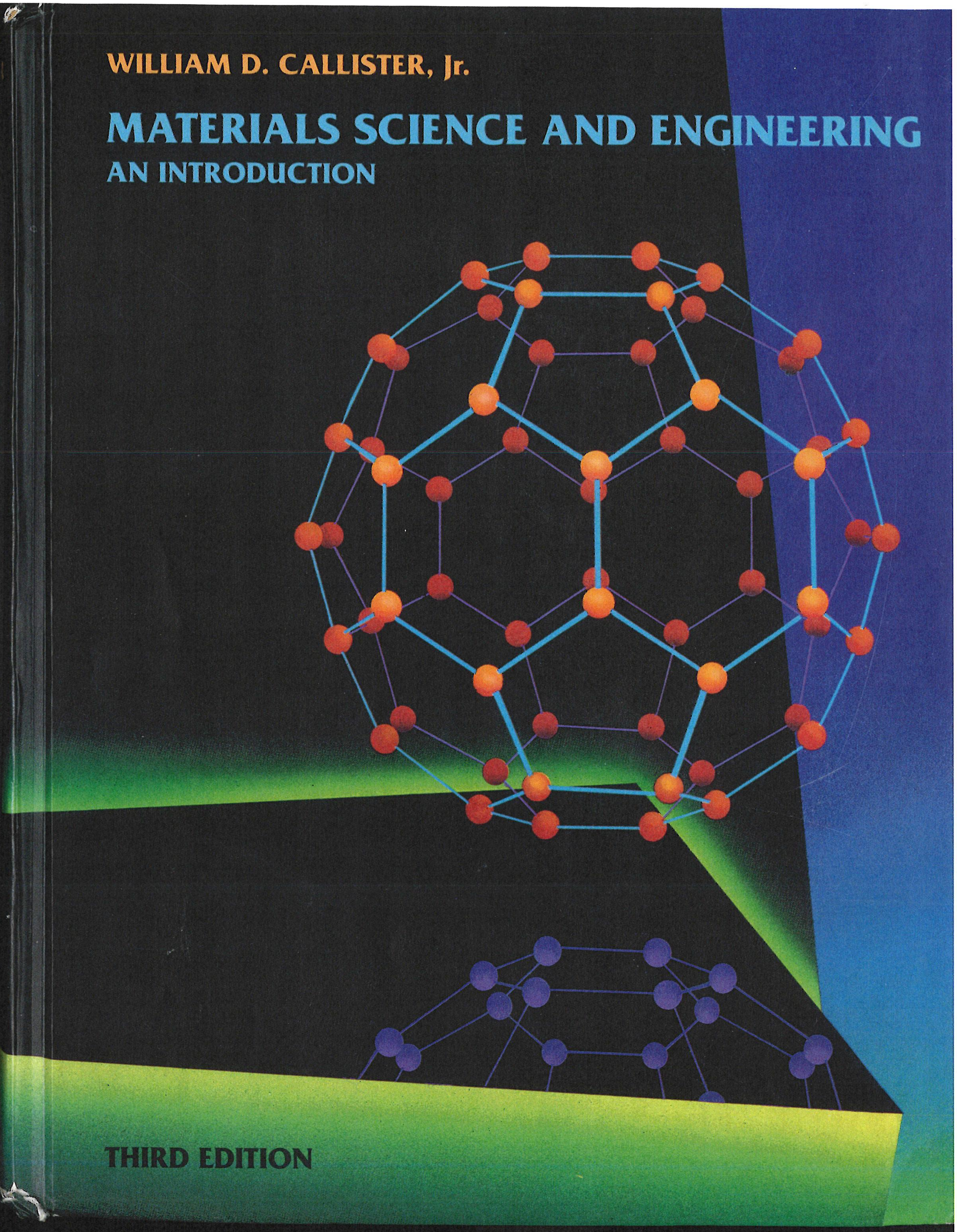
WILLIAM D. CALLISTER, Jr.

MATERIALS SCIENCE AND ENGINEERING

AN INTRODUCTION



THIRD EDITION

Front Cover: The hollow sphere-like object on the front cover represents the geometry assumed by a molecule of a newly discovered form of carbon. The molecule consists of sixty carbon atoms (denoted as C_{60}) that are bonded to one another at the corners of interlocking hexagons and pentagons that circumscribe the sphere. The material composed of the C_{60} molecules is known as *buckminsterfullerene,* named in honor of R. Buckminster Fuller who invented the geodesic dome; the C_{60} molecule is a replica of this dome, which is often referred to as a ''buckyball.'' The class of materials that are composed of these C_{60} molecules are termed the fullerenes. (Permission to use this figure was granted by Jerzy Bernholc, North Carolina State University.)

Back Cover: On the back cover is shown three smaller and hollow ball-like shapes which represent other configurations that have also been observed for molecular carbon. These molecules are composed of fewer than 60 carbons atoms, are less stable than the C_{60} molecule, and have outer surfaces that are also composed of interlocking hexagons and pentagons. The term ''buckybabies'' has been applied to these molecules inasmuch as they are smaller than the C_{60} buckyball. (Permission to use this figure was granted by Richard E. Smalley, Rice University.)

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It next becomes necessary to calculate the strain in the z direction using Equation 6.7. The value for Poisson's ratio for brass is 0.35 (Table 6.1), and thus

$$\epsilon_z = -\frac{\epsilon_x}{\nu} = -\frac{(-2.5 \times 10^{-4})}{0.35} = 7.14 \times 10^{-4}$$

The applied stress may now be computed using Equation 6.4 and the modulus of elasticity, given in Table 6.1 as 14.6 × 10^6 psi (10.1 × 10^4 MPa), as

$$\sigma = \epsilon_z E = (7.14 \times 10^{-4})(14.6 \times 10^6 \text{ psi}) = 10{,}400 \text{ psi}$$

Finally, from Equation 6.1, the applied force may be determined as

$$F = \sigma A_0 = \sigma \left(\frac{d_0}{2}\right)^2 \pi$$

$$= (10{,}400 \text{ psi}) \left(\frac{0.4 \text{ in.}}{2}\right)^2 \pi = 1310 \text{ lb}_f \text{ (5820 N)}$$

PLASTIC DEFORMATION

For most metallic materials, elastic deformation persists only to strains of about 0.005. As the material is deformed beyond this point, the stress is no longer proportional to strain (Hooke's law, Equation 6.4, ceases to be valid), and permanent, nonrecoverable, or **plastic deformation** occurs. Figure 6.9*a* plots schematically the tensile stress–strain behavior into the plastic region for a typical metal. The transition from elastic to plastic is a gradual one for most metals; some

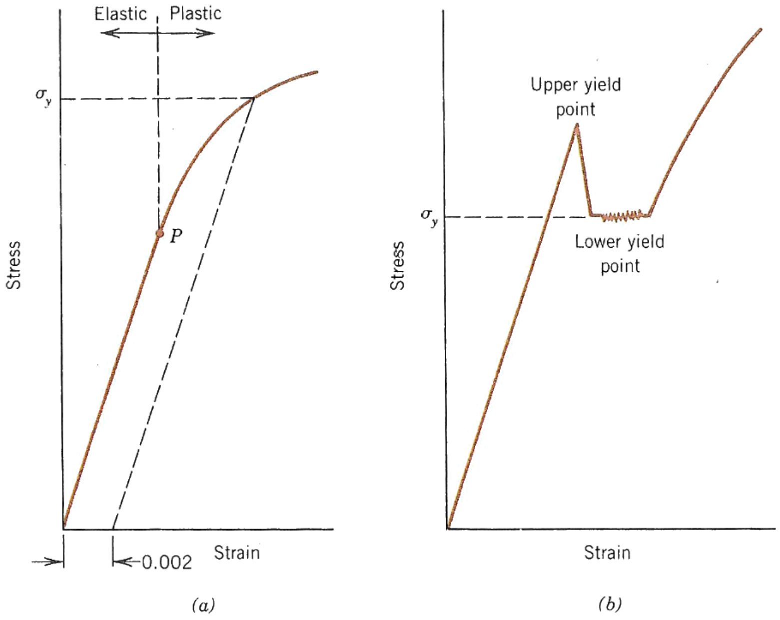

Figure 6.9 (*a*) Typical stress–strain behavior for a metal showing elastic and plastic deformations, the proportional limit P, and the yield strength σ_y, as determined using the 0.002 strain offset method. (*b*) Representative stress–strain behavior found for some steels demonstrating the yield point phenomenon.

curvature results at the onset of plastic deformation, which increases more rapidly with rising stress.

From an atomic perspective, plastic deformation corresponds to the breaking of bonds with original atom neighbors and then reforming bonds with new neighbors as large numbers of atoms or molecules move relative to one another; upon removal of the stress they do not return to their original positions. The mechanism of this deformation is different for crystalline and amorphous materials. For crystalline solids, deformation is accomplished by means of a process called slip, which involves the motion of dislocations as discussed in Section 7.2. Plastic deformation in noncrystalline solids (as well as liquids) occurs by a viscous flow mechanism, which is outlined in Section 13.9.

6.6 TENSILE PROPERTIES

Yielding and Yield Strength

Most structures are designed to ensure that only elastic deformation will result when a stress is applied. It is therefore desirable to know the stress level at which plastic deformation begins, or where the phenomenon of **yielding** occurs. For metals that experience this gradual elastic–plastic transition, the point of yielding may be determined as the initial departure from linearity of the stress–strain curve; this is sometimes called the **proportional limit,** as indicated by point P in Figure 6.9*a*. In such cases the position of this point may not be determined precisely. As a consequence, a convention has been established wherein a straight line is constructed parallel to the elastic portion of the stress–strain curve at some specified strain offset, usually 0.002. The stress corresponding to the intersection of this line and the stress–strain curve as it bends over in the plastic region is defined as the **yield strength** σ_y.[2] This is demonstrated in Figure 6.9*a*.

For those materials having a nonlinear elastic region (Figure 6.5), use of the strain offset method is not possible, and the usual practice is to define the yield strength as the stress required to produce some amount of strain (e.g., $\epsilon = 0.005$).

Some steels and other materials exhibit the tensile stress–strain behavior as shown in Figure 6.9*b*. The elastic–plastic transition is very well defined and occurs abruptly in what is termed a *yield point phenomenon*. At the upper yield point, plastic deformation is initiated with an actual decrease in stress. Continued deformation fluctuates slightly about some constant stress value, termed the lower yield point; stress subsequently rises with increasing strain. For metals that display this effect, the yield strength is taken as the average stress that is associated with the lower yield point, since it is well defined and relatively insensitive to the testing procedure.[3] Thus, it is not necessary to employ the strain offset method for these materials.

The magnitude of the yield strength for a metal is a measure of its resistance to plastic deformation. Yield strengths may range from 5000 psi (35 MPa)

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[2] "Strength" is used in lieu of "stress" because strength is a property of the metal, whereas stress is related to the magnitude of the applied load.

[3] It should be pointed out that to observe the yield point phenomenon, a "stiff" tensile-testing apparatus must be used; by stiff is meant that there is very little elastic deformation of the machine during loading.

which is very close to the value of 14.6×10^6 psi (10.1×10^4 MPa) given for brass in Table 6.1.

(b) The 0.002 strain offset line is constructed as shown in the inset; its intersection with the stress–strain curve is at approximately 36,000 psi (250 MPa), which is the yield strength of the brass.

(c) The maximum load that can be sustained by the specimen is calculated by using Equation 6.1, in which σ is taken to be the tensile strength, from Figure 6.11, 65,000 psi (450 MPa). Solving for F, the maximum load, yields

$$F = \sigma A_0 = \sigma \left(\frac{d_0}{2}\right)^2 \pi = (65{,}000 \text{ psi}) \left(\frac{0.505}{2} \text{ in.}\right)^2 \pi$$

$$= 13{,}000 \text{ lb}_\text{f} \ (5.77 \times 10^4 \text{ N})$$

(d) To compute the change in length, Δl, in Equation 6.2, it is first necessary to determine the strain that is produced by a stress of 50,000 psi. This is accomplished by locating the stress point on the stress–strain curve, point A, and reading the corresponding strain from the strain axis, which is approximately 0.06. Inasmuch as $l_0 = 10$ in., we have

$$\Delta l = \epsilon l_0 = (0.06)(10 \text{ in.}) = 0.6 \text{ in.} \ (15.2 \text{ mm})$$

Ductility

Ductility is another important mechanical property. It is a measure of the degree of plastic deformation that has been sustained at fracture. A material that experiences very little or no plastic deformation upon fracture is termed *brittle*. The tensile stress–strain behaviors for both ductile and brittle materials are schematically illustrated in Figure 6.12.

Ductility may be expressed quantitatively as either *percent elongation* or *percent area reduction*. The percent elongation %EL is the percentage of plastic strain at fracture, or

$$\%\text{EL} = \left(\frac{l_f - l_0}{l_0}\right) \times 100 \tag{6.10}$$

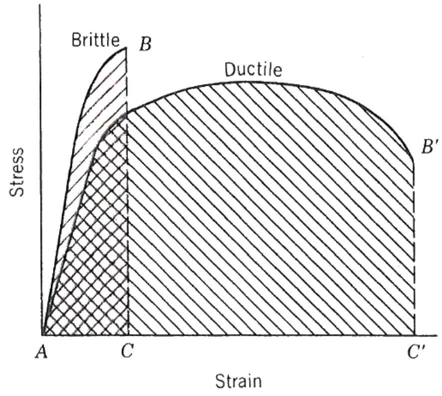

Figure 6.12 Schematic representations of tensile stress–strain behavior for brittle and ductile materials loaded to fracture.

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