Properties of Engineering Materials

Mechanical Properties of Materials

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Introduction

- Mechanical properties of a material determine its behavior when subjected to mechanical stress (examples on materials under stress are aluminum alloy from which an airplane wing is constructed and the steel in an automobile axle).

- Mechanical properties include: elastic modulus, ductility, hardness, etc.

- Two opposite objectives for the product in design and manufacturing:

  - In design: the objective for the product is to withstand stresses without significant change in geometry (dependent on elastic modulus and yield stress).

  - In manufacturing: the objective is to alter the geometry by applying stresses that exceed the yield strength of the material.

Note: it is helpful for the manufacturing engineer to appreciate the design objective and for the designer to be aware of the manufacturing objective.

Stress-Strain relationships

- There are 3 static stresses to which materials can be subjected
  - Tensile stresses: tend to stretch the material
  - Compressive stresses: tend to squeeze the material.
  - Shear stresses: tend to cause adjacent portions of the material to slide against one another.

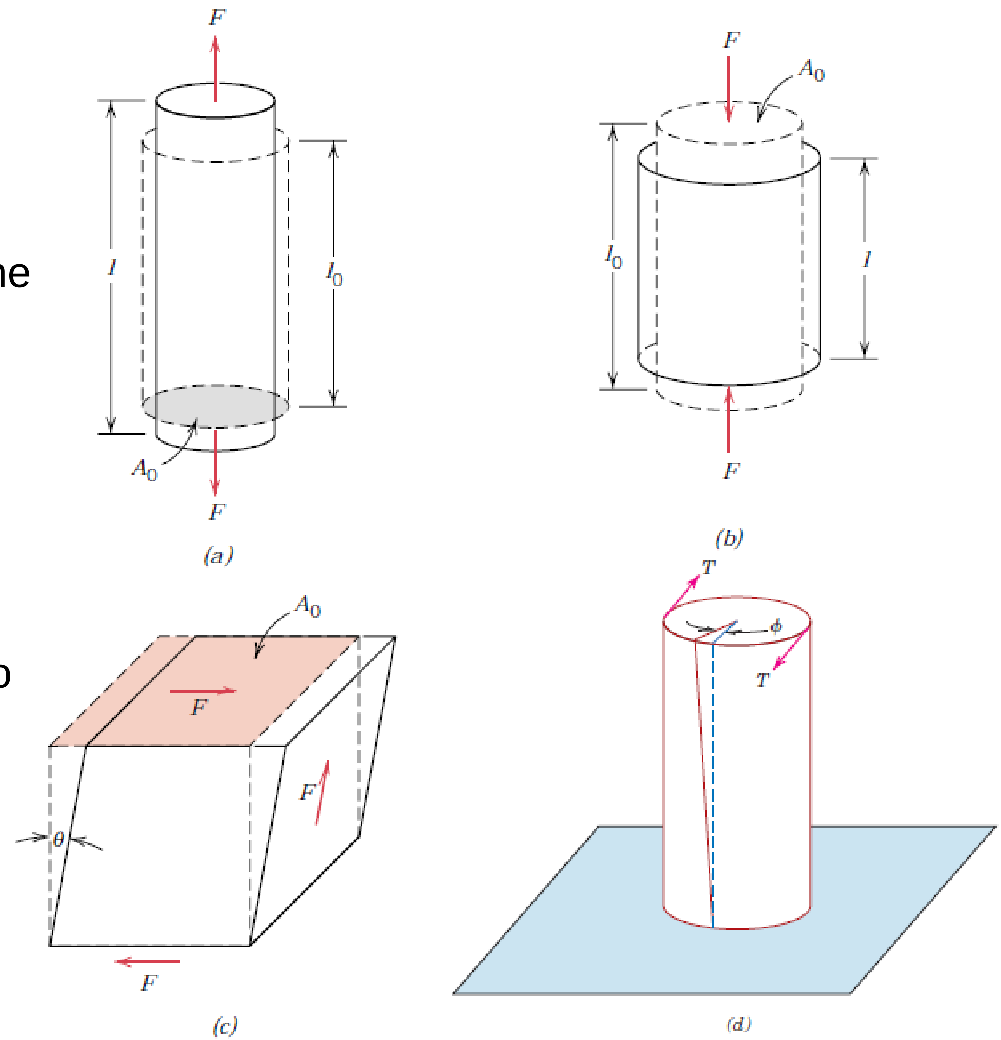


Fig. 1: Materials under static stresses; (a) Tensile, (b) compressive, (c) shear (γ = tan θ), and (d) torsional deformation (i.e., angle of twist Φ) produced by an applied torque T. Dashed lines: shape before deformation.

Stress-Strain relationships; Tensile properties

- Tensile test: most common procedure for studying stress-strain relationships, particularly for metals.
- In the test, force is applied that pulls the material, tending to elongate it and reduce its diameter.
- Standards by ASTM specify the preparation of the test specimen and the test procedure.

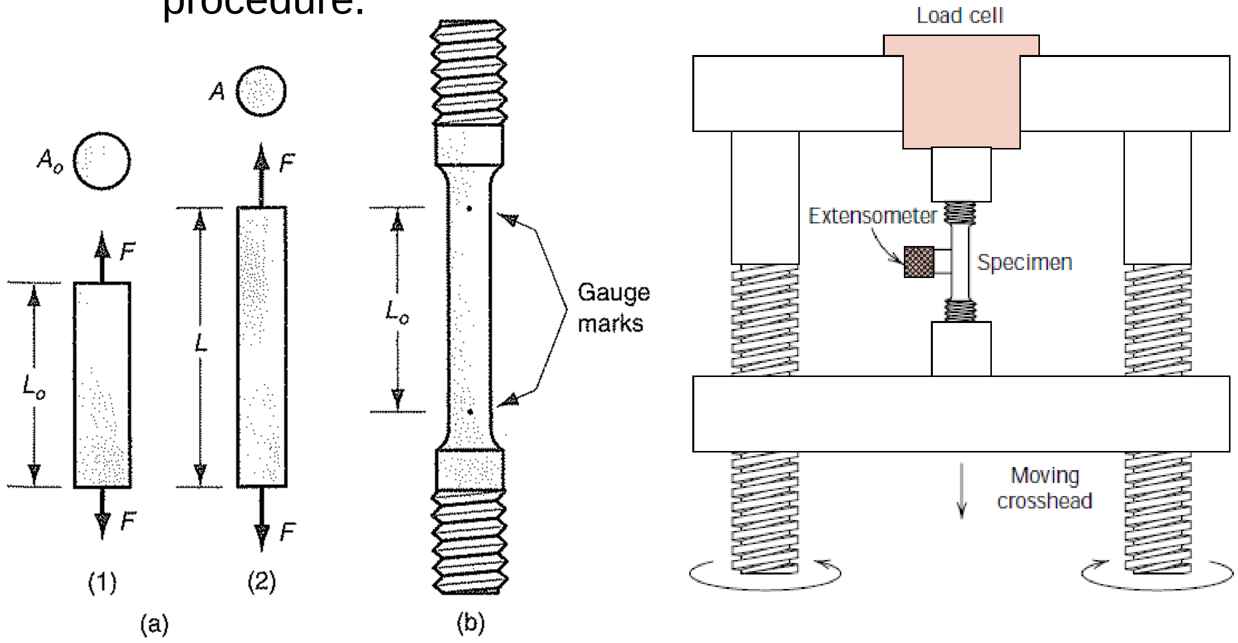


Fig. 2: Tensile specimen and setup of the tensile test. (A_0 & L_0: cross sectional area and length before test, length is measured between the gauge marks (gauge length)).

Stress-Strain relationships; Tensile properties

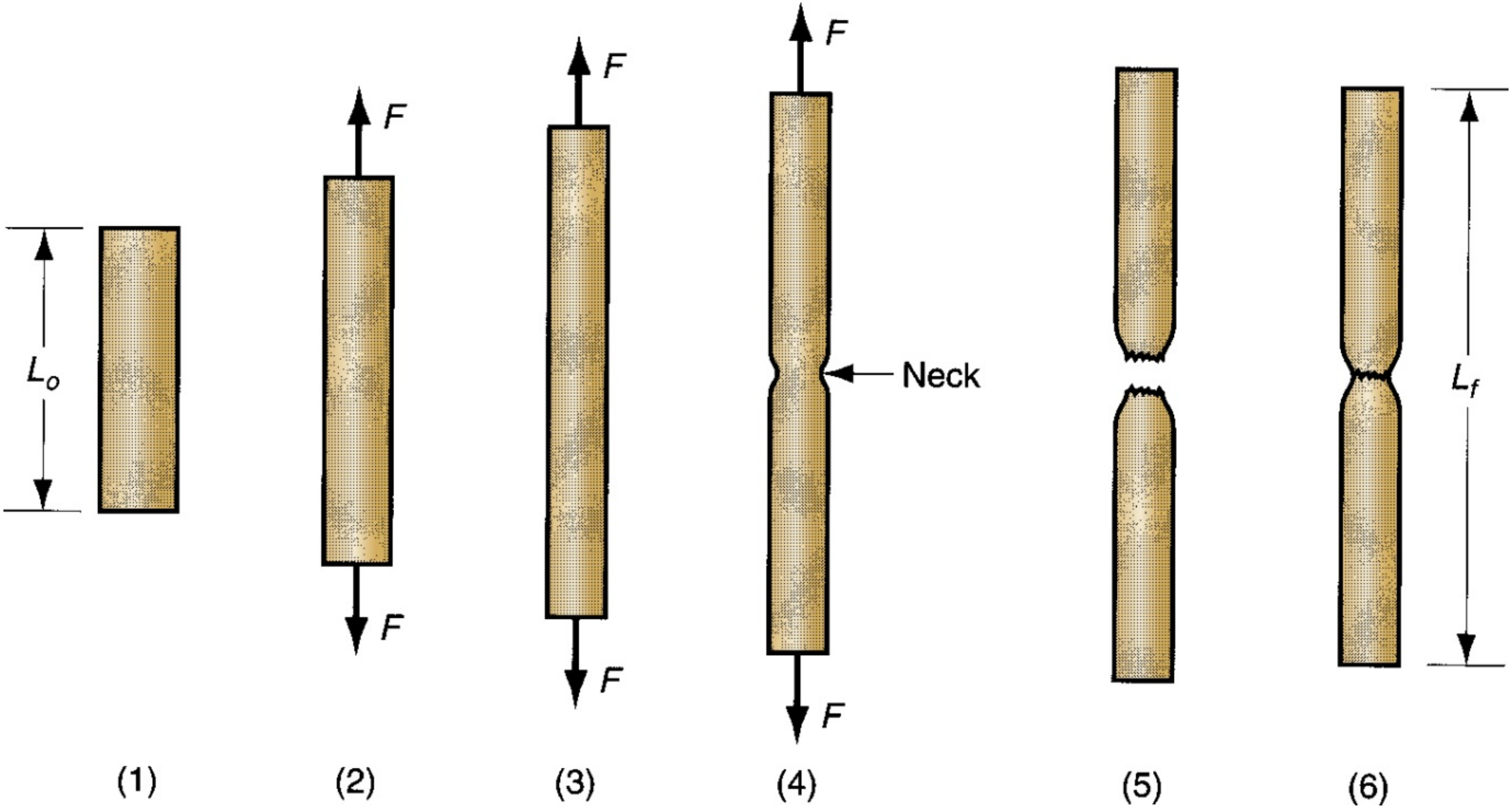


Fig. 3: Progress of a tensile test: (1) beginning of test, no load, (2) uniform elongation and reduction of A_0, (3) Continued elongation, max. load reached, (4) necking begins and load decreases, (5) fracture, and (6) final length can be measured if pieces are put back together.

Stress-Strain relationships; Tensile properties

- 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.

(1) Engineering Stress-Strain: stress and strain defined relative to the original area and length of the specimen.

– Important in design as the designer assumes that the strains experienced by any component will NOT significantly change its shape. The components are designed to withstand the anticipated stresses encountered in service.

Stress-Strain relationships; Tensile properties

- Fig. 4 shows an engineering stress-strain curve for a metallic specimen.

- The engineering stress at any point on the curve is defined as the force divided by the original area:

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

where σ_e: engineering stress, MPa (n / mm^2), F = applied force, N, and A_0 is the original area of the specimen, mm^2.

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

$$e = \frac{L - L_0}{L_0}$$

where e is engineering strain, mm / mm, L = length during the elongation at any point, mm, and L_0 is the gauge length, mm.

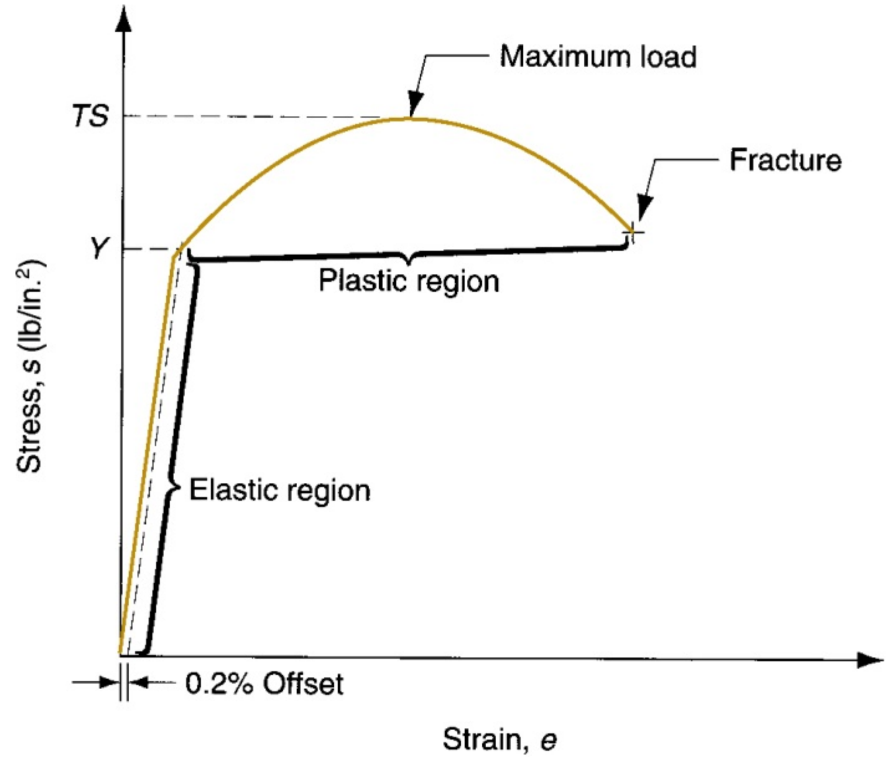


Fig. 4: a typical engineering stress-strain curve for a metallic specimen.

e can be thought of as elongation per unit length.

Stress-Strain relationships; Tensile properties

- The stress-strain relationship in the figure has two regions, elastic and plastic regions:

  (1) In the elastic region: the relationship is linear and the material exhibits elastic behavior by returning to its original length when the load is released. The relationship is defined by ***Hooke's law***:

$$\sigma_e = Ee$$

,where E is modulus of elasticity (MPa). E is the slope, so $E = \Delta \sigma / \Delta e$

  – As stress continues to increase, a point ***Y*** is reached, this is the point where material begins to yield and called the ***yield point*** *or* ***yield strength*** (end of elastic region and transition to plastic region). ***Y*** is defined as the stress at 0.2% strain offset (***Y*** is not always clear on the figure).

Stress-Strain relationships; Tensile properties

- Different yielding behaviors:

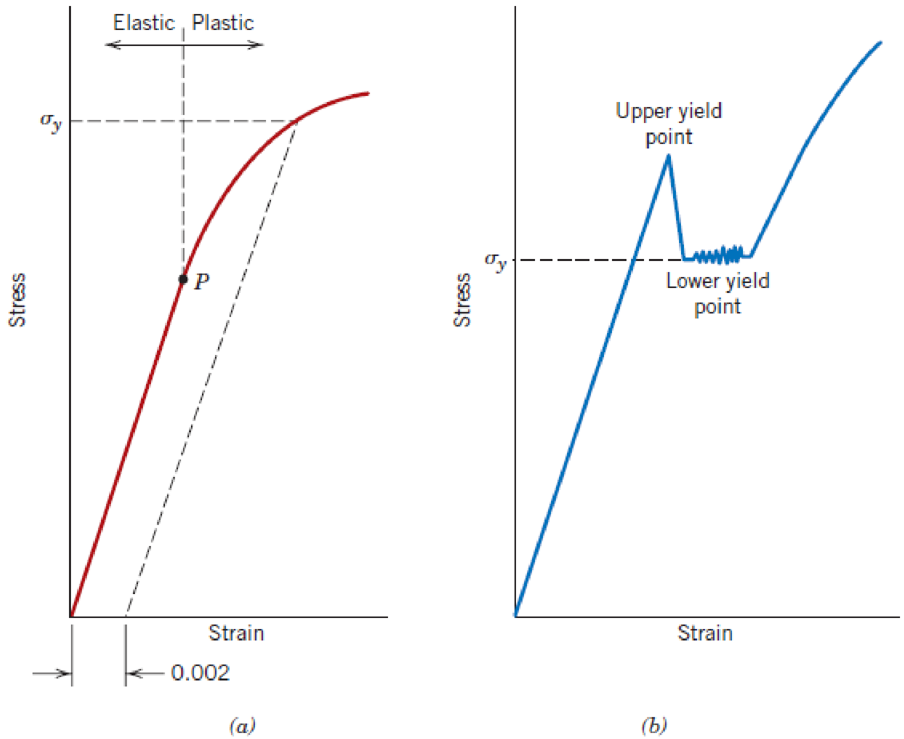


Fig. 5: (*a*) Typical stress– strain behavior for a metal showing elastic and plastic deformations, the proportional limit *P*, and the yield strength as determined using the 0.002 strain offset method. (*b*) Representative stress–strain behavior found for some steels demonstrating the yield point phenomenon.

Stress-Strain relationships; Tensile properties

- When a tensile stress is imposed on a metal specimen, an elastic elongation and accompanying strain ε_z result in the direction of the applied stress as indicated in Figure.

- As a result of this elongation, there will be constrictions in the lateral (*x* and *y*) directions perpendicular to the applied stress; from these contractions, the compressive strains ε_x and ε_y may be determined.

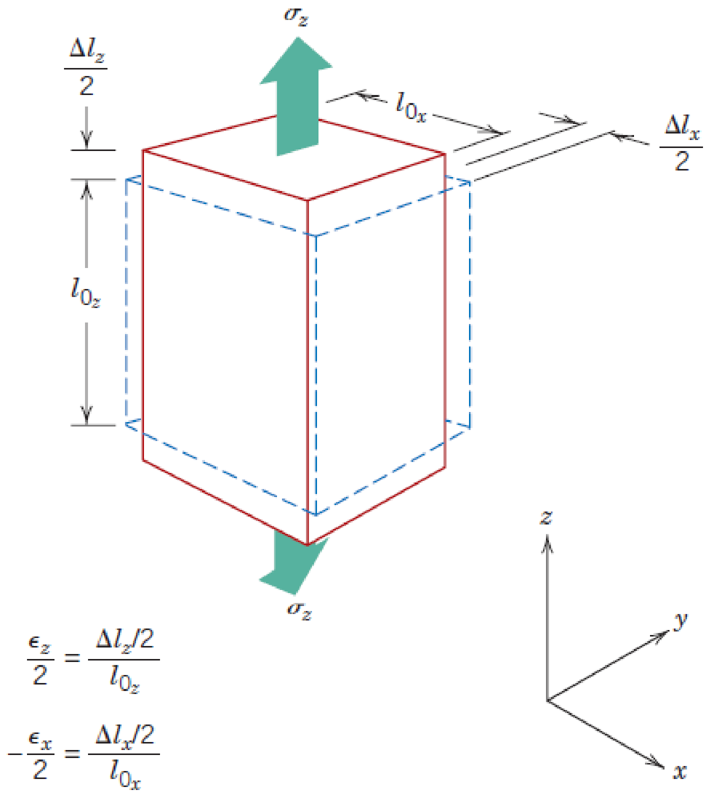


Fig. 6: Axial (*z*) elongation (positive strain) and lateral (*x* and *y*) contractions (negative strains) in response to an imposed tensile stress. Solid lines represent dimensions after stress application; dashed lines, before.

Stress-Strain relationships; Tensile properties

- If the applied stress is uniaxial (only in the *z* direction), and the material is isotropic, then $\varepsilon_x = \varepsilon_y$. A parameter termed **Poisson's ratio** is defined as the ratio of the lateral and axial strains, or

$$\nu = -\frac{\varepsilon_x}{\varepsilon_z} = -\frac{\varepsilon_y}{\varepsilon_z}$$

- For virtually all structural materials, ε_x & ε_y will be of opposite sign; therefore, the negative sign is included in the preceding expression to ensure that ν is positive.

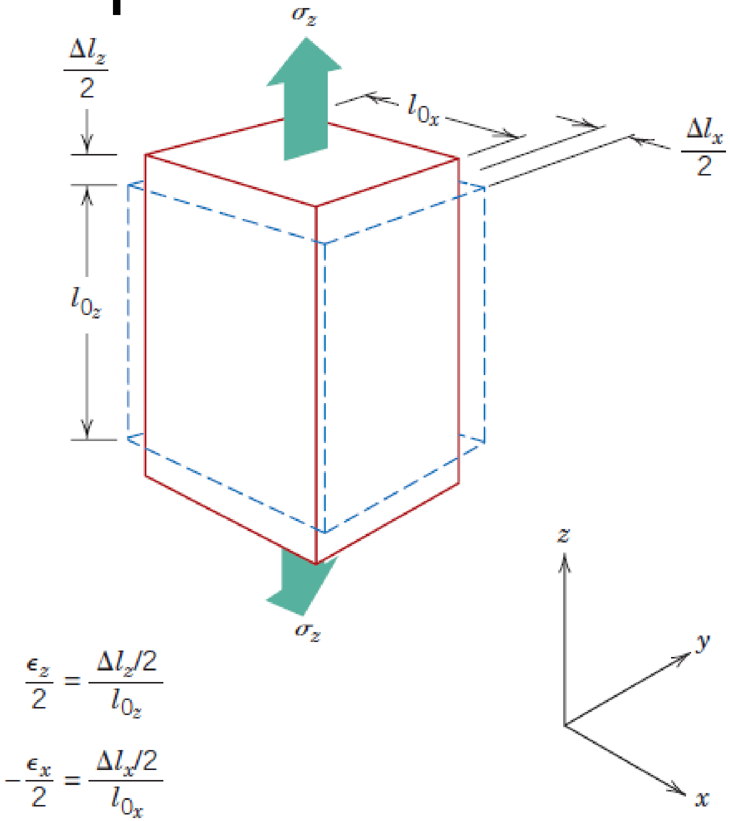


Fig. 6: Axial (*z*) elongation (positive strain) and lateral (*x* and *y*) contractions (negative strains) in response to an imposed tensile stress. Solid lines represent dimensions after stress application; dashed lines, before.

Stress-Strain relationships; Tensile properties

- Theoretically, Poisson's ratio for isotropic materials should be 0.25 ; furthermore, the maximum value for (or that value for which there is no net volume change) is 0.50.
- For many metals and other alloys, values of Poisson's ratio range between 0.25 and 0.35.
- For isotropic materials, shear and elastic moduli are related to each other and to Poisson's ratio according to

$$E = 2G(1 + \nu)$$

- In most metals *G* is about 0.4*E*; thus, if the value of one modulus is known, the other may be approximated.

Stress-Strain relationships; Tensile properties

- The stress-strain relationship in the figure has two regions, elastic and plastic regions:

  (2) In the plastic region: the relationship is no more linear and is no longer guided by Hooke's law. Further stressing will lead to further elongation in the specimen but with faster rate, leading to a dramatic change in the slope.

  – Elongation is accompanied by a uniform reduction in A_0 so as to maintain a constant volume.

  – Finally, the applied load reaches a max. value. The engineering stress calculated at this point is called the *tensile (or ultimate) tensile strength (TS or UTS), where* $TS = F_{max} / A_0$.

  – After crossing the *TS* point, stress starts to decline where ***necking*** occurs; the specimen during necking starts exhibiting localized elongation. The area at the necking narrows down significantly until failure occurs. The stress calculated just before the failure is called ***fracture stress***.

Stress-Strain relationships; Tensile properties

- ***Ductility***: the ability of a material to plastically strain without fracture. Ductility is important in both design and manufacturing. This measure can be taken as either elongation or reduction in area:

(1) Elongation and defined as:

$$EL = \frac{L_f - L_0}{L_0}$$

(2) Area reduction and defined as:

$$AR = \frac{A_0 - A_f}{A_0}$$

Stress-Strain relationships; Tensile properties

- ***Resilience***: is the capacity of a material to absorb energy when it is deformed elastically and then, upon unloading, to have this energy recovered:

- The associated property is the *modulus of resilience, U_r*, which is the strain energy per unit volume required to stress a material from an unloaded state up to the point of yielding.

- the modulus of resilience for a specimen subjected to a uniaxial tension test is just the area under the engineering stress–strain curve taken to yielding, or

$$U_r = \int_0^{\varepsilon_y} \sigma d\varepsilon$$

Assuming a linear elastic region

$$U_r = \frac{1}{2}\sigma_y \varepsilon_y$$

in which ε_y is the strain at yielding.

Stress-Strain relationships; Tensile properties

- ***Resilience***: is the capacity of a material to absorb energy when it is deformed elastically and then, upon unloading, to have this energy recovered:

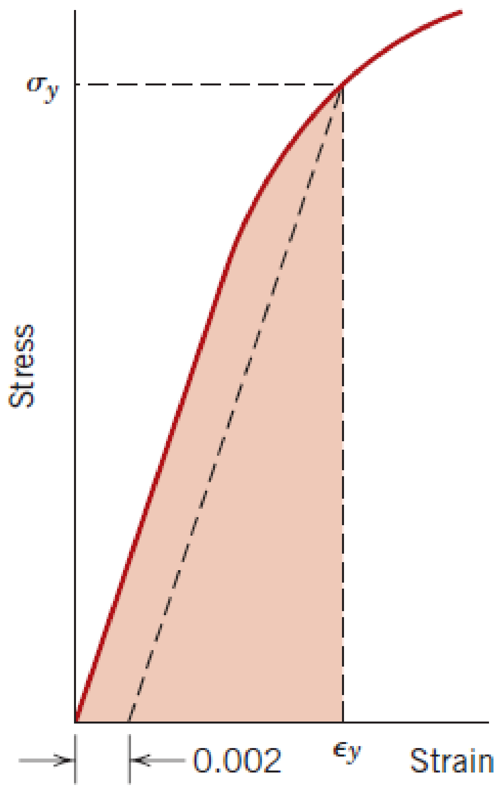


Fig. 7: Schematic representation showing how modulus of resilience (corresponding to the shaded area) is determined from the tensile stress–strain behavior of a material.

Stress-Strain relationships; Tensile properties

- ***Resilience***: is the capacity of a material to absorb energy when it is deformed elastically and then, upon unloading, to have this energy recovered:

- The units of resilience are the product of the units from each of the two axes of the stress–strain plot. For SI units, this is joules per cubic meter (J/m^3, equivalent to Pa).

Incorporation of $\sigma_y = E\varepsilon_y$ into $U_r = \frac{1}{2}\sigma_y \varepsilon_y$

yields

$$U_r = \frac{1}{2}\sigma_y \varepsilon_y = \frac{1}{2}\sigma_y \left(\frac{\sigma_y}{E}\right) = \frac{\sigma_y{}^2}{2E}$$

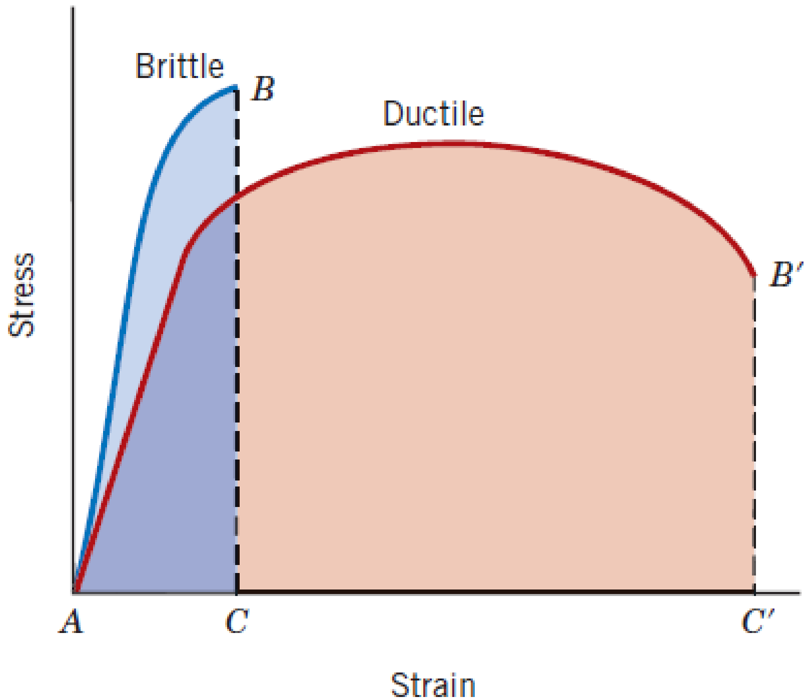
- Thus, resilient materials are those having high yield strengths and low moduli of elasticity; such alloys would be used in spring applications.

Stress-Strain relationships; Tensile properties

- ***Toughness***: is a property that is indicative of a material's resistance to fracture when a crack (or other stress-concentrating defect) is present.
- Because it is nearly impossible (as well as costly) to manufacture materials with zero defects (or to prevent damage during service), fracture toughness is a major consideration for all structural materials.
- Another way of defining toughness is as the ability of a material to absorb energy and plastically deform before fracturing.
- It is the area under the stress-strain curve up to the point of fracture. The units are energy per unit volume of material. For a metal to be tough, it must display both strength and ductility

Stress-Strain relationships; Tensile properties

- ***Toughness***: is a property that is indicative of a material's resistance to fracture when a crack (or other stress-concentrating defect) is present.



Even though the brittle metal has higher yield and tensile strengths, it has a lower toughness than the ductile one, as can be seen by comparing the areas *ABC* and *AB′C′* in Figure.

Fig. 8: Schematic representations of tensile stress–strain behavior for brittle and ductile metals loaded to fracture.

Stress-Strain relationships; Tensile properties

- 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.

(2) True Stress-Strain: stress and strain defined relative to the instantaneous (actual) area that becomes increasingly smaller as the test proceeds.

- The true stress at any point on the curve is defined as the force divided by the instantaneous area:

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

where σ : true stress, MPa (n / mm^2), F = applied force, N, and A is the instantaneous area resisting the load, mm^2.

Stress-Strain relationships; Tensile properties

- Similarly, the ***true strain*** is a more realistic assessment of the instantaneous elongation per unit length of the test specimen. This is done by dividing the total elongation into small increments, calculating the engineering strain for each increment of its starting length, and then adding up the strain values:

$$\varepsilon = \int_{L_0}^{L} \frac{dL}{L} = \ln \frac{L}{L_0}$$

where *L* is the instantaneous length at any moment during deformation

Stress-Strain relationships; Tensile properties

- The elastic region in the true stress-strain curve is almost similar to that of the engineering stress-strain curve (can you guess why). Hence, the elastic region in the true curve obeys Hooke's Law.

- The progressive reduction in area in the true stress-strain curve is considered in the plastic region. Hence, the stress in this region is higher as compared to that of the engineering stress-strain curve.

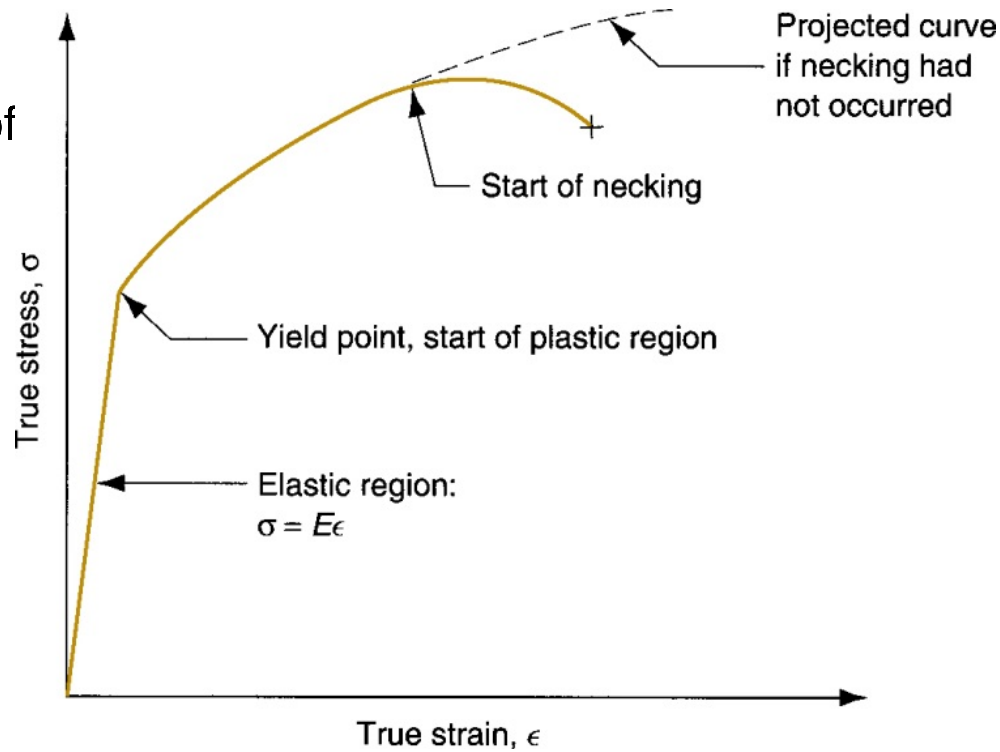


Fig. 9: a typical true stress-strain curve for a metallic specimen.

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

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

Stress-Strain relationships; Tensile properties

- Strain (work) hardening: a property that most metals exhibits during deformation. It means that the metal is getting stronger as strain increases (see true stress-strain curve).

- Strain hardening is important in manufacturing, especially in metal forming processes.

- With plotting the true stress and true strain of the plastic region on a log-log scale, the result would be a linear relationship as in fig. 10, and the relation between true stress and true strain would then be:

$$\sigma = K\varepsilon^n$$

K (strength coefficient) = σ if $\varepsilon = 1$.

n (strain hardening exponent) (slope), and related to a metal's tendency to work harden.

- Flow curve equation. It captures a good approximation of the behavior of metals in the plastic region, including their capacity for strain hardening

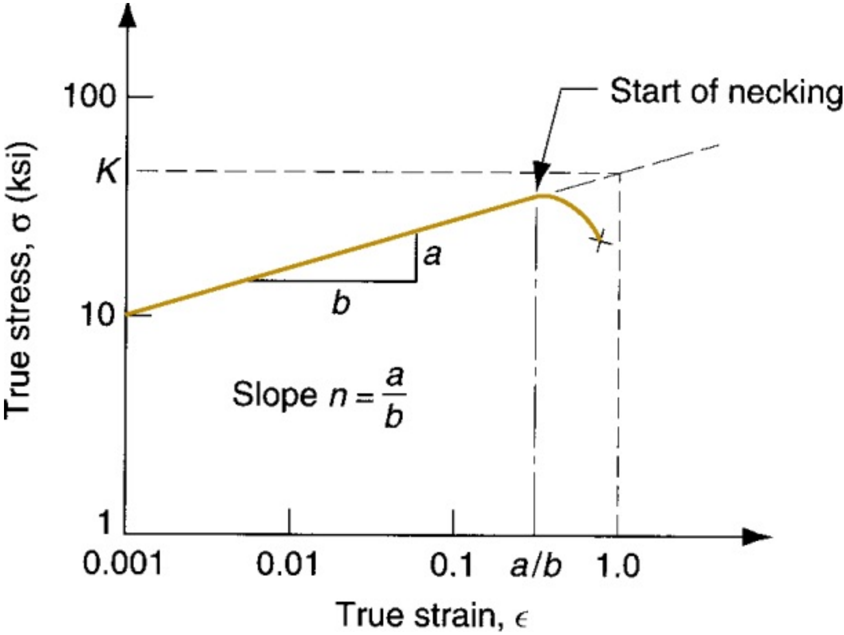


Fig. 10: true stress-strain curve plotted on a log-log scale.

Note: Necking is closely related to strain hardening.

Necking begins when $\varepsilon = n$. A higher n means the metal can be strained further before necking begins

Stress-Strain relationships; Tensile properties

- Much information about elastic-plastic behavior is provided by the true stress-strain diagram; as Hooke's law governs the metal's behavior in the elastic region and the flow curve equation determines the behavior in the plastic region. Three basic forms of stress-strain relationship describe the behavior of nearly all metals:

(a) Perfectly elastic: the material is defined completely by its stiffness indicated by modulus of elasticity. It fractures before yielding or plastic flow; example of these materials are ceramics and thermosetting polymers. These materials are bad for forming.

(b) Elastic and perfectly plastic: as yield stress is reached, the material deforms plastically at the same stress level. Flow curve in this case $K = Y$ and $n = 0$. Happens to metals heated during straining that recrystallization occurs rather than strain hardening. For Pb, this is the situation at RT as the recrystallization temperature for Pb is below RT.

(c) Elastic and strain hardening: obeys Hooke's Law in the elastic region, and starts to flow when Y is reached. Continued deformation requires an ever-increasing stress, given by flow curve whose K is > Y and n is > 0. Most ductile materials behave this way when cold-worked.

Stress-Strain relationships; Tensile properties

- Much information about elastic-plastic behavior is provided by the true stress-strain diagram; as Hooke's law governs the metal's behavior in the elastic region and the flow curve equation determines the behavior in the plastic region. Three basic forms of stress-strain relationship describe the behavior of nearly all metals:

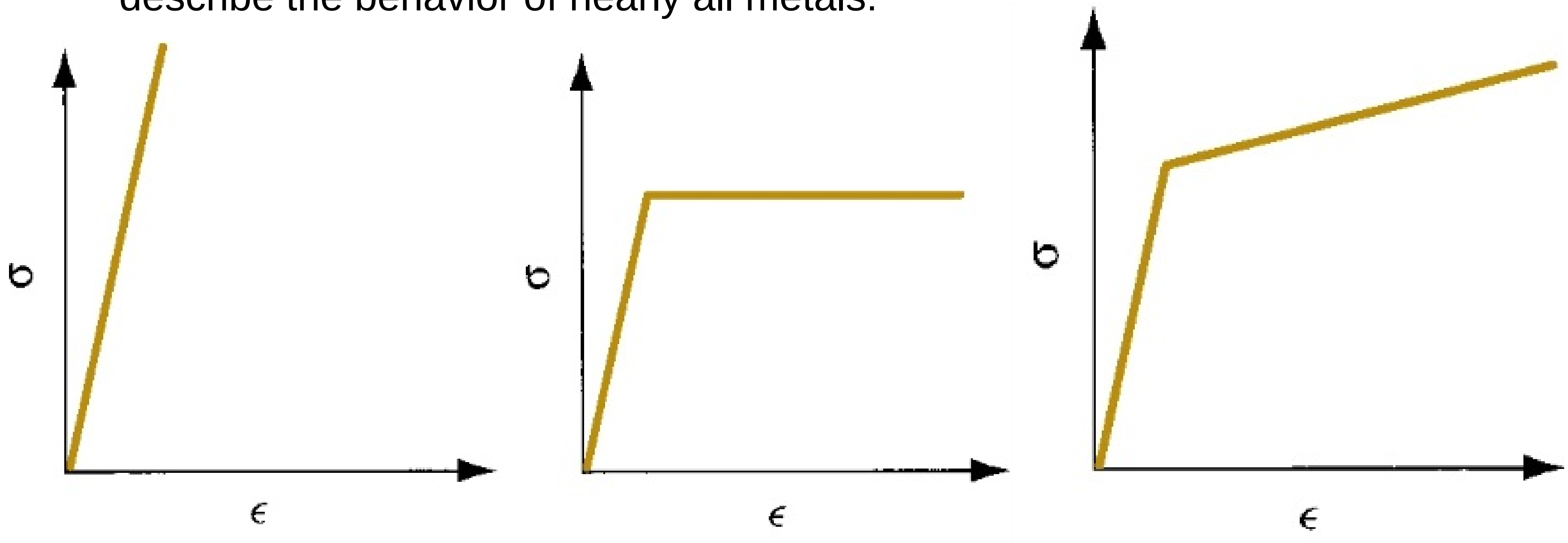


Fig. 11: Three categories of stress-strain relationships: (a) perfectly elastic, (b) elastic and perfectly plastic and (c) elastic and strain hardening.

Stress-Strain relationships; Tensile properties

- **Elastic Recovery after Plastic Deformation**:
  - Upon release of the load during the course of a stress–strain test, some fraction of the total deformation is recovered as elastic strain.
  - During the unloading cycle, the curve traces a near straight-line path from the point of unloading (point *D*), and its slope is virtually identical to the modulus of elasticity, or parallel to the initial elastic portion of the curve.

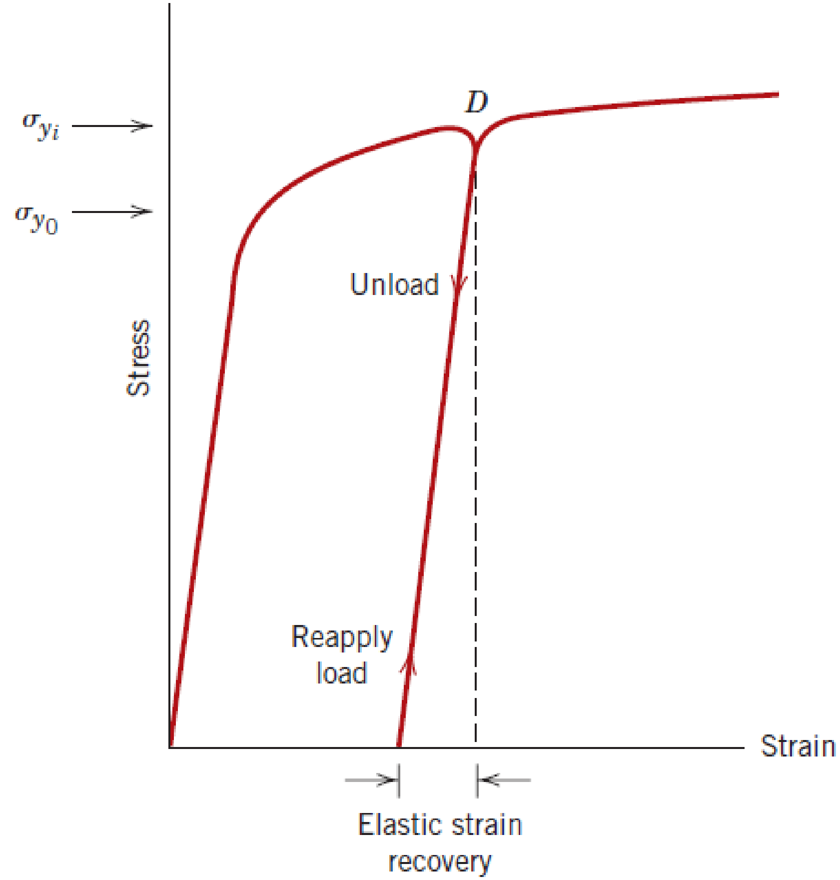
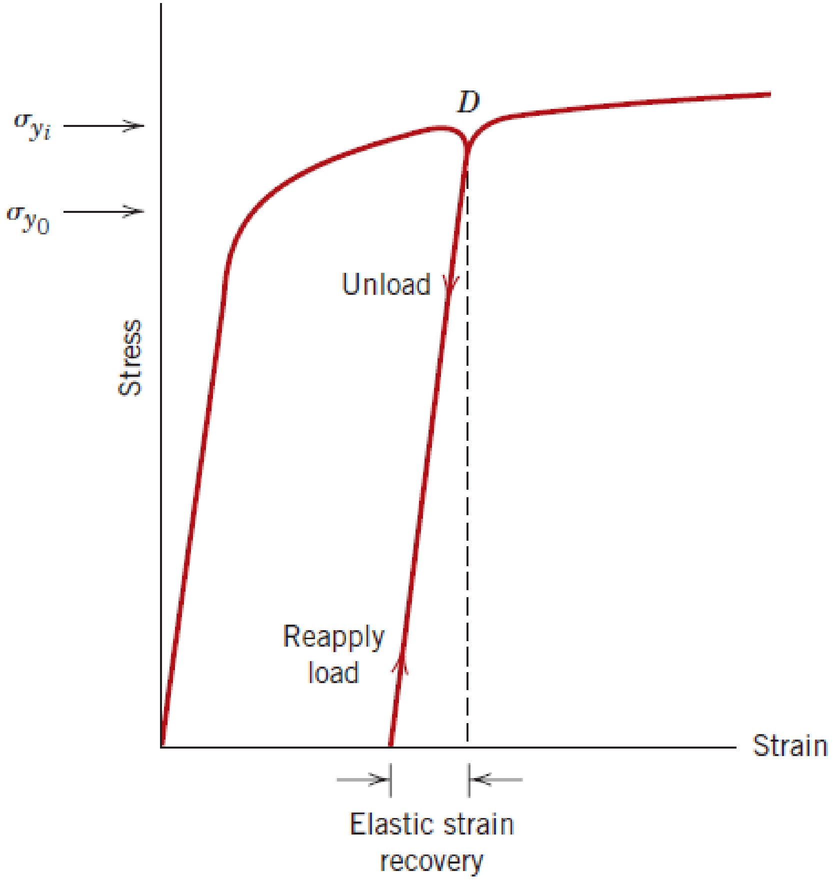


Fig. 12: Schematic tensile stress–strain diagram showing the phenomena of elastic strain recovery and strain hardening. The initial yield strength is designated as σ_{yo}; σ_{yi} is the yield strength after releasing the load at point *D*, and then upon reloading.

Stress-Strain relationships; Tensile properties

- **Elastic Recovery after Plastic Deformation**:
  - The magnitude of this elastic strain, which is regained during unloading, corresponds to the strain recovery, as shown in Figure.
  - If the load is reapplied, the curve will traverse essentially the same linear portion in the direction opposite to unloading; yielding will again occur at the unloading stress level where the unloading began.



Stress-Strain relationships; Compression properties

- Compression test: a test that applies a load that squeezes a cylindrical specimen between two platens (see fig. 13). As the specimen is compressed, its height is reduced and its cross-sectional area is increased. The engineering stress is defined in the same way as in the tensile test; i.e.,

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

- The engineering strain is defined as:

$$e = \frac{h - h_0}{h_0}$$

where h is the height of the specimen at any particular moment into the test in mm, and h_0 is the starting height in mm.

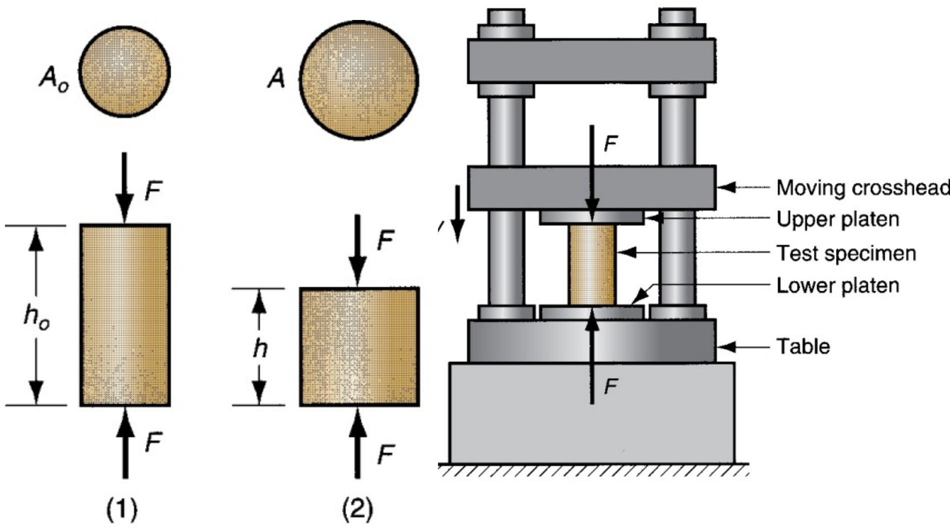


Fig. 13: Compression test: (a) compression force applied to test specimen in (1) and (2) resulting change in height; and (b) setup of the test.

Note that e will have a negative sign, as the height is decreased during compression. This sign is neglected.

Stress-Strain relationships; Compression properties

- Fig. 14 shows an engineering stress-strain curve. The curve has elastic and plastic regions as before, but the shape of the plastic region is different from its tensile test complement. Reasons:
  - Compression causes A to increase, the load increases more rapidly.
  - As the cylindrical specimen is compressed, friction at the surfaces in contact with the platens prevent the cylinder from spreading. Additional energy is consumed by friction during the test, resulting in a higher applied force.
  - This will result in ***barreling*** of the specimen; the middle of the specimen is permitted to increase in A much more than at the ends.
  - Important compression processes include forging, rolling and extrusion.

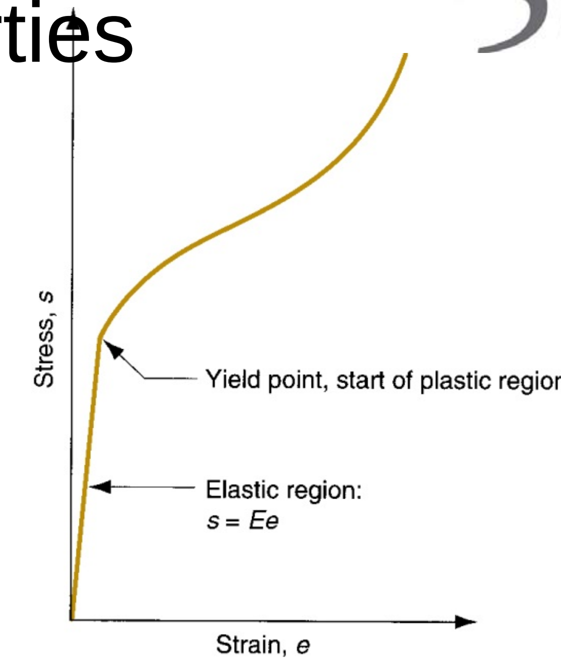


Fig. 14: Typical engineering stress-strain curve for a compression test.

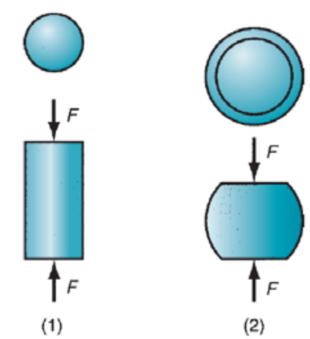


Fig. 15: Barreling effect. (1) before and (2) after compression.

Stress-Strain relationships; Bending & Testing of Brittle Materials

- Bending operations: used to form metal plates and sheets (Fig. 16; showing the setup of the bending test). Bending results in two stress (and strain) components; tensile in the outer half of the bent section and compressive in the inner half.

- ***Bending test*** (also known as ***flexure test***) suits brittle materials that possess elasticity the best; e.g. ceramics.

- These materials do not respond well to traditional tensile testing because of the difficulty in preparing the test specimens and possible misalignment of the press jaws that hold the specimen.

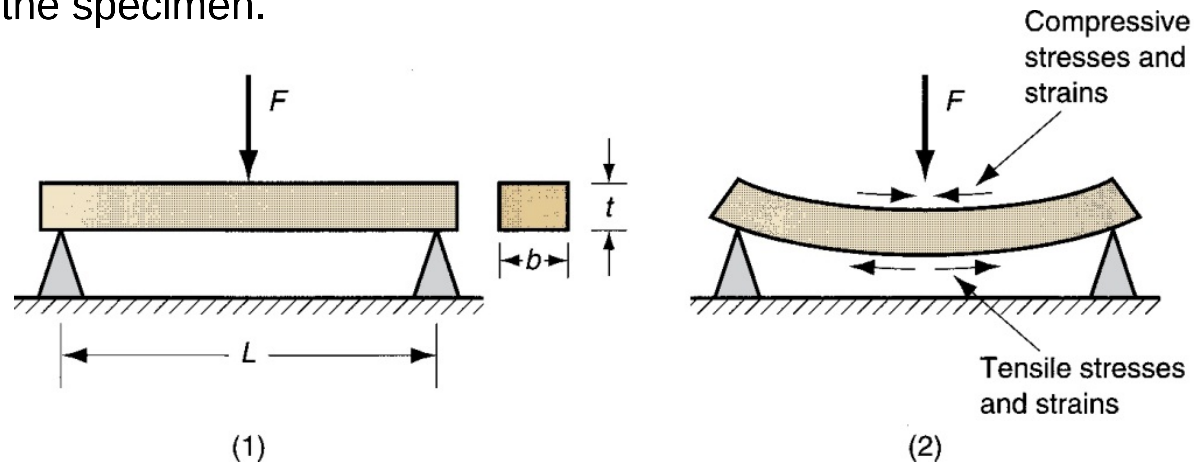


Fig. 16: Bending test setup and specimen: (1) initial loading, and (2) highly stressed and strained specimen

Stress-Strain relationships; Bending & Testing of Brittle Materials

- Specimen's cross-section is rectangular, positioned between supports and load is applied at its center (three-point bending test).
- The specimen bends elastically during the test until immediately before fracture (no plastic region).
- Strength value derived from this test is called ***Transverse Rupture Strength*** (*TRS*):

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

where TRS is in MPa, F: the applied load at fracture in N, L: the length between supports and b and t are dimensions of the cross-section in mm (Fig. 16)

- Flexure test can be utilized for nonbrittle materials such as thermoplastic polymers. These materials deform rather fracture, so TRS cannot be determined. Instead, either of the two measures are used: (1) the load recorded at a given level of deflection, or (2) the deflection observed at a given load.

Stress-Strain relationships; Shear properties

- Shear: involves the application of stresses on opposite directions on either side of an element to deflect it.

- Shear stress is defined as:

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

where τ : shear stress, MPa (n / mm^2), F = applied force, N, and A is the area over which force is applied, mm^2.

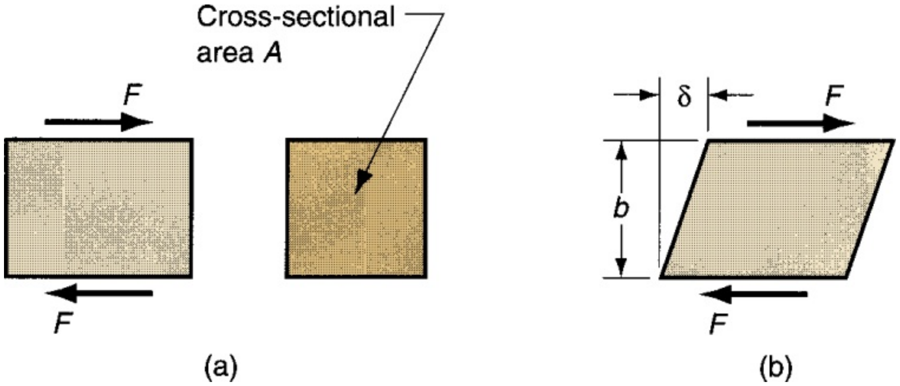


Fig. 17: Shear (a) stress and (b) strain.

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

where γ is shear strain, mm / mm, δ = the deflection of the element, mm, and b is the orthogonal distance over which the deflection occurs, mm.

Stress-Strain relationships; Shear properties

- Shear stresses and strains are commonly tested in a ***torsion test***.

- In torsion test: a thin-walled tubular specimen is subjected to a torque. As torque is increased, a tube deflects by twisting (shear strain for this geometry).

$$\tau = \frac{T}{2\pi R^2 t}$$

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

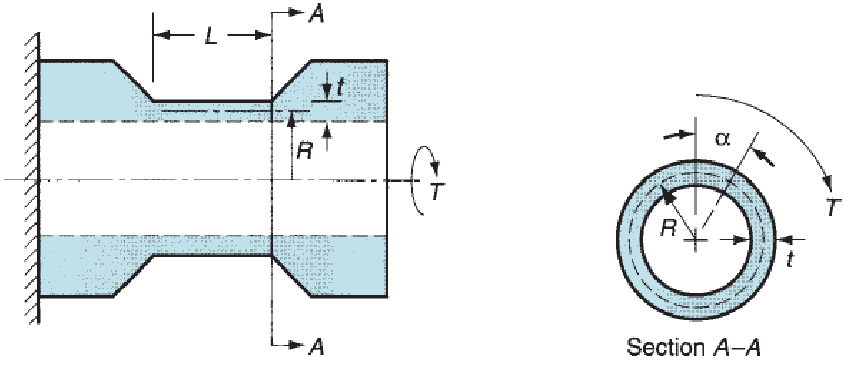


Fig. 18: Torsion test setup.

- Shear strain : $$\gamma = \frac{R\alpha}{L}$$

where α is the angular deflection, radians, and L is the gauge length in mm.

Stress-Strain relationships; Shear properties

- A typical shear stress-strain curve is shown in Fig. 19.

- In the elastic region: $\tau = G\gamma$
  where G: is the ***Shear modulus*** or ***shear modulus of elasticity*** (MPa)

- G is related to *E* by the equation: $G = 0.4E$

  where E is the conventional elastic modulus.

- In the plastic region:

  The material strain hardens to cause the applied torque to continue to increase until fracture.

  Shear strength is the stress at fracture (*S*).

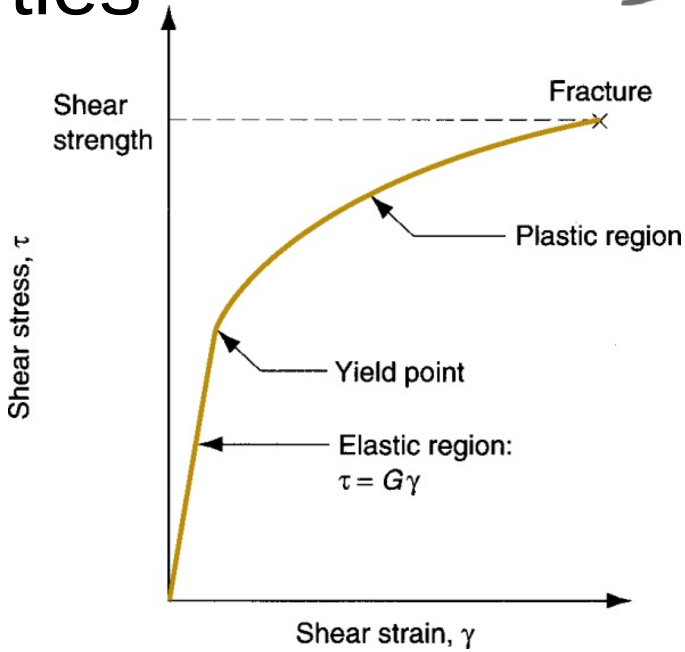


Fig. 19: A typical shear stress-strain curve from a torsion test.

S can be estimated from tensile test data

$$S = 0.7(TS)$$

Engineering and true stress-strain curves for shear are similar. Guess why?

Geometric Considerations of the Stress State

- Stresses that are computed from the tensile, compressive, shear, and torsional force states represented in Fig. 1 act either parallel or perpendicular to planar faces of the bodies represented in these illustrations.

- Consider the cylindrical tensile specimen of Figure 20 that is subjected to a tensile stress σ applied parallel to its axis. Furthermore, consider also the plane *p*-*p′* that is oriented at some arbitrary angle relative to the plane of the specimen end-face.

- Upon this plane *p*-*p′*, the applied stress is no longer a pure tensile one. Rather, a more complex stress state is present that consists of a tensile (or normal) stress σ' that acts normal to the *p*-*p′* plane and, in addition, a shear stress τ' that acts parallel to this plane; both of these stresses are represented in the figure.

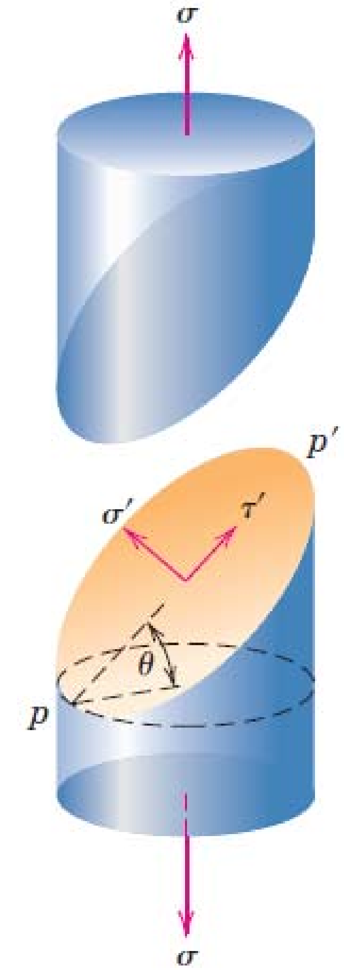


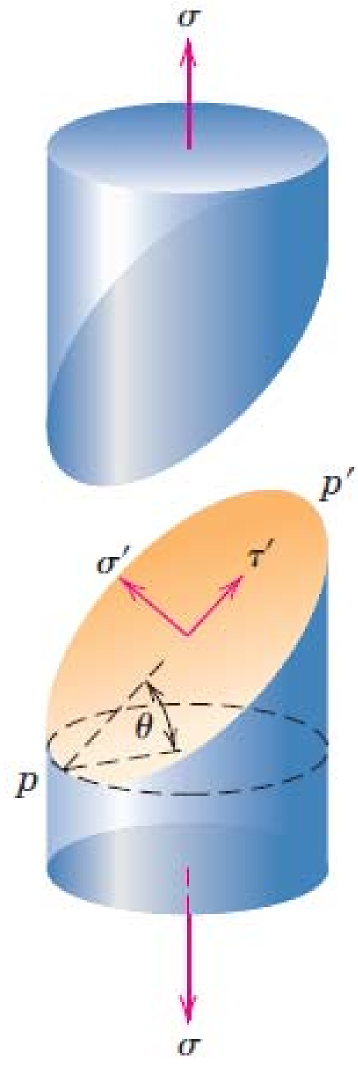
Fig. 20: Schematic representation showing normal σ' and shear τ' stresses that act on a plane oriented at an angle relative to the plane taken perpendicular to the direction along which a pure tensile stress σ is applied.

Geometric Considerations of the Stress State

- σ ' and τ ' can be computed as follows:

$$\sigma' = \sigma \cos^2\theta = \sigma\left(\frac{1+\cos 2\theta}{2}\right)$$

$$\tau' = \sigma \sin\theta \cos\theta = \sigma\left(\frac{\sin 2\theta}{2}\right)$$



Hardness

- ***<u>Hardness</u>***: is a measure of a material’s resistance to localized plastic deformation (permanent indentation).

- High hardness: material is resistant to scratching and wear.

- Mohs scale (qualitative): ranges from 1 on the soft end for talc to 10 for diamond.

- There is a good correlation between the material’s hardness and its strength.

Hardness

- Hardness tests are performed more frequently than any other mechanical test for several reasons:
  - They are simple and inexpensive—ordinarily no special specimen need to be prepared, and the testing apparatus is relatively inexpensive.
  - The test is nondestructive—the specimen is neither fractured nor excessively deformed; a small indentation is the only deformation.
  - Other mechanical properties often may be estimated from hardness data, such as tensile strength

Hardness
Rockwell Hardness Tests

- The most common method used to measure hardness because they are so simple to perform and require no special skills.
- Several indenters (steel ball, conical diamond), several loads can be utilized. Thus, suitable for almost all metal alloys, including polymers.
- Indenter (1.6 or 3.2 mm in diameter) is pressed into the specimen. Load starts at 10 kg to seat the indenter in the material, and then increased up to 150 kg. The indenter penetrates into the material. The distance penetrated (*d*) is converted to Rockwell hardness by the testing machine.

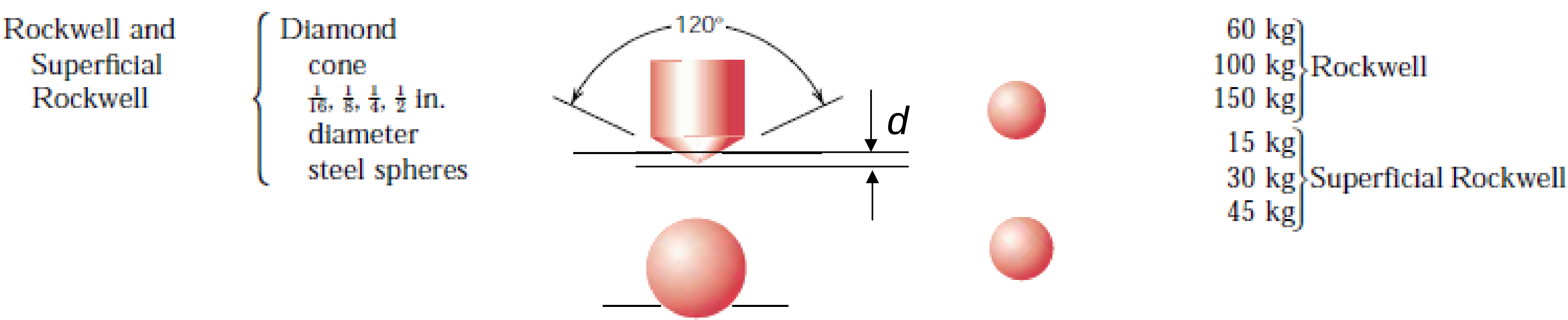


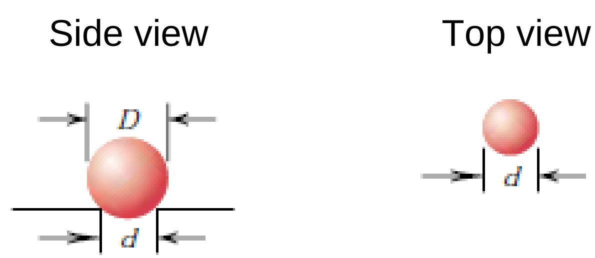
Fig. 21: Rockwell hardness testing technique.

Hardness
Brinell Hardness Tests

- In Brinell tests, as in Rockwell measurements, a hard, spherical indenter (10 mm in diameter) is forced into the surface of the metal to be tested.
- Standard loads range between 500 and 3000 kg.
- The load is then divided into the indentation area to get Brinell Hardness number.

Brinell

10-mm sphere of steel or tungsten carbide



$$HB = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$$

Fig. 22: Brinell hardness testing technique.

Hardness
Vickers Hardness Test

- Uses a pyramid-shaped diamond indenter (10 mm in diameter).
- Impressions made by this indenter are geometrically similar regardless of load.
- Value of load applied depends on the material's hardness.
- Applied loads are much smaller than for Rockwell and Brinell, ranging between 1 and 1000 g.

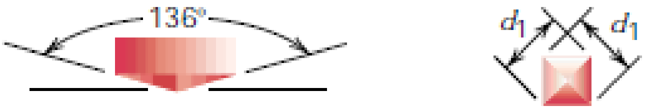
		Side view	Top view	
Vickers microhardness	Diamond pyramid			$HV = 1.854 P/d_1^2$

Fig. 23: Vickers hardness testing technique.

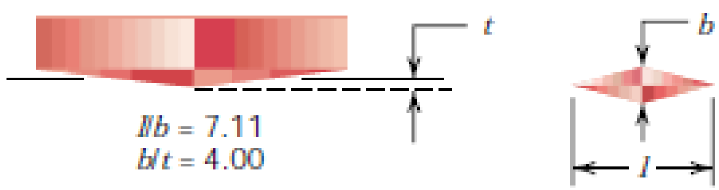
Hardness
Knoop Hardness Test

- Uses a pyramid-shaped diamond indenter with length to width ratio of 7:1.

- Applied loads are the smallest comparing to Rockwell, Brinell and Vickers hardness.

Side view Top view

Knoop microhardness Diamond pyramid



$HK = 14.2P/l^2$

Fig. 24: Vickers hardness testing technique.

Hardness of Various Materials

- **Metals**: For most metals, hardness is closely related to strength.
- Hardness is a form of compression, so one would expect a good correlation between hardness and strength properties determined in a compression test.
- Compression and tensile tests are nearly the same, so the correlation with tensile properties would also be acceptable.
- Brinell hardness exhibits a close correlation with *TS* (MPa) for steels, and the formula is:

$$TS = 3.45HB$$

Metal	Brinell Hardness, HB	Rockwell Hardness, HR[a]	Metal	Brinell Hardness, HB	Rockwell Hardness, HR[a]
Aluminum, annealed	20		Magnesium alloys, hardened[b]	70	35B
Aluminum, cold worked	35		Nickel, annealed	75	40B
Aluminum alloys, annealed[b]	40		Steel, low C, hot rolled[b]	100	60B
Aluminum alloys, hardened[b]	90	52B	Steel, high C, hot rolled[b]	200	95B, 15C
Aluminum alloys, cast[b]	80	44B	Steel, alloy, annealed[b]	175	90B, 10C
Cast iron, gray, as cast[b]	175	10C	Steel, alloy, heat treated[b]	300	33C
Copper, annealed	45		Steel, stainless, austenitic[b]	150	85B
Copper alloy: brass, annealed	100	60B	Titanium, nearly pure	200	95B
Lead	4		Zinc	30	

Hardness of Various Materials

- Ceramics: Brinell hardness is not appropriate for ceramics as they are usually harder than the Brinell hardness indenter.

- Instead, Vickers and Koop hardness tests are used to test ceramics.

Material	*Approximate Knoop Hardness*
Diamond (carbon)	7000
Boron carbide (B_4C)	2800
Silicon carbide (SiC)	2500
Tungsten carbide (WC)	2100
Aluminum oxide (Al_2O_3)	2100
Quartz (SiO_2)	800
Glass	550

Approximate Knoop Hardness (100 g load) for Seven Ceramic Materials.

Hardness of Various Materials

- Polymers: Softer than metals and ceramics, and most hardness tests are conducted by penetration techniques similar to those described for metals. Rockwell and Brinell tests are frequently used for polymers.

Polymer	Brinell Hardness, HB	Polymer	Brinell Hardness, HB
Nylon	12	Polypropylene	7
Phenol formaldehyde	50	Polystyrene	20
Polyethylene, low density	2	Polyvinyl-chloride	10
Polyethylene, high density	4		