion- and heat-resisting alloys.

The basic numerals for the various types of SAE steel are:

Type of steel	Numerals (and digits)
Carbon Steels	1xxx
Plain carbon	10xx
Free cutting (screw stock)	11xx
Free cutting, manganese	X13xx
High Manganese	T13xx
Nickel Steels	2xxx
0. 50 percent nickel	20xx
1. 50 percent nickel	21xx
3. 50 percent nickel	23xx
5. 00 percent nickel	25xx
Nickel-Chromium Steels	3xxx
1. 25 percent nickel, 0.60 percent chromium	31xx
1. 75 percent nickel, 1.00 percent chromium	32xx
3. 50 percent nickel, 1.50 percent chromium	33xx
3. 00 percent nickel, 0.80 percent chromium	34xx
Corrosion- and heat-resisting steels	30xxx
Molybdenum Steels	4xxx
Chromium	41xx
Chromium nickel	43xx
Nickel	46xx and 48xx
Chromium Steels	5xxx
Low chromium	51xx
Medium chromium	52xxx
Corrosion and heat resisting	51xxx
Chromium-Vanadium Steels	6xxx
Tungsten Steels	7xxx and 7xxxx
Silicon-Manganese Steels	9xxx and 7xxxx

The prefix X is used in several instances to denote variations in the range of manganese, sulphur, or chromium.

The prefix T is used with the manganese steels 1300 (series) to avoid confusion with steels of somewhat different manganese range that have been identified by the same numerals but without the prefix.

Table 2 is a condensation of the complete tables of SAE steel numbers and compositions given in the handbook of the Society of Automotive Engineers and in the National Metals Handbook.

TABLE 2.—*Chemical Composition of SAE steels*

[Condensed table—not all SAE steels are included]

CARBON STEELS

SAE number [1]	Carbon (%)	Manganese (%)
1010	0.05 to 0.15	0.30 to 0.60.
1020	0.15 to 0.25	
1030	0.25 to 0.35	0.60 to 0.90.
1040	0.35 to 0.45	
1050	0.45 to 0.55	
1060	0.55 to 0.70	
1070	0.65 to 0.80	
1080	0.75 to 0.90	
1090	0.85 to 1.00	

[1] See note a.

FREE-CUTTING STEELS

SAE number	Carbon (%)	Manganese (%)
1112–1120 [1]	0.08 to 0.25	0.60 to 1.00.
X1314–X1340 [2]	0.10 to 0.45	1.00 to 1.65.

[1] See note f. [2] See note g.

MANGANESE STEELS

SAE number [1]	Carbon (%)	Manganese (%)
T1330	0.25 to 0.35	1.60 to 1.90.
T1340	0.35 to 0.45	
T1350	0.45 to 0.55	

[1] See notes b and c.

NICKEL STEELS

SAE number [1]	Carbon (%)	Nickel (%)
2015	0.10 to 0.20 [2]	0.40 to 0.60.
2115		1.25 to 1.75.
2315		3.25 to 3.75.
2515		4.75 to 5.25.

[1] See notes b and c. [2] See note i.

NICKEL-CHROMIUM STEELS

SAE series [1]	Nickel (%)	Chromium (%)
3100	1.00 to 1.50	0.45 to 0.75.
3200	1.50 to 2.00	0.90 to 1.25.
3300	3.25 to 3.75	1.25 to 1.75.
3400	2.75 to 3.25	0.60 to 0.90.

[1] See notes b, c, and i.

MOLYBDENUM STEELS

SAE series [1]	Nickel (%)	Chromium (%)	Molybdenum (%)
4100		0.50 to 1.10	0.15 to 0.25.
4300	1.50 to 2.00	0.50 to 0.90	0.15 to 0.40.
4600	1.65 to 2.00		0.20 to 0.30.
4800	3.25 to 3.75		

[1] See notes b, c, and i.

CHROMIUM STEELS

SAE number [1]	Chromium (%)	
5100 series [2]	0.60 to 1.10.	
52100 [3]	1.20 to 1.50.	

[1] See note i.
[2] See note b.
[3] Carbon 0.95 to 1.10%; see also note d.

CHROMIUM-VANADIUM STEELS

SAE number [1]	Chromium (%)	Vanadium (%)
6100 series [2]	0.80 to 1.10	0.18.
6195 [3]		

[1] See note i.
[2] See notes b and c.
[3] See notes c and d.

TUNGSTEN STEELS

SAE number [1]	Chromium (%)	Tungsten (%)
71360	3.00 to 4.00	12.00 to 15.00.
71660	3.00 to 4.00	15.00 to 18.00.
7260	0.50 to 1.00	1.50 to 2.00.

[1] Manganese 0.30% maximum; see notes c, e, and i.

SILICON-MANGANESE STEELS

SAE number [1]	Silicon (%)	Manganese (%)
9260	1.80 to 2.00	0.60 to 0.90.

[1] See notes b, c, and i.

Table 2.—*Chemical Composition of SAE steels*—Continued

CORROSION- AND HEAT-RESISTING ALLOYS

SAE number [1]	Chromium (%)	Nickel (%)	Carbon (%)	Manganese (%)
30905	17.00 to 20.00	8.00 to 10.00	0.08 max	0.20 to 0.70.
30915			0.09 to 0.20	
51210	11.50 to 13.00		0.12 max	0.60 max.
X51410	13.00 to 15.00			
51510	14.00 to 16.00			
51710	16.00 to 18.00			
51335	12.00 to 14.00		0.25 to 0.40	

[1] See notes h and i.

NOTES

Designation	Sulphur (%)	Phosphorus (%)	Silicon (%)
a	0.055 max	0.045 max	
b	0.050 max	0.040 max	
c			0.15 to 0.30.
d	0.035 max	0.030 max	
e	0.040 max	0.035 max	
f	0.075 to 0.30	0.045 to 0.13	
g	0.075 to 0.15	0.045 max	
h	Silicon 0.50% max; except in 30905 and 30915, 0.75% max; phosphorus, 0.30% max; sulphur, 0.030% max; except in X51410, 0.15 to 0.50%.		
i	In SAE alloy steels the carbon content progresses as in the carbon steels, the range corresponding to the last two digits of the number.		

(a) PLAIN CARBON STRUCTURAL STEELS

The plain carbon steels, the SAE 1000 ("SAE Ten Hundred") steels range in carbon contents from the SAE 1010 (0.10 percent of C) up to SAE 1095 (0.95 percent of C). As has been stated, the lower carbon steels are carburizing steels, cold-rolled steels, and machinery steels. The medium carbon steels are the forging grades and the higher carbon steels the spring steels or tool steels. "Free-cutting" or "free-machining" carbon steels contain high sulphur (that is, 0.1 to 0.3 percent of sulphur) and are SAE 1100 and SAE X1300 steels.

Very recently a marked advance has been made in controlling the quality of plain carbon steels. Two serious drawbacks in the use of plain carbon steels have been that they frequently were not uniform in their behavior on hardening and also that they were less ductile (more brittle) than heat-treated alloy steels of the same strength.

It has lately been shown that the size of the austenite grains in a steel *at the high temperature* just before quenching is a controlling factor in determining the hardenability of the steel, its tendency to crack during quenching, and its toughness in the hardened condition. Figure 19 illustrates the effect of austenitic grain size on the hardenability. This diagram shows the S curves of the quenching diagrams of two steels of the same composition, but one steel had a very fine grain when heated into the temperature range in which it became austenite (above line A B, fig. 19) while the other steel had a coarse austenitic grain at the same temperature. Figure 19 shows that the fine-grained austenite is less stable (decomposes more quickly) in the temperature range of Ar′ (500 to 600° C) than the coarse-grained austenite. The curve C I, which represents the cooling of these steels under some definite quenching procedure, say quenching in oil, shows that under this quenching condition the fine-grained steel will not harden, but the coarse-grained steel will harden.

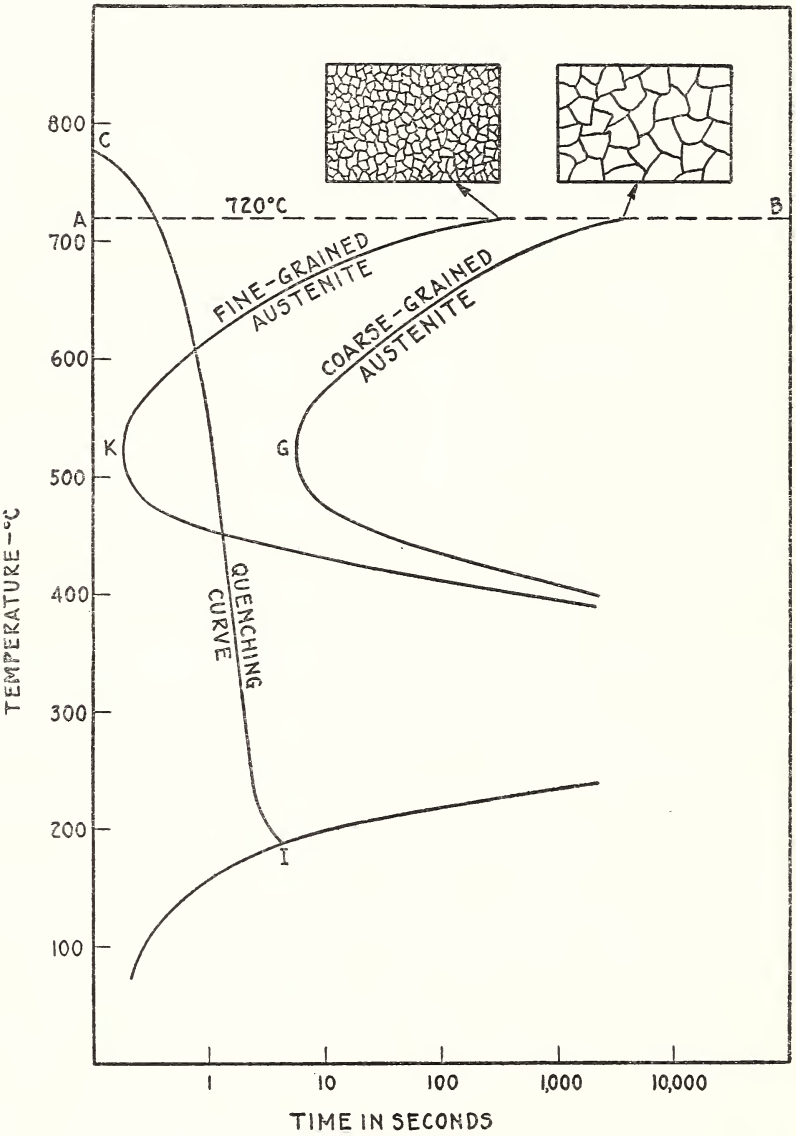

Figure 19.—*Effect of grain size on the hardenability of austenite.*

It has also been shown that while a coarse-grained austenite hardens more easily, in so doing it may develop high stresses within the grains that harden and may crack during hardening. These same internal stresses, or perhaps minute cracks or flaws caused by them in the hardened steel, make a hard steel produced from a coarse-grained austenite more brittle than a steel of the same hardness but made from a fine-grained austenite.

It is for these reasons that steel companies are now undertaking to furnish carbon steels that have been so refined and treated that it is known in advance of heat treatment whether they will form fine grains or coarse grains when heated for quenching.

(b) ALLOY STRUCTURAL STEELS

The advantages of alloy structural steels over plain carbon structural steels are, in general, as follows:

(a) Alloy steels have greater depth of hardening, that is, they can be hardened throughout a thicker cross section.

(b) Alloy steels have a greater ductility and toughness for a given strength and hardness (or greater strength and hardness for a given ductility and toughness).

(c) Alloy steels retain their strength and hardness at higher tempering temperatures.

(d) There is less danger of cracking or distortion of an alloy steel during heat treatment. The reasons why alloy steels possess these advantages can be most easily explained on the basis of the effects that the alloying elements have on the position of the S curve of the steel-quenching diagram.

The steel alloying elements which form solid solutions in austenite displace the upper bend of the S curve of the quenching diagram to the right. This displacement of the curve by an alloying element is independent of any effect of austenitic grain size. For example, figure 20 shows the S curves for the quenching of three steels *all of the same austenitic grain size and carbon content*, but differing in that one is a plain carbon steel, the second a steel containing a small amount, possibly 1 percent, of an alloying element, and the third a steel containing a larger amount, possibly 3 percent of the same alloying element. The effect of the alloying element is to move the S curve to the right, to make the steel more easily hardened as the alloy content increases. And this effect is secured in a steel that may have a fine-grained austenite.

Either coarse-grained austenite or certain alloys in solid solution in austenite may, therefore, make a steel more easily hardenable.

Figure 20 thus shows why an alloy steel is a deeper hardening steel than a plain carbon steel. The center of a 2-inch diameter bar of steel cools much more slowly when the piece is quenched than does the surface. Therefore, if 2-inch bars of a plain carbon steel and of a medium-alloy steel (as shown in fig. 20) are both quenched under conditions that cool the center of the alloy steel just fast enough to harden, it is obvious that the center of the plain carbon steel, cooling at the same rate, will, nevertheless, cool far too slowly to harden—*hence, the greater depth of hardening of alloy steels.*

It is also obvious that the medium-alloy steel of figure 20, inasmuch as it hardens completely with a much slower quench than the plain carbon steel, can be hardened with a smaller difference in temperature between its surface and center during quenching than would be necessary in order to harden the plain carbon steel to the same depth. Unequal cooling, resulting in sharp temperature gradients in a steel that is quenched very rapidly, is largely responsible for cracking and warping during hardening. Consequently the alloy steels that harden under relatively slow quenching and therefore with small temperature gradients in the steel, *are less liable to crack and distort during quenching.*

The alloying elements that are effective in accomplishing the displacement of the S curves to the right and which therefore contribute depth of hardening and freedom from cracking and warping during quenching are: *most effective:* manganese, silicon, and chromium; *moderately effective:* nickel, molybdenum, and tungsten.

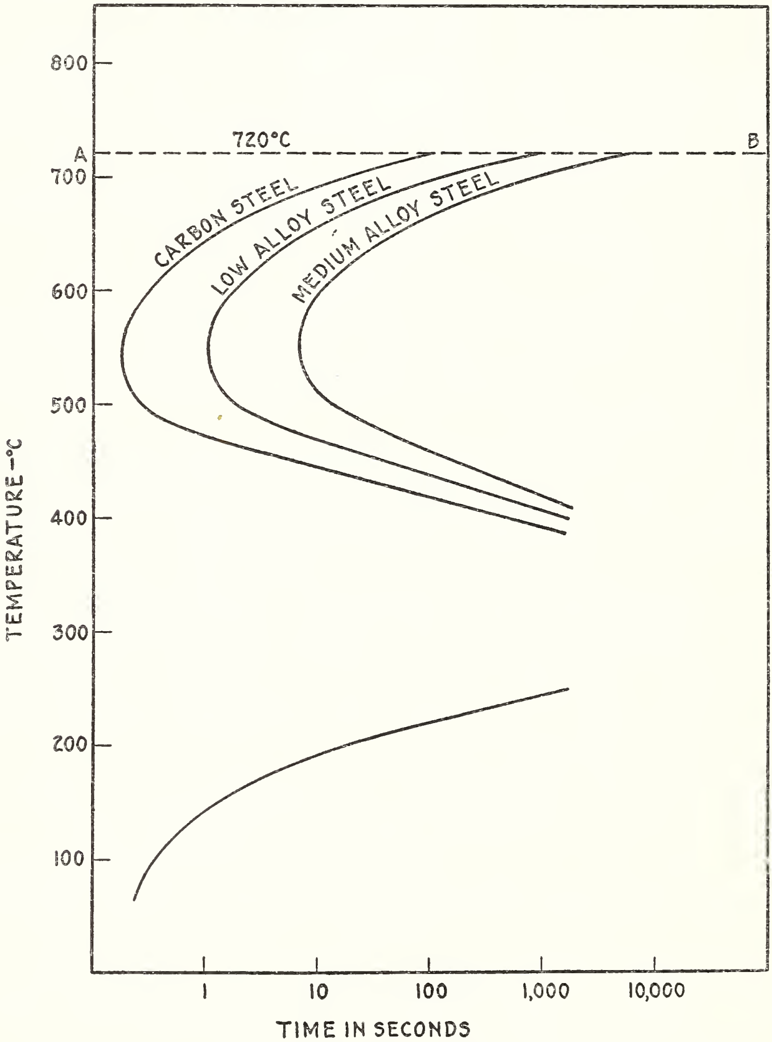

Figure 20.—*Effect of alloying elements on the hardenability of austenite.*

The next outstanding effect of alloying elements on hardenable alloy steels is their influence on the austenitic grain size. Fine-grained austenite is apparently caused by certain oxides or carbides in very fine particles scattered throughout the steel. It has already been stated that coarse-grained austenite tends to cause brittleness in the hardened steel. Conversely, martensite (the hard constituent of quenched steels) formed from fine-grained austenite is relatively tough. Therefore, the steel alloying elements that cause fine-grained austenite are responsible for the greater ductility and toughness in alloy steels. The alloying elements effective in refining austenite grain size by the formation of either oxides or carbides in steel are: *by oxide formation:* aluminum, zirconium, titanium, vanadium, and silicon; *by carbide formation:* vanadium, titanium, tungsten, molybdenum, chromium, and zirconium.

There is another effect of alloying elements which contributes to the increased strength and ductility of alloy steels. This is that certain alloys, aside from any influence they may have on the stability of austenite at Ar′ or the grain size of austenite, are dissolved by ferrite, the low-temperature form of iron, and thereby increase its strength and ductility at ordinary temperatures. This strengthened ferrite, being a constituent of hardened and tempered steels, contributes to increased strength and ductility. The specific alloying elements having this effect are: nickel, manganese, silicon, aluminum, copper, and chromium.

The remaining factor that was named as one of the advantages of alloy steels was their retention of hardness and strength at relatively high tempering temperatures. It has already been pointed out that the hardest constituent of quenched steel (martensite) contains iron carbide or carbon probably in solid solution. As martensite is tempered, this carbon—or the carbides—precipitates and gradually diffuses and agglomerates. The martensite, or rather its decomposition products, becomes softer as this agglomeration of carbides proceeds. Therefore, any factor that hinders the diffusion of carbides during tempering acts to retain hardness and strength. This is actually the effect that many alloying elements have on alloy steels. Such alloying elements are those that readily form carbides, namely: vanadium, tungsten, molybdenum, and chromium.

2. TOOL STEELS

Tool steels include steels used for (a) cutting tools for cutting wood, metal, stone, etc.; (b) dies, punches, and gages; and (c) tools involving high-temperature service (dies for die-casting, hot-forging dies, etc.).

(a) CUTTING STEELS

Steels for cutting tools must have high hardness to resist abrasion at the cutting edge and yet must have sufficient ductility to prevent breaking and chipping at the cutting edge. For fast cutting they must also retain their hardness at elevated temperatures as the tip of the tool becomes very hot. There are five general types of steels or alloys for cutting tools: (1) carbon tool steels; (2) oil-hardening (so-called nondeforming) steels; (3) fast-finishing steels; (4) high-speed steels; and (5) special hard alloys.

The plain carbon steels with 0.60 to 1.5 percent of carbon are excellent steels for tools of small section and simple shapes. When properly heat treated, their hardness at room temperatures is equal to that of the best alloy tool steels, but they lose hardness easily at higher temperatures. If tools are of intricate shapes, plain carbon steels are very liable to deform and crack during hardening. The control of austenitic grain size in carbon tool steels is very important in avoiding cracking and nonuniform hardening.

"Oil-hardening" or "nondeforming" tool steels frequently contain 1.25 to 1.5 percent of manganese, either with or without a little (0.5 percent) tungsten and chromium. These steels harden by quenching in oil and therefore with less temperature gradient, less distortion, and less cracking. They can also operate at slightly higher temperatures than carbon tool steels without losing hardness.

"Fast-finishing steels" or "semi-high-speed steels" contain greater proportions of chromium and tungsten (for example, 5 percent of tungsten and 1 percent of chromium) and will operate at appreciably higher temperatures at the cutting edge without loss of hardness. These steels are, of course, deep-hardening steels and the resistance of the carbides of these two elements to tempering explains their retention of hardness at elevated temperatures. These carbides are also extremely hard and contribute to the resistance of the cutting edge to abrasion.

The "high-speed steels" are a step further in this same direction of increased high-temperature hardness. The most widely known composition of high-speed steels is that of 18 percent of tungsten, 4 percent of chromium, and 1 percent of vanadium (abbreviated often to "18–4–1" high-speed steel). These steels retain a considerable hardness even at a red heat, so-called "red-hardness." The heat treatment of all the tool steels previously discussed is very similar to the heat treatment of carbon steels as discussed in detail in an earlier section. The heat treatment of high-speed steel is, however, rather different. In general, high-speed steels are hardened by: (1) heating slowly and uniformly to about 870° C (1,600° F), (2) then heating more rapidly to 1,260° C (2,300° F) for a short time, (3) quenching in oil (or air or fused salt), and (4) finally reheating to about 590° C (1,100° F) and cooling in air, this last treatment to develop an additional, so-called "secondary" hardness. Cobalt and molybdenum are also alloying constituents of high-speed steels.

Special hard alloys used for cutting tools include such materials as cobalt-chromium-tungsten-carbon alloys (in proportions such as 60–30–8–2, respectively) and alloys made by pressing and sintering very fine powders of tungsten or tantalum carbides mixed with some softer binding metal such as cobalt.

(b) DIE STEELS

Tool steels for dies, punches, and gages must be especially resistant to impact stresses and to abrasion. The steels widely used for such service are medium alloy steels (containing from 1 to 5 percent of alloying elements) such as the nondeforming steels described under cutting tools and many very complex compositions containing chromium, molybdenum, tungsten, vanadium, and nickel, often with two, three, or four alloying elements in a given steel. High-speed steels are also frequently used.

One special steel under this class is the so-called high-carbon high-chromium type. These steels contain from 1.5 to 2.25 percent of carbon and about 12 percent of chromium. They resemble high-speed steels in that their heat treatment requires a preheating, quenching from a high temperature, 1,040° C (1,900° F), and a tempering at about 540° C (1,000° F) to develop secondary hardening. These steels are very resistant to abrasion.

(c) TOOLS FOR HIGH-TEMPERATURE SERVICE

Steels for die-casting dies and for hot-forging dies are types of heat-resistant steels. Chromium is an essential constituent of many of these steels, usually in proportions of up to 5 percent. Tungsten, vanadium, and nickel in considerable proportions may be used with chromium. High-speed steels are, of course, especially suitable for many high-temperature applications.

3. CORROSION-RESISTANT STEELS

Corrosion-resistant steels, often called "stainless steels", are high-chromium steels. They apparently owe their resistance to corrosion to the fact that the chromium in the steel oxidizes very rapidly at any surface of the steel that is in contact with air. The thin, continuous but invisible chromium-oxide film that is thus formed on the surface of the steel is effective in preventing further oxidation of the iron, that is, in preventing stains caused by the formation of red or black iron oxides.

There are very many types and varieties of corrosion-resistant steels, only some of which may be hardened by quenching. The hardenable stainless steels usually contain from 12 to 17 percent of chromium and up to 1 percent of carbon. A few steels contain 17 to 27 percent of chromium and very little carbon (under 0.1 percent) and are not hardenable. A widely known type of nonhardenable stainless steel is that often designated as "18 and 8", signifying its nominal composition of 18 percent of chromium and 8 percent of nickel. This steel is austenitic at room temperature and is therefore not hardenable by quenching and is nonmagnetic.

4. HEAT-RESISTANT STEELS

Steels for high-temperature service must resist scaling and have high "creep" strength. Scaling is the formation of oxides or sulphides on the surface of the steel at high temperatures. Resistance to scaling is aided by the presence of chromium, aluminum, or silicon in steels. These elements seem to act in much the same manner as does chromium in making the stainless steels resistant to corrosion at normal temperatures. That is, by readily forming thin but adherent films of oxide over the steel surface, they resist further oxidation.

Steels are said to creep at elevated temperatures in that a steel bar, at a high temperature and supporting a load, may elongate slowly but steadily, flowing like a bar of *very* viscous wax, that is, the steel is "creeping."

Without discussing creep in detail, it can be said that resistance to creep in steels appears to be produced by the alloying elements that have already been listed as forming carbides which resist tempering, namely, the alloy elements: tungsten, molybdenum, vanadium, and chromium.

5. SPECIAL-PROPERTY STEELS

There are many special-property steels that do not belong to any of the groups so far discussed. No attempt is made here to present a complete list of such steels, but a few of the more commonly used types are mentioned.

Electrical sheet steels are silicon alloy steels (1 to 4 percent of silicon) used as cores in magnetic circuits to reduce core losses.

Magnet steels, designed to retain magnetic properties as permanent magnets, are rather high-carbon (0.6 to 1.25 percent of C) steels containing tungsten, chromium, molybdenum, and often very high proportions of cobalt (20 to 40 percent).

Austenitic manganese steel (or Hadfield's manganese steel) is a nonmagnetic steel containing about 1 percent of carbon and 12 percent of manganese. It is used especially for resistance to abrasion as in stone crushers, tractor shoes, etc. This steel in its initial condition is relatively soft, but has the ability to work harden on the surface to an extreme degree. Its surface is thus kept very hard as a result of the severe abrasion that it receives in service.

X. SOURCES OF INFORMATION

The following references are by no means a complete list of the sources which will be found helpful for general or specialized reading on elementary ferrous metallurgy. Nor, indeed, does it include all the references that have been useful in preparing this review. These references should, however, serve the interested reader as the first step in locating more complete discussions of the various phases of ferrous metallurgy covered by this circular.

ELEMENTARY AND GENERAL TEXTBOOKS

[1] Nontechnical Chats on Iron and Steel, by L. W. Spring, 465 pages. (Frederick A. Stokes Co., New York, N. Y.)

This book is an excellent and interesting discussion of the entire field of the production, properties, and use of iron alloys. It really is written in nontechnical terms as its title states.

[2] The A B C of Iron and Steel, 374 pages. (The Penton Publishing Co., Cleveland, Ohio.)

A book of 23 chapters by 17 authors, each writing on a special field of iron and steel production and fabrication. This book is strictly elementary and easily understandable.

[3] Iron and Steel, by O. F. Hudson and G. D. Bengough, 173 pages. (Constable & Co., Ltd., London.)

An introductory textbook emphasizing the constitution of iron and steel and the effects of mechanical and heat treatment. Also briefly discusses corrosion of iron and steel.

[4] The Making, Shaping, and Treating of Steel, by J. M. Camp and C. B. Francis, 1,142 pages. (Carnegie Steel Co., Pittsburgh, Pa.)

A very complete and detailed discussion of steel refining and steel fabrication.

[5] Principles of Metallurgy of Ferrous Metals, by Leon Cammen, 145 pages. (The American Society of Mechanical Engineers, New York, N. Y.)

A reprint of a series of articles in Mechanical Engineering written in simple language to serve as a manual for mechanical engineers.

[6] An Introduction to the Metallurgy of Iron and Steel, by H. M. Boylston, 511 pages. (John Wiley & Sons, Inc., New York, N. Y.)

[7] The Metallurgy of Iron and Steel, by Bradley Stoughton, 519 pages. (McGraw-Hill Book Co., Inc., New York, N. Y.)

[8] Lectures on Steel and Its Treatment, by John F. Keller, 265 pages. (Evangelical Press, Cleveland, Ohio.)

HANDBOOK

[9] National Metals Handbook, published by The American Society for Metals, Cleveland, Ohio.

This handbook of some 1,500 pages is published in revised form every 2 or 3 years. It is the most complete and detailed handbook for the selection, treating, and testing of metals. It covers the field of both steels and nonferrous metals and alloys.

MORE ADVANCED BOOKS AND BOOKS ON SPECIALIZED SUBJECTS

MECHANICAL WORKING OF METALS

See literature reference 4.

[10] Plastic Working of Metals, by E. V. Crane, 326 pages. (John Wiley & Sons, Inc., New York, N. Y.)

HEAT TREATMENT

[11] Steel and Its Heat Treatment, by D. K. Bullens, 564 pages. (John Wiley & Sons, Inc., New York, N. Y.)

[12] Steel Treating Practice, by R. H. Sherry, 399 pages. (McGraw-Hill Book Co., Inc., New York, N. Y.)

Devotes a large portion of text to detailed discussion of the equipment, arrangement, and operation of a heat-treating shop.

ALLOY STEELS

[13] Automobile Steels, by A. Müller-Hauff and K. Stein, translated by H. Goldschmidt, 219 pages. (John Wiley & Sons, Inc., New York, N. Y.)

[14] Refer also to the several volumes of the Alloys of Iron Monographs, comprising comprehensive critical surveys of all the literature on plain carbon and alloy steels. (Engineering Foundation—McGraw-Hill Book Co., Inc., New York, N. Y.)

TOOL STEELS

[15] Tool Steels, by J. P. Gill, 136 pages. (American Society for Metals, Cleveland, Ohio.)

HIGH-SPEED STEEL

[16] High-Speed Steel, by M. A. Grossman and E. C. Bain, 173 pages. (John Wiley & Sons, Inc., New York, N. Y.)

STAINLESS STEELS

[17] Stainless Iron and Steel, by J. H. S. Monypenny, 575 pages. (John Wiley & Sons, Inc., New York, N. Y.)

This book also includes a discussion of heat-resisting steels.

METALLOGRAPHY

[18] The Metallography and Heat Treatment of Iron and Steel, by A. Sauveur, 535 pages. (The University Press, Cambridge, Mass.)

THEORETICAL METALLURGY

[19] The Science of Metals, by Z. Jeffries and R. S. Archer, 460 pages. (McGraw-Hill Book Co., Inc., New York, N. Y.)

Washington, August 12, 1935.

○