Mechanical Properties (2nd Lec)

If a load is static or changes relatively slowly with time and is applied uniformly over a cross section or surface of a member, the mechanical behavior may be find out by a simple **stress–strain test**; these are most commonly conducted for metals at room temperature. There are three principal ways in which a load may be applied: namely, **tension, compression, and shear** (Figures below). In engineering practice many loads are **torsional** rather than pure shear.

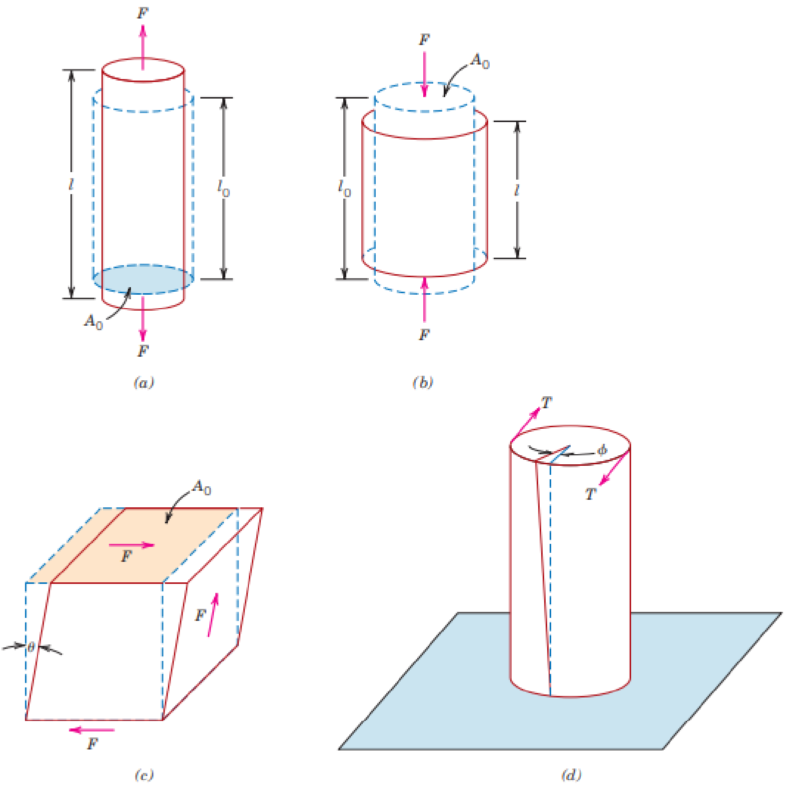


Figure 6.1 (*a*) Schematic illustration of how a tensile load produces an elongation and positive linear strain. Dashed lines represent the shape before deformation; solid lines, after deformation. (*b*) Schematic illustration of how a compressive load produces contraction and a negative linear strain. (*c*) Schematic representation of shear strain γ, where $\gamma = \tan\theta$. (*d*) Schematic representation of torsional deformation (i.e., angle of twist ϕ) produced by an applied torque T.

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). Its Annual Book of ASTM Standards (http://www. astm.org) comprises numerous volumes, which are issued and updated yearly; a large number of these standards relate to mechanical testing techniques.

Tension Tests

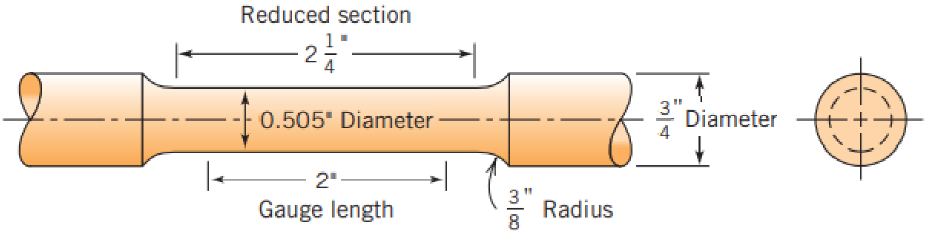
One of the most common mechanical **stress–strain tests** is performed in **tension**. The tension test can be used to ascertain several mechanical properties of materials that are important in design. A specimen is deformed, usually to fracture, with a gradually increasing tensile load that is applied along the long axis of a specimen. A standard tensile specimen.

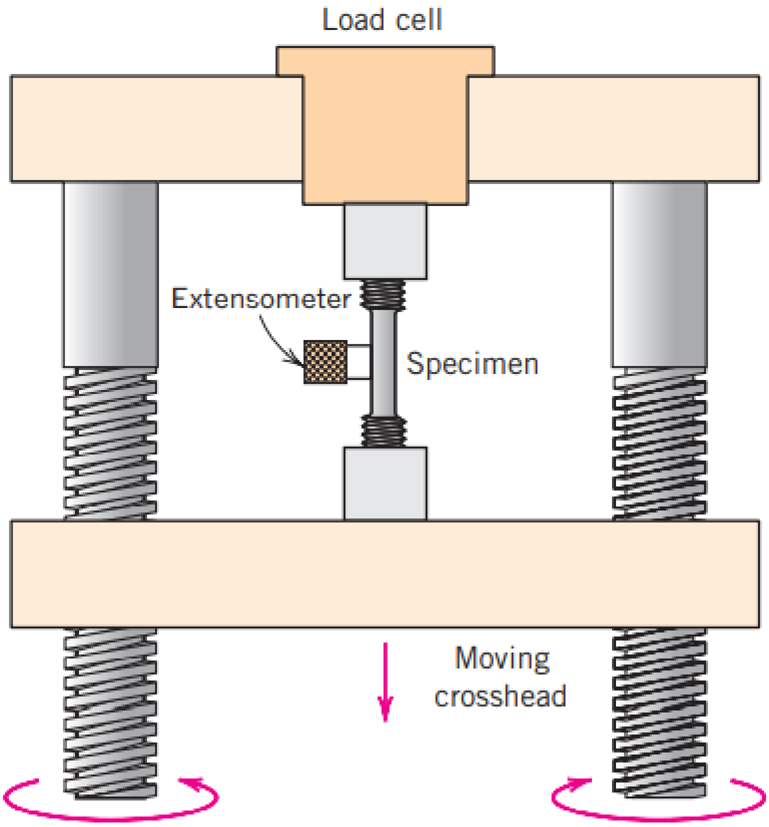
Normally, the cross section is **circular**, but rectangular specimens are also used. This "dogbone" specimen configuration was chosen so that, during testing, deformation is confined to the narrow center region (which has a uniform cross section along its length), and also to reduce the likelihood of fracture at the ends of the specimen. The **standard diameter is approximately 12.8 mm (0.5 in.)**, whereas the reduced section length should be at least four times this diameter; **60 mm** is common. Gauge length is used in ductility computations, **the standard value is 50 mm (**2.0 in.). The specimen is mounted by its ends into the holding grips of the testing apparatus.

The tensile testing machine is designed **to elongate the specimen** at a constant rate and to continuously and simultaneously measure the instantaneous applied load (with a load cell) and the resulting elongations (using an extensometer). A stress–strain test typically takes several minutes to perform and is destructive; that is, the test specimen is permanently deformed and usually fractured.

The output of such a tensile test is recorded (usually on a computer) as load or force versus elongation. These load–deformation characteristics are dependent on the specimen size. For example, it will require twice the load to produce the same elongation if the cross-sectional area of the specimen is doubled.

Figure 6.2 A standard tensile specimen with circular cross section.





Engineering stress σ is defined by the relationship:

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

in which F is the instantaneous load applied perpendicular to the specimen cross section, in units of **newton** (N) or pounds force (lbf), and A_0 is the original crosssectional area before any load is applied (m^2 or in^2). The units of engineering stress are **megapascals**, MPa (SI) (where 1 MPa 10^6 N/m2), and pounds force per square inch, psi (customary U.S.). Engineering strain ϵ is defined according to

$$\epsilon = \frac{l_i - l_0}{l_0} = \frac{\Delta l}{l_0}$$

l_o is the original length before any load is applied and l_i is the instantaneous length. Sometimes the quantity li - l_0 is denoted as Δl and is the deformation elongation or change in length at some instant, as referenced to the original length.

Compression Tests

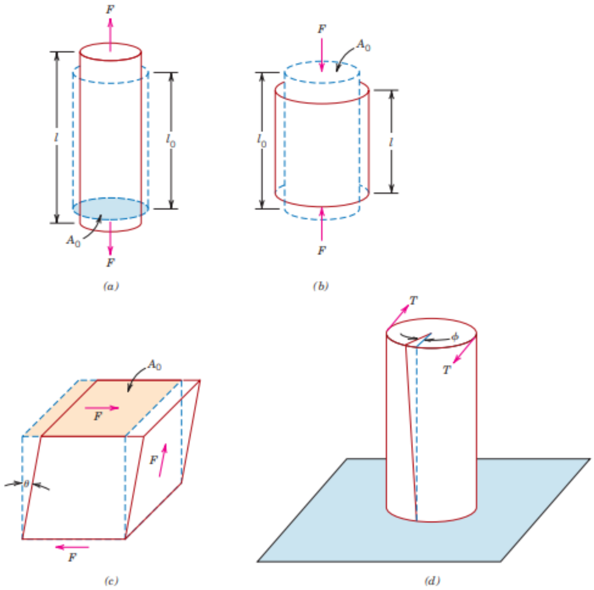
Compression stress–strain tests may be conducted if in-service forces are of this type. A compression test is conducted in a manner similar to the tensile test, except that the force is compressive and the specimen contracts along the direction of the stress.

Shear and Torsional Tests

For tests performed using a pure **shear** force as shown in Figure 6.1c, the shear stress is computed according to

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

where F is the load or force imposed **parallel** to the upper and lower faces, each of which has an area of A_0. The shear strain is defined as the **tangent of the strain angle**. The units for shear stress and strain are the same as for their tensile counterparts MPa.



Torsion is a variation of pure shear, wherein a structural member is **twisted** in the manner of Figure 6.1d; torsional forces produce a rotational motion about the longitudinal axis of one end of the member relative to the other end. Examples of torsion are found for machine axles and drive shafts, and also for twist drills. Torsional tests are normally performed on cylindrical solid shafts or tubes. A shear stress is a function of the applied torque T, whereas shear strain is related to the angle of twist, in the Figure above.

STRESS–STRAIN BEHAVIOR The degree to which a structure deforms or strains **depends on the magnitude of an imposed stress**. For most metals that are stressed in tension and at relatively low levels, stress and strain are proportional to each other through the relationship

$$\sigma = E\epsilon$$

Hooke's law

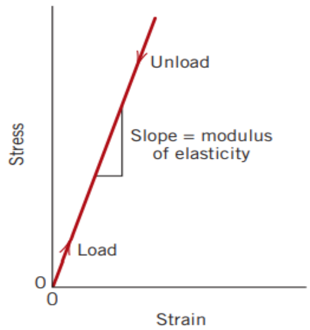
This is known as **Hooke's law**, and the constant E (GPa or psi) is the **modulus of elasticity**, or **Young's modulus**. For most typical metals the magnitude of this modulus ranges between 45 GPa for magnesium, and 407 GPa for tungsten.

•••

Hooke's law—relationship between engineering stress and engineering strain for elastic deformation (tension and compression)

•••

Modulus of elasticity values for several metals at room temperature are presented in the **Table**. Deformation in which stress and strain are proportional is called elastic deformation; a plot of stress versus strain results in a **linear** relationship, as shown in Figure.



The slope of this linear segment corresponds to the modulus of elasticity E. This modulus may be thought of as stiffness, or a material's resistance to elastic deformation. **The greater the modulus, the stiffer the material**, or the **smaller the**

elastic strain that results from the application of a given stress. The modulus is an important design parameter used for computing **elastic deflections**. Elastic deformation is **NONPERMANENT**, which means that when the applied load is released, the piece returns to its original shape. As shown in the stress–strain plot

The Stress / Strain Curve for Mild Steel

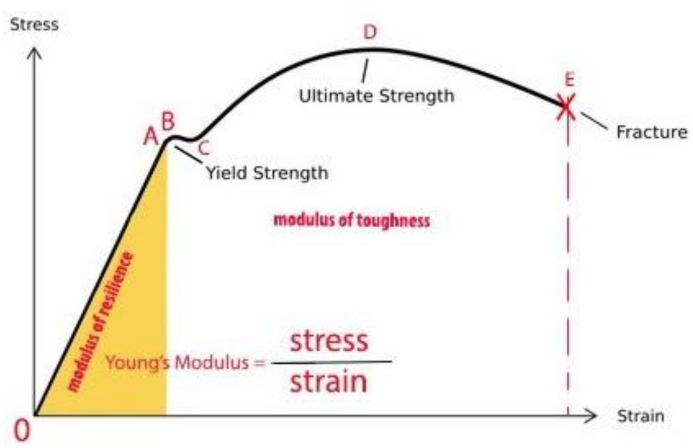


Table: Room-Temperature Elastic and Shear Moduli and Poisson's Ratio for Various Metal Alloys

Metal Alloy	*Modulus of Elasticity* GPa	*Modulus of Elasticity* 10^6 psi	*Shear Modulus* GPa	*Shear Modulus* 10^6 psi	*Poisson's Ratio*
Aluminum	69	10	25	3.6	0.33
Brass	97	14	37	5.4	0.34
Copper	110	16	46	6.7	0.34
Magnesium	45	6.5	17	2.5	0.29
Nickel	207	30	76	11.0	0.31
Steel	207	30	83	12.0	0.30
Titanium	107	15.5	45	6.5	0.34
Tungsten	407	59	160	23.2	0.28

7.2 A cylindrical specimen of a nickel alloy having an elastic modulus of 207 GPa (30 × 106 psi) and an original diameter of 10.2 mm (0.40 in.) will experience only elastic deformation when a tensile load of 8900 N (2000 lbf) is applied. Compute the maximum length of the specimen before deformation if the maximum allowable elongation is 0.25 mm (0.010 in.).

Solution: We are asked to compute the maximum length of a cylindrical nickel specimen (before deformation) that is deformed elastically in tension. For a cylindrical specimen

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

where d_0 is the original diameter. Combining Equations 7.1, 7.2, and 7.5 and solving for l_0 leads to

$$l_0 = \frac{\Delta l}{\varepsilon} = \frac{\Delta l}{\frac{\sigma}{E}} = \frac{\Delta l\, E}{\frac{F}{A_0}} = \frac{\Delta l\, E\pi\left(\frac{d_0}{2}\right)^2}{F} = \frac{\Delta l\, E\pi\, d_0^2}{4F}$$

$$= \frac{(0.25 \times 10^{-3}\ \text{m})(207 \times 10^9\ \text{N/m}^2)\ (\pi)(10.2 \times 10^{-3}\ \text{m})^2}{(4)(8900\ \text{N})}$$

$$= 0.475\ \text{m} = 475\ \text{mm}\ (18.7\ \text{in.})$$

7.3 *Consider a cylindrical nickel wire 2.0 mm (0.08 in.) in diameter and 3 × 10^4 mm (1200 in.) long. Calculate its elongation when a load of 300 N (67 lb_f) is applied. Assume that the deformation is totally elastic.*

<u>Solution</u>

In order to compute the elongation of the Ni wire when the 300 N load is applied we must employ Equations 7.1, 7.2, and 7.5. Solving for Δl and realizing that for Ni, E = 207 GPa (30 x 10^6 psi) (Table 7.1),

$$\Delta l = l_0\varepsilon = l_0\frac{\sigma}{E} = \frac{l_0 F}{E A_0} = \frac{l_0 F}{E\pi\left(\frac{d_0}{2}\right)^2} = \frac{4 l_0 F}{E\pi d_0^2}$$

$$= \frac{(4)(30\ \text{m})(300\ \text{N})}{(207 \times 10^9\ \text{N/m}^2)(\pi)(2 \times 10^{-3}\ \text{m})^2} = 0.0138\ \text{m} = 13.8\ \text{mm}\ (0.53\ \text{in.})$$

Stretching a Rod

A 2.0-m-long steel rod has a cross-sectional area of $0.30\ \text{cm}^2$. The rod is a part of a vertical support that holds a heavy 550-kg platform that hangs attached to the rod's lower end. Ignoring the weight of the rod, what is the tensile stress in the rod and the elongation of the rod under the stress?

Strategy

First we compute the tensile stress in the rod under the weight of the platform in accordance with Equation 12.34. Then we invert Equation 12.36 to find the rod's elongation, using $L_0 = 2.0\ \text{m}$. From Table 12.1, Young's modulus for steel is $Y = 2.0 \times 10^{11}\text{Pa}$.

Solution

Substituting numerical values into the equations gives us

$$\frac{F_\perp}{A} = \frac{(550\ \text{kg})(9.8\ \text{m/s}^2)}{3.0 \times 10^{-5}\ \text{m}^2} = 1.8 \times 10^8\text{Pa}$$

$$\Delta L = \frac{F_\perp}{A}\frac{L_0}{Y} = (1.8 \times 10^8\text{Pa})\frac{2.0\ \text{m}}{2.0 \times 10^{11}\text{Pa}} = 1.8 \times 10^{-3}\text{m} = 1.8\ \text{mm}.$$

Compressive Stress in a Pillar

A sculpture weighing 10,000 N rests on a horizontal surface at the top of a 6.0-m-tall vertical pillar . The pillar's cross-sectional area is $0.20\ \text{m}^2$ and it is made of granite with a mass density of $2700\ \text{kg/m}^3$. Find the compressive stress at the cross-section located 3.0 m below the top of the pillar and the value of the compressive strain of the top 3.0-m segment of the pillar.

Solution

The volume of the pillar segment with height $h = 3.0\ \text{m}$ and cross-sectional area $A = 0.20\ \text{m}^2$ is

$$V = Ah = (0.20\ \text{m}^2)(3.0\ \text{m}) = 0.60\ \text{m}^3.$$

With the density of granite $\rho = 2.7 \times 10^3\ \text{kg/m}^3$, the mass of the pillar segment is

$$m = \rho V = (2.7 \times 10^3\ \text{kg/m}^3)(0.60\ \text{m}^3) = 1.60 \times 10^3\text{kg}.$$

The weight of the pillar segment is

$$w_p = mg = (1.60 \times 10^3\text{kg})(9.80\ \text{m/s}^2) = 1.568 \times 10^4\text{N}.$$

The weight of the sculpture is $w_s = 1.0 \times 10^4\text{N}$, so the normal force on the cross-sectional surface located 3.0 m below the sculpture is

$$F_\perp = w_p + w_s = (1.568 + 1.0) \times 10^4\text{N} = 2.568 \times 10^4\text{N}.$$

Therefore, the stress is

$$\text{stress} = \frac{F_\perp}{A} = \frac{2.568 \times 10^4\text{N}}{0.20\ \text{m}^2} = 1.284 \times 10^5\text{Pa} = 128.4\ \text{kPa}.$$

Young's modulus for granite is $Y = 4.5 \times 10^{10}\text{Pa} = 4.5 \times 10^7\text{kPa}$. Therefore, the compressive strain at this position is

$$\text{strain} = \frac{\text{stress}}{Y} = \frac{128.4\ \text{kPa}}{4.5 \times 10^7\text{kPa}} = 2.85 \times 10^{-6}.$$

For a brass alloy, the stress at which plastic deformation begins is 345 MPa (50,000 psi), and the modulus of elasticity is 103 GPa (15.0 × 106 psi).

(a) What is the maximum load that may be applied to a specimen with a cross-sectional area of 130 mm^2 (0.2 in.2) without plastic deformation?

(b) If the original specimen length is 76 mm (3.0 in.), what is the maximum length to which it may be stretched without causing plastic deformation?

<u>Solution</u>

(a) This portion of the problem calls for a determination of the maximum load that can be applied without plastic deformation (F_y). Taking the yield strength to be 345 MPa, and employment of Equation 7.1 leads to

$$F_y = \sigma_y A_0 = (345 \times 10^6 \text{ N/m}^2)(130 \times 10^{-6} \text{ m}^2)$$

$$= 44{,}850 \text{ N} \quad (10{,}000 \text{ lb}_f)$$

(b) The maximum length to which the sample may be deformed without plastic deformation is determined from Equations 7.2 and 7.5 as

$$l_i = l_0(1 + \varepsilon) = l_0\left(1 + \frac{\sigma}{E}\right)$$

$$= (76 \text{ mm})\left[1 + \frac{345 \text{ MPa}}{103 \times 10^3 \text{ MPa}}\right] = 76.25 \text{ mm} \quad (3.01 \text{ in.})$$

Shear stress and strain

Shear stress and strain are proportional to each other through the expression that gives the relationship between shear stress and shear strain for elastic deformation

$$\tau = G\gamma$$

Where T is the stress, G is the shear modulus, the slope of the linear elastic region of the shear stress–strain curve. The table above also gives the shear moduli for a number of the common metals.

A cleaning person tries to move a heavy, old bookcase on a carpeted floor by pushing tangentially on the surface of the very top shelf. However, the only noticeable effect of this effort is similar to that seen in Figure 12.24, and it disappears when the person stops pushing. The bookcase is 180.0 cm tall and 90.0 cm wide with four 30.0-cm-deep shelves, all partially loaded with books. The total weight of the bookcase and books is 600.0 N. If the person gives the top shelf a 50.0-N push that displaces the top shelf horizontally by 15.0 cm relative to the motionless bottom shelf, find the shear modulus of the bookcase.

Strategy

The only pieces of relevant information are the physical dimensions of the bookcase, the value of the tangential force, and the displacement this force causes. We identify $F_{\|} = 50.0\,\text{N}$, $\Delta x = 15.0\,\text{cm}$, $L_0 = 180.0\,\text{cm}$, and $A = (30.0\,\text{cm})(90.0\,\text{cm}) = 2700.0\,\text{cm}^2$, and we use Equation 12.43 to compute the shear modulus.

Solution

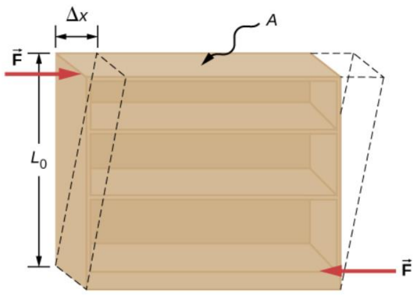
Substituting numbers into the equations, we obtain for the shear modulus

$$S = \frac{F_{\|}}{A}\frac{L_0}{\Delta x} = \frac{50.0\,\text{N}}{2700.0\,\text{cm}^2}\frac{180.0\,\text{cm.}}{15.0\,\text{cm.}} = \frac{2}{9}\frac{\text{N}}{\text{cm}^2} = \frac{2}{9}\times 10^4\frac{\text{N}}{\text{m}^2} = \frac{20}{9}\times 10^3\text{Pa} = 2.222\,\text{kPa}.$$

We can also find shear stress and strain, respectively:

$$\frac{F_{\|}}{A} = \frac{50.0\,\text{N}}{2700.0\,\text{cm}^2} = \frac{5}{27}\,\text{kPa} = 185.2\,\text{Pa}$$

$$\frac{\Delta x}{L_0} = \frac{15.0\,\text{cm}}{180.0\,\text{cm}} = \frac{1}{12} = 0.083.$$



Tensile Strength

After yielding, the stress necessary to continue plastic deformation in metals increases to a maximum, point M in Figure 6.11, and then decreases to the fracture, point F. The tensile strength TS (MPa or psi) is the stress at the maximum on the engineering stress–strain curve. All deformation up to this point is uniform throughout the narrow region of the tensile specimen. However, at this maximum stress, a small constriction or **neck** begins to form at some point, and all subsequent deformation is confined at this neck, as indicated by the schematic specimen insets

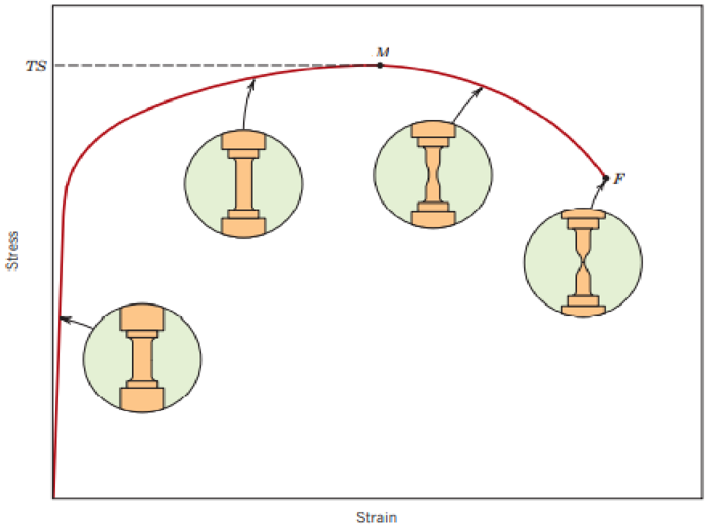
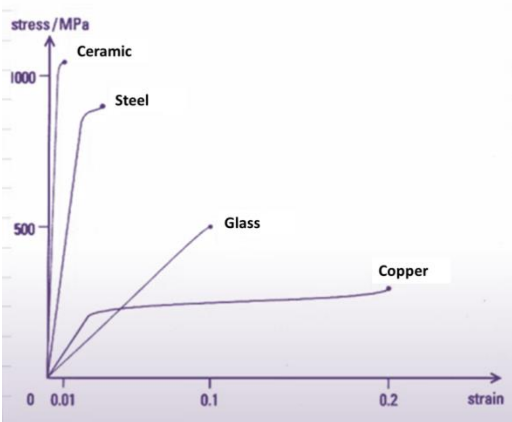


Figure 6.11 Typical engineering stress–strain behavior to fracture, point *F*. The tensile strength *TS* is indicated at point *M*. The circular insets represent the geometry of the deformed specimen at various points along the curve.



Ductility

Ductility is another important mechanical property. **It is a measure of the degree of plastic deformation that has been sustained at fracture**. A metal that experiences very little or no plastic deformation upon fracture is termed brittle. Ductility may be expressed quantitatively as either percent elongation or percent reduction in area. The percent elongation %EL is the percentage of plastic strain at fracture, or

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

where l_f is the fracture length and l_0 is the original gauge length as given before. The magnitude of %EL depends on specimen gauge length. The shorter l_0, the greater the fraction of total elongation from the neck and, consequently, the higher the value of

%EL. Therefore, l_0 should be specified when percent elongation values are cited; it is commonly 50 mm (2 in.). Percent reduction in area %RA is defined as:

$$\%\mathrm{RA} = \left(\frac{A_0 - A_f}{A_0}\right) \times 100$$

Where A_0 is the original cross-sectional area and A_f is the cross-sectional area at the point of fracture. Percent reduction in area values are independent of both l_0 and A_0. Furthermore, for a given material the magnitudes of **%EL** and **%RA** will, in general, be different. Most metals possess at least a moderate degree of ductility at room temperature; however, **some become brittle as the temperature is lowered**.

A knowledge of the ductility of materials is important for at least **two reasons**. **First**, it indicates to a designer the degree to which a **structure will deform** plastically before fracture. **Second**, it specifies the degree of allowable deformation during **fabrication operations**

True Stress and Strain

The decline in the stress necessary to continue deformation past the maximum, point M, seems to indicate that the metal is **becoming weaker**. This is not at all the case; as a matter of fact, it is increasing in strength. However, the cross-sectional area is decreasing rapidly within the neck region, where deformation is occurring. This results in a reduction in the load-bearing capacity of the specimen. The stress is on the basis of the original crosssectional area before any deformation and does not take into account this reduction in area at the neck.

Sometimes it is more significant to use a true stress–true strain scheme. **True stress** is defined as the load F divided by the **instantaneous cross-sectional area** A_i over which deformation is occurring (i.e., the neck, past the tensile point), or

$$\sigma_T = \frac{F}{A_i}$$

Furthermore, it is occasionally more convenient to represent strain as true strain, defined by

$$\epsilon_T = \ln \frac{l_i}{l_0}$$

If no volume change occurs during deformation that is

$$A_i l_i = A_0 l_0$$

true and engineering stress and strain are related according to

$$\sigma_T = \sigma(1 + \epsilon)$$

$$\epsilon_T = \ln(1 + \epsilon)$$

For some metals and alloys the region of the true stress–strain curve from the beginning of plastic deformation to the point at which necking begins may be approximated by

$$\sigma_T = K\epsilon_T^n$$

In this expression, K and n are constants; these values will vary from alloy to alloy and will also depend on the condition of the material (i.e., whether it has been plastically deformed, heat-treated, etc.). The parameter n is often termed the strain-hardening exponent and has a value less than unity. Values of n and K for several alloys are contained in the Table below..

		K	
Material	***n***	***MPa***	***psi***
Low-carbon steel (annealed)	0.21	600	87,000
4340 steel alloy (tempered @ 315°C)	0.12	2650	385,000
304 stainless steel (annealed)	0.44	1400	205,000
Copper (annealed)	0.44	530	76,500
Naval brass (annealed)	0.21	585	85,000
2024 aluminum alloy (heat-treated—T3)	0.17	780	113,000
AZ-31B magnesium alloy (annealed)	0.16	450	66,000

Example

Ductility and True-Stress-at-Fracture Computations

A cylindrical specimen of steel having an original diameter of 12.8 mm (0.505 in.) is tensile-tested to fracture and found to have an engineering fracture strength σ_f of 460 MPa (67,000 psi). If its cross-sectional diameter at fracture is 10.7 mm (0.422 in.), determine:

(a) The ductility in terms of percent reduction in area

(b) The true stress at fracture

Solution

(a) Ductility is computed using Equation 6.12, as

$$\%RA = \frac{\left(\frac{12.8 \text{ mm}}{2}\right)^2 \pi - \left(\frac{10.7 \text{ mm}}{2}\right)^2 \pi}{\left(\frac{12.8 \text{ mm}}{2}\right)^2 \pi} \times 100$$

$$= \frac{128.7 \text{ mm}^2 - 89.9 \text{ mm}^2}{128.7 \text{ mm}^2} \times 100 = 30\%$$

(b) True stress is defined by Equation 6.15, where in this case the area is taken as the fracture area A_f. However, the load at fracture must first be computed from the fracture strength as

$$F = \sigma_f A_0 = (460 \times 10^6 \text{ N/m}^2)(128.7 \text{ mm}^2)\left(\frac{1 \text{ m}^2}{10^6 \text{ mm}^2}\right) = 59{,}200 \text{ N}$$

Thus, the true stress is calculated as

$$\sigma_T = \frac{F}{A_f} = \frac{59{,}200 \text{ N}}{(89.9 \text{ mm}^2)\left(\frac{1 \text{ m}^2}{10^6 \text{ mm}^2}\right)}$$

$$= 6.6 \times 10^8 \text{ N/m}^2 = 660 \text{ MPa } (95{,}700 \text{ psi})$$

HARDNESS

Another mechanical property that may be important to consider is hardness, which is a **measure of a material's resistance to localized plastic deformation** (e.g., a small dent or a scratch). Early hardness tests were based on natural minerals with a scale constructed solely on the ability of one material to scratch another that was softer. A qualitative and somewhat arbitrary hardness indexing scheme was devised, termed the Mohs scale, which ranged from 1 on the soft end for talc to 10 for diamond.

Quantitative hardness techniques have been developed over the years in which a small indenter is forced into the surface of a material to be tested, under controlled conditions of load and rate of application. **The depth or size of the resulting indentation is measured**, which in turn is related to a hardness number; the softer the material, the larger and deeper the indentation, and the lower the hardness index number. Measured hardnesses are only relative and care should be exercised when comparing values determined by different techniques. Hardness tests are performed more **frequently than any other mechanical test** for several reasons:

1. They are simple and inexpensive—ordinarily no special specimen need be prepared, and the testing apparatus is relatively inexpensive.

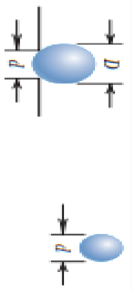
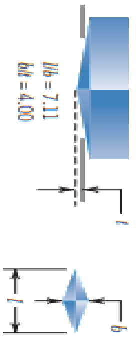
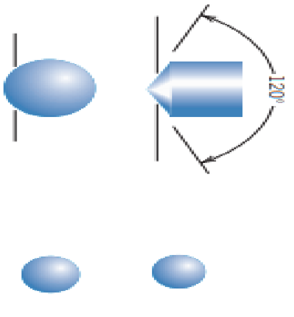
2. The test is nondestructive—the specimen is neither fractured nor excessively deformed; a small indentation is the only deformation.

3. Other mechanical properties often may be estimated from hardness data, such as tensile strength.

Rockwell Hardness Tests

The Rockwell tests constitute the most common method used to measure hardness because they are so simple to perform and require no special skills. Several different scales may be utilized from possible combinations of various indenters and different loads, which permit the testing of virtually all metal alloys (as well as some polymers). Indenters include **spherical** and **hardened steel balls** having diameters of and (1.588, 3.175, 6.350, and 12.70 mm), and a conical diamond (Brale) indenter, which is used for the hardest materials. With this system, a hardness number is determined by the difference in depth of penetration resulting from the application of an initial minor load followed by a larger major load; utilization of a minor load enhances test accuracy. On the basis of the magnitude of both major and minor loads, there are two types of tests: Rockwell and superficial Rockwell. For Rockwell, the minor load is 10 kg, whereas major loads are 60, 100, and 150 kg. Each scale is represented by a letter of the alphabet; several are listed with the corresponding indenter and load in Tables. For superficial tests, 3 kg is the minor load; 15, 30, and 45 kg are the possible major load values. These scales are identified by a 15, 30, or 45 (according to load), followed by N, T, W, X, or Y, depending on indenter. Superficial tests are frequently performed on thin specimens. Table presents several superficial scales.

Table 6.5 Hardness-Testing Techniques

Test	Indenter	Shape of Indentation: Side View / Top View	Load	Formula for Hardness Number[a]
Brinell	10-mm sphere of steel or tungsten carbide		P	$HB = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
Vickers microhardness	Diamond pyramid		P	$HV = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid		P	$HK = 14.2P/l^2$
Rockwell and superficial Rockwell	Diamond cone; $\frac{1}{16}$, $\frac{1}{8}$, $\frac{1}{4}$, $\frac{1}{2}$ in. diameter steel spheres		60 kg, 100 kg, 150 kg } Rockwell; 15 kg, 30 kg, 45 kg } Superficial Rockwell	

Brinell Hardness Tests

In Brinell tests, as in Rockwell measurements, a hard, spherical indenter is forced into the surface of the metal to be tested. The diameter of the hardened steel (or tungsten carbide) indenter is 10.00 mm (0.394 in.). Standard loads range between 500 and 3000 kg in 500-kg increments; during a test, the load is maintained constant for a specified time (between 10 and 30 s). Harder materials require greater applied loads. The Brinell hardness number, HB, is a function of both the magnitude of the load and the diameter of the resulting indentation.

This diameter is measured with a special low-power microscope, utilizing a scale that is etched on the eyepiece. The measured diameter is then converted to the appropriate HB number using a chart; only one scale is employed with this technique. Semiautomatic techniques for measuring Brinell hardness are available. These employ optical scanning systems consisting of a digital camera mounted on a flexible probe, which allows positioning of the camera over the indentation. Data from the camera are transferred to a computer that analyzes the indentation, determines its size, and then calculates the Brinell hardness number. For this technique, surface finish requirements are normally more stringent than for manual measurements. Maximum specimen thickness as well as indentation position (relative to specimen edges) and minimum indentation spacing requirements are the same as for Rockwell tests. In addition, a well-defined indentation is required; this necessitates a smooth flat surface in which the indentation is made.

Knoop and Vickers Microindentation Hardness Tests

Two other hardness-testing techniques are Knoop (pronounced and Vickers (sometimes also called diamond pyramid). For each test a very small diamond indenter having pyramidal geometry is forced into the surface of the specimen. Applied loads are much smaller than for Rockwell and Brinell, ranging between 1 and 1000 g. The resulting impression is observed under a microscope and measured; this measurement is then converted into a hardness number. Careful specimen surface preparation (grinding and polishing) may be necessary to ensure a well-defined indentation that may be accurately measured. The Knoop and Vickers hardness numbers are designated by HK and HV, respectively,18 and hardness scales for both techniques are approximately equivalent. Knoop and Vickers are referred to as micro-indentation testing methods on the basis of indenter size. Both are well suited for measuring the hardness of small, selected specimen regions; furthermore, Knoop is used for testing brittle materials such as ceramics.

The modern micro-indentation hardness-testing equipment has been automated by coupling the indenter apparatus to an image analyzer that incorporates a computer and software package. The software controls important system functions to include indent location, indent spacing, computation of hardness values, and plotting of data.

Correlation between Hardness and Tensile Strength

Both tensile strength and hardness are indicators of a metal's resistance to plastic deformation. Consequently, they are roughly proportional, for tensile strength as a function of the HB for cast iron, steel, and brass. The same proportionality relationship does not hold for all metals. As a rule of thumb for most steels, the HB and the tensile strength are related according to

$$TS(\text{MPa}) = 3.45 \times \text{HB}$$

$$TS(\text{psi}) = 500 \times \text{HB}$$