CHAPTER 1

CARBON AND ALLOY STEELS

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1 INTRODUCTION

Steel is the most common and widely used metallic material in today's society. It can be cast or wrought into numerous forms and can be produced with tensile strengths exceeding 5 GPa. A prime example of the versatility of steel is in the automobile where it is the material of choice and accounts for over 60% of the weight of the vehicle. Steel is highly formable as seen in the contours of the automobile outerbody. Steel is strong and is used in the body frame, motor brackets, driveshaft, and door impact beams of the vehicle. Steel is corrosion resistant when coated with the various zinc-based coatings available today. Steel is dent resistant when compared with other materials and provides exceptional energy absorption in a vehicle collision. Steel is recycled and easily separated from other materials by a magnet. Steel is inexpensive compared with other competing materials such as aluminum and various polymeric materials.

In the past, steel has been described as an alloy of iron and carbon. Today, this description is no longer applicable since in some very important steels, e.g., interstitial-free (IF) steels and type 409 ferritic stainless steels, carbon is considered an impurity and is present in quantities of only a few parts per million. By definition, steel must be at least 50% iron and must contain one or more alloying elements. These elements generally include carbon, manganese, silicon, nickel, chromium, molybdenum, vanadium, titanium, niobium, and aluminum. Each chemical element has a specific role to play in the steelmaking process or in achieving particular properties or characteristics, e.g., strength, hardness, corrosion resistance, magnetic permeability, and machinability.

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2 STEEL MANUFACTURE

In most of the world, steel is manufactured by integrated steel facilities that produce steel from basic raw materials, i.e., iron ore, coke, and limestone. However, the fastest growing segment of the steel industry is the “minimill” that melts steel scrap as the raw material. Both types of facilities produce a wide variety of steel forms, including sheet, plate, structural, railroad rail, and bar products.

Ironmaking. When making steel from iron ore, a blast furnace chemically reduces the ore (iron oxide) with carbon in the form of coke. Coke is a spongelike carbon mass that is produced from coal by heating the coal to expel the organic matter and gases. Limestone (calcium carbonate) is added as a flux for easier melting and slag formation. The slag, which floats atop the molten iron, absorbs many of the unwanted impurities. The blast furnace is essentially a tall hollow cylindrical structure with a steel outer shell lined on the inside with special refractory and graphite brick. The crushed or pelletized ore, coke, and limestone are added as layers through an opening at the top of the furnace, and chemical reduction takes place with the aid of a blast of preheated air entering near the bottom of the furnace (an area called the bosh). The air is blown into the furnace through a number of water-cooled copper nozzles called tuyeres. The reduced liquid iron fills the bottom of the furnace and is tapped from the furnace at specified intervals of time. The product of the furnace is called pig iron because in the early days the molten iron was drawn from the furnace and cast directly into branched mold configurations on the cast house floor. The central branch of iron leading from the furnace was called the “sow” and the side branches were called “pigs.” Today the vast majority of pig iron is poured directly from the furnace into a refractory-lined vessel (submarine car) and transported in liquid form to a basic oxygen furnace (BOF) for refinement into steel.

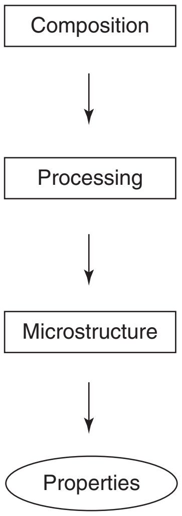
Steelmaking. In the BOF, liquid pig iron comprises the main charge. Steel scrap is added to dilute the carbon and other impurities in the pig iron. Oxygen gas is blown into the vessel by means of a top lance submerged below the liquid surface. The oxygen interacts with the molten pig iron to oxidize undesirable elements. These elements include excess carbon (because of the coke used in the blast furnace, pig iron contains over 2% carbon), manganese, and silicon from the ore and limestone and other impurities like sulfur and phosphorus. While in the BOF, the liquid metal is chemically analyzed to determine the level of carbon and impurity removal. When ready, the BOF is tilted and the liquid steel is poured into a refractory-lined ladle. While in the ladle, certain alloying elements can be added to the steel to produce the desired chemical composition. This process takes place in a ladle treatment station or ladle furnace where the steel is maintained at a particular temperature by external heat from electrodes in the lid placed on the ladle. After the desired chemical composition is achieved, the ladle can be placed in a vacuum chamber to remove undesirable gases such as hydrogen and oxygen. This process is called degassing and is used for higher quality steel products such as railroad rail, sheet, plate, bar, and forged products. Stainless steel grades are usually produced in an induction or electric arc furnace, sometimes under vacuum. To refine stainless steel, the argon–oxygen decarburization (AOD) process is used. In the AOD, an argon–oxygen gas mixture is injected through the molten steel to remove carbon without a substantial loss of chromium (the main element in stainless steel).

Continuous Casting. Today, most steel is cast into solid form in a continuous-casting (also called strand casting) machine. Here, the liquid begins solidification in a water-cooled copper mold while the steel billet, slab, or bloom is withdrawn from the bottom of the mold. The partially solidified shape is continuously withdrawn from the machine and cut to length for further processing. The continuous-casting process can proceed for days or weeks as ladle after ladle of molten steel feeds the casting machine. Some steels are not continuously cast but are poured into individual cast iron molds to form an ingot that is later reduced in size by forging or a rolling process to some other shape. Since the continuous-casting process offers substantial economic and quality advantages over ingot casting, most steel in the world is produced by continuous casting.

Rolling/Forging. Once cast into billet, slab, or bloom form, the steel is hot rolled through a series of rolling mills or squeezed/hammered by forging to produce the final shape. To form hot-rolled sheet, a 50–300-mm-thick slab is reduced to final thickness, e.g., 2 mm, in one or more roughing stands followed by a series of six or seven finishing stands. To obtain thinner steel sheet, e.g., 0.5 mm, the hot-rolled sheet must be pickled in acid to remove the iron oxide scale and further cold rolled in a series of rolling stands called a tandem mill. Because the cold-rolling process produces a hard sheet with little ductility, it is annealed either by batch annealing or continuous annealing. New casting technology is emerging where thin sheets (under 1 mm) can be directly cast from the liquid through water-cooled, rotating rolls that act as a mold as in continuous casting. This new process eliminates many of the steps in conventional hot-rolled sheet processing. Plate steels are produced by hot rolling a slab in a reversing roughing mill and a reversing finishing mill. Steel for railway rails is hot rolled from a bloom in a blooming mill, a roughing mill, and one or more finishing mills. Steel bars are produced from a heated billet that is hot rolled in a series of roughing and finishing mills. Forged steels are produced from an ingot that is heated to forging temperature and squeezed or hammered in a hydraulic press or drop forge. The processing sequence in all these deformation processes can vary depending on the design, layout, and age of the steel plant.

3 DEVELOPMENT OF STEEL PROPERTIES

In order to produce a steel product with the desired properties, basic metallurgical principles are used to control three things:



This means that the steel composition and processing route must be closely controlled in order to produce the proper microstructure. The final microstructure is of utmost importance in determining the properties of the steel product. This section will explore how various microstructures are developed and the unique characteristics of each microstructural component in steel. The next section will discuss how alloy composition also plays a major role.

Iron–Carbon Equilibrium Diagram. Since most steels contain carbon, the basic principles of microstructural development can be explained by the iron–carbon equilibrium diagram. This diagram, shown in Fig. 1, is essentially a map of the phases that exist in iron at various carbon contents and temperatures under equilibrium conditions. Iron is an interesting chemical element in that it undergoes three phase changes when heated from room temperature to liquid. For example, from room temperature to 912°C pure iron exists as ferrite (also called alpha iron), from 912 to 1394°C it exists as austenite (gamma iron), from 1394 to 1538°C it exists as ferrite again (delta iron), and above 1538°C it is liquid. In other words, upon heating, iron undergoes allotropic-phase transformations from ferrite to austenite at 912°C, austenite to ferrite at 1394°C, and ferrite to liquid at 1538°C. Each transformation undergoes a change in crystal structure or arrangement of the iron atoms in the crystal lattice. It must be remembered that all chemical elements in their solid form have specific arrangements of atoms that are essentially the basic building blocks in producing the element in the form that we physically observe. These atomic arrangements form a latticework containing billions of atoms all aligned in a systematic way. Some of these lattices have a cubic arrangement, with an atom at each corner of the cube and another atom at the cube center. This arrangement is called body-centered-cubic (bcc). Others have an atom at each corner of the cube and atoms at the center of each face of the cube. This is called face-centered-cubic (fcc). Other arrangements are hexagonal, some are tetragonal, etc. As an example, pure iron as ferrite has a bcc arrangement. Austenite has a fcc arrangement. Upon heating, bcc ferrite will transform to fcc austenite at 912°C. These arrangements or crystal structures impart different properties to steel. For example, a bcc ferritic stainless steel will have properties much different from a fcc austenitic stainless steel, as described later in this chapter.

Since pure iron is very soft and of low strength, it is of little interest commercially. Therefore, carbon and other alloying elements are added to enhance properties. Adding carbon to pure iron has a profound effect on ferrite and austenite, discussed above. One way to understand the effect of carbon is to examine the iron–carbon diagram (Fig. 1). This is a binary (two-element) diagram of temperature and composition (carbon content) constructed under near-equilibrium conditions. In this diagram, as carbon is added to iron, the ferrite- and austenite-phase fields expand and contract depending upon the carbon level and temperature. Also, there are fields consisting of two phases, e.g., ferrite plus austenite.

Since carbon has a small atomic diameter when compared with iron, it is called an interstitial element because it can fill the interstices between the iron atoms in the cubic lattice. Nitrogen is another interstitial element. On the other hand, elements such as manganese, silicon, nickel, chromium, and molybdenum have atomic diameters similar to iron and are called substitutional alloying elements. These substitutional elements can thus replace iron atoms at the cube corners, faces, or center positions. There are many binary-phase diagrams (Fe–Mn, Fe–Cr, Fe–Mo, etc.) and tertiary-phase diagrams (Fe–C–Mn, Fe–C–Cr, etc.) showing the effect of interstitial and substitutional elements on the phase fields of ferrite and austenite. These diagrams are found in the handbooks listed at the end of the chapter.

Being an interstitial or a substitutional element is important in the development of steel properties. Interstitial elements such as carbon can move easily about the crystal lattice whereas a substitutional element such as manganese is much more difficult to move. The movement of

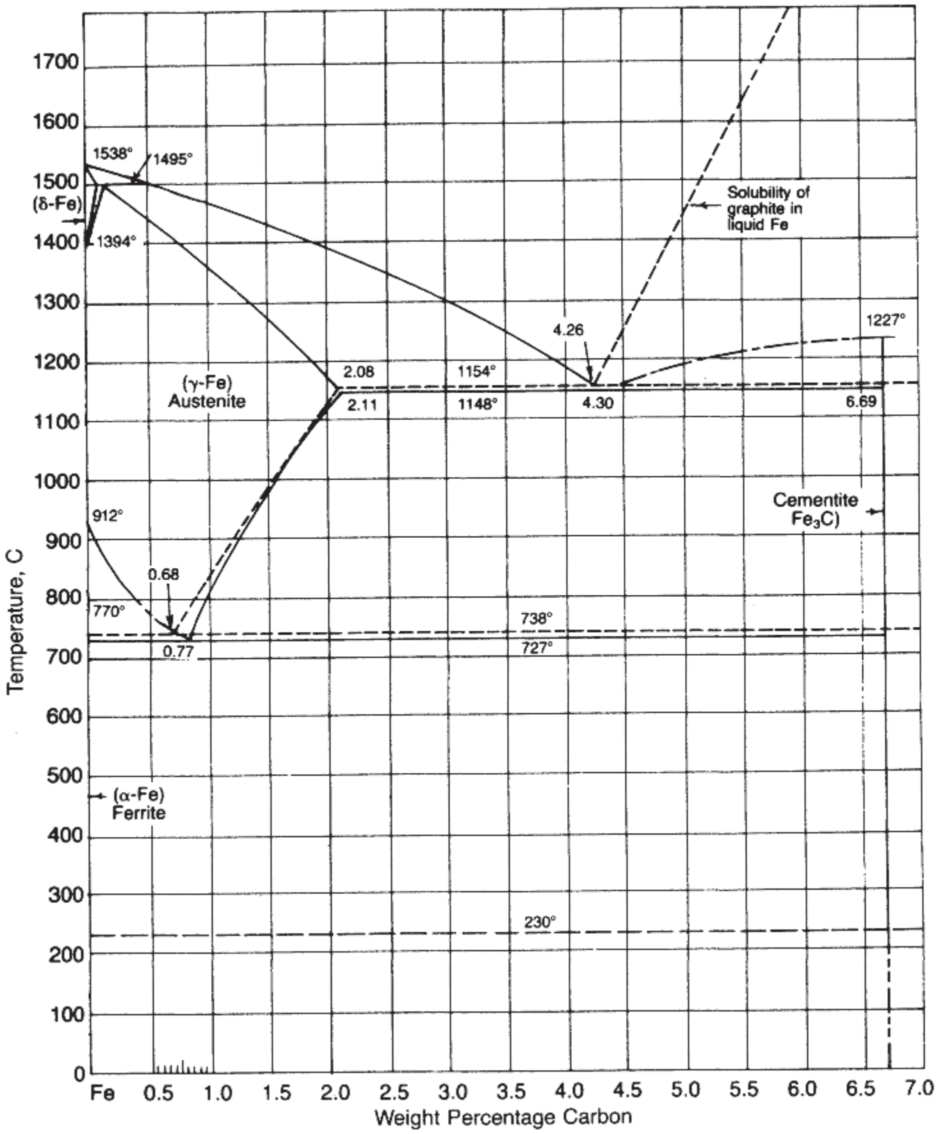


Figure 1 Iron–carbon binary-phase diagram. (*Source: Steels: Heat Treatment and Processing Principles*, ASM International, Materials Park, OH, 1990, p. 2.) Reprinted with permission of ASM International.

elements in a crystal lattice is called diffusion. Diffusion is a controlling factor in the development of microstructure. Another factor is solubility, which is a measure of how much of a particular element can be accommodated by the crystal lattice before it is rejected. In metals, when two or more elements are soluble in the crystal lattice, a solid solution is created (somewhat analogous to a liquid solution of sugar in hot coffee). For example, when added to iron, carbon has very limited solubility in ferrite but is about 100 times more soluble in austenite, as seen in the iron–carbon diagram in Fig. 2 (a limited version of the diagram in Fig. 1). The maximum solubility of carbon in ferrite is about 0.022% C at 727°C while the maximum

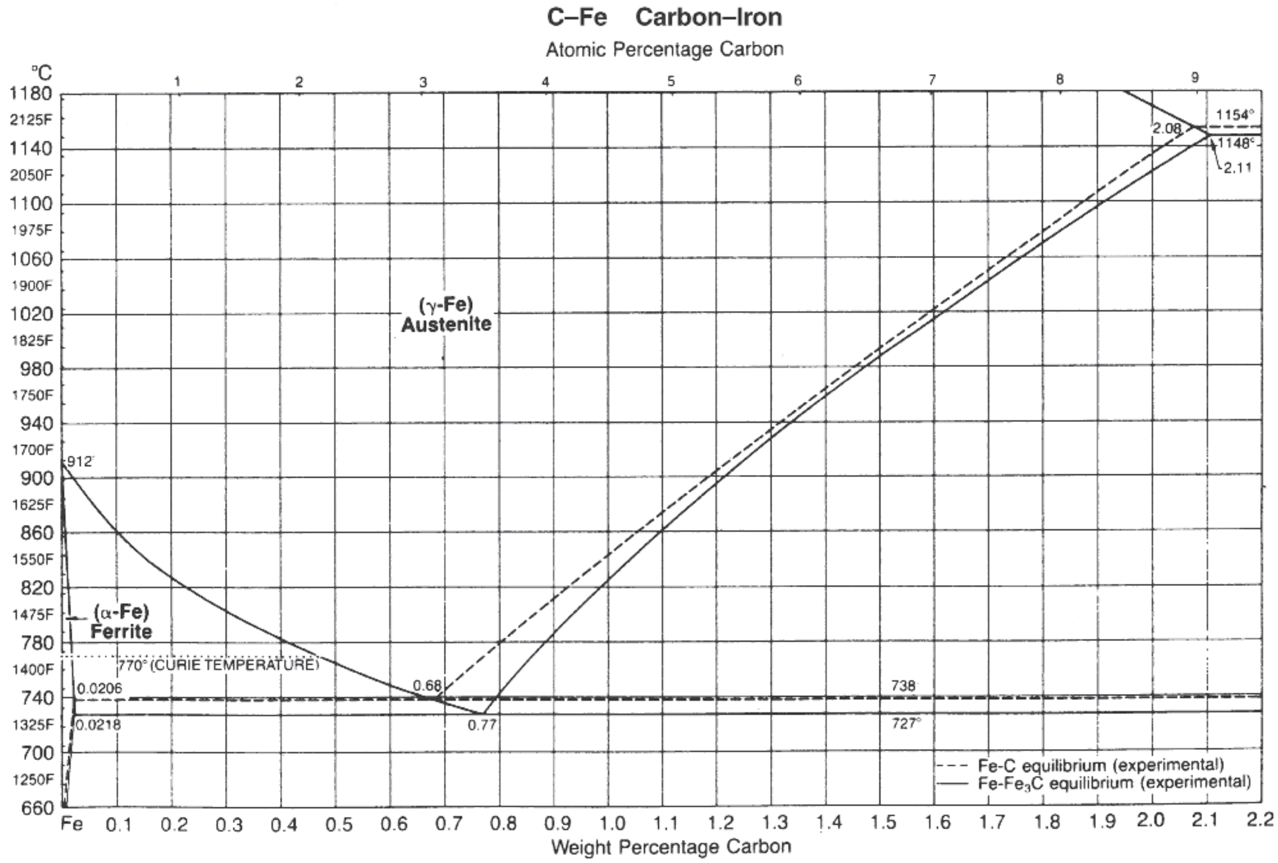


Figure 2 Expanded portion of iron–carbon binary-phase diagram in Fig. 1. (*Source: Steels: Heat Treatment and Processing Principles,* ASM International, Materials Park, OH, 1990, p. 18.) Reprinted with permission of ASM International.

solubility of carbon in austenite is 100 times more, 2.11% C at 1148°C. At room temperature the solubility of carbon in iron is only about 0.005%. Any amount of carbon in excess of the solubility limit is rejected from solid solution and is usually combined with iron to form an iron carbide compound called cementite. This hard and brittle compound has the chemical formula Fe_3C and a carbon content of 6.7%. This is illustrated in the following two examples. The first example is a microstructure of a very low carbon steel (0.002% C), shown in Fig. 3*a*. The microstructure consists of only ferrite grains (crystals) and grain boundaries. The second example is a microstructure of a low-carbon steel containing 0.02% C, in Fig. 3*b*. In this microstructure, cementite can be seen as particles at the ferrite grain boundaries. The excess carbon rejected from the solid solution of ferrite formed this cementite. As the carbon content in steel is increased, another form of cementite appears as a constituent called pearlite, which can be found in most carbon steels. Examples of pearlite in low-carbon (0.08% C) and medium-carbon (0.20% C) steels are seen in Figs. 4*a* and 4*b*. Pearlite has a lamellar (parallel-plate) microstructure, as shown at higher magnification in Fig. 5, and consists of layers of ferrite and cementite. Thus, in these examples, in increasing the carbon level from 0.002–0.02 to 0.08–0.20%, the excess carbon is manifested as a carbide phase in two different forms, cementite particles and cementite in pearlite. Both forms increase the hardness and strength of iron. However, there is a trade-off; cementite also decreases ductility and toughness.

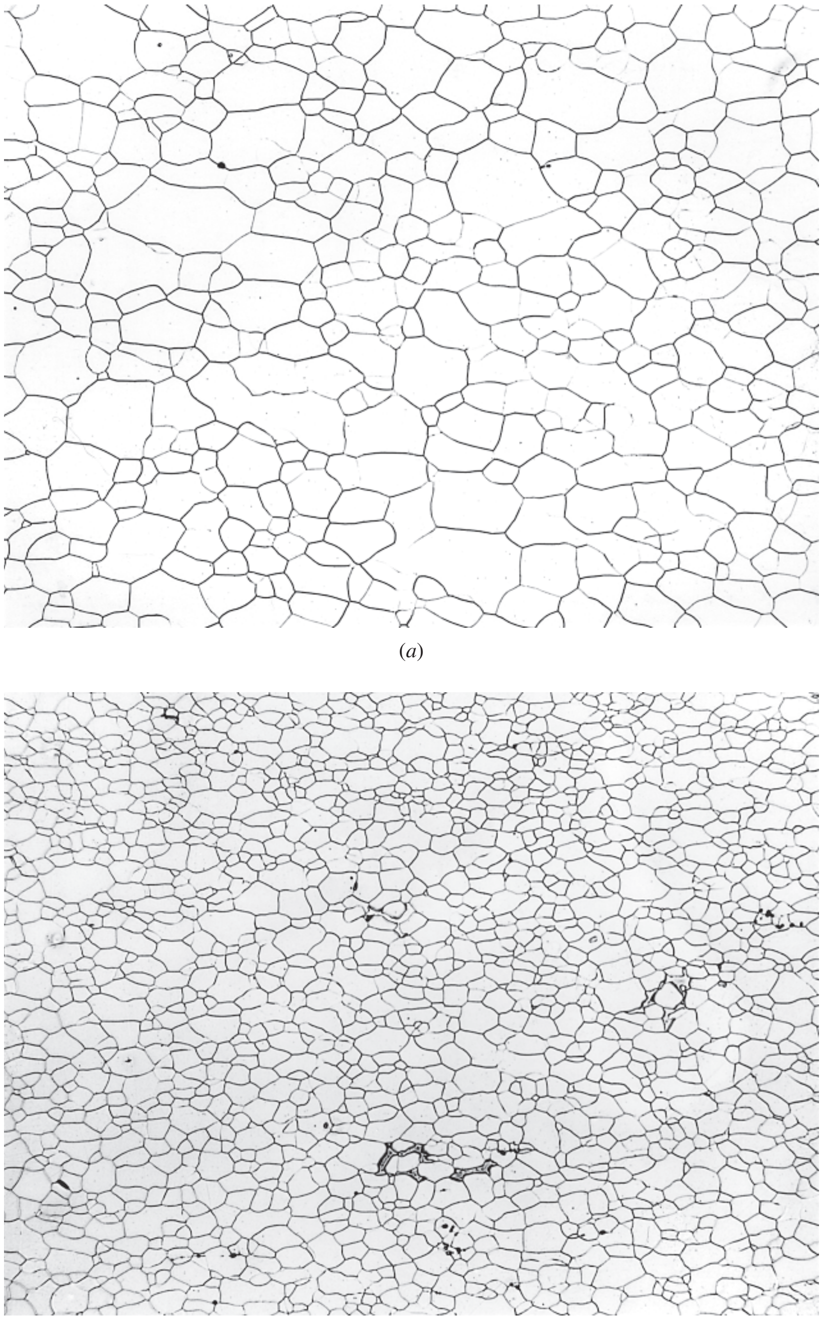
Pearlite forms on cooling austenite through a eutectoid reaction as seen below:

$$\text{Austenite} \leftrightarrow Fe_3C + \text{ferrite}$$

A *eutectoid* reaction occurs when a solid phase or constituent reacts to form two different solid constituents on cooling (a *eutectic* reaction occurs when a liquid phase reacts to form two solid phases). The eutectoid reaction is reversible on heating. In steel, the eutectoid reaction (under equilibrium conditions) takes place at 727°C and can be seen on the iron–carbon diagram (Fig. 1) as the “V” at the bottom left side of the diagram. A fully pearlitic microstructure forms at 0.77% C at the eutectoid temperature of 727°C (the horizontal line on the left side of the iron–carbon diagram). Steels with less than 0.77% C are called *hypoeutectoid* steels and consist of mixtures of ferrite and pearlite with the amount of pearlite increasing as the carbon content increases. The ferrite phase is called a *proeutectoid* phase because it forms prior to the eutectoid transformation that occurs at 727°C. A typical example of proeutectoid ferrite is shown in Fig. 6. In this photomicrograph, the ferrite (the white-appearing constituent) formed on the prior austenite grain boundaries of hypoeutectoid steel with 0.60% C. The remaining constituent (dark appearing) is pearlite. Steels between 0.77% C and about 2% C are called *hypereutectoid* steels and consist of pearlite with proeutectoid cementite. Cementite forms a continuous carbide network at the boundaries of the prior austenite grains. Because there is a carbide network, hypereutectoid steels are characterized as steels with little or no ductility and very poor toughness. This means that in the commercial world the vast majority of carbon steels are hypoeutectoid steels.

Thus, according to the iron–carbon diagram, steels that are processed under equilibrium or near-equilibrium conditions can form (a) pure ferrite at very low carbon levels generally under 0.005% C, (b) ferrite plus cementite particles at slightly higher carbon levels between 0.005% C and 0.022% C, (c) ferrite plus pearlite mixtures between 0.022% C and 0.77%C, (d) 100% pearlite at 0.77% C, and (e) mixtures of pearlite plus cementite networks between 0.77% C and 2% C. The higher the percentage of cementite, the higher the hardness and strength and lower the ductility and toughness of the steel.

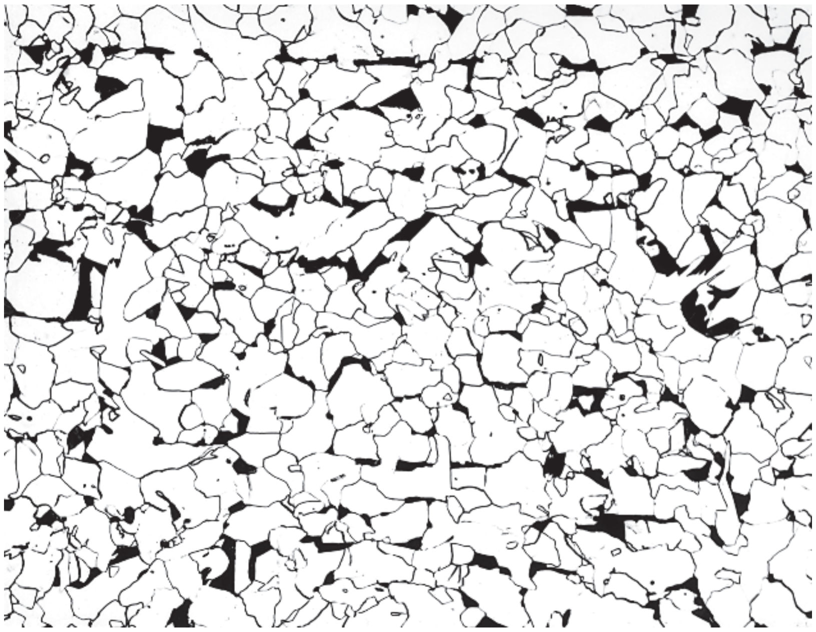
Departure from Equilibrium (Real World). Industrial processes do not occur at equilibrium, and only those processes that take place at extremely slow heating and cooling rates can be considered near equilibrium, and these processes are quite rare. Therefore, under real



(*a*)

(*b*)

Figure 3 (*a*) Photomicrograph of a very low carbon steel showing ferrite grains and (*b*) photomicrograph of a low-carbon steel showing ferrite grains with some cementite on the ferrite grain boundaries. (*a*) 500X and (*b*) 200X. Marshall's etch.



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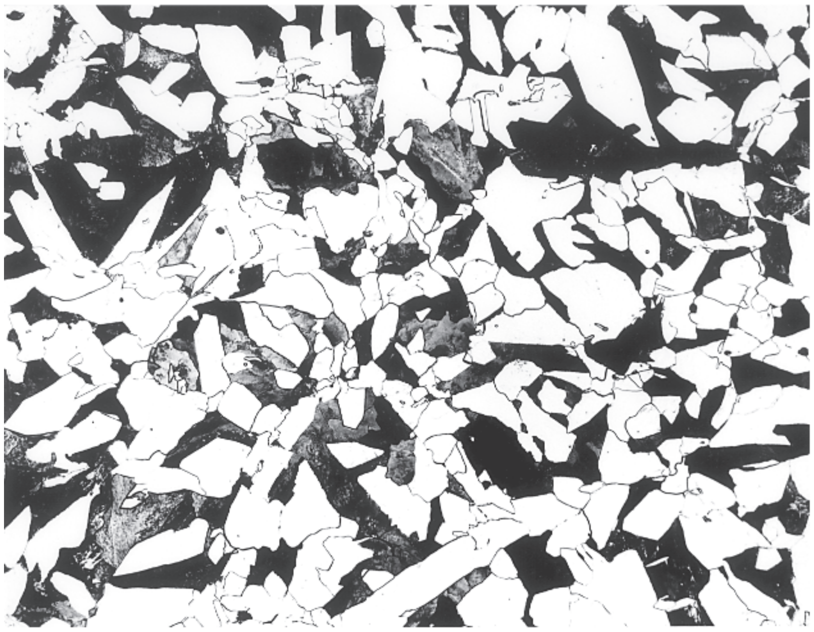


(*b*)

Figure 4 (*a*) Photomicrograph of an SAE/AISI 1008 steel showing ferrite grains and pearlite (dark) and (*b*) photomicrograph of an SAE/AISI 1020 steel showing ferrite grains with an increased amount of pearlite. (*a*) and (*b*) both 200X. 4% picral + 2% nital etch.

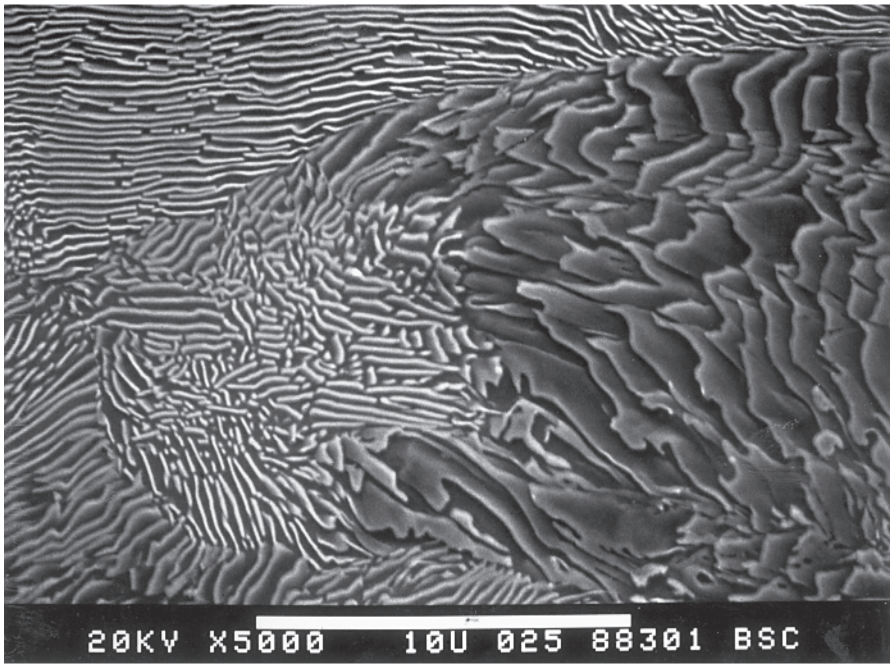


Figure 5 Scanning electron micrograph of pearlite showing the platelike morphology of the cementite. 5000X. 4% picral etch.

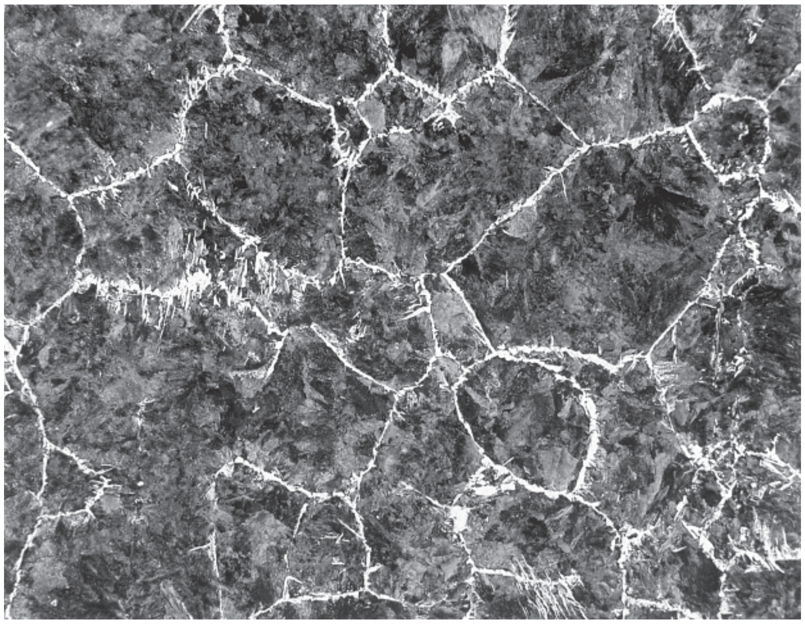


Figure 6 Photomicrograph of a medium-carbon hypoeutectoid steel showing a pearlite matrix and proeutectoid ferrite nucleating on the original (prior) austenite grain boundaries. 200X. 4% picral + 2% nital etch.

conditions, the iron–carbon diagram can only be used as a rough guideline since the equilibrium transformation temperatures shift to lower temperatures on cooling and to higher temperatures on heating. If steels are cooled at very fast rates, e.g., quenching in water, the iron–carbon diagram can no longer be used since there is a major departure from equilibrium. In fact, during the quenching of steel, new constituents form that are not associated with the iron–carbon diagram. Therefore, at fast cooling rates the concept of time–temperature transformation (TTT) diagrams must be considered. These diagrams are constructed under isothermal (constant) temperature (called IT diagrams) or continuous-cooling conditions (called CT diagrams). It is important to know how these diagrams are constructed so that we can understand the development of nonequilibrium microstructures, which are so important in carbon and alloy steels.

Isothermal Transformation Diagram. This diagram is formed by quenching very thin specimens of steel in salt baths set at various temperatures. For example, thin specimens of 0.79% C steel can be quenched into seven different liquid salt baths set at 650, 600, 550, 500, 450, 400, and 200°C. The specimens are held for various times at each temperature, then pulled from the bath and quickly quenched in cold water. The result will be a diagram called an isothermal transformation (IT) diagram, as shown in Fig. 7. The diagram is

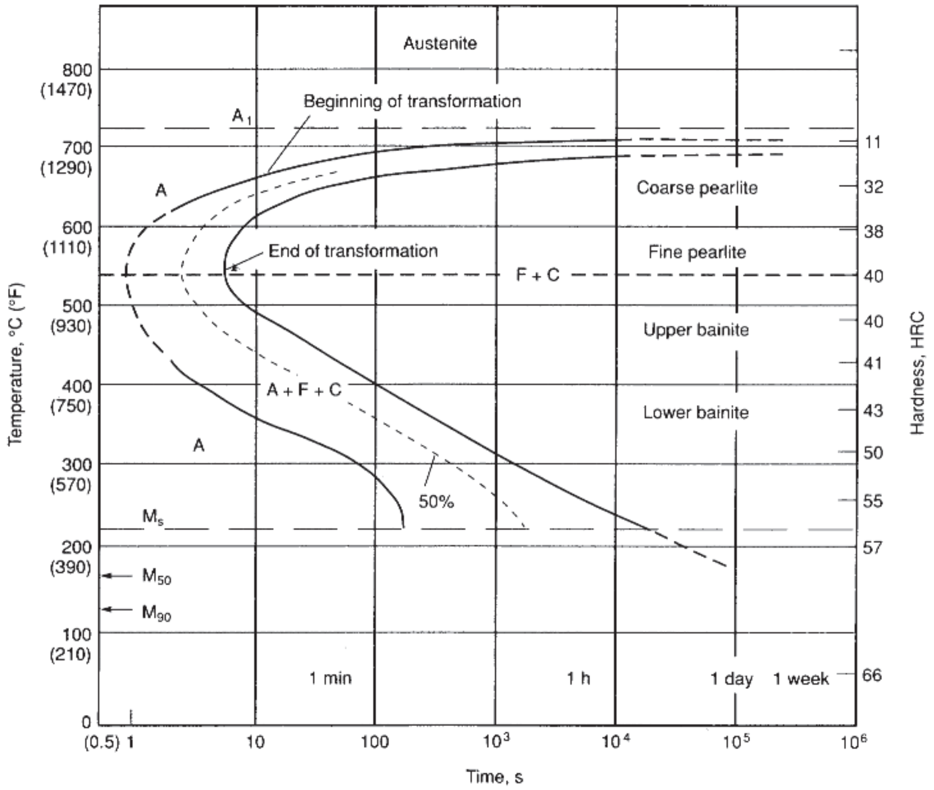


Figure 7 Isothermal transformation diagram of SAE/AISI 1080 steel showing the beginning and end of transformation curves with temperature and time. (*Source*: *ASM Handbook*, Vol. 1, *Properties and Selection: Irons, Steels, and High-Performance Alloys*, ASM International, Materials Park, OH, 1990, p. 128.) Reprinted with permission of ASM International.

essentially a map showing where various constituents form. For example, at 650°C, austenite (A) begins to transform to pearlite if held in the bath for 10 s. The curve drawn through this point is the pearlite transformation start temperature and is labeled the beginning of transformation in Fig. 7. At about 100 s the pearlite transformation is finished. The second curve represents the pearlite transformation finish temperature and is labeled the end of transformation in Fig. 7. In this steel, pearlite forms at all temperatures along the start of the transformation curve from 727°C (the equilibrium temperature of the iron–carbon diagram) to 540°C (the "nose" of the curve). At the higher transformation temperatures, the pearlite interlamellar spacing (the spacing between cementite plates) is very coarse and decreases in spacing as the temperature is decreased, i.e., the nose of the IT diagram is approached. This is an important concept since a steel with a coarse pearlite interlamellar spacing is softer and of lower strength than a steel with a fine pearlite interlamellar spacing. Commercially, rail steels are produced with a pearlitic microstructure, and it has been found that the finer the interlamellar spacing, the harder the rail and the better the wear resistance. This means that rails will last longer in track if produced with the finest spacing allowable. Most rail producers employ an accelerated cooling process called head hardening to obtain the necessary conditions to achieve the finest pearlite spacing in the rail head (the point of wheel contact).

If the specimens are quenched to 450°C and held for various times, pearlite does not form. In fact, pearlite does not isothermally transform at transformation temperatures (in this case, salt pot temperatures) below the nose of the diagram in Fig. 7. The new constituent is called bainite, which consists of ferrite laths with small cementite particles (also called precipitates). An example of the microstructure of bainite is shown in Fig. 8. This form of bainite is called upper bainite because it is formed in the upper portion below the nose of the IT diagram (between about 540 and 400°C). Lower bainite, a finer ferrite–carbide microstructure, forms at lower temperatures (between 400 and about 250°C). Bainite is an important constituent in tough, high-strength, low-alloy steel.

If specimens are quenched into a salt bath at 200°C, a new constituent called martensite will form. The start of the martensitic transformation is shown in Fig. 7 as M_s (at 220°C). Martensite is a form of ferrite that is supersaturated with carbon. In other words, because of the very fast cooling rate, the carbon atoms do not have time to diffuse from their interstitial positions in the bcc lattice to form cementite particles. An example of martensite is shown in Fig. 9. Steel products produced with an as-quenched martensitic microstructure are very hard and brittle, e.g., a razor blade. Most martensitic products are tempered by heating to temperatures between about 350 and 650°C. The tempering process allows some of the carbon to diffuse and form as a carbide phase from the supersaturated iron lattice. This softens the steel and provides some ductility. The degree of softening is determined by the tempering temperature and the time at the tempering temperature. The higher the temperature and the longer the time, the softer the steel. Most steels with martensite are used in the quenched and tempered condition.

Continuous-Cooling Transformation Diagram. The other more useful form of a time—temperature transformation diagram is the continuous-cooling transformation (CT) diagram. This differs from the IT diagram in that it is constructed by cooling small specimens at various cooling rates and measuring the temperatures at which transformations start and finish using a device called a dilatometer (a machine that measures dilation). Each phase transformation undergoes a distinct volume change (positive on cooling and negative on heating) that can be measured by a sensitive length-measuring device in the dilatometer. A CT diagram has

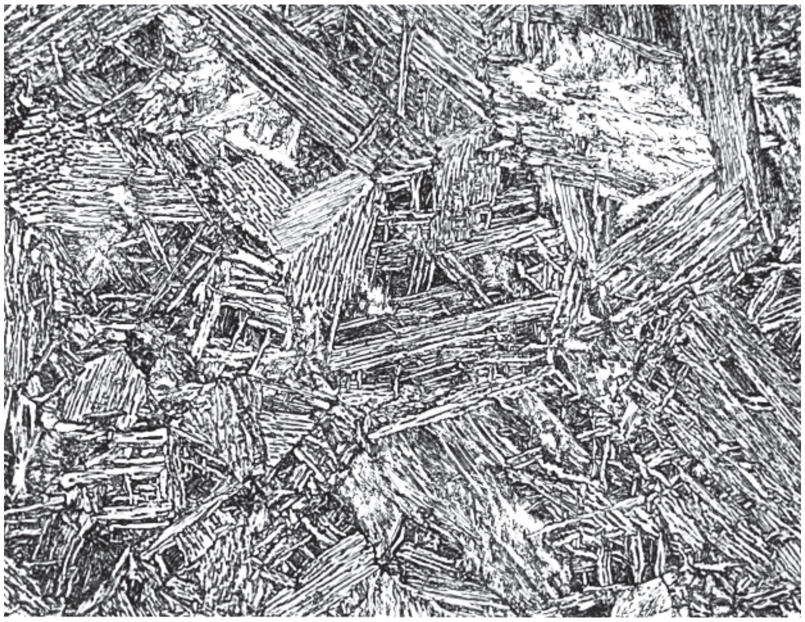


Figure 8 Photomicrograph of a low-alloy steel showing a bainitic microstructure. 500X. 4% picral + 2% nital etch.

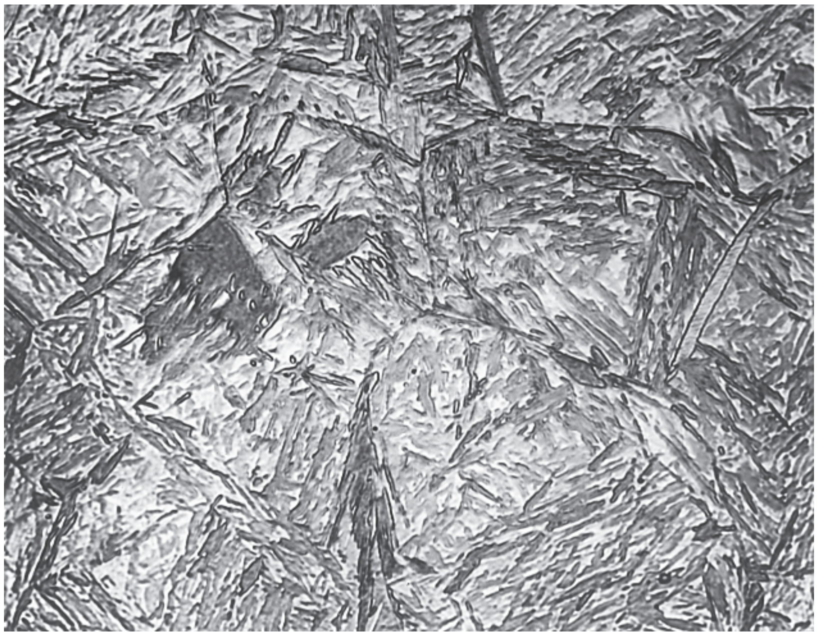


Figure 9 Photomicrograph of a low-alloy steel showing a martensitic microstructure. 1000X. 4% picral + HCl and 10% sodium metabisulfate etch.

similar features to the IT diagram shown in Fig. 7 but is produced by continuous cooling rather than isothermal conditions. A continuous-cooling diagram is applicable for most industrial processes and should be used in lieu of an IT diagram. A CT diagram can also be constructed by quenching one end of a Jominy bar described below.

Hardenability Concept. In thick products, e.g., large-diameter bars, thick plates, and heavy forgings, the through-thickness properties are achieved through hardenability. Hardenability is the ability to induce depth of hardness in a steel product. The hardness level is obtained by controlling the amount of martensite in the microstructure. To increase the depth of hardness, certain alloying elements are added to the steel for increased hardenability. Elements, such as nickel, chromium, and molybdenum, shift the pearlite nose of the IT and CT diagrams to the right (longer times). With the nose out of the way on cooling, martensite can be formed over a wider range of cooling rates when compared with a steel without alloying elements.

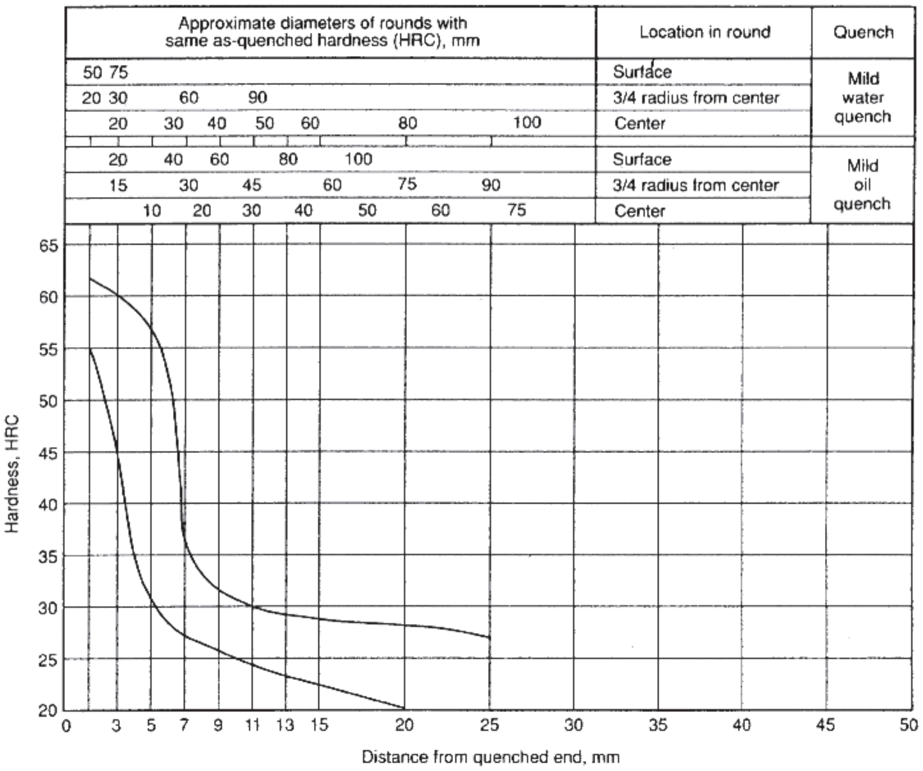
There is a fairly simple test to measure the hardenability of steel called the Jominy test. A 25.4-mm-diameter and 102-mm-long bar is austenitized to 845°C for 1 h and then water quenched at one end of the bar. The quenching takes place in a specially designed fixture where the bar is suspended in the vertical position and water is directed against the machined bottom end face of the bar. After quenching, parallel flats 0.38 mm deep are machined on opposite sides of the bar. Hardness is measured at 1.6-mm ($\frac{1}{16}$-in.) intervals from the quenched end. The hardness is plotted against depth from the quenched end to produce a hardenability curve or band. A hardenability band for medium-carbon Society of Automotive Engineers/American Iron and Steel Institute (SAE/AISI) 1045 steel is shown in Fig. 10*a*. The two curves that form the band represent the maximum and minimum hardness values from many Jominy tests. To illustrate the concept of hardenability, compare the hardenability band for SAE/AISI 1045 steel to low-alloy SAE/AISI 4145 steel in Fig. 10*b*. These steels are similar except that the low-alloy steel has chromium and molybdenum additions as shown below:

C	Mn	Si	Cr	Mo
0.42/0.51	0.50/1.00	0.15/0.35	—	—
0.42/0.49	0.65/1.10	0.15/0.35	0.75/1.20	0.15/0.25

As can be seen from the hardenability bands, the higher manganese, chromium, and molybdenum additions in the SAE/AISI 4145 steel produced a much greater depth of hardness than the plain-carbon steel. For example, a hardness of HRC 45 (Rockwell *C* scale) was achieved at a depth of only 3–6.5 mm in the SAE/AISI 1045 steel compared with a hardness of HRC 45 at a depth of 21–50 mm in the SAE/AISI 4145 steel. This low-alloy steel has many times the depth of hardness or hardenability of the plain-carbon steel. This means that a hardness of HRC 45 can be achieved in the center of a 100-mm-diameter bar of SAE/AISI 4145 steel compared to a 10-mm-diameter bar of SAE/AISI 1045 steel (both water quenched). The depth of hardness is produced by forming martensite near the quenched end of the bar with mixtures of martensite and bainite further in from the end and eventually bainite at the maximum depth of hardness. Hardenability is important since hardness is roughly proportional to tensile strength. To convert hardness to an approximate tensile strength, the conversion table in the American Society for Testing and Materials (ASTM) E140 can be used. A portion of this table is given below:

Hardness			
Rockwell *C* Scale	Vickers	Brinell 3000-kg Load	Approximate Tensile Strength (MPa)
60	697	(654)	—
55	595	560	2075
50	513	481	1760
45	446	421	1480
40	392	371	1250
35	345	327	1080
30	302	286	950
25	266	253	840

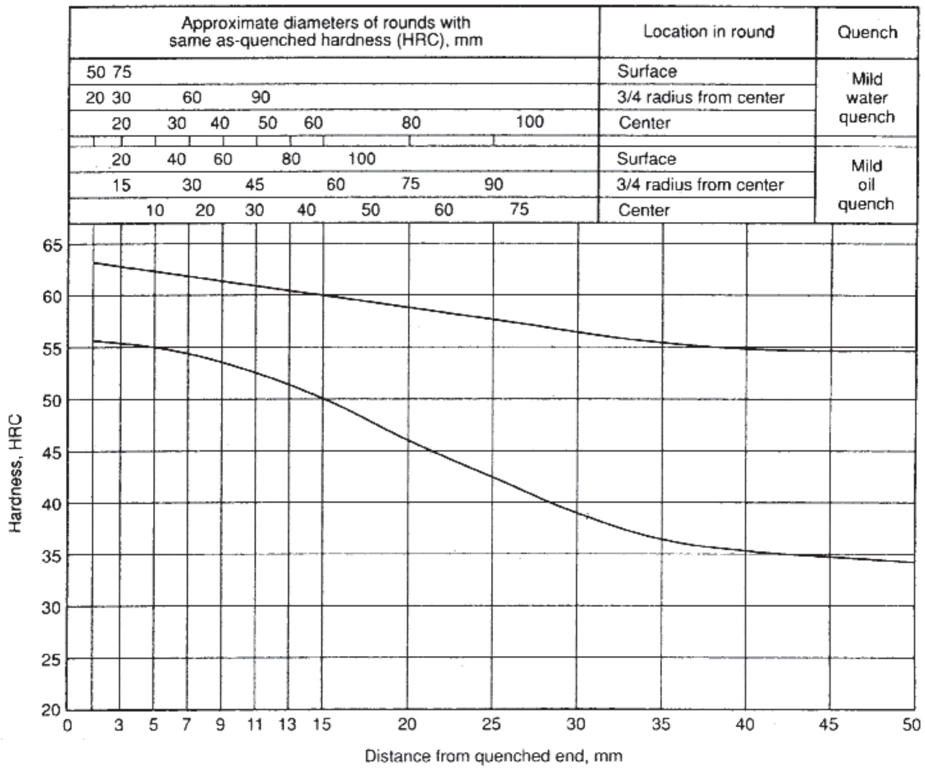
Heat-treating temperatures recommended by SAE
Normalize (for forged or rolled specimens only): 870 °C (1600 °F)
Austenitize: 845 °C (1550 °F)



(*a*)

Figure 10 Hardenability curves for (*a*) SAE/AISI 1045 and (*b*) SAE/AISI 4145 showing depth of hardness with distance from the quenched end of a Jominy bar. (*Source: ASM Handbook*, Vol. 1, *Properties and Selection: Irons, Steels, and High-Performance Alloys*, ASM International, Materials Park, OH, 1997, p. 487.) Reprinted with permission of ASM International.

Heat-treating temperatures recommended by SAE
Normalize (for forged or rolled specimens only): 870 °C (1600 °F)
Austenitize: 845 °C (1550 °F)



(*b*)

Figure 10 (*Continued*)

This table also lists Vickers and Brinell hardness values, which are different types of hardness tests. It can be seen that a hardness of HRC 45 converts to an approximate tensile strength of 1480 MPa.

4 ROLE OF ALLOYING ELEMENTS IN STEEL

In the hardenability concept described in the previous section, alloying elements have a profound effect on depth of hardness. Alloying elements also change the characteristics of the iron–carbon diagram. For example, in the iron–carbon diagram (see Fig. 1) austenite cannot exist below the eutectoid temperature of 727°C. However, there are steels where austenite is the stable phase at room temperature, e.g., austenitic stainless steels and austenitic manganese steels. This can only be achieved through alloying. There are, however, special conditions where small amounts of austenite can be retained at room temperature during rapid quenching of low-alloy steel. When this occurs, the austenite is too rich in alloying elements to transform at room temperature and is thus retained as small regions in a martensitic microstructure.

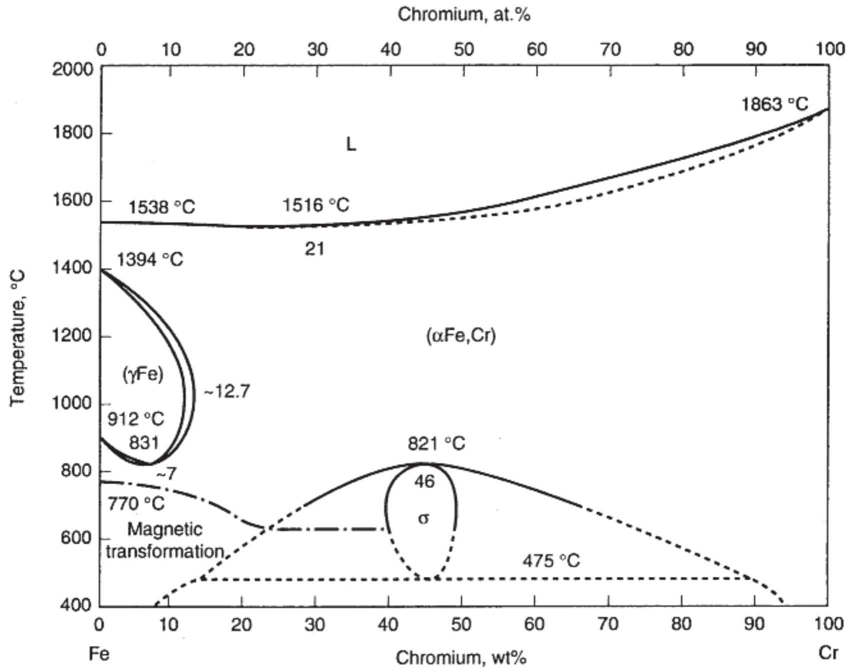


Figure 11 Iron–chromium equilibrium-phase diagram. (*Source: ASM Handbook,* Vol. 20, *Materials Selection and Design,* ASM International, Materials Park, OH, 1997, p. 365.) Reprinted with permission of ASM International.

Because of this, it is called retained austenite. The retained austenite can be transformed through tempering the steel.

In austenitic stainless steels, when nickel is added with chromium, the austenite-phase field is expanded, allowing austenite to be stable at room temperature. The popular SAE/AISI 304 austenitic stainless steel contains 18% Cr and 8% Ni. Austenitic manganese steel (Hadfield steel) contains 12% Mn with 1% C. The Mn and C allow austenite to be stable at room temperature. Because of this ability, nickel and manganese are, therefore, called austenite stabilizers. Other elements are ferrite stabilizers, e.g., chromium, silicon, and molybdenum. A ferrite-stabilizing element expands the ferrite-phase field, and the austenite-phase field is restricted within what is called a gamma loop (gamma, γ, is the symbol for austenite). A gamma loop can be seen in the iron–chromium equilibrium diagram in Fig. 11. The gamma loop is shown at the left side of the diagram. According to this diagram, iron–chromium alloys with 12.7% Cr or higher, the transformation from austenite (γ) to ferrite (α) does not occur and ferrite exists from room temperature to melting. Iron–chromium alloys make up an important class of stainless steels called ferritic and martensitic stainless steels.

Each particular alloying element has an influence on the structure and properties of steel. The following elements are important alloying elements in steel:

Carbon. Carbon is the most common alloying element in steel. It is inexpensive and has a strong influence on hardness and strength. It is the basic and essential alloying element in all plain-carbon, low-alloy, and tool steels. Carbon is an interstitial element that occupies sites between the larger iron atoms in the bcc and fcc lattices. The influence of carbon on the strength of iron can be seen in Fig. 12. Carbon can increase yield strength of pure iron (0% C) with a strength of about 28–190 MPa. At 0.005% C, the

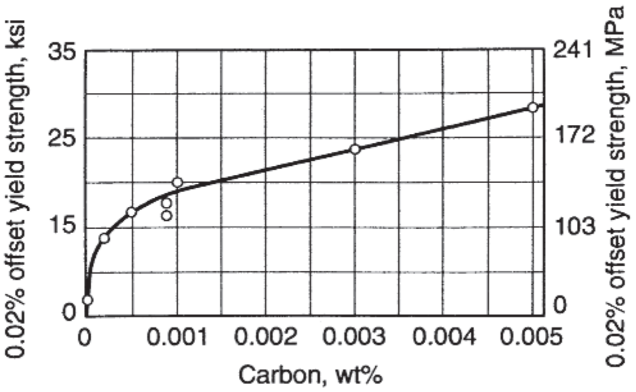


Figure 12 Effect of carbon in solid solution on the yield strength of iron. (*Source: ASM Handbook*, Vol. 20, *Materials Selection and Design*, ASM International, Materials Park, OH, 1997, p. 367.) Reprinted with permission of ASM International.

maximum solubility of carbon at room temperature the sevenfold increase in strength is due to interstitial solid-solution strengthening. Any excess carbon, above 0.005% C, will form an iron carbide compound called cementite (Fe_3C). Cementite can exist as a particle, as a component of lamellar pearlite, or as a proeutectoid network on prior austenite grain boundaries in hypereutectoid steel. Thus, carbon in the form of cementite has a further influence on the strength of steel, as seen in Fig. 13. In this plot, the steels between 0.1% C and 0.8% C contain about 10–100% pearlite. Yield strength peaks at about 425 MPa at 0.6% C whereas tensile strength (ultimate strength) increases to 790 MPa at 0.8% C. These properties are for carbon steels in the air-cooled condition. In a 0.8% C steel, a further increase in strength can be achieved if faster cooling rates are used to produce a finer pearlite interlamellar spacing. In a fully pearlitic, head-hardened rail steel (accelerated cooled), the yield strength can increase to 860 MPa and tensile strength to 1070 MPa. Carbon also has a negative effect on properties, as seen in Fig. 13. For example, the percent reduction in area (as well as total elongation not shown) decreases with increasing carbon. The percent reduction in area is a measure of the cross-sectional area change in a tensile specimen before and after fracture. Notch toughness also decreases with carbon content, as seen in the decrease in upper shelf energy and the increase in transition temperature. Shelf energy is the upper portion or upper shelf of a curve of absorbed energy plotted from a Charpy test.

Manganese. Manganese is also an essential element in all carbon, low-alloy, and alloy steels. Manganese has several roles as an alloying element. One role is to assure that all residual sulfur is combined to form manganese sulfide (MnS). Manganese is generally added to steel with a minimum manganese–sulfur ratio of 20:1. Without manganese the sulfur would combine with iron and form iron sulfide (FeS), which is a brittle compound that lowers toughness and ductility and causes a phenomenon called hot shortness. Hot shortness is a condition where a compound (such as FeS) or insoluble element (such as copper) in steel has a low melting point and thus forms an unacceptable cracklike surface condition during hot rolling. Another role of manganese is in strengthening steel. Manganese is a substitutional element and can replace iron atoms in the bcc or fcc lattice. Each 0.1% Mn added to iron will increase the yield strength by about 3 MPa. Manganese also lowers the eutectoid transformation temperature and lowers the eutectoid carbon content. In large amounts (12% or higher), manganese is

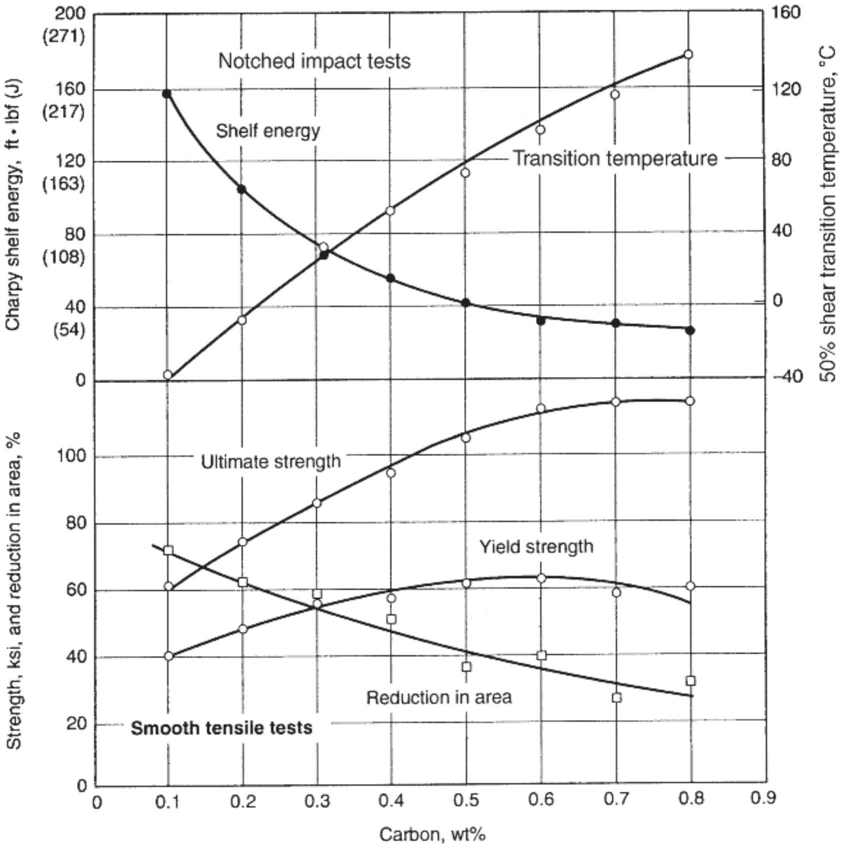


Figure 13 Effect of carbon on the tensile and notched impact properties of ferrite–pearlite steels. (*Source: ASM Handbook,* Vol. 20, *Materials Selection and Design,* ASM International, Materials Park, OH, 1997, p. 367.) Reprinted with permission of ASM International.

an austenite stabilizer in alloy steels and forms a special class of steels called austenitic manganese steels (also called Hadfield manganese steels). These steels are used in applications requiring excellent wear resistance, e.g., in rock crushers and in railway track connections where two rails meet or cross.

Silicon. Silicon is added to many carbon and low-alloy steels as a deoxidizer, i.e., it removes dissolved oxygen from molten steel during the steel-refining process. Oxygen is an undesirable element in steel because it forms oxide inclusions, which can degrade ductility, toughness, and fatigue resistance. Silicon has a moderate effect on strengthening steel but is usually not added for strengthening. Each 0.1% Si increases the yield strength of iron by about 8 MPa. It is a ferrite stabilizer and is found in some stainless steels. Silicon is also added to steel for enhanced electrical properties, e.g., iron–silicon transformer steels at 3.25% Si. These carbon-free steels have high magnetic permeability and low core loss.

Phosphorus. Phosphorus is considered a tramp or residual element in steel and is carefully restricted to levels generally below 0.02%. However, like carbon, phosphorus is an interstitial element that can substantially strengthen iron. For this reason, phosphorus is added to a special class of steels called rephosphorized steels for strength. Rephosphorized steels also have enhanced machinability.

Sulfur. Sulfur is also considered a tramp element in steel and is usually restricted to below about 0.02%. Although an element with a small atomic diameter, sulfur is not considered an interstitial alloying element because it is insoluble in iron. However, as in the case of phosphorus, sulfur is added to a special class of steels called resulfurized steels that have improved machinability. These steels are called free-machining steels.

Copper. In most steels copper is considered a tramp (residual) element and is restricted to levels below 0.04%. Copper, having a much lower melting point than iron, can create a detrimental steel surface condition known as hot shortness. Although not generally added to steel, there is a very special class of steels that contain high levels of copper to take advantage of the precipitation of copper particles during aging (a tempering process). These copper particles increase strength and hardness. Copper is also added to low-alloy steels for atmospheric corrosion protection (these steels are called weathering steels). One problem with copper in steel is that it cannot be oxidized and removed during steel refining. Thus, over time, the copper level of steel produced from steel scrap is slowly increasing.

Nickel. Nickel is an important element because of its positive effect on hardenability. Many important low-alloy steels contain nickel for this reason. Nickel, being a substitutional element in the iron lattice, has a small effect on increasing yield strength. Nickel, being an austenite stabilizer, is also a vital element in austenitic stainless steels. Nickel is also important in steels for cryogenic applications and storage tanks for liquefied hydrocarbon gases. Nickel does not form a carbide and remains in solid solution.

Chromium. Like nickel, chromium has a positive effect on hardenability and is an important alloying element in many low-alloy steels. For corrosion resistance, chromium is present in all stainless steels as a solid-solution element. In addition to hardenability and solid-solution effects, chromium forms several important chromium carbides that are necessary for wear resistance in many tool steels and steels used for rolls in hot- and cold-rolling mills.

Molybdenum. Molybdenum is a potent hardenability element and is found in many low-alloy steels. Molybdenum, like chromium, forms several types of carbides that are important for wear-resistant applications, e.g., tool steels. Molybdenum is added to minimize temper embrittlement in low-alloy steels. Temper embrittlement occurs when low-alloy steels are tempered in the temperature range of 260–370°C. The embrittlement is caused by tramp elements such as phosphorus that accumulate at the prior austenite grain boundaries and thus weaken the boundaries. Adding molybdenum prevents the accumulation of these undesirable elements at the boundaries. Molybdenum also enhances the creep strength of low-alloy steels at elevated temperatures and is used in rotors and other parts of generators in electric power plants. Creep is an undesirable process that allows steel to slowly elongate or creep under load. Eventually the component will fail.

Vanadium. Although vanadium is a potent hardenability element, its most useful role is in the formation of a vanadium nitride and vanadium carbide (it can also be in a combined form of vanadium carbonitride). A very important role of vanadium is in microalloyed steels, also called high-strength, low-alloy (HSLA) steels. These steels are strengthened by precipitation of vanadium nitrides and vanadium carbides (vanadium carbonitrides). The formation of vanadium carbide is important for wear resistance. Vanadium carbide is much harder than iron carbide, chromium carbide, and molybdenum carbide. Vanadium is thus important in high-speed tool steels, which are used as drill bits that retain their hardness as the tool heats by friction.

Tungsten. Tungsten is not an addition to low-alloy steels but is a vital alloying element in high-speed tool steels where it forms hard tungsten carbide particles.

Aluminum. Aluminum is employed as a deoxidizer in steel and is generally used in conjunction with silicon (also a deoxidizer). A deoxidizer removes undesirable oxygen from molten steel. Once removed, the steel is called "killed." Aluminum–silicon deoxidized (killed) steels are known as fine-grain steels. Another important role of aluminum is the formation of aluminum nitride (AlN) precipitate. Many steels depend upon the formation of AlN, especially steels used for sheet-forming applications requiring a high degree of formability such as parts that require deep drawing. These steels are called drawing-quality special-killed (DQSK) steels. The AlN precipitates help in the formation of an optimum crystallographic texture (preferred orientation) in low-carbon sheet steels for these deep-drawing applications. When aluminum combines with nitrogen to form AlN, the dissolved interstitial nitrogen is lowered. Lower interstitial nitrogen (interstitial nitrogen is also called free nitrogen) provides improved ductility. Aluminum can also substitute for silicon in electrical steels for laminations in electric motors and transformer cores.

Titanium. Titanium is a strong deoxidizer but is usually not used solely for that purpose. Titanium is important in microalloyed steels (HSLA steels) because of the formation of titanium nitride (TiN) precipitates. Titanium nitrides pin grain boundary movement in austenite and thus provide grain refinement. Another role of titanium is in steels containing boron where a titanium addition extracts nitrogen from liquid steel so that boron, a strong nitride former, remains in elemental form to enhance hardenability. Because of its affinity for both carbon and nitrogen, titanium is important in IF steels. Interstitial-free steels are an important class of steels with exceptional formability. Titanium, being a strong carbide former, is used as a carbide stabilizer in austenitic stainless steels (AISI type 321), ferritic stainless steels (AISI types 409, 439, and 444), and precipitation-hardening stainless steels (AISI types 600 and 635).

Niobium (Columbium). Niobium is also important in microalloyed (HSLA) steels for its precipitation strengthening through the formation of niobium carbonitrides. Some microalloyed steels employ both vanadium and niobium. Because of its affinity for both carbon and nitrogen, niobium is an element found in some IF steels. Niobium is also added as a carbide stabilizer (prevents carbides from dissolving and re-forming in undesirable locations) in some austenitic stainless steels (AISI types 347, 348, and 384), ferritic stainless steels (AISI types 436 and 444), and precipitation-hardening stainless steels (AISI types 630).

Tantalum. Because of its affinity for carbon, tantalum, like niobium, is added as a carbide stabilizer to some austenitic stainless steels (AISI types 347 and 348).

Boron. On a weight percent basis, boron is the most powerful hardenability element in steel. A minute quantity of boron, e.g., 0.003%, is sufficient to provide ample hardenability in a low-alloy steel. However, boron is a strong nitride former and can only achieve its hardenability capability if in elemental form. Thus, boron must be protected from forming nitrides by adding a sufficient amount of titanium to first combine with the nitrogen in the steel.

Calcium. Calcium is a strong deoxidizer in steel but is not used for that purpose. In an aluminum-deoxidized (killed) steel, calcium combines with sulfur to form calcium sulfide particles. This form of sulfide remains as spherical particles as compared with manganese sulfide, which is soft and elongates into stringers upon hot rolling.

Thus, steels properly treated with calcium do not have the characteristics associated with MnS stringers, i.e., property directionality or anisotropy.

Zirconium. Although expensive and rarely added to steel, zirconium acts like titanium in forming zirconium nitride participates.

Nitrogen. Nitrogen is added to some steels, e.g., steels containing vanadium, to provide sufficient nitrogen for nitride formation. This is important in microalloyed steels containing vanadium. Nitrogen, being an interstitial element like carbon, strengthens ferrite. A number of austenitic stainless steels contain nitrogen for strengthening (AISI types 201, 202, 205, 304N, 304LN, 316N, and 316LN).

Lead. Lead is added to steel for enhanced machinability. Being insoluble in iron, lead particles are distributed through the steel and provide both lubrication and chip-breaking ability during machining. However, leaded steels are being discontinued around the world because of the environmental health problems associated with lead.

Selenium. Selenium is added to some austenitic stainless steels (AISI type 303Se), ferritic stainless steels (AISI type 430Se), and martensitic stainless steels (AISI type 416Se) for improved machined surfaces.

Rare Earth Elements. The rare earth elements cerium and lanthanum are added to steel for sulfide shape control, i.e., the sulfides become rounded instead of stringers. It is usually added in the form of mish metal (a metallic mixture of the rare earth elements).

Residual Elements. Tin, antimony, arsenic, and copper are considered residual elements in steel. They are also called tramp elements. These elements are not intentionally added to steel but remain in steel because they are difficult to remove during steelmaking and refining. Steels made by electric furnace melting employing scrap as a raw material contain higher levels of residual elements than steels made in an integrated steelmaking facility (blast furnace–BOF route). Some electric furnace melting shops use direct-reduced iron pellets to dilute the effect of these residuals.

Hydrogen. Hydrogen gas is also a residual element in steel and can be very deleterious. Hydrogen is soluble in liquid steel and somewhat soluble in austenite. However, it is very insoluble in ferrite and is rejected as atomic hydrogen (H^+). If trapped inside the steel, usually in products such as thick plates, heavy forgings, or railroad rails, hydrogen will accumulate on the surfaces of manganese sulfide inclusions. When this accumulation takes place, molecular hydrogen (H_2) can form and develop sufficient pressure to create internal cracks. As the cracks grow, they form what is termed hydrogen flakes and the product must be scrapped. However, if the product is slow cooled from the rolling temperature, the atomic hydrogen has sufficient time to diffuse from the product, thus avoiding hydrogen damage. Also, most modern steelmakers use degassing to remove hydrogen from liquid steel.

5 HEAT TREATMENT OF STEEL

One of the very important characteristics of steel is the ability to alter the microstructure through heat treatment. As seen in the previous sections, many different microstructural constituents can be produced. Each constituent imparts a particular set of properties to the final product. For example, by quenching a steel in water, the steel becomes very hard but brittle through the formation of martensite. By tempering the quenched steel, some ductility can be restored with some sacrifice in hardness and strength. Also, superior wear properties can be obtained in fully pearlitic microstructures, particularly if an accelerated cooling process is employed to develop a fine interlamellar spacing. Complex parts can be designed by taking advantage of the formability and ductility of ferritic sheet steel through cold rolling and annealing. The amount of pearlite in ferritic steel can be adjusted by carbon content and cooling rate to produce a wide range of hardness and strength. In quenched and tempered steels, a bainitic microstructure has a unique combination of high strength and toughness. Thus steel, more than any other metallic material, can be manipulated through heat treatment to provide a multiplicity of microstructures and final properties. The common types of heat treatment are listed below:

Annealing (Full Annealing). One of the most common heat treatments for steel is annealing. It is used to soften steel and to improve ductility. In this process, the steel is heated into the lower regions of the austenite-phase field and slow cooled to room temperature. The resulting microstructure consists of coarse ferrite or coarse ferrite plus pearlite, depending upon carbon and alloy content of the steel.

Normalizing. Steel is normalized by heating into the austenite-phase field at temperatures somewhat higher than those used by annealing followed by air cooling. Many steels are normalized to establish a uniform ferrite plus pearlite microstructure and a uniform grain size.

Spheroidizing. To produce a steel in its softest possible condition, it is usually spheroidized by heating just above or just below the eutectoid temperature of 727°C and holding at that temperature for an extended time. This process breaks down lamellar pearlite into small spheroids of cementite in a continuous matrix of ferrite, as seen in Fig. 14. To obtain a very uniform dispersion of cementite spheroids, the starting microstructure is usually martensite. This is because carbon is more uniformly distributed in martensite than in lamellar pearlite. The cementite lamella must first dissolve and then redistribute the carbon as spheroids whereas the cementite spheroids can form directly from martensite.

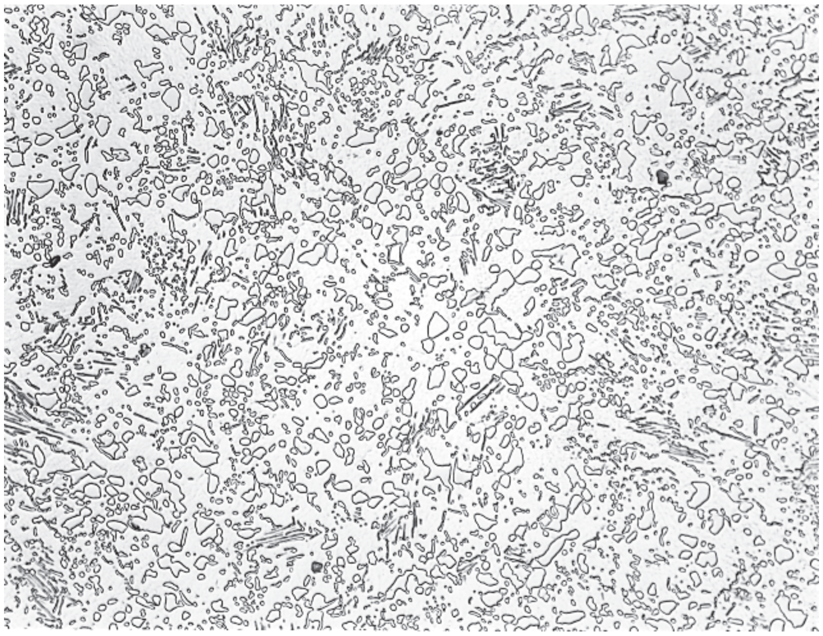


Figure 14 Photomicrograph of a medium-carbon steel in the spheroidized condition. 500X. 4% picral + 2% nital etch.

Process Annealing (Recrystallization Annealing). Process annealing takes place at temperatures just below the eutectoid temperature of 727°C. This treatment is applied to low-carbon, cold-rolled sheet steels to restore ductility. In aluminum-killed steels, the recrystallized ferrite will have an ideal crystallographic texture (preferred orientation) for deep drawing into complex shapes such as oil filter cans and compressor housings. Crystallographic texture is produced by developing a preferred orientation of the ferrite grains, i.e., the crystal axes of the ferrite grains are oriented in a preferred rather than random orientation.

Stress Relieving. Steel products with residual stresses can be heated to temperatures approaching the eutectoid transformation temperature of 727°C to relieve the stress.

Quenching. To produce the higher strength constituents of bainite and martensite, the steel must be heated into the austenite-phase field and rapidly cooled by quenching in oil or water. High-strength, low-alloy steels are produced by this process followed by tempering. It must be noted that employing microalloying additions such as Nb, V, and Ti can also produce HSLA steels. These microalloyed steels obtain their strength by thermomechanical treatment rather than heat treatment.

Tempering. When quenched steels (martensitic steel) are tempered by heating to temperatures approaching the eutectoid temperature of 727°C, the dissolved carbon in the martensite forms cementite particles, and the steels become more ductile. Quenching and tempering are used in a variety of steel products to obtain desired combinations of strength and toughness.

6 CLASSIFICATION AND SPECIFICATIONS OF STEELS

Since there are literally thousands of different steels, it is difficult to classify them in a simple straightforward manner. However, some guidelines can be used. For example, steels are generally classified as carbon steel or alloy steel. A classification system was developed by the SAE as early as 1911 to describe these carbon and alloy steels. The AISI collaborated with SAE to refine the compositional ranges of the classification that are used today. Recently, a Unified Numbering System (UNS) was established that incorporates the SAE/AISI number.

Many steel products are purchased by specifications describing specific compositional, dimensional, and property requirements. Specification organizations such as ASTM have developed numerous specifications for steel products and the testing of steel products. Some specific product user groups in the United States have developed their own specifications, e.g., the American Bureau of Ships (ABS) for ship plate and other marine products, Aerospace Materials Specifications (AMS) for aerospace applications, the American Railway Engineering and Maintenance of Way Association (AREMA) for rail and rail products, the SAE for automotive applications, and the American Society of Mechanical Engineers (ASME) for steels produced to boiler code specifications. In Japan, there are standards developed by the Japanese Industrial Standards (JIS) Committee of the Ministry of International Trade and Industry. In the United Kingdom, there are the British Standards (BS) developed by the British Standards Institute. In Europe, Germany has the Deutsches Institut für Normung (DIN) standards, France the Association Francaise de Normalisation (AFNOR) standards, and Italy the Ente Nazionale Italiano di Unificazione (UNI) standards.

Specifications can be as simple as a hardness requirement, i.e., ASTM A1 for rail steel to elaborate compositional and property requirements as in ASTM A808, “High-strength low-alloy carbon–manganese–niobium–vanadium steel of structural quality with improved notch toughness.” Describing specific specifications is beyond the scope of this handbook, but many of the key sources can be found in the Bibliography at the end of this chapter.

6.1 Carbon Steels

Carbon steels (also called plain-carbon steels) constitute a family of iron–carbon–manganese alloys. In the SAE/AISI system, the carbon steels are classified as follows:

Nonresulfurized carbon steels	10xx series
Resulfurized steels	11xx series
Rephosphorized and resulfurized steels	12xx series
High-manganese carbon steels	15xx series

A four-digit SAE/AISI number is used to classify the carbon steels with the first two digits being the series code and the last two digits being the nominal carbon content in points of carbon (1 point = 0.01% C). For example, SAE/AISI 1020 steel is a carbon steel containing 0.20% C (actually 0.18–0.22% C). The chemical composition limits for the above SAE/AISI 10xx series of carbon steels for semifinished products, forgings, hot- and cold-finished bars, wire, rods, and tubing are listed in *SAE Materials Standards Manual* (SAE HS-30, 1996). There are slight compositional variations for structural shapes, plates, strip, sheet, and welded tubing (see SAE specification J403). The *SAE Manual* gives the SAE/AISI number along with the UNS number. The carbon level spans the range from under 0.06% C to 1.03% C.

Because of the wide range in carbon content, the SAE/AISI 10xx carbon steels are the most commonly used steels in today's marketplace. All SAE/AISI 10xx series carbon steels contain manganese at levels between 0.25 and 1.00%. For a century, manganese has been an important alloying element in steel because it combines with the impurity sulfur to form manganese sulfide (MnS). MnS is much less detrimental than iron sulfide (FeS), which would form without manganese present. Manganese sulfides are usually present in plain and low-alloy steels as somewhat innocuous inclusions. The manganese that does not combine with sulfur strengthens the steel. However, with the development of steelmaking practices to produce very low sulfur steel, manganese is becoming less important in this role.

The SAE/AISI 11xx series of resulfurized steels contain between 0.08 and 0.33% sulfur. Although in most steel sulfur is considered an undesirable impurity and is restricted to less than 0.05%, in the SAE/AISI 11xx and 12xx series of steels, sulfur is added to form excess manganese sulfide inclusions. These are the free-machining steels that have improved machinability over lower sulfur steels due to enhanced chip breaking and lubrication created by the MnS inclusions.

The SAE/AISI 12xx series are also free-machining steels and contain both sulfur (0.16–0.35%) and phosphorus (0.04–0.12%). The SAE/AISI 15xx series contain higher manganese levels (up to 1.65%) than the SAE/AISI 10xx series of carbon steels.

Typical mechanical properties of selected SAE/AISI 10xx and 11xx series of carbon steels are listed in the first part of the table on pp. 20–23, Section 4, of the *ASM Metals Handbook,* Desktop Edition, 1985, for four different processing conditions (as rolled, normalized, annealed, and quenched and tempered). These properties are average properties obtained from many sources, and thus this table should only be used as a guideline. The as-rolled condition represents steel before any heat treatment was applied. Many applications utilize steel in the as-rolled condition. As can be seen from the aforementioned ASM table, yield and tensile strength are greater for steel in the normalized condition. This is because normalizing develops a finer ferrite grain size. Yield and tensile strength are lowest for steels in the annealed condition. This is due to a coarser grain size developed by the slow cooling rate from the annealing temperature. In general, as yield and tensile strength increase, the percent elongation decreases. For example, in the ASM table, annealed SAE/AISI 1080 steel has a tensile strength of 615 MPa and a total elongation of 24.7% compared with the same steel in the normalized condition, with a tensile strength of 1010 MPa and a total elongation of 10%. This relationship holds for most steel.

Special Low-Carbon Steels

These are the steels that are not classified in the aforementioned SAE table or listed in the aforementioned ASM table. As mentioned earlier, carbon is not always beneficial in steels. These are special steels with carbon contents below the lower level of the SAE/AISI 10xx steels. There are a number of steels that are produced with very low carbon levels (less than 0.002% C), and all the remaining free carbon in the steel is tied up as carbides. These steels are known as IF steels, which means that the interstitial elements of carbon and nitrogen are no longer present in elemental form in the iron lattice but are combined with elements such as titanium or niobium as carbides and nitrides (carbonitrides). Interstitial-free steels are required for exceptional formability, especially in applications requiring deep drawability. Drawability is a property that allows the steel to be uniformly stretched (or drawn) in thickness in a closed die without localized thinning and necking (cracking or breaking). An example of a deep-drawn part would be a compressor housing for a refrigerator. With proper heat treatment, IF steels develop a preferred crystallographic orientation that favors a high plastic anisotropy ratio, or r value. High-r-value steels have excellent deep-drawing ability and these steels can form difficult parts. Another type of low-carbon steel is a special class called DQSK steel. This type of aluminum-treated steel also has a preferred orientation and high r value. The preferred orientation is produced by hot rolling the steel on a hot strip mill followed by rapid cooling. The rapid cooling keeps the aluminum and interstitial elements from forming aluminum nitride particles (i.e., the Al and N atoms are in solid solution in the iron lattice). After rolling, the steel is annealed to allow aluminum nitride to precipitate. The aluminum nitride plays an important role in the development of the optimum crystallographic texture. The DQSK steel is used in deep-drawing applications that are not as demanding as those requiring IF steel.

A new family of steels called bake-hardening steels also have a low, but controlled carbon content. These steels gain strength during the paint–bake cycle of automotive production. Controlled amounts of both carbon and nitrogen combine with carbonitride-forming elements such as titanium and niobium during the baking cycle (generally 175°C for 30 min). The precipitation of these carbonitrides during the paint–bake cycle strengthens the steel by a process called aging.

Enameling steel is produced with as little carbon as possible because during the enameling process carbon in the form of carbides can react with the frit (the particles of glasslike material that melts to produce the enamel coating) to cause defects in the coating. Thus, steels to be used for enameling are generally decarburized in a special reducing atmosphere during batch annealing. In this process, the carbon dissipates from the steel. After decarburization, the sheet steel is essentially pure iron. Enamel coatings are used for many household appliances such as washers and dryers, stovetops, ovens, and refrigerators. Also, steel tanks in most hot-water heaters have a glass (or enameled) inside coating.

Electrical steels and motor lamination steels are also produced with as low a carbon content as possible. Dissolved carbon and carbides in these steels are avoided because the magnetic properties are degraded. The carbides, if present in the steel, inhibit the movement of the magnetic domains and lower the electrical efficiency. These steels are used in applications employing alternating current (AC) in transformers and electric motors. Most electric motors for appliances and other applications have sheet steel stacked in layers (called laminations) that are wound in copper wire. Electrical steels used for transformers contain silicon, which is added to enhance the development of a specific crystallographic orientation that favors electrical efficiency.

6.2 Alloy Steels

Alloy steels are alloys of iron with the addition of one or more of the following elements: carbon, manganese, silicon, nickel, chromium, molybdenum, and vanadium. The alloy steels cover a wide range of steels, including low-alloy steels, stainless steels, heat-resistant steels, and tool steels. Some alloy steels, such as austenitic stainless steels, do not contain intentional additions of carbon. Silicon, when required, is added as a deoxidizer to the molten steel. Nickel provides strength and assists in hardening the steel by quenching and tempering heat treatment. This latter effect is called hardenability, which has been described earlier. Chromium is found in stainless steels for corrosion resistance. Chromium and molybdenum also assist in hardenability of the low-alloy steels. Vanadium strengthens the steel by forming precipitates of vanadium carbonitride. Vanadium is also a potent hardenability element.

Low-Alloy Steels

There is an SAE/AISI four-digit classification system for the low-alloy steels. As in the carbon steels, the first two digits are for the alloy class and the last two (or three) digits are for the carbon content. Because of the various combinations of elements, the system is more extensive than that used for the carbon steels. The general SAE/AISI classification system for low-alloy steels is as follows:

Manganese steels	13xx series
Nickel steels	23xx, 25xx series
Nickel–chromium steels	31xx, 32xx, 33xx, and 34xx series
Molybdenum steels	40xx, 44xx series
Chromium–molybdenum steels	41xx series
Nickel–chromium–molybdenum steels	43xx and 47xx series 81xx, 86xx, 87xx, and 88xx series 93xx, 94xx, 97xx, and 98xx series
Nickel–molybdenum steels	46xx and 48xx series
Chromium steels	50xx and 51xx series 50xxx, 51xxx, and 52xxx series
Chromium–vanadium steels	61xx series
Tungsten–chromium steels	71xxx, 72xx series
Silicon–manganese steels	92xx series
Boron steels	xxBxx series
Leaded steels	xxLxx series

The boron-containing steels are low-alloy steels with boron added in the amount of 0.0005–0.003%. Boron is a strong hardenability element. The leaded steels contain 0.15–0.35% lead for improved machinability (however, lead is no longer favored as an alloying addition because of health concerns).

A table in the aforementioned SAE HS-30 lists the composition limits of most of the families of the SAE/AISI low-alloy steels listed above. These steels are supplied in the form of bar, plate, and forged products and are usually heat treated to obtain specific mechanical properties, especially high strength and toughness. Mechanical properties of selected SAE/AISI low-alloy steels in the as-rolled, annealed, normalized, and quenched and tempered conditions are listed in the aforementioned ASM table. These properties are average properties and should only be used as a guideline. For example, SAE/AISI 4340 steel is usually heat treated by heating the component to 950–1000°C followed by quenching in oil. The component is then tempered at a temperature between 205 and 650°C. According to the aforementioned ASM table, this nickel–chromium–molybdenum steel in the quenched and tempered condition (tempered at 205°C) can achieve a yield strength of 1675 MPa and a tensile strength of 1875 MPa. Quenched and tempered low-alloy steels are used in a large number of applications requiring high strength and good toughness. Note that in the annealed condition SAE/AISI 4340 steel has a yield strength of only 745 MPa.

Other Low-Alloy Steels

There are a number of important steels that do not fit into the SAE/AISI classification system described above. Such classes are the microalloyed steels also called HSLA steels, dual-phase steels, trip steels, and high-performance steels.

Microalloyed (High-Strength, Low-Alloy) Steels. Microalloying is a term applied to steels that contain small additions of alloying elements that retard austenite recrystallization and pin austenite grain boundary movement by the formation of small carbide and/or nitride precipitates. These elements include vanadium, niobium, and titanium. These HSLA steels are produced for a variety of plates, structural shapes, bars, and sheet applications with yield strength varying from 290 to 690 MPa. These steels are covered under numerous SAE and ASTM specifications. The SAE high-strength, low-alloy steels are covered under specifications J410, J1392, and J1442 and the ASTM high-strength, low-alloy steels are covered under various specifications, including A242, A440, A441, A572, A588, A606, A607, A618, A633, A656, A690, A709, A714, A715, A808, A812, A841, A860, and A871. These HSLA steels have found wide application in areas such as bridge construction (structural beams), off-shore oil and natural gas platforms, ship hull and deck plate, and electrical transmission towers and poles. In the automobile, HSLA steels are used for safety (ultrahigh-strength impact door beams and energy-absorbing bumper assemblies) and for increasing fuel economy through thinner (lighter weight) chassis structural sections. Microalloyed HSLA steels are also employed in large-diameter gas transmission pipelines.

Dual-Phase Steels. A relatively recent development, dual-phase steels are produced by rapidly cooling a medium-carbon steel, containing vanadium or molybdenum, from the two-phase ferrite plus austenite region. The austenite transforms into islands of martensite (stabilized at room temperature by the V and Mo additions) in a ferrite matrix. Depending upon the alloy content, the martensite islands can also contain austenite that is retained below the transformation temperature (called retained austenite). Thus, dual-phase steel may contain both martensite and austenite as a second phase (called MA constituent). The unique characteristic of dual-phase steels is the continuous yielding behavior during deformation; i.e., there is a lack of a yield point during deformation. This provides increased uniform elongation and work hardening so that those components or parts produced from dual-phase steel actually gain strength during the forming operation. Dual-phase steels are being applied in applications such as automobile wheel rims and wheel disks. Because of their energy-absorbing characteristics, dual-phase steels are being used in critical locations of the automobile for safety to protect the occupants in the event of a crash.

Trip Steels. Similar to dual-phase steels, trip steels have emerged as an energy-absorbing high-strength steel for the automobile. The term “trip” is derived from the mechanism of *tr*ansformation *i*nduced *p*lasticity. These steels contain a high percentage of retained austenite (10–15%). The austenite transforms to martensite during the forming of the part, thus providing enhanced formability or transforms upon impact in a crash.

High-Performance Steels. There are a number of high-performance steels that are used in critical applications. These low-alloy steels, such as HY80 and HY100, are used in applications requiring high strength and excellent toughness. The “80” and “100” in the codes represent the minimum yield strength in ksi units. Another family of low-alloy steels is used in heat exchangers, high-temperature piping, and boiler applications. These steels, like $2\frac{1}{4}$% Cr–1% Mo, find wide use in these applications. Other high-performance steels are the Ni–Cr–Mo steels used as rotors for large steam generators and motors in electric power plants. These steels must withstand temperatures of superheated steam and must maintain high strength, superior toughness, as well as high fatigue strength and creep resistance. The Ni–Cr–Mo–V steels are also used in pressure vessels in nuclear reactors.

Higher Alloy Steels

There is a distinction between the low-alloy steels described above and the higher alloy steels (usually containing over 8% alloying elements). The higher alloy steels include stainless steels, tool steels, heat-resistant steels, wear-resistant steels, and ultrahigh-strength steels.

Stainless Steels. Stainless steels are corrosion-resistant steels that contain at least 10.5% chromium. Chromium is unique in that it forms a passive layer on the steel surface that provides protection from corrosion. There are basically five types of stainless steels: austenitic, ferritic, duplex, martensitic, and precipitation-hardening steels. These five types of stainless steel have a somewhat simplified classification system as follows:

Austenitic stainless steels with low nickel	2xx series
Austenitic stainless steels	3xx series
Ferritic stainless steels	4xx series
Duplex stainless steel	29
Martensitic stainless steels	4xx series
Precipitation-strengthening stainless steels	6xx (xx-x PH)

The classification system is different for the stainless steels than the system for SAE/AISI low-alloy steels in that the last two digits (xx) do not represent the carbon content and have no particular compositional meaning. Unfortunately, the classification system has some confusion with the ferritic and martensitic stainless steels both of the 4xx series. The 2xx series of austenitic stainless steels were developed during the 1950s when nickel became scarce. In these steels, manganese and nitrogen were substituted for the lower nickel level in order to maintain strength. Each type of stainless steel is expanded upon below:

AUSTENITIC STAINLESS STEELS. Austenitic stainless steels have sufficient alloying to stabilize austenite at room temperature. These steels, being austenitic, are nonmagnetic. Austenitic stainless steels have excellent low-temperature toughness, weldability, and corrosion resistance. On the other hand, they have relatively low yield strength and can only be strengthened by cold working the steel, by precipitation hardening, or by interstitial or substitutional solid-solution strengthening.

The table on pp. 15.1–15.4 of the *ASM Metals Handbook,* Desktop Edition, 1985, lists the composition limits of the austenitic stainless steels. In general, the 3xx series are iron–chromium–nickel alloys that contain 16–26% chromium and 6–22% nickel. The popular type 304 austenitic stainless steel contains 18–20% Cr and 8–12% Ni and is often referred to as "18–8" stainless steel for the chromium and nickel content. There are many compositional variations of austenitic stainless steels. The following list summarizes these variations:

201	Low nickel replaced with manganese and nitrogen
202	Higher Mn than 201
205	Higher Mn and N than 202
301	Lower Ni and Cr to increase work-hardening ability
302	General-purpose 18–8 stainless steel
302B	Scaling resistance improved with Si

303	Enhanced machinability with a S addition
303Se	Improved machined surfaces with a selenium addition
304	Popular 18–8 stainless steel, lower C than 302
304L	Low-carbon 304 for improved corrosion resistance
304LN	Low-carbon 304 with nitrogen added for strength
304H	Higher carbon 304
304Cu	Copper added for improved cold working
304N	Nitrogen added for strength
305	Higher Ni for reduced work hardening
308	Higher Cr and Ni for weldability
309	High Cr and Ni for heat resistance
309S	Lower carbon 309
309Cb	Niobium (columbium) added
310	Higher Cr and Ni than 309 for improved heat resistance
310S	Lower carbon 310
310Cb	Niobium (columbium) added
314	Higher Si for improved heat resistance
316	Mo added for improved corrosion resistance
316F	Higher S and P for machinability
316L	Lower C for improved corrosion resistance and weldability
316LN	Lower C and higher nitrogen (for strength)
316H	Higher carbon 316
316N	Nitrogen added for strength
316Ti	Titanium added
316Cb	Niobium (columbium) added
317	Higher Cr and Mo for improved corrosion resistance
317L	Low-carbon 317 for improved weldability
321	Titanium added to minimize Cr carbide precipitation
330	High Ni to minimize carburization and improve thermal shock
347	Nb and Ta added to minimize Cr carbide precipitation
347H	Higher carbon 347
348	Ta and Co added for restricted nuclear applications
348H	Higher carbon 348
384	Higher Ni for decreased work hardening

The limiting of carbon is important in austenitic stainless steels. When heated, carbon forms chromium carbide that precipitates on the austenite grain boundaries and produces a condition known as sensitization. Because the chromium is tied up as carbide, the chromium adjacent to the boundaries will be depleted in chromium and corrosion can take place. Sensitization is reversible by heating the steel to temperatures between 1040 and 1150°C followed by rapid cooling to room temperature. The high temperature dissolves the carbides and the rapid cooling prevents reprecipitation of the carbides. More on austenitic stainless steel can be found in Chapter 2.

FERRITIC STAINLESS STEELS. The ferritic stainless steels are basically iron–chromium alloys with chromium ranging from 10.5 to 27%. The compositional limits for the ferritic stainless steels are listed in the aforementioned ASM table. Nickel is absent in ferritic stainless steels except for minor amounts, i.e., less than 1%, in some alloys. These steels have a microstructure of ferrite at room temperature and are magnetic. Type 409 stainless steel with the lowest chromium level (10.5–11.75%) is the least expensive of the ferritic stainless steel series and is used for automotive exhaust systems because it far outlasts carbon steel in that application. There are fewer variations of ferritic stainless steels than austenitic stainless steels. The ferritic stainless steels are listed below:

405	Low Cr with Al added
409	Low Cr, for automotive exhaust applications
429	Slightly less Cr, better weldability
430	General-purpose ferritic stainless steel
430F	Free machining with higher S and P
430Se	Selenium added for improved machined surfaces
434	Mo added for improved corrosion resistance
436	Mo, Nb, and Ta added for corrosion and heat resistance
439	Low C, Ti added to minimize sensitization
442	Higher Cr for improved oxide scaling resistance
444	Low C, Mo for corrosion resistance, Ti and Nb for sensitization
446	Highest Cr for improved scaling resistance

Ferritic stainless steels are described in more detail in Chapter 2.

DUPLEX STAINLESS STEELS. Type 329 is an iron–chromium alloy with 2.5–5% nickel and 1–2% molybdenum that has a mixed (duplex) microstructure of approximately equal percentages of ferrite and austenite. There are many more duplex stainless steels that have priority compositions and trade names (see Bibliography at the end of chapter). The corrosion characteristics of these duplex stainless steels are similar to austenitic stainless steels. However, they have higher strength and better resistance to stress–corrosion cracking than austenitic stainless steels. Duplex stainless steels are discussed in Chapter 2.

MARTENSITIC STAINLESS STEELS. To produce martensite in a stainless steel, the alloy must be transformed from the austenite-phase field. According to the equilibrium-phase diagram, this means that they have restricted chromium levels within the range required to form the gamma loop where austenite exists (see Fig. 11). The gamma loop is the region between 800 and 1400°C and 0 and 12.7% Cr in Fig. 11. Since austenite only exists in this restricted region, the steel must be heated within this temperature range and quenched to room temperature to form martensite. Martensitic stainless steels contain added carbon, which expands the gamma loop to allow higher chromium contents to be used. Because they can be heat treated, the martensitic stainless steels generally have higher strength than the austenitic and ferritic stainless steels. The martensitic stainless steels are listed below:

403	Select quality for highly stressed parts
410	General-purpose martensitic stainless steel
414	Ni added for improved corrosion
416	Higher P and S for improved machinability
416Se	Se added for improved machined surfaces
420	Higher C for increased strength
420F	Free machining with higher P and S
422	Mo, V, and W added for increased strength and toughness
431	Higher Cr, Ni added for improved corrosion resistance
440A	Highest Cr, C added for increased hardness
440B	Highest Cr, more C added for increased hardness/toughness
440C	Highest Cr, highest C for increased hardness/toughness
501	Low Cr, Mo added
502	Low C, Mo added

The compositional ranges for the martensitic stainless steels are shown in the aforementioned ASM table. Martensitic stainless steels are discussed in the next chapter.

PRECIPITATION-HARDENING STAINLESS STEELS. The precipitation-hardening stainless steels are iron–chromium–nickel alloys that develop high strength and toughness through additions of Al, Ti, Nb, V, and/or N, which form precipitates during an aging heat treatment. The base microstructures of precipitation-hardening stainless steels can be either martensitic or austenitic depending upon composition and processing. Some selected grades are listed below:

600	Austenitic grade with Mo, Al, Ti, V, and B added
630	Martensitic grade with Cu and Nb added
631	Austenitic grade with Al added
633	Austenitic grade with Mo and N added
635	Martensitic grade with Al and Ti added

The compositional ranges of the precipitation-hardening stainless steels are listed in the aforementioned ASM table.

OTHER STAINLESS STEELS. There are many stainless steels that do not fall within the AISI classification system. These steels have proprietary compositions and trade names. Details of many of these steels can be found in Chapter 2 and in the Bibliography at the end of this chapter.

Tool Steels. Tool steels are alloy steels that are used to cut or machine other materials. Tool steels contain various levels of Cr, Ni, Mo, W, V, and Co. The categories of tool steels are:

M series	Molybdenum high-speed steels
T series	Tungsten high-speed steels
Cr series	Chromium hot-work steels
H series	Molybdenum hot-work steels
A series	Air-hardening medium-alloy cold-work steels
D series	High-carbon high-chromium cold-work steels
O series	Oil-hardening cold-work steels
S series	Shock-resistant steels
L series	Low-alloy special-purpose tool steels
P series	Low-carbon mold steels
W series	Water-hardening tool steels

The compositional ranges of the various tool steels are listed in the table on pp. 758–759 of the *ASM Metals Handbook,* Vol. 20, 10th Edition, 1997. The high-speed steels are used in high-speed cutting tools such as drill bits. The hot-work tool steels are used in operations that utilize dies for punching, shearing, and forming materials at elevated temperatures, and the cold-work steels are used in similar operations at room temperature.

Heat-Resistant Steels. The upper temperature limit for use of carbon steels is about 370°C because of excessive oxidation and loss of strength. However, there are a number of alloy steels, called heat-resistant steels, that can be used at temperatures of 540–650°C. These steels include some of the ferritic stainless steels (405, 406, 409, 430, 434, and 439), quenched and tempered martensitic stainless steels (403, 410, 416, 422, and 431), precipitation-hardening martensitic stainless steels (15-5 PH, 17-4 PH, and PH 13-8 Mo), precipitation-hardening semiaustenitic stainless steels (AM-350, AM-355, 17-7 PH, and PH 15-7 Mo), and austenitic stainless steels (404, 309, 310, 316, 317, 321, 347, 202, and 216). In addition to the stainless steels, there are a number of proprietary alloys containing various levels of Cr, Ni, Mo, Nb, Ti, Cu, Al, Mn, V, N, or Si. The properties that are important to heat-resistant steels are creep and stress rupture. Creep is time-dependent strain occurring under stress. In more common terms creep is elongation or sagging of a part over time at elevated temperature. Stress rupture is a measure of the elevated temperature durability of material. These steels are generally specified under the ASME Boiler and Pressure Vessel Code.

Wear-Resistant Steels (*Austenitic Manganese Steels*). An important series of alloy steels are the austenitic manganese steels that contain 1.2% carbon and a minimum of 11% manganese. These steels, invented by Sir Robert Hadfield in 1882, are wear resistant and tough. Because they are difficult to hot work, these steels are usually cast into the final product form. The chemical compositional ranges for some selected austenitic manganese steels (ASTM A128) are listed below:

Grade	C	Mn	Cr	Mo	Ni	Si
A	1.55–1.35	11 (min)	—	—	—	1 (max)
B1	0.9–1.05	11.5–14	—	—	—	1 (max)
C	1.05–1.35	11.5–14	1.5–2.5	—	—	1 (max)
D	0.7–1.3	11.5–14	—	—	3–4	1 (max)
E1	0.7–1.3	11.5–14	—	0.9–1.2	—	1 (max)

The carbon addition is necessary to maintain an austenitic microstructure at room temperature. All grades must be heat treated by solution annealing at 1010–1090°C for 1–2 h per 25 mm of thickness followed by rapid water quenching. Because these alloys work harden during use, they are used in applications involving earthmoving (bucket blades), mining and quarrying (rock crushers), and railway trackwork (frogs, switches, and crossings).

Ultrahigh-Strength Steel

MARAGING STEEL. Another important series of alloy steels are the maraging steels. They are considered ultrahigh-strength steels because they can be heat treated to yield strength levels as high as 2.5 GPa. They also have excellent ductility and toughness. There are basically four grades that are produced to strength levels between 1.4 and 2.5 GPa.

Grade	Ni	Co	Mo	Ti	Al
18Ni (200)	18	8.5	3.3	0.2	0.1
18Ni (250)	18	8.5	5.0	0.4	0.1
18Ni (300)	18	9.0	5.0	0.7	0.1
18Ni (350)	18	12.5	4.2	1.6	0.1

The numbers in parentheses represent the nominal yield strength level in ksi. All maraging steels must be heat treated to achieve the desired properties. The heat treatment cycle for the 18Ni (200), 18Ni (250), and 18Ni (300) grades requires a solution treatment at 820°C for 1 h per 25 mm of thickness, cooling to room temperature, and an aging treatment at 480°C for 4 h. The 18Ni (350) grade has an extended aging time of 12 h. The heat treatment develops a martensitic microstructure on cooling from austenite at 820°C. The aging step precipitates intermetallic compounds, e.g., Ni_3Mo, that strengthen the martensitic matrix. Maraging steels can be machined before the aging treatment and have good weldability and excellent fracture toughness. They have found applications in missile and aircraft parts that require exceptional performance.

Music Wire. One of the strongest steel products commercially available is music wire. These wires can achieve levels of tensile strength approaching 5 GPa. The steel is basically SAE/AISI 1080. To obtain the ultrahigh-strength levels, rods of SAE/AISI 1080 are isothermally transformed to fine pearlite in a process known as patenting. The rods are then cold drawn to wire using large reductions in wire diameter through each die. The cold reduction forces the ferrite and cementite in the microstructure to align in a preferred orientation or fiber texture. The wires are used in musical instruments where they can be stretched under high tension to achieve certain musical notes. Ultrahigh-strength wires are also used to strengthen the rubber in automobile tires.

7 SUMMARY

Steel is one of the most versatile materials in today's society. It can be produced with a wide range of properties and is used in millions of applications. For example, stainless steels are used for their corrosion resistance, interstitial-free steels are used for their excellent formability characteristics, iron–silicon alloys are used for their electrical properties, austenitic manganese steels are used for their wear and abrasion resistance, microalloyed steels are used for their high strength, patented and cold-drawn eutectoid steel wires are used for their ultrahigh strength, dual-phase and trip steels are used for their energy absorption capability in a vehicle collision, and tool steels are used for their outstanding ability to cut and machine other materials. No other material can span such a range of properties and characteristics.

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