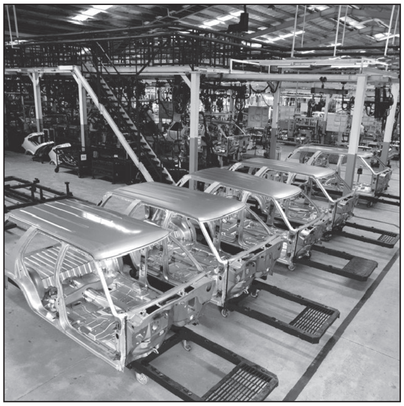
6

CHAPTER

Mechanical Properties of Metals I



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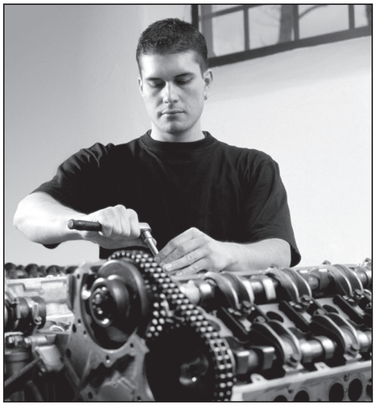

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Metals are formed into functional shapes using a wide variety of metal-forming operations under both cold and hot conditions. Perhaps one of the most important examples, revealing the use of metal-forming operations, is in manufacturing of automobile parts (both body and engine). The engine block is usually made of cast iron or aluminum alloys; the cylinder and other openings in the block are made by drilling, boring, and tapping operations; the cylinder heads are also cast of aluminum alloys; connecting rods, crankshafts, and cams are forged (sometimes cast) and are then finish ground; the body panels, including the roof, trunk lid, doors, and side panels, are stamped from steel sheets and are then spot-welded together (left figure). As the number of operations to produce a part increases, so does the cost of the part and therefore the overall product. To reduce the cost, manufacturers follow the "Near Net Shape" manufacturing concepts, in which the product is formed with the least number of operations and with the least amount of finish machining or grinding required. Automotive parts with complex and nonsymmetrical shapes such as bevel gears or universal joints are forged almost ready-to-install. ■

LEARNING OBJECTIVES

By the end of this chapter, students will be able to

1. Describe the forming operations that are used to shape metals into functional shapes. Differentiate between wrought alloy and cast products. Differentiate between hot- and cold-forming processes.
2. Explain the engineering and true definition of stress and strain.
3. Explain the differences between elastic and plastic deformation at the atomic, micro-, and macro-scales.
4. Explain the differences between normal and shearing stresses and strains.
5. Explain what a tensile test is, what type of machine is used to perform the tensile tests, and what information regarding the properties of a material can be extracted from such tests.
6. Define hardness and explain how is it measured. Describe various available hardness scales.
7. Describe the plastic deformation of a single crystal at the atomic level. Describe the concepts of slip, dislocations, and twins, and their role in plastic deformation of a single crystal.
8. Define critical slip systems in BCC, FCC, and HCP single crystals.
9. Describe Schmid's law and its application in determination of the critical resolved shear stress.
10. Describe the effect of the plastic deformation process on properties and grain structure of polycrystalline materials.
11. Explain the effect of grain size (Hall-Petch equation) and grain boundary on the plastic deformation and properties of a metal.
12. Describe various strengthening mechanisms used for metals.
13. Describe the annealing process and its impact on properties and microstructure of a cold-worked metal.
14. Describe the superplastic behavior in metals.
15. Describe what a nanocrystalline metal is and what advantages it may offer.

6.1 THE PROCESSING OF METALS AND ALLOYS

6.1.1 The Casting of Metals and Alloys

Most metals are processed by first melting the metal in a furnace that functions as a reservoir for the molten metal. Alloying elements can be added to the molten metal to produce various alloy compositions. For example, solid magnesium metal may be added to molten aluminum and, after melting, may be mechanically mixed with the aluminum to produce a homogeneous melt of an aluminum-magnesium alloy. After oxide impurities and unwanted hydrogen gas are removed from the molten Al–Mg alloy, it is cast into a mold of a direct-chill semicontinuous casting unit, as shown in Figure 4.8. Huge sheet ingots, such as those shown in Figure 4.1, are produced in this way. Other types of ingots with different cross sections are cast in a similar way; for example, extrusion ingots are cast with circular cross sections.

Ingots are then used to manufacture semifinished products such as sheet[1] and plate[2]. Sheets and plates are produced by rolling ingots into reduced thicknesses. Plates and sheets are classified as such based on their thickness; plates are thicker than sheets. Extruded shapes such as channels and structural shapes are produced from extrusion ingots, and rod and wire are manufactured from wire bar ingots. All these products that are manufactured through significant permanent/plastic deformation of the metal by hot and cold working of large ingots are called *wrought alloy products.* The effects of permanent/plastic deformation on the structure and properties of metals will be treated in Sections 6.5 and 6.6.

On a smaller scale, molten metal may be cast into a mold that is in the shape of the final product, and usually only a small amount of machining or other finishing operation is required to produce the final casting. Products made in this manner are called *cast products* and the alloys used to produce them, *casting alloys.* For example, pistons used in automobile engines are usually made by casting molten metal into a permanent steel mold. A schematic diagram of a simple permanent mold containing a casting is shown in Figure 6.1. Figure 6.2*a* shows an operator pouring metal metal into

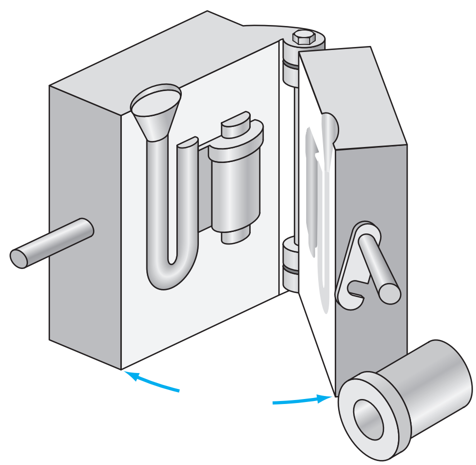
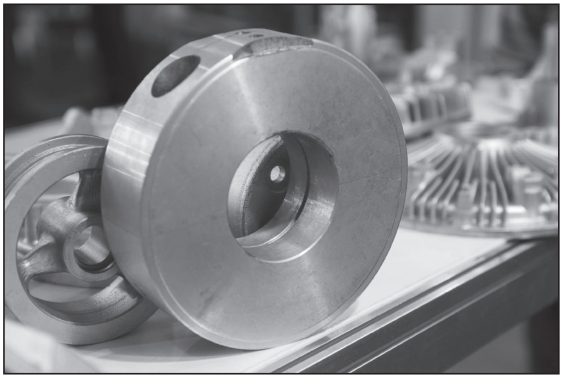


Figure 6.1
Permanent mold casting. Solidified casting with gate and metal core is shown in the left half of the mold. The completed casting is shown in front of the mold.
(Source: H. F. Taylor, M. C. Flemings, and J. Wulff, *Foundry Engineering,* Wiley, 1959, p. 58.)

[1] For this book, *sheet* is defined as a rolled product rectangular in cross section and form of thickness 0.006 to 0.249 in. (0.015 to 0.063 cm).
[2] For this book, *plate* is defined as a rolled product rectangular in cross section and form of thickness 0.250 in. (0.635 cm) or more.

(*a*)

(*b*)



(*c*)

Figure 6.2

(*a*) Permanent mold casting of aluminum alloy parts. (*b*) Castings after being removed from the mold. (*c*) Cast components finished and ready for use.

((*a*) ©Monty Rakusen/Cultura Creative/Alamy; (*b*) ©Ty Wright/Bloomberg via Getty Images; (*c*) ©DmyTo/iStock/Getty Images Plus)

a permanent mold to produce castings; Figure 6.2*b* shows the castings after they have been removed from the mold. After being trimmed, heat-treated, and machined, the finished somponent (Figure 6.2*c*) is ready for installation and use.

6.1.2 Hot and Cold Rolling of Metals and Alloys

Hot and cold rolling are commonly used methods for fabricating metals and alloys. Long lengths of metal sheet and plate with uniform cross sections can be produced by these processes.

Hot Rolling of Sheet Ingots **Hot rolling** of sheet ingots is carried out first since greater reductions in thickness can be taken with each rolling pass when the metal is hot. Before hot rolling, sheet and plate ingots are preheated to a high temperature (depending on the recrystallization temperature of the metal). However, sometimes it is possible to hot roll the ingot-slabs directly from the caster. After removal from the preheat furnace, the ingot sections are usually hot rolled in a reversing break-down rolling mill (Fig. 6.3).

Hot rolling is continued until the temperature of the slab drops so low that continued rolling becomes too difficult. The slab is then reheated and hot rolling is continued, usually until the hot-rolled strip is thin enough to be wound into a coil. In most large-scale operations, hot rolling of the slab is carried out by using a series of four-high rolling mills alone and in series, as shown for the hot rolling of steel strip in Figure 6.4.

Cold Rolling of Metal Sheet[3] After hot rolling, which may also include some **cold rolling,** the coils of metal are usually given a reheating treatment called **annealing** to soften the metal to remove any cold work introduced during the hot-rolling operation. Cold rolling, which normally is done at room temperature, is again usually carried out with four-high rolling mills either alone or in series (Fig. 6.5). Figure 6.6 shows some sheet steel being cold-rolled on an industrial rolling mill.

The **percent cold reduction** due to a rolling process of a plate or sheet of metal can be calculated as follows:

$$\%\text{ cold reduction} = \frac{\text{initial metal thickness} - \text{final metal thickness}}{\text{initial metal thickness}} \times 100\% \qquad \textbf{(6.1)}$$

EXAMPLE PROBLEM 6.1

Calculate the percent cold reduction in cold rolling an aluminum sheet alloy from 0.120 to 0.040 in.

■ **Solution**

$$\begin{aligned}\%\text{ cold reduction} &= \frac{\text{initial thickness} - \text{final thickness}}{\text{initial thickness}} \times 100\% \\ &= \frac{0.120\text{ in.} - 0.040\text{ in.}}{0.120\text{ in.}} \times 100\% = \frac{0.080\text{ in.}}{0.120\text{ in.}} \times 100\% \\ &= 66.7\%\end{aligned}$$

[3] Cold rolling of metals is usually carried out below the recrystallization temperature of the metal and results in the strain hardening of the metal.

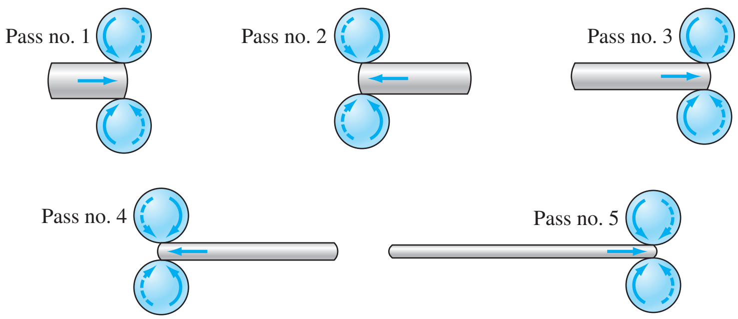


Figure 6.3
Diagrammatic representation of the sequence of hot-rolling operations involved in reducing an ingot to a slab on a reversing two-high mill.
(Source: H. E. McGannon (ed.), *The Making, Shaping, and Treating of Steel,* 9th ed., United States Steel, 1971, p. 677.)

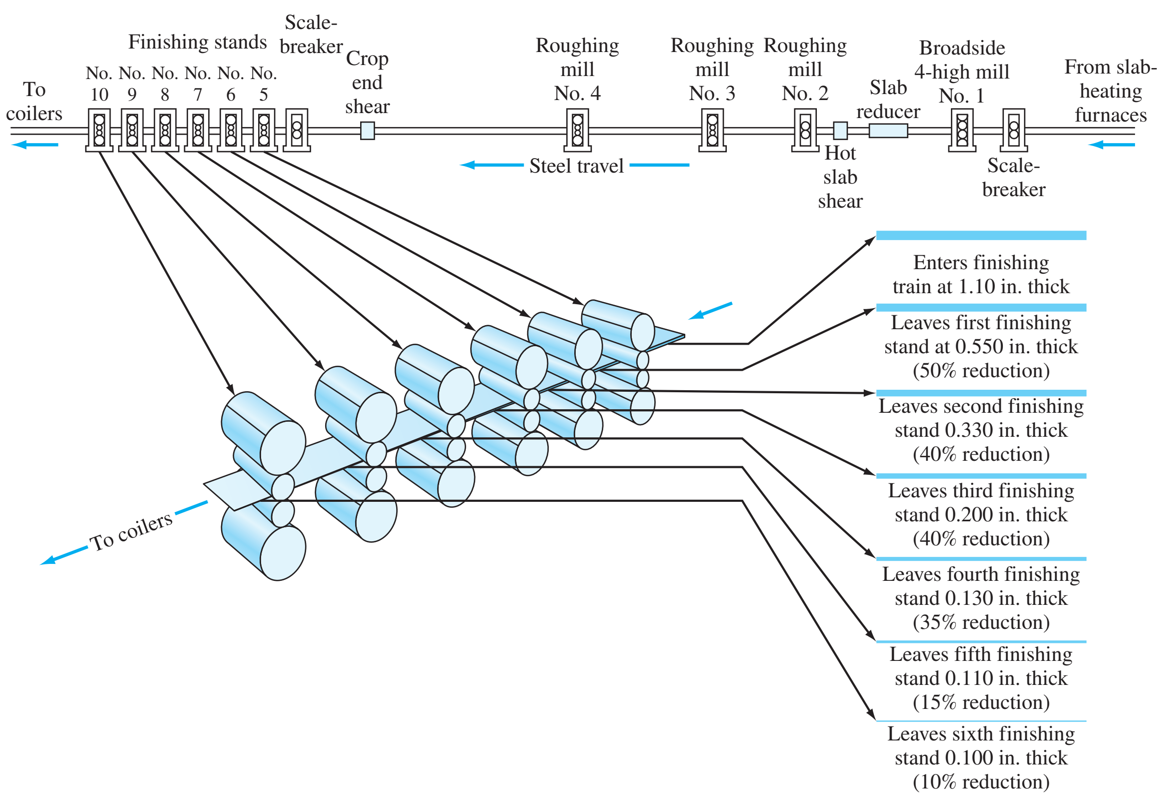


Figure 6.4
Typical reductions per pass in the finishing stands of a hot-strip mill equipped with four roughing stands and six finishing stands. Drawing is not to scale.
(Source: H. E. McGannon (ed.), *The Making, Shaping, and Treating of Steel,* 9th ed., United States Steel, 1971, p. 937.)

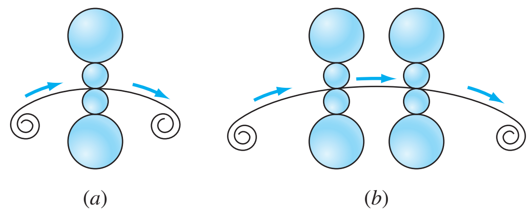


Figure 6.5
Schematic drawing illustrating the metal path during the cold rolling of metal sheet by four-high rolling mills: (*a*) single mill and (*b*) two mills in series.

Figure 6.6
Cold rolling sheet steel. Mills of this type are used for cold rolling steel strip, tin plate, and nonferrous metals.
(©Sputnik/Alamy)

EXAMPLE PROBLEM 6.2

A sheet of a 70% Cu–30% Zn alloy is cold-rolled 20% to a thickness of 3.00 mm. The sheet is then further cold-rolled to 2.00 mm. What is the total percent cold work?

■ **Solution**

We first determine the starting thickness of the sheet by considering the first cold reduction of 20%. Let x equal the starting thickness of the sheet. Then,

$$\frac{x - 3.00\text{ mm}}{x} = 0.20$$

or

$$x - 3.00 \text{ mm} = 0.20\,x$$
$$x = 3.75 \text{ mm}$$

We can now determine the *total* percent cold work from the starting thickness to the finished thickness from the relationship

$$\frac{3.75 \text{ mm} - 2.00 \text{ mm}}{3.75 \text{ mm}} = \frac{1.75 \text{ mm}}{3.75 \text{ mm}} = 0.466 \text{ or } 46.6\%$$

6.1.3 Extrusion of Metals and Alloys

Extrusion is a plastic-forming process in which a material under high pressure is reduced in cross section by forcing it through an opening in a die (Fig. 6.7). For most metals, the extrusion process is used to produce cylindrical bars or hollow tubes. For the more readily extrudable metals, such as aluminum and copper and some of their alloys, shapes with irregular cross sections are also commonly produced. Most metals are extruded hot since the deformation resistance of the metal is lower than if it is extruded cold. During extrusion, the metal of a billet in the container of an extrusion press is forced by a ram through a die so that the metal is continuously deformed into a long length of metal with a uniform desired cross section.

The two main types of extrusion processes are *direct extrusion* and *indirect extrusion*. In direct extrusion, the metal billet is placed in a container of an extrusion press and forced directly through the die by the ram (Fig. 6.7*a*). In indirect extrusion, a hollow ram holds the die, with the other end of the container of the extrusion press being closed by a plate (Fig. 6.7*b*). The frictional forces and power requirements for indirect extrusion are lower than those for direct extrusion. However, the loads that can be applied by using a hollow ram in the indirect process are more limited than those that can be used for direct extrusion.

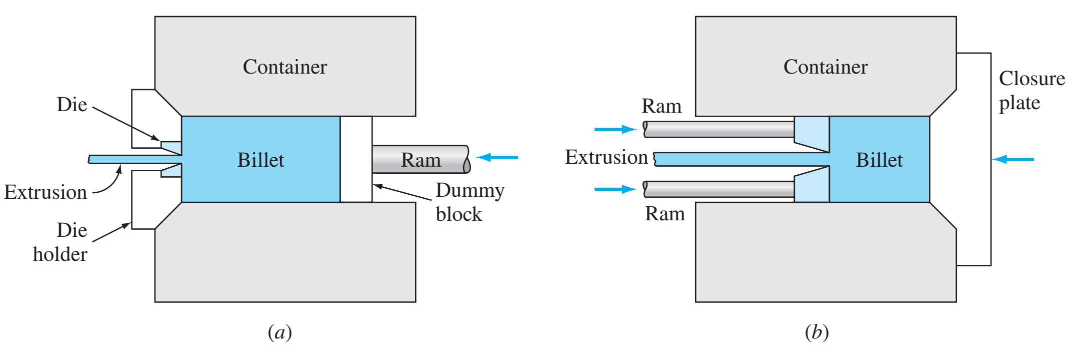


Figure 6.7
Two basic types of extrusion processes for metals: (*a*) direct and (*b*) indirect.
(Source: G. Dieter, *Mechanical Metallurgy,* 2d ed., McGraw-Hill, 1976, p. 639.)

Animation

The extrusion process is used primarily for producing bar shapes, tube, and irregular shapes of the lower-melting nonferrous metals such as aluminum and copper and their alloys. However, with the development of powerful extrusion presses and improved lubricants such as glass, some carbon and stainless steels can also be hot-extruded.

6.1.4 Forging

Forging is another primary method for working metals into useful shapes. In the forging process the metal is hammered or pressed into a desired shape. Most forging operations are carried out with the metal in the hot condition, although in some cases the metal may be forged cold. There are two major types of forging methods: *hammer* and *press forging*. In hammer forging, a drop hammer repeatedly exerts a striking force against the surface of the metal. In press forging, the metal is subjected to a slowly increasing compressive force (Fig. 6.8).

Forging processes can also be classified as *open-die forging* or *closed-die forging*. Open-die forging is carried out between two flat dies or dies with very simple shapes such as vees or semicircular cavities (Fig. 6.9) and is particularly useful for producing large parts such as steel shafts for electric steam turbines and generators. In closed-die forging, the metal to be forged is placed between two dies that have the upper

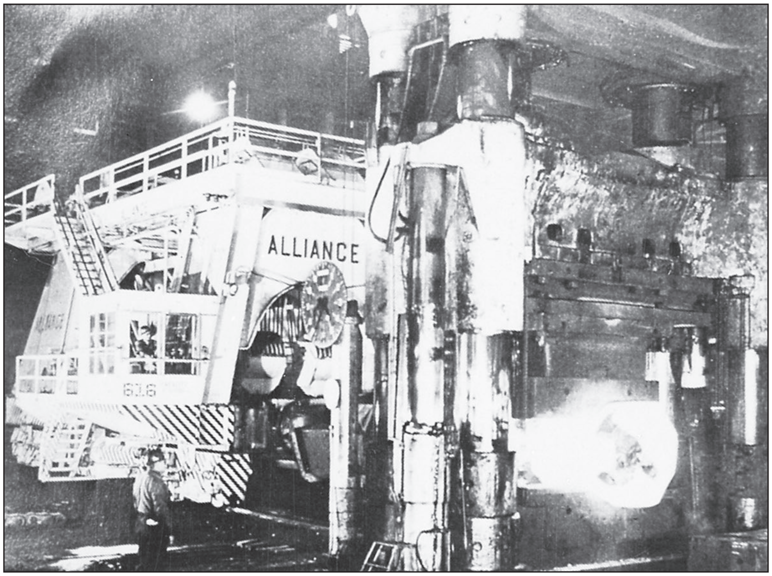


Figure 6.8
Heavy-duty manipulator holding an ingot in position while a 10,000-ton press squeezes the hot steel into the rough shape of the finished product.
(Courtesy of United States Steel Corporation)

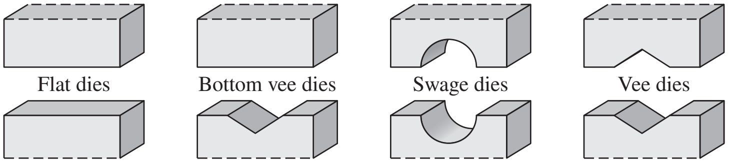


Figure 6.9
Basic shapes for open-die forging.
(Source: H. E. McGannon (ed.), *The Making, Shaping, and Treating of Steel,* 9th ed., United States Steel, 1971, p. 1045.)

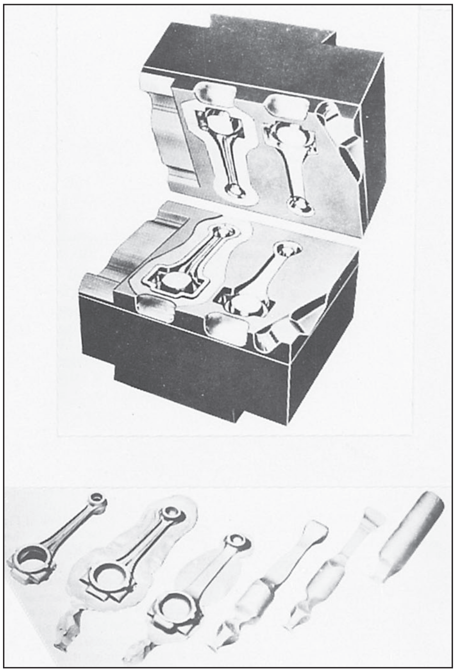


Figure 6.10
A set of closed forging dies used to produce an automobile connecting rod.
(Courtesy of the Forging Industry Association.)

and lower impressions of the desired shape of the forging. Closed-die forging can be carried out by using a single pair of dies or multiple-impression dies. An example of a closed-die forging in which multiple-impression dies are used is the automobile engine connecting rod (Fig. 6.10).

In general, the forging process is used for producing irregular shapes that require working to improve the structure of the metal by reducing porosity and refining the internal structure. For example, a wrench that has been forged will be tougher and less likely to break than one that was simply cast into shape. Forging is also sometimes used to break down the as-cast ingot structure of some highly alloyed metals (e.g., some tool steels) so that the metal is made more homogeneous and less likely to crack during subsequent working.

6.1.5 Other Metal-Forming Processes

There are many types of secondary metal-forming processes whose descriptions are beyond the scope of this book. However, two of these processes, *wire drawing* and *deep drawing* of sheet metal, will be briefly described.

Wire drawing is an important metal-forming process. Starting rod or wire stock is drawn through one or more tapered wire-drawing dies (Fig. 6.11). For steel wire drawing, a tungsten carbide inner "nib" is inserted inside a steel casing. The hard carbide provides a wear-resistant surface for the reduction of the steel wire. Special precautions must be taken to make sure the surface of the stock to be drawn into wire is clean and properly lubricated. Intermediate softening heat treatments are sometimes necessary when the drawn wire work hardens during processing. The procedures used vary considerably, depending on the metal or alloy being drawn and the final diameter and temper desired.

EXAMPLE PROBLEM 6.3

The **percent cold reduction** due to a drawing process to reduce the diameter of a wire or a rod of metal can be calculated as follows:

$$\%\text{ cold reduction} = \frac{\text{initial cross\_sectional area} - \text{final cross\_sectional area}}{\text{initial cross\_sectional area}} \times 100\% \qquad \textbf{(6.2)}$$

Calculate the percent cold reduction when an annealed copper wire is cold-drawn from a diameter of 1.27 mm (0.050 in.) to a diameter of 0.813 mm (0.032 in.).

■ **Solution**

$$\begin{aligned}\%\text{ cold reduction} &= \frac{\text{change in cross-sectional area}}{\text{original area}} \times 100\% \qquad \textbf{(6.2)}\\ &= \frac{(\pi/4)(1.27\text{ mm})^2 - (\pi/4)(0.813\text{ mm})^2}{(\pi/4)(1.27\text{ mm})^2} \times 100\%\\ &= \left[1 - \frac{(0.813)^2}{(1.27)^2}\right](100\%)\\ &= (1 - 0.41)(100\%) = 59\% \blacktriangleleft\end{aligned}$$

Deep drawing is another metal-forming process and is used for shaping flat sheets of metal into cup-shaped articles. A metal blank is placed over a shaped die and then is pressed into the die with a punch (Fig. 6.12). Usually a hold-down device is used to allow the metal to be pressed smoothly into the die to prevent wrinkling of the metal.

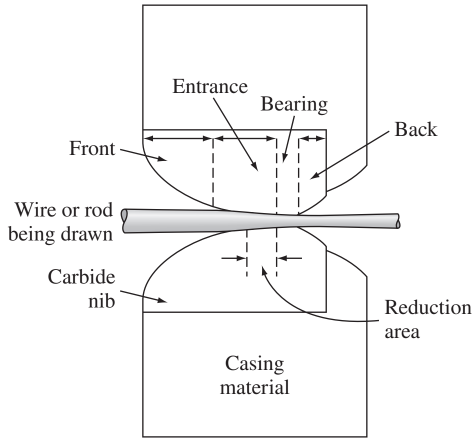


Figure 6.11
Section through a wire-drawing die.
(Source: "Wire and Rods, Alloy Steel," *Steel Products Manual,* American Iron and Steel Institute, 1975.)

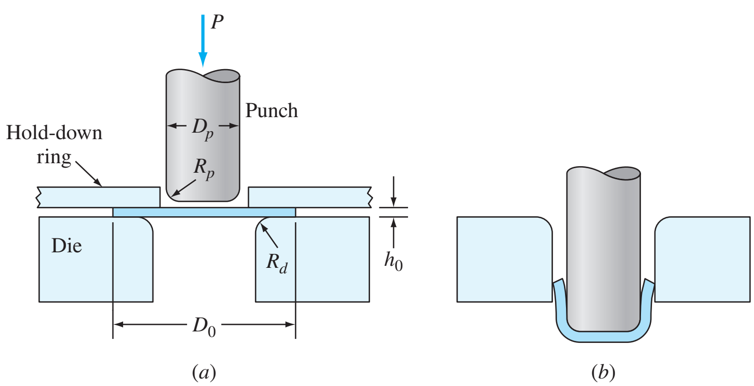


Figure 6.12
Deep drawing of a cylindrical cup (*a*) before drawing and (*b*) after drawing.
(Source: G. Dieter, *Mechanical Metallurgy,* 2d ed., McGraw-Hill, 1976, p. 688.)

6.2 STRESS AND STRAIN IN METALS

In the first section of this chapter, we briefly examined most of the principal methods by which metals are processed into semifinished wrought and cast products. Let us now investigate how the mechanical properties of strength and ductility are evaluated for engineering applications.

6.2.1 Elastic and Plastic Deformation

When a piece of metal is subjected to any type of a force, such as a uniaxial tensile force, deformation of the metal occurs. If the metal recovers and returns to its original dimensions when the force is removed, the metal is said to have undergone **elastic or recoverable deformation.** The amount of elastic or recoverable deformation a metal can undergo is small. The reason is that during elastic deformation the metal atoms are distorted in shape and slightly displaced from their original positions but not to the extent that any bonds are broken or any atoms take up new positions. Thus, when the force on a metal that has been elastically deformed is removed, the metal atoms return to their original shapes and positions, and the metal recovers its original shape. If the metal is deformed to such an extent that it cannot fully recover its original dimensions, it is said to have undergone **plastic or permanent deformation**. During plastic deformation, the bonds between metal atoms are broken, and atoms are *permanently* displaced from their original positions and take up new positions. The ability of some metals to be extensively plastically deformed without fracture is one of the most useful engineering properties of metals. For example, the extensive plastic deformability of steel enables automobile parts such as fenders, hoods, and doors to be stamped out mechanically without the metal fracturing (refer to the chapter-opening discussion).

Deformation in metals and other materials, elastic or plastic, is produced as a result of the action of forces or loads. These loads may be applied in the form of a tensile force, compressive force, shear force, torsion, or bending. Such loads produce a variety of stresses in metals, including tensile, compressive, and shear stresses. These stresses, in turn, produce strains and subsequently deformations. In the next section, we define various types of stresses and strains and how to determine them.

6.2.2 Engineering Stress and Engineering Strain

Engineering Stress Let us consider a cylindrical rod of length l_0 and cross-sectional area A_0 subjected to a uniaxial tensile force F, as shown in Figure 6.13. By definition, the **engineering stress σ** on the bar is equal to the average uniaxial tensile force F on the bar divided by the *original* cross-sectional area A_0 of the bar. Because F is normal (perpendicular) to the area, this stress is also called the *normal* stress. Thus,

$$\text{Engineering stress } \sigma \ (\textit{normal stress}) = \frac{F \text{ (average uniaxial tensile force)}}{A_0 \text{ (original cross-sectional area)}} \qquad \textbf{(6.3)}$$

The units for engineering stress are:

U.S. customary: pounds force per square inch ($lb_f/in.^2$, or psi);
lb_f = pounds force
SI: newtons per square meter (N/m^2) or pascals (Pa), where 1 N/m^2 = 1 Pa

The conversion factors for psi to pascals are

$$1 \text{ psi} = 6.89 \times 10^3 \text{ Pa}$$
$$10^6 \text{ Pa} = 1 \text{ megapascal} = 1 \text{ MPa}$$
$$1000 \text{ psi} = 1 \text{ ksi} = 6.89 \text{ MPa}$$

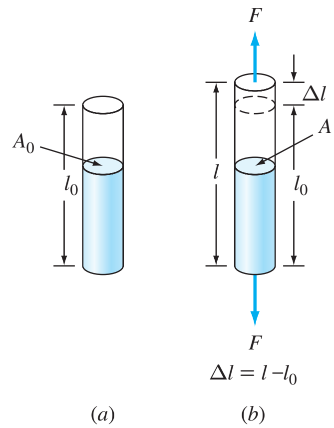


Figure 6.13
Elongation of a cylindrical metal rod subjected to a uniaxial tensile force *F*. (*a*) The rod with no force on it; and (*b*) the rod subjected to a uniaxial tensile force *F*, which elongates the rod from length l_0 to *l*.

EXAMPLE PROBLEM 6.4

A 0.500-in.-diameter aluminum bar is subjected to a tensile force of 2500 lb_f. Calculate the normal engineering stress in pounds per square inch (psi) on the bar.

■ **Solution**

$$\sigma = \frac{\text{force}}{\text{original cross-sectional area}} = \frac{F}{A_0}$$

$$= \frac{2500\ \text{lb}_f}{(\pi/4)(0.500\ \text{in.})^2} = 12{,}700\ \text{lb}_f/\text{in.}^2 \blacktriangleleft$$

EXAMPLE PROBLEM 6.5

A 2500 kg mass is hanging from a 1.25-cm-diameter bar. Calculate the normal engineering stress on the bar in megapascals (MPa).

■ **Solution**

The load on the bar is calculated based on the gravity pull of the 2500 kg mass. In SI units, the force on the bar is equal to the mass of the load times the acceleration of gravity ($g = 9.81$ m/s^2), or

$$F = mg = (2500\ \text{kg})(9.81\ \text{m/s}^2) = 24{,}500\ \text{N}$$

The diameter d of the bar = 1.25 cm = 0.0125 m. Thus, the engineering stress on the bar is

$$\sigma = \frac{F}{A_0} = \frac{F}{(\pi/4)(d^2)} = \frac{24{,}500 \text{ N}}{(\pi/4)(0.0125 \text{ m})^2}$$
$$= (2.00 \times 10^8 \text{ Pa})\left(\frac{1 \text{ MPa}}{10^6 \text{ Pa}}\right) = 200 \text{ MPa} \blacktriangleleft$$

Engineering Strain When a uniaxial tensile force is applied to a rod, such as that shown in Figure 6.13, it causes the rod to be elongated in the direction of the force (or perpendicular to the cross section). Such a displacement over the full length of the bar is called *normal engineering strain.* By definition, **engineering strain,** which is caused by the action of a uniaxial tensile force on a metal sample, is the ratio of the change in length of the sample in the direction of the force divided by the original length of the sample considered. Thus, the normal engineering strain for the metal bar shown in Figure 6.13 (or for a similar-type metal sample) is

$$\text{Engineering strain } \epsilon \text{ (\textit{normal strain})} = \frac{l - l_0}{l_0} = \frac{\Delta l \text{ (change in length of sample)}}{l_0 \text{ (original length of sample)}} \quad \textbf{(6.4)}$$

where l_0 = original length of sample and l = new length of sample after being extended by a uniaxial tensile force. In most cases, engineering strain is determined by using a small length, usually 2 in., called the *gage length,* within a much longer, for example, 8 in., sample (see Example Problem 6.6).

The *units for engineering strain* ϵ are:

U.S. customary: inches per inch (in./in.)
SI: meters per meter (m/m)

Thus, engineering strain has *dimensionless units.* In industrial practice, it is common to convert engineering strain into *percent strain:*

$$\% \text{ engineering strain} = \text{engineering strain} \times 100\%$$

EXAMPLE PROBLEM 6.6

A sample of commercially pure aluminum 0.500 in. wide, 0.040 in. thick, and 8 in. long that has gage markings 2.00 in. apart in the middle of the sample is strained so that the gage markings are 2.65 in. apart (Fig. 6.14). Calculate the normal engineering strain and the percent engineering strain that the sample undergoes.

■ **Solution**

$$\text{Engineering strian } \epsilon = \frac{l - l_0}{l_0} = \frac{2.65 \text{ in.} - 2.00 \text{ in.}}{2.00 \text{ in.}} = \frac{0.65 \text{ in.}}{2.00 \text{ in.}} = 0.325 \blacktriangleleft$$
$$\% \text{ elongation} = 0.325 \times 100\% = 32.5\% \blacktriangleleft$$

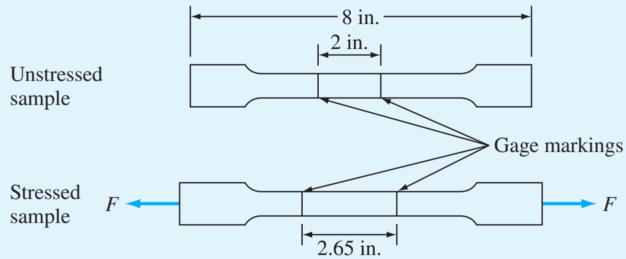


Figure 6.14
Flat tensile specimen before and after testing.

6.2.3 Poisson's Ratio

A longitudinal elastic deformation of a metal produces an accompanying lateral dimensional change. As shown in Figure 6.15*b*, a tensile stress σ_z produces a normal tensile strain $+\epsilon_z$ and lateral normal compressive strains of $-\epsilon_x$ and $-\epsilon_y$. For isotropic behavior,[4] ϵ_x and ϵ_y are equal. The ratio is called *Poisson's ratio*. For ideal materials,

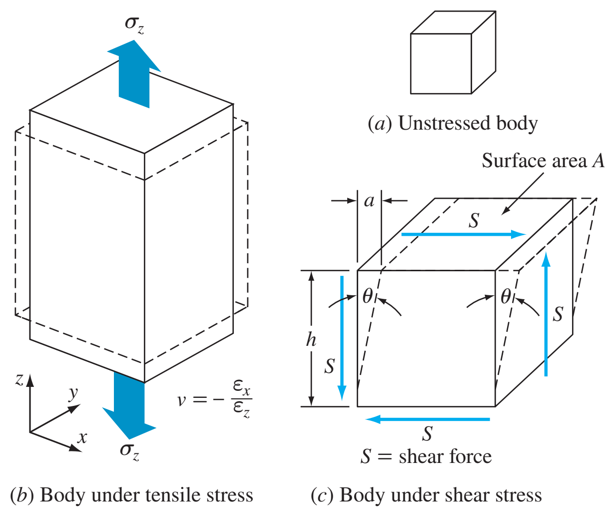


Figure 6.15
(*a*) Unstressed cubic body. (*b*) Cubic body subjected to tensile stress. The ratio of the elastic contraction perpendicular to the extension is designated Poisson's ratio *v*. (*c*) Cubic body subjected to pure shear forces *S* acting over surface areas *A*. The shear stress τ acting on the body is equal to *S/A*.

[4] *Isotropic:* exhibiting properties with the same values when measured along axes in all directions.

Table 6.1 Typical room-temperature values of elastic constants for isotropic materials

Material	Modulus of Elasticity, 10^6 psi (GPa)	Shear Modulus, 10^6 psi (GPa)	Poisson's Ratio
Aluminum alloys	10.5 (72.4)	4.0 (27.5)	0.31
Copper	16.0 (110)	6.0 (41.4)	0.33
Steel (plain carbon and low-alloy)	29.0 (200)	11.0 (75.8)	0.33
Stainless steel (18-8)	28.0 (193)	9.5 (65.6)	0.28
Titanium	17.0 (117)	6.5 (44.8)	0.31
Tungsten	58.0 (400)	22.8 (157)	0.27

(Source: G. Dieter, *Mechanical Metallurgy,* 3rd ed., McGraw-Hill, 1986.)

$v = 0.5$. However, for real materials, Poisson's ratio typically ranges from 0.25 to 0.4, with an average of about 0.3. Table 6.1 lists v values for some metals and alloys.

$$v = -\frac{\epsilon \text{ (lateral)}}{\epsilon \text{ (longitudinal)}} = -\frac{\epsilon_x}{\epsilon_z} = -\frac{\epsilon_y}{\epsilon_z} \tag{6.5}$$

6.2.4 Shear Stress and Shear Strain

Until now, we have discussed the elastic and plastic deformation of metals and alloys under uniaxial tensile stresses producing normal stresses and strains. Another important method by which a metal can be deformed is under the action of a **shear stress.** The action of a simple shear stress couple (shear stresses act in pairs) on a cubic body is shown in Figure 6.15*c*, where a shearing force S acts over an area A. The shear stress τ is related to the shear force S by

$$\tau \text{ (shear stress)} = \frac{S \text{ (shear force)}}{A \text{ (area over which shear force acts)}} \tag{6.6}$$

The units for shear stress are the same as for uniaxial normal tensile stress:

U.S. customary: pounds force per square inch ($lb_f/in.^2$, or psi)
SI: newtons per square meter (N/m^2) or pascals (Pa)

The **shear strain γ** is defined in terms of the amount of the shear displacement a in Figure 6.15*c* divided by the distance h over which the shear acts, or

$$\gamma = \frac{a}{h} = \tan\theta \tag{6.7}$$

For pure elastic shear, the proportionality between shear and stress is

$$\tau = G\gamma \tag{6.8}$$

where G is the elastic modulus.

We can generalize that normal stresses and strains result in changes in length and volume of the metal while shearing stresses and strains result in changes in the shape of the metal (compare Figures 6.13 and 6.15). We will be concerned with shear stresses when we discuss the plastic deformation of metals in Section 6.5.

6.3 THE TENSILE TEST AND THE ENGINEERING STRESS-STRAIN DIAGRAM

The *tensile test* is used to evaluate the strength and stiffness of metals and alloys among other properties. In this test, a metal sample is pulled to failure in a relatively short time at a constant rate. Figure 6.16 is a picture of a modern tensile testing machine, and Figure 6.17 illustrates schematically how the sample is tested in tension.

The force (load) on the specimen being tested is measured by the load cell, while the strain is obtained from the extensometer attached to the specimen (Fig. 6.18), and the data is collected in a computer-controlled software package.

Figure 6.16
Modern tensile testing machine. The force (load) on the specimen is measured by the load cell while the strain is measured by the clip-on extensometer. The data is collected and analyzed by computer-controlled software.
(Courtesy of the Instron® Corporation)

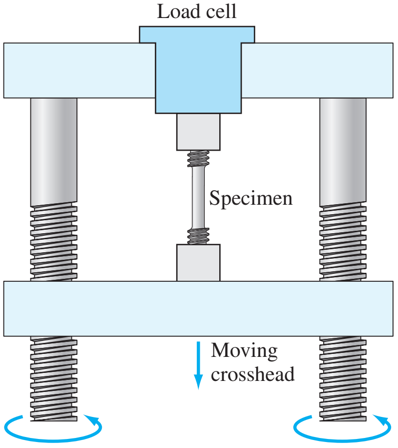


Figure 6.17
Schematic illustration showing how the tensile machine of Figure 6.16 operates. Note, however, that the crosshead of the machine in Figure 6.16 moves up and down.
(Source: H. W. Hayden, W. G. Moffatt and J. Wulff, *The Structure and Properties of Materials,* vol. III, Mechanical Behavior, Wiley, 1965, Fig. 1.1, p. 2.)

The types of samples used for the tensile test vary considerably. For metals with a thick cross section such as plate, a 0.50-in.-diameter round specimen is commonly used (Fig. 6.19*a*). For metal with thinner cross sections such as sheet, a flat specimen is used (Fig. 6.19*b*). A 2-in. gage length within the specimen is the most commonly used gage length for tensile tests.

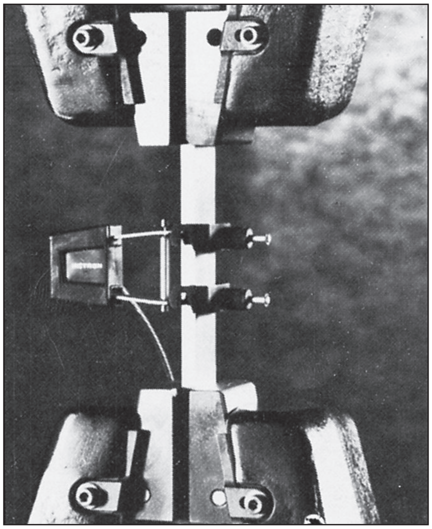


Figure 6.18
Close-up of the tensile machine extensometer that measures the strain that the sample undergoes during the tensile test. The extensometer is attached to the sample by small spring clamps.
(Courtesy of the Instron® Corporation)

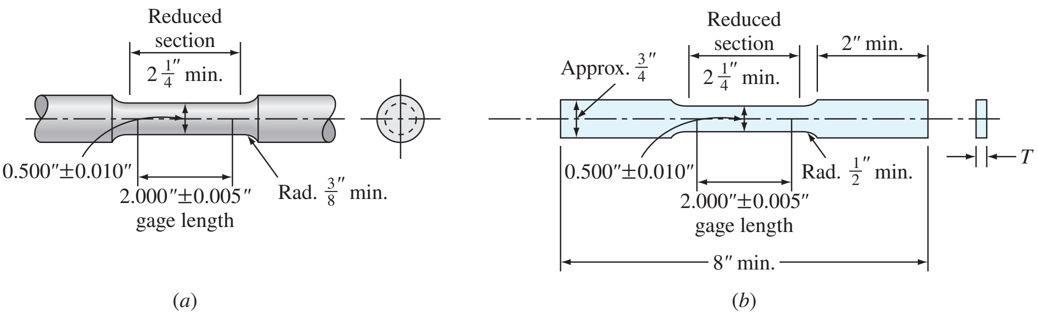


Figure 6.19
Examples of the geometrical shape of commonly used tension test specimens. (*a*) Standard round tension test specimen with 2-in. gage length. (*b*) Standard rectangular tension test specimen with 2-in. gage length.
(Source: H. E. McGannon (ed.), *The Making, Shaping, and Treating of Steel,* 9th ed., United States Steel, 1971, p. 1220.)

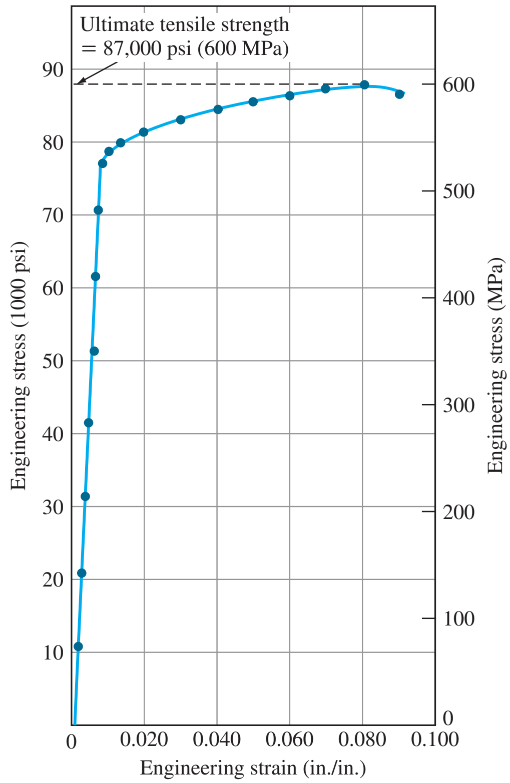


Figure 6.20
Normal engineering stress-strain diagram for a high-strength aluminum alloy (7075-T6). The specimens for the diagram were taken from $\frac{5}{8}$-in. plate and had a 0.50-in. diameter with a 2-in. gage length.
(Source: Aluminum Company of America.)

The force data obtained from the chart paper for the tensile test can be converted to normal engineering stress data, and a plot of normal engineering stress versus normal engineering strain can be constructed. Figure 6.20 shows an **engineering stress-strain diagram** for a high-strength aluminum alloy.

6.3.1 Mechanical Property Data Obtained from the Tensile Test and the Engineering Stress-Strain Diagram

The mechanical properties of metals and alloys that are of engineering importance for structural design and can be obtained from the engineering tensile test are:

1. Modulus of elasticity
2. Yield strength at 0.2% offset
3. Ultimate tensile strength

4. Percent elongation at fracture
5. Percent reduction in area at fracture
6. Modulus of resilience
7. Toughness (static)

Modulus of Elasticity In the first part of the tensile test, the metal is deformed elastically. That is, if the load on the specimen is released, the specimen will return to its original length. For metals, the maximum elastic deformation is small and usually less than 0.5% (0.005). In general, metals and alloys show a linear relationship between stress and strain in the elastic region of the engineering stress-strain diagram, which is described by Hooke's law:[5]

$$\sigma \text{ (stress)} = E\epsilon \text{ (strain)} \qquad \textbf{(6.9)}$$

or

$$E = \frac{\sigma \text{ (stress)}}{\epsilon \text{ (strain)}} \text{ (units of psi or Pa)}$$

where E is the **modulus of elasticity,** or *Young's modulus.*[6]

The modulus of elasticity is a measure of stiffness or rigidity (resistance to elastic deformation) of the metal and is related to the bonding strength between atoms in a metal or alloy. Table 6.1 lists the elastic moduli for some common metals. Metals with high elastic moduli are relatively stiff and do not undergo elastic deformation easily. Steels, for example, have high elastic moduli values of 30×10^6 psi (207 GPa),[7] whereas aluminum alloys have lower elastic moduli of about 10 to 11×10^6 psi (69 to 76 GPa). Note that in the elastic region of the stress-strain diagram, the modulus does not change with increasing stress.

Yield Strength The **yield strength** (YS or σ_y) is a very important value for use in engineering structural design since it is the stress at which a metal or alloy shows significant plastic deformation. Because there is no definite point on the stress-strain curve where elastic strain ends and plastic strain begins, the yield strength is chosen to be that stress at which a specific amount of strain is observed. For American engineering structural design, the yield strength is chosen as the value of stress when 0.2% plastic strain has taken place, as indicated on the engineering stress-strain diagram of Figure 6.21.

The 0.2% yield strength, also called the *0.2% offset yield strength,* is determined from the engineering stress-strain diagram, as shown in Figure 6.21. First, a line is drawn parallel to the elastic (linear) part of the stress-strain plot at 0.002 in./in. (m/m) strain, as indicated on Figure 6.21. Then at the point where this line intersects the upper part of the stress-strain curve, a horizontal line is drawn to the stress axis. The 0.2% offset yield strength is the stress where the horizontal line intersects the stress axis, and in the case of the stress-strain curve of Figure 6.21, the yield strength is 78,000 psi. It should be pointed out that the 0.2% offset yield strength is arbitrarily chosen, and thus the yield

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[5] Robert Hooke (1635–1703). English physicist who studied the elastic behavior of solids.
[6] Thomas Young (1773–1829). English physicist.
[7] SI prefix G = giga = 10^9.

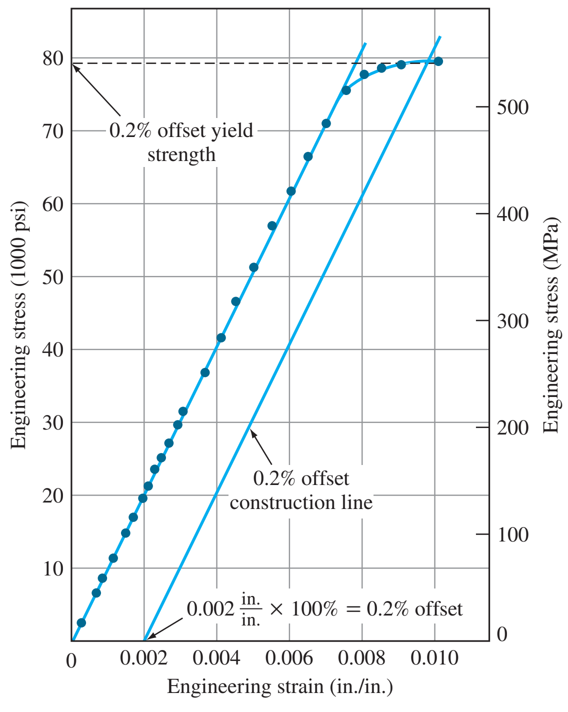


Figure 6.21
Linear part of engineering stress-strain diagram of Figure 6.20 expanded on the strain axis to make a more accurate determination of the 0.2% offset yield strength.
(Source: Aluminum Company of America.)

strength could have been chosen at any other small amount of permanent deformation. For example, a 0.1% offset yield strength is commonly used in the United Kingdom.

Ultimate Tensile Strength The **ultimate tensile strength** (UTS or σ_u) is the maximum strength reached in the engineering stress-strain curve. When one wishes to know which metals are stronger, it is generally the ultimate tensile strengths that are compared. For ductile metals, the specimen develops a localized decrease in cross-sectional area around the UTS point (commonly called *necking*). Fig. 6.22 shows the end stages of the necking process. Once the necking process begins, the engineering stress-strain curve will begin to dip down until fracture occurs. The dip in the engineering stress-strain curve is a result of the actual reduction in cross-sectional area of the specimen producing large stresses at the same load, while the engineering stress is determined by using the *original* cross-sectional area of the specimen. In other words, the stress in the specimen continues to increase up to the stress at fracture. It is only because we use the original cross-sectional area to determine engineering stress that the stress on the engineering stress-strain diagram decreases at the latter part of the test. The more ductile a metal is, the more the specimen will neck before fracture, and

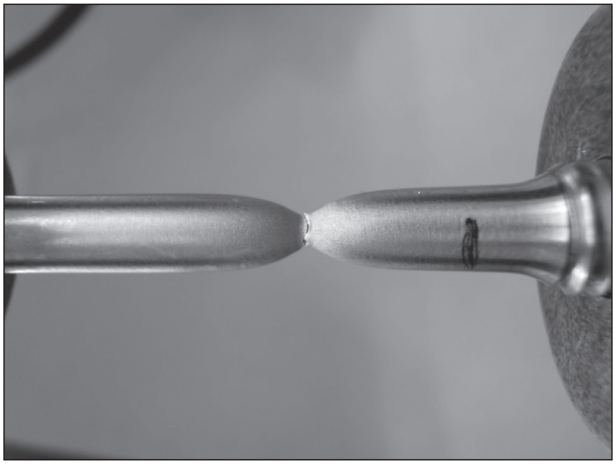


Figure 6.22
Necking in a stainless steel round specimen. The specimen was originally uniformly cylindrical. After being subjected to uniaxial tension forces, the specimen decreased in cross section, or "necked" in the middle prior to fracture.
(©G2MT Laboratories)

hence the more the decrease in the stress on the stress-strain curve beyond the maximum stress. For the high-strength aluminum alloy whose stress-strain curve is shown in Figure 6.20, there is only a small decrease in stress beyond the maximum stress because this material has relatively low ductility.

The ultimate tensile strength of a metal is determined by drawing a horizontal line from the maximum point on the stress-strain curve to the stress axis. The stress where this line intersects the stress axis is called the *ultimate tensile strength,* or sometimes just the *tensile strength.* For the aluminum alloy of Figure 6.20, the ultimate tensile strength is 87,000 psi.

The ultimate tensile strength is not used much in engineering design for ductile alloys since too much plastic deformation takes place before it is reached. However, the ultimate tensile strength can give some indication of the presence of defects. If the metal contains porosity or inclusions, these defects may cause the ultimate tensile strength of the metal to be lower than normal.

Percent Elongation The amount of elongation that a tensile specimen undergoes during testing provides a value for the ductility of a metal. Ductility of metals is most commonly expressed as *percent elongation,* starting with a gage length usually of 2 in. (5.1 cm) (Fig. 6.19). In general, the higher the ductility (the more deformable the metal is), the higher the percent elongation. For example, a sheet of 0.062-in. (1.6-mm) commercially pure aluminum (alloy 1100-0) in the soft condition has a high percent elongation of 35%, whereas the same thickness of the high-strength aluminum alloy 7075-T6 in the fully hard condition has a percent elongation of only 11%.

As previously mentioned, during the tensile test an extensometer can be used to continuously measure the strain of the specimen being tested. However, the percent elongation of a specimen after fracture can be measured by fitting the fractured specimen together and measuring the final elongation with calipers.
The percent elongation can then be calculated from the equation

$$\begin{aligned}\%\ \text{elongation} &= \frac{\text{final length}^* - \text{initial length}^*}{\text{initial length}} \times 100\% \\ &= \frac{l - l_0}{l_0} \times 100\%\end{aligned} \tag{6.10}$$

The percent elongation at fracture is of engineering importance not only as a measure of ductility but also as an index of the quality of the metal. If porosity or inclusions are present in the metal or if damage due to overheating the metal has occurred, the percent elongation of the specimen tested may be decreased below normal.

Percent Reduction in Area The *ductility* of a metal or alloy can also be expressed in terms of the percent reduction in area. This quantity is usually obtained from a tensile test using a specimen 0.50 in. (12.7 mm) in diameter. After the test, the diameter of the reduced cross section at the fracture is measured. Using the measurements of the initial and final diameters, the percent reduction in area can be determined from the equation

$$\begin{aligned}\%\ \text{reduction in area} &= \frac{\text{initial area} - \text{final area}}{\text{initial area}} \times 100\% \\ &= \frac{A_0 - A_f}{A_0} \times 100\%\end{aligned} \tag{6.11}$$

EXAMPLE PROBLEM 6.7

A 0.500-in.-diameter round sample of a 1030 carbon steel is pulled to failure in a tensile testing machine. The diameter of the sample was 0.343 in. at the fracture surface. Calculate the percent reduction in area of the sample.

■ **Solution**

$$\begin{aligned}\%\ \text{reduction in area} &= \frac{A_0 - A_f}{A_0} \times 100\% = \left(1 - \frac{A_f}{A_0}\right)(100\%) \\ &= \left[1 - \frac{(\pi/4)(0.343\ \text{in.})^2}{(\pi/4)(0.500\ \text{in.})^2}\right](100\%) \\ &= (1 - 0.47)(100\%) = 53\% \quad \blacktriangleleft\end{aligned}$$

The percent reduction in area, like the percent elongation, is a measure of the ductility of the metal and is also an index of quality. The percent reduction in area may be decreased if defects such as inclusions and/or porosity are present in the metal specimen.

* The initial length is the length between the gage marks on the specimen before testing. The final length is the length between these same gage marks just prior to fracture (see Example Problem 6.6).

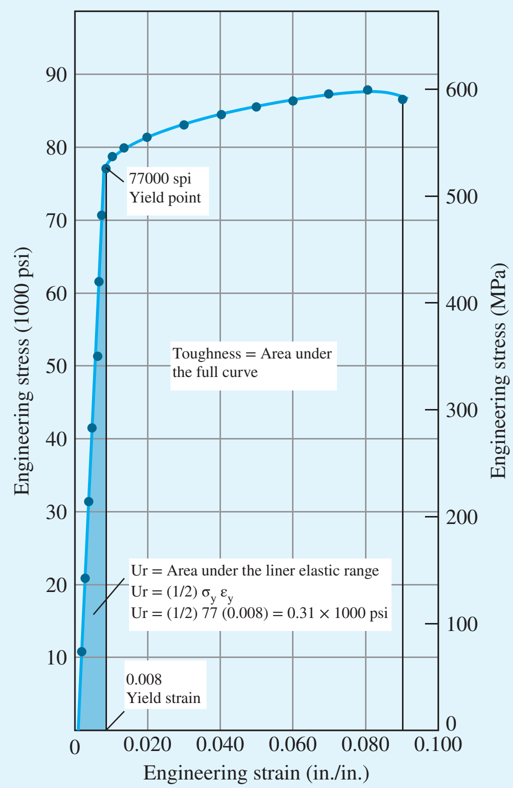
Modulus of Resilience The *modulus of resilience*, U_r, is the amount of energy absorbed by a loaded material just prior to yielding. This energy is fully recovered once the load is removed. This property can be determined by calculating the area under the linear elastic portion of the engineering stress-strain diagram using Eq. 6.12. The units of the modulus of resilience will be in terms of energy per unit volume [J/m^3 or N·m/m^3 (lb·in/in^3) or N/m^2 (lb/in^2)].

$$U_r = \frac{1}{2}\sigma_y \varepsilon_y \qquad \textbf{(6.12)}$$

Toughness The *modulus of toughness* is used to describe a combination of strength and ductility behaviors. Materials with high strength and ductility will be tougher than those with lower strength and/or ductility. The modulus of toughness is determined by calculating the area under the full stress-strain curve. One can define the modulus of toughness as the amount of energy per unit volume required to bring a sample to fracture in a tensile test.

EXAMPLE PROBLEM 6.8

For the given engineering stress-strain diagram, please find the modulus of resilience U_r and the toughness of the material.



■ **Solution**

The modulus of resilience U_r is equal to the area under the linear elastic range of the stress-strain diagram. This area can be estimated by Eq. 6.12. Based on the preceding diagram, the yield strength σ_y can be estimated as 77,000 psi, yield strain σ_y can be estimated as 0.008.

$$U_r = \frac{1}{2}\sigma_y \varepsilon_y = \frac{1}{2}(77{,}000 \text{ psi})(0.008) = 0.3 \times 1000 \text{ psi} = 300 \text{ psi}$$

The toughness of the materials can be estimated by measuring the area under the full stress-strain curve. If one estimates the total number of white squares under the stress-strain curve as 32 squares, and knowing that the area of each square is 200 psi (10,000 × 0.02), one can estimate the white area as 6400 psi.

Therefore the total area or toughness of the material will be estimated at **6700 psi or (lb.in.)/in.^{3}** (300 + 6400). This value represents the amount of energy per unit volume required to bring a sample to fracture in static tension.

The percent reduction in area, like the percent elongation, is a measure of the ductility of the metal and is also an index of quality. The percent reduction in area may be decreased if defects such as inclusions and/or porosity are present in the metal specimen.

6.3.2 Comparison of Engineering Stress-Strain Curves for Selected Alloys

Engineering stress-strain curves for selected metals and alloys are shown in Figure 6.23. Alloying a metal with other metals or nonmetals and heat treatment can greatly affect the tensile strength and ductility of metals. The stress-strain curves of Figure 6.23 show a great variation in ultimate tensile strength. Elemental magnesium has a UTS of 35 ksi (1 ksi = 1000 psi), whereas SAE 1340 steel water-quenched and tempered at 700°F (370°C) has a UTS of 240 ksi.

6.3.3 True Stress and True Strain

The engineering stress is calculated by dividing the applied force F on a tensile test specimen by its original cross-sectional area A_0 (Eq. 6.3). Since the cross-sectional area of the test specimen changes continuously during a tensile test, the engineering stress calculated is not precise. During the tensile test, after necking of the sample occurs (Fig. 6.22), the engineering stress decreases as the strain increases, leading to a maximum engineering stress in the engineering stress-strain curve (Fig. 6.24). Thus, once necking begins during the tensile test, the true stress is higher than the engineering stress. We define the true stress and true strain by the following:

$$\text{True stress } \sigma_t = \frac{F \text{ (average uniaxial force on the test sample)}}{A_i \text{ (instantaneous minimum cross-sectional area of sample)}} \qquad \textbf{(6.13)}$$

$$\text{True strain } \epsilon_t = \int_{l_0}^{l_i} \frac{dl}{l} = \ln \frac{l_i}{l_0} \qquad \textbf{(6.14)}$$

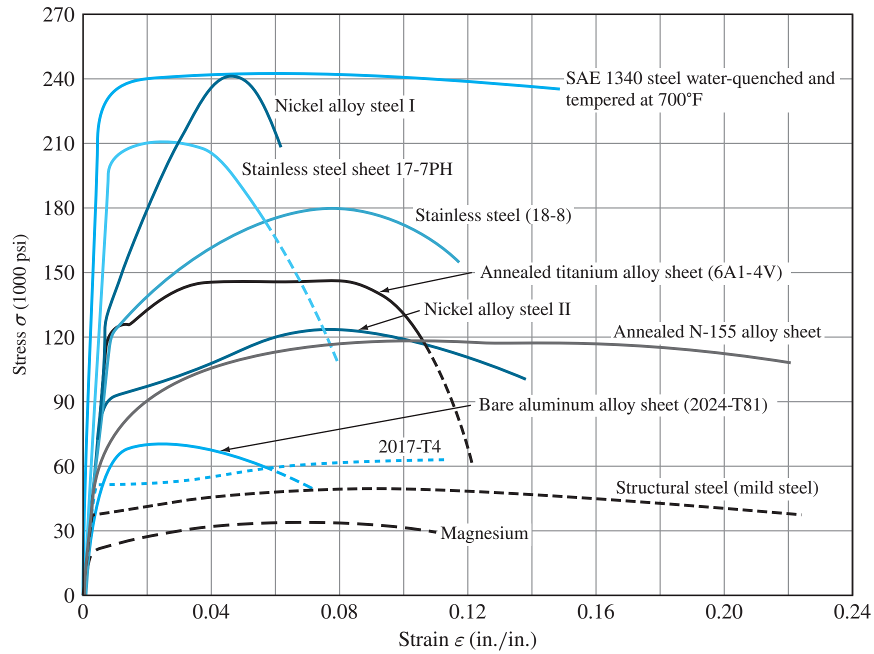


Figure 6.23

Engineering stress-strain curves for selected metals and alloys.

(Source: Marin, *Mechanical Behavior of Engineering Materials,* 1st ed., 1962.)

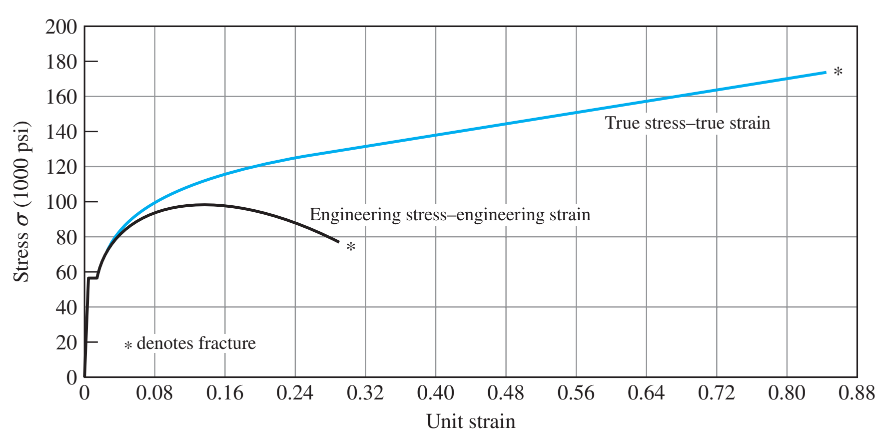


Figure 6.24

Comparison of the true stress–true strain curve with the engineering (nominal) stress-strain diagram for a low-carbon steel.

(Source: H. E. McGannon (ed.), *The Making, Shaping, and Treating of Steel,* 9th ed., United States Steel, 1971.)

where l_0 is the original gage length of the sample and l_i is the instantaneous extended gage length during the test. If we assume constant volume of the gage-length section of the test specimen during the test, then $l_0 A_0 = l_i A_i$ or

$$\frac{l_i}{l_0} = \frac{A_0}{A_i} \qquad \text{and} \qquad \epsilon_t = \ln\frac{l_i}{l_0} = \ln\frac{A_0}{A_i} \tag{6.15}$$

Figure 6.24 compares engineering stress-strain and true stress-strain curves for a low-carbon steel.

Engineering designs are not based on true stress at fracture since as soon as the yield strength is exceeded, the material starts to deform. Engineers use instead the 0.2% offset engineering yield stress for structural designs with the proper safety factors. However, for research, sometimes the true stress-strain curves are needed.

EXAMPLE PROBLEM 6.9

Compare the engineering stress and strain with the true test and strain for the tensile test of a low-carbon steel that has the following test values.

Load applied to specimen = 17,000 lb_f Initial specimen diameter = 0.500 in.

Diameter of specimen under 17,000 lb_f load = 0.472 in.

■ **Solution**

$$\text{Area at start } A_0 = \frac{\pi}{4}d^2 = \frac{\pi}{4}(0.500 \text{ in.})^2 = 0.196 \text{ in.}^2$$

$$\text{Area under load } A_i = \frac{\pi}{4}(0.472 \text{ in.})^2 = 0.175 \text{ in.}^2$$

Assuming no volume change during extension, $A_0 l_0 = A_i l_i$ or $l_i/l_0 = A_0/A_i$.

$$\text{Engineering stress} = \frac{F}{A_0} = \frac{17{,}000 \text{ lb}_f}{0.196 \text{ in.}^2} = 86{,}700 \text{ psi} \blacktriangleleft$$

$$\text{Engineering strain} = \frac{\Delta l}{l} = \frac{l_i - l_0}{l_0} = \frac{A_0}{A_i} - 1 = \frac{0.196 \text{ in.}^2}{0.175 \text{ in.}^2} - 1 = 0.12$$

$$\text{True stress} = \frac{F}{A_i} = \frac{17{,}000 \text{ lb}_f}{0.175 \text{ in.}^2} = 97{,}100 \text{ psi} \blacktriangleleft$$

$$\text{True strain} = \ln\frac{l_i}{l_0} = \ln\frac{A_0}{A_i} = \ln\frac{0.196 \text{ in.}^2}{0.175 \text{ in.}^2} = \ln 1.12 = 0.113$$

6.4 HARDNESS AND HARDNESS TESTING

Hardness is a measure of the resistance of a metal to permanent (plastic) deformation. The hardness of a metal is measured by forcing an indenter into its surface. The indenter material, which is usually a ball, pyramid, or cone, is made of a material much harder than the material being tested. For example, hardened steel, tungsten carbide, or diamond are commonly used materials for indenters. For most standard

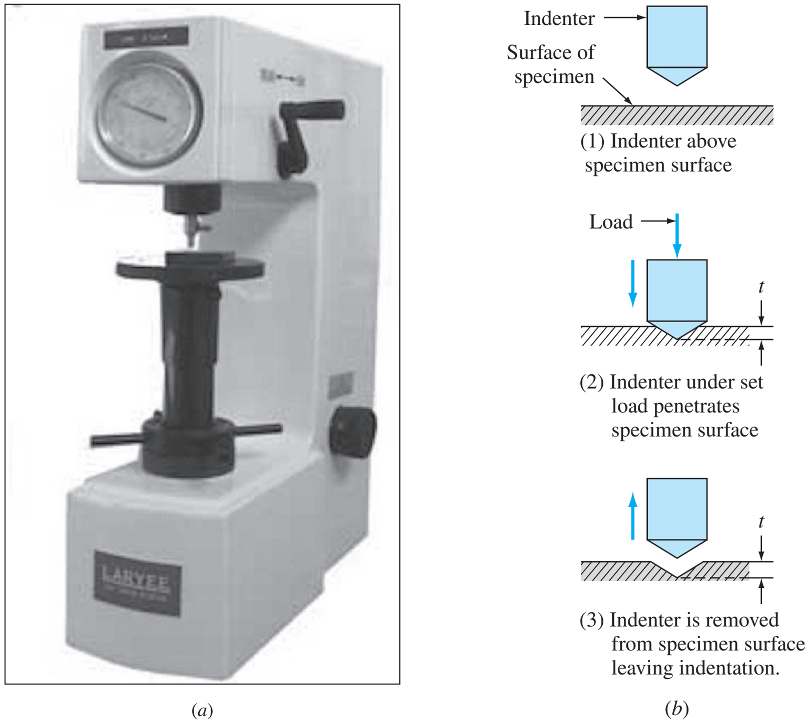


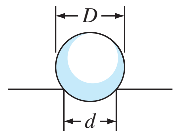
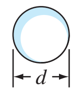
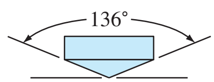
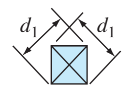
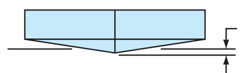
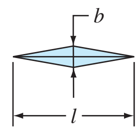
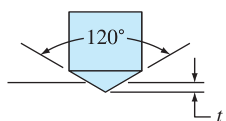
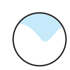
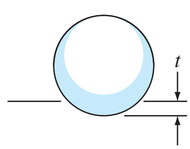
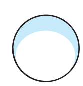
Figure 6.25
(*a*) A Rockwell hardness tester. (*b*) Steps in the measurement of hardness with a diamond-cone indenter. The depth *t* determines the hardness of the material. The lower the value of *t*, the harder the material.
(©Laryee)

hardness tests a known load is applied slowly by pressing the indenter at 90° into the metal surface being tested [Fig. 6.25*b* (2)]. After the indentation has been made, the indenter is withdrawn from the surface [Fig. 6.25*b* (3)]. An empirical hardness number is then calculated or read off a dial (or digital display), which is based on the cross-sectional area or depth of the impression.

Table 6.2 lists the types of indenters and types of impressions associated with four common hardness tests: Brinell, Vickers, Knoop, and Rockwell. The hardness number for each of these tests depends on the shape of the indentation and the applied load. Figure 6.25 shows a modern Rockwell hardness tester, which has a digital readout display.

The hardness of a metal depends on the ease with which it plastically deforms. Thus a relationship between hardness and strength for a particular metal can be determined empirically. The hardness test is much simpler than the tensile test and can be nondestructive (i.e., the small indentation of the indenter may not be detrimental to the use of an object). For these reasons, the hardness test is used extensively in industry for quality control.

Table 6.2 Hardness tests

		Shape of Indentation			
Test	**Indenter**	**Side View**	**Top View**	**Load**	**Formula for Hardness Number**
Brinell	10 mm sphere of steel or tungsten carbide			P	$BHN = \dfrac{2P}{\pi D\left(D - \sqrt{D^2 - d^2}\right)}$
Vickers	Diamond pyramid			P	$VHN = \dfrac{1.72P}{d_1^2}$
Knoop microhardness	Diamond pyramid	 $l/b = 7.11$ $b/t = 4.00$		P	$KHN = \dfrac{14.2P}{l^2}$
Rockwell A C D	Diamond cone			60 kg 150 kg 100 kg	$R_A =$ $R_C =$ $R_D =$ $100 - 500t$
B F G	$\frac{1}{16}$-in.-diameter steel sphere			100 kg 60 kg 150 kg 100 kg	$R_B =$ $R_F =$ $R_G =$ $R_E =$ $130 - 500t$
E	$\frac{1}{8}$-in.-diameter steel sphere				

(Source: H. W. Hayden, W. G. Moffatt, and J. Wulff, *The Structure and Properties of Materials,* vol. III, Wiley, 1965, p. 12.)

6.5 PLASTIC DEFORMATION OF METAL SINGLE CRYSTALS

6.5.1 Slipbands and Slip Lines on the Surface of Metal Crystals

Let us first consider the permanent deformation of a rod of a zinc single crystal by stressing it beyond its elastic limit. An examination of the zinc crystal after the deformation shows that step markings appear on its surface, which are called **slipbands**. The slipbands in a hypothetical HCP metal single crystal are shown schematically in Figure 6.26*a*. The slipbands are caused by the slip or shear deformation of metal atoms

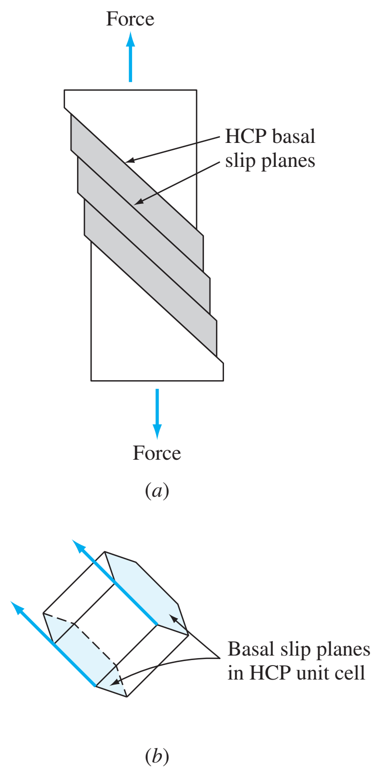


Figure 6.26
Plastically deformed HCP single crystal showing slipbands: (*a*) schematic side view indicating HCP basal slip planes in crystal, and (*b*) HCP unit cell indicating basal slip planes.

on specific crystallographic planes called *slip planes.* The deformed HCP single-crystal surface illustrates the formation of slipbands with **slip** primarily taking place on the HCP basal planes (Fig. 6.26*b*).

In single crystals of ductile FCC metals like copper and aluminum, slip occurs on multiple slip planes, and as a result, the slipband pattern on the surface of these metals when they are deformed is more uniform (Fig. 6.27). A closer examination of the slipped surface of metals at high magnification shows that slip has occurred on many slip planes within the slipbands (Fig. 6.28). These fine steps are called *slip lines* and are usually about 50 to 500 atoms apart, whereas slipbands are commonly separated by about 10,000 atom diameters. Unfortunately, the terms “slipband” and “slip line” are often used interchangeably.

Figure 6.27
Slipband pattern on surface of copper single crystal after 0.9 percent deformation. (Magnification 100×.)
(Courtesy of American Institute of Mining, Metallurgical, and Petroleum Engineers)

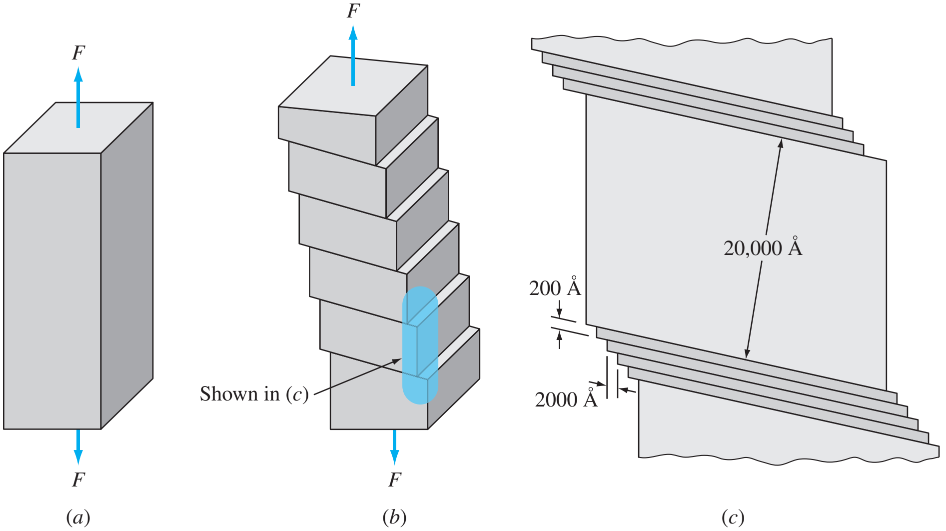


Figure 6.28
The formation of slipbands during plastic deformation. (*a*) A single crystal under a tensile force. (*b*) Slipbands appear when the applied stress exceeds the yield stress. Blocks of crystal slide past each other. (*c*) The shaded region of (*b*) has been magnified. Slip occurs on a large number of closely packed slip planes that are parallel. This region is called a slipband and appears as a line at lower magnification.
(Source: Eisenstadt, M., *Introduction to Mechanical Properties of Materials: An Ecological Approach,* 1st ed., 1971.)

Animation

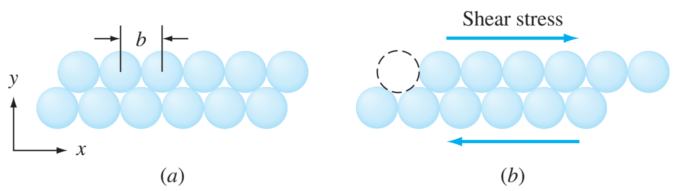


Figure 6.29
Large groups of atoms in large metal crystals do *not* slide over each other simultaneously during plastic shear deformation, as indicated in this figure, since the process requires too much energy. A lower-energy process involving the slippage of a small group of atoms takes place instead.

6.5.2 Plastic Deformation in Metal Crystals by the Slip Mechanism

Figure 6.29 shows a possible atomic model for the slippage of one block of atoms over another in a perfect metal crystal. Calculations made from this model determine that the strength of metal crystals should be about 1000 to 10,000 times greater than their observed shear strengths. Thus, this mechanism for atomic slip in large real metal crystals must be incorrect.

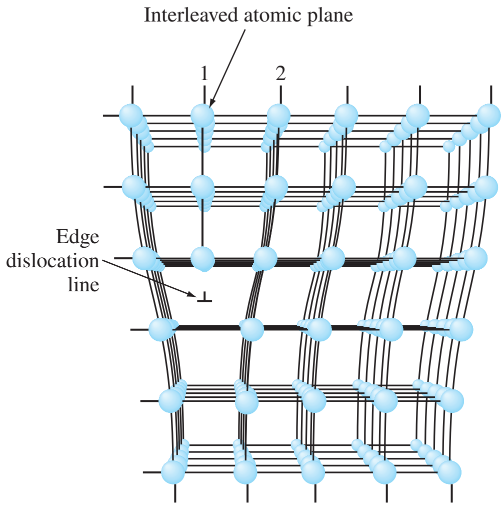
In order for large metal crystals to deform at their observed low shear strengths, a high density of crystalline imperfections known as *dislocations* must be present. These dislocations are created in large numbers ($\sim 10^6$ cm/cm^3) as the metal solidifies, and when the metal crystal is deformed, many more are created so that a highly deformed crystal may contain as high as 10^{12} cm/cm^3 of dislocations. Figure 6.30 shows schematically how an *edge dislocation* can produce a unit of slip under a low *shear stress.* A relatively small amount of stress is required for slip by this process since only a small group of atoms slips over each other at any instant.

An analogous situation to the movement of a dislocation in a metal crystal under a shear stress can be envisaged by the movement of a carpet with a ripple in it across a very large floor. Moving the carpet by pulling on one end may be impossible because of the friction between the floor and the carpet. However, by putting a ripple in the carpet (analogous to a dislocation in a metal crystal), the carpet may be moved by pushing the ripple in the carpet one step at a time across the floor (Fig. 6.30*d*).

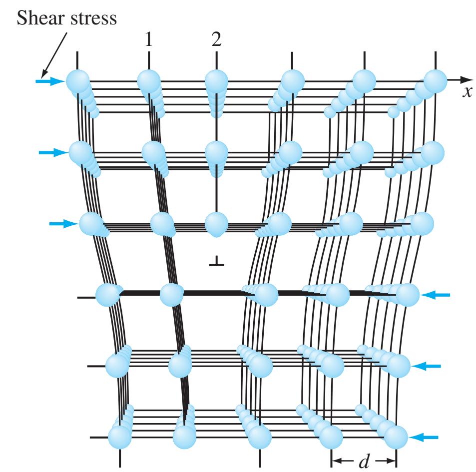
Dislocations in real crystals can be observed in the transmission electron microscope in thin metal foils and appear as lines due to the atomic disarray at the dislocations that interfere with the transmission path of the electron beam of the microscope. Figure 6.31 shows a network of dislocations created in mechanically rolled nickel-aluminum alloys. The cells are distinctly observable and the alloy is loaded with dislocations.

6.5.3 Slip Systems

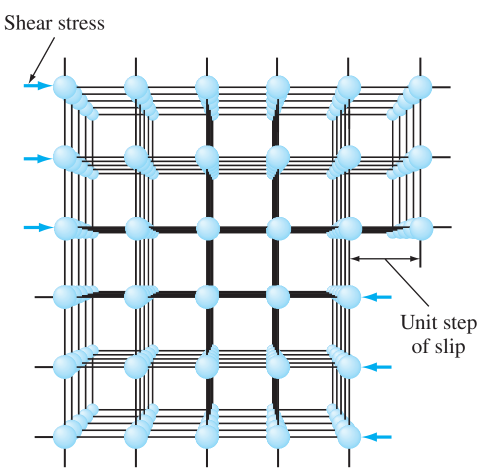
Dislocations produce atomic displacements on specific crystallographic slip planes and in specific crystallographic slip directions. The slip planes are usually the most densely packed planes, which are also the farthest separated. Slip is favored on close-packed



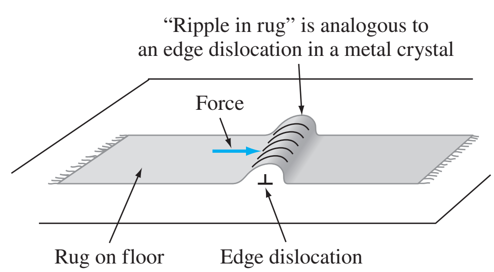
(*a*) An edge dislocation, pictured as formed by an extra half plane of atoms.



(*b*) A low stress causes a shift of atomic bonds to free a new interleaved plane.



(*c*) Repetition of this process causes the dislocation to move across the crystal.



(*d*)

Figure 6.30
Schematic illustration of how the motion of an edge dislocation produces a unit step of slip under a low shear stress. (*a*) An edge dislocation, pictured as formed by an extra half plane of atoms. (*b*) A low stress causes a shift of atomic bonds to free a new interleaved plane. (*c*) Repetition of this process causes the dislocation to move across the crystal. This process requires less energy than the one depicted in Figure 6.28. (*d*) The "ripple in the rug" analogy. A dislocation moves through a metal crystal during plastic deformation in a manner similar to a ripple that is pushed along a carpet lying on a floor. In both cases, a small amount of relative movement is caused by the passage of the dislocation or ripple, and hence a relatively low amount of energy is expended in this process.
((*a-c*) Source: A.G. Guy, *Essentials of Materials Science,* McGraw-Hill, 1976, p. 153.)

Animation

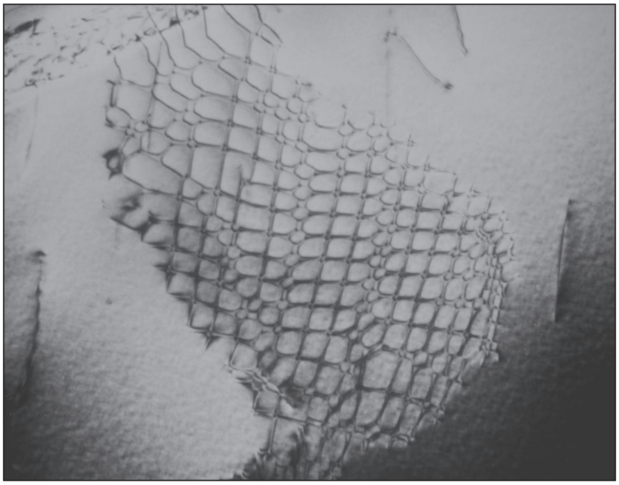
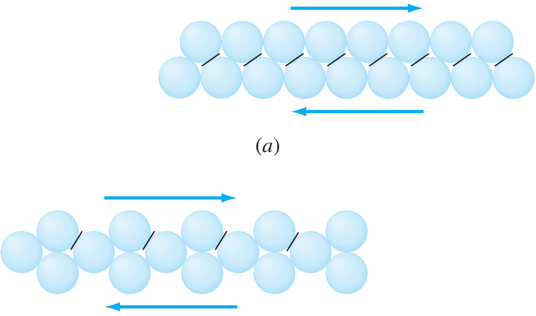


Figure 6.31
Dislocation cell structure in a mechanically rolled nickel-aluminum alloy sample as revealed by transmission electron microscopy. The cells are clearly visible and loaded with dislocations.
(©Professor I. Baker/Science Source)



(*a*)

(*b*)

Figure 6.32
Comparison of atomic slip on (*a*) a close-packed plane and (*b*) a non–close-packed plane. Slip is favored on the close-packed plane because less force is required to move the atoms from one position to the next closest one, as indicated by the slopes of the bars on the atoms. Note that dislocations move one atomic slip step at a time.
(Source: A. H. Cottrell, The Nature of Metals, "Materials," *Scientific American,* September 1967, p. 48.)

planes since a lower shear stress for atomic displacement is required than for less densely packed planes (Fig. 6.32). However, if slip on the close-packed planes is restricted due to local high stresses, for example, then planes of lower atomic packing can become operative. Slip in the close-packed directions is also favored since less energy is required to move the atoms from one position to another if the atoms are closer together.

A combination of a slip plane and a slip direction is called a **slip system.** Slip in metallic structures occurs on a number of slip systems that are characteristic for each crystal structure. Table 6.3 lists the predominant slip planes and slip directions for FCC, BCC, and HCP crystal structures.

For metals with the FCC crystal structure, slip takes place on the close-packed $\{111\}$ octahedral planes and in the $\langle 1\bar{1}0\rangle$ close-packed directions. There are eight $\{111\}$ octahedral planes in the FCC crystal structure (Fig. 6.33). The (111)-type planes at opposite faces of the octahedron that are parallel to each other are considered the same type of (111) slip plane. Thus, there are only four different types of (111) slip planes in the FCC crystal structure. Each (111)-type plane contains three $[1\bar{1}0]$-type slip directions. The reverse directions are not considered different slip directions. Thus, for the FCC lattice there are 4 slip planes $\times$ 3 slip directions = 12 slip systems (Table 6.3).

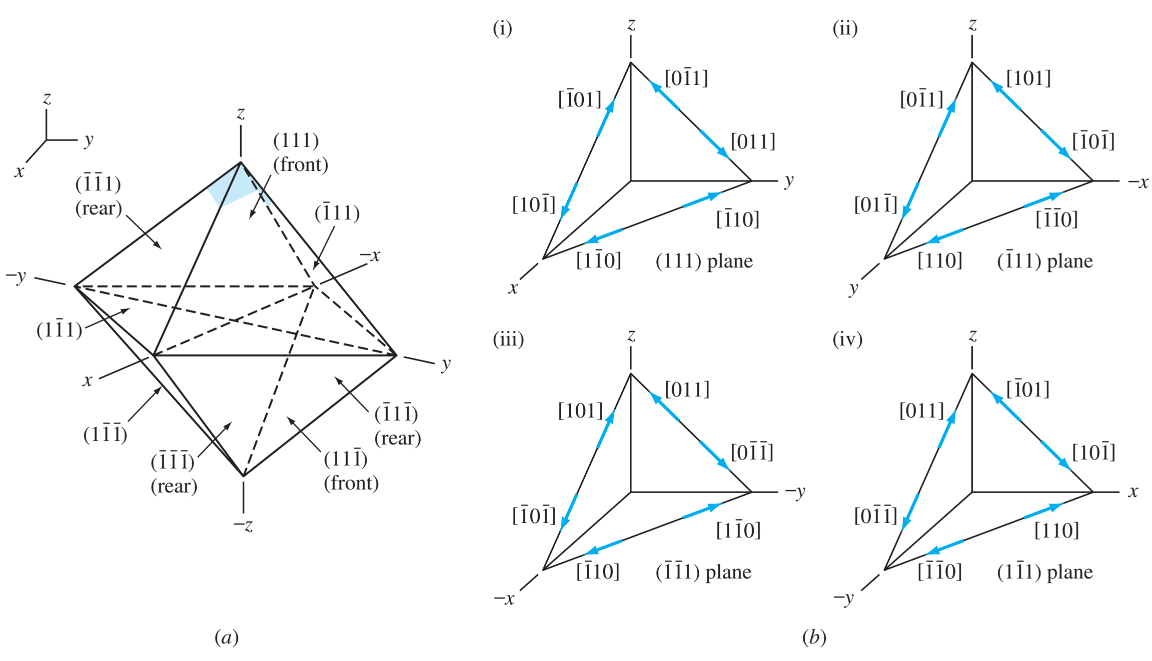
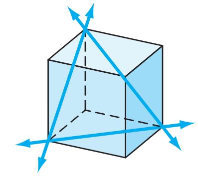
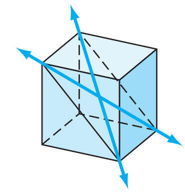
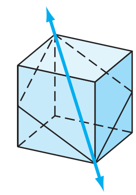
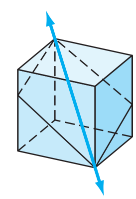
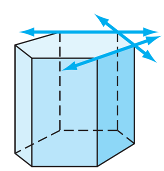
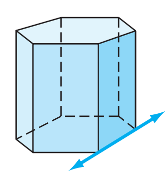
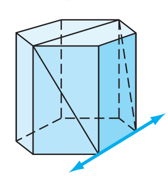


Figure 6.33

Slip planes and directions for the FCC crystal structure. (*a*) Only four of the eight $\{111\}$ octahedral planes are considered slip planes since planes opposite each other are considered the same slip plane. (*b*) For each slip $\langle 1\bar{1}0\rangle$ plane there are three slip directions since opposite directions are considered to be only one slip direction. Note that slip directions are only shown for the upper four slip planes of the octahedral FCC planes. Thus, there are four slip planes and three slip directions, giving a total of 12 slip systems for the FCC crystal structure.

Table 6.3 Slip systems observed in crystal structures

Structure	Slip Plane	Slip Direction	Number of Slip Systems	
FCC: Cu, Al, Ni, Pb, Au, Ag, γFe, . . .	$\{111\}$	$\langle 1\bar{1}0\rangle$	$4 \times 3 = 12$	
BCC: αFe, W, Mo, β brass	$\{110\}$	$\langle \bar{1}11\rangle$	$6 \times 2 = 12$	
αFe, Mo, W, Na	$\{211\}$	$\langle \bar{1}11\rangle$	$12 \times 1 = 12$	
αFe, K	$\{321\}$	$\langle \bar{1}11\rangle$	$24 \times 1 = 24$	
HCP: Cd, Zn, Mg, Ti, Be, . . .	$\{0001\}$	$\langle 11\bar{2}0\rangle$	$1 \times 3 = 3$	
Ti (prism planes)	$\{10\bar{1}0\}$	$\langle 11\bar{2}0\rangle$	$3 \times 1 = 3$	
Ti, Mg (pyramidal planes)	$\{10\bar{1}1\}$	$\langle 11\bar{2}0\rangle$	$6 \times 1 = 6$	

(Source: H. W. Hayden, W. G. Moffatt, and J. Wulff, *The Structure and Properties of Materials,* vol. III, Wiley, 1965, p. 100.)

The BCC structure is *not* a close-packed structure and does not have a predominant plane of highest atomic packing like the FCC structure. The {110} planes have the highest atomic density, and slip commonly takes place on these planes. However, slip in BCC metals also occurs on {112} and {123} planes. Since the slip planes in the BCC structure are not close-packed as in the case of the FCC structure, higher shear stresses are needed for slip in BCC than in FCC metals. The slip direction in BCC metals is always of the $\langle\bar{1}11\rangle$ type. Since there are six (110)-type slip planes of which each can slip in two $[\bar{1}11]$ directions, there are $6 \times 2 = 12$ $\{110\}$ $\langle\bar{1}11\rangle$ slip systems.

In the HCP structure, the basal plane (0001) is the closest-packed plane and is the common slip plane for HCP metals such as Zn, Cd, and Mg that have high *c/a* ratios (Table 6.3). However, for HCP metals such as Ti, Zr, and Be that have low *c/a* ratios, slip also occurs commonly on prism $\{10\bar{1}0\}$ and pyramidal $\{10\bar{1}1\}$ planes. In all cases, the slip direction remains $\langle 11\bar{2}0\rangle$. The limited number of slip systems in HCP metals restricts their ductilities.

6.5.4 Critical Resolved Shear Stress for Metal Single Crystals

The stress required to cause slip in a pure-metal single crystal depends mainly on the crystal structure of the metal, its atomic bonding characteristics, the temperature at which it is deformed, and the orientation of the active slip planes with respect to the shear stresses. Slip begins within the crystal when the shear stress on the slip plane in the slip direction reaches a required level called the *critical resolved shear stress,* τ_c. Essentially, this value is the yield stress of a single crystal and is equivalent to the yield stress of a polycrystalline metal or alloy determined by a stress-strain tensile test curve.

Table 6.4 lists values for the critical resolved shear stresses of some pure-metal single crystals at room temperature. The HCP metals Zn, Cd, and Mg have low critical resolved shear stresses ranging from 0.18 to 0.77 MPa. The HCP metal titanium, on the other hand, has a very high τ_c of 13.7 MPa. It is believed that some covalent bonding mixed with metallic bonding is partly responsible for this high value of τ_c. Pure FCC metals such as Ag and Cu have low τ_c values of 0.48 and 0.65 MPa, respectively, because of their multiple slip systems.

6.5.5 Schmid's Law

The relationship between a uniaxial stress acting on a cylinder of a pure metal single crystal and the resulting resolved shear stress produced on a slip system within the cylinder can be derived as follows: Consider a uniaxial tensile stress σ acting on a metal cylinder, as shown in Figure 6.34. Let A_0 be the area normal to the axial force F, and A_1 the area of the slip plane or shear area on which the resolved shear force F_r is acting. We can orient the slip plane and slip direction by defining the angles ϕ and λ. ϕ is the angle between the uniaxial force F and the normal to the slip plane area A_1, and λ is the angle between the axial force and the slip direction.

In order for dislocations to move in the slip system, a sufficient resolved shear stress acting in the slip direction must be produced by the applied axial force. The resolved shear stress is

$$\tau_r = \frac{\text{shear force}}{\text{shear area (slip plane area)}} = \frac{F_r}{A_1} \tag{6.16}$$

Table 6.4 Room-temperature slip systems and critical resolved shear stress for metal single crystals

Metal	Crystal Structure	Purity (%)	Slip Plane	Slip Direction	Critical Shear Stress (MPa)
Zn	HCP	99.999	(0001)	$[11\bar{2}0]$	0.18
Mg	HCP	99.996	(0001)	[1120]	0.77
Cd	HCP	99.996	(0001)	$[11\bar{2}0]$	0.58
Ti	HCP	99.99	(1010)	$[11\bar{2}0]$	13.7
		99.9	(1010)	$[11\bar{2}0]$	90.1
Ag	FCC	99.99	(111)	$[1\bar{1}0]$	0.48
		99.97	(111)	$[1\bar{1}0]$	0.73
		99.93	(111)	$[1\bar{1}0]$	1.3
Cu	FCC	99.999	(111)	$[1\bar{1}0]$	0.65
		99.98	(111)	$[1\bar{1}0]$	0.94
Ni	FCC	99.8	(111)	$[1\bar{1}0]$	5.7
Fe	BCC	99.96	(110)	$[\bar{1}11]$	27.5
			(112)		
			(123)		
Mo	BCC	. . .	(110)	$[\bar{1}11]$	49.0

(Source: G. Dieter, *Mechanical Metallurgy,* 2nd ed., McGraw-Hill, 1976, p. 129.)

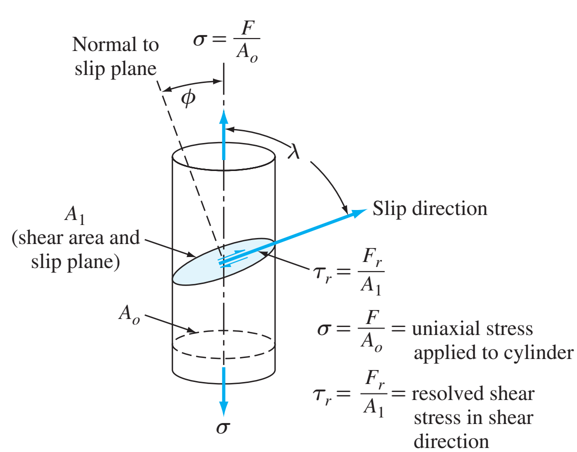


Figure 6.34
Axial stress σ can produce a resolved shear stress τ_r and cause dislocation motion in slip plane A_1 in the slip direction.

The resolved shear force F_r is related to the axial force F by $F_r = F \cos \lambda$. The area of the slip plane (shear area) $A_1 = A_0/\cos \phi$. By dividing the shear force $F \cos \lambda$ by the shear area $A_0/\cos \phi$, we obtain

$$\tau_r = \frac{F \cos \lambda}{A_0/\cos \phi} = \frac{F}{A_0} \cos \lambda \cos \phi = \sigma \cos \lambda \cos \phi \qquad \textbf{(6.17)}$$

which is called *Schmid's law*. Let us now consider an example problem to calculate the resolved shear stress when a slip system is acted upon by an axial stress.

It is useful to note that in cubic systems, the direction indices of a direction perpendicular to a slip plane are the same as the Miller indices of the crystal plane. You can use this information to determine the angle between the loading axis and the axis normal to the slip plane using Eq. 3.4.

EXAMPLE PROBLEM 6.10

Calculate the resolved shear stress on the (111) $[0\bar{1}1]$ slip system of a unit cell in an FCC nickel single crystal if a stress of 13.7 MPa is applied in the [001] direction of a unit cell.

■ **Solution**

By geometry, the angle λ between the applied stress and the slip direction is 45°, as shown in Figure EP6.9*a*. In the cubic system, the direction indices of the normal to a crystal plane are the same as the Miller indices of the crystal plane. Therefore, the normal to the (111) plane that is the slip plane is the [111] direction. From Figure EP6.9*b*,

$$\cos \phi = \frac{a}{\sqrt{3}\,a} = \frac{1}{\sqrt{3}} \quad \text{or} \quad \phi = 54.74°$$

$$\tau_r = \sigma \cos \lambda \cos \phi = (13.7 \text{ MPa})(\cos 45°)(\cos 54.74°) = 5.6 \text{ MPa} \blacktriangleleft$$

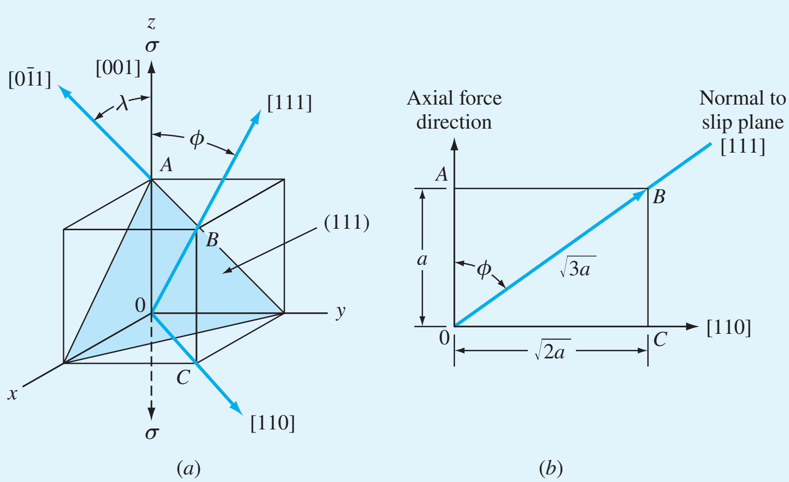


Figure EP6.9
An FCC unit cell is acted upon by a [001] tensile stress producing a resolved shear stress on the (111) $[0\bar{1}1]$ slip system.

6.5.6 Twinning

A second important plastic deformation mechanism that can occur in metals is **deformation twinning.** In this process a part of the atomic lattice is deformed so that it forms a mirror image of the undeformed lattice next to it (Fig. 6.35). The crystallographic plane of symmetry between the undeformed and deformed parts of the metal lattice is called the *twinning plane.* Twinning, like slip, occurs in a specific direction called the *twinning direction.* However, in slip the atoms on one side of the slip plane all move equal distances (Fig. 6.30), whereas in twinning the atoms move distances proportional to their distance from the twinning plane (Fig. 6.35). Figure 6.36 illustrates the basic difference between slip and twinning on the surface of a metal after deformation. Slip leaves a series of steps (lines) (Fig. 6.36*a*), whereas twinning leaves small but well-defined regions of the crystal deformed (Fig. 6.36*b*). Figure 6.37 shows some deformation twins on the surface of titanium metal.

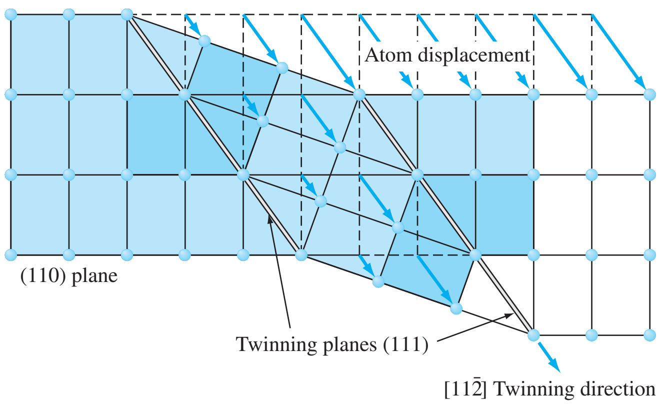


Figure 6.35
Schematic diagram of the twinning process in an FCC lattice.
(Source: H. W. Hayden, W. G. Moffatt and J. Wulff, *The Structure and Properties of Materials,* vol. III, Wiley, 1965, p. 111.)

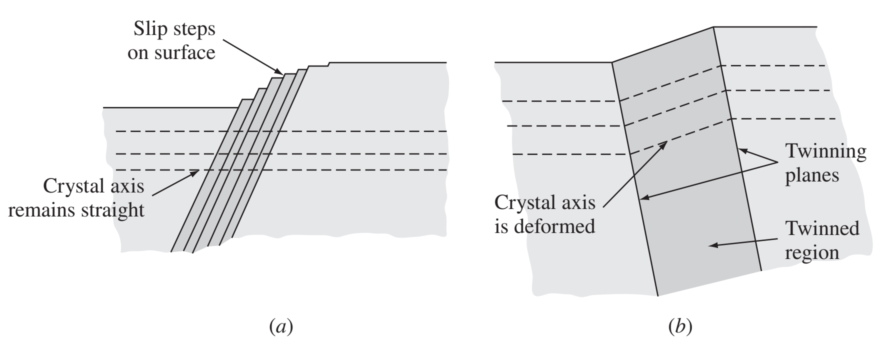


Figure 6.36
Schematic diagram of surfaces of a deformed metal after (*a*) slip and (*b*) twinning.

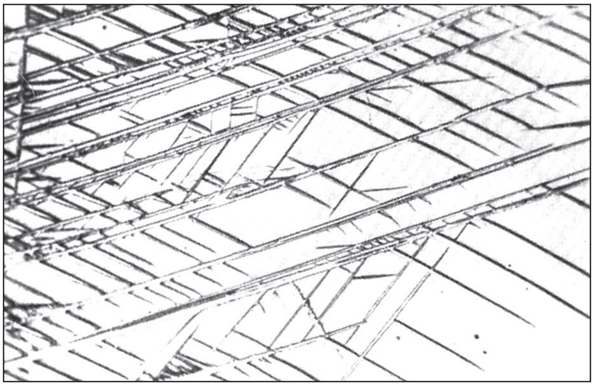


Figure 6.37
Deformation twins in unalloyed (99.77%) titanium. (Magnification 150×.)
(Courtesy of American Institute of Mining, Metallurgical, and Petroleum Engineers)

Twinning only involves a small fraction of the total volume of the metal crystal, and so the amount of overall deformation that can be produced by twinning is small. However, the important role of twinning in deformation is that the lattice orientation changes that are caused by twinning may place new slip systems into favorable orientation with respect to the shear stress and thus enable additional slip to occur. Of the three major metallic unit-cell structures (BCC, FCC, and HCP), twinning is most important for the HCP structure because of its small number of slip systems. However, even with the assistance of twinning, HCP metals like zinc and magnesium are still less ductile than the BCC and FCC metals that have more slip systems.

Deformation twinning is observed at room temperature for the HCP metals. Twinning is found in the BCC metals such as Fe, Mo, W, Ta, and Cr in crystals that were deformed at very low temperatures. Twinning has also been found in some of these BCC metal crystals at room temperature when they have been subjected to very high strain rates. The FCC metals show the least tendency to form deformation twins. However, deformation twins can be produced in some FCC metals if the stress level is high enough and the temperature sufficiently low. For example, copper crystals deformed at 4 K at high stress levels can form deformation twins.

6.6 PLASTIC DEFORMATION OF POLYCRYSTALLINE METALS

6.6.1 Effect of Grain Boundaries on the Strength of Metals

Almost all engineering alloys are polycrystalline. Single-crystal metals and alloys are used mainly for research purposes and only in a few cases for engineering applications.[8] Grain boundaries strengthen metals and alloys by acting as barriers to dislocation movement except at high temperatures, where they become regions of weakness. For most applications where strength is important, a fine grain size is desirable, and so most metals are fabricated with a fine grain size. In general, at room temperature, fine-grained metals are stronger, harder, tougher, and more susceptible to strain hardening. However, they are less resistant to corrosion and creep (deformation under constant load at elevated temperatures; see Sec. 7.4). A fine grain size also results in a more uniform and isotropic behavior of materials. In Section 4.5, the ASTM grain size number and a method to determine the average grain diameter of a metal using metallography techniques were discussed. These parameters allow us to make a relative comparison of grain density and therefore grain boundary density in metals. Accordingly, for two components made of the same alloy, the component that has a larger ASTM grain size number or a smaller average grain diameter is stronger. The relationship between strength and grain size is of great importance to engineers. The well known *Hall–Petch equation,* Eq. 6.18, is an empirical (based on experimental measurements and not on theory) equation that relates the yield strength of a metal, σ_y, to its average grain diameter d as follows:

$$\sigma_y = \sigma_0 + k/(d)^{1/2} \tag{6.18}$$

where σ_0 and k are constants related to the material of interest. A similar effect exists between hardness (Vickers microhardness test) and grain size. The equation clearly shows that as grain diameter decreases, the yield strength of the material increases. Considering that the conventional grain diameters may range from a few hundred microns to a few microns, one may expect a significant change in strength through grain refinement. The values for σ_0 and k for selected materials are given in Table 6.5. It is important to note that the Hall–Petch equation does not apply to (1) extremely coarse or extremely fine grain sizes and (2) metals used at elevated temperatures.

Figure 6.38 compares the tensile stress-strain curves for single-crystal and polycrystalline unalloyed copper at room temperature. At all strains, the polycrystalline copper is stronger than the single-crystal copper. At 20% strain, the tensile strength of the polycrystalline copper is 40 ksi (276 MPa) as compared to 8 ksi (55 MPa) for single-crystal copper.

Table 6.5 Hall–Petch relationship constants for selected materials

	σ_0 (MPa)	k (MPa · m$^{1/2}$)
Cu	25	0.11
Ti	80	0.40
Mild steel	70	0.74
Ni_3Al	300	1.70

[8] Single-crystal turbine blades have been developed for use in gas turbine engines to avoid grain boundary cracking at high temperatures and stresses. See F.L. Ver Snyder and M.E. Shank, *Mater. Sci. Eng.,* **6:**213–247(1970).

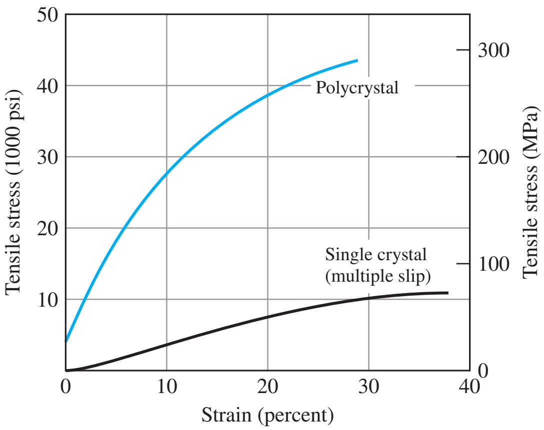


Figure 6.38
Stress-strain curves for single-crystal and polycrystalline copper. The single crystal is oriented for multiple slip. The polycrystal shows higher strength at all strains.
(Source: M. Eisenstadt, *Introduction to Mechanical Properties of Materials,* Macmillan, 1971, p. 258.)

During the plastic deformation of metals, dislocations moving along on a particular slip plane cannot go directly from one grain into another in a straight line. As shown in Figure 6.39, slip lines change directions at grain boundaries. Thus, each grain has its own set of dislocations on its own preferred slip planes, which have different orientations from those of neighboring grains. As the number of grains increases and grain diameter becomes smaller, dislocations within each grain can travel a smaller distance before they encounter the grain boundary, at which point their movement is terminated (dislocation pileup). It is for this reason that fine-grained materials possess a higher strength. Figure 6.40 shows clearly a high-angle grain boundary that is acting as a barrier to dislocation movement and has caused dislocations to pile up at the grain boundary.

6.6.2 Effect of Plastic Deformation on Grain Shape and Dislocation Arrangements

Grain Shape Changes with Plastic Deformation Let us consider the plastic deformation of annealed samples[9] of unalloyed copper that have an equiaxed grain structure. Upon cold plastic deformation, the grains are sheared relative to each other by the generation, movement, and rearrangement of dislocations. Figure 6.41 shows the

[9] Samples in the annealed conditions have been plastically deformed and then reheated to such an extent that a grain structure in which the grains are approximately equal in all directions (equiaxed) is produced.

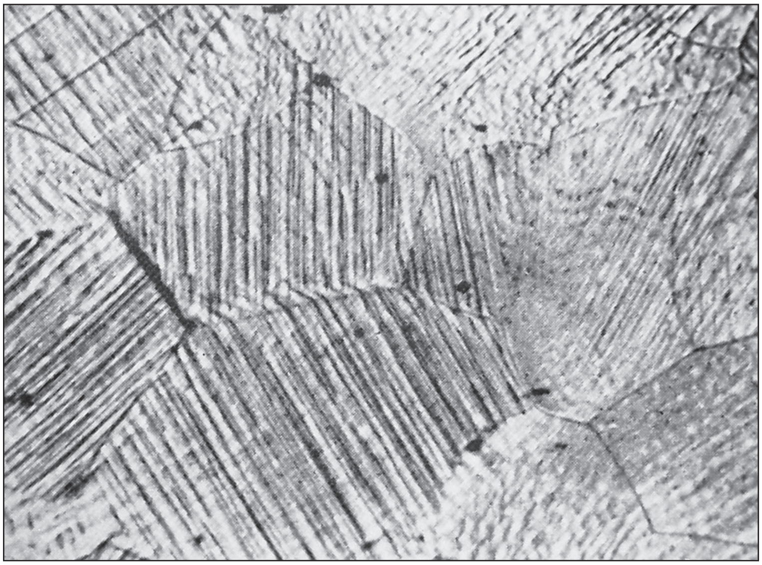


Figure 6.39
Polycrystalline copper that has been plastically deformed. Note that the slipbands are parallel within a grain but are discontinuous across the grain boundaries. (Magnification 60×.)
(Courtesy of Jixi Zhang)

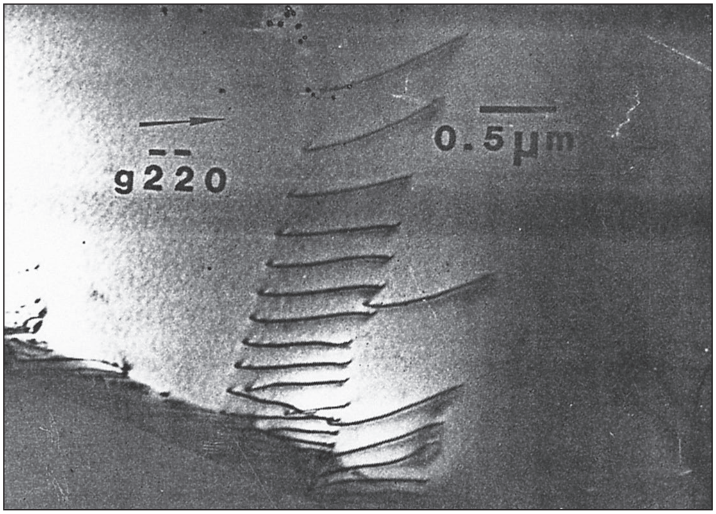
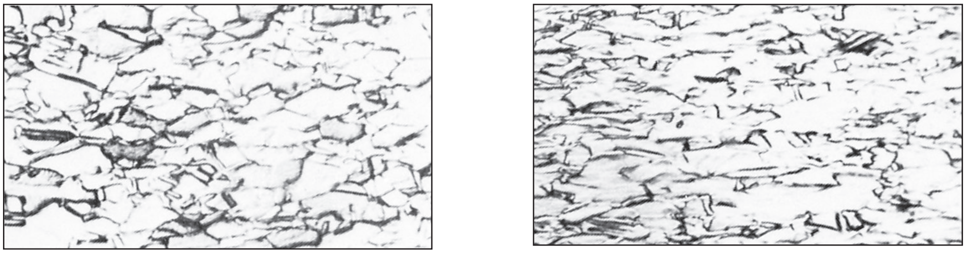
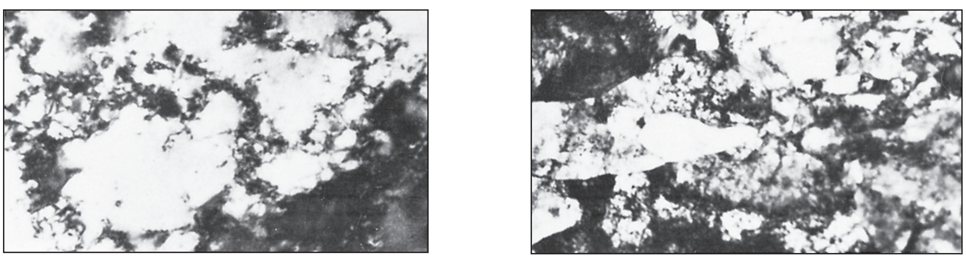


Figure 6.40
Dislocations piled up against a grain boundary (bottom right) as observed with a transmission electron microscope in a thin foil of titanium alloy. (S: screw dislocation; M: mixed mode).
(Source: Royaly Society)



(*a*) (*b*)

Figure 6.41
Optical micrographs of deformation structures of unalloyed copper that was cold-rolled to reductions of (*a*) 30 percent and (*b*) 50 percent. (Etch: potassium dichromate; magnification 300×.)
(©ASM International)



(*a*) (*b*)

Figure 6.42
Transmission electron micrographs of deformation structures of unalloyed copper that was cold-rolled to reductions of (*a*) 30% and (*b*) 50%. Note that these electron micrographs correspond to the optical micrographs of Figure 6.41. (Thin-foil specimens, magnification 30,000×.)
(©ASM International)

microstructures of samples of unalloyed copper sheet that was cold-rolled to reductions of 30% and 50%. Note that with increased cold rolling the grains are more elongated in the rolling direction as a consequence of dislocation movements.

Dislocation Arrangement Changes with Plastic Deformation The dislocations in the unalloyed copper sample after 30% plastic deformation form cell-like configurations with clear areas in the centers of the cells (Fig. 6.42*a*). With increased cold plastic deformation to 50% reduction, the cell structure becomes denser and elongated in the direction of rolling (Fig. 6.42*b*).

6.6.3 Effect of Cold Plastic Deformation on Increasing the Strength of Metals

As shown by the electron micrographs of Figure 6.42, the dislocation density increases with increased cold deformation. The exact mechanism by which the dislocation density is increased by cold working is not completely understood. New dislocations are created by the cold deformation and must interact with those already existing. As the dislocation density increases with deformation, it becomes more and more difficult for the dislocations to move through the existing "forest of dislocations," and thus the metal work or strain hardens with increased cold deformation.

When ductile metals such as copper, aluminum, and iron that have been annealed are cold-worked at room temperature, they strain-harden because of the dislocation interaction just described. Figure 6.43 shows how cold working at room temperature increases the tensile strength of unalloyed copper from about 30 ksi (200 MPa) to 45 ksi (320 MPa) with 30% cold work. Associated with the increase in tensile strength, however, is a decrease in elongation (ductility), as observed in Figure 6.43. With 30% cold work, the elongation of unalloyed copper decreases from about 52% to 10% elongation.

Cold working or **strain hardening** is one of the most important methods for strengthening some metals. For example, pure copper and aluminum can be strengthened significantly only by this method. Thus, cold-drawn unalloyed copper wire can be produced with different strengths (within certain limitations) by varying the amount of strain hardening.

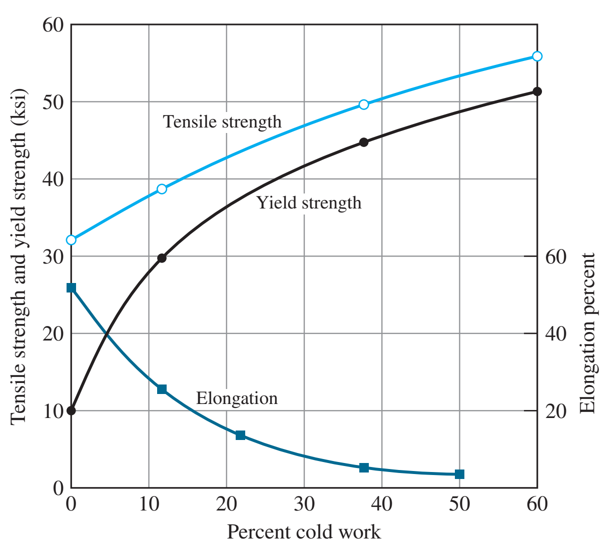


Figure 6.43
Percent cold work versus tensile strength and elongation for unalloyed oxygen-free copper. Cold work is expressed as a percent reduction in cross-sectional area of the metal being reduced.

EXAMPLE PROBLEM 6.11

We wish to produce a 0.040-in.-thick sheet of oxygen-free copper with a tensile strength of 45 ksi. What percent cold work must the metal be given? What must the starting thickness of the metal be before cold rolling?

■ **Solution**

From Figure 6.43, the percent cold work must be 25%. Thus, the starting thickness must be

$$\frac{x - 0.040 \text{ in.}}{x} = 0.25$$

$$x = 0.053 \text{ in.} \blacktriangleleft$$

6.7 SOLID-SOLUTION STRENGTHENING OF METALS

Another method besides cold working by which the strength of metals can be increased is **solid-solution strengthening.** The addition of one or more elements to a metal can strengthen it by the formation of a solid solution. The structure of *substitutional* and *interstitial solid solutions* has already been discussed in Section 4.3 and should be referred to for review. When substitutional (solute) atoms are mixed in the solid state with those of another metal (solvent), stress fields are created around each solute atom. These stress fields interact with dislocations and make their movement more difficult, and thus the solid solution becomes stronger than the pure metal.

Two important factors in solid-solution strengthening are:

1. *Relative-size factor.* Differences in atomic size of solute and solvent atoms affect the amount of solid-solution strengthening because of the crystal lattice distortions produced. Lattice distortions make dislocation movement more difficult and hence strengthen the metallic solid solution.
2. *Short-range order.* Solid solutions are rarely random in atomic mixing, and some kind of short-range order or clustering of like atoms takes place. As a result, dislocation movement is impeded by different bonding structures.

In addition to these factors, there are others that also contribute to solid-solution strengthening but will not be dealt with in this book.

As an example of solid-solution strengthening, let us consider a solid-solution alloy of 70 wt% Cu and 30 wt% Zn (cartridge brass). The tensile strength of unalloyed copper with 30% cold work is about 48 ksi (330 MPa) (Fig. 6.43). However, the tensile strength of the 70 wt% Cu–30 wt% Zn alloy with 30% cold work is about 72 ksi (500 MPa) (Fig. 6.44). Thus, solid-solution strengthening in this case produced an increase in strength in the copper of about 24 ksi (165 MPa). On the other hand, the ductility of the copper by the 30% zinc addition after 30% cold work was reduced from about 65% to 10% (Fig. 6.44).

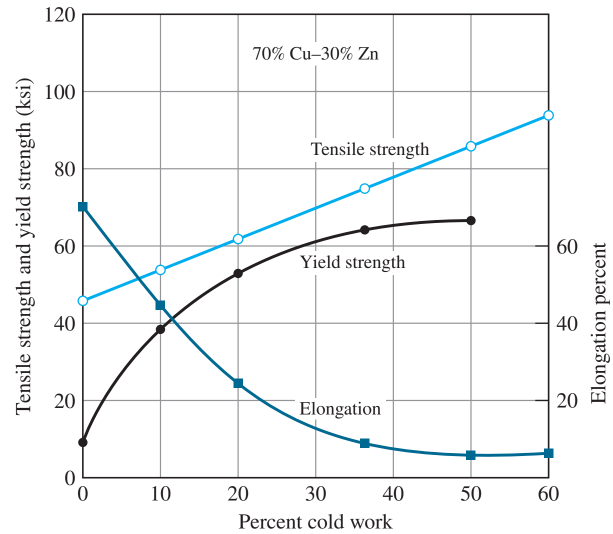


Figure 6.44
Percent cold work versus tensile strength and elongation for 70 wt% Cu–30 wt% Zn alloy. Cold work is expressed as a percent reduction in cross-sectional area of the metal being reduced (see Eq. 6.2).

6.8 RECOVERY AND RECRYSTALLIZATION OF PLASTICALLY DEFORMED METALS

In previous sections, the effect of plastic deformation on the mechanical properties and microstructural features of metals was discussed. When metal-forming processes such as rolling, forging, extrusion, and others are performed cold, the work material has many dislocations and other defects, and the grains are stretched and deformed; as a result, the worked metal is significantly stronger but less ductile. Many times the reduced ductility of the cold-worked metal is undesirable, and a softer metal is required. To achieve this, the cold-worked metal is heated in a furnace. If the metal is reheated to a sufficiently high temperature for a long enough time, the cold-worked metal structure will go through a series of changes called (1) **recovery,** (2) **recrystallization,** and (3) **grain growth.** Figure 6.45 shows these structural changes schematically as the temperature of the metal is increased along with the corresponding changes in mechanical properties. This reheating treatment that softens a cold-worked metal is called **annealing,** and the terms *partial anneal* and *full anneal* are often used to refer to degrees of softening. Let us now examine these structural changes in more detail, starting with the heavily cold-worked metal structure.

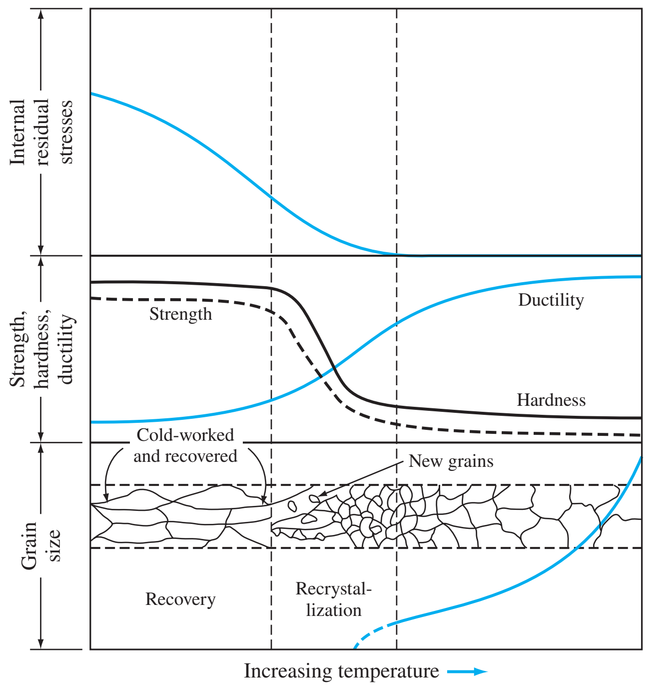


Figure 6.45
Effect of annealing on the structure and mechanical property changes of a cold-worked metal.
(Source: Z. D. Jastrzebski, *The Nature and Properties of Engineering Materials,* 2nd ed., Wiley, 1976, p. 228.)

6.8.1 Structure of a Heavily Cold-Worked Metal before Reheating

When a metal is heavily cold-worked, much of the strain energy expended in the plastic deformation is stored in the metal in the form of dislocations and other imperfections such as point defects. Thus a strain-hardened metal has a higher internal energy than an unstrained one. Figure 6.46*a* shows the microstructure (100×) of an Al 0.8% Mg alloy sheet that has been cold-worked with 85% reduction. Note that the grains are greatly elongated in the rolling direction. At higher magnification (20,000×), a thin-foil transmission electron micrograph (Fig. 6.47) shows the structure to consist of a cellular network with cell walls of high dislocation density. A fully cold-worked metal has a density of approximately 10^{12} dislocation lines/cm^2.

6.8.2 Recovery

When a cold-worked metal is heated in the recovery temperature range that is just below the recrystallization temperature range, internal stresses in the metal are relieved (Fig. 6.45). During recovery, sufficient thermal energy is supplied to allow

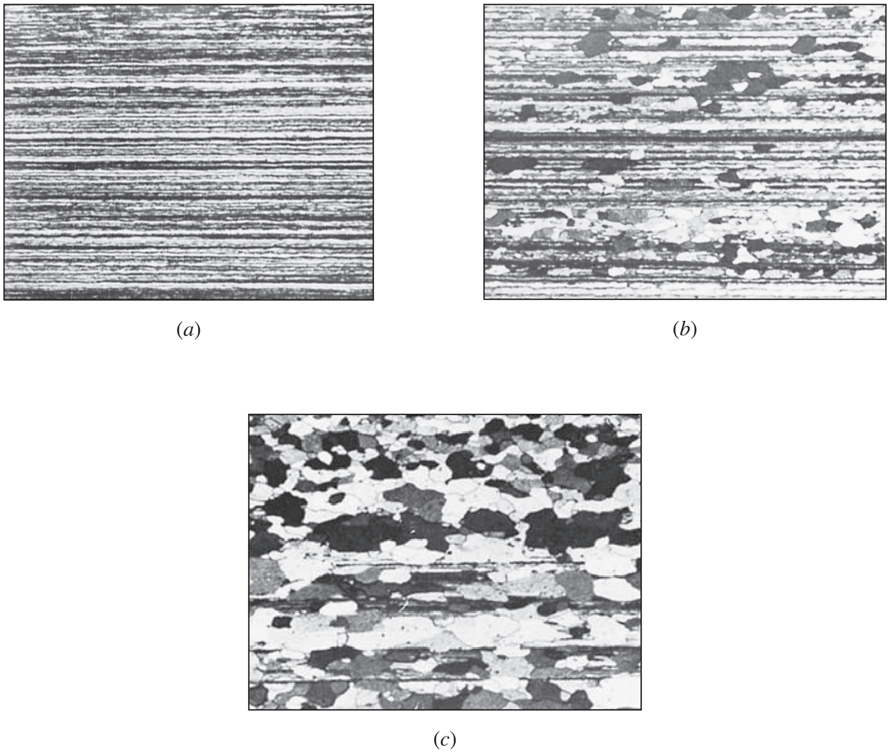


Figure 6.46
Aluminum alloy 5657 (0.8% Mg) sheet showing microstructures after cold rolling 85% and subsequent reheating (optical micrographs at 100× viewed under polarized light). (*a*) Cold-worked 85%; longitudinal section. Grains are greatly elongated. (*b*) Cold-worked 85% and stress-relieved at 302°C (575°F) for 1 h. Structure shows onset of recrystallization, which improves the formability of the sheet. (*c*) Cold-worked 85% and annealed at 316°C (600°F) for 1 h. Structure shows recrystallized grains and bands of unrecrystallized grains.
((a-c): ©ASM International)

the dislocations to rearrange themselves into lower-energy configurations (Fig. 6.48). Recovery of many cold-worked metals (such as pure aluminum) produces a subgrain structure with low-angle grain boundaries, as shown in Fig. 6.48*b*. This recovery process is called *polygonization,* and often it is a structural change that precedes recrystallization. The internal energy of the recovered metal is lower than that of the cold-worked state since many dislocations are annihilated or moved into lower-energy configurations by the recovery process. During recovery, the strength of a cold-worked metal is reduced only slightly, but its ductility is usually significantly increased (Fig. 6.45).

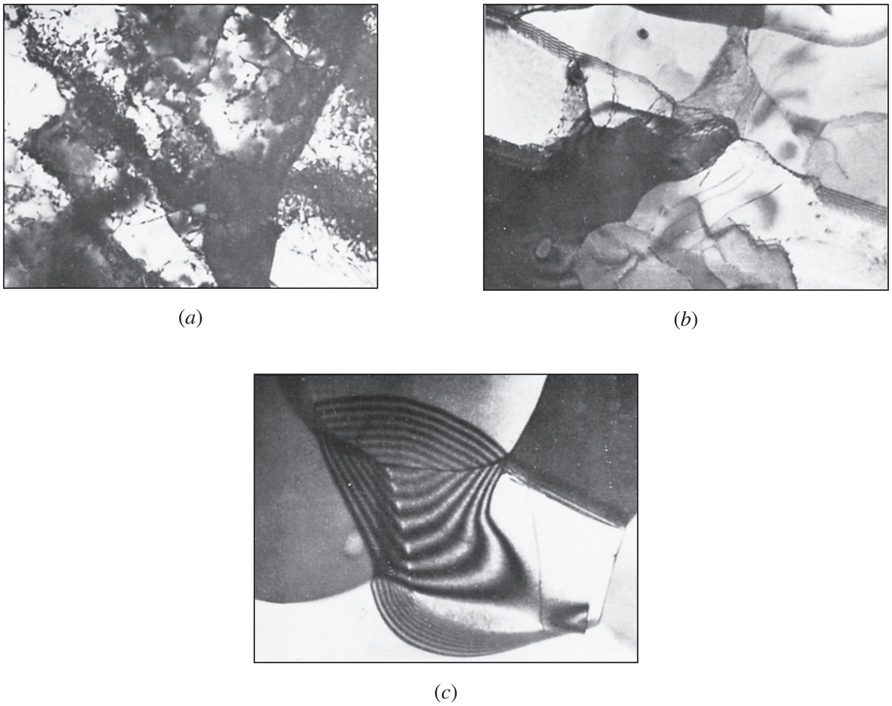


Figure 6.47
Aluminum alloy 5657 (0.8% Mg) sheet showing microstructures after cold rolling 85% and subsequent reheating. The microstructures shown in this figure were obtained by using thin-foil transmission electron microscopy. (Magnified 20,000×.) (*a*) Sheet was cold-worked 85%; micrograph shows dislocation tangles and banded cells (subgrains) caused by cold working extensively. (*b*) Sheet was cold-worked 85% and subsequently stress-relieved at 302°C (575°F) for 1 h. Micrograph shows dislocation networks and other low-angle boundaries produced by polygonization. (*c*) Sheet was cold-worked 85% and annealed at 316°C (600°F) for 1 h. Micrograph shows recrystallized structure and some subgrain growth.

6.8.3 Recrystallization

Upon heating a cold-worked metal to a sufficiently high temperature, new strain-free grains are nucleated in the recovered metal structure and begin to grow (Fig. 6.46*b*), forming a recrystallized structure. After a long enough time at a temperature at which recrystallization takes place, the cold-worked structure is completely replaced with a recrystallized grain structure, as shown in Fig. 6.46*c*.

Primary recrystallization occurs by two principal mechanisms: (1) an isolated nucleus can expand with a deformed grain (Fig. 6.49*a*) or (2) an original high-angle grain boundary can migrate into a more highly deformed region of the metal

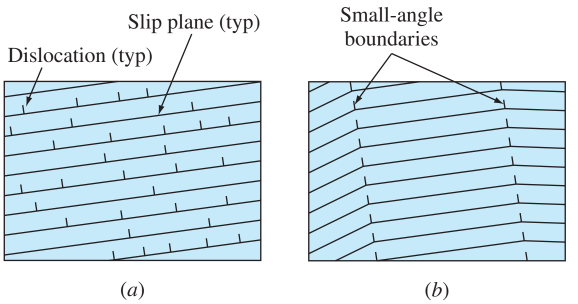


Figure 6.48
Schematic representation of polygonization in a deformed metal. (*a*) Deformed metal crystal showing dislocations piled up on slip planes. (*b*) After recovery heat treatment, dislocations move to form small-angle grain boundaries.
(Source: L. E. Tanner and I. S. Servi, *Metals Handbook, vol.* 8, 8th ed., American Society for Metals, 1973, p. 222.)

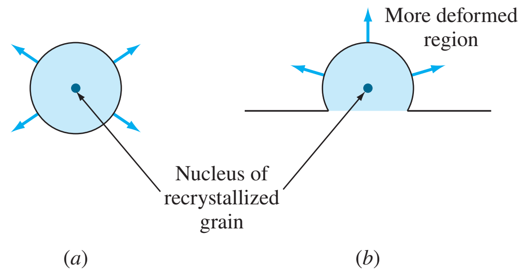


Figure 6.49
Schematic model of the growth of a recrystallized grain during the recrystallization of a metal. (*a*) Isolated nucleus expanded by growth within a deformed grain. (*b*) Original high-angle grain boundary migrating into a more highly deformed region of metal.

(Fig. 6.49*b*). In either case, the structure on the concave side of the moving boundary is strain-free and has a relatively low internal energy, whereas the structure on the convex side of the moving interface is highly strained with a high dislocation density and high internal energy. Grain boundary movement is therefore away from the boundary's center of curvature. Thus, the growth of an expanding new grain during primary recrystallization leads to an overall decrease in the internal energy of the metal by replacing deformed regions with strain-free regions.

The tensile strength of a cold-worked metal is greatly decreased and its ductility increased by an annealing treatment that causes the metal structure to be recrystallized. For example, the tensile strength of a 0.040-in. (1-mm) sheet of 85% Cu–15% Zn brass that had been cold-rolled to 50% reduction was decreased from 75 to 45 ksi (520 to 310 MPa) by annealing 1 h at 400°C (Fig. 6.50*a*). The ductility of the sheet, on the other hand, was increased from 3% to 38% with the annealing treatment (Fig. 6.50*b*). Figure 6.51 shows a schematic diagram of a continuous annealing process for sheet steel.

Important factors that affect the recrystallization process in metals and alloys are (1) amount of prior deformation of the metal, (2) temperature, (3) time, (4) initial grain size, and (5) composition of the metal or alloy. The recrystallization of a metal can take place over a range of temperatures, and the range is dependent to some extent on the variables just listed. Thus, one cannot refer to the recrystallization temperature of a metal in the same sense as the melting temperature of a pure metal. The following generalizations can be made about the recrystallization process:

1. A minimum amount of deformation of the metal is necessary for recrystallization to be possible.
2. The smaller the degree of deformation (above the minimum), the higher the temperature needed to cause recrystallization.

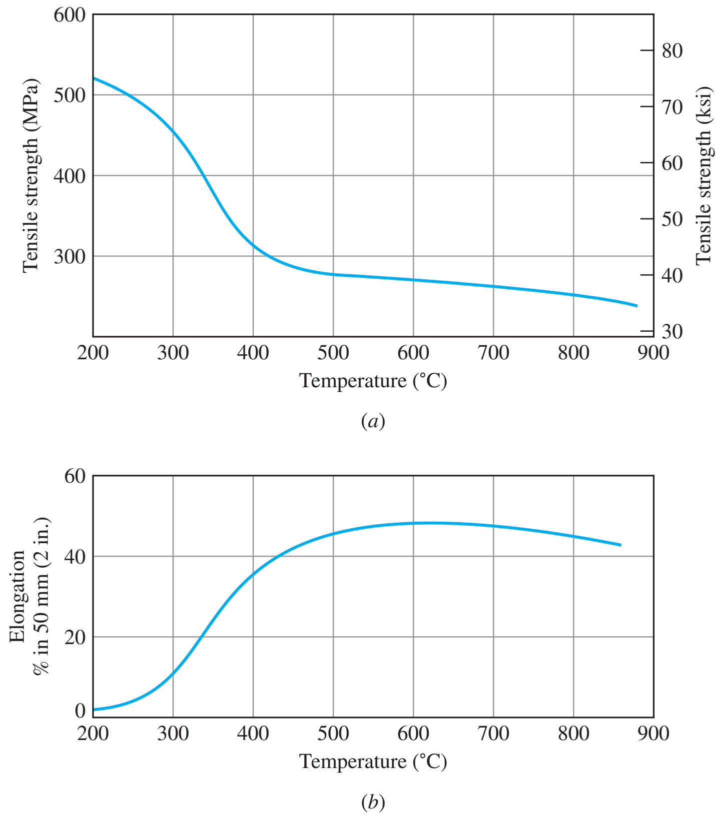


Figure 6.50

Effect of annealing temperature on (*a*) the tensile strength and (*b*) elongation of a 50% cold-rolled 85% Cu–15% Zn, 0.040-in. (1 mm) thick sheet. (Annealing time was 1 h at temperature.)

(Source: *Metals Handbook,* vol. 2, 9th ed., American Society for Metals, 1979, p. 320.)

3. Increasing the temperature for recrystallization decreases the time necessary to complete it (see Fig. 6.52).

4. The final grain size depends mainly on the degree of deformation. The greater the degree of deformation, the lower the annealing temperature for recrystallization and the smaller the recrystallized grain size.

5. The larger the original grain size, the greater the amount of deformation required to produce an equivalent recrystallization temperature.

6. The recrystallization temperature decreases with increasing purity of the metal. Solid-solution alloying additions always increase the recrystallization temperature.

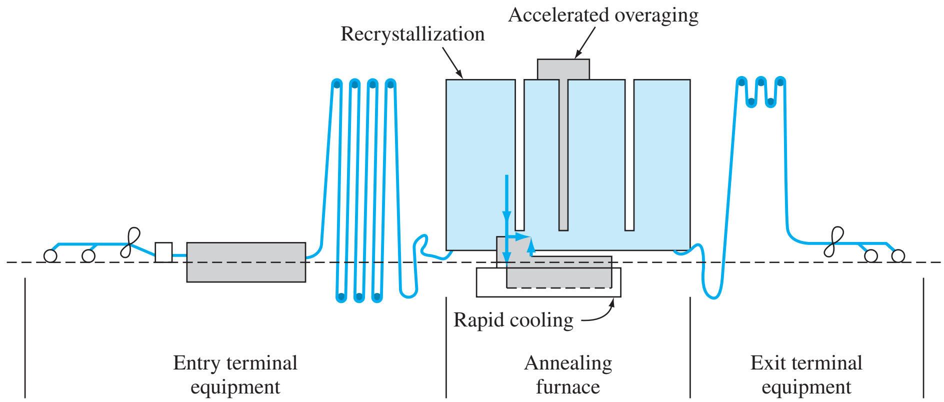


Figure 6.51
Continuous annealing schematic diagram.
(Source: W. L. Roberts, *Flat Processing of Steel,* Marcel Dekker, 1988.)

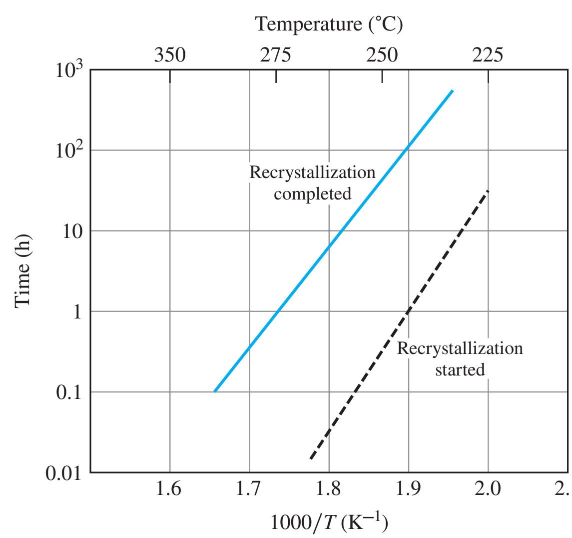


Figure 6.52
Time-temperature relations for the recrystallization of 99.0% Al cold-worked 75%. The solid line is for recrystallization finished and the dashed line for recrystallization started. Recrystallization in this alloy follows an Arrhenius-type relationship of ln t versus $1/T(K^{-1})$.
(Source: *Aluminum,* vol. 1, American Society for Metals, 1967, p. 98.)

EXAMPLE PROBLEM 6.12

If it takes 9.0×10^3 min to recrystallize a piece of copper at 88°C and 200 min at 135°C, what is the activation energy for the process, assuming the process obeys the Arrhenius rate equation and the time to recrystallize $= Ce^{-Q/RT}$, where $R = 8.314$ J/(mol · K) and T is in kelvins?

■ **Solution**

$$t_1 = 9.0 \times 10^3 \text{ min}; \; T_1 = 88^\circ\text{C} + 273 = 361 \text{ K}$$
$$t_2 = 200 \text{ min}; \; T_2 = 135^\circ\text{C} + 273 = 408 \text{ K} \tag{6.19}$$
$$t_1 = Ce^{Q/RT_1} \quad \text{or} \quad 9.0 \times 10^3 \text{ min} = Ce^{Q/R(361\text{ K})}$$
$$t_2 = Ce^{Q/RT_2} \quad \text{or} \quad 200 \text{ min} = Ce^{Q/R(408\text{ K})} \tag{6.20}$$

Dividing Eq. 6.19 by 6.20 gives

$$45 = \exp\left[\frac{Q}{8.314}\left(\frac{1}{361} - \frac{1}{408}\right)\right]$$

$$\ln 45 = \frac{Q}{8.314}(0.00277 - 0.00245) = 3.80$$

$$Q = \frac{3.80 \times 8.314}{0.000319} = 99{,}038 \text{ J/mol or } 99.0 \text{ kJ/mol} \blacktriangleleft$$

6.9 SUPERPLASTICITY IN METALS

A careful examination of Figure 6.23 shows that most metals, even those that are classified as ductile, undergo a limited amount of plastic deformation prior to fracture. For example, mild steel undergoes 22% elongation before fracture in uniaxial tensile tests. As discussed in Section 6.1, many metal-forming operations are performed at elevated temperatures in order to achieve a higher degree of plastic deformation by increasing the ductility of the metal. **Superplasticity** refers to the ability of some metal alloys, such as some aluminum and titanium alloys, to deform as much as 2000% at elevated temperatures and slow loading rates. These alloys do not behave superplastically when loaded at normal temperatures. For example, annealed Ti alloy (6Al-4V) elongates close to 12% prior to fracture in a conventional tensile test at room temperature. The same alloy, when tested at elevated temperatures (840°C to 870°C) and at very low loading rates ($1.3 \times 10^{-4}\ s^{-1}$), can elongate as much as 750% to 1170%. To achieve superplasticity, the material and the loading process must meet certain conditions:

1. The material must possess very fine grain size (5–10 μm) and be highly strain-rate sensitive.
2. A high loading temperature greater than 50% of the melt temperature of the metal is required.
3. A low and controlled strain rate in the range of 0.01 to 0.0001 s^{-1} is required.[10]

[10] High strain rate ($>10^{-2}s^{-1}$) superplasticity has been reported in some aluminum alloys.

These requirements are not easily achievable for all materials, and therefore not all materials can attain superplastic behavior. In most cases, condition (1) is very difficult to achieve, that is, ultrafine grain size.[11]

Superplastic behavior is an extremely useful property that can be used to manufacture complex structural components. The question is, "What is the deformation mechanism that accounts for this incredible level of plastic deformation?" In previous sections, we discussed the role of dislocations and their movements on the plastic behavior of materials under room temperature loading. As dislocations move across the grain, plastic deformation is produced. But as grain size decreases, the movement of dislocations becomes more limited and the material becomes stronger. However, metallographical analysis of materials that undergo superplastic behavior has revealed very limited dislocation activity inside the grain. This supports the fact that superplastic materials are susceptible to other deformation mechanisms such as grain boundary sliding and grain boundary diffusion. At elevated temperatures, a large amount of strain is believed to be accumulated by the sliding and rotation of individual grains or clusters of grains relative to each other. There is also a belief that grain boundary sliding is accommodated by a gradual change in grain shape as matter is moved by diffusion across the grain boundary. Figure 6.53 shows schematically the superplacticity effect in Zn-22% Al alloy at a temperature of 473 K (200°C) and various strain rates. It is clear from the figure that in order to achieve such extreme deformation levels, the grains must undergo significant sliding and rotation.

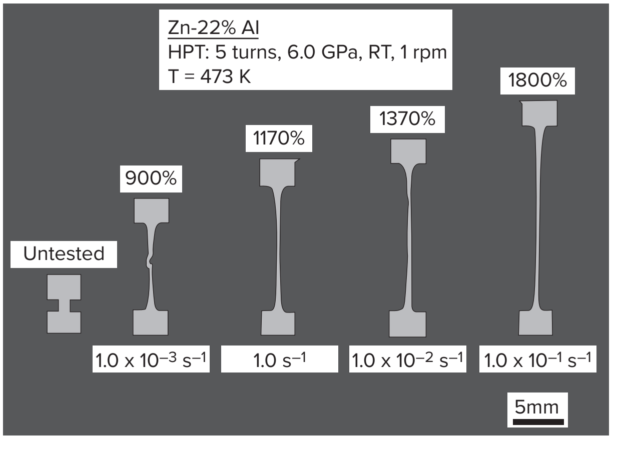
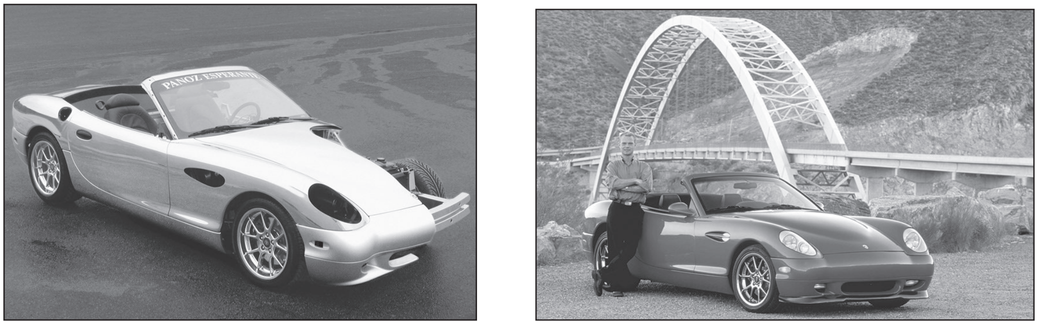


Figure 6.53
Superplastic deformation in Zn-22% Al alloy tensile test specimens. Note levels of plastic deformation exceeding 900% at various strain rates. In comparison, normal deformation level in metals rarely exceeds 25%.

[11] Static and dynamic recrystallization, mechanical alloying, and other techniques are used to create ultrafine grain structure.



(*a*) (*b*)

Figure 6.54
The hood for an automobile made of superplastic aluminum using the blow-molding method.
((a-b): Courtesy of Panoz Auto)

Many manufacturing processes exist that take advantage of the superplastic behavior of materials to produce complex components. Blow forming is one such process in which a superplastic material is forced under gas pressure to deform and take the shape of a die. Figure 6.54 shows the hood of an automobile that is made from superplastically formed aluminum alloy using the blow-forming method. Also, superplastic behavior can be combined with diffusion bonding (a metal-joining method) to produce structural components with limited material waste.

6.10 NANOCRYSTALLINE METALS

In Chapter 1, the concept of nanotechnology and nanostructured materials was introduced. Any material with length scale features below 100 nm is classified as *nanostructured.* According to this definition, all metals with average grain diameters less than 100 nm are considered nanostructured or nanocrystalline. The question is, "What are the advantages of **nanocrystalline metals**?" Metallurgists have always been aware that by reducing the grain size, a harder, stronger, and tougher metal may be produced as evidenced by the Hall–Petch equation (6.18). It has also been known that at ultrafine grain-size levels (not necessarily nanocrystalline) and under certain temperature and loading rate conditions, some materials can deform plastically to many times their conventional levels, that is, they achieve superplasticity.

Noting the characteristics attributed to ultrafine grain sizes and extrapolating the Hall–Petch equation for nanocrystalline metals, one can foresee some extraordinary possibilities. Consider the possibility that, according to the Hall–Petch equation, if the average grain diameter of a metal decreases from 10 mm to 10 μm, its yield strength will increase by a factor of 31. Is this possible? How do nanograins affect the ductility, toughness, fatigue, and creep behavior of metals? How can we produce bulk metals with nanocrystalline structure? These questions and others like them are the driving force in research and development in the field of nanocrystalline metals. Therefore, at least in metal-manufacturing industries, the potential for improved properties with reduced grain size or dispersing secondary nanophases has been known for many decades. The difficulty has been in developing metal-forming techniques that can produce truly nanocrystalline ($d < 100$ nm) metals. In recent decades, new techniques for producing such materials have been developed, and older techniques have been improved. Thus, those studying these materials are enthusiastic.

It has been reported that the modulus of elasticity of nanocrystalline materials is comparable to bulk microcrystalline materials for grain sizes exceeding 5 nm. For d less than 5 nm, a decrease in the modulus of elasticity of metals such as nanocrystalline iron has been reported. It is not completely clear why such a drop in the modulus of elasticity occurs; one may find a reason by considering that for such small grains, the majority of the atoms are positioned on the surface of the grain (as opposed to inside the grain) and therefore along the grain boundary. This is completely opposite what is found in microcrystalline materials.

As discussed previously, the hardness and strength of materials increase with a decrease in grain size. This increase in hardness and strength is due to dislocation pileup and the hindrance of dislocation motion for conventional grains. For nanocrystalline materials, most available data are based on hardness values obtained from nanohardness tests. This is mostly due to the fact that tensile specimens with nanocrystalline structure are hard to produce. But since strength and hardness are closely correlated, nanohardness tests are acceptable at this time. It has been established that as grain size decreases to around 10 nm, the hardness increases by factors of four to six for nanocrystalline copper and six to eight for nanocrystalline nickel when compared to large-grained metals ($d > 1\ \mu$m). Although this is an impressive increase, it still falls drastically short of the prediction made by the Hall–Petch equation. Additionally, there are published data that indicate a "negative Hall–Petch effect" at the finest grain size ($d < 30$ nm), indicating that a softening mechanism is at work. Some researchers believe that it is entirely possible that at such small grain levels, the concept of a moving dislocation or dislocation pileup is no longer applicable and other mechanisms, such as grain boundary sliding, diffusion, etc., are at work.

Arguments have been made that in the upper nanocrystalline range (50 nm $< d$ < 100 nm), dislocation-related activities similar to those seen with microcrystalline metals dominate, while in the lower nanocrystalline range ($d < 50$ nm), dislocation activity (formation and movement) decreases significantly. Stresses needed to activate dislocation sources are extremely high at such small grain sizes. Some in situ HRTEM studies have been performed that support this argument. Finally, the strengthening and deformation mechanisms of nanocrystalline materials are not yet well understood, and more theoretical and experimental research is needed. In the next chapter, the ductility and toughness characteristics of these materials will be discussed.

6.11 SUMMARY

Metals and alloys are processed into different shapes by various manufacturing methods. Some of the most important industrial processes are casting, rolling, extruding, wire drawing, forging, and deep drawing.

When a uniaxial stress is applied to a long metal bar, the metal deforms elastically at first and then plastically, causing permanent deformation. For many engineering designs, the engineer is interested in the 0.2% offset yield strength, ultimate tensile strength, and elongation (ductility) of a metal or alloy. These quantities are obtained from the engineering stress-strain diagram originating from a tensile test. The hardness of a metal may also be of engineering importance. Commonly used hardness scales in industry are Rockwell B and C and Brinell (BHN).

Grain size has a direct impact on the properties of a metal. Metals with fine grain size are stronger and have more uniform properties. The strength of metal is related to its grain size through an empirical relationship called the Hall–Petch equation. Metals with grain size in the nanoscale range (nanocrystalline metals) are expected to have ultra-high strength and hardness as predicted by the Hall–Petch equation.

When a metal is plastically deformed by cold working, the metal becomes strain hardened, resulting in an increase in its strength and a decrease in its ductility. The strain hardening can be removed by giving the metal an annealing heat treatment. When the strain-hardened metal is slowly heated to a high temperature below its melting temperature, the processes of recovery, recrystallization, and grain growth take place, and the metal is softened. By combining strain hardening and annealing, large thickness reductions of metal sections can be accomplished without fracture.

By deforming some metals at high temperature and slow-loading rates, it is possible to achieve superplasticity, that is, deformation on the order of 1000% to 2000%. The grain size must be ultrafine to achieve superplasticity.

Plastic deformation of metals takes place most commonly by the slip process, involving the movement of dislocations. Slip usually takes place on the closest-packed planes and in the closest-packed directions. The combination of a slip plane and a slip direction constitutes a slip system. Metals with a high number of slip systems are more ductile than those with only a few slip systems. Many metals deform by twinning when slip becomes difficult.

Grain boundaries at lower temperatures usually strengthen metals by providing barriers to dislocation movement. However, under some conditions of high-temperature deformation, grain boundaries become regions of weakness due to grain boundary sliding.

6.12 DEFINITIONS

Sec. 6.1

Hot working of metals: permanent deformation of metals and alloys above the temperature at which a strain-free microstructure is produced continuously (recrystallization temperature).

Cold working of metals: permanent deformation of metals and alloys below the temperature at which a strain-free microstructure is produced continuously (recrystallization temperature). Cold working causes a metal to be strain-hardened.

Percent cold reduction:

$$\%\text{ cold reduction} = \frac{\text{change in cross-sectional area}}{\text{original cross-sectional area}} \times 100\%$$

Annealing: a heat treatment used on a metal to soften it.

Extrusion: a plastic-forming process in which a material under high pressure is reduced in cross section by forcing it through an opening in a die.

Forging: a primary-processing method for working metals into useful shapes in which the metal is hammered or pressed into shape.
Wire drawing: a process in which wire stock is drawn through one or more tapered dies to the desired cross section.
Deep drawing: A metal-forming process for shaping flat sheets of metal into cup-shaped articles.

Sec. 6.2
Elastic deformation: if a metal deformed by a force returns to its original dimensions after the force is removed, the metal is said to be elastically deformed.
Engineering stress σ: average uniaxial force divided by original cross-sectional area ($\sigma = F/A_0$).
Engineering strain ϵ: change in length of sample divided by the original length of sample ($\epsilon = \Delta l/l_0$).
Shear stress τ: shear force S divided by the area A over which the shear force acts ($\tau = S/A$).
Shear strain γ: shear displacement a divided by the distance h over which the shear acts ($\gamma = a/h$).

Sec. 6.3
Engineering stress-strain diagram: experimental plot of engineering stress versus engineering strain; σ is normally plotted as the y axis and ϵ as the x axis.
Modulus of elasticity *E:* stress divided by strain (σ/ϵ) in the elastic region of an engineering stress-strain diagram for a metal ($E = \sigma/\epsilon$).
Yield strength: the stress at which a specific amount of strain occurs in the engineering tensile test. In the U.S., the yield strength is determined for 0.2% strain.
Ultimate tensile strength (UTS): the maximum stress in the engineering stress-strain diagram.

Sec. 6.4
Hardness: a measure of the resistance of a material to permanent deformation.

Sec. 6.5
Slip: the process of atoms moving over each other during the permanent deformation of a metal.
Slipbands: line markings on the surface of a metal due to slip caused by permanent deformation.
Slip system: a combination of a slip plane and a slip direction.
Deformation twinning: a plastic deformation process that occurs in some metals and under certain conditions. In this process, a large group of atoms displaced to form a region of a metal crystal lattice that is a mirror image of a similar region along a twinning plane.

Sec. 6.6
Hall–Petch relationship: an empirical equation that relates the strength of a metal to its grain size.
Strain hardening (strengthening): the hardening of a metal or alloy by cold working. During cold working, dislocations multiply and interact, leading to an increase in the strength of the metal.

Sec. 6.7
Solid-solution hardening (strengthening): strengthening a metal by alloying additions that form solid solutions. Dislocations have more difficulty moving through a metal lattice when the atoms are different in size and electrical characteristics, as is the case with solid solutions.

Sec. 6.8
Annealing: a heat-treatment process applied to a cold-worked metal to soften it.
Recovery: the first stage in the annealing process that results in removal of residual stresses and formation of low-energy dislocation configurations.
Recrystallization: the second stage of the annealing process in which new grains start to grow and dislocation density decreases significantly.
Grain growth: the third stage of the annealing process in which new grains start to grow in an equiaxed manner.

Sec. 6.9
Superplasticity: the ability of some metals to deform plastically by 1000% to 2000% at high temperatures and low loading rates.

Sec. 6.10
Nanocrystalline metals: metals with grain size smaller than 100 nm.

6.13 PROBLEMS

Answers to problems marked with an asterisk are given at the end of the book.

Knowledge and Comprehension Problems

6.1 (*a*) How are metal alloys made by the casting process? (*b*) Distinguish between wrought alloy products and cast alloy products.

6.2 Why are cast metal sheet ingots hot-rolled first instead of being cold-rolled?

6.3 What type of heat treatment is given to the rolled metal sheet after hot and "warm" rolling? What is its purpose?

6.4 Describe and illustrate the following types of extrusion processes: (*a*) direct extrusion and (*b*) indirect extrusion. What is an advantage of each process?

6.5 Describe the forging process. What is the difference between hammer and press forging?

6.6 What is the difference between open-die and closed-die forging? Illustrate. Give an example of a metal product produced by each process.

6.7 Describe the wire-drawing process. Why is it necessary to make sure the surface of the incoming wire is clean and lubricated?

6.8 Distinguish between elastic and plastic deformation (use schematics).

6.9 Define (*a*) engineering stress and strain and (*b*) true stress and strain. (*c*) What are the U.S. customary and SI units for stress and strain? (*d*) Distinguish between normal and shear stress. (*e*) Distinguish between normal strain and shear strain.

6.10 Define (*a*) modulus of elasticity, (*b*) yield strength, (*c*) ultimate tensile strength, (*d*) modulus of resilience, (*e*) toughness, (*f*) Poisson's ratio, (*g*) ductility.

6.11 (*a*) Define the hardness of a metal. (*b*) How is the hardness of a material determined by a hardness testing machine?

6.12 What types of indenters are used in (*a*) the Brinell hardness test, (*b*) Rockwell C hardness test, and (*c*) Rockwell B hardness test?

6.13 What are slipbands and slip lines? What causes the formation of slipbands on a metal surface?

6.14 Describe the slip mechanism that enables a metal to be plastically deformed without fracture.

6.15 (*a*) Why does slip in metals usually take place on the densest-packed planes? (*b*) Why does slip in metals usually take place in the closest-packed directions?

6.16 (*a*) What are the principal slip planes and slip directions for FCC metals? (*b*) What are the principal slip planes and slip directions for BCC metals? (*c*) What are the principal slip planes and slip directions for HCP metals?

6.17 What other types of slip planes are important other than the basal planes for HCP metals with low c/a ratios?

6.18 Define the critical resolved shear stress for a pure metal single crystal. What happens to the metal from the macroscale point of view and behavior point of view once critical resolved shear stress is exceeded?

6.19 Describe the deformation twinning process that occurs in some metals when they are plastically deformed.

6.20 What is the difference between the slip and twinning mechanisms of plastic deformation of metals?

6.21 What important role does twinning play in the plastic deformation of metals with regard to deformation of metals by slip?

6.22 By what mechanism do grain boundaries strengthen metals?

6.23 What experimental evidence shows that grain boundaries arrest slip in polycrystalline metals?

6.24 (*a*) Describe the grain shape changes that occur when a sheet of alloyed copper with an original equiaxed grain structure is cold-rolled with 30% and 50% cold reductions. (*b*) What happens to the dislocation substructure?

6.25 How is the ductility of a metal normally affected by cold working? Why?

6.26 (*a*) What is solid-solution strengthening? Describe the two main types. (*b*) What are two important factors that affect solid-solution hardening?

6.27 What are the three main metallurgical stages that a sheet of cold-worked metal such as aluminum or copper goes through as it is heated from room temperature to an elevated temperature just below its melting point?

6.28 Describe the microstructure of a heavily cold-worked metal of an Al–0.8% Mg alloy as observed with an optical microscope at 100× (see Fig. 6.46*a*). Describe the microstructure of the same material at 20,000× (see Fig. 6.47*a*).

6.29 Describe what occurs microscopically when a cold-worked sheet of metal such as aluminum undergoes a recovery heat treatment.

6.30 When a cold-worked metal is heated into the temperature range where recovery takes place, how are the following affected: (*a*) internal residual stresses, (*b*) strength, (*c*) ductility, and (*d*) hardness?

6.31 Describe what occurs microscopically when a cold-worked sheet of metal such as aluminum undergoes a recrystallization heat treatment.

6.32 When a cold-worked metal is heated into the temperature range where recrystallization takes place, how are the following affected: (*a*) internal residual stresses, (*b*) strength, (*c*) ductility, and (*d*) hardness?

6.33 Describe two principal mechanisms whereby primary recrystallization can occur.

6.34 What are five important factors that affect the recrystallization process in metals?

6.35 What generalizations can be made about the recrystallization temperature with respect to (*a*) the degree of deformation, (*b*) the temperature, (*c*) the time of heating at temperature, (*d*) the final grain size, and (*e*) the purity of the metal?

6.36 Define superplasticity and list the conditions under which superplasticity can be achieved. Why is this an important behavior?

6.37 Discuss the major deformation mechanism that results in extensive plastic deformation in superplasticity.

6.38 Why are nanocrystalline materials stronger? Answer based on dislocation activity.

Application and Analysis Problems

6.39 A 70% Cu–30% Zn brass sheet is 0.0955 cm thick and is cold-rolled with a 30% reduction in thickness. What must be the final thickness of the sheet?

6.40 A sheet of aluminum alloy is cold-rolled 30% to a thickness of 0.080 in. If the sheet is then cold-rolled to a final thickness of 0.064 in., what is the total percent cold work done?

6.41 Calculate the percent cold reduction when an aluminum wire is cold-drawn from a diameter of 5.25 mm to a diameter of 2.30 mm.

6.42 A brass wire is cold-drawn 25% to a diameter of 1.10 mm. It is then further cold-drawn to 0.900 mm. What is the total percent cold reduction?

6.43 What is the relationship between engineering strain and percent elongation?

6.44 A tensile specimen of cartridge brass sheet has a cross section of 0.320 in. × 0.120 in. and a gage length of 2.00 in. Calculate the engineering strain that occurred during a test if the distance between gage markings is 2.35 in. after the test.

6.45 A 0.505-in.-diameter rod of an aluminum alloy is pulled to failure in a tension test. If the final diameter of the rod at the fractured surface is 0.440 in., what is the percent reduction in area of the sample due to the test?

6.46 The following engineering stress-strain data were obtained for a 0.2% C plain-carbon steel. (*a*) Plot the engineering stress-strain curve. (*b*) Estimate the yield strength of the metal. (*c*) Determine the ultimate tensile strength of the alloy. (*d*) Determine the percent elongation at fracture. (*e*) Estimate the modulus of resilience. (*f*) Estimate the toughness of the metal.

Engineering Stress (ksi)	Engineering Strain (in./in.)	Engineering Stress (ksi)	Engineering Strain (in./in.)
0	0	76	0.08
30	0.001	75	0.10
55	0.002	73	0.12
60	0.005	69	0.14
68	0.01	65	0.16
72	0.02	56	0.18
74	0.04	51	(Fracture) 0.19
75	0.06		

6.47 In Figure 6.23, estimate the toughness of SAE 1340 and annealed N-155 alloy sheet. Which material has the highest modulus of elasticity?

6.48 The following engineering stress-strain data were obtained at the beginning of a tensile test for a 0.2% C plain carbon steel. (*a*) Plot the engineering stress-strain curve for these data. (*b*) Determine the 0.2% offset yield stress for this steel. (*c*) Determine the tensile elastic modulus of this steel. (*d*) Estimate the modulus of resilience. (Note that these data only give the beginning part of the stress-strain curve.)

Engineering Stress (ksi)	Engineering Strain (in./in.)	Engineering Stress (ksi)	Engineering Strain (in./in.)
0	0	60	0.0035
15	0.0005	66	0.004
30	0.001	70	0.006
40	0.0015	72	0.008
50	0.0020		

6.49 In Figure 6.23, estimate the UTS for each metal. Also, identify the material with the largest ductility.

6.50 A 0.505-in.-diameter aluminum alloy test bar is subjected to a load of 25,000 lb. If the diameter of the bar is 0.490 in. at this load, determine (*a*) the engineering stress and strain and (*b*) the true stress and strain.

6.51 A 20-cm-long rod with a diameter of 0.250 cm is loaded with a 5000 N weight. If the diameter decreases to 0.210 cm, determine (*a*) the engineering stress and strain at this load and (*b*) the true stress and strain at this load.

6.52 A stress of 75 MPa is applied in the [001] direction on an FCC single crystal of copper. Calculate (*a*) the resolved shear stress acting on the (111) $[\bar{1}01]$ slip system and (*b*) the resolved shear stress acting on the (111) $[\bar{1}10]$ slip system. (*c*) Using data in Table 6.4, determine if slip occurs in any of the above systems.

6.53 A stress of 55 MPa is applied in the [001] direction of a BCC single crystal of molybdenum. Calculate (*a*) the resolved shear stress acting on the (101) $[\bar{1}11]$ system and (*b*) the resolved shear stress acting on the (110) $[\bar{1}11]$ system. (*c*) Using data in Table 6.4, determine if slip occurs in any of the above systems.

6.54 The highest yield strength of a single crystal of copper is given in Table 6.4 to be 0.94 MPa. The yield strength of the same metal but in a polycrystalline form is given to be approximately 6 MPa. How do you explain the difference?

6.55 A 2-in. rod of a metal specimen is compressed to half its length. Determine both the engineering and the true strain at this point. Compare the values and draw a conclusion.

6.56 Compare the yield strength of a copper specimen with an average grain diameter of 0.8 μm with another copper specimen with an average grain diameter of 80 nm using the Hall–Petch equation.

6.57 A specimen of commercially pure titanium has a strength of 140 MPa. Estimate its average grain diameter using the Hall–Petch equation.

6.58 The average grain diameter of an aluminum alloy is 14 μm with a strength of 185 MPa. The same alloy with an average grain diameter of 50 μm has a strength of 140 MPa. (*a*) Determine the constants for the Hall–Petch equation for this alloy. (*b*) How much more should you reduce the grain size if you desired a strength of 220 MPa?

6.59 An oxygen-free copper rod must have a tensile strength of 50.0 ksi and a final diameter of 0.250 in. (*a*) What amount of cold work must the rod undergo (see Fig. 6.43)? (*b*) What must the initial diameter of the rod be?

6.60 A 70% Cu–30% Zn brass sheet is to be cold-rolled from 0.070 to 0.040 in. (*a*) Calculate the percent cold work, and (*b*) estimate the tensile strength, yield strength, and elongation from Figure 6.44.

6.61 A 70% Cu–30% Zn brass wire is cold-drawn 20% to a diameter of 2.80 mm. The wire is then further cold-drawn to a diameter of 2.45 mm. (*a*) Calculate the total percent cold work that the wire undergoes. (*b*) Estimate the wire's tensile and yield strengths and elongation from Figure 6.44.

6.62 If it takes 115 h to 50% recrystallize an 1100-H18 aluminum alloy sheet at 250°C and 10 h at 285°C, calculate the activation energy in kilojoules per mole for this process. Assume an Arrhenius-type rate behavior.

6.63 If it takes 12.0 min to 50% recrystallize a piece of high-purity copper sheet at 140°C and 200 min at 88°C, how many minutes are required to recrystallize the sheet 50% at 100°C? Assume an Arrhenius-type rate behavior.

6.64 If it takes 80 h to completely recrystallize an aluminum sheet at 250°C and 6 h at 300°C, calculate the activation energy in kilojoules per mole for this process. Assume an Arrhenius-type rate behavior.

Synthesis and Evaluation Problems

6.65 How would you manufacture large propellers for large ships? What factors would influence the selection of material for this application?

6.66 If you were to make a large number of components from gold, silver, or other precious metals, what metal-forming process would you use and why?

6.67 A 20-mm-diameter, 350-mm-long rod made of an aluminum alloy 7075-T6 (use Figure 6.20 to estimate properties) is used in aircraft. Determine the elongation in the rod if a load of 60 kN is applied. What percentage of this elongation is elastic? At what load does the rod yield? What is the maximum load the bar can take without fracture?

6.68 If you were to select a material for the construction of a robotic arm that would result in the smallest amount of elastic deformation (important for positional accuracy of the arm) and weight were not a critical criterion, which one of the metals given in Figure 6.23 would you select? Why?

6.69 Consider the casting of a thick cylindrical shell made of cast iron. If the casting process is controlled such that solidification takes place from the inner walls of the tube outward, and as the outer layers solidify, they shrink and compress the inner layers, what would be the advantage of developed compressive stresses?

6.70 Consider casting a cube and a sphere on the same volume from the same metal. Which one would solidify faster? Why?

6.71 The load versus deformation data in the tensile testing of an unknown metal specimen are given in the following table:

Load (lb)	Elongation (in.)	Load (lb)	Elongation (in.)
0	0	23,000	0.16
2,500	0.0020	21,000	0.19
4,900	0.0040	18,250	0.21
13,000	0.010	17,250	0.22
19,000	0.014	15,250	0.23 (fracture)
20,000	0.026		
21,100	0.060		
22,200	0.11		

Plot the load deformation diagram for the unknown metal. Estimate (*a*) the load at which yield occurs, (*b*) the slope of the straight portion of the curve, (*c*) ultimate load, (*d*) elongation at failure, (*e*) energy under the linear portion of the curve. Does this curve tell you anything about the general material properties of the unknown metal?

6.72 In Problem 6.70, if the specimen has a cross-sectional area of 0.25 in.^{2} and a gauge length of 2, plot the engineering stress-strain diagram for the unknown metal. Estimate (*a*) the 0.2% offset yield strength, (*b*) the modulus of elasticity, (*c*) ultimate tensile strength, (*d*) percent elongation at failure, (*e*) modulus of resilience, and (*f*) toughness. What is the difference between the results here and those in the previous problem (you must solve the previous problem). Which of these properties can help you identify the general metal alloy category?

6.73 When manufacturing complex shapes using cold forging or shape rolling operations, the mechanical properties such as yield strength, tensile strength, and ductility measure differently depending on the location and direction on the manufactured part. (*a*) How do you explain this from a microscale point of view? (*b*) Will this happen during hot forging or rolling? Explain your answer.

6.74 (*a*) State the assumption behind the development of Eq. 6.15. (*b*) Is Eq. 6.15 (or its underlying assumption) valid throughout the engineering stress-strain curve?

6.75 Draw a generic engineering stress-strain diagram for a ductile metal and highlight the key strength points (yield, ultimate, and fracture strength) on the curve. (*a*) Schematically, show what happens if you load the specimen just below its yield point and then unload to zero. (*b*) Will the specimen behave differently if you load it again? Explain.

6.76 (*a*) Draw a generic engineering stress-strain diagram for a ductile metal and highlight the key strength points (yield, ultimate, and fracture strength) on the curve. Schematically, show what happens if you load the specimen just below its ultimate tensile strength point and then unload to zero. (*b*) Will the specimen behave differently if you load it again? Explain.

6.77 (*a*) Derive the relationship between true strain and engineering strain. (Hint: Start with the expression for engineering strain.) (*b*) Derive a relationship between true stress and engineering strain. (Hint: Start with $\sigma_t = F/A_i = (F/A_o)(A_o/A_i)$.)

6.78 The engineering yield strength of a copper alloy is 23.9 ksi and the modulus of elasticity is 16×10^6 psi. (*a*) Estimate the engineering strain just before yield. (*b*) What is the corresponding true strain? Are you surprised? Explain.

6.79 For the alloy in Problem 6.77, the engineering ultimate tensile strength is 38.8 ksi where the corresponding engineering strain 0.18. The reduction in area just before fracture is measured to be 34%. Determine (*a*) the true stress corresponding to the engineering ultimate tensile strength and (*b*) the true strain just before fracture.

6.80 The material for a rod of cross-sectional area 2.70 in.^{2} and length 75.0 in. must be selected such that under an axial load of 120,000.0 lb, it will not yield and the elongation in the bar will remain below 0.105 in. (*a*) Provide a list of at least three different metals that would satisfy these conditions. (*b*) Narrow the list down if cost is an issue. (*c*) Narrow the list down if corrosion is an issue. Use Appendix I for properties and cost of common alloys only.

6.81 What do E, G, v, U_r, and toughness tell you about a material (explain the physical significance of each to a nonengineer)?

6.82 A cylindrical component is loaded in tension until the cross-sectional area is reduced by 25% (the specimen does not neck or fracture). (*a*) Determine the true strain for the specimen at this loading level. (*b*) If you were to calculate the uniaxial stress in the specimen under the given conditions, would you use the true stress or the engineering stress? Support your answer by showing the difference.

6.83 Referring to Figures 6.20 and 6.21 (read the figure captions for details), determine (*a*) the change in length of the aluminum specimen (gage length) when the engineering stress reaches 85 ksi. (*b*) If at this point the specimen is slowly unloaded to zero load, what will the length of the specimen be in the unloaded state? (Show the unloading curve schematically).

6.84 (*a*) Show, using the definition of the Poisson's ratio, that it would be impossible to have a negative Poisson's ratio for isotropic materials. (*b*) What would it mean for a material to have a negative Poisson's ratio?

6.85 A one-inch cube of tempered stainless steel (alloy 316) is loaded along its z direction under a tensile stress of 60.00 ksi. (*a*) Draw a schematic of the cube before and after loading, showing the changes in dimension. (*b*) Repeat the problem assuming the cube is made of tempered aluminum (alloy 2024). Use Figure 6.15*b* and Appendix I for relevant data.

6.86 A one-inch cube of tempered stainless steel (alloy 316) is loaded on the same face with a shear stress of 30.00 ksi. Draw a schematic of the cube before and after loading, showing any changes in the shape. ($G = 11.01 \times 10^6$ psi; use Fig. 6.17*c*)

6.87 Three different metal alloys are tested for their hardness using the Rockwell scale. Metal 1 was rated at 60 R_B, metal 2 at 60 R_C, and metal 3 at 60 R_F. What do these ratings tell about these metals? Give an example of a component that is made of a metal that has a hardness of around 60 R_C.

6.88 A fellow student asks you, "What is the yield strength of titanium?" Can you answer this question? Explain.

6.89 A fellow student asks you, "What is the modulus of elasticity of plain carbon steel?" Can you answer this question? Explain.

6.90 A fellow student asks you, "What is the hardness of aluminum?" Can you answer this question? Explain.

6.91 Why do BCC metals in general require a higher value of τ_c than FCC metals when they both have the same number of slip systems?

6.92 Determine the tensile stress that must be applied to the $[1\bar{1}0]$ axis of a high-purity copper single crystal to cause slip on the $(1\bar{1}\bar{1})[0\bar{1}1]$ slip system. The resolved shear stress for the crystal is 0.85 MPa.

6.93 In the loading of a single crystal, (*a*) determine the angles ϕ and λ for which the maximum resolved shear stress occurs. (*b*) What will resolved shear stress be at this position (in terms of σ)?

6.94 (*a*) In the loading of a single crystal, how would you orient the crystal with respect to the loading axis to cause a resolved shear stress of zero? (*b*) What is the physical significance of this, that is, under these conditions, what happens to the crystal as σ increases?

6.95 Starting with a 2-in.-diameter rod of brass, we would like to process 0.2-in.-diameter rods that possess minimum yield strength of 40 ksi and a minimum elongation to fracture of 40% (see Fig. 6.44). Design a process that achieves that. Hint: Reduction of the diameter directly from 2 in. to 0.6 in. is not possible; why?

6.96 Why is it difficult to improve both strength and ductility simultaneously?

6.97 For a given application, a rod of copper of one-inch diameter is to be used. You have copper rods of various cross-sections available to you; however, all the bars are fully annealed with a yield strength of 10.0 ksi. The material must have a yield strength of at least 30.0 ksi and an elongation ability of at least 20.0%. Design a process that would achieve the expected goals. Use Figure 6.43 for your solution.

6.98 Without referring to tensile strength data or tables, which of the following substitutional solid solutions would you select if higher tensile strength was the selection criterion: Cu–30 wt% Zn or Cu–30 wt% Ni? Hint: Compare melt temperatures of Cu, Ni, and Zn.

6.99 The cupro-nickel substitutional solid solution alloys Cu–40 wt% Ni and Ni–10 wt% Cu have similar tensile strengths. For a given application in which only tensile strength is important, which one would you select?

6.100 In the rolling process, the selection of the roller material is critical. Based on your knowledge of both hot and cold rolling, what properties should the roller material have?