CHAPTER TWO

Mechanical Properties of Materials

Why Study *The Mechanical Properties of Metals?*

It is incumbent on engineers to understand how the various mechanical properties are measured and what these properties represent; they may be called upon to design structures/components using predetermined materials such that unacceptable levels of deformation and/or failure will not occur.

Many materials, when in service, are subjected to forces or loads; examples include the aluminum alloy from which an airplane wing is constructed and the steel in an automobile axle. In such situations it is necessary to know the characteristics of the material and to design the member from which it is made such that any resulting deformation will not be excessive and fracture will not occur. The mechanical behavior of a material reflects the relationship between its response or deformation to an applied load or force.

A modern Rockwell hardness tester.

Important mechanical properties are : strength, hardness, ductility, and stiffness.

❖ Definitions of Mechanical Properties of materials :

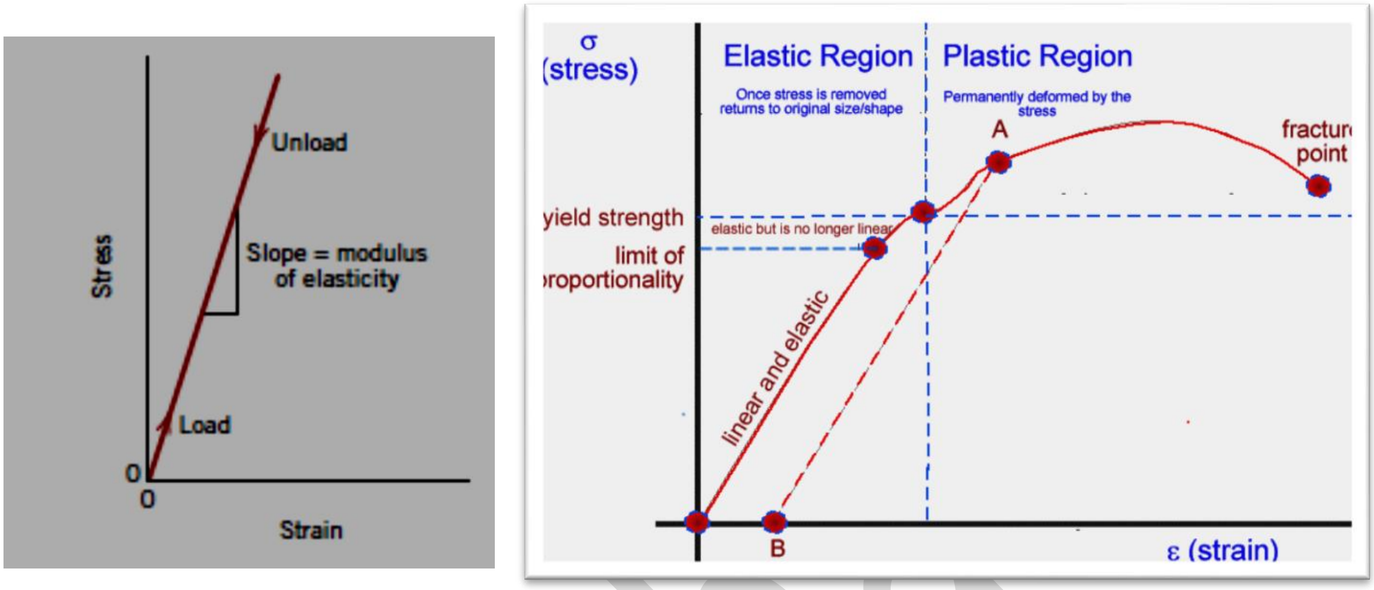
1. **Strength:** The strength of material is its ability to resist the application of force without rupture . In service, a material may have to withstand tension, compression or shear forces . The unit of strength is (N/m^2).

2. **Stress:** It is defined as the intensity of the internal distributed forces or components of forces resisting a change in the form of the body . It is measured as the force per unit area . There are three types of stresses namely: tension, compression and shear .

3. **Strain:** It is a deformation or change produced in material in its dimensions due to the effect of stress on it . It is a ratio or dimensionless number (has no unit) . There are three types of strains corresponding to the type of stresses namely , tensile , compressive , and shearing strain . Strain also known to be of two categories: elastic strain and plastic strain .

   - **Elastic strain** : It is the change in dimensions of a body when some load is applied to it . It is a reversible strain, it disappears after removal of stress or applied load . It is proportional to the applied stress . In this strain , after the removal of load , same atomic neighbors without any displacement are retained. Figure (2.1a) shows an elastic strain .

   - **Plastic strain** : It is the deformation or change in dimensions of a body which remain in it after the release of load .It is a result of the permanent displacement of the atoms inside the material. Figure (2.1b) shows the elastic and plastic strain .



Figure(2.1) : Schematic stress–strain diagram showing linear elastic deformation for loading and unloading cycles.(a) and elastic & plastic region (b).

4. **Elasticity :** The elasticity of a metal is its power of returning to its original shape after deformation by force .

5. **Plasticity :** It is the property of the material enabling it to retain the deformation produced by load permanently . Plasticity is necessary for forging, and metals may be rendered plastic by heating them .

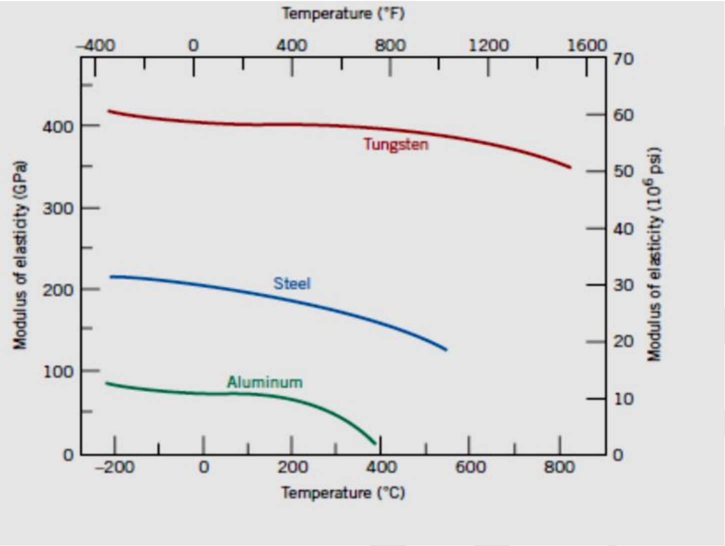
6. **Modulus of elasticity :** It is the ratio of the stress applied and strain produced within the elastic limit of the material .It is the criterion of the stiffness of material .

$$Y = \frac{\sigma}{\varepsilon}$$

Where : Y = Modulus of elasticity . (young modulus).
σ= Elastic stress.
ε = Elastic strain.

Values of the modulus of elasticity for ceramic materials are about the

same as for metals; for polymers they are lower .These differences are a direct consequence of the different types of atomic bonding in the three materials types.
Furthermore, with increasing temperature, the modulus of elasticity diminishes, as is shown for several metals in Figure (2.2)

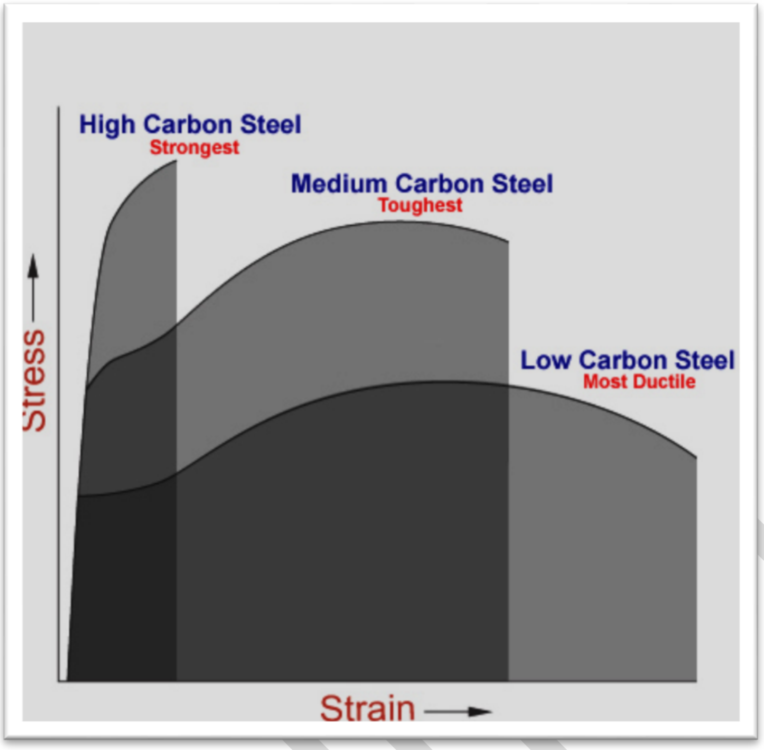


Figure(2.2): Modulus of elasticity verses temperature for different materials

7. **Stiffness :** It is the property of material enabling it to resist deformation under stresses **.**

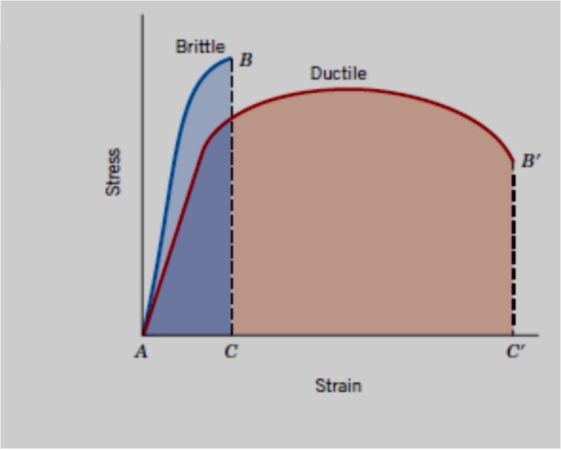
8. **Toughness :** It is the ability of material to resist fracture due to high impact loads like hammer blows .
   There are several variables that have a profound influence on the toughness of a material. These variables are:
   - Strain rate (rate of loading)
   - Temperature
   - Notch effect

   The area under the curve of stress- strain curve represents the toughness of material shown in figure (2.3).



Figure(2.3): toughness for different type of steel

9. **Ductility :** It is the property of a material enabling it to draw into wire with application of a tensile force . a ductile material must be both strong and plastic as shown in figure (2.4). Another expression , It is a measure of the degree of plastic deformation that has been sustained at fracture.



Figure(2.4):Schematic representations of tensile stress–strain behavior for brittle and ductile materials loaded to fracture.

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 , and Percent reduction in area %RA is defined as :

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

Where : where A_0 is the original cross-sectional area and A_f is the cross-sectional area at the point of fracture.

10. **Brittleness:** It is the property of breaking of a material without much permanent distortion. It is the property apposite to plasticity or ductility . See figure (2.4).

11. **Hardness :** The hardness of metal is a measure of its ability to withstand scratching , wear and abrasion indentation by harder bodies .

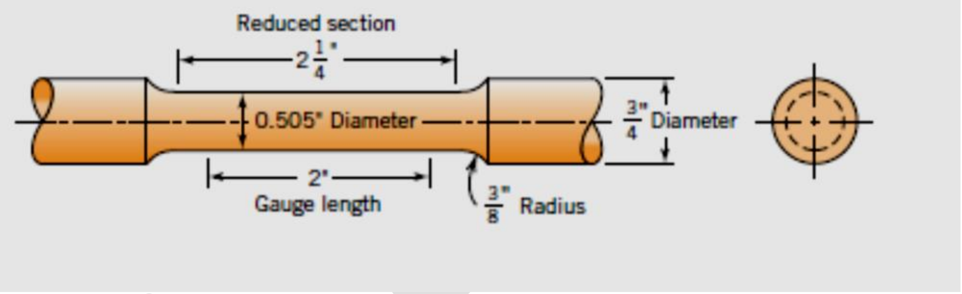
❖ Engineering testing of materials :

1. Tensile Test :

One of the most common mechanical stress–strain tests is performed in *tension*. As will be seen, 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 unaxially along the long axis of a specimen. A standard tensile specimen is shown in Figure (2.5).

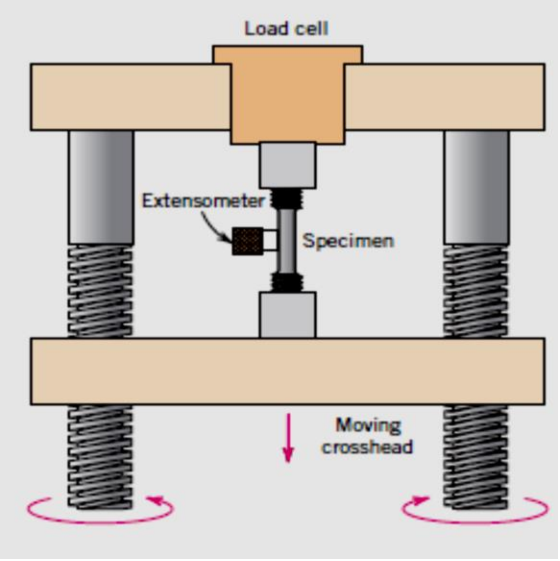
Normally, the cross section is circular, but rectangular specimens are also used. This "dog bone" specimen configuration was chosen so that, during testing, deformation is confined to the narrow center region (which has a uniform cross section along its length), and, also, to reduce the likelihood of 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, as discussed in number 9, the standard value is 50 mm (2.0 in.). The specimen is mounted by its ends into the holding grips of the testing apparatus (Figure 2.6). 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.



Figure(2.5): A standard tensile specimen .

Figure(2.6): Tensile test machine



Critical factors (load and elongation) are normalized to the respective parameters of (engineering stress) and (engineering strain) **. Engineering stress** is defined by the relationship:

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

Where : F : is the instantaneous load applied perpendicular to the specimen cross section, in units of newtons (N) or pounds force ,
and A_0 : is the original cross sectional area before any load is applied (m^2 or $in.^2$). The units of engineering stress are mega pascals, MPa (SI) (where 1 MPa = N/m2), and pounds force per square inch, psi

Engineering strain is defined according to :

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

Where : l_0 :is the original length before any load is applied,
And l_i : is the instantaneous length.
Engineering strain is unit less (m/m) .
Sometimes strain is also expressed as a percentage, in which the strain value is multiplied by 100.

Stress–Strain Behavior:

From figure(2.7) , we can see the following :

1. The part (OA) : This part is a straight line . For most metals that are stressed in tension and at relatively low levels, stress and strain are proportional to each other through the relationship

$$\sigma = E\epsilon$$

This is known as Hooke's law, and the constant of proportionality E

(GPa or psi) is the **modulus of elasticity,** or *Young's modulus*

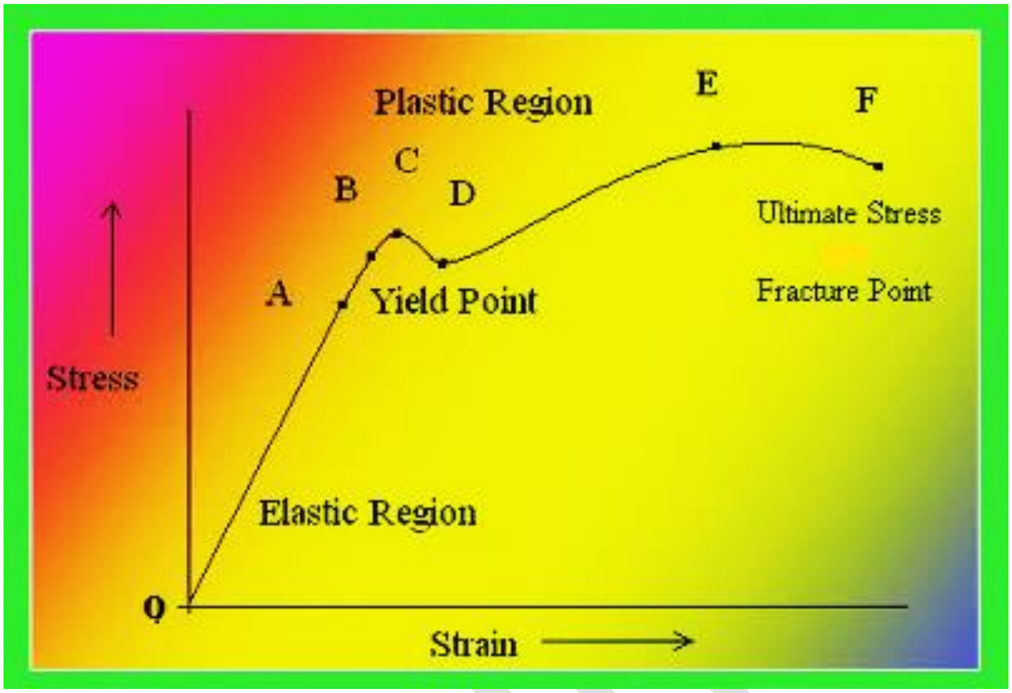


Figure (2.7) : Stress- strain curve for mild steel

For most typical metals the magnitude of this modulus ranges between 45 GPa ,for magnesium, and 407 GPa ,for tungsten. Modulus of elasticity values for several metals at room temperature are presented in Table 6.1.

Table 6.1 Room-Temperature Elastic and Shear Moduli, and Poisson's Ratio for Various Metal Alloys

	Modulus of Elasticity		Shear Modulus		
Metal Alloy	GPa	10^6 psi	GPa	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

2. Point (B): Represent elastic limit which is defined that is a maximum stress that metal can be loaded without plastic deformation .

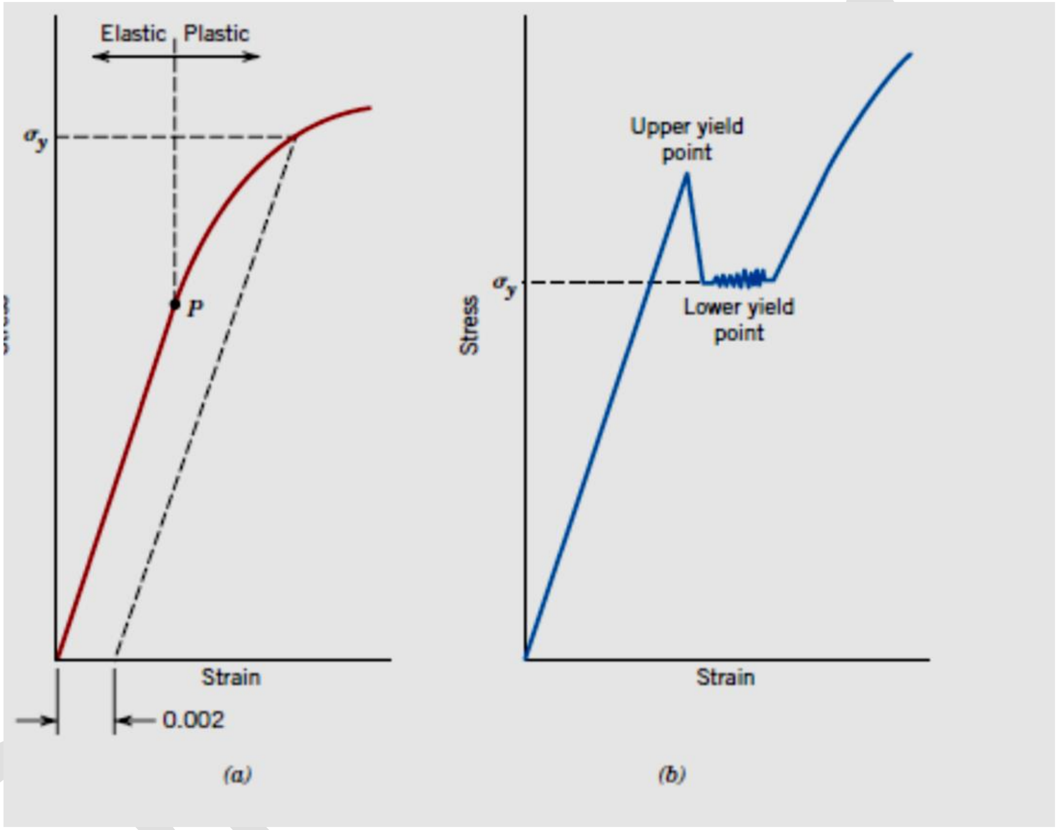
3. Point (C) : Yield point : It is applied stress to occur plastic deformation (strain) without increasing in applied load . Most structures are designed to ensure that only elastic deformation will result when a stress is applied. A structure or component that has plastically deformed, or experienced a permanent change in shape, may not be capable of functioning as intended.

It is therefore desirable to know the stress level at which plastic deformation begins, or where the phenomenon of **yielding** occurs. For metals that experience this gradual elastic–plastic transition, the point of yielding may be determined as the initial departure from linearity of the stress–strain curve; this is sometimes called the **proportional limit**, as indicated by point *P* in Figure (2.8a). In such cases the position of this point may not be determined precisely. As a consequence, a convention has been established wherein a straight line is constructed parallel to the elastic portion of the stress–strain curve at some specified strain offset, usually 0.002.

The stress corresponding to the intersection of this line and the stress–strain curve as it bends over in the plastic region is defined as the **yield strength**. This is demonstrated in Figure (2.8a).

Some steels and other materials exhibit the tensile stress–strain behavior as shown in Figure 2.8b. The elastic–plastic transition is very well defined and occurs abruptly in what is termed a *yield point phenomenon*.

The magnitude of the yield strength for a metal is a measure of its resistance to plastic deformation. Yield strengths may range from 35 MPa (5000 psi) for a low strength aluminum to over 1400 MPa (200,000 psi) for high-strength steels.

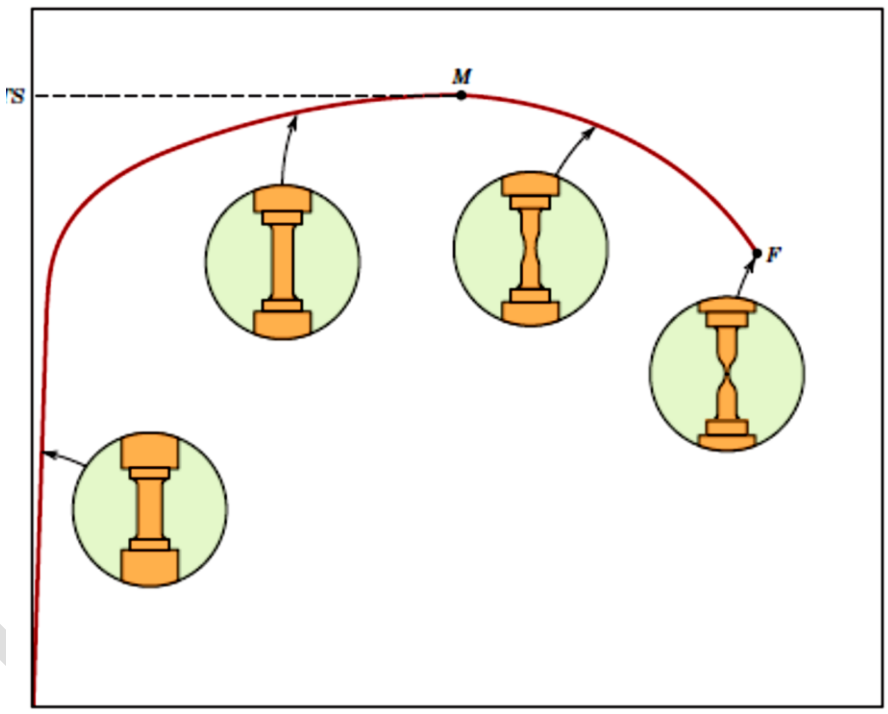


Figure(2.8) : (a). yielding strength determined using .002 strain offset method , (b).yield point phenomenon for some steels

4. **Point(E) :** Maximum strength (ultimate strength) : After yielding, the stress necessary to continue , plastic deformation in metals increases to a maximum .

$$Max.\ strength = \frac{Max.load}{A_0}$$

5. **Point (F) :** Fracture point **:** At this maximum stress, a small constriction or neck begins to form at some points, and all subsequent deformation is confined at this neck . This phenomenon is termed "necking," and fracture ultimately occurs at the neck. The fracture strength corresponds to the stress at fracture. Fifure(2.9) represents stages of stress –strain curve



Figure(2.9): 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.

True Stress and Strain:

Sometimes it is more meaningful 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).

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

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, if

$$A_i l_i = A_0 l_0$$

true and engineering stress and strain are related according to:

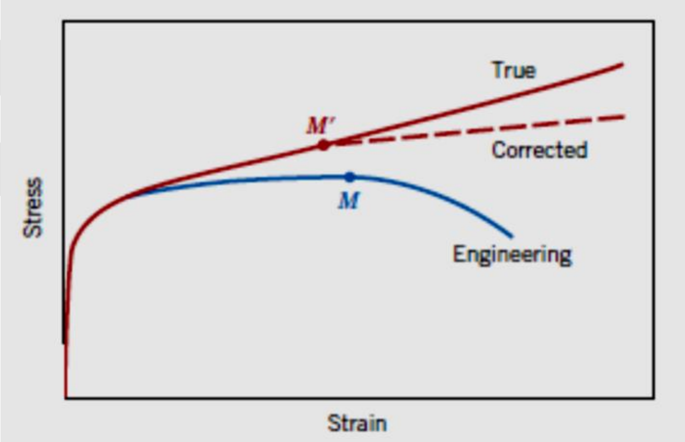
Conversion of engineering stress to true stress

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

Conversion of engineering strain to true strain

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

A schematic comparison of engineering and true stress–strain behaviors is made in Figure (2.10). It is worth noting that the true stress necessary to sustain increasing strain continues to rise past the tensile point M .



Figure(2.10): True and Engineering stress-strain

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

True stress-true strain relationship in plastic region of deformation (to point of necking)

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

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 Table 6.4.

Table 6.4 Tabulation of *n* and *K* Values (Equation 6.19) for Several Alloys

		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

Mechanical Property Determinations from Stress–Strain Plot

From the tensile stress–strain behavior for the brass specimen shown in Figure 6.12, determine the following:

(a) The modulus of elasticity

(b) The yield strength at a strain offset of 0.002

(c) The maximum load that can be sustained by a cylindrical specimen having an original diameter of 12.8 mm (0.505 in.)

(d) The change in length of a specimen originally 250 mm (10 in.) long that is subjected to a tensile stress of 345 MPa (50,000 psi)

Solution

(a) The modulus of elasticity is the slope of the elastic or initial linear portion of the stress–strain curve. The strain axis has been expanded in the inset, Figure 6.12, to facilitate this computation. The slope of this linear region is the rise over the run, or the change in stress divided by the corresponding change in strain; in mathematical terms,

$$E = \text{slope} = \frac{\Delta\sigma}{\Delta\epsilon} = \frac{\sigma_2 - \sigma_1}{\epsilon_2 - \epsilon_1} \tag{6.10}$$

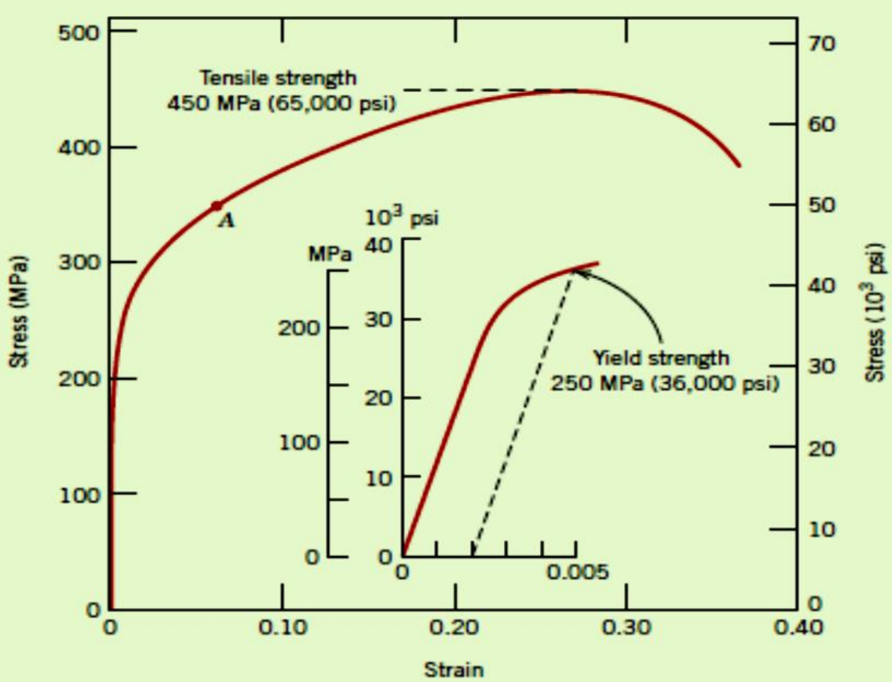


Figure 6.12 The stress–strain behavior for the brass specimen discussed in Example Problem 6.3.

Inasmuch as the line segment passes through the origin, it is convenient to take both σ_1 and ϵ_1 as zero. If σ_2 is arbitrarily taken as 150 MPa, then ϵ_2 will have a value of 0.0016. Therefore,

$$E = \frac{(150 - 0)\text{ MPa}}{0.0016 - 0} = 93.8\text{ GPa } (13.6 \times 10^6\text{ psi})$$

which is very close to the value of 97 GPa (14×10^6 psi) given for brass in Table 6.1.

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

(c) The maximum load that can be sustained by the specimen is calculated by using Equation 6.1, in which σ is taken to be the tensile strength, from Figure 6.12, 450 MPa (65,000 psi). Solving for F, the maximum load, yields

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

$$= (450 \times 10^6\text{ N/m}^2)\left(\frac{12.8 \times 10^{-3}\text{ m}}{2}\right)^2 \pi = 57{,}900\text{ N } (13{,}000\text{ lb}_f)$$

(d) To compute the change in length, Δl, in Equation 6.2, it is first necessary to determine the strain that is produced by a stress of 345 MPa. This is accomplished by locating the stress point on the stress–strain curve, point A, and reading the corresponding strain from the strain axis, which is approximately 0.06. Inasmuch as $l_0 = 250$ mm, we have

$$\Delta l = \epsilon l_0 = (0.06)(250\text{ mm}) = 15\text{ mm } (0.6\text{ in.})$$