MECHANICAL PROPERTIES OF MATERIALS

INTRODUCTION

Mechanical properties of a material determine its behavior when subjected to mechanical stresses. These properties include elastic modulus, ductility, hardness, and various measures of strength. Mechanical properties are important in design because the function and performance of a product depend on its capacity to resist deformation under the stresses encountered in service. In design, the usual objective is for the product and its components to withstand these stresses without significant change in geometry. This capability depends on properties such as elastic modulus and yield strength. In manufacturing, the objective is just the opposite. Here, stresses that exceed the yield strength of the material must be applied to alter its shape. Mechanical processes such as forming and machining succeed by developing forces that exceed the material's resistance to deformation. Thus, there is the following dilemma: Mechanical properties that are desirable to the designer, such as high strength, usually make the manufacture of the product more difficult. It is helpful for the manufacturing engineer to appreciate the design viewpoint and for the designer to be aware of the manufacturing viewpoint.

2.1 Stress–Strain Relationships

There are three types of static stresses to which materials can be subjected: tensile, compressive, and shear. Tensile stresses tend to stretch the material, compressive stresses tend to squeeze it, and shear involves stresses that tend to cause adjacent portions of the material to slide against each other.

The stress–strain curve is the basic relationship that describes the mechanical properties of materials for all three types.

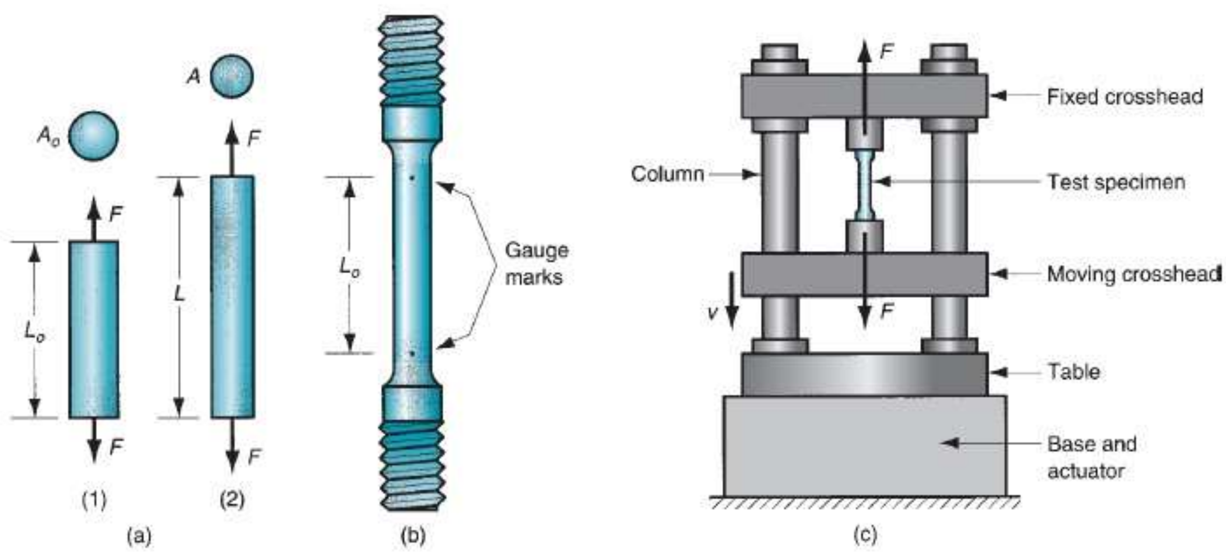


FIGURE 2.1 Tensile test: (a) tensile force applied in (1) and (2) resulting elongation of material; (b) typical test specimen; and (c) setup of the tensile test.

2.1.1 Tensile Properties

The tensile test is the most common procedure for studying the stress–strain relationship, particularly for metals. In the test, a force is applied that pulls the material, tending to elongate it and reduce its diameter, as shown in Figure 2.1(a). Standards by ASTM (American Society for Testing and Materials) specify the preparation of the test specimen and the conduct of the test itself. The typical specimen and general setup of the tensile test is illustrated in Figure 2.1(b) and (c), respectively.

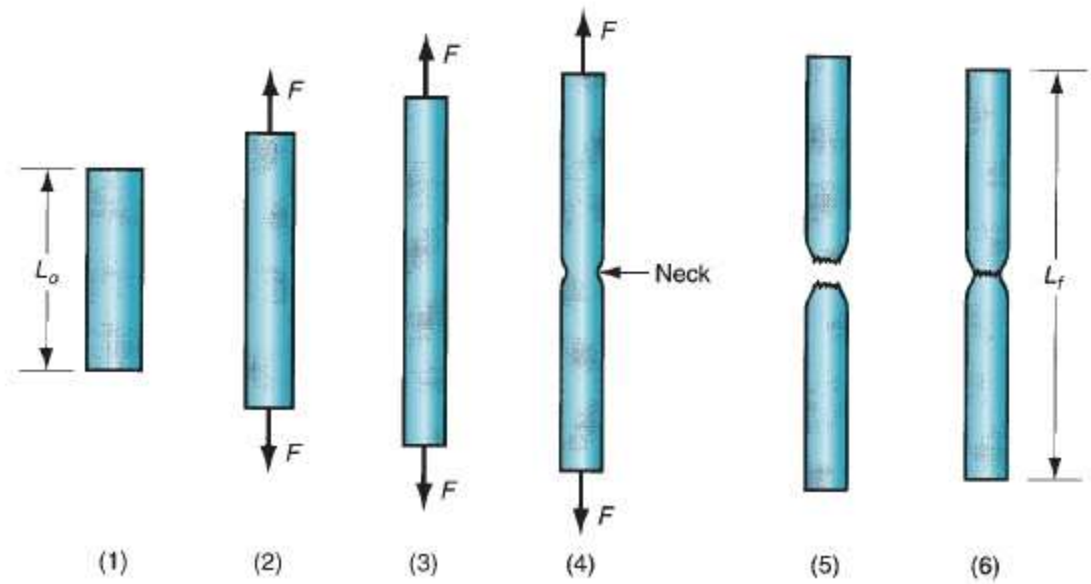


FIGURE 2.2: Typical progress of a tensile test: (1) beginning of test, no load; (2) uniform elongation and reduction of cross-sectional area; (3) continued elongation, maximum load reached; (4) necking begins, load begins to decrease; and (5) fracture. If pieces are put back together as in, (6) final length can be measured.

The starting test specimen has an original length L_o and area A_o. The length is measured as the distance between the gage marks, and the area is measured as the (usually round) cross section of the specimen. During the testing of a metal, the specimen stretches, then necks, and finally fractures, as shown in Figure 2.2.The load and the change in length of the specimen are recorded as testing proceeds, to provide the data required to determine the stress–strain relationship. There are two different types of stress–strain curves:

(1) Engineering stress–strain and

(2) True stress–strain.

The first is more important in design, and the second is more important in manufacturing.

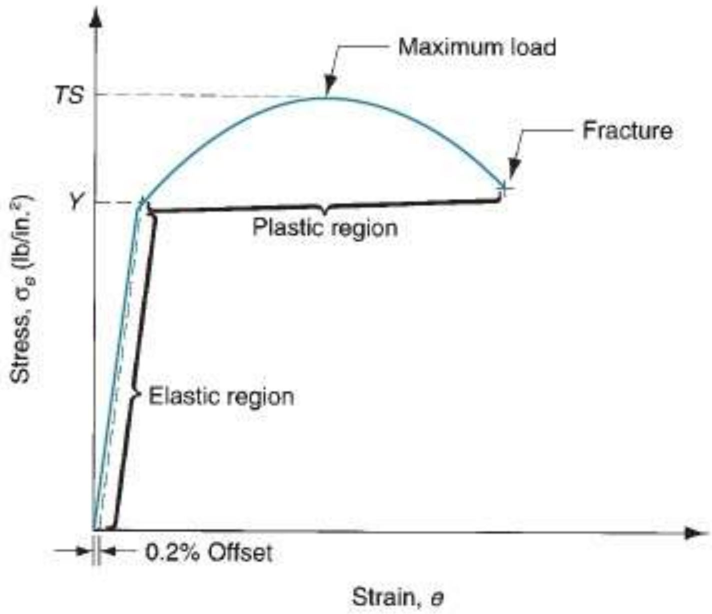


FIGURE 2.3: Typical engineering stress–strain plot in a tensile test of a metal.

Engineering Stress–Strain: The engineering stress and strain in a tensile test are defined relative to the original area and length of the test specimen. These values are of interest in design because the designer expects that the strains experienced by any component of the product will not significantly change its shape. The components are designed to withstand the anticipated stresses encountered in service.

A typical engineering stress–strain curve from a tensile test of a metallic specimen is illustrated in Figure 2.3. The engineering stress at any point on the curve is defined as the force divided by the original area:

$$s = \frac{F}{A_o}$$

where s = engineering stress, MPa (lb/in^2), F = applied force in the test, N (lb), and
A_o = original area of the test specimen, mm^2 (in^2).

The engineering strain at any point in the test is given by

$$e = \frac{L - L_o}{L_o}$$

where e = engineering strain, mm/mm (in/in); L = length at any point during the elongation, mm (in); and Lo = original gage length, mm (in).

The units of engineering strain are given as mm/mm (in/in), but think of it as representing elongation per unit length, without units.

The stress–strain relationship in Figure 2.3 has two regions, indicating two distinct forms of behavior: (1) elastic and (2) plastic. In the elastic region, the relationship between stress and strain is linear, and the material exhibits elastic behavior by returning to its original length when the load (stress) is released. The relationship is defined by Hooke's law:

s = Ee

where E = modulus of elasticity, MPa (lb/in^2), a measure of the inherent stiffness of a material.

It is a constant of proportionality whose value is different for different materials.

Table 2.1 presents typical values for several materials, metals and nonmetals.

Metals	Modulus of Elasticity MPa	Modulus of Elasticity lb/in²	Ceramics and Polymers	Modulus of Elasticity MPa	Modulus of Elasticity lb/in²
Aluminum and alloys	69×10^3	10×10^6	Alumina	345×10^3	50×10^6
Cast iron	138×10^3	20×10^6	Diamond[a]	1035×10^3	150×10^6
Copper and alloys	110×10^3	16×10^6	Plate glass	69×10^3	10×10^6
Iron	209×10^3	30×10^6	Silicon carbide	448×10^3	65×10^6
Lead	21×10^3	3×10^6	Tungsten carbide	552×10^3	80×10^6
Magnesium	48×10^3	7×10^6	Nylon	3.0×10^3	0.40×10^6
Nickel	209×10^3	30×10^6	Phenol formaldehyde	7.0×10^3	1.00×10^6
Steel	209×10^3	30×10^6	Polyethylene (low density)	0.2×10^3	0.03×10^6
Titanium	117×10^3	17×10^6	Polyethylene (high density)	0.7×10^3	0.10×10^6
Tungsten	407×10^3	59×10^6	Polystyrene	3.0×10^3	0.40×10^6

As stress increases, some point in the linear relationship is finally reached at which the material begins to yield. This yield point Y of the material can be identified in the figure by the change in slope at the end of the linear region. Because the start of yielding is usually difficult to see in a plot of test data (it does not usually occur as an abrupt change in slope), Y is typically defined as the stress at which a strain offset of 0.2% from the straight line has occurred. More specifically, it is the point where the stress–strain curve for the material intersects a line that is parallel to the straight portion of the curve but offset from it by a strain of 0.2%. The yield point is a strength characteristic of the material, and is therefore often referred to as the yield strength (other names include yield stress and elastic limit).

The yield point marks the transition to the plastic region and the start of plastic deformation of the material. The relationship between stress and strain is no longer guided by Hooke's law. As the load is increased beyond the yield point, elongation of the specimen proceeds, but at a much faster rate than before, causing the slope of the curve to change dramatically, as shown in Figure 2.3. Elongation is accompanied by a uniform reduction in cross-sectional area, consistent with maintaining constant volume. Finally, the applied load F reaches a maximum value, and the engineering stress calculated at this point is called the tensile strength or ultimate tensile strength of the material. It is denoted as TS where TS = $\frac{F_{max}}{A_0}$. TS and Y are important strength properties in design calculations. (They are also used in manufacturing calculations.) Some typical values of yield strength and tensile strength are listed in Table 2.2 for selected metals.

TABLE 2.2 Yield strength and tensile strength for selected metals.

Metal	Yield Strength MPa	Yield Strength lb/in²	Tensile Strength MPa	Tensile Strength lb/in²	Metal	Yield Strength MPa	Yield Strength lb/in²	Tensile Strength MPa	Tensile Strength lb/in²
Aluminum, annealed	28	4,000	69	10,000	Nickel, annealed	150	22,000	450	65,000
Aluminum, CW[a]	105	15,000	125	18,000	Steel, low C[a]	175	25,000	300	45,000
Aluminum alloys[a]	175	25,000	350	50,000	Steel, high C[a]	400	60,000	600	90,000
Cast iron[a]	275	40,000	275	40,000	Steel, alloy[a]	500	75,000	700	100,000
Copper, annealed	70	10,000	205	30,000	Steel, stainless[a]	275	40,000	650	95,000
Copper alloys[a]	205	30,000	410	60,000	Titanium, pure	350	50,000	515	75,000
Magnesium alloys[a]	175	25,000	275	40,000	Titanium alloy	800	120,000	900	130,000

To the right of the tensile strength on the stress–strain curve, the load begins to decline, and the test specimen typically begins a process of localized elongation known as necking.

Instead of continuing to strain uniformly throughout its length, straining becomes concentrated in one small section of the specimen. The area of that section narrows down (necks) significantly until failure occurs. The stress calculated immediately before failure is known as the fracture stress.

The amount of strain that the material can endure before failure is also a mechanical property of interest in many manufacturing processes. The common measure of this property is ductility, the ability of a material to plastically strain without fracture. This measure can be taken as either elongation or area reduction. Elongation is defined as:

EL = $\frac{L_f - L_o}{L_o}$

where EL = Elongation, often expressed as a percent; L_f = specimen length at fracture, mm(in), measured as the distance between gage marks after the two parts of the specimen have been put back together; and L_o = original specimen length, mm (in).

Area reduction AR is defined as:

AR = $\frac{A_o - A_f}{A_o}$

where AR = Area reduction, often expressed as a percent; A_f = area of the cross section at the point of fracture, mm2(in2); and A_o = original area, mm^2 (in^2).

There are problems with both of these ductility measures because of necking that occurs in metallic test specimens and the associated non uniform effect on elongation and area reduction. Despite these difficulties, percent elongation and percent area reduction are the most commonly used measures of ductility in engineering practice. Some typical values of percent elongation for various materials (mostly metals) are listed in Table 2.3.

TABLE 2.3 Ductility as a percent of elongation (typical values) for various selected materials.

Material	Elongation	Material	Elongation
Metals		*Metals, continued*	
Aluminum, annealed	40%	Steel, low C[a]	30%
Aluminum, cold worked	8%	Steel, high C[a]	10%
Aluminum alloys, annealed[a]	20%	Steel, alloy[a]	20%
Aluminum alloys, heat treated[a]	8%	Steel, stainless, austenitic[a]	55%
Aluminum alloys, cast[a]	4%	Titanium, nearly pure	20%
Cast iron, gray[a]	0.6%	Zinc alloy	10%
Copper, annealed	45%	*Ceramics*	0[b]
Copper, cold worked	10%	*Polymers*	
Copper alloy: brass, annealed	60%	Thermoplastic polymers	100%
Magnesium alloys[a]	10%	Thermosetting polymers	1%
Nickel, annealed	45%	Elastomers (e.g., rubber)	1%[c]

True Stress–Strain: Thoughtful readers may be troubled by the use of the original area of the test specimen to calculate engineering stress, rather than the actual (instantaneous) area that becomes increasingly smaller as the test proceeds. If the actual area were used, the calculated stress value would be higher. The stress value obtained by dividing the instantaneous value of area into the applied load is defined as the true stress:

$$\sigma = \frac{F}{A}$$

where σ true stress, MPa (lb/in²); F = force, N(lb); and A = actual (instantaneous) area resisting the load, mm^2 (in^2).

Similarly, true strain provides a more realistic assessment of the ‘‘instantaneous’’ elongation per unit length of the material. The value of true strain in a tensile test can be estimated by dividing the total elongation into small increments, calculating the engineering strain for each increment on the basis of its starting length, and then adding up the strain values. In the limit, true strain is defined as

$\in = \int_{L_o}^{L} \frac{dL}{L} = \ln\frac{L}{L_o}$

where L = instantaneous length at any moment during elongation.
At the end of the test (or other deformation), the final strain value can be calculated using $L = L_f$.
When the engineering stress–strain data in Figure 2.3 are plotted using the true stress and strain values, the resulting curve would appear as in Figure 2.4.

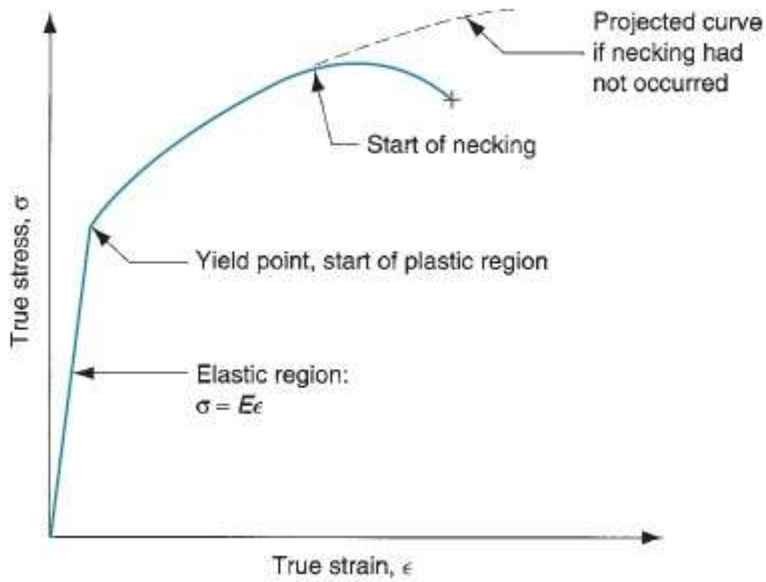


FIGURE 2.4 True stress–strain curve for the previous engineering stress–strain plot in Figure 2.3.

In the elastic region, the plot is virtually the same as before. Strain values are small, and true strain is nearly equal to engineering strain for most metals of interest. The respective stress values are also very close to each other. The reason for these near equalities is that the cross-sectional area of the test specimen is not significantly reduced in the elastic region. Thus, Hooke's law can be used to relate true stress to true strain: $\boldsymbol{\sigma = E\in}$.
The difference between the true stress–strain curve and its engineering counterpart occurs in the plastic region. The stress values are higher in the plastic region because the instantaneous cross-sectional area of the specimen, which has been continuously reduced during elongation, is now used in the computation. As in the previous curve, a downturn finally occurs as a result of necking. A dashed line is used in the figure to indicate the projected continuation of the true stress–strain plot if necking had not occurred.
As strain becomes significant in the plastic region, the values of true strain and engineering strain diverge. True strain can be related to the corresponding engineering strain by

$$\in = \ln(1+e)$$

Similarly, true stress and engineering stress can be related by the expression

$$\sigma = s(1+e)$$

In Figure 2.4, note that stress increases continuously in the plastic region until necking begins. When this happened in the engineering stress–strain curve, its significance was lost because an admittedly erroneous area value was used to calculate stress. Now when the true stress also increases, it cannot be dismissed so lightly. What it means is that the metal is becoming stronger as strain increases. This is the property called strain hardening that was mentioned in the previous chapter in the discussion of metallic crystal structures, and it is a property that most metals exhibit to a greater or lesser degree.
Strain hardening, or work hardening as it is often called, is an important factor in certain manufacturing processes, particularly metal forming. Consider the behavior of a metal as it is affected by this property. If the portion of the true stress–strain curve representing the plastic

region were plotted on a log–log scale, the result would be a linear relationship, as shown in Figure 2.5.

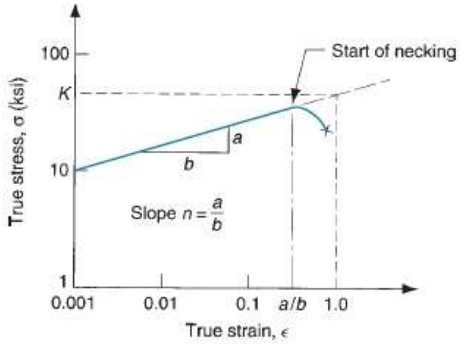


FIGURE 2.5 True stress–strain curve plotted on log–log scale.

Because it is a straight line in this transformation of the data, the relationship between true stress and true strain in the plastic region can be expressed as:

$\boldsymbol{\sigma} = \mathbf{K}\boldsymbol{\in}^{\boldsymbol{n}}$

This equation is called the flow curve, and it provides a good approximation of the behavior of metals in the plastic region, including their capacity for strain hardening. The constant K is called the strength coefficient, MPa (lb/in^2), and it equals the value of true stress at a true strain value equal to one. The parameter n is called the strain hardening exponent, and it is the slope of the line in Figure 2.5. Its value is directly related to a metal's tendency to work harden. Typical values of K and n for selected metals are given in Table 2.4.

TABLE 3.4 Typical values of strength coefficient K and strain hardening exponent n for selected metals

Material	Strength Coefficient, K		Strain Hardening Exponent, n
	MPa	lb/in^2	
Aluminum, pure, annealed	175	25,000	0.20
Aluminum alloy, annealed[a]	240	35,000	0.15
Aluminum alloy, heat treated	400	60,000	0.10
Copper, pure, annealed	300	45,000	0.50
Copper alloy: brass[a]	700	100,000	0.35
Steel, low C, annealed[a]	500	75,000	0.25
Steel, high C, annealed[a]	850	125,000	0.15
Steel, alloy, annealed[a]	700	100,000	0.15
Steel, stainless, austenitic, annealed	1200	175,000	0.40

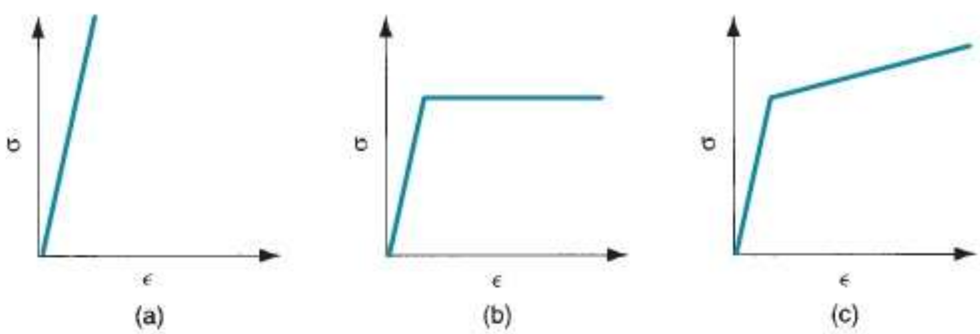
Necking in a tensile test and metal-forming operations that stretch the workpart is closely related to strain hardening. As the test specimen is elongated during the initial part of the test (before necking begins), uniform straining occurs throughout the length because if any element in the specimen becomes strained more than the surrounding metal, its strength increases because of work hardening, thus making it more resistant to additional strain until the surrounding metal has been strained an equal amount. Finally, the strain becomes so large that uniform straining cannot be sustained. A weak point in the length develops (because of buildup of dislocations at grain boundaries, impurities in the metal, or other factors), and necking is initiated, leading to failure. Empirical evidence reveals that necking begins for a particular metal when the true strain reaches a value equal to the strain-hardening exponent n. Therefore, a higher n value means that the metal can be strained further before the onset of necking during tensile loading.

Types of Stress–Strain Relationships: Much information about elastic–plastic behavior is provided by the true stress–strain curve. As indicated, Hooke's law ($\boldsymbol{\sigma} = \mathbf{E}\boldsymbol{\in}$.) governs the metal's behavior in the elastic region, and the flow curve ($\boldsymbol{\sigma = K\in^{n}}$) determines the behavior in the plastic region. Three basic forms of stress–strain relationship describe the behavior of nearly all types of solid materials, shown in Figure 2.6:

1. Perfectly elastic: The behavior of this material is defined completely by its stiffness, indicated by the modulus of elasticity E. It fractures rather than yielding to plastic flow.
Brittle materials such as ceramics, many cast irons, and thermosetting polymers possess stress–strain curves that fall into this category. These materials are not good candidates for forming operations.

2. Elastic and perfectly plastic: This material has a stiffness defined by E. Once the yield strength Y is reached, the material deforms plastically at the same stress level. The flow curve is given by K = Y and n = 0. Metals behave in this fashion when they have been heated to sufficiently high temperatures that they recrystallize rather than strain harden during deformation. Lead exhibits this behavior at room temperature because room temperature is above the recrystallization point for lead.

3. Elastic and strain hardening: This material obeys Hooke's law in the elastic region. It begins to flow at its yield strength Y. Continued deformation requires an ever-increasing stress, given by a flow curve whose strength coefficient K is greater than Y and whose strain-hardening exponent n is greater than zero. The flow curve is generally represented as a linear function on a natural logarithmic plot. Most ductile metals behave this way when cold worked.



Three categories of stress– strain relationship: (a) perfectly elastic, (b) elastic and perfectly plastic, and (c) elastic and strain hardening.

2.1.2 Compression Properties

A compression test applies a load that squeezes a cylindrical specimen between two platens, as illustrated in Figure .27.

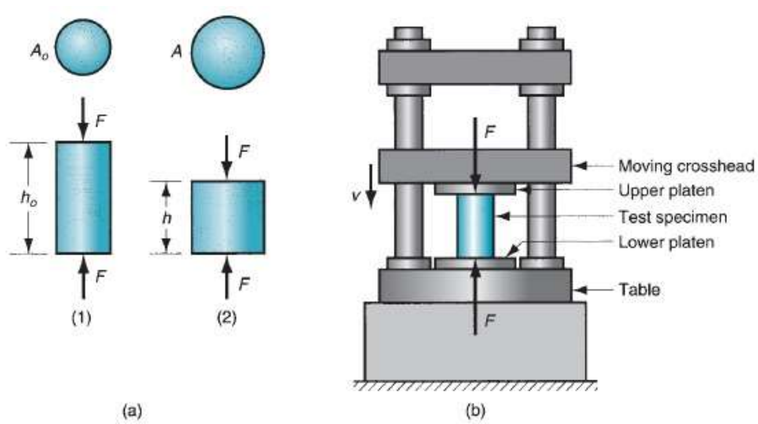


FIGURE 3.7 Compression test: (a) compression force applied to test piece in (1), and (2) resulting change in height; and (b) setup for the test, with size of test specimen exaggerated.

As the specimen is compressed, its height is reduced and its cross-sectional area is increased. Engineering stress is defined as

s = $\frac{F}{F_o}$

where A_o = original area of the specimen.

This is the same definition of engineering stress used in the tensile test. The engineering strain is defined as:

e = $\frac{h - h_o}{h_o}$

where h = height of the specimen at a particular moment into the test, mm (in); and h_o = starting height, mm (in).

Because the height is decreased during compression, the value of e will be negative.

The negative sign is usually ignored when expressing values of compression strain.

When engineering stress is plotted against engineering strain in a compression test, the results appear as in Figure 2.8.

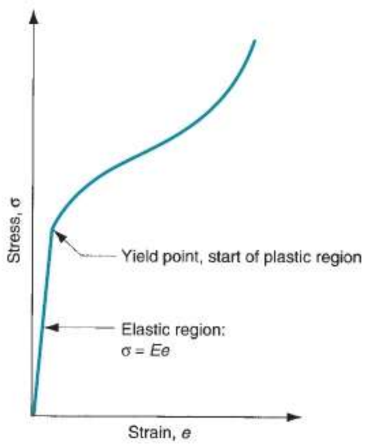


FIGURE 2.8 Typical engineering stress– strain curve for a compression test.

The curve is divided into elastic and plastic regions, as before, but the shape of the plastic portion of the curve is different from its tensile test complement.

Because compression causes the cross section to increase (rather than decrease as in the tensile test), the load increases more rapidly than previously. This results in a higher value of calculated engineering stress.

Something else happens in the compression test that contributes to the increase in stress. As the cylindrical specimen is squeezed, friction at the surfaces in contact with the platens tends to prevent the ends of the cylinder from spreading. Additional energy is consumed by this friction during the test, and this results in a higher applied force. It also shows up as an increase in the computed engineering stress. Hence, owing to the increase in cross-sectional area and friction between the specimen and the platens, the characteristic engineering stress–strain curve is obtained in a compression test as seen in the figure.

Another consequence of the friction between the surfaces is that the material near the middle of the specimen is permitted to increase in area much more than at the ends. This results in the characteristic barreling of the specimen, as seen in Figure 2.9.

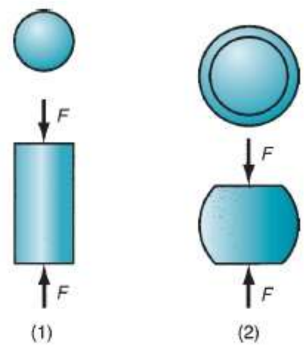


FIGURE 3.9 Barreling effect in a compression test: (1) start of test; and (2) after considerable compression has occurred.

Although differences exist between the engineering stress–strain curves in tension and compression, when the respective data are plotted as true stress–strain, the relationships are nearly identical (for almost all materials).Because tensile test results are more abundant in the literature, values of the flow curve parameters (K and n) can be derived from tensile test data and applied with equal validity to a compression operation. What must be done in using the tensile test results for a compression operation is to ignore the effect of necking, a phenomenon that is peculiar to straining induced by tensile stresses. In compression, there is no corresponding collapse of the work. In previous plots of tensile stress–strain curves, the data were extended beyond the point of necking by means of the dashed lines. The dashed lines better represent the behavior of the material in compression than the actual tensile test data.

Compression operations in metal forming are much more common than stretching operations. Important compression processes in industry include rolling, forging, and extrusion.

2.1.3 Bending and Testing of Brittle Materials

Bending operations are used to form metal plates and sheets. As shown in Figure 2.10, the process of bending a rectangular cross section subjects the material to tensile stresses (and strains) in the outer half of the bent section and compressive stresses (and strains) in the inner half. If the material does not fracture, it becomes permanently (plastically) bent as shown in (2.1) of Figure 2.10.

Hard, brittle materials (e.g., ceramics), which possess elasticity but little or no plasticity, are often tested by a method that subjects the specimen to a bending load.

These materials do not respond well to traditional tensile testing because of problems in preparing the test specimens and possible misalignment of the press jaws that hold the specimen. The bending test (also known as the flexure test) is used to test the strength of these materials, using a setup illustrated in the first diagram in Figure 2.10. In this procedure, a specimen of rectangular cross section is positioned between two supports, and a load is applied at its center. In this configuration, the test is called a three-point bending test. A four-point configuration is also sometimes used. These brittle materials do not flex to the exaggerated extent shown in Figure 2.10; instead they deform elastically until immediately before fracture. Failure usually occurs because the ultimate tensile strength of the outer fibers of the specimen has been exceeded. This results in cleavage, a failure mode associated with ceramics and metals operating at low service temperatures, in which separation rather than slip occurs along certain crystallographic planes. The strength value derived from this test is called the transverse rupture strength, calculated from the formula

$$TRS = \frac{1.5FL}{bt^2}$$

where TRS = transverse rupture strength, MPa (lb/in^2); F = applied load at fracture, N(lb); L = length of the specimen between supports, mm(in); and b and t are the dimensions of the cross section of the specimen as shown in the figure, mm (in).
The flexure test is also used for certain non-brittle materials such as thermoplastic polymers. In this case, because the material is likely to deform rather than fracture, TRS cannot be determined based on failure of the specimen. Instead, either of two measures is used: (1) the load recorded at a given level of deflection, or (2) the deflection observed at a given load.

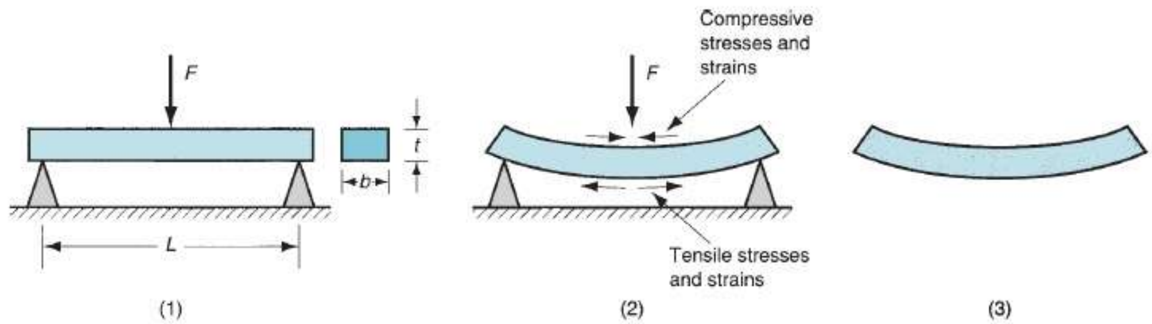


FIGURE 3.10 Bending of a rectangular cross section results in both tensile and compressive stresses in the material: (1) initial loading; (2) highly stressed and strained specimen; and (3) bent part.

2.1.4 Shear Properties

Shear involves application of stresses in opposite directions on either side of a thin element to deflect it, as shown in Figure 2.11.

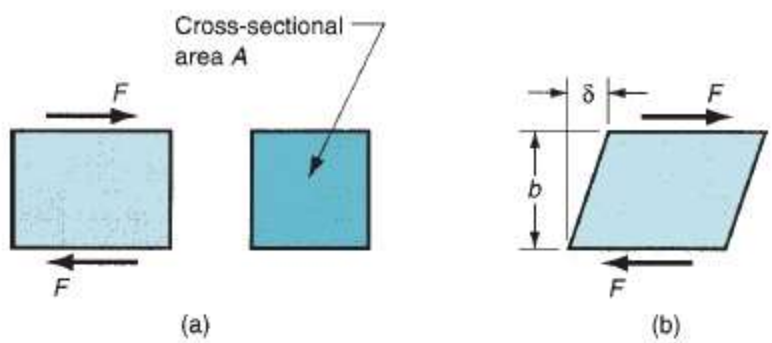


FIGURE 2.11 Shear (a) stress and (b) strain.

The shear stress is defined as: $\tau = \frac{F}{A}$

where t = shear stress, lb/in^2 (MPa); F = applied force, N(lb); and A = area over which the force is applied, in^2 (mm^2).

Shear strain can be defined as: $\gamma = \frac{\delta}{b}$

where γ = shear strain, mm/mm (in/in); δ = the deflection of the element, mm (in); and b = the orthogonal distance over which deflection occurs, mm (in).
Shear stress and strain are commonly tested in a torsion test, in which a thin-walled tubular specimen is subjected to a torque as shown in Figure 2.12.

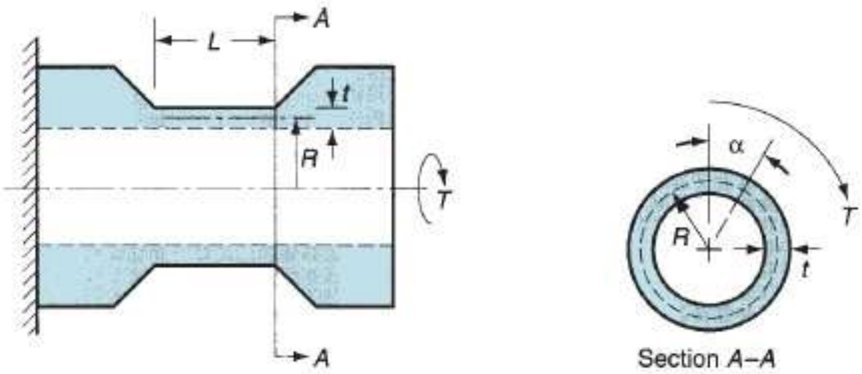


FIGURE 2.12 Torsion test setup.

As torque is increased, the tube deflects by twisting, which is a shear strain for this geometry.

The shear stress can be determined in the test by the equation: $\tau = \frac{T}{2\pi R^2 t}$

where T = applied torque, N-mm (lb-in); R ¼ radius of the tube measured to the neutral axis of the wall, mm (in); and t ¼ wall thickness, mm (in).

The shear strain can be determined by measuring the amount of angular deflection of the tube, converting this into a distance deflected, and dividing by the gauge length L.

Reducing this to a simple expression

$$\gamma = \frac{R \propto}{L}$$

where α the angular deflection (radians).

A typical shear stress–strain curve is shown in Figure 2.13.

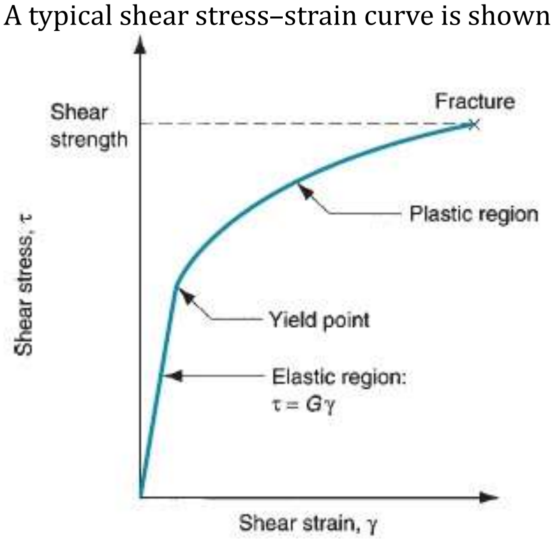


FIGURE 2.13 Typical shear stress– strain curve from a torsion test.

In the elastic region, the relationship is defined by: $\tau = G\gamma$

where G ¼ the shear modulus, or shear modulus of elasticity, MPa (lb/in^2). For most materials, the shear modulus can be approximated by G = 0.4E, where E is the conventional elastic modulus.

In the plastic region of the shear stress–strain curve, the material strain hardens to cause the applied torque to continue to increase until fracture finally occurs. The relationship in this region is similar to the flow curve. The shear stress at fracture can be calculated and this is used as the shear strength S of the material. Shear strength can be estimated from tensile strength data by the approximation: S = 0.7(TS).

Because the cross-sectional area of the test specimen in the torsion test does not change as it does in the tensile and compression tests, the engineering stress–strain curve for shear derived from the torsion test is virtually the same as the true stress–strain curve.

2.2 Hardness

The hardness of a material is defined as its resistance to permanent indentation. Good hardness generally means that the material is resistant to scratching and wear. For many engineering applications, including most of the tooling used in manufacturing, scratch and wear resistance are important characteristics. As the reader shall see later in this section, there is a strong correlation between hardness and strength.

2.2.1 Hardness Tests

Hardness tests are commonly used for assessing material properties because they are quick and convenient. However, a variety of testing methods are appropriate because of differences in hardness among different materials. The best-known hardness tests are Brinell and Rockwell.

Brinell Hardness Test: The Brinell hardness test is widely used for testing metals and nonmetals of low to medium hardness. It is named after the Swedish engineer who developed it around 1900. In the test, a hardened steel (or cemented carbide) ball of 10-mmdiameter is pressed into the surface of a specimen using a load of 500, 1500, or 3000 kg. The load is then divided into the indentation area to obtain the Brinell Hardness Number (BHN). In equation form

$$HB = \frac{2F}{\pi D_b\left(D_b - \sqrt{D_b^2 - D_i^2}\right)}$$

where HB = Brinell Hardness Number (BHN); F = indentation load, kg; D_b = diameter of the ball, mm; and D_i = diameter of the indentation on the surface, mm.

These dimensions are indicated in Figure 2.14(a). The resulting BHN has units of kg/ mm^2, but the units are usually omitted in expressing the number. For harder materials (above 500 BHN), the cemented carbide ball is used because the steel ball experiences elastic deformation that compromises the accuracy of the reading. Also, higher loads (1500 and 3000 kg) are typically used for harder materials. Because of differences in results under different loads, it is considered good practice to indicate the load used in the test when reporting HB readings.

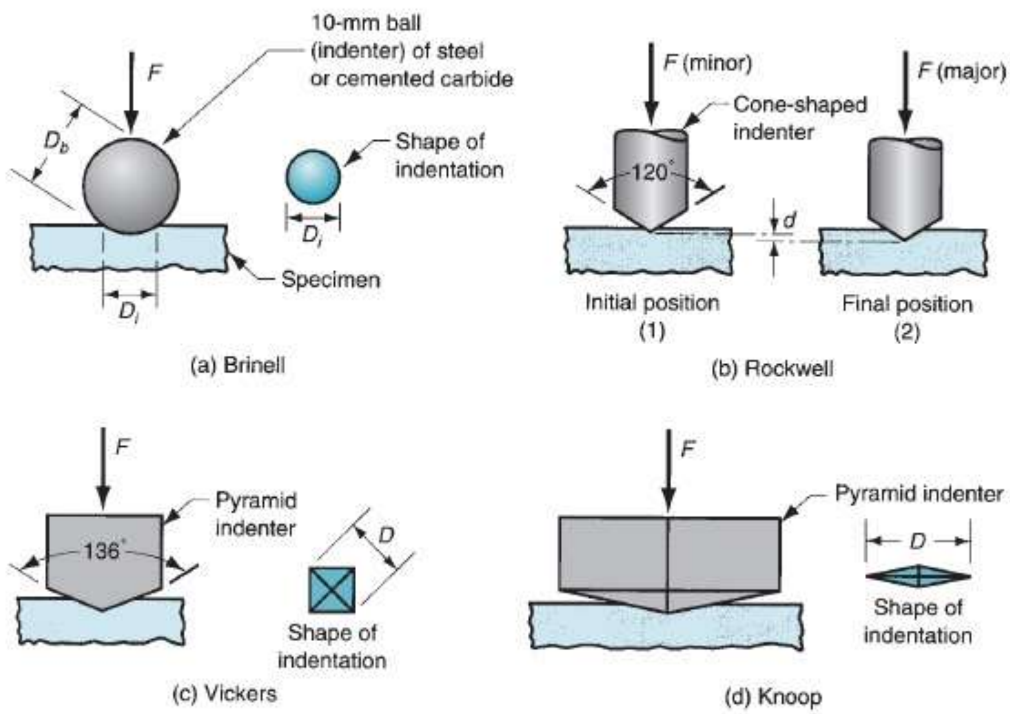


FIGURE 2.14 Hardness testing methods: (a) Brinell; (b) Rockwell: (1) initial minor load and (2) major load, (c) Vickers, and (d) Knoop.

Rockwell Hardness Test: This is another widely used test, named after the metallurgist who developed it in the early 1920s. It is convenient to use, and several enhancements over the years have made the test adaptable to a variety of materials.

In the Rockwell Hardness Test, a cone-shaped indenter or small-diameter ball, with diameter = 1.6 or 3.2 mm (1/16 or 1/8 in) is pressed into the specimen using a minor load of 10 kg, thus seating the indenter in the material. Then, a major load of 150 kg (or other value) is applied, causing the indenter to penetrate into the specimen a certain distance beyond its initial position. This additional penetration distance d is converted into a Rockwell hardness reading by the testing machine. The sequence is depicted in Figure 2.14(b). Differences in load and indenter geometry provide various Rockwell scales for different materials. The most common scales are indicated in Table 2.5.

Vickers Hardness Test This test, also developed in the early 1920s, uses a pyramid shaped indenter made of diamond. It is based on the principle that impressions made by this indenter are geometrically similar regardless of load. Accordingly, loads of various size are applied, depending on the hardness of the material to be measured. The Vickers Hardness (HV) is then determined from the formula

HV $=\frac{1.854F}{D^2}$

where F ¼applied load, kg, andD ¼ the diagonal of the impression made by the indenter, mm, as indicated in Figure 2.14(c).

The Vickers test can be used for all metals and has one of the widest scales among hardness tests.

Knoop Hardness Test: The Knoop test, developed in 1939, uses a pyramid-shaped diamond indenter, but the pyramid has a length-to-width ratio of about 7:1, as indicated in Figure 2.14(d), and the applied loads are generally lighter than in the Vickers test. It is a microhardness test, meaning that it is suitable for measuring small, thin specimens or hard materials that might fracture if a heavier load were applied. The indenter shape facilitates reading of the impression under the lighter loads used in this test. The Knoop hardness value (HK) is determined according to the formula:

HK $1.42\frac{F}{D^2}$

where F ¼ load, kg; and D ¼ the long diagonal of the indentor, mm.

Because the impression made in this test is generally very small, considerable care must be taken in preparing the surface to be measured.

2.3 Effect of Temperature on Properties

Temperature has a significant effect on nearly all properties of a material. It is important for the designer to know the material properties at the operating temperatures of the product when in service. It is also important to know how temperature affects mechanical properties in manufacturing. At elevated temperatures, materials are lower in strength and higher in ductility. The general relationships for metals are depicted in Figure 2.15. Thus, most metals can be formed more easily at elevated temperatures than when they are cold.

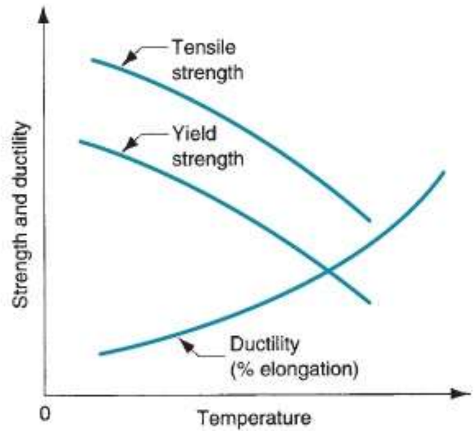


FIGURE 2.15 General effect of temperature on strength and ductility

Hot Hardness: A property often used to characterize strength and hardness at elevated temperatures is hot hardness. Hot hardness is simply the ability of a material to retain hardness at elevated temperatures; it is usually presented as either a listing of hardness values at different temperatures or as a plot of hardness versus temperature, as in Figure 2.16. Steels can be alloyed to achieve significant improvements in hot hardness, as shown in the figure.

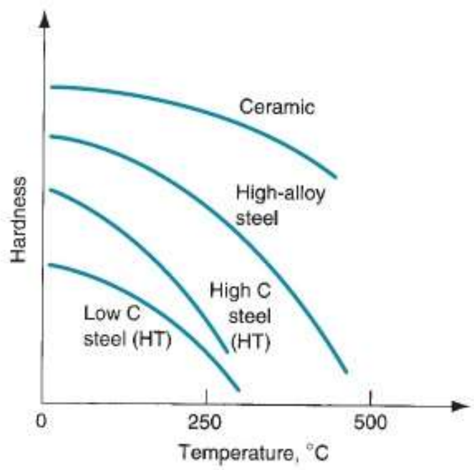


FIGURE 2.16 Hot hardness—typical hardness as a function of temperature for several materials.

Ceramics exhibit superior properties at elevated temperatures. These materials are often selected for high temperature applications, such as turbine parts, cutting tools, and refractory applications. The outside skin of a shuttle spacecraft is lined with ceramic tiles to withstand the friction heat of high-speed re-entry into the atmosphere.

Good hot hardness is also desirable in the tooling materials used in many manufacturing operations. Significant amounts of heat energy are generated in most metalworking processes, and the tools must be capable of withstanding the high temperatures involved.

Recrystallization Temperature: Most metals behave at room temperature according to the flow curve in the plastic region. As the metal is strained, it increases in strength because of strain hardening (the strain-hardening exponent $n>0$).However, if the metal is heated to a sufficiently elevated temperature and then deformed, strain hardening does not occur.

Instead, new grains are formed that are free of strain, and the metal behaves as a perfectly plastic material; that is, with a strain-hardening exponent $n=0$.The formation of new strain free grains is a process called recrystallization, and the temperature at which it occurs is about one-half the melting point ($0.5T_m$), as measured on an absolute scale (R or K). This is called the recrystallization temperature. Recrystallization takes time. The recrystallization temperature for a particular metal is usually specified as the temperature at which complete formation of new grains requires about 1 hour.

PRACTICE QUESTION

2.1What is the dilemma between design and manufacturing in terms of mechanical properties?
2.2. What are the three types of static stresses to which materials are subjected?
2.3. State Hooke's law.
2.4. What is the difference between engineering stress and true stress in a tensile test?
2.5. Define tensile strength of a material.
2.6. Define yield strength of a material.
2.7. Why cannot a direct conversion be made between the ductility measures of elongation and reduction in area using the assumption of constant volume?
2.8. What is work hardening?
2.9. In what case does the strength coefficient have the same value as the yield strength?
2.10. How does the change in cross-sectional area of a test specimen in a compression test differ from its counterpart in a tensile test specimen?