Chapter 11 Applications and Processing of Metal Alloys

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(a)

(a) The aluminum beverage can in various stages of production. The can is formed from a single sheet of an aluminum alloy. Production operations include drawing, dome forming, trimming, cleaning, decorating, and neck and flange forming.
(b) A workman inspecting a roll of aluminum sheet.

Daniel R. Patmore/© AP/Wide World Photos.

(b)

WHY STUDY *Applications and Processing of Metal Alloys?*

Engineers are often involved in materials selection decisions, which necessitates that they have some familiarity with the general characteristics of a wide variety of metals and their alloys (as well as other material types). In addition, access to databases containing property values for a large number of materials may be required.

On occasion, fabrication and processing procedures adversely affect some of the properties of metals. For example, in Section 10.8 we note that some steels may become embrittled during tempering heat treatments. Also, some stainless steels are made susceptible to intergranular corrosion (Section 17.7) when they are heated for long time periods within a specific temperature range. In addition, as we discuss in Section 11.6, regions adjacent to weld junctions may experience decreases in strength and toughness as a result of undesirable microstructural alterations. It is important that engineers become familiar with possible consequences attendant to processing and fabricating procedures in order to prevent unanticipated material failures.

Learning Objectives

After studying this chapter, you should be able to do the following:

1. Name four different types of steels and cite compositional differences, distinctive properties, and typical uses for each.
2. Name the five cast iron types and describe the microstructure and note the general mechanical characteristics for each.
3. Name seven different types of nonferrous alloys and cite the distinctive physical and mechanical characteristics and list at least three typical applications for each.
4. Name and describe four forming operations that are used to shape metal alloys.
5. Name and describe five casting techniques.
6. State the purposes of and describe procedures for the following heat treatments: process annealing, stress relief annealing, normalizing, full annealing, and spheroidizing.
7. Define *hardenability*.
8. Generate a hardness profile for a cylindrical steel specimen that has been austenitized and then quenched, given the hardenability curve for the specific alloy, as well as quenching rate–versus–bar diameter information.
9. Using a phase diagram, describe and explain the two heat treatments that are used to precipitation harden a metal alloy.
10. Make a schematic plot of room-temperature strength (or hardness) versus the logarithm of time for a precipitation heat treatment at constant temperature. Explain the shape of this curve in terms of the mechanism of precipitation hardening.

11.1 INTRODUCTION

Often a materials problem is really one of selecting the material that has the right combination of characteristics for a specific application. Therefore, the people who are involved in the decision making should have some knowledge of the available options. The first portion of this chapter provides an abbreviated overview of some of the commercial alloys and their general properties and limitations.

Materials selection decisions may also be influenced by the ease with which metal alloys may be formed or manufactured into useful components. Alloy properties are altered by fabrication processes, and, in addition, further property alterations may be induced by the employment of appropriate heat treatments. Therefore, in the latter sections of this chapter we consider the details of some of these treatments, including annealing procedures, the heat treating of steels, and precipitation hardening.

Types of Metal Alloys

Metal alloys, by virtue of composition, are often grouped into two classes—ferrous and nonferrous. Ferrous alloys, those in which iron is the principal constituent, include steels and cast irons. These alloys and their characteristics are the first topics of discussion of this section. The nonferrous ones—all alloys that are not iron based—are treated next.

11.2 FERROUS ALLOYS

ferrous alloy

Ferrous alloys—those in which iron is the prime constituent—are produced in larger quantities than any other metal type. They are especially important as engineering construction materials. Their widespread use is accounted for by three factors: (1) iron-containing compounds exist in abundant quantities within the Earth's crust; (2) metallic iron and steel alloys may be produced using relatively economical extraction, refining, alloying, and fabrication techniques; and (3) ferrous alloys are extremely versatile, in that they may be tailored to have a wide range of mechanical and physical properties. The principal disadvantage of many ferrous alloys is their susceptibility to corrosion. This section discusses compositions, microstructures, and properties of a number of different classes of steels and cast irons. A taxonomic classification scheme for the various ferrous alloys is presented in Figure 11.1.

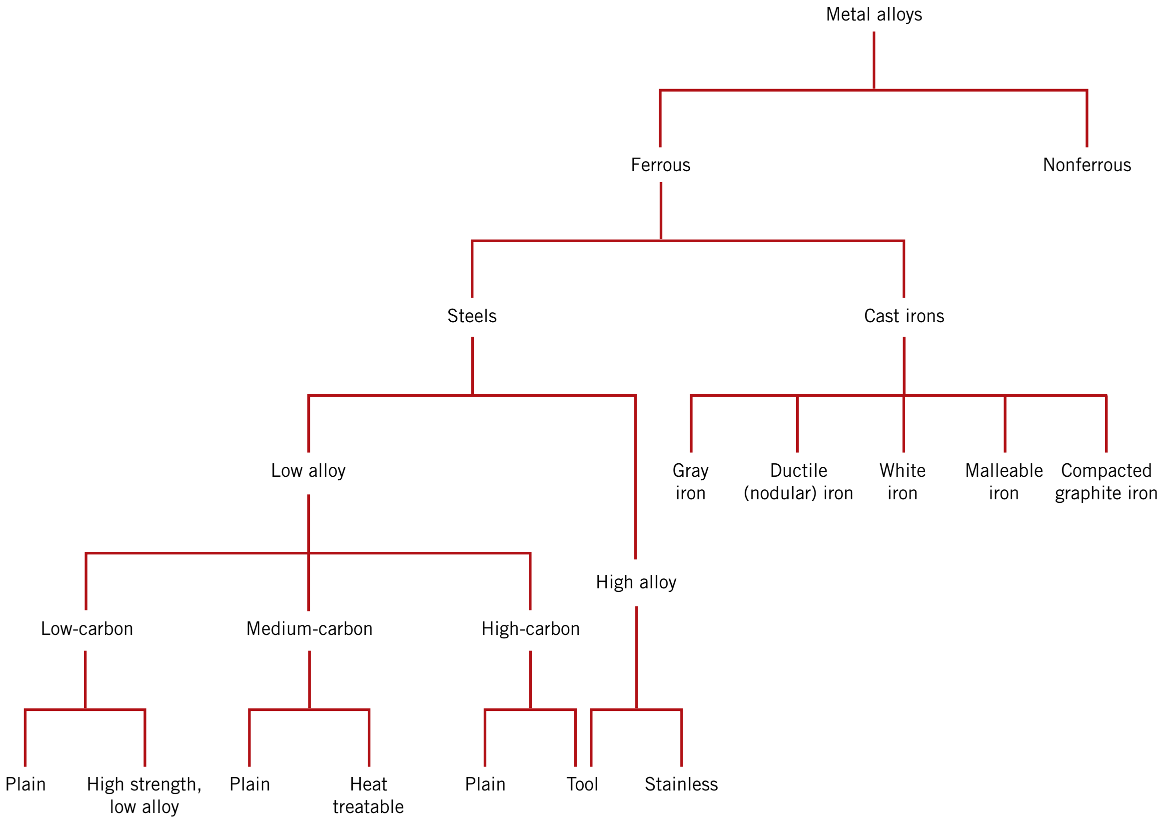

Figure 11.1 Classification scheme for the various ferrous alloys.

Steels

Steels are iron–carbon alloys that may contain appreciable concentrations of other alloying elements; there are thousands of alloys that have different compositions and/or heat treatments. The mechanical properties are sensitive to the content of carbon, which is normally less than 1.0 wt%. Some of the more common steels are classified according to carbon concentration into low-, medium-, and high-carbon types. Subclasses also exist within each group according to the concentration of other alloying elements.

plain carbon steel

alloy steel

Plain carbon steels contain only residual concentrations of impurities other than carbon and a little manganese. For **alloy steels,** more alloying elements are intentionally added in specific concentrations.

Low-Carbon Steels

Of the different steels, those produced in the greatest quantities fall within the low-carbon classification. These generally contain less than about 0.25 wt% C and are unresponsive to heat treatments intended to form martensite; strengthening is accomplished by cold work. Microstructures consist of ferrite and pearlite constituents. As a consequence, these alloys are relatively soft and weak but have outstanding ductility and toughness; in addition, they are machinable, weldable, and, of all steels, are the least expensive to produce. Typical applications include automobile body components, structural shapes (e.g., I-beams, channel and angle iron), and sheets that are used in pipelines, buildings, bridges, and tin cans. Tables 11.1a and 11.1b present the compositions and mechanical properties of several plain low-carbon steels. They typically have a yield strength of 275 MPa (40,000 psi), tensile strengths between 415 and 550 MPa (60,000 and 80,000 psi), and a ductility of 25%EL.

high-strength, low-alloy steel

Another group of low-carbon alloys are the **high-strength, low-alloy (HSLA) steels.** They contain other alloying elements such as copper, vanadium, nickel, and molybdenum in combined concentrations as high as 10 wt%, and they possess higher strengths than the plain low-carbon steels. Most may be strengthened by heat treatment, giving tensile strengths in excess of 480 MPa (70,000 psi); in addition, they are ductile, formable, and machinable. Several are listed in Tables 11.1a and 11.1b. In normal atmospheres,

Table 11.1a **Compositions of Four Plain Low-Carbon Steels and Three High-Strength, Low-Alloy Steels**

Designation[a]		*Composition (wt%)*[b]		
AISI/SAE or ASTM Number	*UNS Number*	*C*	*Mn*	*Other*
		Plain Low-Carbon Steels		
1010	G10100	0.10	0.45	
1020	G10200	0.20	0.45	
A36	K02600	0.29	1.00	0.20 Cu (min)
A516 Grade 70	K02700	0.31	1.00	0.25 Si
		High-Strength, Low-Alloy Steels		
A440	K12810	0.28	1.35	0.30 Si (max), 0.20 Cu (min)
A633 Grade E	K12002	0.22	1.35	0.30 Si, 0.08 V, 0.02 N, 0.03 Nb
A656 Grade 1	K11804	0.18	1.60	0.60 Si, 0.1 V, 0.20 Al, 0.015 N

[a] The codes used by the American Iron and Steel Institute (AISI), the Society of Automotive Engineers (SAE), and the American Society for Testing and Materials (ASTM), and in the Uniform Numbering System (UNS) are explained in the text.

[b] Also a maximum of 0.04 wt% P, 0.05 wt% S, and 0.30 wt% Si (unless indicated otherwise).

Source: Adapted from *Metals Handbook: Properties and Selection: Irons and Steels,* Vol. 1, 9th edition, B. Bardes (Editor), 1978. Reproduced by permission of ASM International, Materials Park, OH.

Table 11.1b Mechanical Characteristics of Hot-Rolled Material and Typical Applications for Various Plain Low-Carbon and High-Strength, Low-Alloy Steels

AISI/SAE or ASTM Number	*Tensile Strength [MPa (ksi)]*	*Yield Strength [MPa (ksi)]*	*Ductility [%EL in 50 mm (2 in.)]*	*Typical Applications*
		Plain Low-Carbon Steels		
1010	325 (47)	180 (26)	28	Automobile panels, nails, and wire
1020	380 (55)	210 (30)	25	Pipe; structural and sheet steel
A36	400 (58)	220 (32)	23	Structural (bridges and buildings)
A516 Grade 70	485 (70)	260 (38)	21	Low-temperature pressure vessels
		High-Strength, Low-Alloy Steels		
A440	435 (63)	290 (42)	21	Structures that are bolted or riveted
A633 Grade E	520 (75)	380 (55)	23	Structures used at low ambient temperatures
A656 Grade 1	655 (95)	552 (80)	15	Truck frames and railway cars

the HSLA steels are more resistant to corrosion than the plain carbon steels, which they have replaced in many applications where structural strength is critical (e.g., bridges, towers, support columns in high-rise buildings, pressure vessels).

Medium-Carbon Steels

The medium-carbon steels have carbon concentrations between about 0.25 and 0.60 wt%. These alloys may be heat-treated by austenitizing, quenching, and then tempering to improve their mechanical properties. They are most often utilized in the tempered condition, having microstructures of tempered martensite. The plain medium-carbon steels have low hardenabilities (Section 11.8) and can be successfully heat-treated only in very thin sections and with very rapid quenching rates. Additions of chromium, nickel, and molybdenum improve the capacity of these alloys to be heat-treated (Section 11.8), giving rise to a variety of strength–ductility combinations. These heat-treated alloys are stronger than the low-carbon steels, but at a sacrifice of ductility and toughness. Applications include railway wheels and tracks, gears, crankshafts, and other machine parts and high-strength structural components calling for a combination of high strength, wear resistance, and toughness.

The compositions of several of these alloyed medium-carbon steels are presented in Table 11.2a. Some comment is in order regarding the designation schemes that are also included. The Society of Automotive Engineers (SAE), the American Iron and Steel Institute (AISI), and the American Society for Testing and Materials (ASTM) are responsible for the classification and specification of steels as well as other alloys. The AISI/SAE designation for these steels is a four-digit number: the first two digits indicate the alloy content; the last two give the carbon concentration. For plain carbon steels, the first two digits are 1 and 0; alloy steels are designated by other initial two-digit combinations (e.g., 13, 41, 43). The third and fourth digits represent the weight

Table 11.2a
AISI/SAE and UNS Designation Systems and Composition Ranges for Plain Carbon Steel and Various Low-Alloy Steels

AISI/SAE Designation[a]	*UNS Designation*	*Composition Ranges (wt% of Alloying Elements in Addition to C)*[b]			
		Ni	*Cr*	*Mo*	*Other*
10xx, Plain carbon	G10xx0				
11xx, Free machining	G11xx0				0.08–0.33 S
12xx, Free machining	G12xx0				0.10–0.35 S, 0.04–0.12 P
13xx	G13xx0				1.60–1.90 Mn
40xx	G40xx0			0.20–0.30	
41xx	G41xx0		0.80–1.10	0.15–0.25	
43xx	G43xx0	1.65–2.00	0.40–0.90	0.20–0.30	
46xx	G46xx0	0.70–2.00		0.15–0.30	
48xx	G48xx0	3.25–3.75		0.20–0.30	
51xx	G51xx0		0.70–1.10		
61xx	G61xx0		0.50–1.10		0.10–0.15 V
86xx	G86xx0	0.40–0.70	0.40–0.60	0.15–0.25	
92xx	G92xx0				1.80–2.20 Si

[a] The carbon concentration, in weight percent times 100, is inserted in the place of "xx" for each specific steel.

[b] Except for 13xx alloys, manganese concentration is less than 1.00 wt%.
Except for 12xx alloys, phosphorus concentration is less than 0.35 wt%.
Except for 11xx and 12xx alloys, sulfur concentration is less than 0.04 wt%.
Except for 92xx alloys, silicon concentration varies between 0.15 and 0.35 wt%.

percent carbon multiplied by 100. For example, a 1060 steel is a plain carbon steel containing 0.60 wt% C.

A unified numbering system (UNS) is used for uniformly indexing both ferrous and nonferrous alloys. Each UNS number consists of a single-letter prefix followed by a five-digit number. The letter is indicative of the family of metals to which an alloy belongs. The UNS designation for these alloys begins with a G, followed by the AISI/SAE number; the fifth digit is a zero. Table 11.2b contains the mechanical characteristics and typical applications of several of these steels, which have been quenched and tempered.

High-Carbon Steels

The high-carbon steels, normally having carbon contents between 0.60 and 1.4 wt%, are the hardest, strongest, and yet least ductile of the carbon steels. They are almost always used in a hardened and tempered condition and, as such, are especially wear resistant and capable of holding a sharp cutting edge. The tool and die steels are high-carbon alloys, usually containing chromium, vanadium, tungsten, and molybdenum. These alloying elements combine with carbon to form very hard and wear-resistant carbide compounds (e.g., $Cr_{23}C_6$, V_4C_3, and WC). Some tool steel compositions and their applications are listed in Table 11.3. These steels are used as cutting tools and dies for forming and shaping materials, as well as in knives, razors, hacksaw blades, springs, and high-strength wire.

Table 11.2b Typical Applications and Mechanical Property Ranges for Oil-Quenched and Tempered Plain Carbon and Alloy Steels

AISI Number	*UNS Number*	*Tensile Strength [MPa (ksi)]*	*Yield Strength [MPa (ksi)]*	*Ductility [%EL in 50 mm (2 in.)]*	*Typical Applications*
			Plain Carbon Steels		
1040	G10400	605–780 (88–113)	430–585 (62–85)	33–19	Crankshafts, bolts
1080[a]	G10800	800–1310 (116–190)	480–980 (70–142)	24–13	Chisels, hammers
1095[a]	G10950	760–1280 (110–186)	510–830 (74–120)	26–10	Knives, hacksaw blades
			Alloy Steels		
4063	G40630	786–2380 (114–345)	710–1770 (103–257)	24–4	Springs, hand tools
4340	G43400	980–1960 (142–284)	895–1570 (130–228)	21–11	Bushings, aircraft tubing
6150	G61500	815–2170 (118–315)	745–1860 (108–270)	22–7	Shafts, pistons, gears

[a] Classified as high-carbon steels.

Stainless Steels

stainless steel

The **stainless steels** are highly resistant to corrosion (rusting) in a variety of environments, especially the ambient atmosphere. Their predominant alloying element is chromium; a concentration of at least 11 wt% Cr is required. Corrosion resistance may also be enhanced by nickel and molybdenum additions.

Stainless steels are divided into three classes on the basis of the predominant phase constituent of the microstructure—martensitic, ferritic, or austenitic. Table 11.4 lists

Table 11.3 Designations, Compositions, and Applications for Six Tool Steels

AISI Number	*UNS Number*	*Composition (wt%)[a]*						*Typical Applications*
		C	*Cr*	*Ni*	*Mo*	*W*	*V*	
M1	T11301	0.85	3.75	0.30 max	8.70	1.75	1.20	Drills, saws; lathe and planer tools
A2	T30102	1.00	5.15	0.30 max	1.15	—	0.35	Punches, embossing dies
D2	T30402	1.50	12	0.30 max	0.95	—	1.10 max	Cutlery, drawing dies
O1	T31501	0.95	0.50	0.30 max	—	0.50	0.30 max	Shear blades, cutting tools
S1	T41901	0.50	1.40	0.30 max	0.50 max	2.25	0.25	Pipe cutters, concrete drills
W1	T72301	1.10	0.15 max	0.20 max	0.10 max	0.15 max	0.10 max	Blacksmith tools, woodworking tools

[a] The balance of the composition is iron. Manganese concentrations range between 0.10 and 1.4 wt%, depending on alloy; silicon concentrations between 0.20 and 1.2 wt%, depending on the alloy.

Source: Adapted from *ASM Handbook,* Vol. 1, *Properties and Selection: Irons, Steels, and High-Performance Alloys,* 1990. Reprinted by permission of ASM International, Materials Park, OH.

Table 11.4 Designations, Compositions, Mechanical Properties, and Typical Applications for Austenitic, Ferritic, Martensitic, and Precipitation-Hardenable Stainless Steels

AISI Number	UNS Number	Composition (wt%)[a]	Condition[b]	Mechanical Properties			Typical Applications
				Tensile Strength [MPa (ksi)]	Yield Strength [MPa (ksi)]	Ductility [%EL in 50 mm (2 in.)]	
Ferritic							
409	S40900	0.08 C, 11.0 Cr, 1.0 Mn, 0.50 Ni, 0.75 Ti	Annealed	380 (55)	205 (30)	20	Automotive exhaust components, tanks for agricultural sprays
446	S44600	0.20 C, 25 Cr, 1.5 Mn	Annealed	515 (75)	275 (40)	20	Valves (high temperature), glass molds, combustion chambers
Austenitic							
304	S30400	0.08 C, 19 Cr, 9 Ni, 2.0 Mn	Annealed	515 (75)	205 (30)	40	Chemical and food processing equipment, cryogenic vessels
316L	S31603	0.03 C, 17 Cr, 12 Ni, 2.5 Mo, 2.0 Mn	Annealed	485 (70)	170 (25)	40	Welding construction
Martensitic							
410	S41000	0.15 C, 12.5 Cr, 1.0 Mn	Annealed Q & T	485 (70) 825 (120)	275 (40) 620 (90)	20 12	Rifle barrels, cutlery, jet engine parts
440A	S44002	0.70 C, 17 Cr, 0.75 Mo, 1.0 Mn	Annealed Q & T	725 (105) 1790 (260)	415 (60) 1650 (240)	20 5	Cutlery, bearings, surgical tools
Precipitation Hardenable							
17-7PH	S17700	0.09 C, 17 Cr, 7 Ni, 1.0 Al, 1.0 Mn	Precipitation hardened	1450 (210)	1310 (190)	1–6	Springs, knives, pressure vessels

[a] The balance of the composition is iron.

[b] Q & T denotes quenched and tempered.

Source: Adapted from *ASM Handbook*, Vol. 1, *Properties and Selection: Irons, Steels, and High-Performance Alloys,* 1990. Reprinted by permission of ASM International, Materials Park, OH.

several stainless steels by class, along with composition, typical mechanical properties, and applications. A wide range of mechanical properties combined with excellent resistance to corrosion make stainless steels very versatile in their applicability.

Martensitic stainless steels are capable of being heat-treated in such a way that martensite is the prime microconstituent. Additions of alloying elements in significant concentrations produce dramatic alterations in the iron–iron carbide phase diagram

(Figure 9.24). For austenitic stainless steels, the austenite (or γ) phase field is extended to room temperature. Ferritic stainless steels are composed of the α-ferrite (BCC) phase. Austenitic and ferritic stainless steels are hardened and strengthened by cold work because they are not heat-treatable. The austenitic stainless steels are the most corrosion resistant because of the high chromium contents and also the nickel additions; they are produced in the largest quantities. Both martensitic and ferritic stainless steels are magnetic; the austenitic stainlesses are not.

Some stainless steels are frequently used at elevated temperatures and in severe environments because they resist oxidation and maintain their mechanical integrity under such conditions; the upper temperature limit in oxidizing atmospheres is about 1000°C (1800°F). Equipment employing these steels includes gas turbines, high-temperature steam boilers, heat-treating furnaces, aircraft, missiles, and nuclear power–generating units. Also included in Table 11.4 is one ultrahigh-strength stainless steel (17-7PH), which is unusually strong and corrosion resistant. Strengthening is accomplished by precipitation-hardening heat treatments (Section 11.9).

Concept Check 11.1 Briefly explain why ferritic and austenitic stainless steels are not heat-treatable. *Hint:* You may want to consult the first portion of Section 11.3.

[*The answer may be found at www.wiley.com/college/callister (Student Companion Site).*]

Cast Irons

cast iron

Generically, **cast irons** are a class of ferrous alloys with carbon contents above 2.14 wt%; in practice, however, most cast irons contain between 3.0 and 4.5 wt% C and, in addition, other alloying elements. A reexamination of the iron–iron carbide phase diagram (Figure 9.24) reveals that alloys within this composition range become completely liquid at temperatures between approximately 1150°C and 1300°C (2100°F and 2350°F), which is considerably lower than for steels. Thus, they are easily melted and amenable to casting. Furthermore, some cast irons are very brittle, and casting is the most convenient fabrication technique.

Cementite (Fe_3C) is a metastable compound, and under some circumstances it can be made to dissociate or decompose to form α-ferrite and graphite, according to the reaction

Decomposition of iron carbide to form α-ferrite and graphite

$$\mathrm{Fe_3C} \rightarrow 3\mathrm{Fe}\,(\alpha) + \mathrm{C}\,(\text{graphite}) \tag{11.1}$$

Thus, the true equilibrium diagram for iron and carbon is not that presented in Figure 9.24, but rather as shown in Figure 11.2. The two diagrams are virtually identical on the iron-rich side (e.g., eutectic and eutectoid temperatures for the Fe–Fe_3C system are 1147°C and 727°C, respectively, as compared to 1153°C and 740°C for Fe–C); however, Figure 11.2 extends to 100 wt% C such that graphite is the carbon-rich phase, instead of cementite at 6.7 wt% C (Figure 9.24).

This tendency to form graphite is regulated by the composition and rate of cooling. Graphite formation is promoted by the presence of silicon in concentrations greater than about 1 wt%. Also, slower cooling rates during solidification favor graphitization (the formation of graphite). For most cast irons, the carbon exists as graphite, and both microstructure and mechanical behavior depend on composition and heat treatment. The most common cast iron types are gray, nodular, white, malleable, and compacted graphite.

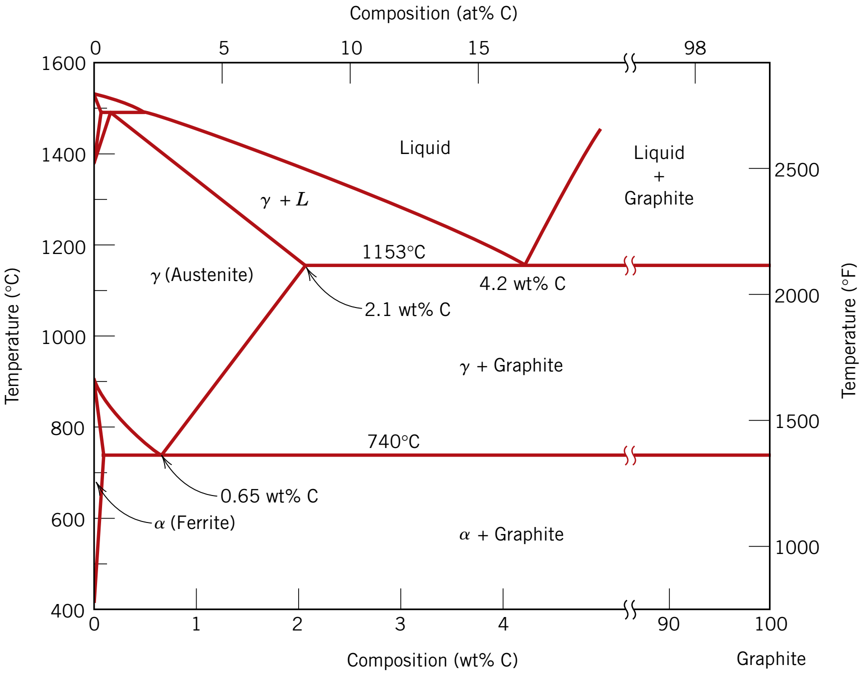

Figure 11.2 The true equilibrium iron–carbon phase diagram with graphite instead of cementite as a stable phase. [Adapted from *Binary Alloy Phase Diagrams,* T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

Gray Iron

gray cast iron

The carbon and silicon contents of **gray cast irons** vary between 2.5 and 4.0 wt% and 1.0 and 3.0 wt%, respectively. For most of these cast irons, the graphite exists in the form of flakes (similar to corn flakes), which are normally surrounded by an α-ferrite or pearlite matrix; the microstructure of a typical gray iron is shown in Figure 11.3*a*. Because of these graphite flakes, a fractured surface takes on a gray appearance—hence its name.

Mechanically, gray iron is comparatively weak and brittle in tension as a consequence of its microstructure; the tips of the graphite flakes are sharp and pointed and may serve as points of stress concentration when an external tensile stress is applied. Strength and ductility are much higher under compressive loads. Typical mechanical properties and compositions of several common gray cast irons are listed in Table 11.5. Gray irons have some desirable characteristics and are used extensively. They are very effective in damping vibrational energy; this is represented in Figure 11.4, which compares the relative damping capacities of steel and gray iron. Base structures for machines and heavy equipment that are exposed to vibrations are frequently constructed of this material. In addition, gray irons exhibit a high resistance to wear. Furthermore, in the molten state they have a high fluidity at casting temperature, which permits casting pieces that have intricate shapes; also, casting shrinkage is low. Finally, and perhaps most important, gray cast irons are among the least expensive of all metallic materials.

Gray irons having microstructures different from that shown in Figure 11.3*a* may be generated by adjusting composition and/or using an appropriate treatment. For example, lowering the silicon content or increasing the cooling rate may prevent the complete dissociation of cementite to form graphite (Equation 11.1). Under these circumstances the microstructure consists of graphite flakes embedded in a pearlite matrix. Figure 11.5 compares schematically the several cast iron microstructures obtained by varying the composition and heat treatment.

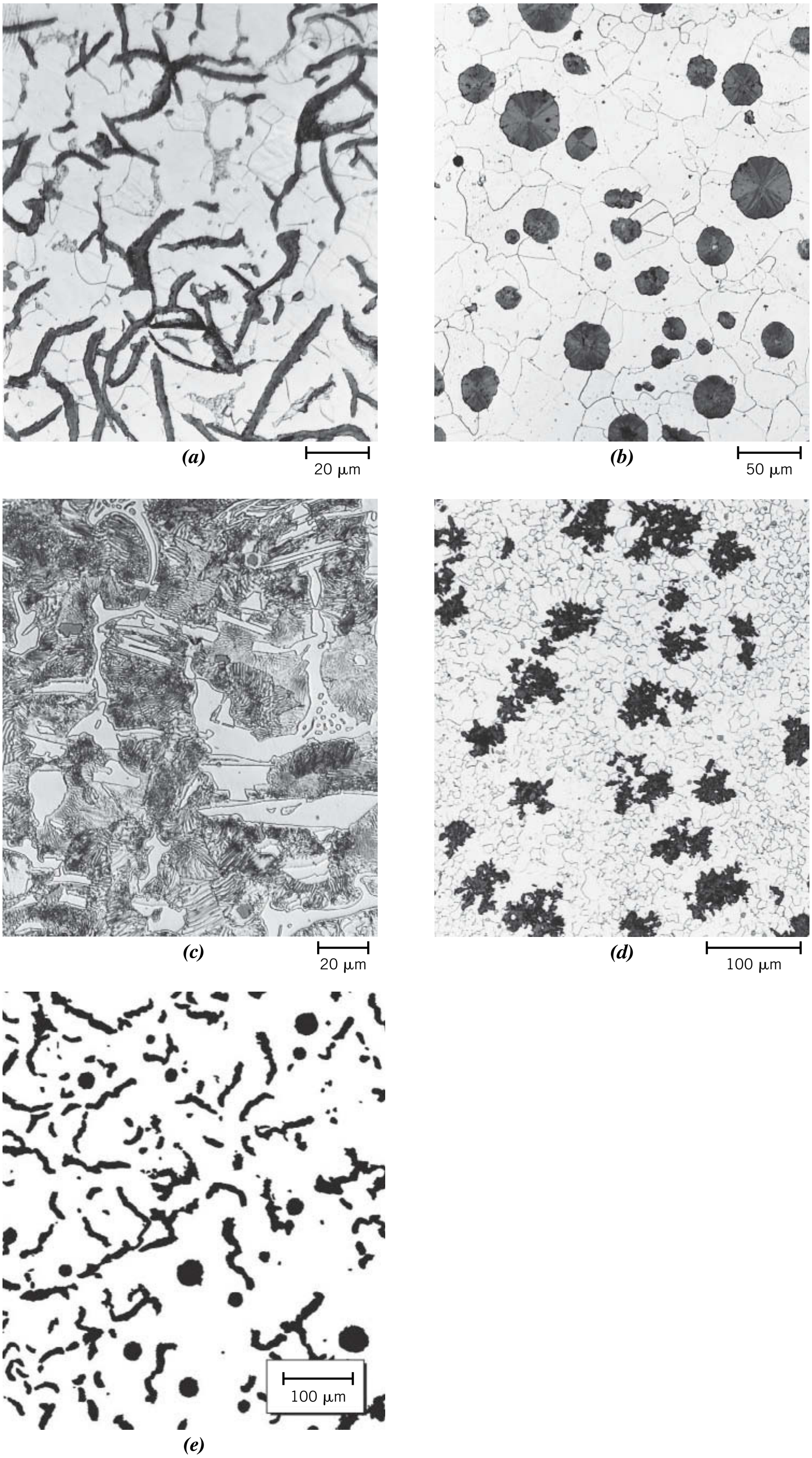

Figure 11.3 Optical photomicrographs of various cast irons. (*a*) Gray iron: the dark graphite flakes are embedded in an α-ferrite matrix. 500×. (*b*) Nodular (ductile) iron: the dark graphite nodules are surrounded by an α-ferrite matrix. 200×. (*c*) White iron: the light cementite regions are surrounded by pearlite, which has the ferrite–cementite layered structure. 400×. (*d*) Malleable iron: dark graphite rosettes (temper carbon) in an α-ferrite matrix. 150×. (*e*) Compacted graphite iron: dark graphite wormlike particles are embedded within an α-ferrite matrix. 100×. [Figures (*a*) and (*b*) courtesy of C. H. Brady and L. C. Smith, National Bureau of Standards, Washington, DC (now the National Institute of Standards and Technology, Gaithersburg, MD). Figure (*c*) courtesy of Amcast Industrial Corporation. Figure (*d*) reprinted with permission of the Iron Castings Society, Des Plaines, IL. Figure (*e*) courtesy of Sinter-Cast, Ltd.]

Table 11.5 Designations, Minimum Mechanical Properties, Approximate Compositions, and Typical Applications for Various Gray, Nodular, Malleable, and Compacted Graphite Cast Irons

Grade	UNS Number	Composition (wt%)[a]	Matrix Structure	Mechanical Properties: Tensile Strength [MPa (ksi)]	Mechanical Properties: Yield Strength [MPa (ksi)]	Mechanical Properties: Ductility [%EL in 50 mm (2 in.)]	Typical Applications
				Gray Iron			
SAE G1800	F10004	3.40–3.7 C, 2.55 Si, 0.7 Mn	Ferrite + pearlite	124 (18)	—	—	Miscellaneous soft iron castings in which strength is not a primary consideration
SAE G2500	F10005	3.2–3.5 C, 2.20 Si, 0.8 Mn	Ferrite + pearlite	173 (25)	—	—	Small cylinder blocks, cylinder heads, pistons, clutch plates, transmission cases
SAE G4000	F10008	3.0–3.3 C, 2.0 Si, 0.8 Mn	Pearlite	276 (40)	—	—	Diesel engine castings, liners, cylinders, and pistons
				Ductile (Nodular) Iron			
ASTM A536							
60–40–18	F32800	3.5–3.8 C, 2.0–2.8 Si, 0.05 Mg, <0.20 Ni, <0.10 Mo	Ferrite	414 (60)	276 (40)	18	Pressure-containing parts such as valve and pump bodies
100–70–03	F34800		Pearlite	689 (100)	483 (70)	3	High-strength gears and machine components
120–90–02	F36200		Tempered martensite	827 (120)	621 (90)	2	Pinions, gears, rollers, slides
				Malleable Iron			
32510	F22200	2.3–2.7 C, 1.0–1.75 Si, <0.55 Mn	Ferrite	345 (50)	224 (32)	10	General engineering service at normal and elevated temperatures
45006	F23131	2.4–2.7 C, 1.25–1.55 Si, <0.55 Mn	Ferrite + pearlite	448 (65)	310 (45)	6	
				Compacted Graphite Iron			
ASTM A842							
Grade 250	—	3.1–4.0 C, 1.7–3.0 Si, 0.015–0.035 Mg, 0.06–0.13 Ti	Ferrite	250 (36)	175 (25)	3	Diesel engine blocks, exhaust manifolds, brake discs for high-speed trains
Grade 450	—		Pearlite	450 (65)	315 (46)	1	

[a] The balance of the composition is iron.

Source: Adapted from *ASM Handbook*, Vol. 1, *Properties and Selection: Irons, Steels, and High-Performance Alloys*, 1990. Reprinted by permission of ASM International, Materials Park, OH.

Ductile (or Nodular) Iron

ductile (nodular) iron

Adding a small amount of magnesium and/or cerium to the gray iron before casting produces a distinctly different microstructure and set of mechanical properties. Graphite still forms, but as nodules or spherelike particles instead of flakes. The resulting alloy is called **ductile** or **nodular iron,** and a typical microstructure is shown in Figure 11.3*b*. The matrix phase surrounding these particles is either pearlite or ferrite, depending on heat treatment (Figure 11.5); it is normally pearlite for an as-cast piece. However, a heat treatment for several hours at about 700°C (1300°F) yields a ferrite matrix, as in this photomicrograph. Castings are stronger and much more ductile than gray iron, as a comparison of their mechanical properties in Table 11.5 shows. In fact, ductile iron has mechanical characteristics approaching those of steel. For example, ferritic ductile irons have tensile strengths between 380 and 480 MPa (55,000 and 70,000 psi) and ductilities (as percent elongation) from 10% to 20%. Typical applications for this material include valves, pump bodies, crankshafts, gears, and other automotive and machine components.

White Iron and Malleable Iron

white cast iron

malleable iron

For low-silicon cast irons (containing less than 1.0 wt% Si) and rapid cooling rates, most of the carbon exists as cementite instead of graphite, as indicated in Figure 11.5. A fracture surface of this alloy has a white appearance, and thus it is termed **white cast iron.** An optical photomicrograph showing the microstructure of white iron is presented in Figure 11.3*c*. Thick sections may have only a surface layer of white iron that was "chilled" during the casting process; gray iron forms at interior regions, which cool more slowly. As a consequence of large amounts of the cementite phase, white iron is extremely hard but also very brittle, to the point of being virtually unmachinable. Its use is limited to applications that necessitate a very hard and wear-resistant surface, without a high degree of ductility—for example, as rollers in rolling mills. Generally, white iron is used as an intermediary in the production of yet another cast iron, **malleable iron.**

Heating white iron at temperatures between 800°C and 900°C (1470°F and 1650°F) for a prolonged time period and in a neutral atmosphere (to prevent oxidation) causes a decomposition of the cementite, forming graphite, which exists in the form of clusters or rosettes surrounded by a ferrite or pearlite matrix, depending on cooling rate, as indicated in Figure 11.5. A photomicrograph of a ferritic malleable iron is presented in Figure 11.3*d*. The microstructure is similar to that of nodular iron (Figure 11.3*b*), which accounts for relatively high strength and appreciable ductility or malleability. Some typical mechanical characteristics are also listed in Table 11.5. Representative applications include connecting rods, transmission gears, and differential cases for the automotive industry, and also flanges, pipe fittings, and valve parts for railroad, marine, and other heavy-duty services.

Gray and ductile cast irons are produced in approximately the same amounts; however, white and malleable cast irons are produced in smaller quantities.

Concept Check 11.2 It is possible to produce cast irons that consist of a martensite matrix in which graphite is embedded in either flake, nodule, or rosette form. Briefly describe the treatment necessary to produce each of these three microstructures.

[*The answer may be found at www.wiley.com/college/callister (Student Companion Site).*]

Compacted Graphite Iron

compacted graphite iron

A relatively recent addition to the family of cast irons is **compacted graphite iron** (abbreviated *CGI*). As with gray, ductile, and malleable irons, carbon exists as graphite,

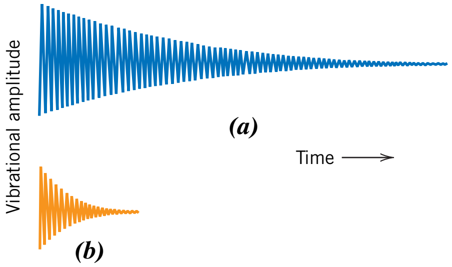

Figure 11.4 Comparison of the relative vibrational damping capacities of (*a*) steel and (*b*) gray cast iron.
(From *Metals Engineering Quarterly,* February 1961. Copyright © 1961. Reproduced by permission of ASM International, Materials Park, OH.)

whose formation is promoted by the presence of silicon. Silicon content ranges between 1.7 and 3.0 wt%, whereas carbon concentration is normally between 3.1 and 4.0 wt%. Two CGI materials are included in Table 11.5.

Microstructurally, the graphite in CGI alloys has a wormlike (or vermicular) shape; a typical CGI microstructure is shown in the optical micrograph of Figure 11.3*e*. In a sense, this microstructure is intermediate between that of gray iron (Figure 11.3*a*) and

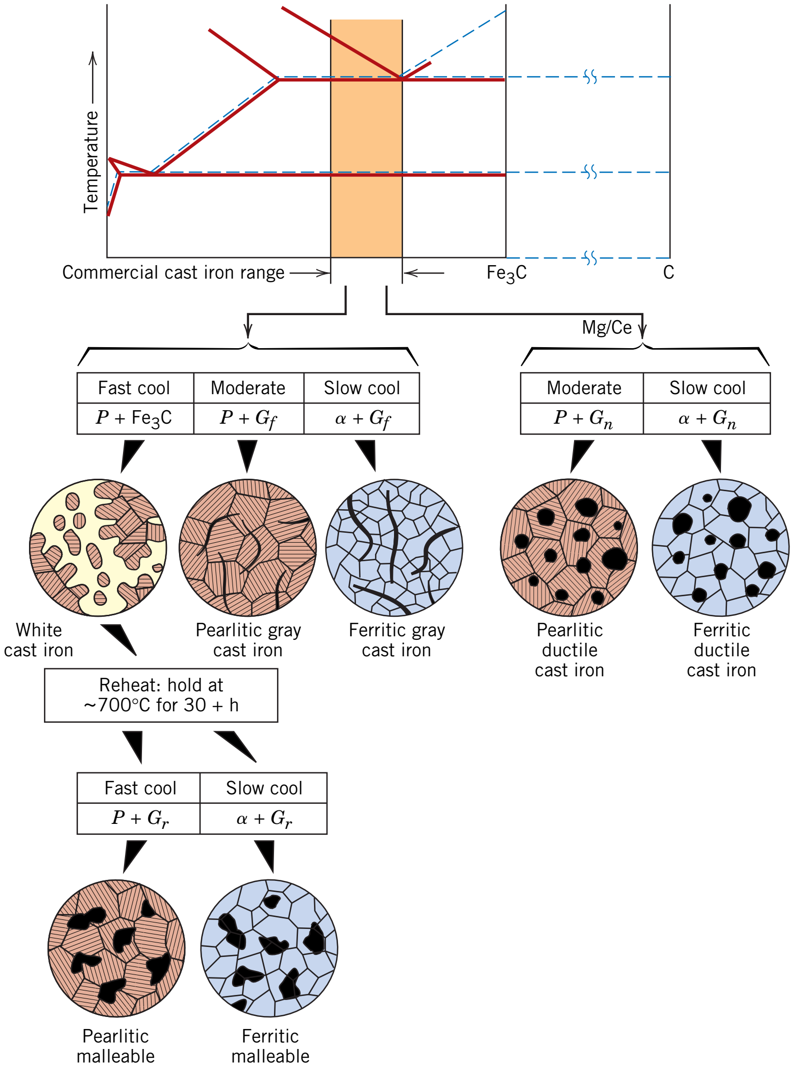

Figure 11.5 From the iron–carbon phase diagram, composition ranges for commercial cast irons. Also shown are schematic microstructures that result from a variety of heat treatments. G_f, flake graphite; G_r, graphite rosettes; G_n, graphite nodules; P, pearlite; α, ferrite.
(Adapted from W. G. Moffatt, G. W. Pearsall, and J. Wulff, *The Structure and Properties of Materials,* Vol. I, *Structure,* p. 195. Copyright © 1964 by John Wiley & Sons, New York.)

ductile (nodular) iron (Figure 11.3*b*), and, in fact, some of the graphite (less than 20%) may be as nodules. However, sharp edges (characteristic of graphite flakes) should be avoided; the presence of this feature leads to a reduction in fracture and fatigue resistance of the material. Magnesium and/or cerium is also added, but concentrations are lower than for ductile iron. The chemistries of CGIs are more complex than for the other cast iron types; compositions of magnesium, cerium, and other additives must be controlled so as to produce a microstructure that consists of the wormlike graphite particles while at the same time limiting the degree of graphite nodularity, and preventing the formation of graphite flakes. Furthermore, depending on heat treatment, the matrix phase will be pearlite and/or ferrite.

As with the other types of cast irons, the mechanical properties of CGIs are related to microstructure: graphite particle shape, as well as the matrix phase/microconstituent. An increase in degree of nodularity of the graphite particles leads to enhancements of both strength and ductility. Furthermore, CGIs with ferritic matrices have lower strengths and higher ductilities than those with pearlitic matrices. Tensile and yield strengths for compacted graphite irons are comparable to values for ductile and malleable irons, yet are greater than those observed for the higher-strength gray irons (Table 11.5). In addition, ductilities for CGIs are intermediate between values for gray and ductile irons; moduli of elasticity range between 140 and 165 GPa (20×10^6 and 24×10^6 psi).

Compared to the other cast iron types, desirable characteristics of CGIs include the following:

- Higher thermal conductivity
- Better resistance to thermal shock (i.e., fracture resulting from rapid temperature changes)
- Lower oxidation at elevated temperatures

Compacted graphite irons are now being used in a number of important applications, including diesel engine blocks, exhaust manifolds, gearbox housings, brake discs for high-speed trains, and flywheels.

11.3 NONFERROUS ALLOYS

Steel and other ferrous alloys are consumed in exceedingly large quantities because they have such a wide range of mechanical properties, may be fabricated with relative ease, and are economical to produce. However, they have some distinct limitations chiefly (1) a relatively high density, (2) a comparatively low electrical conductivity, and (3) an inherent susceptibility to corrosion in some common environments. Thus, for many applications it is advantageous or even necessary to use other alloys that have more suitable property combinations. Alloy systems are classified either according to the base metal or according to some specific characteristic that a group of alloys share. This section discusses the following metal and alloy systems: copper, aluminum, magnesium, and titanium alloys; the refractory metals; the superalloys; the noble metals; and miscellaneous alloys, including those that have nickel, lead, tin, zirconium, and zinc as base metals. Figure 11.6 represents a classification scheme for nonferrous alloys discussed in this section.

On occasion, a distinction is made between cast and wrought alloys. Alloys that are so brittle that forming or shaping by appreciable deformation is not possible typically are cast; these are classified as *cast alloys*. However, those that are amenable to mechanical deformation are termed **wrought alloys.**

wrought alloy

In addition, the heat-treatability of an alloy system is mentioned frequently. "Heat-treatable" designates an alloy whose mechanical strength is improved by precipitation hardening (Section 11.9) or a martensitic transformation (normally the former), both of which involve specific heat-treating procedures.

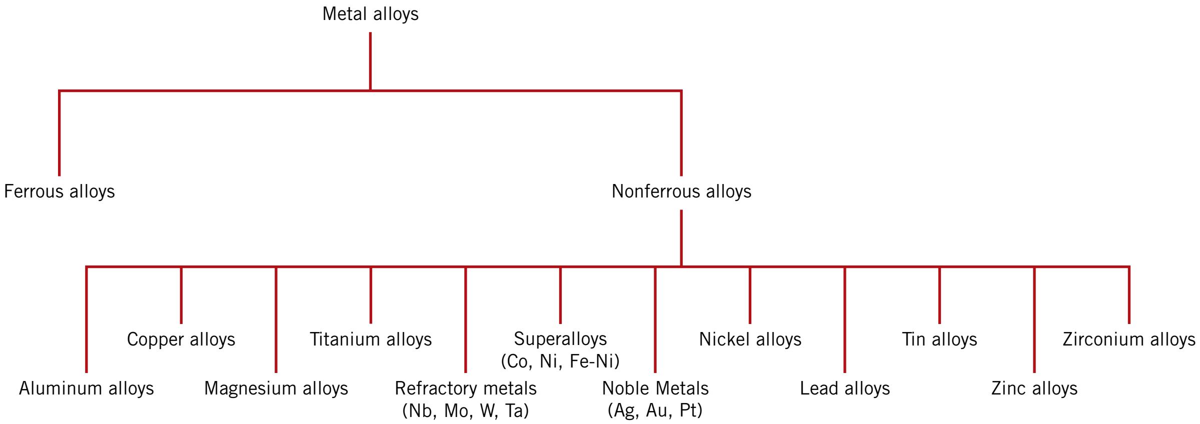

Figure 11.6 Classification scheme for the various nonferrous alloys.

Copper and Its Alloys

Copper and copper-based alloys, possessing a desirable combination of physical properties, have been used in quite a variety of applications since antiquity. Unalloyed copper is so soft and ductile that it is difficult to machine; also, it has an almost unlimited capacity to be cold worked. Furthermore, it is highly resistant to corrosion in diverse environments including the ambient atmosphere, seawater, and some industrial chemicals. The mechanical and corrosion-resistance properties of copper may be improved by alloying. Most copper alloys cannot be hardened or strengthened by heat-treating procedures; consequently, cold working and/or solid-solution alloying must be used to improve these mechanical properties.

brass

The most common copper alloys are the **brasses,** for which zinc, as a substitutional impurity, is the predominant alloying element. As may be observed for the copper–zinc phase diagram (Figure 9.19), the α phase is stable for concentrations up to approximately 35 wt% Zn. This phase has an FCC crystal structure, and α-brasses are relatively soft, ductile, and easily cold worked. Brass alloys having a higher zinc content contain both α and β' phases at room temperature. The β' phase has an ordered BCC crystal structure and is harder and stronger than the α phase; consequently, $\alpha + \beta'$ alloys are generally hot worked.

Some of the common brasses are yellow, naval, and cartridge brass; muntz metal; and gilding metal. The compositions, properties, and typical uses of several of these alloys are listed in Table 11.6. Some of the common uses for brass alloys include costume jewelry, cartridge casings, automotive radiators, musical instruments, electronic packaging, and coins.

bronze

The **bronzes** are alloys of copper and several other elements, including tin, aluminum, silicon, and nickel. These alloys are somewhat stronger than the brasses, yet they still have a high degree of corrosion resistance. Table 11.6 lists several of the bronze alloys and their compositions, properties, and applications. Generally they are used when, in addition to corrosion resistance, good tensile properties are required.

The most common heat-treatable copper alloys are the beryllium coppers. They possess a remarkable combination of properties: tensile strengths as high as 1400 MPa (200,000 psi), excellent electrical and corrosion properties, and wear resistance when properly lubricated; they may be cast, hot worked, or cold worked. High strengths are attained by precipitation-hardening heat treatments (Section 11.9). These alloys are costly because of the beryllium additions, which range between 1.0

Table 11.6 Compositions, Mechanical Properties, and Typical Applications for Eight Copper Alloys

				Mechanical Properties			
Alloy Name	*UNS Number*	*Composition (wt%)*[a]	*Condition*	*Tensile Strength [MPa (ksi)]*	*Yield Strength [MPa (ksi)]*	*Ductility [%EL in 50 mm (2 in.)]*	*Typical Applications*
			Wrought Alloys				
Electrolytic tough pitch	C11000	0.04 O	Annealed	220 (32)	69 (10)	45	Electrical wire, rivets, screening, gaskets, pans, nails, roofing
Beryllium copper	C17200	1.9 Be, 0.20 Co	Precipitation hardened	1140–1310 (165–190)	965–1205 (140–175)	4–10	Springs, bellows, firing pins, bushings, valves, diaphragms
Cartridge brass	C26000	30 Zn	Annealed Cold-worked (H04 hard)	300 (44) 525 (76)	75 (11) 435 (63)	68 8	Automotive radiator cores, ammunition components, lamp fixtures, flashlight shells, kickplates
Phosphor bronze, 5% A	C51000	5 Sn, 0.2 P	Annealed Cold-worked (H04 hard)	325 (47) 560 (81)	130 (19) 515 (75)	64 10	Bellows, clutch disks, diaphragms, fuse clips, springs, welding rods
Copper–nickel, 30%	C71500	30 Ni	Annealed Cold-worked (H02 hard)	380 (55) 515 (75)	125 (18) 485 (70)	36 15	Condenser and heat-exchanger components, saltwater piping
			Cast Alloys				
Leaded yellow brass	C85400	29 Zn, 3 Pb, 1 Sn	As cast	234 (34)	83 (12)	35	Furniture hardware, radiator fittings, light fixtures, battery clamps
Tin bronze	C90500	10 Sn, 2 Zn	As cast	310 (45)	152 (22)	25	Bearings, bushings, piston rings, steam fittings, gears
Aluminum bronze	C95400	4 Fe, 11 Al	As cast	586 (85)	241 (35)	18	Bearings, gears, worms, bushings, valve seats and guards, pickling hooks

[a] The balance of the composition is copper.

Source: Adapted from *ASM Handbook,* Vol. 2, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* 1990. Reprinted by permission of ASM International, Materials Park, OH.

and 2.5 wt%. Applications include jet aircraft landing gear bearings and bushings, springs, and surgical and dental instruments. One of these alloys (C17200) is included in Table 11.6.

Concept Check 11.3 What is the main difference between brass and bronze?

[*The answer may be found at* www.wiley.com/college/callister *(Student Companion Site).*]

Aluminum and Its Alloys

Aluminum and its alloys are characterized by a relatively low density (2.7 g/cm^3 as compared to 7.9 g/cm^3 for steel), high electrical and thermal conductivities, and a resistance to corrosion in some common environments, including the ambient atmosphere. Many of these alloys are easily formed by virtue of high ductility; this is evidenced by the thin aluminum foil sheet into which the relatively pure material may be rolled. Because aluminum has an FCC crystal structure, its ductility is retained even at very low temperatures. The chief limitation of aluminum is its low melting temperature [660°C (1220°F)], which restricts the maximum temperature at which it can be used.

The mechanical strength of aluminum may be enhanced by cold work and by alloying; however, both processes tend to decrease resistance to corrosion. Principal alloying elements include copper, magnesium, silicon, manganese, and zinc. Non-heat-treatable alloys consist of a single phase, for which an increase in strength is achieved by solid-solution strengthening. Others are rendered heat-treatable (capable of being precipitation hardened) as a result of alloying. In several of these alloys, precipitation hardening is due to the precipitation of two elements other than aluminum to form an intermetallic compound such as $MgZn_2$.

temper designation

Generally, aluminum alloys are classified as either cast or wrought. Composition for both types is designated by a four-digit number that indicates the principal impurities and, in some cases, the purity level. For cast alloys, a decimal point is located between the last two digits. After these digits is a hyphen and the basic **temper designation**—a letter and possibly a one- to three-digit number, which indicates the mechanical and/or heat treatment to which the alloy has been subjected. For example, F, H, and O represent, respectively, the as-fabricated, strain-hardened, and annealed states. Table 11.7 presents the temper designation scheme for aluminum alloys. Furthermore, compositions, properties, and applications of several wrought and cast alloys are given in Table 11.8. Common applications of aluminum alloys include aircraft structural parts, beverage cans, bus bodies, and automotive parts (engine blocks, pistons, and manifolds).

specific strength

Recent attention has been given to alloys of aluminum and other low-density metals (e.g., Mg and Ti) as engineering materials for transportation, to effect reductions in fuel consumption. An important characteristic of these materials is **specific strength,** which is quantified by the tensile strength–specific gravity ratio. Even though an alloy of one of these metals may have a tensile strength that is inferior to that of a denser material (such as steel), on a weight basis it will be able to sustain a larger load.

A generation of new aluminum–lithium alloys have been developed recently for use by the aircraft and aerospace industries. These materials have relatively low densities (between about 2.5 and 2.6 g/cm^3), high specific moduli (elastic modulus–specific gravity ratios), and excellent fatigue and low-temperature toughness properties. Furthermore, some of them may be precipitation hardened. However, these materials are more costly to manufacture than the conventional aluminum alloys because special processing techniques are required as a result of lithium's chemical reactivity.

Concept Check 11.4 Explain why, under some circumstances, it is not advisable to weld a structure that is fabricated with a 3003 aluminum alloy. *Hint:* You may want to consult Section 7.12.

[*The answer may be found at www.wiley.com/college/callister (Student Companion Site).*]

Table 11.7 Temper Designation Scheme for Aluminum Alloys

Designation	*Description*
	Basic Tempers
F	As-fabricated—by casting or cold working
O	Annealed—lowest strength temper (wrought products only)
H	Strain-hardened (wrought products only)
W	Solution heat-treated—used only on products that precipitation harden naturally at room temperature over periods of months or years
T	Solution heat-treated—used on products that strength stabilize within a few weeks—followed by one or more digits
	Strain-Hardened Tempers[a]
H1	Strain hardened only
H2	Strain-hardened and then partially annealed
H3	Strain-hardened and then stabilized
	Heat-Treating Tempers[b]
T1	Cooled from an elevated-temperature shaping process and naturally aged
T2	Cooled from an elevated-temperature shaping process, cold-worked, and naturally aged
T3	Solution heat treated, cold worked, and naturally aged
T4	Solution heat treated and naturally aged
T5	Cooled from an elevated-temperature shaping process and artificially aged
T6	Solution heat treated and artificially aged
T7	Solution heat treated and overaged or stabilized
T8	Solution heat treated, cold worked, and artificially aged
T9	Solution heat treated, artificially aged, and cold worked
T10	Cooled from an elevated-temperature shaping process, cold worked, and artificially aged

[a] Two additional digits may be added to denote degree of strain hardening.
[b] Additional digits (the first of which cannot be zero) are used to denote variations of these 10 tempers.

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Magnesium and Its Alloys

Perhaps the most outstanding characteristic of magnesium is its density, 1.7 g/cm^3, which is the lowest of all the structural metals; therefore, its alloys are used where light weight is an important consideration (e.g., in aircraft components). Magnesium has an HCP crystal structure, is relatively soft, and has a low elastic modulus: 45 GPa (6.5×10^6 psi). At room temperature, magnesium and its alloys are difficult to deform; in fact, only small degrees of cold work may be imposed without annealing. Consequently, most fabrication is by casting or hot working at temperatures between 200°C and 350°C (400°F and 650°F). Magnesium, like aluminum, has a moderately low melting temperature [651°C (1204°F)]. Chemically, magnesium alloys are relatively unstable and especially susceptible to corrosion in marine environments. However, corrosion or oxidation resistance is reasonably good in the normal atmosphere; it is believed that this behavior is due to impurities rather than being an inherent characteristic of Mg alloys. Fine magnesium powder ignites easily when heated in air; consequently, care should be exercised when handling it in this state.

Table 11.8 Compositions, Mechanical Properties, and Typical Applications for Several Common Aluminum Alloys

				Mechanical Properties			
Aluminum Association Number	*UNS Number*	*Composition (wt%)*[a]	*Condition (Temper Designation)*	*Tensile Strength [MPa (ksi)]*	*Yield Strength [MPa (ksi)]*	*Ductility [%EL in 50 mm (2 in.)]*	*Typical Applications/ Characteristics*
			Wrought, Nonheat-Treatable Alloys				
1100	A91100	0.12 Cu	Annealed (O)	90 (13)	35 (5)	35–45	Food/chemical handling and storage equipment, heat exchangers, light reflectors
3003	A93003	0.12 Cu, 1.2 Mn, 0.1 Zn	Annealed (O)	110 (16)	40 (6)	30–40	Cooking utensils, pressure vessels and piping
5052	A95052	2.5 Mg, 0.25 Cr	Strain hardened (H32)	230 (33)	195 (28)	12–18	Aircraft fuel and oil lines, fuel tanks, appliances, rivets, and wire
			Wrought, Heat-Treatable Alloys				
2024	A92024	4.4 Cu, 1.5 Mg, 0.6 Mn	Heat-treated (T4)	470 (68)	325 (47)	20	Aircraft structures, rivets, truck wheels, screw machine products
6061	A96061	1.0 Mg, 0.6 Si, 0.30 Cu, 0.20 Cr	Heat-treated (T4)	240 (35)	145 (21)	22–25	Trucks, canoes, railroad cars, furniture, pipelines
7075	A97075	5.6 Zn, 2.5 Mg, 1.6 Cu, 0.23 Cr	Heat-treated (T6)	570 (83)	505 (73)	11	Aircraft structural parts and other highly stressed applications
			Cast, Heat-Treatable Alloys				
295.0	A02950	4.5 Cu, 1.1 Si	Heat-treated (T4)	221 (32)	110 (16)	8.5	Flywheel and rear-axle housings, bus and aircraft wheels, crankcases
356.0	A03560	7.0 Si, 0.3 Mg	Heat-treated (T6)	228 (33)	164 (24)	3.5	Aircraft pump parts, automotive transmission cases, water-cooled cylinder blocks
			Aluminum–Lithium Alloys				
2090	—	2.7 Cu, 0.25 Mg, 2.25 Li, 0.12 Zr	Heat-treated, cold-worked (T83)	455 (66)	455 (66)	5	Aircraft structures and cryogenic tankage structures
8090	—	1.3 Cu, 0.95 Mg, 2.0 Li, 0.1 Zr	Heat-treated, cold-worked (T651)	465 (67)	360 (52)	—	Aircraft structures that must be highly damage tolerant

[a] The balance of the composition is aluminum.

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Table 11.9 Compositions, Mechanical Properties, and Typical Applications for Six Common Magnesium Alloys

				Mechanical Properties			
ASTM Number	*UNS Number*	*Composition (wt%)*[a]	*Condition*	*Tensile Strength [MPa (ksi)]*	*Yield Strength [MPa (ksi)]*	*Ductility [%EL in 50 mm (2 in.)]*	*Typical Applications*
			Wrought Alloys				
AZ31B	M11311	3.0 Al, 1.0 Zn, 0.2 Mn	As extruded	262 (38)	200 (29)	15	Structures and tubing, cathodic protection
HK31A	M13310	3.0 Th, 0.6 Zr	Strain hardened, partially annealed	255 (37)	200 (29)	9	High strength to 315°C (600°F)
ZK60A	M16600	5.5 Zn, 0.45 Zr	Artificially aged	350 (51)	285 (41)	11	Forgings of maximum strength for aircraft
			Cast Alloys				
AZ91D	M11916	9.0 Al, 0.15 Mn, 0.7 Zn	As cast	230 (33)	150 (22)	3	Die-cast parts for automobiles, luggage, and electronic devices
AM60A	M10600	6.0 Al, 0.13 Mn	As cast	220 (32)	130 (19)	6	Automotive wheels
AS41A	M10410	4.3 Al, 1.0 Si, 0.35 Mn	As cast	210 (31)	140 (20)	6	Die castings requiring good creep resistance

[a] The balance of the composition is magnesium.

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These alloys are also classified as either cast or wrought, and some of them are heat-treatable. Aluminum, zinc, manganese, and some of the rare earths are the major alloying elements. A composition–temper designation scheme similar to that for aluminum alloys is also used. Table 11.9 lists several common magnesium alloys and their compositions, properties, and applications. These alloys are used in aircraft and missile applications, as well as in luggage. Furthermore, in recent years the demand for magnesium alloys has increased dramatically in a host of different industries. For many applications, magnesium alloys have replaced engineering plastics that have comparable densities because the magnesium materials are stiffer, more recyclable, and less costly to produce. For example, magnesium is employed in a variety of handheld devices (e.g., chainsaws, powertools, hedge clippers), automobiles (e.g., steering wheels and columns, seat frames, transmission cases), and audio, video, computer, and communications equipment (e.g., laptop computers, camcorders, TV sets, cellular telephones).

Concept Check 11.5 On the basis of melting temperature, oxidation resistance, yield strength, and degree of brittleness, discuss whether it would be advisable to hot work or to cold work (a) aluminum alloys and (b) magnesium alloys. *Hint:* You may want to consult Sections 7.10 and 7.12.

[*The answer may be found at* www.wiley.com/college/callister *(Student Companion Site).*]

Titanium and Its Alloys

Titanium and its alloys are relatively new engineering materials that possess an extraordinary combination of properties. The pure metal has a relatively low density (4.5 g/cm^3), a high melting point [1668°C (3035°F)], and an elastic modulus of 107 GPa (15.5×10^6 psi). Titanium alloys are extremely strong; room-temperature tensile strengths as high as 1400 MPa (200,000 psi) are attainable, yielding remarkable specific strengths. Furthermore, the alloys are highly ductile and easily forged and machined.

Unalloyed (i.e., commercially pure) titanium has a hexagonal close-packed crystal structure, sometimes denoted as the α phase at room temperature. At 883°C (1621°F), the HCP material transforms into a body-centered cubic (or β) phase. This transformation temperature is strongly influenced by the presence of alloying elements. For example, vanadium, niobium, and molybdenum decrease the α-to-β transformation temperature and promote the formation of the β phase (i.e., are β-phase stabilizers), which may exist at room temperature. In addition, for some compositions, both α and β phases coexist. On the basis of which phase(s) is (are) present after processing, titanium alloys fall into four classifications: α, β, $\alpha + \beta$, and near α.

The α-titanium alloys, often alloyed with aluminum and tin, are preferred for high-temperature applications because of their superior creep characteristics. Furthermore, strengthening by heat treatment is not possible because α is the stable phase; consequently, these materials are normally used in annealed or recrystallized states. Strength and toughness are satisfactory, whereas forgeability is inferior to that of the other Ti alloy types.

The β titanium alloys contain sufficient concentrations of β-stabilizing elements (V and Mo) such that, upon cooling at sufficiently rapid rates, the β (metastable) phase is retained at room temperature. These materials are highly forgeable and exhibit high fracture toughnesses.

The $\alpha + \beta$ materials are alloyed with stabilizing elements for both constituent phases. The strength of these alloys may be improved and controlled by heat treatment. A variety of microstructures is possible that consist of an α phase and a retained or transformed β phase. In general, these materials are quite formable.

Near-α alloys are also composed of both α and β phases, with only a small proportion of β—that is, they contain low concentrations of β stabilizers. Their properties and fabrication characteristics are similar to those of the α materials, except that a greater diversity of microstructures and properties are possible for near-α alloys.

The major limitation of titanium is its chemical reactivity with other materials at elevated temperatures. This property has necessitated the development of nonconventional refining, melting, and casting techniques; consequently, titanium alloys are quite expensive. In spite of this reactivity at high temperature, the corrosion resistance of titanium alloys at normal temperatures is unusually high; they are virtually immune to air, marine, and a variety of industrial environments. Table 11.10 presents several titanium alloys along with their typical properties and applications. They are commonly used in airplane structures, space vehicles, surgical implants, and in the petroleum and chemical industries.

The Refractory Metals

Metals that have extremely high melting temperatures are classified as refractory metals. Included in this group are niobium (Nb), molybdenum (Mo), tungsten (W), and tantalum (Ta). Melting temperatures range between 2468°C (4474°F) for niobium and 3410°C (6170°F), the highest melting temperature of any metal, for tungsten. Interatomic bonding in these metals is extremely strong, which accounts for the melting temperatures, and, in addition, large elastic moduli and high strengths and hardnesses, at ambient as well as elevated temperatures. The applications of these metals are varied.

Table 11.10 Compositions, Mechanical Properties, and Typical Applications for Several Common Titanium Alloys

Alloy Type	Common Name (UNS Number)	Composition (wt%)	Condition	*Average Mechanical Properties* Tensile Strength [MPa (ksi)]	Yield Strength [MPa (ksi)]	Ductility [%EL in 50 mm (2 in.)]	Typical Applications
Commercially pure	Unalloyed (R50250)	99.5 Ti	Annealed	240 (35)	170 (25)	24	Jet engine shrouds, cases and airframe skins, corrosion-resistant equipment for marine and chemical processing industries
α	Ti-5Al-2.5Sn (R54520)	5 Al, 2.5 Sn, balance Ti	Annealed	826 (120)	784 (114)	16	Gas turbine engine casings and rings; chemical processing equipment requiring strength to temperatures of 480°C (900°F)
Near α	Ti-8Al-1Mo-1V (R54810)	8 Al, 1 Mo, 1 V, balance Ti	Annealed (duplex)	950 (138)	890 (129)	15	Forgings for jet engine components (compressor disks, plates, and hubs)
$\alpha + \beta$	Ti-6Al-4V (R56400)	6 Al, 4 V, balance Ti	Annealed	947 (137)	877 (127)	14	High-strength prosthetic implants, chemical-processing equipment, airframe structural components
$\alpha + \beta$	Ti-6Al-6V-2Sn (R56620)	6 Al, 2 Sn, 6 V, 0.75 Cu, balance Ti	Annealed	1050 (153)	985 (143)	14	Rocket engine case airframe applications and high-strength airframe structures
β	Ti-10V-2Fe-3Al	10 V, 2 Fe, 3 Al, balance Ti	Solution + aging	1223 (178)	1150 (167)	10	Best combination of high strength and toughness of any commercial titanium alloy; used for applications requiring uniformity of tensile properties at surface and center locations; high-strength airframe components

Source: Adapted from *ASM Handbook*, Vol. 2, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*, 1990. Reprinted by permission of ASM International, Materials Park, OH.

For example, tantalum and molybdenum are alloyed with stainless steel to improve its corrosion resistance. Molybdenum alloys are used for extrusion dies and structural parts in space vehicles; incandescent light filaments, x-ray tubes, and welding electrodes employ tungsten alloys. Tantalum is immune to chemical attack by virtually all environments at temperatures below 150°C and is frequently used in applications requiring such a corrosion-resistant material.

The Superalloys

The superalloys have superlative combinations of properties. Most are used in aircraft turbine components, which must withstand exposure to severely oxidizing environments and high temperatures for reasonable time periods. Mechanical integrity under these conditions is critical; in this regard, density is an important consideration because centrifugal stresses are diminished in rotating members when the density is reduced. These materials are classified according to the predominant metal(s) in the alloy, of which there are three groups—iron–nickel, nickel, and cobalt. Other alloying elements include the refractory metals (Nb, Mo, W, Ta), chromium, and titanium. Furthermore, these alloys are also categorized as wrought or cast. Compositions of several of them are presented in Table 11.11.

In addition to turbine applications, superalloys are used in nuclear reactors and petrochemical equipment.

Table 11.11 Compositions for Several Superalloys

	Composition (wt%)								
Alloy Name	***Ni***	***Fe***	***Co***	***Cr***	***Mo***	***W***	***Ti***	***Al***	***C***	***Other***
						Iron–Nickel (Wrought)				
A-286	26	55.2	—	15	1.25	—	2.0	0.2	0.04	0.005 B, 0.3 V
Incoloy 925	44	29	—	20.5	2.8	—	2.1	0.2	0.01	1.8 Cu
						Nickel (Wrought)				
Inconel-718	52.5	18.5	—	19	3.0	—	0.9	0.5	0.08	5.1 Nb, 0.15 max Cu
Waspaloy	57.0	2.0 max	13.5	19.5	4.3	—	3.0	1.4	0.07	0.006 B, 0.09 Zr
						Nickel (Cast)				
Rene 80	60	—	9.5	14	4	4	5	3	0.17	0.015 B, 0.03 Zr
Mar-M-247	59	0.5	10	8.25	0.7	10	1	5.5	0.15	0.015 B, 3 Ta, 0.05 Zr, 1.5 Hf
						Cobalt (Wrought)				
Haynes 25 (L-605)	10	1	54	20	—	15	—	—	0.1	
						Cobalt (Cast)				
X-40	10	1.5	57.5	22	—	7.5	—	—	0.50	0.5 Mn, 0.5 Si

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The Noble Metals

The noble or precious metals are a group of eight elements that have some physical characteristics in common. They are expensive (precious) and are superior or notable (noble) in properties—characteristically soft, ductile, and oxidation resistant. The noble metals are silver, gold, platinum, palladium, rhodium, ruthenium, iridium, and osmium; the first three are most common and are used extensively in jewelry. Silver and gold may be strengthened by solid-solution alloying with copper; sterling silver is a silver–copper alloy containing approximately 7.5 wt% Cu. Alloys of both silver and gold are employed as dental restoration materials. Some integrated circuit electrical contacts are of gold. Platinum is used for chemical laboratory equipment, as a catalyst (especially in the manufacture of gasoline), and in thermocouples to measure elevated temperatures.

Miscellaneous Nonferrous Alloys

The preceding discussion covers the vast majority of nonferrous alloys; however, a number of others are found in a variety of engineering applications, and a brief mention of these is worthwhile.

Nickel and its alloys are highly resistant to corrosion in many environments, especially those that are basic (alkaline). Nickel is often coated or plated on some metals that are susceptible to corrosion as a protective measure. Monel, a nickel-based alloy containing approximately 65 wt% Ni and 28 wt% Cu (the balance is iron), has very high strength and is extremely corrosion resistant; it is used in pumps, valves, and other components that are in contact with acid and petroleum solutions. As already mentioned, nickel is one of the principal alloying elements in stainless steels and one of the major constituents in the superalloys.

Lead, tin, and their alloys find some use as engineering materials. Both lead and tin are mechanically soft and weak, have low melting temperatures, are quite resistant to many corrosion environments, and have recrystallization temperatures below room temperature. Some common solders are lead–tin alloys, which have low melting temperatures. Applications for lead and its alloys include x-ray shields and storage batteries. The primary use of tin is as a very thin coating on the inside of plain carbon steel cans (tin cans) that are used for food containers; this coating inhibits chemical reactions between the steel and the food products.

Unalloyed zinc also is a relatively soft metal having a low melting temperature and a subambient recrystallization temperature. Chemically, it is reactive in a number of common environments and, therefore, susceptible to corrosion. Galvanized steel is just plain carbon steel that has been coated with a thin zinc layer; the zinc preferentially corrodes and protects the steel (Section 17.9). Typical applications of galvanized steel are familiar (sheet metal, fences, screen, screws, etc.). Common applications of zinc alloys include padlocks, plumbing fixtures, automotive parts (door handles and grilles), and office equipment.

Although zirconium is relatively abundant in the Earth's crust, not until quite recent times were commercial refining techniques developed. Zirconium and its alloys are ductile and have other mechanical characteristics that are comparable to those of titanium alloys and the austenitic stainless steels. However, the primary asset of these alloys is their resistance to corrosion in a host of corrosive media, including superheated water. Furthermore, zirconium is transparent to thermal neutrons, so that its alloys have been used as cladding for uranium fuel in water-cooled nuclear reactors. In terms of cost, these alloys are also often the materials of choice for heat exchangers, reactor vessels, and piping systems for the chemical-processing and nuclear industries. They are also used in incendiary ordnance and in sealing devices for vacuum tubes.

MATERIALS OF IMPORTANCE

Metal Alloys Used for Euro Coins

On January 1, 2002, the euro became the single legal currency in 12 European countries; since that date, several other nations have also joined the European monetary union and have adopted the euro as their official currency. Euro coins are minted in eight different denominations: 1 and 2 euros, as well as 50, 20, 10, 5, 2, and 1 euro cent. Each coin has a common design on one face; the reverse face design is one of several chosen by the monetary union countries. Several of these coins are shown in Figure 11.7.

In deciding which metal alloys to use for these coins, a number of issues were considered, most of them centered on material properties.

- The ability to distinguish a coin of one denomination from that of another denomination is important. This may be accomplished by having coins of different sizes, colors, and shapes. With regard to color, alloys must be chosen that retain their distinctive colors, which means that they do not easily tarnish in the air and other commonly encountered environments.
- Security is an important issue—that is, producing coins that are difficult to counterfeit. Most vending machines use electrical conductivity to identify coins, to prevent false coins from being used. This means that each coin must have its own unique *electronic signature,* which depends on its alloy composition.

Figure 11.7 Photograph showing 1-euro, 2-euro, 20-euro-cent, and 50-euro-cent coins. (Photograph courtesy of Outokumpu Copper.)

- The alloys chosen must be *coinable,* or easy to mint—that is, sufficiently soft and ductile to allow design reliefs to be stamped into the coin surfaces.
- The alloys must be wear resistant (i.e., hard and strong) for long-term use and so that the reliefs stamped into the coin surfaces are retained. Strain hardening (Section 7.10) occurs during the stamping operation, which enhances hardness.
- High degrees of corrosion resistance in common environments are required for the alloys selected, to ensure minimal material losses over the lifetimes of the coins.
- It is highly desirable to use alloys of a base metal (or metals) that retains (retain) its (their) intrinsic value(s).
- Alloy recyclability is another requirement for the alloy(s) used.
- The alloy(s) from which the coins are made should relate to human health considerations—that is, have antibacterial characteristics so that undesirable microorganisms will not grow on their surfaces.

Copper was selected as the base metal for all euro coins, because it and its alloys satisfy these criteria. Several different copper alloys and alloy combinations are used for the eight different coins, as follows:

- 2-euro coin: This coin is termed *bimetallic*—it consists of an outer ring and an inner disk. For the outer ring, a 75Cu–25Ni alloy is used, which has a silver color. The inner disk is composed of a three-layer structure—high-purity nickel that is clad on both sides with a nickel brass alloy (75Cu–20Zn–5Ni); this alloy has a gold color.
- 1-euro coin: This coin is also bimetallic, but the alloys used for its outer ring and inner disk are reversed from those for the 2-euro coin.
- 50-, 20-, and 10-euro-cent pieces: These coins are made of a “Nordic gold” alloy—89Cu–5Al–5Zn–1Sn.
- 5-, 2-, and 1-euro-cent pieces: Copper-plated steels are used for these coins.

Appendix B tabulates a wide variety of properties (density, elastic modulus, yield and tensile strengths, electrical resistivity, coefficient of thermal expansion, etc.) for a large number of metals and alloys.

Fabrication of Metals

Metal fabrication techniques are normally preceded by refining, alloying and often heat-treating processes that produce alloys with the desired characteristics. The classifications of fabrication techniques include various metal-forming methods, casting, powder metallurgy, welding, and machining; often two or more must be used before a piece is finished. The methods chosen depend on several factors; the most important are the properties of the metal, the size and shape of the finished piece, and the cost. The metal fabrication techniques we discuss are classified according to the scheme illustrated in Figure 11.8.

11.4 FORMING OPERATIONS

Forming operations are those in which the shape of a metal piece is changed by plastic deformation; for example, forging, rolling, extrusion, and drawing are common forming techniques. The deformation must be induced by an external force or stress, the magnitude of which must exceed the yield strength of the material. Most metallic materials are especially amenable to these procedures, being at least moderately ductile and capable of some permanent deformation without cracking or fracturing.

hot working

When deformation is achieved at a temperature above that at which recrystallization occurs, the process is termed **hot working** (Section 7.12); otherwise, it is cold working. With most of the forming techniques, both hot- and cold-working procedures are possible. For hot-working operations, large deformations are possible, which may be successively repeated because the metal remains soft and ductile. Also, deformation energy requirements are less than for cold working. However, most metals experience some surface oxidation, which results in material loss and a poor final surface finish. **Cold working** produces an increase in strength with the attendant decrease in ductility because the metal strain hardens; advantages over hot working include a higher-quality surface finish, better mechanical properties and a greater variety of them, and closer dimensional control of the finished piece. On occasion, the total deformation is accomplished in a series of steps in which the piece is successively cold worked a small amount and then process annealed (Section 11.7); however, this is an expensive and inconvenient procedure.

cold working

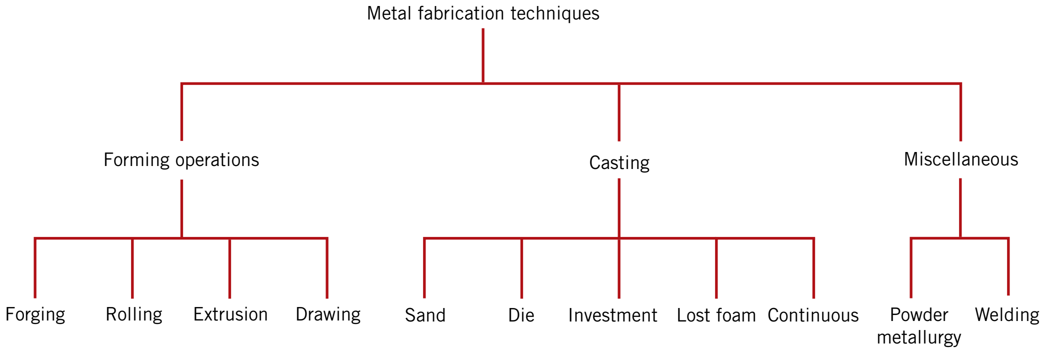

Figure 11.8 Classification scheme of metal fabrication techniques discussed in this chapter.

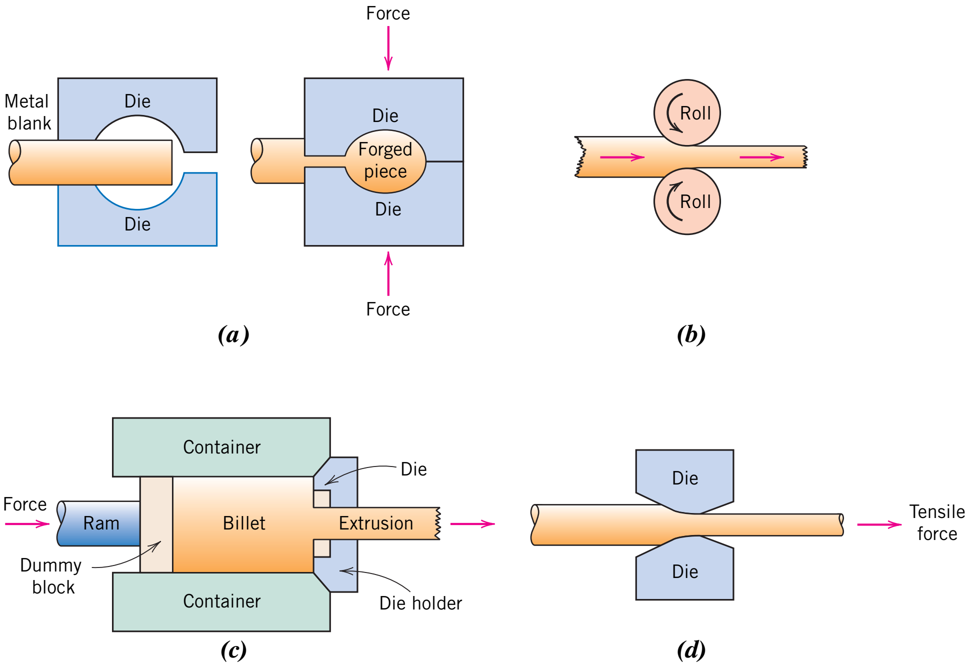

Figure 11.9 Metal deformation during (*a*) forging, (*b*) rolling, (*c*) extrusion, and (*d*) drawing.

The forming operations to be discussed are illustrated schematically in Figure 11.9.

Forging

forging

Forging is mechanically working or deforming a single piece of a usually hot metal; this may be accomplished by the application of successive blows or by continuous squeezing. Forgings are classified as either closed or open die. For closed die, a force is brought to bear on two or more die halves having the finished shape such that the metal is deformed in the cavity between them (Figure 11.9*a*). For open die, two dies having simple geometric shapes (e.g., parallel flat, semicircular) are employed, normally on large workpieces. Forged articles have outstanding grain structures and the best combination of mechanical properties. Wrenches, automotive crankshafts, and piston connecting rods are typical articles formed using this technique.

Rolling

rolling

Rolling, the most widely used deformation process, consists of passing a piece of metal between two rolls; a reduction in thickness results from compressive stresses exerted by the rolls. Cold rolling may be used in the production of sheet, strip, and foil with a high-quality surface finish. Circular shapes, as well as I-beams and railroad rails, are fabricated using grooved rolls.

Extrusion

extrusion

For **extrusion,** a bar of metal is forced through a die orifice by a compressive force that is applied to a ram; the extruded piece that emerges has the desired shape and a reduced cross-sectional area. Extrusion products include rods and tubing that have rather complicated cross-sectional geometries; seamless tubing may also be extruded.

Drawing

drawing

Drawing is the pulling of a metal piece through a die having a tapered bore by means of a tensile force that is applied on the exit side. A reduction in cross section results, with a corresponding increase in length. The total drawing operation may consist of a number of dies in a series sequence. Rod, wire, and tubing products are commonly fabricated in this way.

11.5 CASTING

Casting is a fabrication process in which a completely molten metal is poured into a mold cavity having the desired shape; upon solidification, the metal assumes the shape of the mold but experiences some shrinkage. Casting techniques are employed when (1) the finished shape is so large or complicated that any other method would be impractical; (2) a particular alloy is so low in ductility that forming by either hot or cold working would be difficult; and (3) in comparison to other fabrication processes, casting is the most economical. The final step in the refining of even ductile metals may involve a casting process. A number of different casting techniques are commonly employed, including sand, die, investment, lost-foam, and continuous casting. Only a cursory treatment of each of these is offered.

Sand Casting

With sand casting, probably the most common method, ordinary sand is used as the mold material. A two-piece mold is formed by packing sand around a pattern that has the shape of the intended casting. A *gating system* is usually incorporated into the mold to expedite the flow of molten metal into the cavity and to minimize internal casting defects. Sand-cast parts include automotive cylinder blocks, fire hydrants, and large pipe fittings.

Die Casting

In die casting, the liquid metal is forced into a mold under pressure and at a relatively high velocity and allowed to solidify with the pressure maintained. A two-piece permanent steel mold or die is employed; when clamped together, the two pieces form the desired shape. When the metal has solidified completely, the die pieces are opened and the cast piece is ejected. Rapid casting rates are possible, making this an inexpensive method; furthermore, a single set of dies may be used for thousands of castings. However, this technique lends itself only to relatively small pieces and to alloys of zinc, aluminum, and magnesium, which have low melting temperatures.

Investment Casting

For investment (sometimes called *lost-wax*) casting, the pattern is made from a wax or plastic that has a low melting temperature. Around the pattern a fluid slurry is poured that sets up to form a solid mold or investment; plaster of paris is usually used. The mold is then heated, such that the pattern melts and is burned out, leaving behind a mold cavity having the desired shape. This technique is employed when high dimensional accuracy, reproduction of fine detail, and an excellent finish are required—for example, in jewelry and dental crowns and inlays. Also, blades for gas turbines and jet engine impellers are investment cast.

Lost-Foam Casting

A variation of investment casting is *lost-foam* (or *expendable pattern*) *casting*. Here, the expendable pattern is a foam that can be formed by compressing polystyrene beads into the desired shape and then bonding them together by heating. Alternatively, pattern shapes can be cut from sheets and assembled with glue. Sand is then packed around the pattern to form the mold. As the molten metal is poured into the mold, it replaces the pattern, which vaporizes. The compacted sand remains in place, and, upon solidification, the metal assumes the shape of the mold.

With lost-foam casting, complex geometries and tight tolerances are possible. Furthermore, in comparison to sand casting, lost-foam casting is a simpler, quicker, and less expensive process and there are fewer environmental wastes. Metal alloys that most commonly use this technique are cast irons and aluminum alloys; furthermore, applications include automobile engine blocks, cylinder heads, crankshafts, marine engine blocks, and electric motor frames.

Continuous Casting

At the conclusion of extraction processes, many molten metals are solidified by casting into large ingot molds. The ingots are normally subjected to a primary hot-rolling operation, the product of which is a flat sheet or slab; these are more convenient shapes as starting points for subsequent secondary metal-forming operations (forging, extrusion, drawing). These casting and rolling steps may be combined by a *continuous casting* (sometimes termed *strand casting*) process. Using this technique, the refined and molten metal is cast directly into a continuous strand that may have either a rectangular or circular cross section; solidification occurs in a water-cooled die having the desired cross-sectional geometry. The chemical composition and mechanical properties are more uniform throughout the cross sections for continuous castings than for ingot-cast products. Furthermore, continuous casting is highly automated and more efficient.

11.6 MISCELLANEOUS TECHNIQUES

Powder Metallurgy

powder metallurgy

Yet another fabrication technique involves the compaction of powdered metal followed by a heat treatment to produce a denser piece. The process is appropriately called **powder metallurgy,** frequently designated as P/M. Powder metallurgy makes it possible to produce a virtually nonporous piece having properties almost equivalent to those of the fully dense parent material. Diffusional processes during the heat treatment are central to the development of these properties. This method is especially suitable for metals having low ductilities, because only small plastic deformation of the powder particles need occur. Metals with high melting temperatures are difficult to melt and cast, and fabrication is expedited using P/M. Furthermore, parts that require very close dimensional tolerances (e.g., bushings and gears) may be economically produced using this technique.

Concept Check 11.6 **(a)** Cite two advantages of powder metallurgy over casting. **(b)** Cite two disadvantages.

[*The answer may be found at www.wiley.com/college/callister (Student Companion Site).*]

Welding

welding

In a sense, welding may be considered to be a fabrication technique. In **welding,** two or more metal parts are joined to form a single piece when one-part fabrication is expensive or inconvenient. Both similar and dissimilar metals may be welded. The joining bond is metallurgical (involving some diffusion) rather than just mechanical, as with riveting and bolting. A variety of welding methods exist, including arc and gas welding, as well as brazing and soldering.

During arc and gas welding, the workpieces to be joined and the filler material (i.e., welding rod) are heated to a sufficiently high temperature to cause both to melt; upon solidification, the filler material forms a fusion joint between the workpieces. Thus, there is a region adjacent to the weld that may have experienced microstructural and property alterations; this region is termed the *heat-affected zone* (sometimes abbreviated *HAZ*). Possible alterations include the following:

1. If the workpiece material was previously cold worked, this heat-affected zone may have experienced recrystallization and grain growth, and thus a decrease of strength, hardness, and toughness. The *HAZ* for this situation is represented schematically in Figure 11.10.
2. Upon cooling, residual stresses may form in this region that weaken the joint.
3. For steels, the material in this zone may have been heated to temperatures sufficiently high so as to form austenite. Upon cooling to room temperature, the microstructural products that form depend on cooling rate and alloy composition. For plain carbon steels, normally pearlite and a proeutectoid phase will be present. However, for alloy steels, one microstructural product may be martensite, which is ordinarily undesirable because it is so brittle.
4. Some stainless steels may be "sensitized" during welding, which renders them susceptible to intergranular corrosion, as explained in Section 17.7.

A relatively modern joining technique is that of laser beam welding, in which a highly focused and intense laser beam is used as the heat source. The laser beam melts the parent metal, and, upon solidification, a fusion joint is produced; often a filler material need not be used. Some of the advantages of this technique are as follows: (1) it is a noncontact process, which eliminates mechanical distortion of the workpieces; (2) it can be rapid and highly automated; (3) energy input to the workpiece is low, and therefore the heat-affected zone size is minimal; (4) welds may be small in size and very precise; (5) a large variety of metals and alloys may be joined using this technique; and (6) porosity-free welds with strengths equal to or in excess of the base metal are possible. Laser beam welding is used extensively in the automotive and electronic industries, where high quality and rapid welding rates are required.

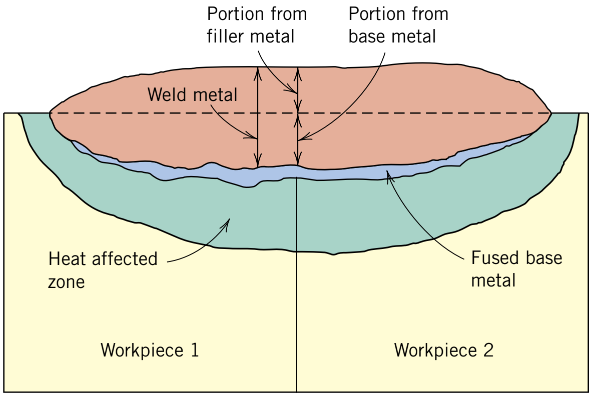

Figure 11.10 Schematic cross-sectional representation showing the zones in the vicinity of a typical fusion weld. [From *Iron Castings Handbook,* C. F. Walton and T. J. Opar (Editors), Iron Castings Society, Des Plaines, IL, 1981.]

Concept Check 11.7 What are the principal differences between welding, brazing, and soldering? You may need to consult other references.

[*The answer may be found at* www.wiley.com/college/callister *(Student Companion Site).*]

Thermal Processing of Metals

Earlier chapters discussed a number of phenomena that occur in metals and alloys at elevated temperatures—for example, recrystallization and the decomposition of austenite. These are effective in altering the mechanical characteristics when appropriate heat treatments or thermal processes are used. In fact, the use of heat treatments on commercial alloys is an exceedingly common practice. Therefore, we consider next the details of some of these processes, including annealing procedures, the heat treating of steels, and precipitation hardening.

11.7 ANNEALING PROCESSES

annealing

The term **annealing** refers to a heat treatment in which a material is exposed to an elevated temperature for an extended time period and then slowly cooled. Typically, annealing is carried out to (1) relieve stresses; (2) increase softness, ductility, and toughness; and/or (3) produce a specific microstructure. A variety of annealing heat treatments are possible; they are characterized by the changes that are induced, which often are microstructural and are responsible for the alteration of the mechanical properties.

Any annealing process consists of three stages: (1) heating to the desired temperature, (2) holding or "soaking" at that temperature, and (3) cooling, usually to room temperature. Time is an important parameter in these procedures. During heating and cooling, temperature gradients exist between the outside and interior portions of the piece; their magnitudes depend on the size and geometry of the piece. If the rate of temperature change is too great, temperature gradients and internal stresses may be induced that may lead to warping or even cracking. Also, the actual annealing time must be long enough to allow for any necessary transformation reactions. Annealing temperature is also an important consideration; annealing may be accelerated by increasing the temperature because diffusional processes are normally involved.

Process Annealing

process annealing

Process annealing is a heat treatment that is used to negate the effects of cold work—that is, to soften and increase the ductility of a previously strain-hardened metal. It is commonly used during fabrication procedures that require extensive plastic deformation, to allow a continuation of deformation without fracture or excessive energy consumption. Recovery and recrystallization processes are allowed to occur. Typically, a fine-grained microstructure is desired, and therefore, the heat treatment is terminated before appreciable grain growth has occurred. Surface oxidation or scaling may be prevented or minimized by annealing at a relatively low temperature (but above the recrystallization temperature) or in a nonoxidizing atmosphere.

Stress Relief

Internal residual stresses may develop in metal pieces in response to the following: (1) plastic deformation processes such as machining and grinding; (2) nonuniform cooling of a piece that was processed or fabricated at an elevated temperature, such as a weld or a casting; and (3) a phase transformation that is induced upon cooling in which parent and product phases have different densities. Distortion and warpage may result if these residual stresses are not removed. They may be eliminated by a **stress relief** annealing heat treatment in which the piece is heated to the recommended temperature, held there long enough to attain a uniform temperature, and finally cooled to room temperature in air. The annealing temperature is typically a relatively low one such that effects resulting from cold working and other heat treatments are not affected.

stress relief

Annealing of Ferrous Alloys

Several different annealing procedures are employed to enhance the properties of steel alloys. However, before they are discussed, some comment relative to the labeling of phase boundaries is necessary. Figure 11.11 shows the portion of the iron–iron carbide phase diagram in the vicinity of the eutectoid. The horizontal line at the eutectoid temperature, conventionally labeled A_1, is termed the **lower critical temperature,** below which, under equilibrium conditions, all austenite has transformed into ferrite and cementite phases. The phase boundaries denoted as A_3 and A_{cm} represent the **upper critical temperature** lines for hypoeutectoid and hypereutectoid steels, respectively. For temperatures and compositions above these boundaries, only the austenite phase prevails. As explained in Section 9.20, other alloying elements shift the eutectoid and the positions of these phase boundary lines.

lower critical temperature

upper critical temperature

Normalizing

Steels that have been plastically deformed by, for example, a rolling operation, consist of grains of pearlite (and most likely a proeutectoid phase), which are irregularly shaped and relatively large and vary substantially in size. An annealing heat treatment called **normalizing** is used to refine the grains (i.e., to decrease the average grain size) and produce a more uniform and desirable size distribution; fine-grained pearlitic steels are tougher than coarse-grained ones. Normalizing is accomplished by heating at least 55°C (100°F) above the upper critical temperature—that is, above A_3 for compositions less than the eutectoid (0.76 wt% C), and above A_{cm} for compositions greater than the eutectoid, as represented in Figure 11.11. After sufficient time has been allowed for the alloy to completely transform to austenite—a procedure termed **austenitizing**—the treatment is terminated by cooling in air. A normalizing cooling curve is superimposed on the continuous-cooling transformation diagram (Figure 10.26).

normalizing

austenitizing

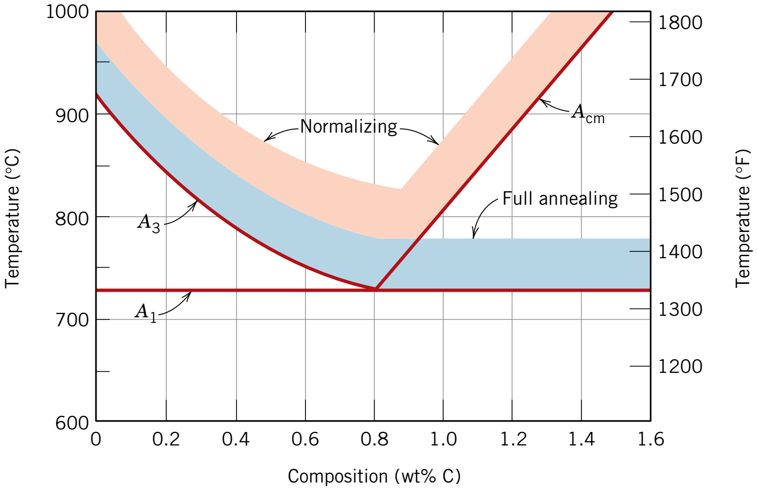

Figure 11.11 The iron–iron carbide phase diagram in the vicinity of the eutectoid, indicating heat-treating temperature ranges for plain carbon steels. (Adapted from G. Krauss, *Steels: Heat Treatment and Processing Principles,* ASM International, 1990, page 108.)

Full Anneal

full annealing

A heat treatment known as **full annealing** is often used in low- and medium-carbon steels that will be machined or will experience extensive plastic deformation during a forming operation. In general, the alloy is treated by heating to a temperature of about 50°C above the A_3 line (to form austenite) for compositions less than the eutectoid, or, for compositions in excess of the eutectoid, 50°C above the A_1 line (to form austenite and Fe_3C phases), as noted in Figure 11.11. The alloy is then furnace cooled—that is, the heat-treating furnace is turned off, and both furnace and steel cool to room temperature at the same rate, which takes several hours. The microstructural product of this anneal is coarse pearlite (in addition to any proeutectoid phase) that is relatively soft and ductile. The full-anneal cooling procedure (also shown in Figure 10.26) is time consuming; however, a microstructure having small grains and a uniform grain structure results.

Spheroidizing

Medium- and high-carbon steels having a microstructure containing even coarse pearlite may still be too hard to machine or plastically deform conveniently. These steels, and in fact any steel, may be heat-treated or annealed to develop the spheroidite structure as described in Section 10.5. Spheroidized steels have a maximum softness and ductility and are easily machined or deformed. The **spheroidizing** heat treatment, during which there is a coalescence of the Fe_3C to form the spheroid particles, can take place by several methods, as follows:

spheroidizing

- Heating the alloy at a temperature just below the eutectoid [line A_1 in Figure 11.11, or at about 700°C (1300°F)] in the $\alpha + Fe_3C$ region of the phase diagram. If the precursor microstructure contains pearlite, spheroidizing times will typically range between 15 and 25 h.
- Heating to a temperature just above the eutectoid temperature and then either cooling very slowly in the furnace or holding at a temperature just below the eutectoid temperature.
- Heating and cooling alternately within about ± 50°C of the A_1 line of Figure 11.11.

To some degree, the rate at which spheroidite forms depends on prior microstructure. For example, it is slowest for pearlite, and the finer the pearlite, the more rapid the rate. Also, prior cold work increases the spheroidizing reaction rate.

Still other annealing treatments are possible. For example, glasses are annealed, as outlined in Section 13.10, to remove residual internal stresses that render the material excessively weak. In addition, microstructural alterations and the attendant modification of mechanical properties of cast irons, as discussed in Section 11.2, result from what are, in a sense, annealing treatments.

11.8 HEAT TREATMENT OF STEELS

Conventional heat treatment procedures for producing martensitic steels typically involve continuous and rapid cooling of an austenitized specimen in some type of quenching medium, such as water, oil, or air. The optimum properties of a steel that has been quenched and then tempered can be realized only if, during the quenching heat treatment, the specimen has been converted to a high content of martensite; the formation of any pearlite and/or bainite will result in other than the best combination of mechanical characteristics. During the quenching treatment, it is impossible to cool the specimen at a uniform rate throughout—the surface always cools more rapidly than interior regions. Therefore, the austenite transforms over a range of temperatures, yielding a possible variation of microstructure and properties with position within a specimen.

The successful heat treating of steels to produce a predominantly martensitic microstructure throughout the cross section depends mainly on three factors: (1) the composition of the alloy, (2) the type and character of the quenching medium, and (3) the size and shape of the specimen. The influence of each of these factors is now addressed.

Hardenability

hardenability

The influence of alloy composition on the ability of a steel alloy to transform to martensite for a particular quenching treatment is related to a parameter called **hardenability.** For every steel alloy, there is a specific relationship between the mechanical properties and the cooling rate. *Hardenability* is a term used to describe the ability of an alloy to be hardened by the formation of martensite as a result of a given heat treatment. Hardenability is not "hardness," which is the resistance to indentation; rather, hardenability is a qualitative measure of the rate at which hardness drops off with distance into the interior of a specimen as a result of diminished martensite content. A steel alloy that has a high hardenability is one that hardens, or forms martensite, not only at the surface, but also to a large degree throughout the entire interior.

The Jominy End-Quench Test

Jominy end-quench test

One standard procedure widely used to determine hardenability is the **Jominy end-quench test.**[1] With this procedure, except for alloy composition, all factors that may influence the depth to which a piece hardens (i.e., specimen size and shape and quenching treatment) are maintained constant. A cylindrical specimen 25.4 mm (1.0 in.) in diameter and 100 mm (4 in.) long is austenitized at a prescribed temperature for a prescribed time. After removal from the furnace, it is quickly mounted in a fixture as diagrammed in Figure 11.12*a*. The lower end is quenched by a jet of water of specified flow rate and temperature. Thus, the cooling rate is a maximum at the quenched end and diminishes with position from this point along the length of the specimen. After the piece has cooled to room temperature, shallow flats 0.4 mm (0.015 in.) deep are ground along the specimen length and Rockwell hardness measurements are made for the first 50 mm (2 in.) along each flat (Figure 11.12*b*); for the first 12.8 mm ($\frac{1}{2}$ in.), hardness

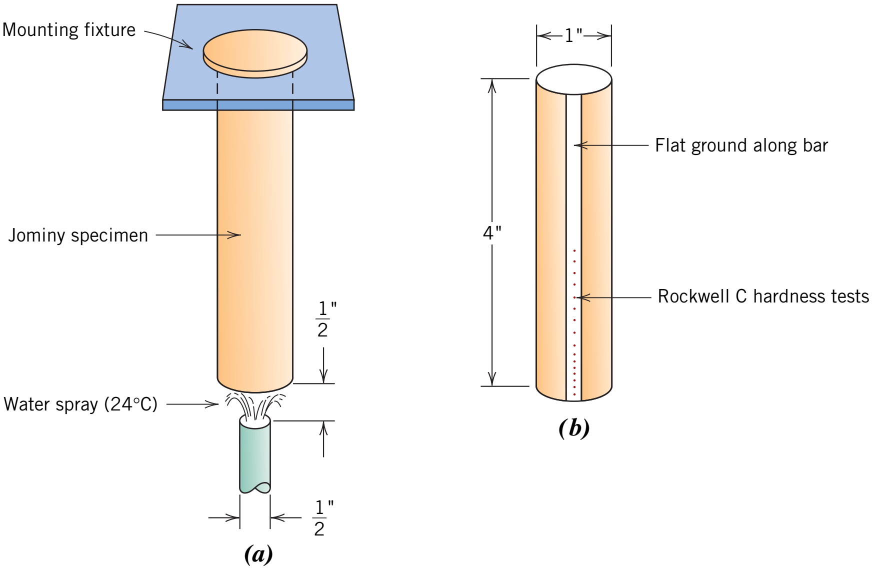

Figure 11.12 Schematic diagram of Jominy end-quench specimen (*a*) mounted during quenching and (*b*) after hardness testing from the quenched end along a ground flat.
(Adapted from A. G. Guy, *Essentials of Materials Science*. Copyright 1978 by McGraw-Hill Book Company, New York.)

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[1] ASTM Standard A255, "Standard Test Methods for Determining Hardenability of Steel."

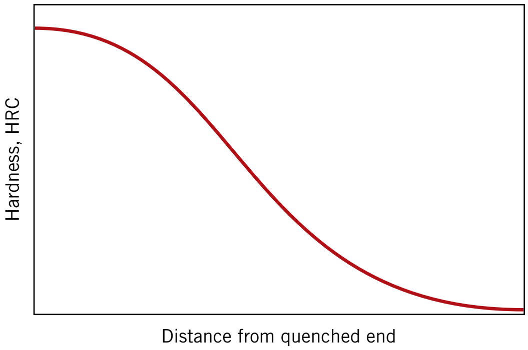


Figure 11.13 Typical hardenability plot of Rockwell C hardness as a function of distance from the quenched end.

readings are taken at 1.6-mm ($\frac{1}{16}$ in.) intervals, and for the remaining 38.4 mm ($1\frac{1}{2}$ in.), every 3.2 mm ($\frac{1}{8}$ in.). A hardenability curve is produced when hardness is plotted as a function of position from the quenched end.

Hardenability Curves

A typical hardenability curve is represented in Figure 11.13. The quenched end is cooled most rapidly and exhibits the maximum hardness; 100% martensite is the product at this position for most steels. Cooling rate decreases with distance from the quenched end, and the hardness also decreases, as indicated in the figure. With diminishing cooling rate, more time is allowed for carbon diffusion and the formation of a greater proportion of the softer pearlite, which may be mixed with martensite and bainite. Thus, a steel that is highly hardenable retains large hardness values for relatively long distances; a steel with low hardenability does not. Also, each steel alloy has its own unique hardenability curve.

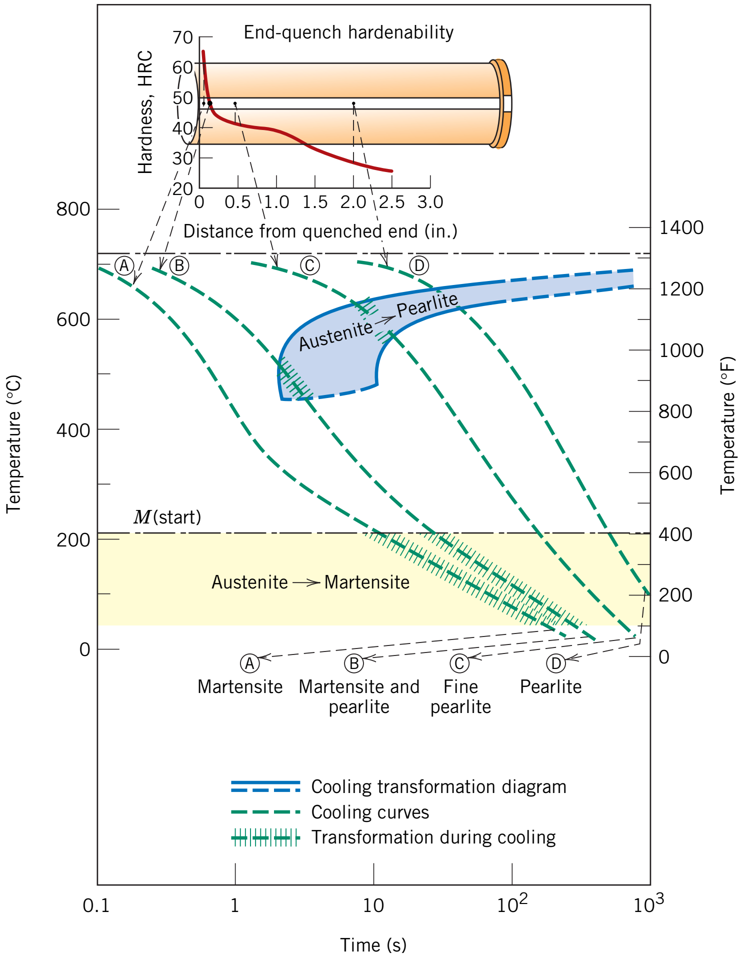
Sometimes, it is convenient to relate hardness to a cooling rate rather than to the location from the quenched end of a standard Jominy specimen. Cooling rate [taken at 700°C (1300°F)] is typically shown on the upper horizontal axis of a hardenability diagram; this scale is included with the hardenability plots presented here. This correlation between position and cooling rate is the same for plain carbon steels and many alloy steels because the rate of heat transfer is nearly independent of composition. On occasion, cooling rate or position from the quenched end is specified in terms of Jominy distance, one Jominy distance unit being 1.6 mm ($\frac{1}{16}$ in.).

A correlation may be drawn between position along the Jominy specimen and continuous-cooling transformations. For example, Figure 11.14 is a continuous-cooling transformation diagram for a eutectoid iron–carbon alloy onto which are superimposed the cooling curves at four different Jominy positions together with the corresponding microstructures that result for each. The hardenability curve for this alloy is also included.

Figure 11.15 shows the hardenability curves for five different steel alloys all having 0.40 wt% C, but differing amounts of other alloying elements. One specimen is a plain carbon steel (1040); the other four (4140, 4340, 5140, and 8640) are alloy steels. The compositions of the four alloy steels are included within the figure. The significance of the alloy designation numbers (e.g., 1040) is explained in Section 11.2. Several details are worth noting from this figure. First, all five alloys have identical hardnesses at the quenched end (57 HRC); this hardness is a function of carbon content only, which is the same for all of these alloys.

Probably the most significant feature of these curves is shape, which relates to hardenability. The hardenability of the plain carbon 1040 steel is low because the hardness drops off precipitously (to about 30 HRC) after a relatively short Jominy distance (16.4 mm, $\frac{1}{4}$ in.). By way of contrast, the decreases in hardness for the other four

Figure 11.14 Correlation of hardenability and continuous-cooling information for an iron–carbon alloy of eutectoid composition.
[Adapted from H. Boyer (Editor), *Atlas of Isothermal Transformation and Cooling Transformation Diagrams,* 1977. Reproduced by permission of ASM International, Materials Park, OH.]



alloy steels are distinctly more gradual. For example, at a Jominy distance of 50 mm (2 in.), the hardnesses of the 4340 and 8640 alloys are approximately 50 and 32 HRC, respectively; thus, of these two alloys, the 4340 is more hardenable. A water-quenched specimen of the 1040 plain carbon steel would harden only to a shallow depth below the surface, whereas for the other four alloy steels the high quenched hardness would persist to a much greater depth.

The hardness profiles in Figure 11.15 are indicative of the influence of cooling rate on the microstructure. At the quenched end, where the quenching rate is approximately 600°C/s (1100°F/s), 100% martensite is present for all five alloys. For cooling rates less than about 70°C/s (125°F/s) or Jominy distances greater than about 6.4 mm ($\frac{1}{4}$ in.), the microstructure of the 1040 steel is predominantly pearlitic, with some proeutectoid ferrite. However, the microstructures of the four alloy steels consist primarily of a mixture of martensite and bainite; bainite content increases with decreasing cooling rate.

This disparity in hardenability behavior for the five alloys in Figure 11.15 is explained by the presence of nickel, chromium, and molybdenum in the alloy steels. These alloying elements delay the austenite-to-pearlite and/or bainite reactions, as explained previously; this permits more martensite to form for a particular cooling rate, yielding a greater hardness. The right-hand axis of Figure 11.15 shows the approximate percentage of martensite that is present at various hardnesses for these alloys.

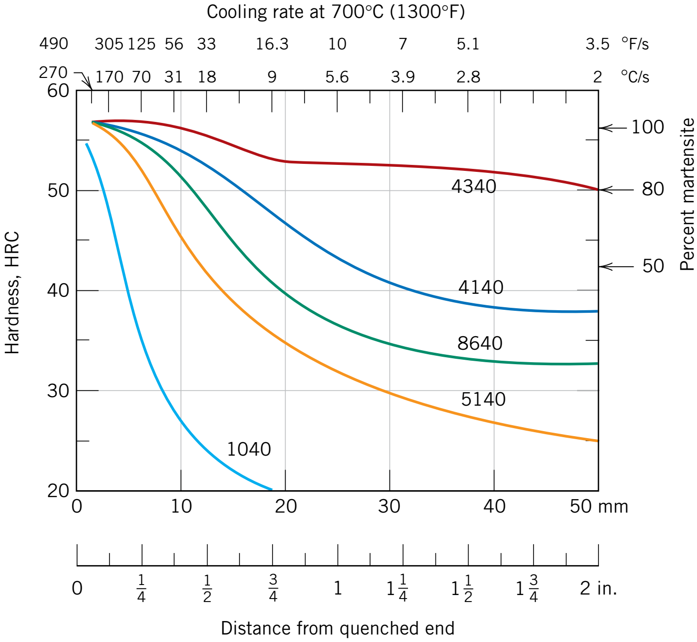


Figure 11.15 Hardenability curves for five different steel alloys, each containing 0.4 wt% C. Approximate alloy compositions (wt%) are as follows: 4340—1.85 Ni, 0.80 Cr, and 0.25 Mo; 4140—1.0 Cr and 0.20 Mo; 8640—0.55 Ni, 0.50 Cr, and 0.20 Mo; 5140—0.85 Cr; and 1040 is an unalloyed steel. (Adapted from figure furnished courtesy Republic Steel Corporation.)

The hardenability curves also depend on carbon content. This effect is demonstrated in Figure 11.16 for a series of alloy steels in which only the concentration of carbon is varied. The hardness at any Jominy position increases with the concentration of carbon.

Also, during the industrial production of steel, there is always a slight, unavoidable variation in composition and average grain size from one batch to another. This variation results in some scatter in measured hardenability data, which frequently are plotted

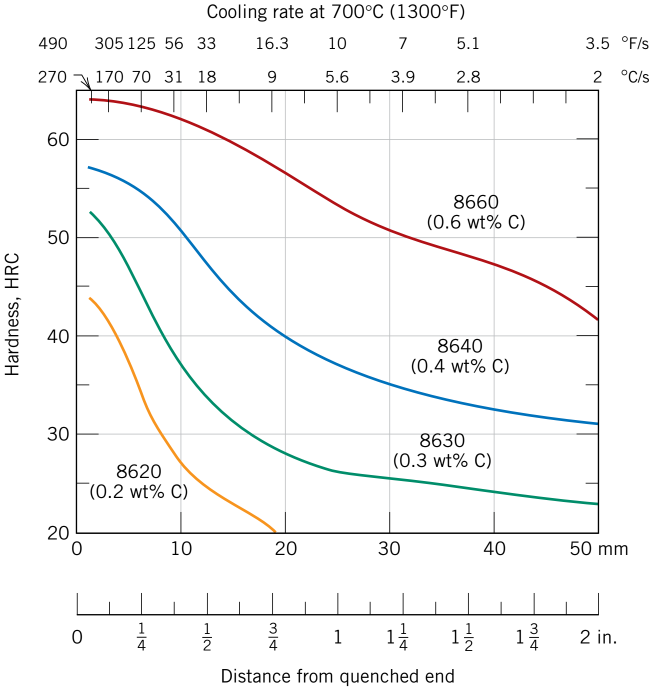


Figure 11.16 Hardenability curves for four 8600 series alloys of indicated carbon content. (Adapted from figure furnished courtesy Republic Steel Corporation.)

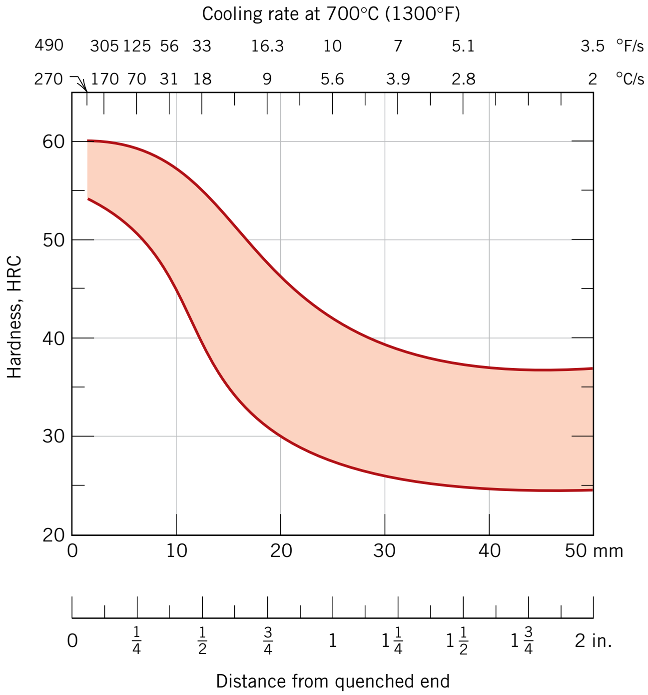


Figure 11.17 The hardenability band for an 8640 steel indicating maximum and minimum limits.
(Adapted from figure furnished courtesy Republic Steel Corporation.)

as a band representing the maximum and minimum values that would be expected for the particular alloy. Such a hardenability band is plotted in Figure 11.17 for an 8640 steel. An H following the designation specification for an alloy (e.g., 8640H) indicates that the composition and characteristics of the alloy are such that its hardenability curve lies within a specified band.

Influence of Quenching Medium, Specimen Size, and Geometry

The preceding treatment of hardenability discussed the influence of both alloy composition and cooling or quenching rate on the hardness. The cooling rate of a specimen depends on the rate of heat energy extraction, which is a function of the characteristics of the quenching medium in contact with the specimen surface, as well as of the specimen size and geometry.

Severity of quench is a term often used to indicate the rate of cooling; the more rapid the quench, the more severe is the quench. Of the three most common quenching media—water, oil, and air—water produces the most severe quench, followed by oil, which is more effective than air.[2] The degree of agitation of each medium also influences the rate of heat removal. Increasing the velocity of the quenching medium across the specimen surface enhances the quenching effectiveness. Oil quenches are suitable for the heat treating of many alloy steels. In fact, for higher-carbon steels, a water quench is too severe because cracking and warping may be produced. Air cooling of austenitized plain carbon steels ordinarily produces an almost totally pearlitic structure.

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[2] Aqueous polymer quenchants [solutions composed of water and a polymer—normally poly(alkylene glycol) or PAG] have recently been developed that provide quenching rates between those of water and oil. The quenching rate can be tailored to specific requirements by changing polymer concentration and quench bath temperature.

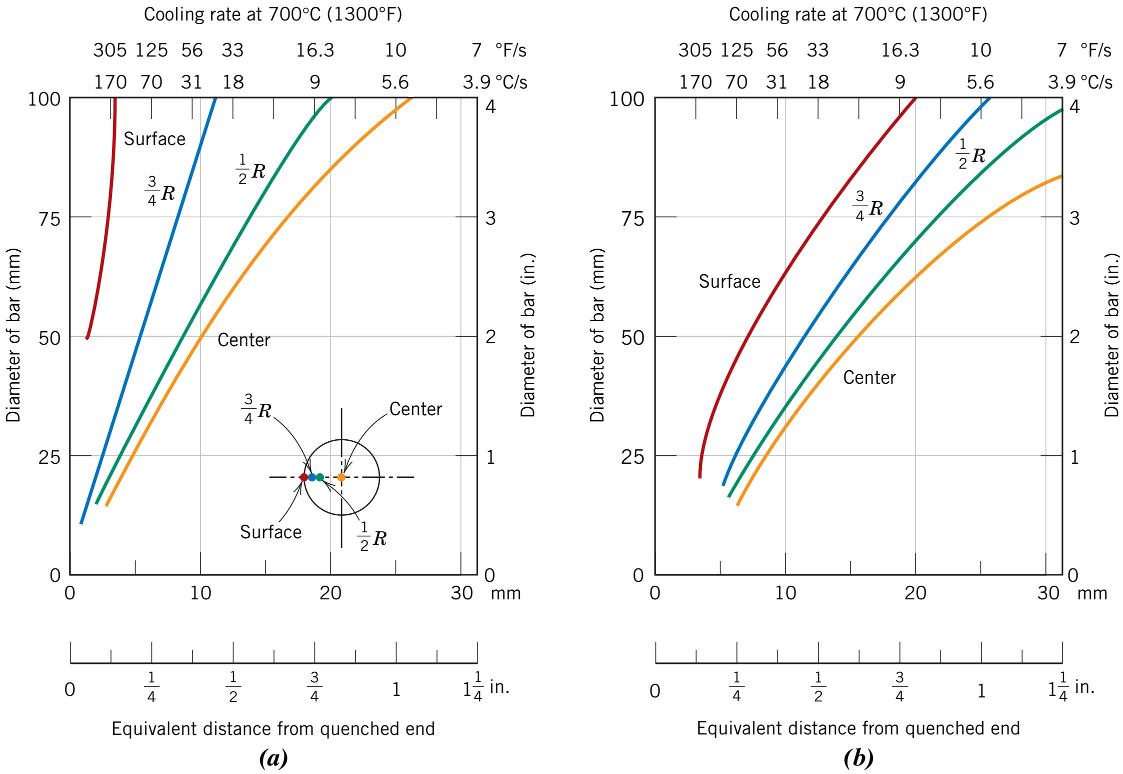


Figure 11.18 Cooling rate as a function of the diameter at the surface, the three-quarter radius ($\frac{3}{4}R$), the midradius ($\frac{1}{2}R$), and the center positions for cylindrical bars quenched in mildly agitated (*a*) water and (*b*) oil. Equivalent Jominy positions are included along the bottom axes.

[Adapted from *Metals Handbook: Properties and Selection: Irons and Steels,* Vol. 1, 9th edition, B. Bardes (Editor), 1978. Reproduced by permission of ASM International, Materials Park, OH.]

During the quenching of a steel specimen, heat energy must be transported to the surface before it can be dissipated into the quenching medium. As a consequence, the cooling rate within and throughout the interior of a steel structure varies with position and depends on the geometry and size. Figures 11.18*a* and 11.18*b* show the quenching rate at 700°C (1300°F) as a function of diameter for cylindrical bars at four radial positions (surface, three-quarters radius, midradius, and center). Quenching is in mildly agitated water (Figure 11.18*a*) and oil (Figure 11.18*b*); cooling rate is also expressed as equivalent Jominy distance because these data are often used in conjunction with hardenability curves. Diagrams similar to those in Figure 11.18 have also been generated for geometries other than cylindrical (e.g., flat plates).

One utility of such diagrams is in the prediction of the hardness traverse along the cross section of a specimen. For example, Figure 11.19*a* compares the radial hardness distributions for cylindrical plain carbon (1040) and alloy (4140) steel specimens; both have a diameter of 50 mm (2 in.) and are water quenched. The difference in hardenability is evident from these two profiles. Specimen diameter also influences the hardness distribution, as demonstrated in Figure 11.19*b*, which plots the hardness profiles for oil-quenched 4140 cylinders 50 and 75 mm (2 and 3 in.) in diameter. Example Problem 11.1 illustrates how these hardness profiles are determined.

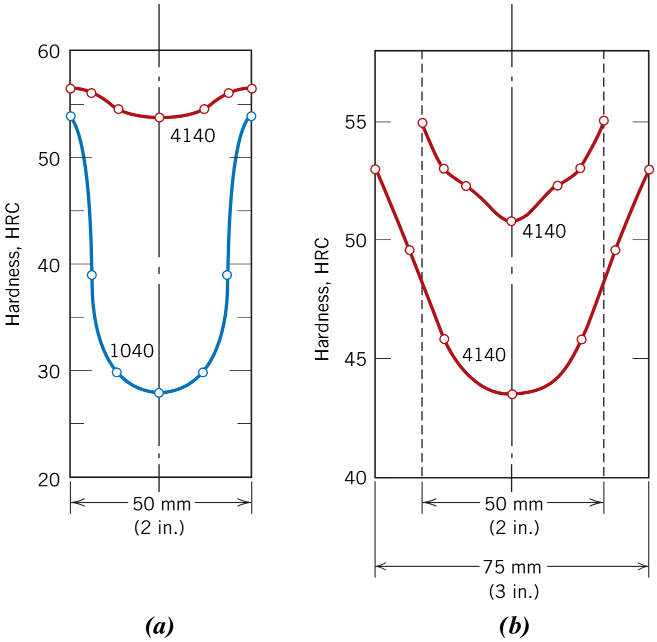


Figure 11.19 Radial hardness profiles for (*a*) 50-mm- (2-in.-) diameter cylindrical 1040 and 4140 steel specimens quenched in mildly agitated water, and (*b*) 50- and 75-mm- (2- and 3-in.-) diameter cylindrical specimens of 4140 steel quenched in mildly agitated oil.

As far as specimen shape is concerned, because the heat energy is dissipated to the quenching medium at the specimen surface, the rate of cooling for a particular quenching treatment depends on the ratio of surface area to the mass of the specimen. The larger this ratio, the more rapid is the cooling rate and, consequently, the deeper is the hardening effect. Irregular shapes with edges and corners have larger surface-to-mass ratios than regular and rounded shapes (e.g., spheres and cylinders) and are thus more amenable to hardening by quenching.

A multitude of steels are responsive to a martensitic heat treatment, and one of the most important criteria in the selection process is hardenability. Hardenability curves, when used in conjunction with plots such as those in Figure 11.18 for various quenching media, may be used to ascertain the suitability of a specific steel alloy for a particular application. Conversely, the appropriateness of a quenching procedure for an alloy may be determined. For parts that are to be involved in relatively high stress applications, a minimum of 80% martensite must be produced throughout the interior as a consequence of the quenching procedure. Only a 50% minimum is required for moderately stressed parts.

Concept Check 11.8 Name the three factors that influence the degree to which martensite is formed throughout the cross section of a steel specimen. For each, tell how the extent of martensite formation may be increased.

[*The answer may be found at* www.wiley.com/college/callister *(Student Companion Site).*]

EXAMPLE PROBLEM 11.1

Determination of Hardness Profile for Heat-Treated 1040 Steel

Determine the radial hardness profile for a cylindrical specimen of 1040 steel of diameter 50 mm (2 in.) that has been quenched in moderately agitated water.

Solution

First, evaluate the cooling rate (in terms of the Jominy end-quench distance) at center, surface, midradius, and three-quarter radius positions of the cylindrical specimen. This is accomplished using the cooling rate–versus–bar diameter plot for the appropriate quenching medium—in this case, Figure 11.18*a*. Then, convert the cooling rate at each of these radial positions into a hardness value from a hardenability plot for the particular alloy. Finally, determine the hardness profile by plotting the hardness as a function of radial position.

This procedure is demonstrated in Figure 11.20, for the center position. Note that for a water-quenched cylinder of 50 mm (2 in.) diameter, the cooling rate at the center is equivalent to that approximately 9.5 mm $\left(\frac{3}{8}\text{ in.}\right)$ from the Jominy specimen quenched end (Figure 11.20*a*). This corresponds to a hardness of about 28 HRC, as noted from the hardenability plot for the 1040 steel alloy (Figure 11.20*b*). Finally, this data point is plotted on the hardness profile in Figure 11.20*c*.

Surface, midradius, and three-quarter radius hardnesses are determined in a similar manner. The complete profile has been included, and the data used are shown in the following table.

Radial Position	***Equivalent Distance from Quenched End [mm (in.)]***	***Hardness (HRC)***
Center	9.5 $\left(\frac{3}{8}\right)$	28
Midradius	8 $\left(\frac{5}{16}\right)$	30
Three-quarters radius	4.8 $\left(\frac{3}{16}\right)$	39
Surface	1.6 $\left(\frac{1}{16}\right)$	54

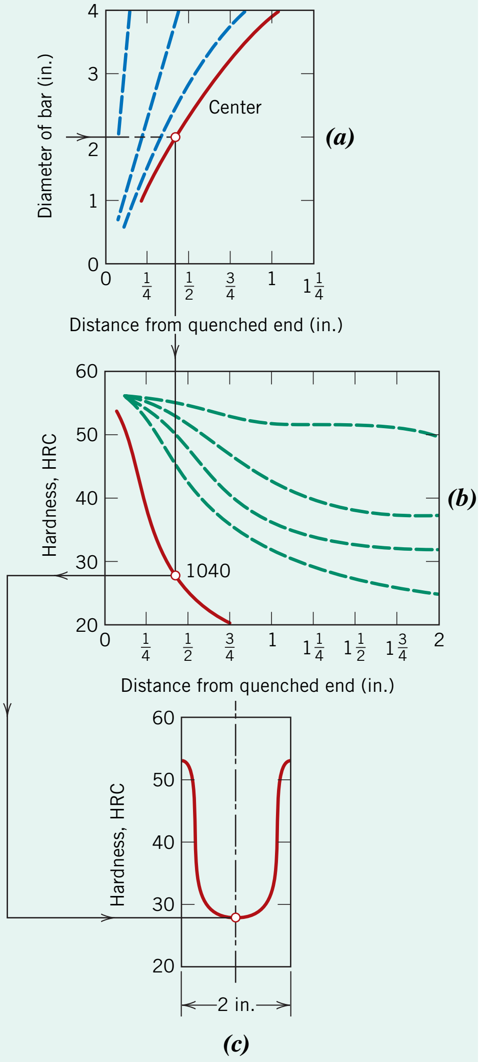


Figure 11.20 Use of hardenability data in the generation of hardness profiles. (*a*) The cooling rate is determined at the center of a water-quenched specimen of diameter 50 mm (2 in.). (*b*) The cooling rate is converted into an HRC hardness for a 1040 steel. (*c*) The Rockwell hardness is plotted on the radial hardness profile.

DESIGN EXAMPLE 11.1

Steel Alloy and Heat Treatment Selection

It is necessary to select a steel alloy for a gearbox output shaft. The design calls for a 1-in.-diameter cylindrical shaft having a surface hardness of at least 38 HRC and a minimum ductility of 12%EL. Specify an alloy and treatment that meet these criteria.

Solution

First, cost is also most likely an important design consideration. This would probably eliminate relatively expensive steels, such as stainless steels and those that are precipitation hardenable. Therefore, let us begin by examining plain carbon steels and low-alloy steels and what treatments are available to alter their mechanical characteristics.

It is unlikely that merely cold working one of these steels would produce the desired combination of hardness and ductility. For example, from Figure 6.19, a hardness of 38 HRC corresponds to a tensile strength of 1200 MPa (175,000 psi). The tensile strength as a function of percent cold work for a 1040 steel is represented in Figure 7.19*b*. Here it may be noted that at 50%CW, a tensile strength of only about 900 MPa (130,000 psi) is achieved; furthermore, the corresponding ductility is approximately 10%EL (Figure 7.19*c*). Hence, both of these properties fall short of those specified in the design; furthermore, cold working other plain carbon steels or low-alloy steels would probably not achieve the required minimum values.

Another possibility is to perform a series of heat treatments in which the steel is austenitized, quenched (to form martensite), and finally tempered. Let us now examine the mechanical properties of various plain carbon steels and low-alloy steels that have been heat-treated in this manner. The surface hardness of the quenched material (which ultimately affects the tempered hardness) depends on both alloy content and shaft diameter, as discussed in the previous two sections. For example, the degree to which surface hardness decreases with diameter is represented in Table 11.12 for a 1060 steel that was oil quenched. Furthermore, the tempered surface hardness also depends on tempering temperature and time.

As-quenched and tempered hardness and ductility data were collected for one plain carbon steel (AISI/SAE 1040) and several common and readily available low-alloy steels, data for which are presented in Table 11.13. The quenching medium (either oil or water) is indicated, and tempering temperatures were 540°C (1000°F), 595°C (1100°F), and 650°C (1200°F). As may be noted, the only alloy–heat treatment combinations that meet the stipulated criteria are 4150/oil–540°C temper, 4340/oil–540°C temper, and 6150/oil–540°C temper; data for these alloys/heat treatments are boldfaced in the table. The costs of these three materials are probably comparable; however, a cost analysis should be conducted.

Table 11.12 Surface Hardnesses for Oil-Quenched Cylinders of 1060 Steel Having Various Diameters

Diameter (in.)	*Surface Hardness (HRC)*
0.5	59
1	34
2	30.5
4	29

Furthermore, the 6150 alloy has the highest ductility (by a narrow margin), which would give it a slight edge in the selection process.

Table 11.13 Rockwell C Hardness (Surface) and Percent Elongation Values for 1-in.-Diameter Cylinders of Six Steel Alloys in the As-Quenched Condition and for Various Tempering Heat Treatments

Alloy Designation/ Quenching Medium	*As-Quenched*	*Tempered at 540°C (1000°F)*		*Tempered at 595°C (1100°F)*		*Tempered at 650°C (1200°F)*	
	Hardness (HRC)	*Hardness (HRC)*	*Ductility (%EL)*	*Hardness (HRC)*	*Ductility (%EL)*	*Hardness (HRC)*	*Ductility (%EL)*
1040/oil	23	(12.5)[a]	26.5	(10)[a]	28.2	(5.5)[a]	30.0
1040/water	50	(17.5)[a]	23.2	(15)[a]	26.0	(12.5)[a]	27.7
4130/water	51	31	18.5	26.5	21.2	—	—
4140/oil	55	33	16.5	30	18.8	27.5	21.0
4150/oil	62	**38**	**14.0**	35.5	15.7	30	18.7
4340/oil	57	**38**	**14.2**	35.5	16.5	29	20.0
6150/oil	60	**38**	**14.5**	33	16.0	31	18.7

[a] These hardness values are only approximate because they are less than 20 HRC.

As the previous section notes, for cylindrical steel alloy specimens that have been quenched, surface hardness depends not only upon alloy composition and quenching medium, but also upon specimen diameter. Likewise, the mechanical characteristics of steel specimens that have been quenched and subsequently tempered will also be a function of specimen diameter. This phenomenon is illustrated in Figure 11.21, which, for an oil-quenched 4140 steel, plots tensile strength, yield strength, and ductility (%EL) versus tempering temperature for four diameters—12.5 mm (0.5 in.), 25 mm (1 in.), 50 mm (2 in.), and 100 mm (4 in.).

11.9 PRECIPITATION HARDENING

precipitation hardening

The strength and hardness of some metal alloys may be enhanced by the formation of extremely small, uniformly dispersed particles of a second phase within the original phase matrix; this must be accomplished by phase transformations that are induced by appropriate heat treatments. The process is called **precipitation hardening** because the small particles of the new phase are termed *precipitates*. *Age hardening* is also used to designate this procedure because the strength develops with time, or as the alloy ages. Examples of alloys that are hardened by precipitation treatments include aluminum–copper, copper–beryllium, copper–tin, and magnesium–aluminum; some ferrous alloys are also precipitation hardenable.

Precipitation hardening and the treating of steel to form tempered martensite are totally different phenomena, even though the heat treatment procedures are similar; therefore, the processes should not be confused. The principal difference lies in the mechanisms by which hardening and strengthening are achieved. These should become apparent with the following explanation of precipitation hardening.

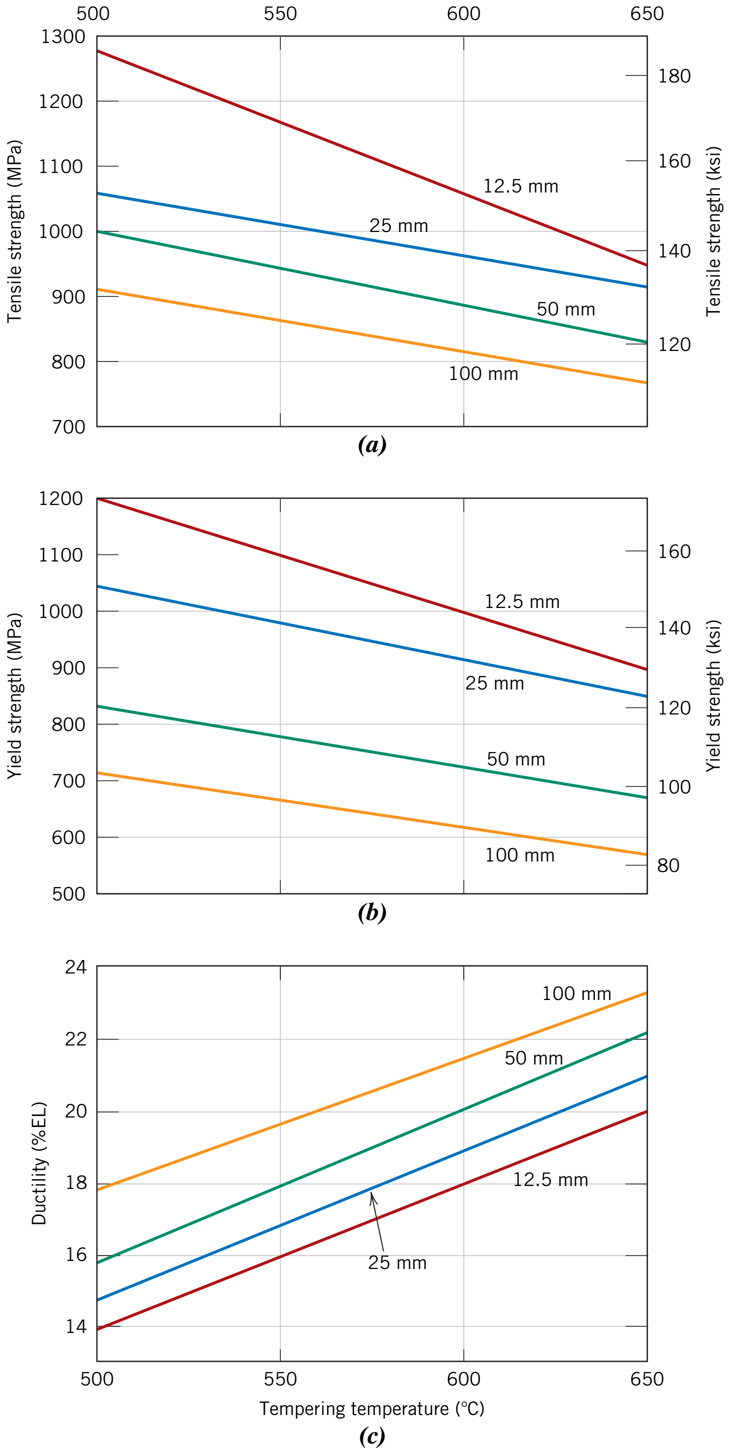


Figure 11.21 For cylindrical specimens of an oil-quenched 4140 steel, (*a*) tensile strength, (*b*) yield strength, and (*c*) ductility (percent elongation) versus tempering temperature for diameters of 12.5 mm (0.5 in.), 25 mm (1 in.), 50 mm (2 in.), and 100 mm (4 in.).

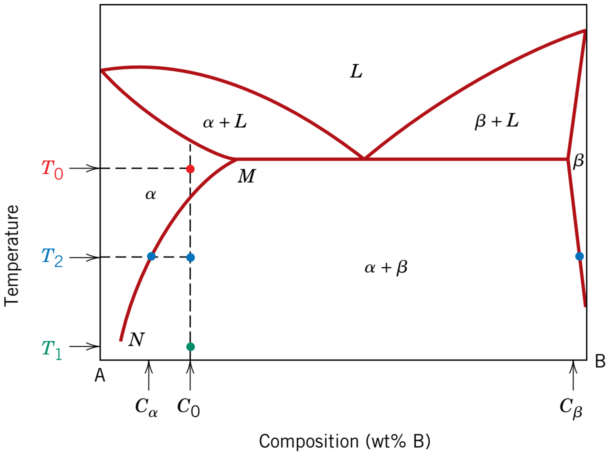


Figure 11.22 Hypothetical phase diagram for a precipitation-hardenable alloy of composition C_0.

Heat Treatments

Inasmuch as precipitation hardening results from the development of particles of a new phase, an explanation of the heat treatment procedure is facilitated by use of a phase diagram. Even though, in practice, many precipitation-hardenable alloys contain two or more alloying elements, the discussion is simplified by reference to a binary system. The phase diagram must be of the form shown for the hypothetical A–B system in Figure 11.22.

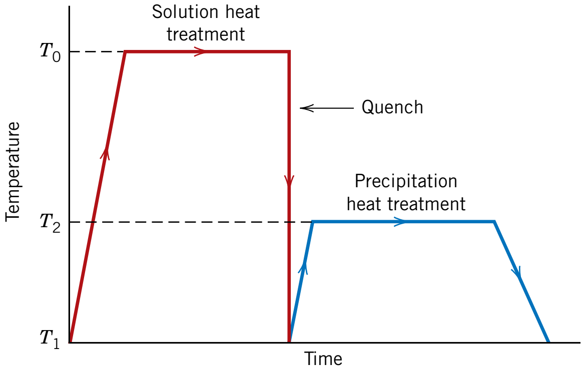
Two requisite features must be displayed by the phase diagrams of alloy systems for precipitation hardening: an appreciable maximum solubility of one component in the other, on the order of several percent; and a solubility limit that rapidly decreases in concentration of the major component with temperature reduction. Both of these conditions are satisfied by this hypothetical phase diagram (Figure 11.22). The maximum solubility corresponds to the composition at point *M*. In addition, the solubility limit boundary between the α and $\alpha + \beta$ phase fields diminishes from this maximum concentration to a very low B content in A at point *N*. Furthermore, the composition of a precipitation-hardenable alloy must be less than the maximum solubility. These conditions are necessary but *not* sufficient for precipitation hardening to occur in an alloy system. An additional requirement is discussed in what follows.

Solution Heat Treating

solution heat treatment

Precipitation hardening is accomplished by two different heat treatments. The first is a **solution heat treatment** in which all solute atoms are dissolved to form a single-phase solid solution. Consider an alloy of composition C_0 in Figure 11.22. The treatment consists of heating the alloy to a temperature within the α-phase field—say, T_0—and waiting until all of the β phase that may have been present is completely dissolved. At this point, the alloy consists only of an α phase of composition C_0. This procedure is followed by rapid cooling or quenching to temperature T_1, which for many alloys is room temperature, to the extent that any diffusion and the accompanying formation of any of the β phase are prevented. Thus, a nonequilibrium situation exists in which only the α-phase solid solution supersaturated with B atoms is present at T_1; in this state the alloy is relatively soft and weak. Furthermore, for most alloys diffusion rates at T_1 are extremely slow, such that the single α phase is retained at this temperature for relatively long periods.

Figure 11.23 Schematic temperature-versus-time plot showing both solution and precipitation heat treatments for precipitation hardening.



Precipitation Heat Treating

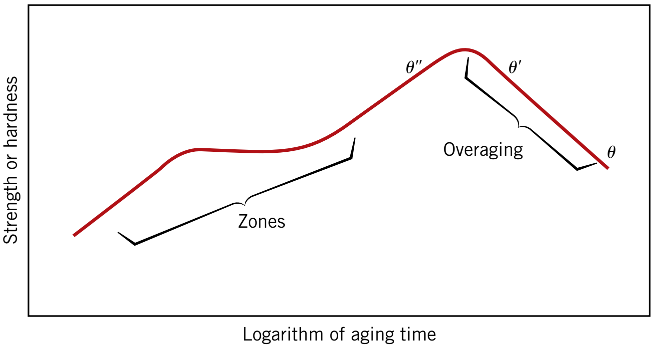
precipitation heat treatment

For the second or **precipitation heat treatment,** the supersaturated α solid solution is ordinarily heated to an intermediate temperature T_2 (Figure 11.22) within the $\alpha + \beta$ two-phase region, at which temperature diffusion rates become appreciable. The β precipitate phase begins to form as finely dispersed particles of composition C_β, which process is sometimes termed *aging*. After the appropriate aging time at T_2, the alloy is cooled to room temperature; normally, this cooling rate is not an important consideration. Both solution and precipitation heat treatments are represented on the temperature-versus-time plot in Figure 11.23. The character of these β particles, and subsequently the strength and hardness of the alloy, depend on both the precipitation temperature T_2 and the aging time at this temperature. For some alloys, aging occurs spontaneously at room temperature over extended time periods.

overaging

The dependence of the growth of the precipitate β particles on time and temperature under isothermal heat treatment conditions may be represented by C-shape curves similar to those in Figure 10.18 for the eutectoid transformation in steels. However, it is more useful and convenient to present the data as tensile strength, yield strength, or hardness at room temperature as a function of the logarithm of aging time, at constant temperature T_2. The behavior for a typical precipitation-hardenable alloy is represented schematically in Figure 11.24. With increasing time, the strength or hardness increases, reaches a maximum, and finally diminishes. This reduction in strength and hardness that occurs after long time periods is known as **overaging.** The influence of temperature is incorporated by the superposition, on a single plot, of curves at a variety of temperatures.

Figure 11.24 Schematic diagram showing strength and hardness as a function of the logarithm of aging time at constant temperature during the precipitation heat treatment.



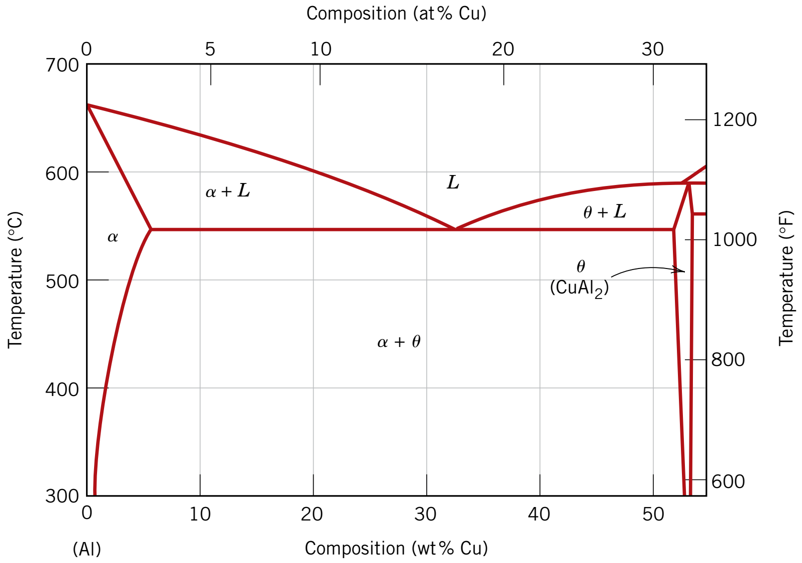


Figure 11.25 The aluminum-rich side of the aluminum–copper phase diagram.
(Adapted from J. L. Murray, *International Metals Review,* **30,** 5, 1985. Reprinted by permission of ASM International.)

Mechanism of Hardening

Precipitation hardening is commonly employed with high-strength aluminum alloys. Although a large number of these alloys have different proportions and combinations of alloying elements, the mechanism of hardening has perhaps been studied most extensively for the aluminum–copper alloys. Figure 11.25 presents the aluminum-rich portion of the aluminum–copper phase diagram. The α phase is a substitutional solid solution of copper in aluminum, whereas the intermetallic compound $CuAl_2$ is designated the θ phase. For an aluminum–copper alloy of, say, composition 96 wt% Al–4 wt% Cu, in the development of this equilibrium θ phase during the precipitation heat treatment, several transition phases are first formed in a specific sequence. The mechanical properties are influenced by the character of the particles of these transition phases. During the initial hardening stage (at short times, Figure 11.24), copper atoms cluster together in very small, thin discs that are only one or two atoms thick and approximately 25 atoms in diameter; these form at countless positions within the α phase. The clusters, sometimes called *zones,* are so small that they are really not regarded as distinct precipitate particles. However, with time and the subsequent diffusion of copper atoms, zones become particles as they increase in size. These precipitate particles then pass through two transition phases (denoted as θ'' and θ'), before the formation of the equilibrium θ phase (Figure 11.26*c*). Transition phase particles for a precipitation-hardened 7150 aluminum alloy are shown in the electron micrograph of Figure 11.27.

The strengthening and hardening effects shown in Figure 11.24 result from the innumerable particles of these transition and metastable phases. As shown in the figure, maximum strength coincides with the formation of the θ'' phase, which may be preserved upon cooling the alloy to room temperature. Overaging results from continued particle growth and the development of θ' and θ phases.

The strengthening process is accelerated as the temperature is increased. This is demonstrated in Figure 11.28*a*, a plot of yield strength versus the logarithm of time for a 2014 aluminum alloy at several different precipitation temperatures. Ideally, temperature and time for the precipitation heat treatment should be designed to produce a hardness or strength in the vicinity of the maximum. Associated with an increase in

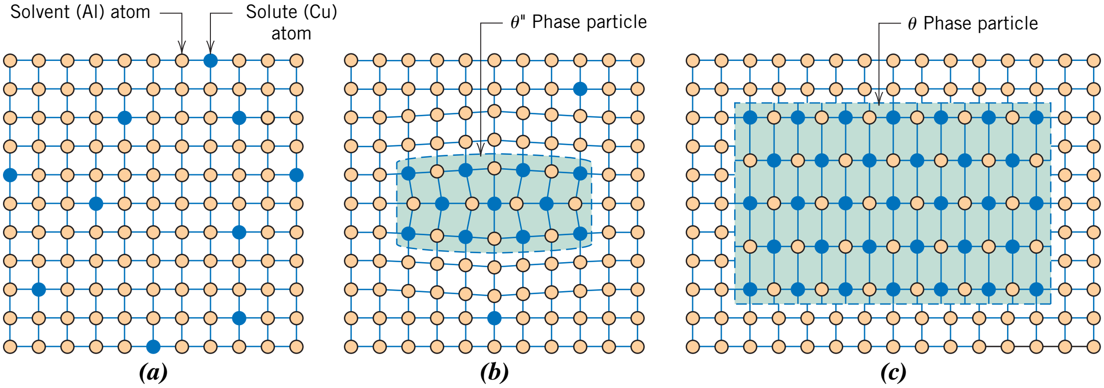


Figure 11.26 Schematic depiction of several stages in the formation of the equilibrium precipitate (θ) phase. (*a*) A supersaturated α solid solution. (*b*) A transition, θ'', precipitate phase. (*c*) The equilibrium θ phase, within the α-matrix phase.

strength is a reduction in ductility, which is demonstrated in Figure 11.28*b* for the same 2014 aluminum alloy at the same temperatures.

Not all alloys that satisfy the aforementioned conditions relative to composition and phase diagram configuration are amenable to precipitation hardening. In addition, lattice strains must be established at the precipitate–matrix interface. For aluminum–copper alloys, there is a distortion of the crystal lattice structure around and within the vicinity of particles of these transition phases (Figure 11.26*b*). During plastic deformation, dislocation motions are effectively impeded as a result of these distortions, and, consequently, the alloy becomes harder and stronger. As the θ phase forms, the resultant overaging (softening and weakening) is explained by a reduction in the resistance to slip that is offered by these precipitate particles.

Alloys that experience appreciable precipitation hardening at room temperature and after relatively short time periods must be quenched to and stored under refrigerated conditions. Several aluminum alloys that are used for rivets exhibit this behavior.

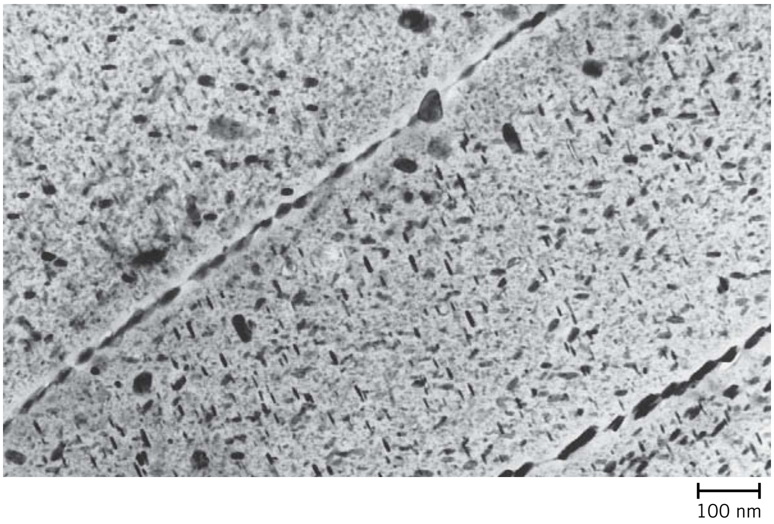


Figure 11.27 A transmission electron micrograph showing the microstructure of a 7150–T651 aluminum alloy (6.2 wt% Zn, 2.3 wt% Cu, 2.3 wt% Mg, 0.12 wt% Zr, the balance Al) that has been precipitation hardened. The light matrix phase in the micrograph is an aluminum solid solution. The majority of the small plate-shaped dark precipitate particles are a transition η' phase, the remainder being the equilibrium η ($MgZn_2$) phase. Note that grain boundaries are "decorated" by some of these particles. 90,000×.
(Courtesy of G. H. Narayanan and A. G. Miller, Boeing Commercial Airplane Company.)

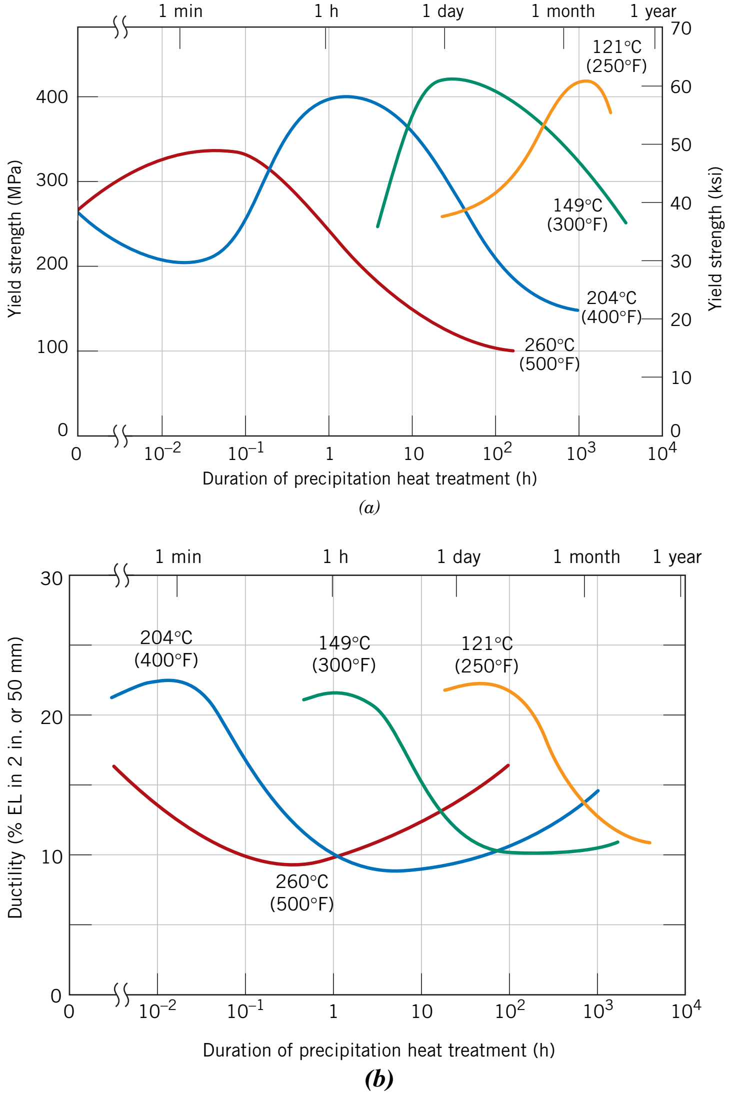


Figure 11.28 The precipitation hardening characteristics of a 2014 aluminum alloy (0.9 wt% Si, 4.4 wt% Cu, 0.8 wt% Mn, 0.5 wt% Mg) at four different aging temperatures: (*a*) yield strength, and (*b*) ductility (%EL). [Adapted from *Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals,* Vol. 2, 9th edition, H. Baker (Managing Editor), 1979. Reproduced by permission of ASM International, Materials Park, OH.]

natural aging, artificial aging

They are driven while still soft, then allowed to age harden at the normal ambient temperature. This is termed **natural aging; artificial aging** is carried out at elevated temperatures.

Miscellaneous Considerations

The combined effects of strain hardening and precipitation hardening may be employed in high-strength alloys. The order of these hardening procedures is important in the production of alloys having the optimum combination of mechanical properties. Normally, the alloy is solution heat-treated and then quenched. This is followed by cold working and finally by the precipitation-hardening heat treatment. In the final treatment, little strength loss is sustained as a result of recrystallization. If the alloy is precipitation hardened before cold working, more energy must be expended in its deformation; in addition, cracking may also result because of the reduction in ductility that accompanies the precipitation hardening.

Most precipitation-hardened alloys are limited in their maximum service temperatures. Exposure to temperatures at which aging occurs may lead to a loss of strength due to overaging.

SUMMARY

Ferrous Alloys

- *Ferrous alloys* (steels and cast irons) are those in which iron is the prime constituent. Most steels contain less than 1.0 wt% C and, in addition, other alloying elements, which render them susceptible to heat treatment (and an enhancement of mechanical properties) and/or more corrosion resistant.
- Ferrous alloys are used extensively as engineering materials because
  Iron-bearing compounds are abundant.
  Economical extraction, refining, and fabrication techniques are available.
  They may be tailored to have a wide variety of mechanical and physical properties.
- Limitations of ferrous alloys include the following:
  Relatively high densities
  Comparatively low electrical conductivities
  Susceptibility to corrosion in common environments
- The most common types of steels are plain low-carbon, high-strength low-alloy, medium-carbon, tool, and stainless.
- Plain carbon steels contain (in addition to carbon) a little manganese and only residual concentrations of other impurities.
- Stainless steels are classified according to the main microstructural constituent. The three classes are ferritic, austenitic, and martensitic.
- Cast irons contain higher carbon contents than steels—normally between 3.0 and 4.5 wt% C—as well as other alloying elements, notably silicon. For these materials, most of the carbon exists in graphite form rather than combined with iron as cementite.
- Gray, ductile (or nodular), malleable, and compacted graphite irons are the four most widely used cast irons; the last three are reasonably ductile.

Nonferrous Alloys

- All other alloys fall within the nonferrous category, which is further subdivided according to base metal or some distinctive characteristic that is shared by a group of alloys.
- Nonferrous alloys may be further subclassified as either wrought or cast. Alloys that are amenable to forming by deformation are classified as wrought. Cast alloys are relatively brittle, and therefore fabrication by casting is most expedient.
- Seven classifications of nonferrous alloys were discussed—copper, aluminum, magnesium, titanium, the refractory metals, the superalloys, and the noble metals—as well as a miscellaneous category (nickel, lead, tin, zinc, and zirconium).

Forming Operations

- *Forming operations* are those in which a metal piece is shaped by plastic deformation.
- When deformation is carried out above the recrystallization temperature, it is termed *hot working;* otherwise, it is *cold working*.
- Forging, rolling, extrusion, and drawing are among the more common forming techniques (Figure 11.9).

Casting

- Depending on the properties and shape of the finished piece, casting may be the most desirable and economical fabrication process.
- The most common casting techniques are sand, die, investment, lost-foam, and continuous casting.

Miscellaneous Techniques

- Powder metallurgy involves compacting powder metal particles into a desired shape, which is then densified by heat treatment. P/M is used primarily for metals that have low ductilities and/or high melting temperatures.
- Welding is used to join together two or more workpieces; a fusion bond forms by melting portions of the workpieces and, in some instances, a filler material.

Annealing Processes

- *Annealing* is the exposure of a material to an elevated temperature for an extended time period followed by cooling to room temperature at a relatively slow rate.
- During process annealing, a cold-worked piece is rendered softer yet more ductile as a consequence of recrystallization.
- Internal residual stresses that have been introduced are eliminated during a stress-relief anneal.
- For ferrous alloys, normalizing is used to refine and improve the grain structure.

Heat Treatment of Steels

- For high-strength steels, the best combination of mechanical characteristics may be realized if a predominantly martensitic microstructure is developed over the entire cross section; this is converted into tempered martensite during a tempering heat treatment.
- *Hardenability* is a parameter used to ascertain the influence of composition on the susceptibility to the formation of a predominantly martensitic structure for some specific heat treatment. Martensite content is determined using hardness measurements.
- Determination of hardenability is accomplished by the standard Jominy end-quench test (Figure 11.12), from which hardenability curves are generated.
- A *hardenability curve* plots hardness versus distance from the quenched end of a Jominy specimen. Hardness decreases with distance from the quenched end (Figure 11.13) because the quenching rate decreases with this distance, as does the martensite content. Each steel alloy has its own distinctive hardenability curve.
- The quenching medium also influences the extent to which martensite forms. Of the common quenching media, water is the most efficient, followed by aqueous polymers, oil, and air, in that order. Increasing the degree of medium agitation also enhances the quenching efficiency.
- Relationships among cooling rate and specimen size and geometry for a specific quenching medium frequently are expressed on empirical charts (Figures 11.18*a* and 11.18*b*). These plots may be used in conjunction with hardenability data to predict cross-sectional hardness profiles (Example Problem 11.1).

Precipitation Hardening

- Some alloys are amenable to *precipitation hardening*—that is, to strengthening by the formation of very small particles of a second, or precipitate, phase.
- Control of particle size and, subsequently, strength is accomplished by two heat treatments:

  In the first, or *solution,* heat treatment, all solute atoms are dissolved to form a single-phase solid solution; quenching to a relatively low temperature preserves this state.

During the second, or *precipitation,* treatment (at constant temperature), precipitate particles form and grow; strength, hardness, and ductility depend on heat-treating time (and particle size).

- Strength and hardness increase with time to a maximum and then decrease during overaging (Figure 11.24). This process is accelerated with rising temperature (Figure 11.28*a*).
- The strengthening phenomenon is explained in terms of an increased resistance to dislocation motion by lattice strains that are established in the vicinity of these microscopically small precipitate particles.

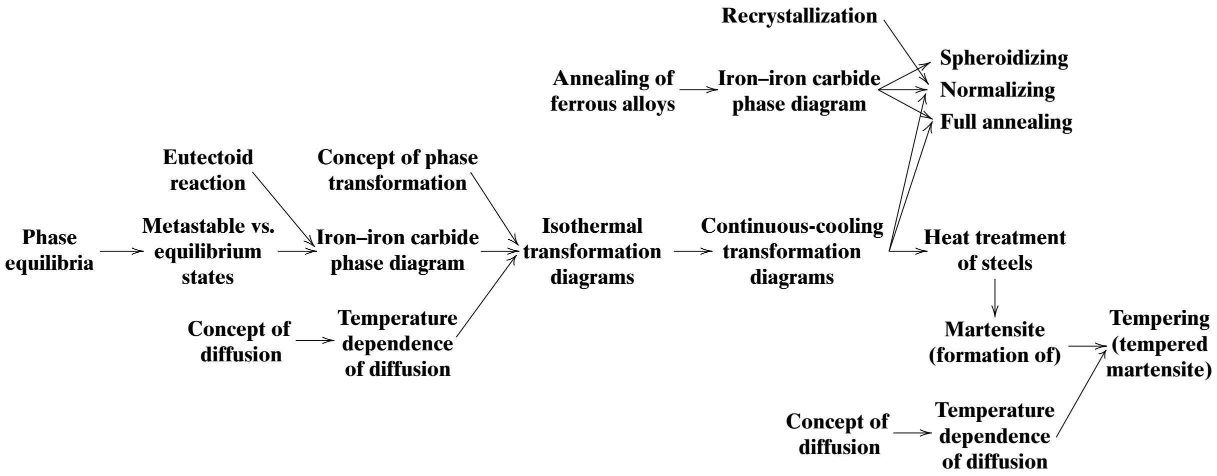
Processing/Structure/Properties/Performance Summary

At this time, we have completed our processing/structure/properties/performance commentary for steels. By way of summary, Figure 11.29 shows relationships of these processing, structure, and property elements for this group of alloys. It was compiled from summaries provided in previous chapters and, in addition, includes topics discussed in this chapter.

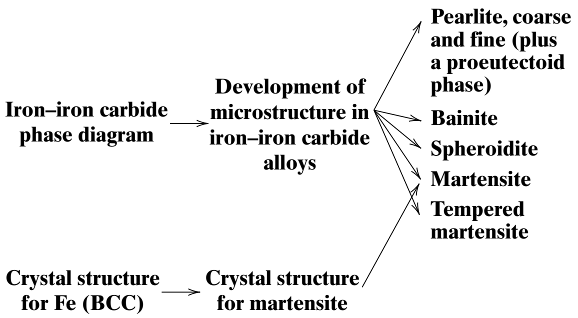
For the most part, the individual components found in the interrelationships of Figure 11.29 are conceptual in nature—that is, they represent the scientific (as opposed to engineering) aspects of materials. We have also generated a processing/structure/properties/performance relational diagram (for steel alloys) taken from the materials engineering perspective; it is shown in Figure 11.30.

Important Terms and Concepts

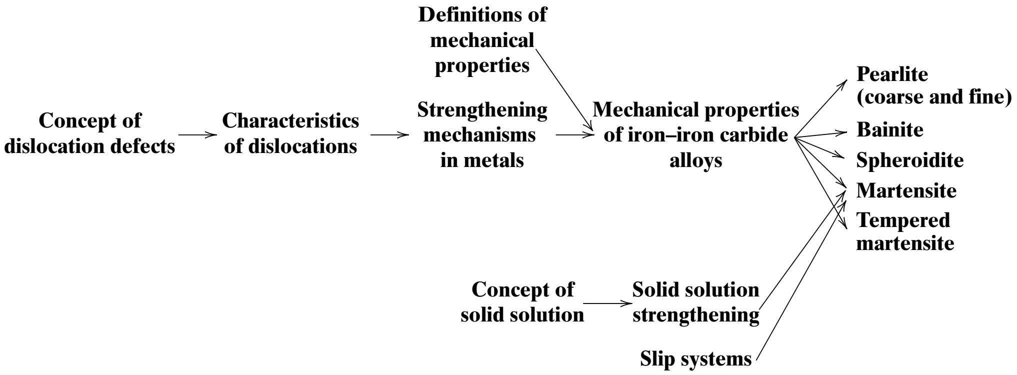
alloy steel
annealing
artificial aging
austenitizing
brass
bronze
cast iron
cold working
compacted graphite iron
drawing
ductile (nodular) iron
extrusion
ferrous alloy
forging
full annealing
gray cast iron
hardenability
high-strength, low-alloy (HSLA) steel
hot working
Jominy end-quench test
lower critical temperature
malleable cast iron
natural aging
nonferrous alloy
normalizing
overaging
plain carbon steel
powder metallurgy (P/M)
precipitation hardening
precipitation heat treatment
process annealing
rolling
solution heat treatment
specific strength
spheroidizing
stainless steel
stress relief
temper designation
upper critical temperature
welding
white cast iron
wrought alloy



PROCESSING



STRUCTURE



PROPERTIES

Figure 11.29 Schematic diagram that summarizes the elements of processing, structure, and properties for steel alloys from a materials science perspective.

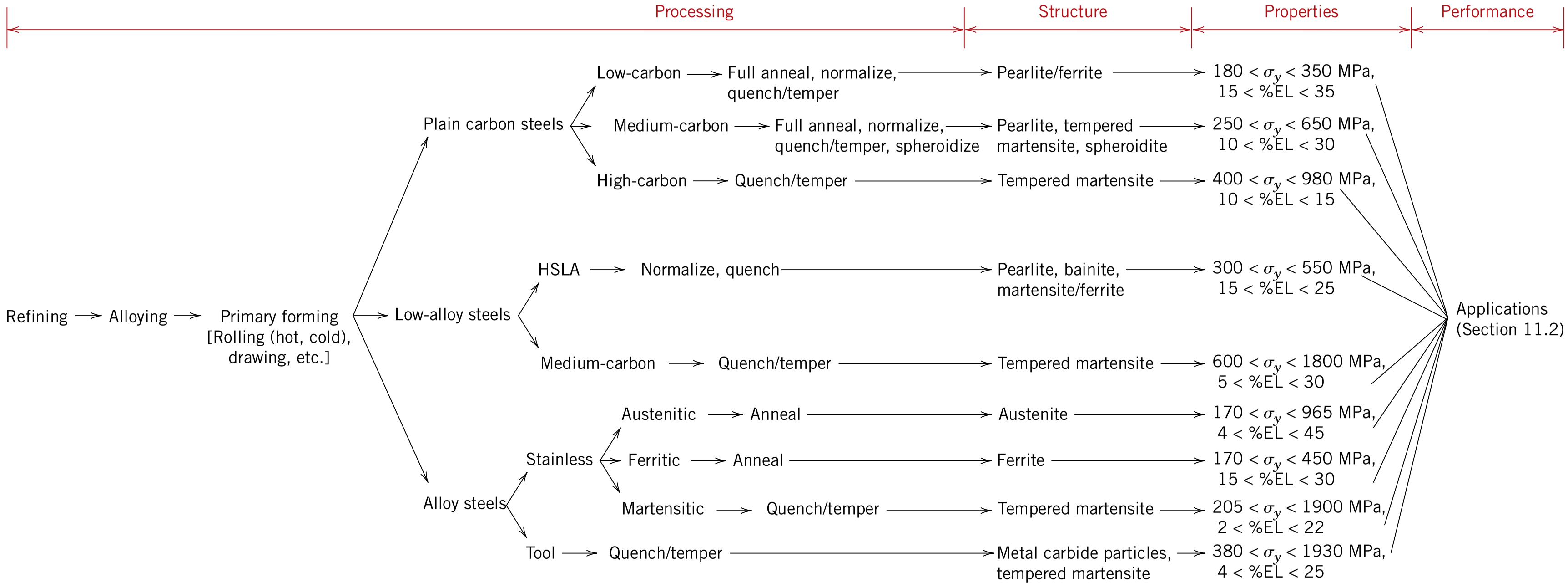


Figure 11.30 Schematic diagram that summarizes the elements of processing, structure, properties, and performance for steel alloys from a materials engineering perspective.

REFERENCES

ASM Handbook, Vol. 1, *Properties and Selection: Irons, Steels, and High-Performance Alloys,* ASM International, Materials Park, OH, 1990.

ASM Handbook, Vol. 2, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*, ASM International, Materials Park, OH, 1990.

ASM Handbook, Vol. 4, *Heat Treating*, ASM International, Materials Park, OH, 1991.

ASM Handbook, Vol. 6, *Welding, Brazing and Soldering,* ASM International, Materials Park, OH, 1993.

ASM Handbook, Vol. 14A, *Metalworking: Bulk Forming*, ASM International, Materials Park, OH, 2005.

ASM Handbook, Vol. 14B, *Metalworking: Sheet Forming,* ASM International, Materials Park, OH, 2006.

ASM Handbook, Vol. 15, *Casting,* ASM International, Materials Park, OH, 2008.

Davis, J. R. (Editor), *Cast Irons,* ASM International, Materials Park, OH, 1996.

Dieter, G. E., *Mechanical Metallurgy,* 3rd edition, McGraw-Hill, New York, 1986. Chapters 15–21 provide an excellent discussion of various metal-forming techniques.

Frick, J. (Editor), *Woldman's Engineering Alloys,* 9th edition, ASM International, Materials Park, OH, 2000.

Heat Treater's Guide: Standard Practices and Procedures for Irons and Steels, 2nd edition, ASM International, Materials Park, OH, 1995.

Henkel, D. P., and A. W. Pense, *Structures and Properties of Engineering Materials,* 5th edition, McGraw-Hill, New York, 2001.

Kalpakjian, S., and S. R. Schmid, *Manufacturing Processes for Engineering Materials,* 5th edition, Prentice Hall, Upper Saddle River, NJ, 2008.

Krauss, G., *Steels: Processing, Structure, and Performance,* ASM International, Materials Park, OH, 2005.

Metals and Alloys in the Unified Numbering System, 12th edition, Society of Automotive Engineers and American Society for Testing and Materials, Warrendale, PA, 2012.

Worldwide Guide to Equivalent Irons and Steels, 5th edition, ASM International, Materials Park, OH, 2006.

Worldwide Guide to Equivalent Nonferrous Metals and Alloys, 4th edition, ASM International, Materials Park, OH, 2001.

QUESTIONS AND PROBLEMS

⊕ *Problem available (at instructor's discretion) in* WileyPLUS

Ferrous Alloys

11.1 ⊕ **(a)** List the four classifications of steels.

(b) For each, briefly describe the properties and typical applications.

11.2 **(a)** Cite three reasons why ferrous alloys are used so extensively.

(b) Cite three characteristics of ferrous alloys that limit their use.

11.3 ⊕ What is the function of alloying elements in tool steels?

11.4 ⊕ Compute the volume percent of graphite, V_{Gr}, in a 2.5 wt% C cast iron, assuming that all the carbon exists as the graphite phase. Assume densities of 7.9 and 2.3 g/cm^3 for ferrite and graphite, respectively.

11.5 On the basis of microstructure, briefly explain why gray iron is brittle and weak in tension.

11.6 Compare gray and malleable cast irons with respect to

(a) composition and heat treatment

(b) microstructure

(c) mechanical characteristics.

11.7 Compare white and nodular cast irons with respect to

(a) composition and heat treatment

(b) microstructure

(c) mechanical characteristics.

11.8 ⊕ Is it possible to produce malleable cast iron in pieces having large cross-sectional dimensions? Why or why not?

Nonferrous Alloys

11.9 ⊕ What is the principal difference between wrought and cast alloys?

11.10 Why must rivets of a 2017 aluminum alloy be refrigerated before they are used?

11.11 What is the chief difference between heat-treatable and non-heat-treatable alloys?

11.12 Give the distinctive features, limitations, and applications of the following alloy groups: titanium alloys, refractory metals, superalloys, and noble metals.

Forming Operations

11.13 ⊕ Cite advantages and disadvantages of hot working and cold working.

11.14 **(a)** Cite advantages of forming metals by extrusion as opposed to rolling.

(b) Cite some disadvantages.

Casting

11.15 ⊕ List four situations in which casting is the preferred fabrication technique.

11.16 Compare sand, die, investment, lost-foam, and continuous-casting techniques.

Miscellaneous Techniques

11.17 If it is assumed that, for steel alloys, the average cooling rate of the heat-affected zone in the vicinity of a weld is 10°C/s, compare the microstructures and associated properties that will result for 1080 (eutectoid) and 4340 alloys in their HAZs.

11.18 Describe one problem that might exist with a steel weld that was cooled very rapidly.

Annealing Processes

11.19 In your own words, describe the following heat-treatment procedures for steels and, for each, the intended final microstructure:

(a) full annealing

(b) normalizing

(c) quenching

(d) tempering.

11.20 Cite three sources of internal residual stresses in metal components. What are two possible adverse consequences of these stresses?

11.21 Give the approximate minimum temperature at which it is possible to austenitize each of the following iron–carbon alloys during a normalizing heat treatment:

(a) 0.15 wt% C

(b) 0.50 wt% C

(c) 1.10 wt% C.

11.22 Give the approximate temperature at which it is desirable to heat each of the following iron–carbon alloys during a full anneal heat treatment:

(a) 0.20 wt% C

(b) 0.60 wt% C

(c) 0.76 wt% C

(d) 0.95 wt% C.

11.23 What is the purpose of a spheroidizing heat treatment? On what classes of alloys is it normally used?

Heat Treatment of Steels

11.24 Briefly explain the difference between *hardness* and *hardenability*.

11.25 What influence does the presence of alloying elements (other than carbon) have on the shape of a hardenability curve? Briefly explain this effect.

11.26 How would you expect a decrease in the austenite grain size to affect the hardenability of a steel alloy? Why?

11.27 Name two thermal properties of a liquid medium that influence its quenching effectiveness.

11.28 Construct radial hardness profiles for the following:

(a) A cylindrical specimen of an 8640 steel alloy of diameter 75 mm (3 in.) that has been quenched in moderately agitated oil

(b) A cylindrical specimen of a 5140 steel alloy of diameter 50 mm (2 in.) that has been quenched in moderately agitated oil

(c) A cylindrical specimen of an 8630 steel alloy of diameter 90 mm ($3\frac{1}{2}$ in.) that has been quenched in moderately agitated water

(d) A cylindrical specimen of an 8660 steel alloy of diameter 100 mm (4 in.) that has been quenched in moderately agitated water

11.29 Compare the effectiveness of quenching in moderately agitated water and oil by graphing on a single plot radial hardness profiles for cylindrical specimens of an 8640 steel of diameter 75 mm (3 in.) that have been quenched in both media.

Precipitation Hardening

11.30 Compare precipitation hardening (Section 11.9) and the hardening of steel by quenching and tempering (Sections 10.5, 10.6, and 10.8) with regard to the following:

(a) The total heat treatment procedure

(b) The microstructures that develop

(c) How the mechanical properties change during the several heat treatment stages

11.31 What is the principal difference between natural and artificial aging processes?

DESIGN PROBLEMS

Ferrous Alloys
Nonferrous Alloys

11.D1 The following is a list of metals and alloys:

Plain carbon steel
Brass
Gray cast iron
Platinum
Stainless steel
Titanium alloy
Magnesium
Zinc
Tool steel
Aluminum
Tungsten

Select from this list the one metal or alloy that is best suited for each of the following applications, and cite at least one reason for your choice:

(a) The block of an internal combustion engine

(b) Condensing heat exchanger for steam

(c) Jet engine turbofan blades

(d) Drill bit

(e) Cryogenic (i.e., very low temperature) container

(f) As a pyrotechnic (i.e., in flares and fireworks)

(g) High-temperature furnace elements to be used in oxidizing atmospheres

11.D2 A group of new materials are the metallic glasses (or amorphous metals). Write an essay about these materials in which you address the following issues:

(a) compositions of some of the common metallic glasses

(b) characteristics of these materials that make them technologically attractive

(c) characteristics that limit their use

(d) current and potential uses

(e) at least one technique used to produce metallic glasses.

11.D3 Of the following alloys, pick the one(s) that may be strengthened by heat treatment, cold work, or both: 410 stainless steel, 4340 steel, F10004 cast iron, C26000 cartridge brass, 356.0 aluminum, ZK60A magnesium, R56400 titanium, 1100 aluminum, and zinc.

11.D4 A structural member 250 mm (10 in.) long must be able to support a load of 44,400 N (10,000 lb_f) without experiencing any plastic deformation. Given the following data for brass, steel, aluminum, and titanium, rank them from least to greatest weight in accordance with these criteria.

Alloy	*Yield Strength [MPa (ksi)]*	*Density (g/cm^3)*
Brass	345 (50)	8.5
Steel	690 (100)	7.9
Aluminum	275 (40)	2.7
Titanium	480 (70)	4.5

11.D5 Discuss whether it would be advisable to hot work or cold work the following metals and alloys on the basis of melting temperature, oxidation resistance, yield strength, and degree of brittleness: platinum, molybdenum, lead, 304 stainless steel, and copper.

Heat Treatment of Steels

11.D6 A cylindrical piece of steel 38 mm ($1\frac{1}{2}$ in.) in diameter is to be quenched in moderately agitated oil. Surface and center hardnesses must be at least 50 and 40 HRC, respectively. Which of the following alloys satisfy these requirements: 1040, 5140, 4340, 4140, and 8640? Justify your choice(s).

11.D7 A cylindrical piece of steel 57 mm ($2\frac{1}{4}$ in.) in diameter is to be austenitized and quenched such that a minimum hardness of 45 HRC is to be produced throughout the entire piece. Of the alloys 8660, 8640, 8630, and 8620, which qualifies if the quenching medium is **(a)** moderately agitated water or **(b)** moderately agitated oil? Justify your choice(s).

11.D8 A cylindrical piece of steel 44 mm ($1\frac{3}{4}$ in.) in diameter is to be austenitized and quenched such that a microstructure consisting of at least 50% martensite will be produced throughout the entire piece. Of the alloys 4340, 4140, 8640, 5140, and 1040, which qualify if the quenching medium is **(a)** moderately agitated oil and **(b)** moderately agitated water? Justify your choice(s).

11.D9 A cylindrical piece of steel 50 mm (2 in.) in diameter is to be quenched in moderately agitated water. Surface and center hardnesses must be at least 50 and 40 HRC, respectively. Which of the following alloys satisfy these requirements: 1040, 5140, 4340, 4140, 8620, 8630, 8640, and 8660? Justify your choice(s).

11.D10 A cylindrical piece of 4140 steel is to be austenitized and quenched in moderately agitated oil. If the microstructure is to consist of at least 80% martensite throughout the entire piece, what is the maximum allowable diameter? Justify your answer.

11.D11 A cylindrical piece of 8660 steel is to be austenitized and quenched in moderately agitated oil. If the hardness at the surface of the piece must be at least 58 HRC, what is the maximum allowable diameter? Justify your answer.

11.D12 Is it possible to temper an oil-quenched 4140 steel cylindrical shaft 25 mm (1 in.) in diameter so as to give a minimum yield strength of 950 MPa (140,000 psi) and a minimum ductility of 17%EL? If so, specify a tempering temperature. If this is not possible, then explain why.

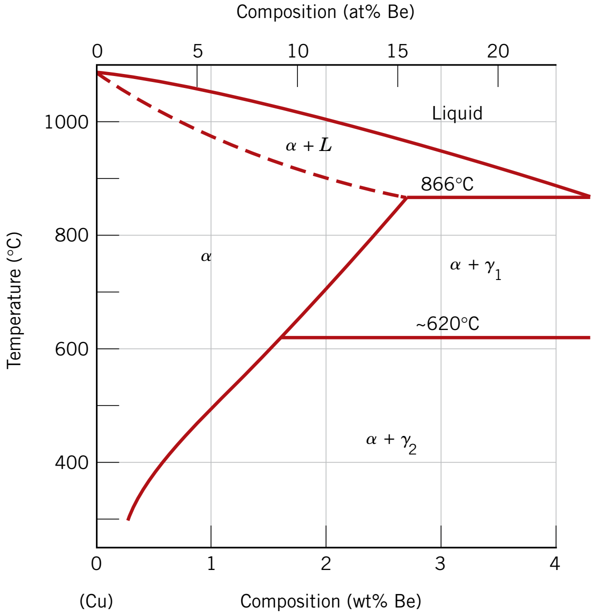


Figure 11.31 The copper-rich side of the copper–beryllium phase diagram.
[Adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 2, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

11.D13 Is it possible to temper an oil-quenched 4140 steel cylindrical shaft 50 mm (2 in.) in diameter so as to give a minimum tensile strength of 900 MPa (130,000 psi) and a minimum ductility of 20%EL? If so, specify a tempering temperature. If this is not possible, then explain why.

Precipitation Hardening

11.D14 Copper-rich copper–beryllium alloys are precipitation hardenable. After consulting the portion of the phase diagram shown in Figure 11.31, do the following:

(a) Specify the range of compositions over which these alloys may be precipitation hardened.

(b) Briefly describe the heat-treatment procedures (in terms of temperatures) that would be used to precipitation harden an alloy having a composition of your choosing yet lying within the range given for part (a).

11.D15 A solution heat-treated 2014 aluminum alloy is to be precipitation hardened to have a minimum yield strength of 345 MPa (50,000 psi) and a ductility of at least 12%EL. Specify a practical precipitation heat treatment in terms of temperature and time that would give these mechanical characteristics. Justify your answer.

11.D16 Is it possible to produce a precipitation hardened 2014 aluminum alloy having a minimum yield strength of 380 MPa (55,000 psi) and a ductility of at least 15%EL? If so, specify the precipitation heat treatment. If it is not possible, then explain why.

FUNDAMENTALS OF ENGINEERING QUESTIONS AND PROBLEMS

11.1FE Which of the following elements is the primary constituent of ferrous alloys?

(A) Copper
(B) Carbon
(C) Iron
(D) Titanium

11.2FE Which of the following microconstituents/phases is (are) typically found in a low-carbon steel?

(A) Austenite
(B) Pearlite
(C) Ferrite
(D) Both pearlite and ferrite

11.3FE Which of the following characteristics distinguishes the stainless steels from other steel types?

(A) They are more corrosion resistant.
(B) They are stronger.
(C) They are more wear resistant.
(D) They are more ductile.

11.4FE Hot working takes place at a temperature above a metal's

(A) melting temperature
(B) recrystallization temperature
(C) eutectoid temperature
(D) glass transition temperature

11.5FE Which of the following may occur during an annealing heat treatment?

(A) Stresses may be relieved.
(B) Ductility may increase.
(C) Toughness may increase.
(D) All of the above.

11.6FE Which of the following influences the hardenability of a steel?

(A) Composition of the steel
(B) Type of quenching medium
(C) Character of the quenching medium
(D) Size and shape of the specimen