MECHANICAL PROPERTIES OF MATERIALS

Manufacturing materials, IE251

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MECHANICAL PROPERTIES OF MATERIALS

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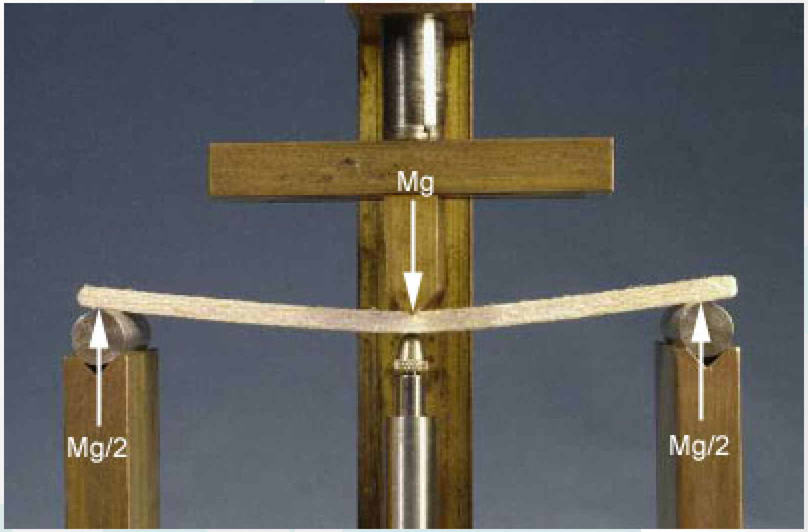
Bending test



Bending Test (also called *flexure test*)

Specimen of rectangular cross-section is positioned between two supports, and a load is applied at its center

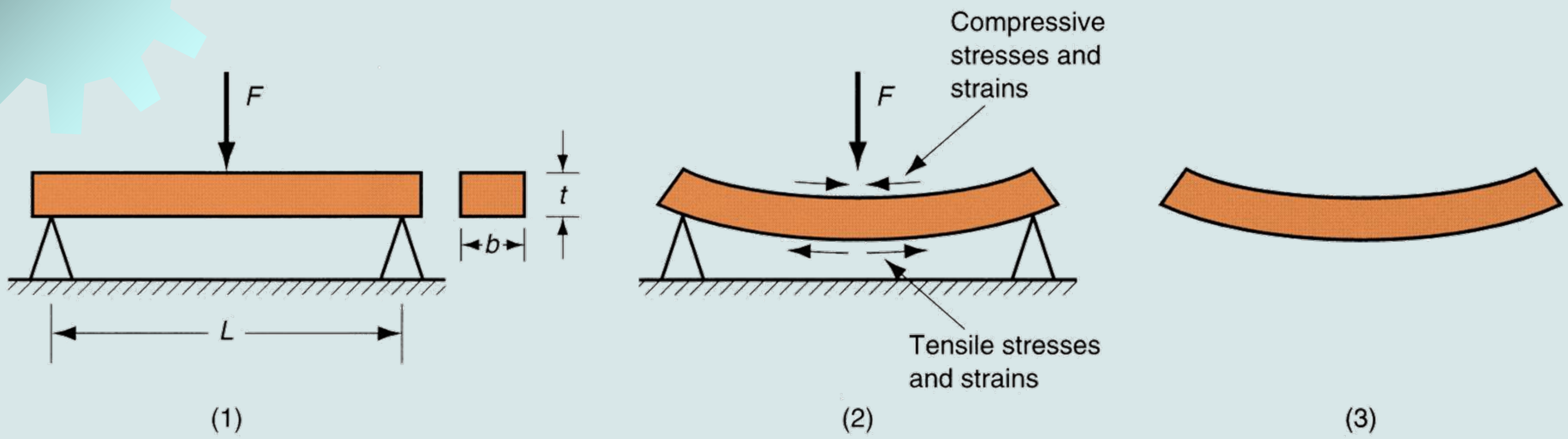
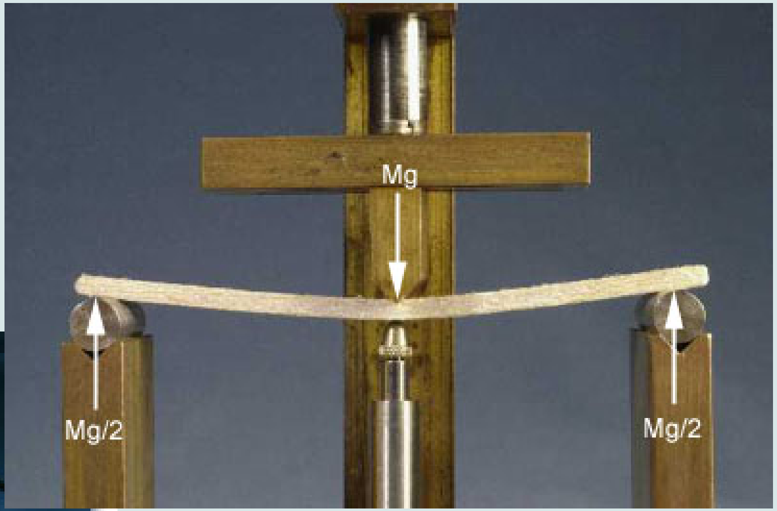
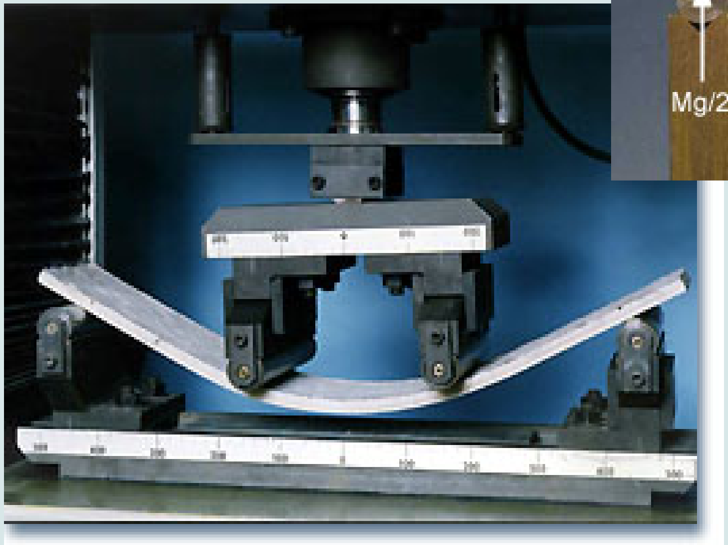


Figure 3.10 Bending of a rectangular cross-section results in both tensile and compressive stresses in the material: (1) initial loading; (2) highly stressed and strained specimen; and (3) bent part.

Bending Test

3-point and 4-point bending tests:





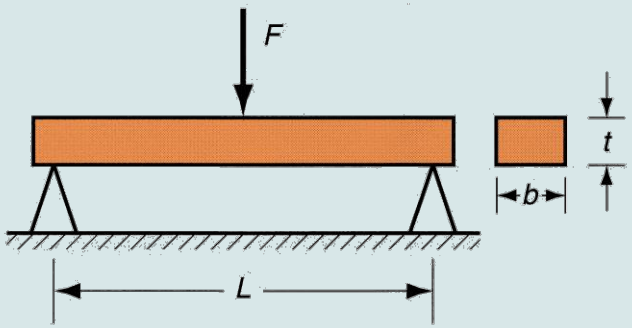
Testing of Brittle Materials

- Hard brittle materials (e.g., ceramics) possess elasticity but little or no plasticity
- Often tested by a *bending test*
- Brittle materials do not flex
- They deform elastically until fracture
  - Failure occurs because tensile strength of outer fibers of specimen are exceeded
  - Failure type: *cleavage* - common with ceramics and metals at low temperatures, in which separation rather than slip occurs along certain crystallographic planes

Transverse Rupture Strength

The strength value derived from the bending test:

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



where

TRS = Transverse Rupture Strength;

F = applied load at fracture;

L = length of specimen between supports; and

b and *t* are dimensions of cross-section

$$\sigma = \frac{MC}{I}$$

$$C = \frac{t}{2},\ I = \frac{1}{12}bt^3, M = \frac{FL}{4}$$

$$\sigma = \frac{MC}{I} = \frac{\frac{FL}{4} \cdot \frac{t}{2}}{\frac{1}{12}bt^3} = \frac{1.5FL}{bt^2}$$

Shear test

Shear Test (also known as *torsion* test)

Application of stresses in opposite directions on either side of a thin element

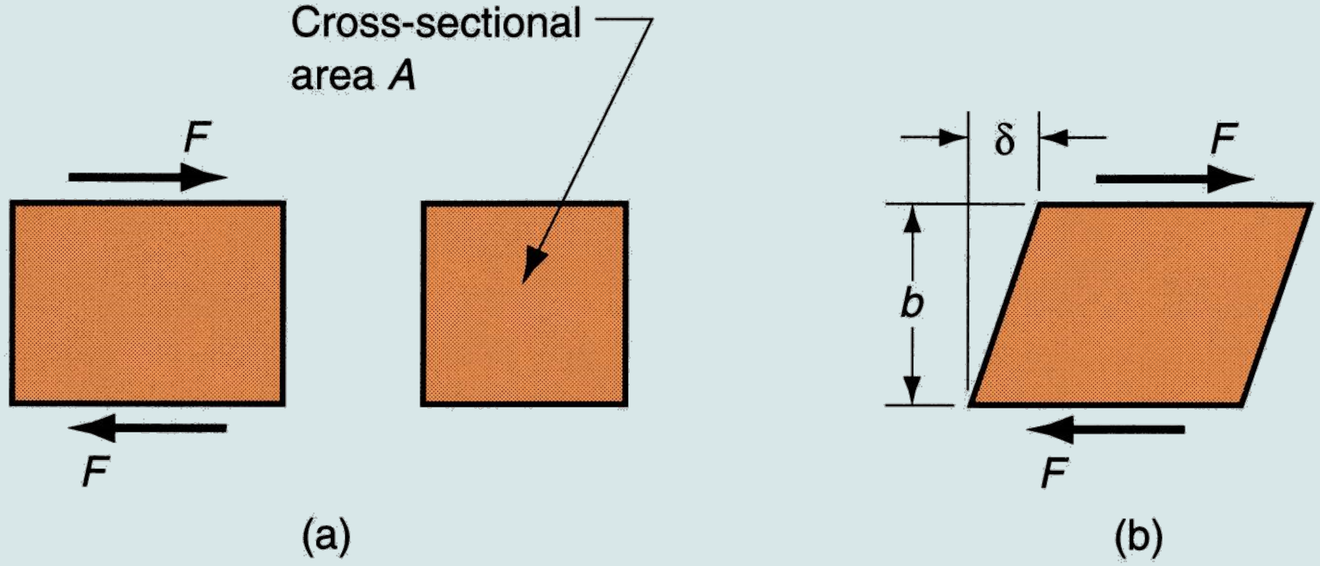
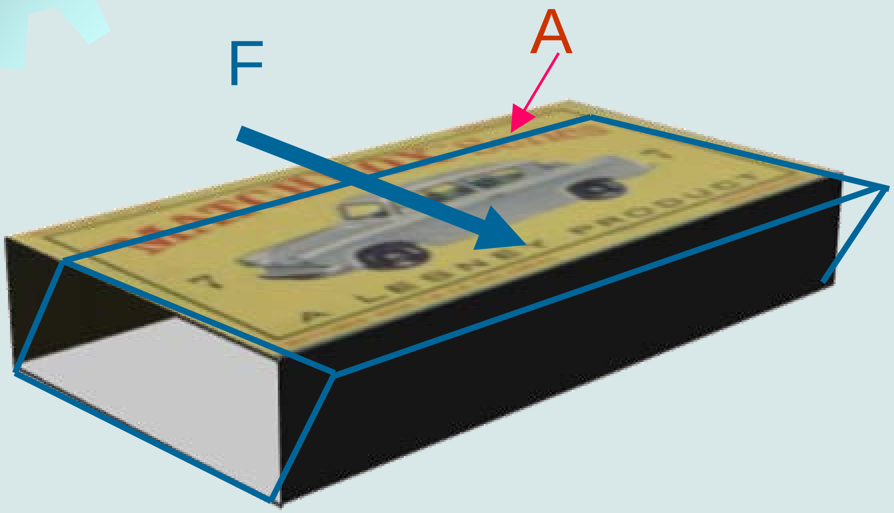
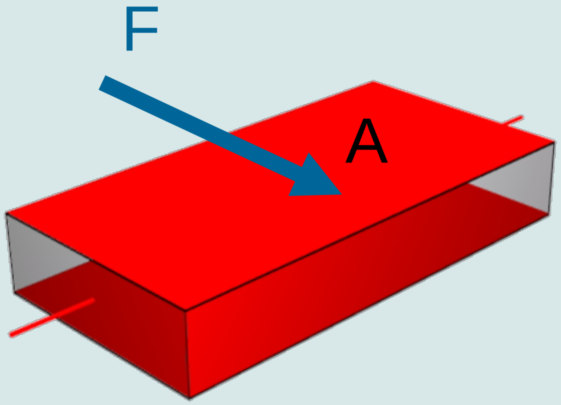


Figure 3.11 Shear (a) stress and (b) strain.

Shear Test

Deform a matchbox and see the deformations in all sides of the box. The area over which the deflection occurs is the area of consideration.





Shear Stress and Strain

Shear stress defined as $\tau = \frac{F}{A}$

where F = applied force; and A = area over which deflection occurs.

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

where

δ = deflection element; and

b = distance over which deflection occurs

Torsion Stress-Strain Curve

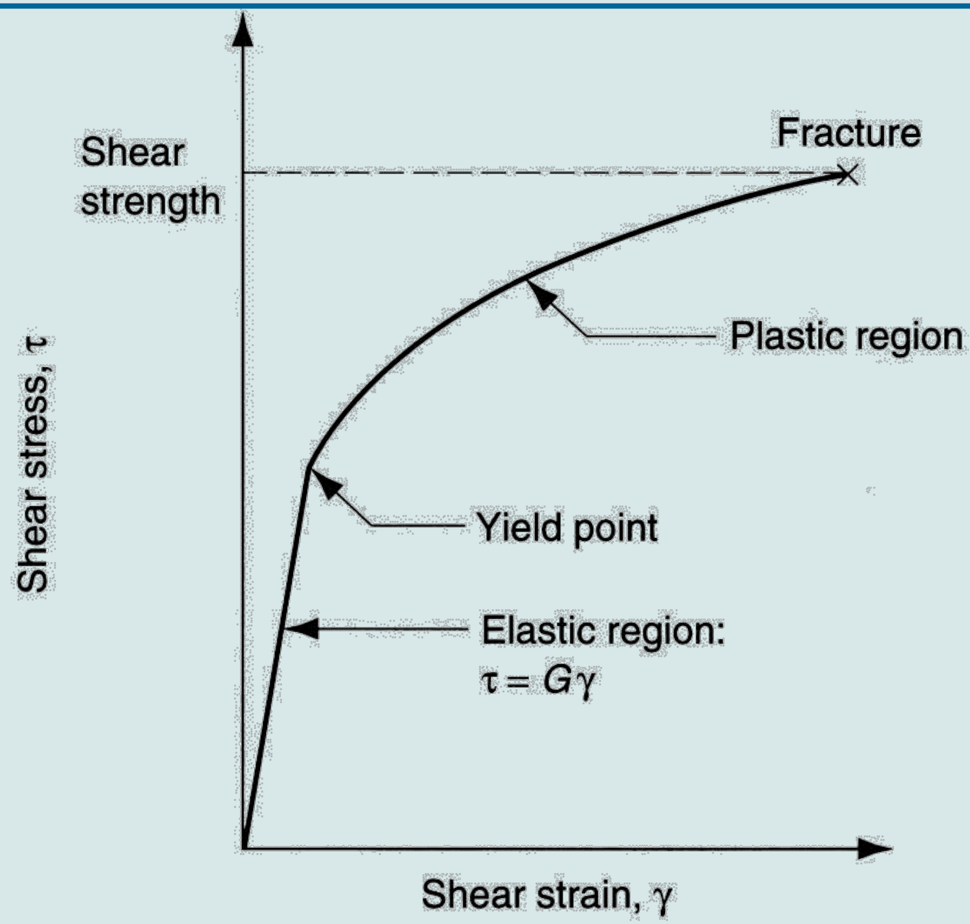


Figure 3.13 Typical shear stress-strain curve from a torsion test.

Shear Elastic Stress-Strain Relationship

In the elastic region, the relationship is defined as

$$\tau = G\gamma$$

where G = *shear modulus*, or *shear modulus of elasticity*

For most materials, $G \cong 0.4E$, where E = elastic modulus

Shear Plastic Stress-Strain Relationship

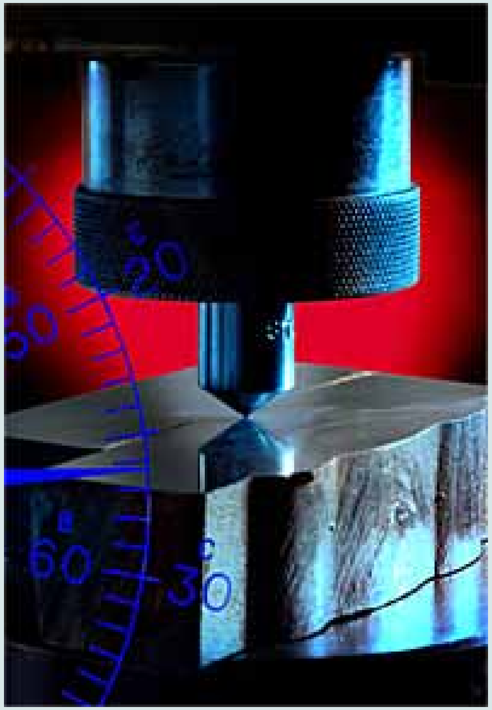
- Relationship similar to flow curve for a tensile test
- Shear stress at fracture = *shear strength S*
  - Shear strength can be estimated from tensile strength: $S \cong 0.7(TS)$
- Since cross-sectional area of test specimen in torsion test does not change as in tensile and compression, engineering stress-strain curve for shear ≅ true stress-strain curve

Hardness

Hardness

Resistance to permanent indentation

- Good hardness generally means material is resistant to scratching and wear
- Most tooling used in manufacturing must be hard for scratch and wear resistance



Hardness Tests

- Commonly used for assessing material properties because they are quick and convenient
- Variety of testing methods are appropriate due to differences in hardness among different materials
- Most well-known hardness tests are *Brinell* and *Rockwell*
- Other test methods are also available, such as Vickers, Knoop, Scleroscope, and durometer

Brinell Hardness Test

- Widely used for testing metals and nonmetals of low to medium hardness

- A hard ball is pressed into specimen surface with a load of 500, 1500, or 3000 kg

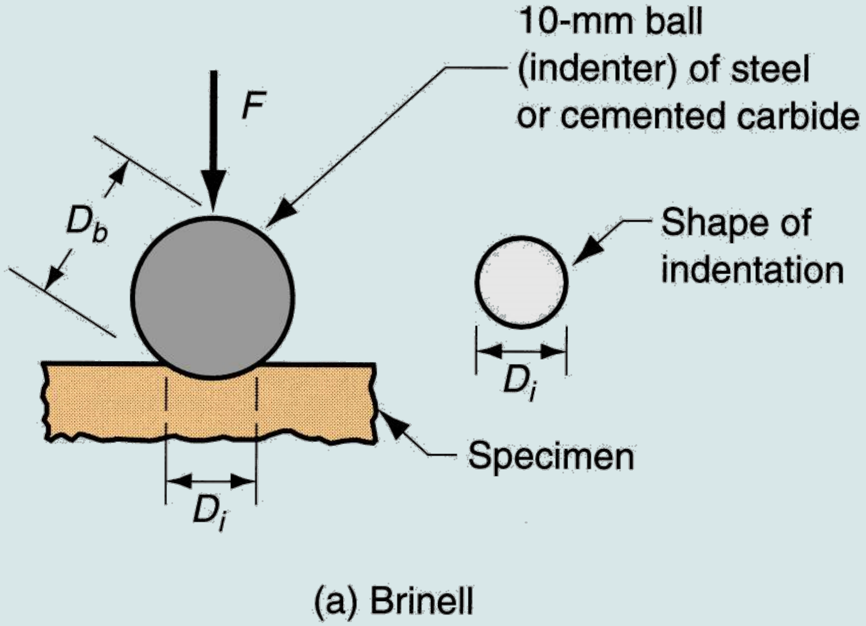


Figure 3.14 Hardness testing methods: (a) Brinell

Brinell Hardness Number

Load divided into indentation area = Brinell Hardness Number (BHN)

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

where

HB = Brinell Hardness Number (BHN),

F = indentation load, kg;

D_b = diameter of ball, mm, and

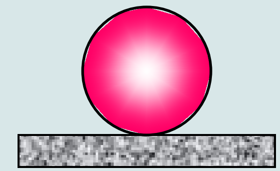
D_i = diameter of indentation, mm

Brinell Hardness Number

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

Lets work on two extreme cases:

D_i is extremely low (lets consider it as zero!):



$$HB = \frac{2F}{\pi D_b (D_b - \sqrt{D_b^2})} = \frac{2F}{\pi D_b (D_b - D_b)} = \frac{2F}{0} = \infty$$

This means that if there is almost no indentation, the material is extremely hard!

In case $D_i = D_b$ (the whole ball is inserted into the specimen):

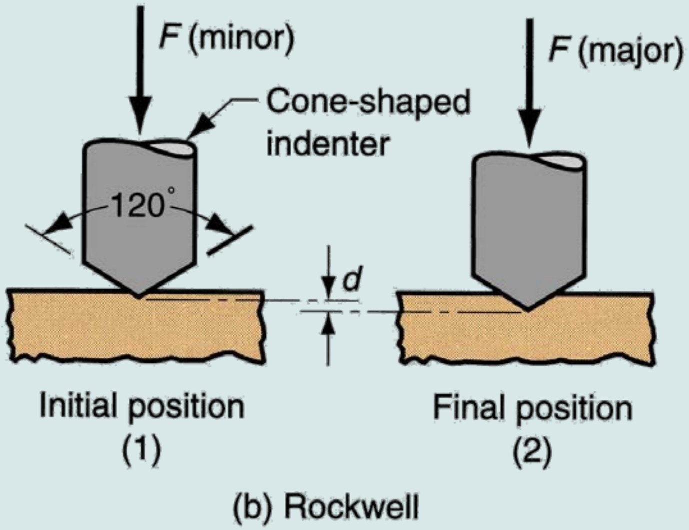
$$HB = \frac{2F}{\pi D_b (D_b - \sqrt{D_b^2 - D_b^2})} = \frac{2F}{\pi D_b^2} = \frac{F}{\frac{\pi}{2} D_b^2} = \frac{F}{2\pi R_b^2} = \frac{F}{A^*}$$

A^* is the area of the semisphere. This means that HB number is in fact the force divided by the area of contact!

Rockwell Hardness Test

Figure 3.14 Hardness testing methods: (b) Rockwell:

(1) initial minor load and (2) major load.



- Another widely used test
- A cone shaped indenter is pressed into specimen using a minor load of 10 kg, thus seating indenter in material
- Then, a major load of 150 kg is applied, causing indenter to penetrate beyond its initial position
- Additional penetration distance *d* is converted into a Rockwell hardness reading by the testing machine

Effect of Temperature on Properties

Effect of Temperature on Properties

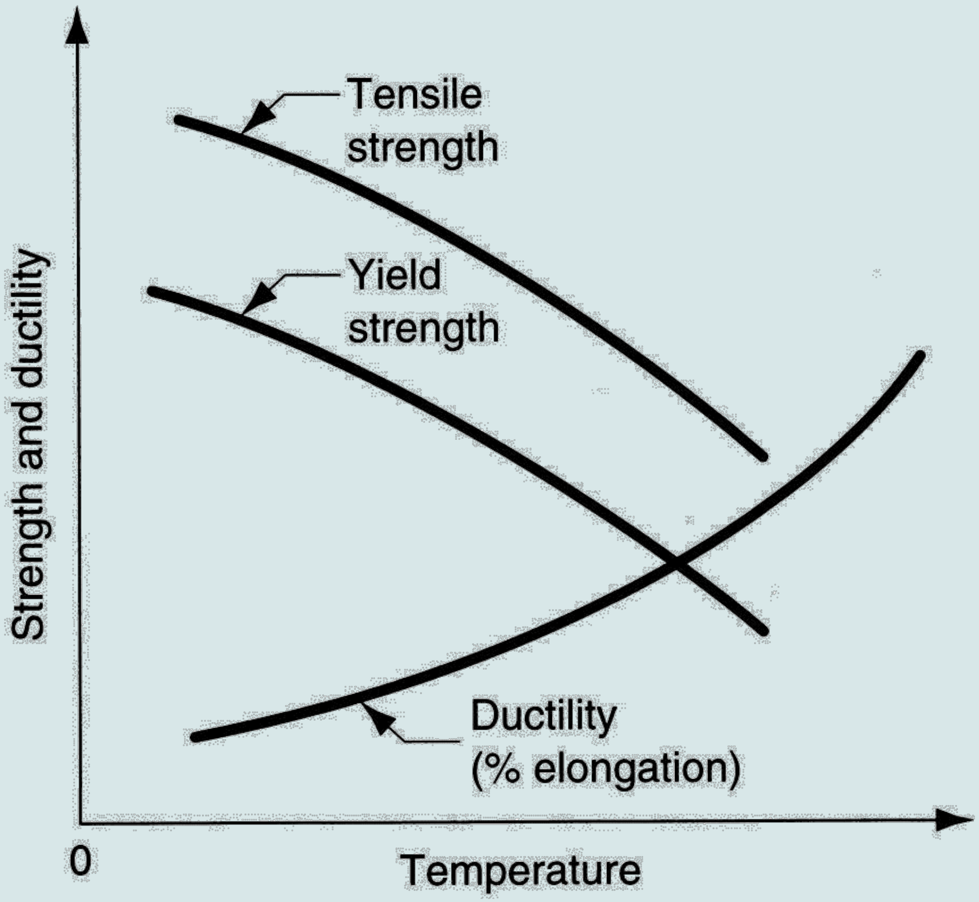


Figure 3.15 General effect of temperature on strength and ductility.

Hot Hardness

Ability of a material to retain hardness at elevated temperatures

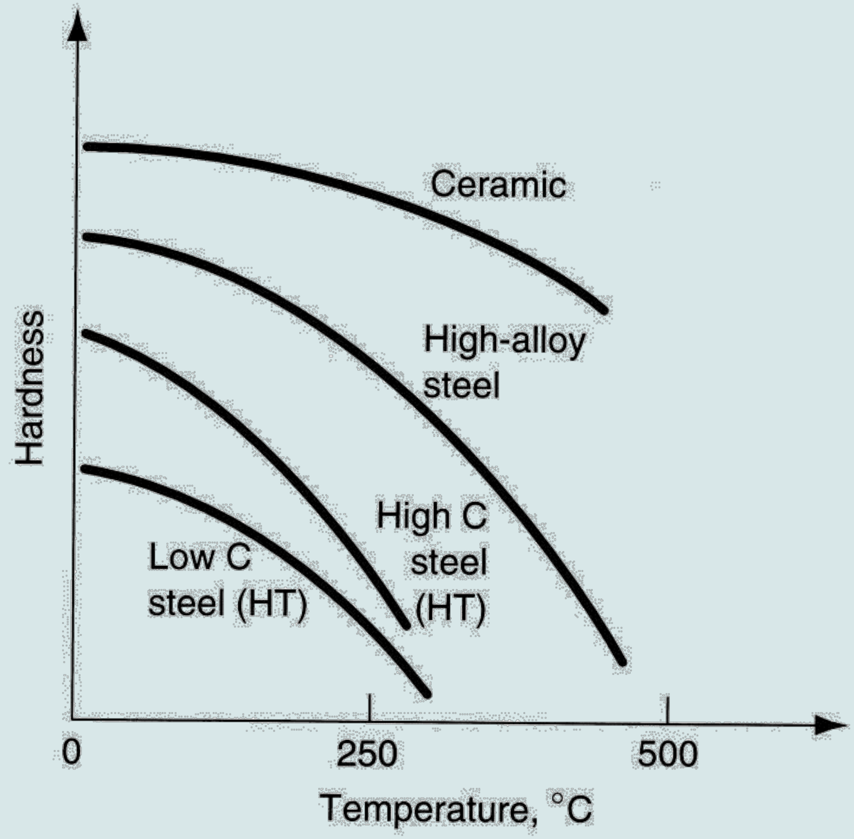


Figure 3.16 Hot hardness - typical hardness as a function of temperature for several materials.

Recrystallization in Metals

- Most metals strain-harden at room temperature according to the flow curve ($n > 0$)

- But if heated to sufficiently high temperature and deformed, strain hardening does not occur
  - Instead, new grains are formed that are free of strain
  - The metal behaves as a perfectly plastic material; that is, $n = 0$

Recrystallization Temperature

- Formation of new strain-free grains is called *recrystallization*
- *Recrystallization temperature* of a given metal = about one-half its melting point (0.5 T_m) as measured on an absolute temperature scale
- Recrystallization takes time - the recrystallization temperature is specified as the temperature at which new grains are formed in about <u>one hour</u>

Recrystallization and Manufacturing

- Heating a metal to its recrystallization temperature prior to deformation allows a greater amount of straining, and lower forces and power are required to perform the process

- Forming metals at temperatures above recrystallization temperature is called *hot working*

Fluid Properties and Manufacturing

Fluid Properties and Manufacturing

- Fluids flow - They take the shape of the container that holds them
- Many manufacturing processes are accomplished on materials converted from solid to liquid by heating
  - Called *solidification processes*
- Examples:
  - Metals are cast in molten state
  - Glass is formed in a heated and fluid state
  - Polymers are almost always shaped as fluids

Viscosity in Fluids

Viscosity is the resistance to flow that is characteristic of a given fluid

- Flow is a defining characteristic of fluids, but the tendency to flow varies for different fluids
- Viscosity is a measure of the internal friction when velocity gradients are present in the fluid

The more viscous the fluid, the higher the internal friction and the greater the resistance to flow

Reciprocal of viscosity is *fluidity* - the ease with which a fluid flows

Viscosity

Viscosity can be defined using two parallel plates separated by a distance *d* and a fluid fills the space between the two plates

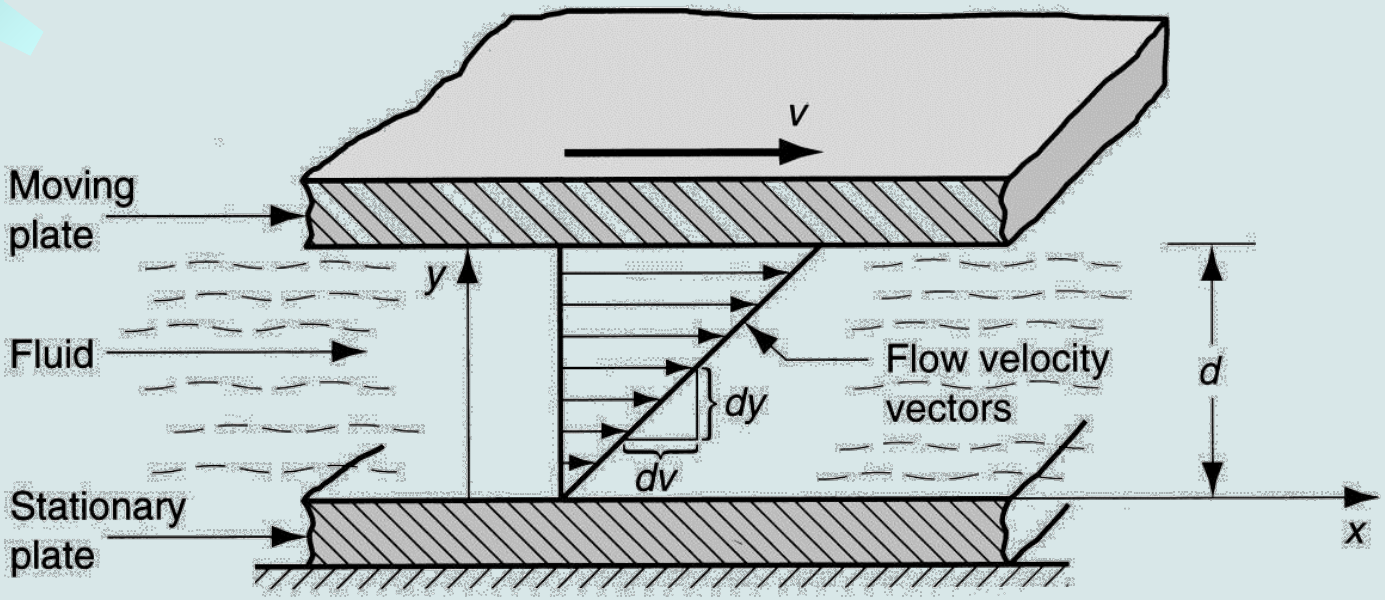


Figure 3.17 Fluid flow between two parallel plates, one stationary and the other moving at velocity *v*

Shear Stress

- Shear stress is the frictional force exerted by the fluid per unit area
- Motion of the upper plate is resisted by a frictional force resulting from the shear viscosity of the fluid
- This force *F* can be reduced to a *shear stress* τ by dividing by plate area *A*

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

Shear Rate

Shear stress is related to *shear rate*, defined as the change in velocity *dv* relative to *dy*

$$\dot{\gamma} = \frac{dv}{dy}$$

Shear rate = velocity gradient perpendicular to flow direction

where $\dot{\gamma}$ = shear rate, [1/s];

dv = change in velocity, [m/s]; and

dy = change in distance *y*, [m]

Shear Viscosity

Shear viscosity is the fluid property that defines the relationship between F/A and *dv*/*dy*, that is,

$$\frac{F}{A} = \eta \frac{dv}{dy}$$

or

$$\tau = \mu \dot{\gamma}$$

where η = a constant of proportionality called the *coefficient of viscosity*, [Pa-s]

- For *Newtonian* fluids, viscosity is a constant
- For non-Newtonian fluids, it is not

Coefficient of Viscosity

- Rearranging, Shear viscosity (also called coefficient of viscosity) can be expressed:

$$\mu = \frac{\tau}{\dot{\gamma}}$$

- Viscosity of a fluid is the ratio of shear stress to shear rate during flow

Viscosity of Polymers and Flow Rate

Viscosity of Polymers and Flow Rate

- Viscosity of a thermoplastic polymer melt is not constant
  - It is affected by flow rate
  - Its behavior is non-Newtonian
- A fluid that exhibits this decreasing viscosity with increasing shear rate is called *pseudoplastic*
- This complicates analysis of polymer shaping processes such as injection molding

Newtonian versus Pseudoplastic Fluids

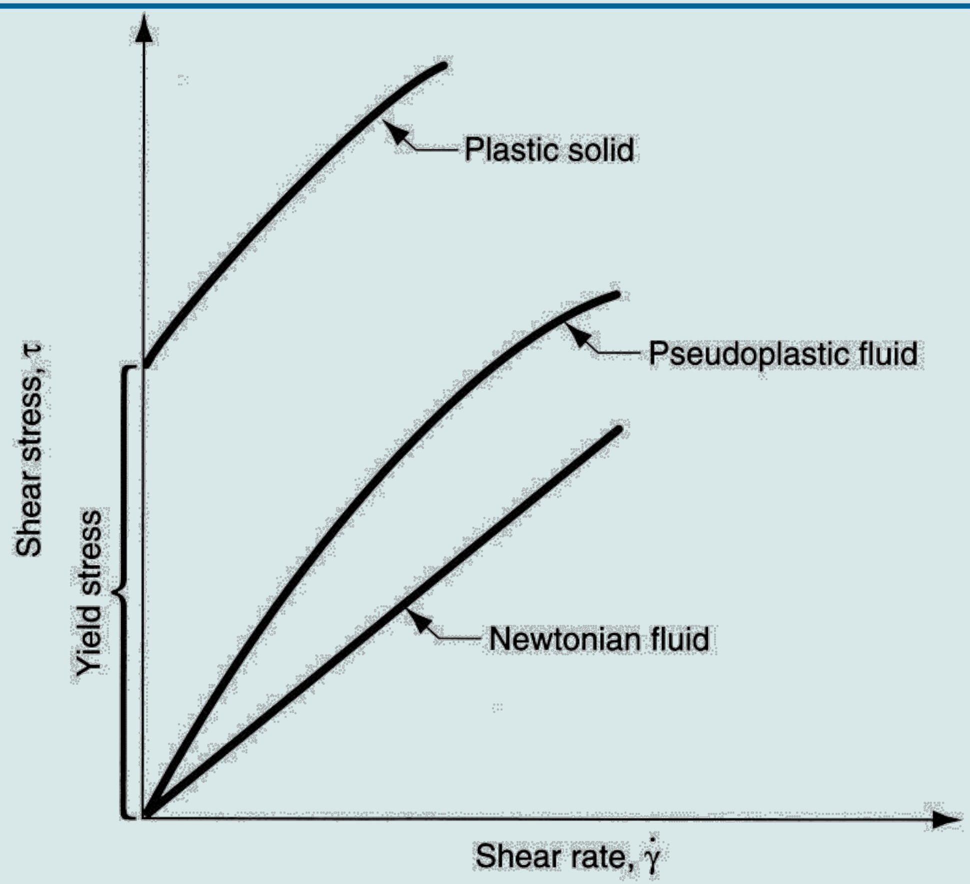


Figure 3.18 Viscous behaviors of Newtonian and pseudoplastic fluids. Polymer melts exhibit pseudoplastic behavior. For comparison, the behavior of a plastic solid material is shown.

Viscoelastic Behavior

Material property that determines the strain that the material experiences when subjected to combinations of stress and temperature over time

- Combination of viscosity and elasticity

Elastic versus Viscoelastic Behavior

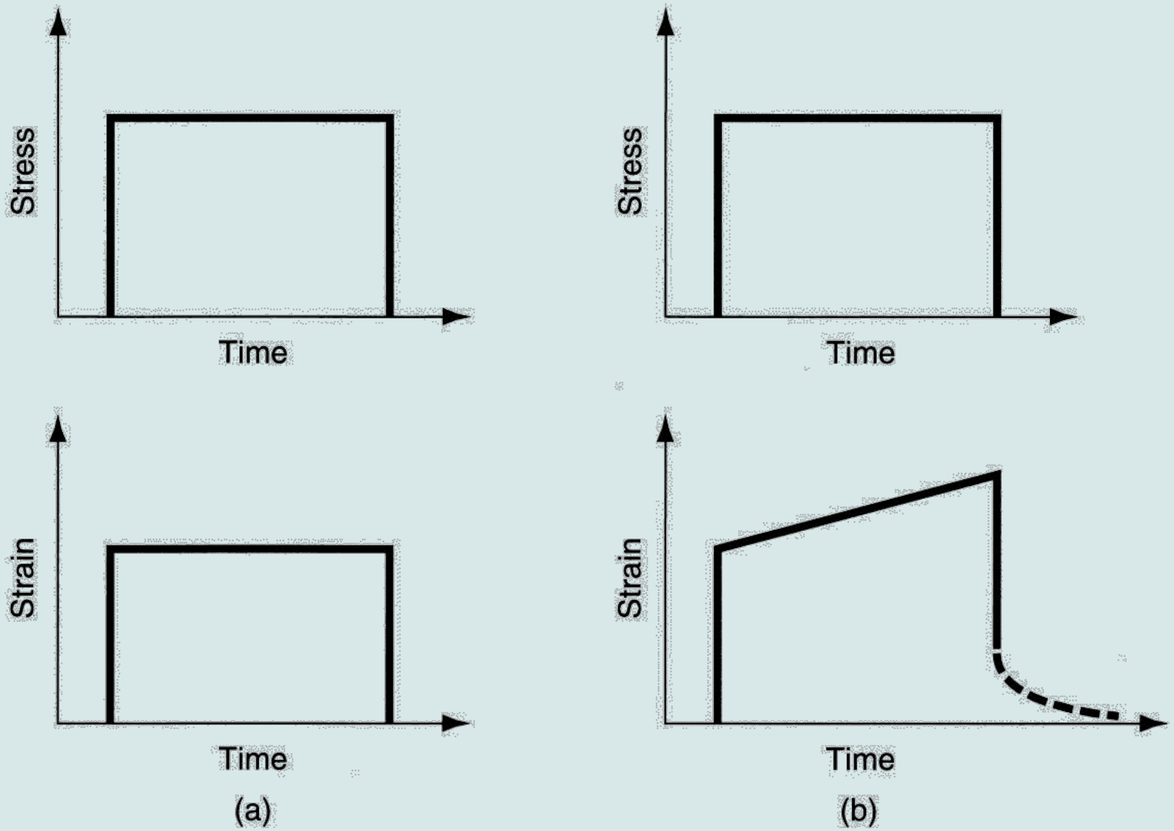


Figure 3.19 (a) perfectly elastic response of material to stress applied over time; and (b) response of a viscoelastic material under same conditions. The material in (b) takes a strain that is a function of time and temperature.

Viscoelastic Behavior of Polymers: Shape Memory

- A problem in extrusion of polymers is *die swell*, in which the profile of extruded material grows in size, reflecting its tendency to return to its previously larger cross section in the extruder barrel immediately before being squeezed through the smaller die opening