Mechanical properties of materials

The main goal of this chapter is to introduce the basic concepts associated with mechanical properties. We will learn terms such as hardness, stress, strain, elastic and plastic deformation, viscoelasticity, and strain rate. We will also review some of the testing procedures that engineers use to evaluate many of these properties. These concepts will be discussed using illustrations from real-world applications.

Mechanical properties are of concern to a variety of parties (e.g., producers and consumers of materials, research organizations, government agencies) that have differing interests. Consequently, it is imperative that there be some consistency in the manner in which tests are conducted, and in the interpretation of their results. This consistency is accomplished by using standardized testing techniques. Establishment and publication of these standards are often coordinated by professional societies. In the United States the most active organization is the American Society for Testing and Materials (ASTM).

3-1- Terminology for mechanical properties

There are different types of forces or “stresses” that are encountered in dealing with mechanical properties of materials. In general, we define **stress** as the force acting per unit area over which the force is applied. Tensile, compressive, and shear stresses are illustrated in Figure 3-1(a). **Strain** is defined as the change in dimension per unit length. Stress is typically expressed in psi (pounds per square inch) or Pa (Pascals). Strain has no dimensions and is often expressed as in./in. or cm/cm.

Tensile and compressive stresses are normal stresses. A normal stress arises when the applied force acts perpendicular to the area of interest.

Tension causes elongation in the direction of the applied force, whereas compression causes shortening. A shear stress arises when the applied force acts in a direction parallel to the area of interest. Many loadbearing applications involve tensile or compressive stresses. Shear stresses are often encountered in the processing of materials using such techniques as polymer extrusion. Shear stresses are also found in structural applications. Note that even a simple tensile stress applied along one direction will cause a shear stress in other directions.

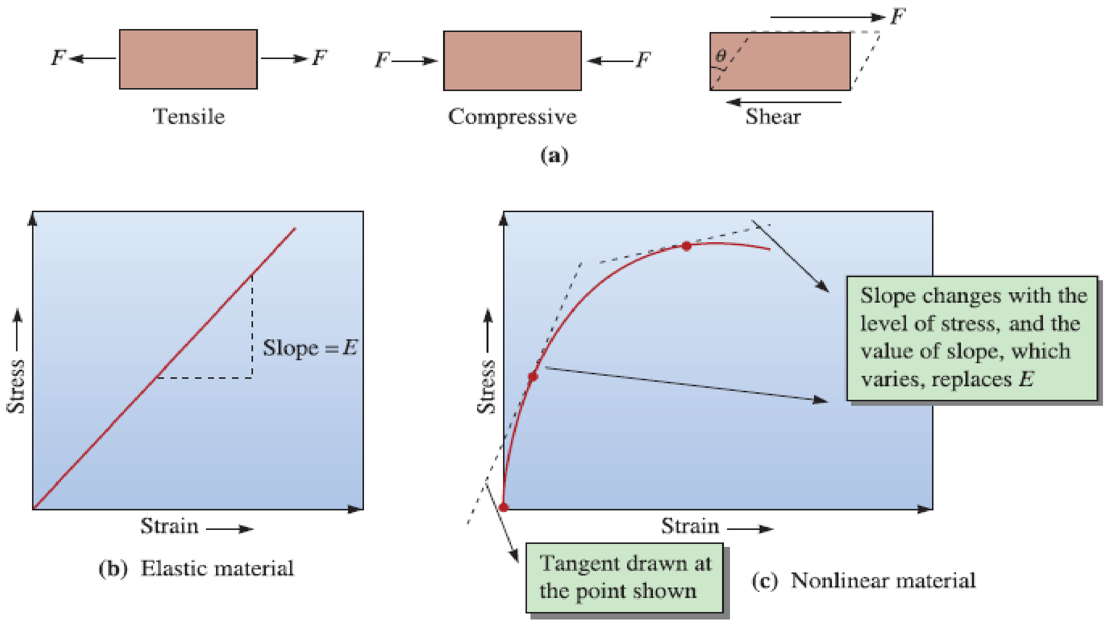

Figure 3-1 (a) Tensile, compressive, and shear stresses. F is the applied force. (b) Illustration showing how Young's modulus is defined for an elastic material. (c) For nonlinear materials, we use the slope of a tangent as a varying quantity that replaces the Young's modulus.

Elastic strain is defined as fully recoverable strain resulting from an applied stress. The strain is "elastic" if it develops instantaneously (i.e., the strain occurs as soon as the force is applied), remains as long as the stress is applied, and is recovered when the force is withdrawn. A material subjected to an elastic strain does not show any permanent deformation (i.e., it returns to its original shape after the force or stress is removed). Consider stretching a stiff metal spring by a small amount and letting go. If the spring immediately returns to its original dimensions, the strain developed in the spring was elastic.

In many materials, elastic stress and elastic strain are linearly related. The slope of a tensile stress-strain curve in the linear regime defines the **Young's modulus** or **modulus of elasticity** (*E*) of a material [Figure 3-1(b)]. The units of ***E*** are measured in pounds per square inch (psi) or Pascals (Pa) (same as those of stress). Large elastic deformations are observed in **elastomers** (e.g., natural rubber, silicones), for which the relationship between elastic strain and stress is non-linear. In elastomers, the large elastic strain is related to the coiling and uncoiling of spring-like molecules. In dealing with such materials, we use the slope of the tangent at any given value of stress or strain and consider that as a varying quantity that replaces the Young's modulus [Figure 3-1(c)]. We define the **shear modulus** (*G*) as the slope of the linear part of the shear stress-shear strain curve.

Permanent or **plastic deformation** in a material is known as the **plastic strain**. In this case, when the stress is removed, the material does *not* go back to its original shape. A dent in a car is plastic deformation! Note that the word "plastic" here does not refer to strain in a plastic (polymeric) material, but rather to permanent strain in any material.

The rate at which strain develops in a material is defined as the **strain rate**. Units of strain rate are s^{-1}. You will learn later in this chapter that the rate at which a material is deformed is important from a mechanical properties perspective. Many materials considered to be ductile behave as brittle solids when the strain rates are high.

A **viscous material** is one in which the strain develops over a period of time and the material does not return to its original shape after the stress is removed. The development of strain takes time and is not in phase with the applied stress. Also, the material will remain deformed when the applied stress is removed (i.e., the strain will be plastic). A **viscoelastic** (or **anelastic**) material can be thought of as a material with a response between that of a viscous material and an elastic material. The term "anelastic" is typically used for metals, while the term "viscoelastic" is usually associated with polymeric materials. Many plastics (solids and molten) are viscoelastic.

In a viscoelastic material, the development of a permanent strain is similar to that in a viscous material. Unlike a viscous material, when the applied stress is removed, part of the strain in a viscoelastic material will recover over a period of time. Recovery of strain refers to a change in shape of a material after the stress causing deformation is removed. A qualitative description of development of strain as a function of time in relation to an applied force in elastic, viscous, and viscoelastic materials is shown in Figure 3-2. In viscoelastic materials held under constant strain, if we wait, the level of stress decreases over a period of time. This is known as **stress relaxation**. Recovery of strain and stress relaxation are different terms and should not be confused. A common example of stress relaxation is provided by the nylon strings in a tennis racket. We know that the level of stress, or the "tension," as the tennis players call it, decreases with time.

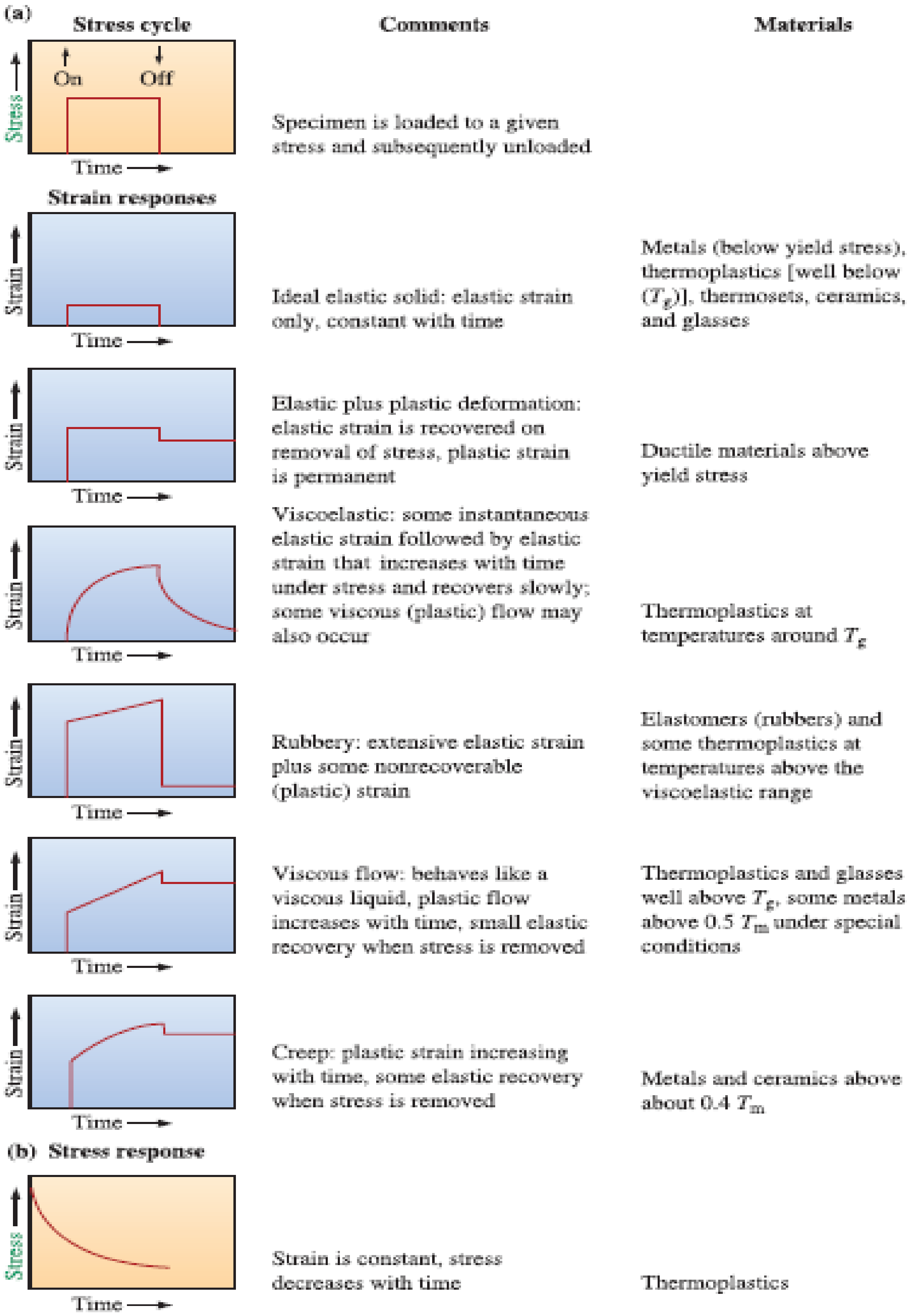

Figure 3-2 (a) Various types of strain response to an imposed stress where T_g = glass transition temperature and T_m = melting point. (b) Stress relaxation in a viscoelastic material. Note the vertical axis is stress. Strain is constant.

3-2- the tensile test: use of the stress–strain diagram

The tensile test is popular since the properties obtained can be applied to design different components. The tensile test measures the resistance of a material to a static or slowly applied force. The strain rates in a tensile test are typically small (10^{-4} to 10^{-2} s^{-1}). A test setup is shown in Figure 3-3; a typical specimen has a diameter of 0.505 in. and a gage length of 2 in. The specimen is placed in the testing machine and a force *F*, called the **load**, is applied. A universal testing machine on which tensile and compressive tests can be performed often is used.

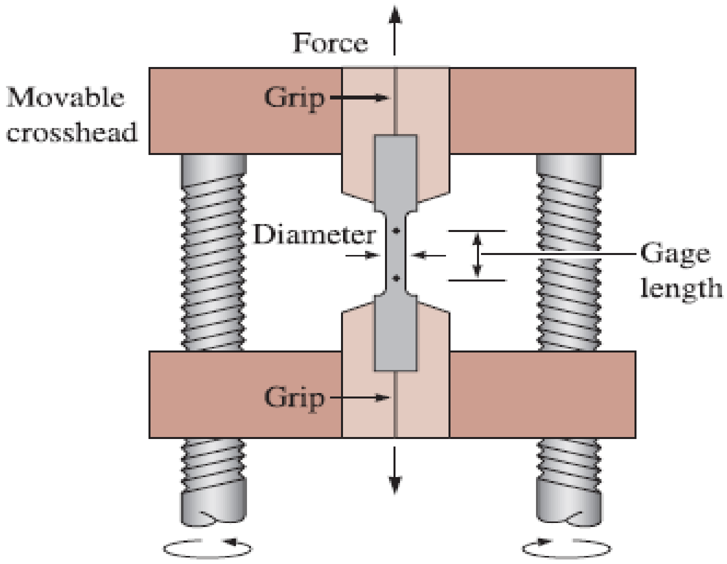

Figure 3-3 A unidirectional force is applied to a specimen in the tensile test by means of the moveable crosshead. The crosshead movement can be performed using screws or a hydraulic mechanism.

A **strain gage** or **extensometer** is used to measure the amount that the specimen stretches between the gage marks when the force is applied. Thus, the change in length of the specimen (Δl) is measured with respect to the original length (l_0). Information concerning the strength, Young's modulus, and ductility of a material can be obtained from such a tensile test. Typically, a tensile test is conducted on metals, alloys, and plastics.

Tensile tests can be used for ceramics; however, these are not very popular because the sample may fracture while it is being aligned.

Figure 4-3 shows *qualitatively* the stress–strain curves for a typical (a) metal, (b) thermoplastic material, (c) elastomer, and (d) ceramic (or glass) under relatively small strain rates. The scales in this figure are qualitative and different for each material. In practice, the actual magnitude of stresses and strains will be very different. The temperature of the plastic material is assumed to be above its **glass-transition temperature** (T_g). The temperature of the metal is assumed to be room temperature. Metallic and thermoplastic materials show an initial elastic region followed by a non-linear plastic region. A separate curve for elastomers (e.g., rubber or silicones) is also included since the behavior of these materials is different from other polymeric materials. For elastomers, a large portion of the deformation is elastic and nonlinear. On the other hand, ceramics and glasses show only a linear elastic region and almost no plastic deformation at room temperature.

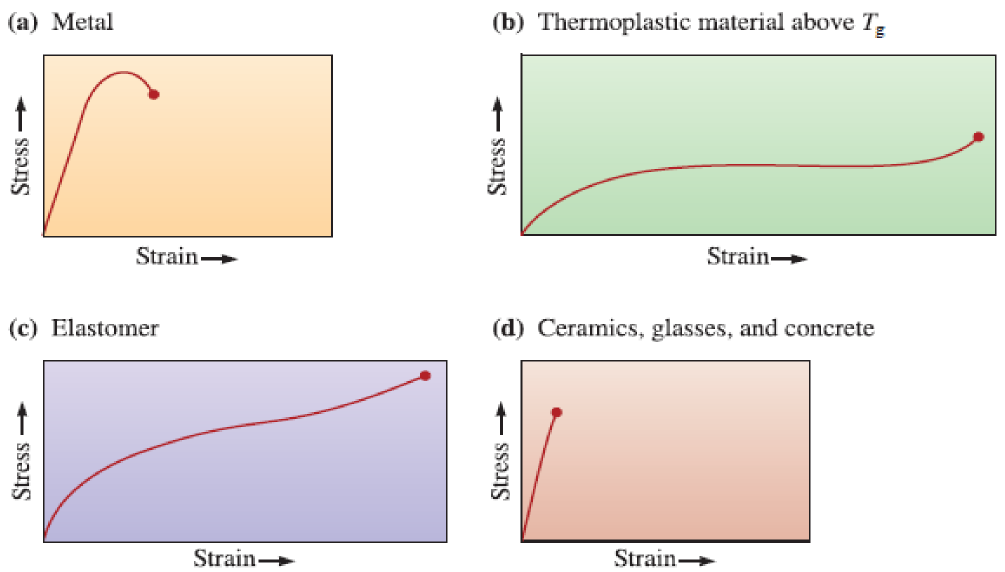

Figure 3-4 Tensile stress–strain curves for different materials. Note that these are qualitative. The magnitudes of the stresses and strains should not be compared.

3-3- engineering stress and strain

The results of a single test apply to all sizes and cross-sections of specimens for a given material if we convert the force to stress and the distance between gage marks to strain. **Engineering stress** and **engineering strain** are defined by the following equations:

Engineering stress= $S = \frac{F}{A_O}$ ....(3 − 1)

Engineering strain= $e = \frac{\Delta l}{l_o}$ ....(3 − 2)

Where A_0 is the *original* cross-sectional area of the specimen before the test begins, l_0 is the *original* distance between the gage marks, and Δl is the change in length after force F is applied. The stress-strain curve (Figure 3-5) is used to record the results of a tensile test.

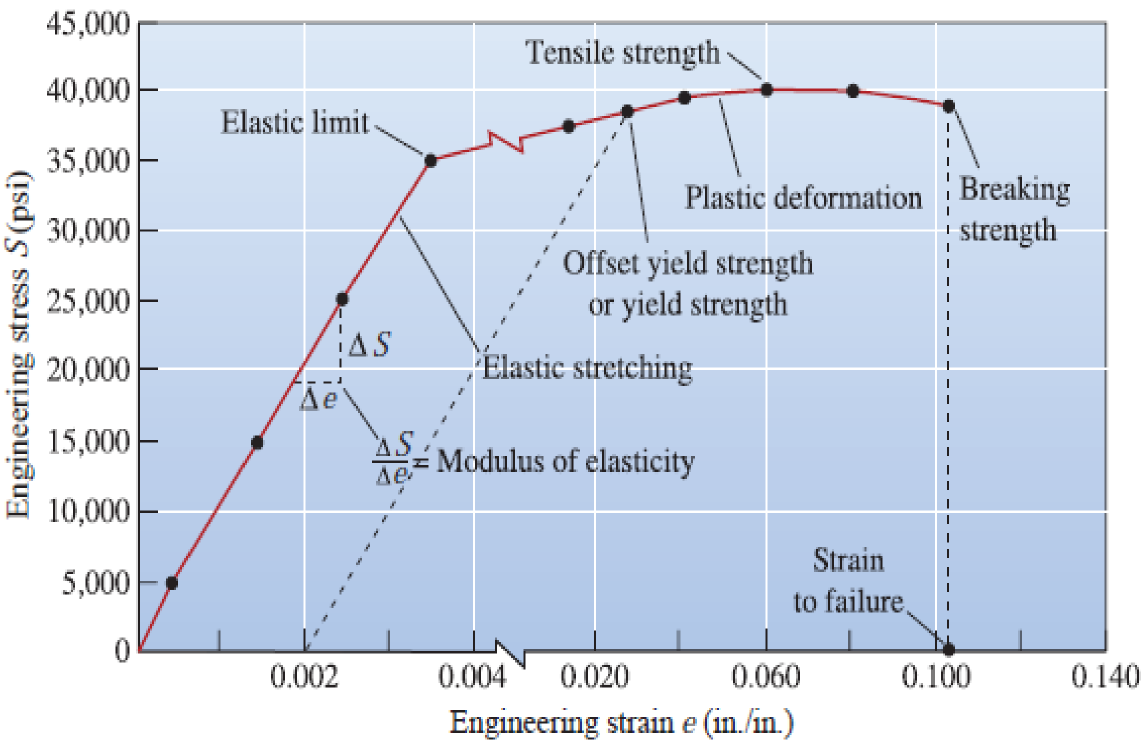

Figure 3-5 The engineering stress–strain curve for an aluminum alloy.

Units

Many different units are used to report the results of the tensile test. The most common units for stress are pounds per square inch (psi) and MegaPascals (MPa). The units for strain include inch inch, centimeter centimeter, and meter meter, and thus, strain is often written as unitless. The conversion factors for stress are summarized in Table 3-1. Because strain is dimensionless, no conversion factors are required to change the system of units.

Table 3-1 units and conversion factors

1 pound (lb) = 4.448 Newtons (N)
1 psi = pounds per square inch
1 MPa = MegaPascal = MegaNewtons per square meter (MN/m^2)
= Newtons per square millimeter (N/mm^2) = 10^6 Pa
1 GPa = 1000 MPa = GigaPascal
1 ksi = 1000 psi = 6.895 MPa
1 psi = 0.006895 MPa
1 MPa = 0.145 ksi = 145 psi

***Example 3-1:* Design of a Suspension Rod**

An aluminum rod is to withstand an applied force of 45,000 pounds. The engineering stress–strain curve for the aluminum alloy to be used is shown in Figure 5-3. To ensure safety, the maximum allowable stress on the rod is limited to 25,000 psi, which is below the yield strength of the aluminum. The rod must be at least 150 in. long but must deform elastically no more than 0.25 in. when the force is applied. Design an appropriate rod.

Solution:

From the definition of engineering strain,

$$e = \frac{\Delta l}{l_o}$$

For a rod that is 150 in. long, the strain that corresponds to an extension of 0.25 in. is

$$e = \frac{0.25\ in.}{150\ in.} = 0.00167$$

According to Figure 3-5, this strain is purely elastic, and the corresponding stress value is approximately 17,000 psi, which is below the 25,000 psi limit. We use the definition of engineering stress to calculate the required cross-sectional area of the rod:

$$S = \frac{F}{A_0}$$

Note that the stress must not exceed 17,000 psi, or consequently, the deflection will be greater than 0.25 in. Rearranging,

$$A_0 = \frac{F}{S} = \frac{45{,}000 \text{ lb}}{17{,}000 \text{ psi}} = 2.65 \text{ in.}^2$$

The rod can be produced in various shapes, provided that the cross-sectional area is 2.65 in.^{2} For a round cross section, the minimum diameter to ensure that the stress is not too high is

$$A_0 = \frac{\pi d^2}{4} = 2.65 \text{ in.}^2 \quad \text{or} \quad d = 1.84 \text{ in.}$$

Thus, one possible design that meets all of the specified criteria is a suspension rod that is 150 in. long with a diameter of 1.84 in.

3-4- Properties obtained from the tensile test

1- Yield strength

As we apply stress to a material, the material initially exhibits elastic deformation. The strain that develops is completely recovered when the applied stress is removed. As we continue to increase the applied stress, the material eventually "yields" to the applied stress and exhibits both elastic and plastic deformation. The critical stress value needed to initiate plastic deformation is defined as the **elastic limit** of the material. In metallic materials, this is usually the stress required for dislocation motion, or slip, to be initiated. In polymeric materials, this stress will correspond to disentanglement of polymer molecule chains or sliding of chains past each other. The **proportional limit** is defined as the level of stress above which the relationship between stress and strain is not linear.

In most materials, the elastic limit and proportional limit are quite close; however, neither the elastic limit nor the proportional limit values can be determined precisely. Measured values depend on the sensitivity of the equipment used. We, therefore, define them at an **offset strain value** (typically, but not always, 0.002 or 0.2%). We then draw a line parallel to the linear portion of the engineering stress-strain curve starting at this offset value of strain. The stress value corresponding to the intersection of this line and the engineering stress-strain curve is defined as the **offset yield strength**, also often stated as the **yield strength**. The 0.2% offset yield strength for gray cast iron is 40,000 psi as shown in Figure 3-6(a). Engineers normally prefer to use the offset yield strength for design purposes because it can be reliably determined. For some materials, the transition from elastic deformation to plastic flow is rather abrupt. This transition is known as the **yield point phenomenon**. In these materials, as plastic deformation begins, the stress value drops first from the *upper yield point* (S_2) [Figure 3-6(b)]. The stress value then oscillates around an average value defined as the *lower yield point* (S_1). For these materials, the yield strength is usually defined from the 0.2% strain offset. The stress-strain curve for certain low-carbon steels displays the yield point phenomenon [Figure 3-6(b)]. The material is expected to plastically deform at stress S_1; however, small interstitial atoms clustered around the dislocations interfere with slip and raise the yield point to S_2. Only after we apply the higher stress S_2 do the dislocations slip. After slip begins at S_2, the dislocations move away from the clusters of small atoms and continue to move very rapidly at the lower stress S_1.

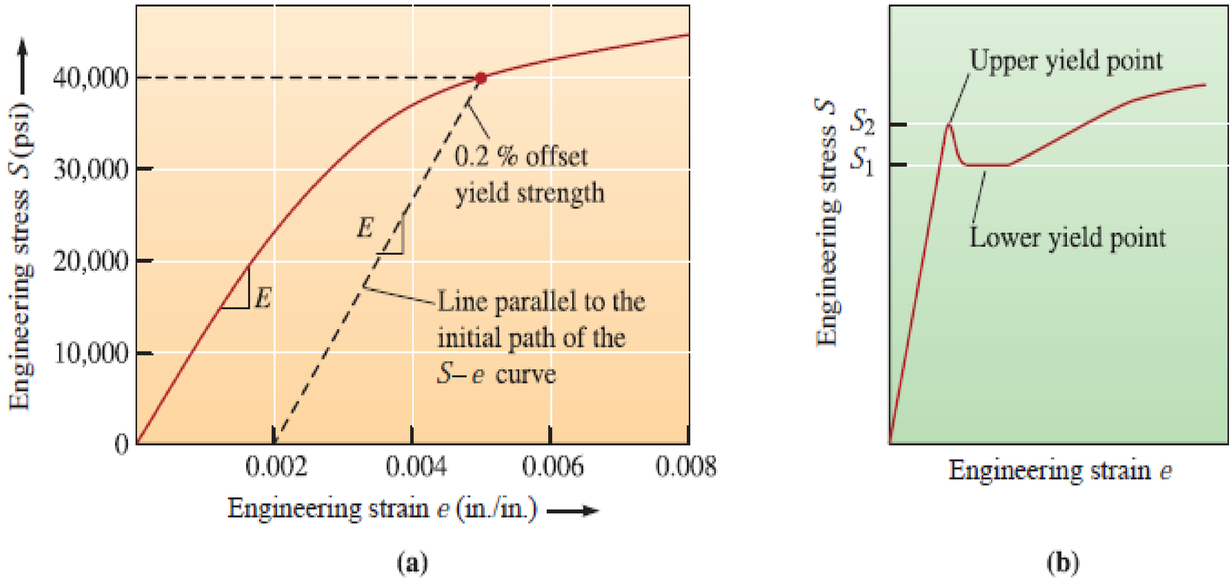

Figure 3-6 (a) Determining the 0.2% offset yield strength in gray cast iron, and (b) upper and lower yield point behavior in a low carbon steel.

2- Tensile strength

The stress obtained at the highest applied force is the **tensile strength** (S_{UTS}), which is the maximum stress on the engineering stress-strain curve. This value is also commonly known as the **ultimate tensile strength**. In many ductile materials, deformation does not remain uniform. At some point, one region deforms more than others and a large local decrease in the cross-sectional area occurs (Figure 3-7). This locally deformed region is called a "neck." This phenomenon is known as **necking**. Because the cross-sectional area becomes smaller at this point, a lower force is required to continue its deformation, and the engineering stress, calculated from the *original* area A_0, decreases. The tensile strength is the stress at which necking begins in ductile metals. In compression testing, the materials will bulge; thus necking is seen only in a tensile test.

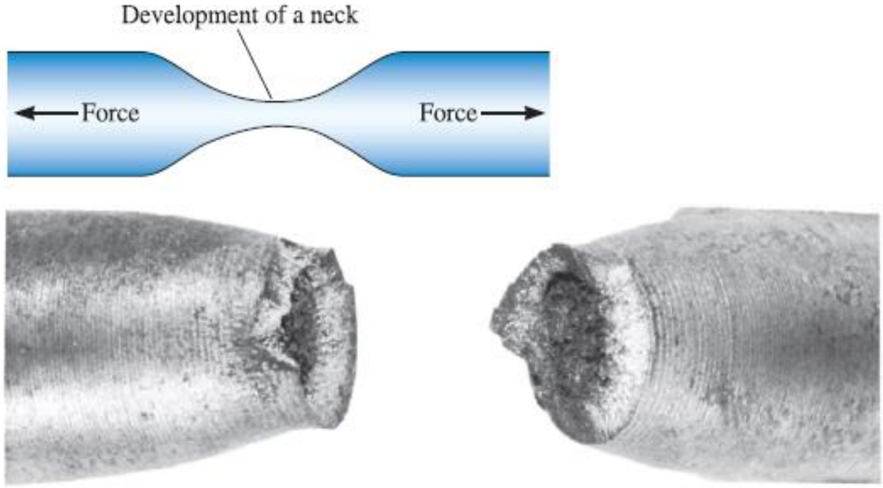

Figure 3-7 Localized deformation of a ductile material during a tensile test produces a necked region. The micrograph shows a necked region in a fractured sample.

3- *Elastic properties*

The modulus of elasticity, or *Young's modulus* (E), is the slope of the stress-strain curve in the elastic region. This relationship between stress and strain in the elastic region is known as **Hooke's Law**:

$$E = \frac{S}{e} \;\ldots\ldots\ldots..(3-3)$$

The modulus is closely related to the binding energies of the atoms. A steep slope in the force-distance graph at the equilibrium spacing indicates that high forces are required to separate the atoms and cause the material to stretch elastically. Thus, the material has a high modulus of elasticity. Binding forces, and thus the modulus of elasticity, are typically higher for high melting point materials (Table 3-2). In metallic materials, the modulus of elasticity is considered a microstructure *insensitive* property since the value is dominated by the stiffness of atomic bonds. Grain size or other microstructural features do not have a very large effect on the Young's modulus. Note that Young's modulus does depend on such factors as orientation of a single crystal material (i.e., it depends upon crystallographic direction). For ceramics, the Young's modulus depends on the level of porosity. The Young's modulus of a composite depends upon the stiffness and amounts of the individual components.

The **stiffness** of a component is proportional to its Young's modulus. (The stiffness also depends on the component dimensions.) A component with a high modulus of elasticity will show much smaller changes in dimensions if the applied stress causes only elastic deformation when compared to a component with a lower elastic modulus. Figure 3-8 compares the elastic behavior of steel and aluminum. If a stress of 30,000 psi is applied to each material, the steel deforms elastically 0.001 in./in.; at the same stress, aluminum deforms 0.003 in./in. The elastic modulus of steel is about three times higher than that of aluminum.

Table 3-2 Elastic properties and melting temperature (Tm) of selected materials.

Material	T_m (°C)	E (psi)	Poisson's ratio (ν)
Pb	327	2.0×10^6	0.45
Mg	650	6.5×10^6	0.29
Al	660	10.0×10^6	0.33
Cu	1085	18.1×10^6	0.36
Fe	1538	30.0×10^6	0.27
W	3410	59.2×10^6	0.28
Al_2O_3	2020	55.0×10^6	0.26
Si_3N_4		44.0×10^6	0.24

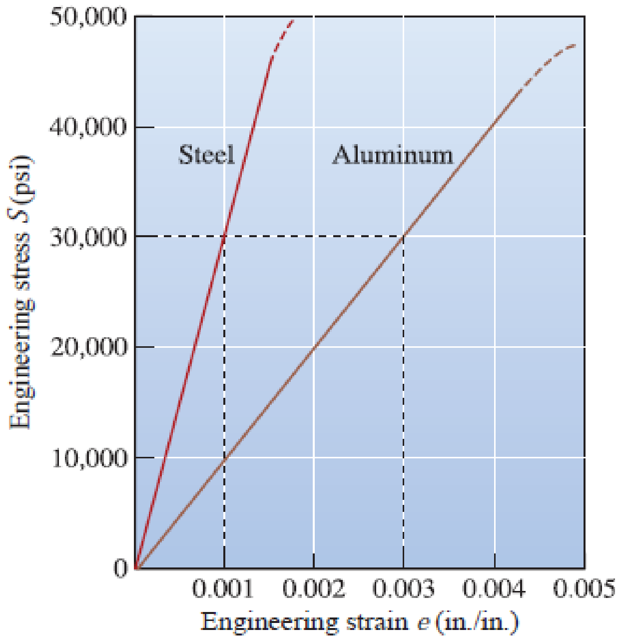

Figure 3-8 Comparison of the elastic behavior of steel and aluminum. For a given stress, aluminum deforms elastically three times as much as does steel (i.e., the elastic modulus of aluminum is about three times lower than that of steel).

Poisson's ratio, *v*, relates the longitudinal elastic deformation produced by a simple tensile or compressive stress to the lateral deformation that occurs simultaneously:

$$v = \frac{-e_{lateral}}{e_{longitudinal}} \quad \dots\dots\dots(3-4)$$

For many metals in the elastic region, the Poisson's ratio is typically about 0.3 (Table 3-2). During a tensile test, the ratio increases beyond yielding to about 0.5, since during plastic deformation, volume remains constant. Some interesting structures, such as some honeycomb structures and foams, exhibit negative Poisson's ratios. *Note: Poisson's ratio should not be confused with the kinematic viscosity, both of which are denoted by the Greek letter v.*

The **modulus of resilience** (E_r), the area contained under the elastic portion of a stress-strain curve, is the elastic energy that a material absorbs during loading and subsequently releases when the load is removed. For linear elastic behavior:

$$E_r = \left(\frac{1}{2}\right) \text{(Yield strength)(Strain at yielding)} \quad \ldots\ldots \text{(3-5)}$$

4- Tensile Toughness

The energy absorbed by a material prior to fracture is known as **tensile toughness** and is sometimes measured as the area under the true stress–strain curve (also known as the **work of fracture**). Since it is easier to measure engineering stress–strain, engineers often equate tensile toughness to the area under the engineering stress–strain curve.

Example 3-2: ***Young's Modulus of an Aluminum Alloy***

Calculate the modulus of elasticity of the aluminum alloy for which the engineering stress–strain curve is shown in Figure 3-5. Calculate the length of a bar of initial length 50 in. when a tensile stress of 30,000 psi is applied.

Solution:

When a stress of 34,948 psi is applied, a strain of 0.0035 in./in. is produced. Thus,

$$\text{Modulus of elasticity} = E = \frac{S}{e} = \frac{34{,}948 \text{ psi}}{0.0035} = 10 \times 10^6 \text{ psi}$$

Note that any combination of stress and strain in the elastic region will produce this result. From Hooke's Law,

$$e = \frac{S}{E} = \frac{30{,}000 \text{ psi}}{10 \times 10^6 \text{ psi}} = 0.003 \text{ in./in.}$$

From the definition of engineering strain,

$$e = \frac{\Delta l}{l_0}$$

Thus,

$$\Delta l = e(l_0) = 0.003 \text{ in./in.}(50 \text{ in.}) = 0.15 \text{ in.}$$

When the bar is subjected to a stress of 30,000 psi, the total length is given by

$$l = \Delta l + l_0 = 0.15 \text{ in.} + 50 \text{ in.} = 50.15 \text{ in.}$$

5- Ductility

Ductility is the ability of a material to be permanently deformed without breaking when a force is applied. There are two common measures of ductility. The **percent elongation** quantifies the permanent plastic deformation at failure (i.e., the elastic deformation recovered after fracture is not included) by measuring the distance between gage marks on the specimen before and after the test. Note that the strain after failure is smaller than the strain at the breaking point, because the elastic strain is recovered when the load is removed. The percent elongation can be written as:

$$\%\boldsymbol{Elongation} = \frac{\boldsymbol{l_f - l_o}}{\boldsymbol{l_o}}\boldsymbol{x100} \quad \dots\dots(\boldsymbol{3-6})$$

Where l_f is the distance between gage marks after the specimen breaks.
A second approach is to measure the percent change in the cross-sectional area at the point of fracture before and after the test. The **percent reduction in area** describes the amount of thinning undergone by the specimen during the test:

$$\%\boldsymbol{Reduction\ in\ area} = \frac{\boldsymbol{A_o - A_f}}{\boldsymbol{A_o}}\boldsymbol{x100} \quad \dots\dots(\boldsymbol{3-7})$$

Where A_f is the final cross-sectional area at the fracture surface. Ductility is important to both designers of load-bearing components and manufacturers of components (bars, rods, wires, plates, I-beams, fibers, etc.) utilizing materials processing.

Example 3-3:* *Ductility of an Aluminum Alloy

The aluminum alloy has a final length after failure of 2.195 in. and a final diameter of 0.398 in. at the fractured surface. Calculate the ductility of this alloy. The results of a tensile test of a 0.505 in. diameter aluminum alloy test bar, initial length (l_o) = 2 in.

Solution:

$$\%Elongation = \frac{l_f - l_o}{l_o} x100 = \frac{2.195 - 2.000}{2.000} x100 = 9.75\%$$

$$\%Elongation = \frac{A_o - A_f}{A_o} x100$$

$$= \frac{(\pi/4)(0.505)^2 - (\pi/4)(0.398)^2}{(\pi/4)(0.505)^2} x100\%$$

$$= 37.9\%$$

6- *Effect of temperature*

Mechanical properties of materials depend on temperature (Figure 3-9). Yield strength, tensile strength, and modulus of elasticity decrease at higher temperatures, whereas ductility commonly increases. A materials fabricator may wish to deform a material at a high temperature (known as *hot working*) to take advantage of the higher ductility and lower required stress.

In metals, the yield strength decreases rapidly at higher temperatures due to a decreased dislocation density and an increase in grain size via grain growth or a related process known as recrystallization. Similarly, any strengthening that may have occurred due to the formation of ultrafine precipitates may also decrease as the precipitates begin to either grow in size or dissolve into the matrix.

Increased temperatures also play an important role in forming polymeric materials and inorganic glasses. In many polymer-processing operations, such as extrusion or the stretch-blow process, the increased ductility of polymers at higher temperatures is advantageous. Again, a word of caution concerning the use of the term “high temperature”. For polymers, the term “high temperature” generally means a temperature higher than the glass-transition temperature (T_g). For our purpose, the glass-transition temperature is a temperature below which materials behave as brittle materials. Above the glass-transition temperature, plastics become ductile. The glass-transition temperature is not a fixed temperature, but depends on the rate of cooling as well as the polymer molecular weight distribution. Many plastics are ductile at room temperature because their glass-transition temperatures are *below* room temperature. To summarize, many polymeric materials will become harder and more brittle as they are exposed to temperatures that are below their glass-transition temperatures. The reasons for loss of ductility at lower temperatures in polymers and metallic materials are different; however, this is a factor that played a role in the failures of the *Titanic* in 1912 and the *Challenger* in 1986.

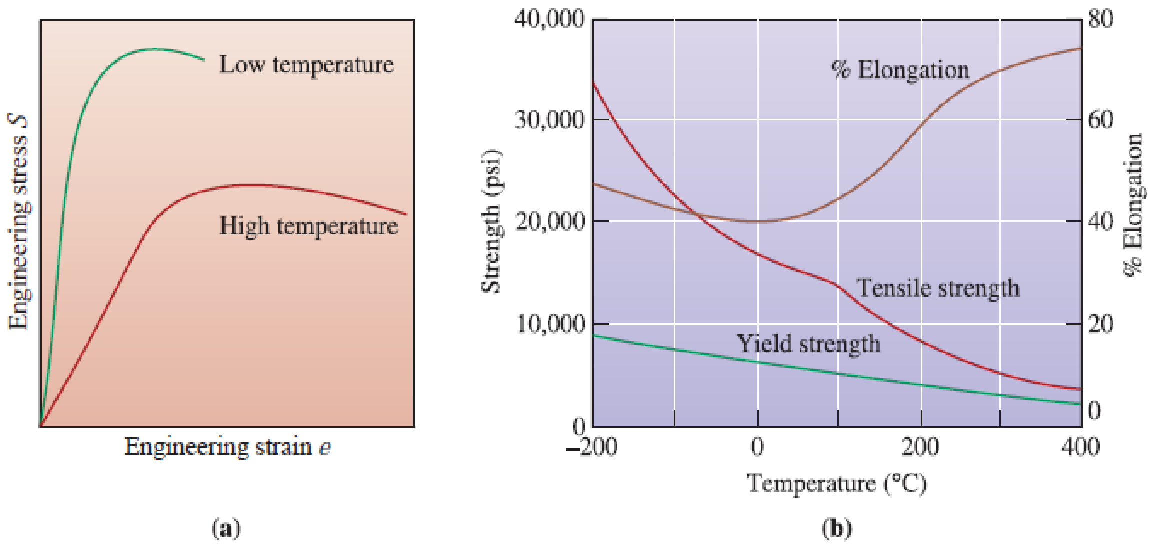

Figure 3-9 The effect of temperature (a) on the stress–strain curve and (b) on the tensile properties of an aluminum alloy.

Ceramic and glassy materials are generally considered brittle at room temperature. As the temperature increases, glasses can become more ductile. As a result, glass processing (e.g., fiber drawing or bottle manufacturing) is performed at high temperatures.

3-5- True stress and true strain

The decrease in engineering stress beyond the tensile strength on an engineering stress–strain curve is related to the definition of engineering stress. We used the original area A_o in our calculations, but this is not precise because the area continually changes. We define **true stress** and **true strain** by the following equations:

$$True\ stress = \sigma = \frac{F}{A} \quad \ldots\ldots\ldots (3-8)$$

$$True\ strain = \varepsilon = \int_{l_o}^{l} \frac{dl}{l} = \ln\left(\frac{l}{l_o}\right) \quad \ldots\ldots\ldots (3-9)$$

Where A is the instantaneous area over which the force F is applied, l is the instantaneous sample length, and l_o is the initial length. In the case of metals, plastic deformation is essentially a constant-volume process (i.e., the creation and propagation of dislocations results in a negligible volume change in the material). When the constant volume assumption holds, we can write:

$$A_o l_o = Al \ or\ A = \frac{A_o l_o}{l} \quad \ldots\ldots\ldots\ldots..(3-10)$$

And using the definitions of engineering stress S and engineering strain e, Equation 3-8 can be written as:

$$\sigma = \frac{F}{A} = \frac{F}{A_o}\left(\frac{l}{l_o}\right) = S\left(\frac{l_o + \Delta l}{l_o}\right) = S(1+e) \quad \ldots\ldots\ldots (3-11)$$

It can also be shown that

$$\varepsilon = \ln(1+e) \quad \ldots\ldots\ldots\ldots (3-12)$$

Thus, it is a simple matter to convert between the engineering stress–strain and true stress–strain systems. Note that the expressions in Equations 3-11 and 3-12 are not valid after the onset of necking, because after necking begins, the distribution of strain along the gage length is not uniform. After necking begins, Equation 3-9 must be used to calculate the true stress and the expression:

$$\varepsilon = \ln\left(\frac{A_o}{A}\right) \quad \ldots\ldots\ldots (3-13)$$

3-6- The bend test for brittle materials

In ductile metallic materials, the engineering stress–strain curve typically goes through a maximum; this maximum stress is the tensile strength of the material. Failure occurs at a lower engineering stress after necking has reduced the cross-sectional area supporting the load. In more brittle materials, failure occurs at the maximum load, where the tensile strength and breaking strength are the same (Figure 3-10).

In many brittle materials, the normal tensile test cannot easily be performed because of the presence of flaws at the surface. Often, just placing a brittle material in the grips of the tensile testing machine causes cracking. These materials may be tested using the **bend test** [Figure 3-11(a)]. By applying the load at three points and causing bending, a tensile force acts on the material opposite the midpoint. Fracture begins at this location. The **flexural strength**, or **modulus of rupture**, describes the material's strength:

Flexural strength for three - point bend test $\sigma_{bend} = \frac{3FL}{2wh^2} \quad \ldots\ldots.(3-14)$

Where F is the fracture load, L is the distance between the two outer points, w is the width of the specimen, and h is the height of the specimen.

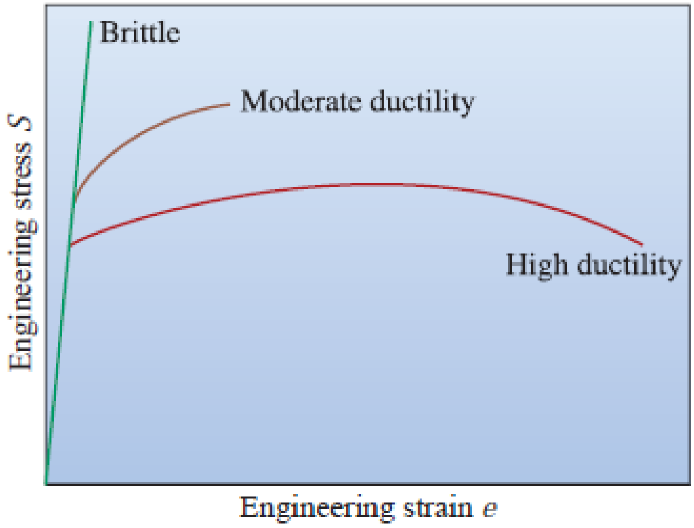

Figure 3-10 The engineering stress–strain behavior of brittle materials compared with that of more ductile materials.

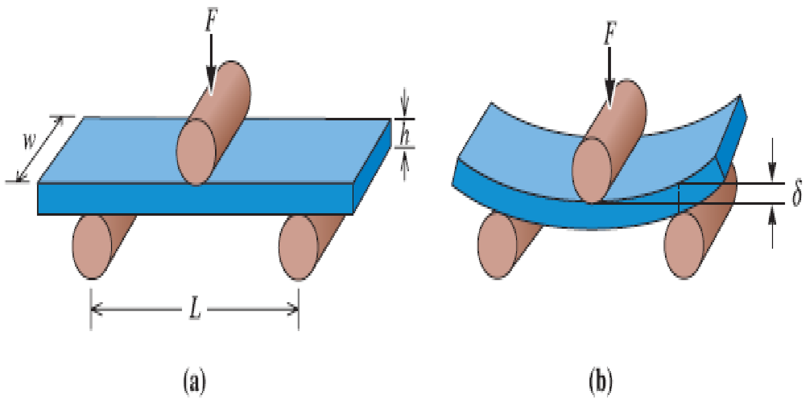

Figure 3-11 (a) The bend test often used for measuring the strength of brittle materials, and (b) the deflection δ obtained by bending.

The flexural strength has units of stress. The results of the bend test are similar to the stress-strain curves; however, the stress is plotted versus deflection rather than versus strain (Figure 3-12). The corresponding bending moment diagram is shown in Figure 3-13(a). The modulus of elasticity in bending, or the **flexural modulus** (E_{bend}), is calculated as:

$$\text{Flexural modulus } E_{bend} = \frac{L^3 F}{4wh^3\delta} \quad \dots\dots..(3-15)$$

Where δ is the deflection of the beam when a force F is applied.

This test can also be conducted using a setup known as the four-point bend test [Figure 3-13(b)]. The maximum stress or flexural stress for a four-point bend test is given by:

$$\sigma_{bend} = \frac{3FL_1}{4wh^2} \quad \dots\dots\dots (3-16)$$

For the specific case in which in Figure 3-13(b). Note that the derivations of Equations 3-14 through 3-16 assume a linear stress–strain response (and thus cannot be correctly applied to many polymers).

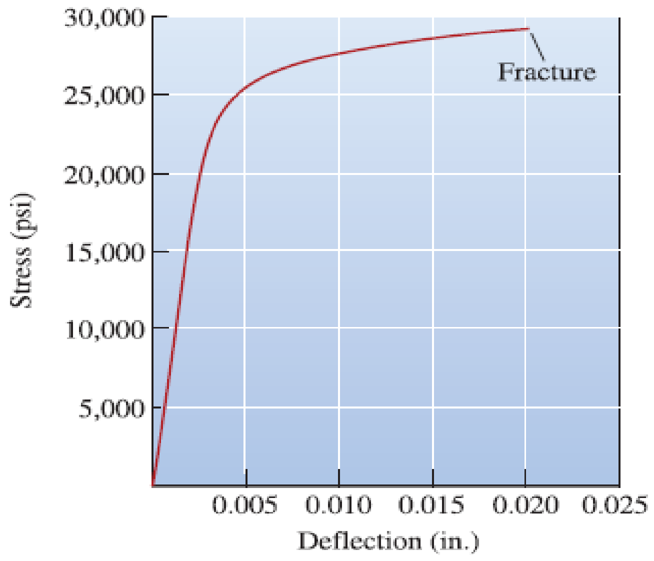

Figure 3-12 Stress-deflection curve for an MgO ceramic obtained from a bend test.

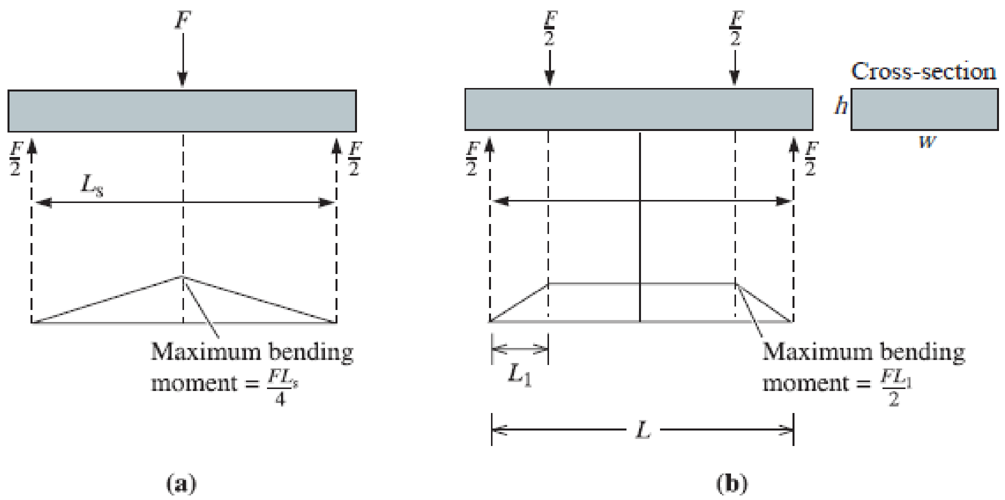

Figure 3-13 (a) Three-point and (b) four-point bend test setup.

The four-point bend test is better suited for testing materials containing flaws. This is because the bending moment between the inner platens is constant [Figure 3-13(b)]; thus samples tend to break randomly unless there is a flaw that locally raises the stress.

Since cracks and flaws tend to remain closed in compression, brittle materials such as concrete are often incorporated into designs so that only compressive stresses act on the part. Often, we find that brittle materials fail at much higher compressive stresses than tensile stresses.

Example 3-4: Flexural Strength of Composite Materials

The flexural strength of a composite material reinforced with glass fibers is 45,000 psi, and the flexural modulus is 18 x 10^6 psi. A sample, which is 0.5 in. wide, 0.375 in. high, and 8 in. long, is supported between two rods 5 in. apart. Determine the force required to fracture the material and the deflection of the sample at fracture, assuming that no plastic deformation occurs.

<u>Solution:</u>

Based on the description of the sample, w = 0.5 in., h = 0.375 in., and L = 5 in. From Equation 3-14:

$$45{,}000 \text{ psi} = \frac{3FL}{2wh^2} = \frac{(3)(F)(5 \text{ in.})}{(2)(0.5 \text{ in.})(0.375 \text{ in.})^2} = 106.7F$$

$$F = \frac{45{,}000}{106.7} = 422 \text{ lb}$$

Therefore, the deflection, from Equation 6-20, is

$$18 \times 10^6 \text{ psi} = \frac{L^3F}{4wh^3\delta} = \frac{(5 \text{ in.})^3(422 \text{ lb})}{(4)(0.5 \text{ in.})(0.375 \text{ in.})^3\delta}$$

$$\delta = 0.0278 \text{ in.}$$

In this calculation, we assumed a linear relationship between stress and strain and also that there is no viscoelastic behavior.

3-7- Hardness of materials

The **hardness test** measures the resistance to penetration of the surface of a material by a hard object. Hardness as a term is not defined precisely. Hardness, depending upon the context, can represent resistance to scratching or indentation and a qualitative measure of the strength of the material. In general, in **macrohardness** measurements, the load applied is ~2 N. A variety of hardness tests have been devised, but the most commonly used are the Rockwell test and the Brinell test. Different indenters used in these tests are shown in Figure 3-14.

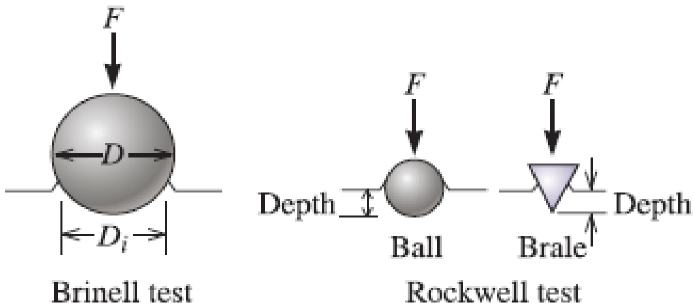

Figure 3-14 Indenters for the Brinell and Rockwell hardness tests.

In the *Brinell hardness test*, a hard steel sphere (usually 10 mm in diameter) is forced into the surface of the material. The diameter of the impression, typically 2 to 6 mm, is measured and the Brinell hardness number (abbreviated as HB or BHN) is calculated from the following equation:

$$HB = \frac{2F}{\pi D\left[D - \sqrt{D^2 - D_i^2}\right]} \quad \dots\dots\dots..(3-17)$$

Where F is the applied load in kilograms, D is the diameter of the indenter in millimeters, and D_i is the diameter of the impression in millimeters. The Brinell hardness has units of kg/mm^2.

The *Rockwell hardness test* uses a small-diameter steel ball for soft materials and a diamond cone, or Brale, for harder materials. The depth of penetration of the indenter is automatically measured by the testing machine and converted to a Rockwell hardness number (HR). Since an optical measurement of the indentation dimensions is not needed, the Rockwell test tends to be more popular than the Brinell test. Several variations of the Rockwell test are used, including those described in Table 3-3. A Rockwell *C* (HRC) test is used for hard steels, whereas a Rockwell *F* (HRF) test might be selected for aluminum. Rockwell tests provide a hardness number that has no units.

Table 3-3 Comparison of typical hardness tests.

Test	Indenter	Load	Application
Brinell	10-mm ball	3000 kg	Cast iron and steel
Brinell	10-mm ball	500 kg	Nonferrous alloys
Rockwell *A*	Brale	60 kg	Very hard materials
Rockwell *B*	1/16-in. ball	100 kg	Brass, low-strength steel
Rockwell *C*	Brale	150 kg	High-strength steel
Rockwell *D*	Brale	100 kg	High-strength steel
Rockwell *E*	1/8-in. ball	100 kg	Very soft materials
Rockwell *F*	1/16-in. ball	60 kg	Aluminum, soft materials
Vickers	Diamond square pyramid	10 kg	All materials
Knoop	Diamond elongated pyramid	500 g	All materials

Hardness numbers are used primarily as a *qualitative* basis for comparison of materials, specifications for manufacturing and heat treatment, quality control, and correlation with other properties of materials. For example, Brinell hardness is related to the tensile strength of steel by the approximation:

$$Tensile\ Strength\ (Psi) = 500HP \quad \text{........ (3-18)}$$

Hardness correlates well with wear resistance. A separate test is available for measuring the wear resistance. A material used in crushing or grinding of ores should be very hard to ensure that the material is not eroded or abraded by the hard feed materials. Similarly, gear teeth in the transmission or the drive system of a vehicle should be hard enough that the teeth do not wear out. Typically we find that polymer materials are exceptionally soft, metals and alloys have intermediate hardness, and ceramics are exceptionally hard.

The Knoop hardness (HK) test is a **microhardness test**, forming such small indentations that a microscope is required to obtain the measurement. In these tests, the load applied is less than 2 N. The Vickers test, which uses a diamond pyramid indenter, can be conducted either as a macro or microhardness test. Microhardness tests are suitable for materials that may have a surface that has a higher hardness than the bulk, materials in which different areas show different levels of hardness, or samples that are not macroscopically flat.

3-8- Strain rate effects and impact behavior

When a material is subjected to a sudden, intense blow, in which the strain rate ($\dot{\gamma}$ or $\dot{\varepsilon}$) is extremely rapid, it may behave in much more brittle a manner than is observed in the tensile test.

Many test procedures have been devised, including the *Charpy* test and the *Izod* test (Figure 3-15). The Izod test is often used for plastic materials. The test specimen may be either notched or unnotched; V-notched specimens better measure the resistance of the material to crack propagation.

In the test, a heavy pendulum, starting at an elevation h_o, swings through its arc, strikes and breaks the specimen, and reaches a lower final elevation h_f. If we know the initial and final elevations of the pendulum, we can calculate the difference in potential energy. This difference is the

impact energy absorbed by the specimen during failure. For the Charpy test, the energy is usually expressed in foot-pounds (ft lb) or joules (J), where 1 ft lb = 1.356 J. The results of the Izod test are expressed in units of ft lb/ in. or J/ m. The ability of a material to withstand an impact blow is often referred to as the **impact toughness** of the material.

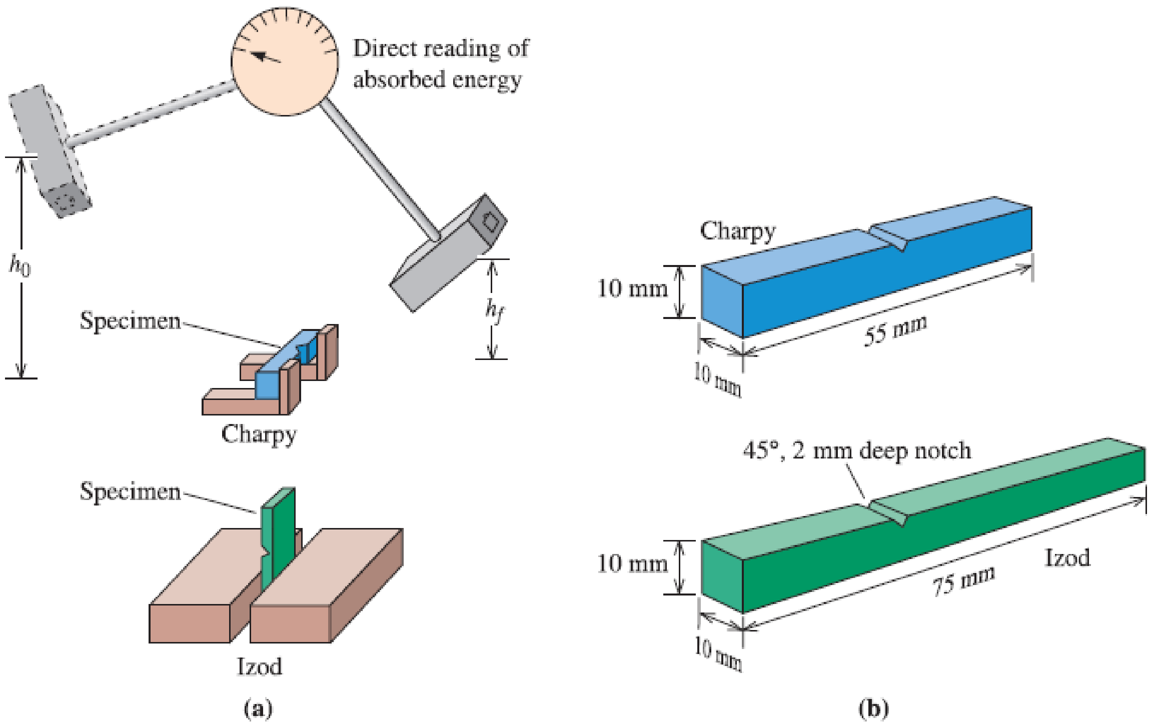

Figure 3-15 The impact test: (a) the Charpy and Izod tests, and (b) dimensions of typical specimens.

As we mentioned before, in some situations, we consider the area under the true or engineering stress-strain curve as a measure of **tensile toughness**. In both cases, we are measuring the energy needed to fracture a material. The difference is that, in tensile tests, the strain rates are much smaller compared to those used in an impact test. Another difference is that in an impact test we usually deal with materials that have a notch. **Fracture toughness** of a material is defined as the ability of a material containing flaws to withstand an applied load.

3-9- Ductile to brittle transition temperature (DBTT)

The ductile to brittle transition temperature is the temperature at which the failure mode of a material changes from ductile to brittle fracture. This temperature may be defined by the average energy between the ductile and brittle regions, at some specific absorbed energy, or by some characteristic fracture appearance. A material subjected to an impact blow during service should have a transition temperature *below* the temperature of the material's surroundings.

Not all materials have a distinct transition temperature (Figure 3-16). BCC metals have transition temperatures, but most FCC metals do not. FCC metals have high absorbed energies, with the energy decreasing gradually and, sometimes, even increasing as the temperature decreases. As mentioned before, the effect of this transition in steel may have contributed to the failure of the *Titanic*.

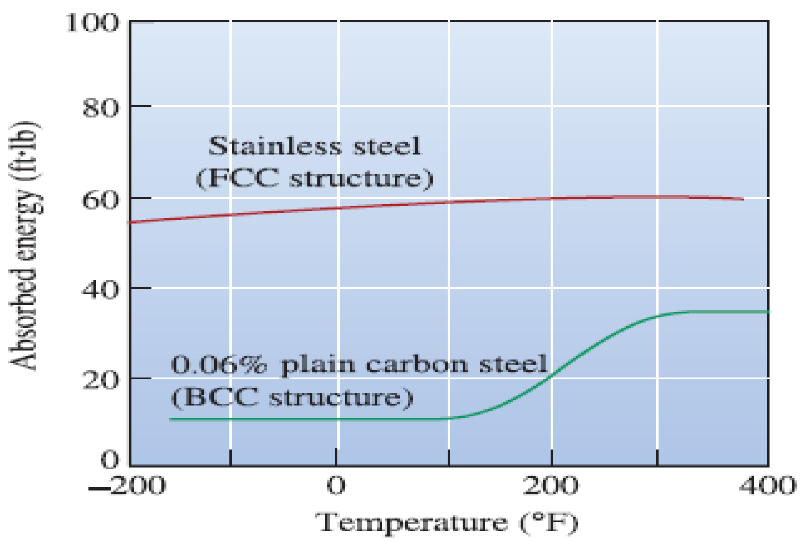

Figure 3-16 The Charpy V-notch properties for a BCC carbon steel and an FCC stainless steel. The FCC crystal structure typically leads to higher absorbed energies and no transition temperature.

In polymeric materials, the ductile to brittle transition temperature is related closely to the glass-transition temperature and for practical purposes is treated as the same. As mentioned before, the transition temperature of the polymers used in booster rocket O-rings and other factors led to the *Challenger* disaster.