MECHANICAL PROPERTIES OF MATERIALS

1. Stress-Strain Relationships
2. Hardness
3. Effect of Temperature on Properties
4. Fluid Properties
5. Viscoelastic Behavior of Polymers

Mechanical Properties in Design and Manufacturing

Mechanical properties determine a material's behavior when subjected to mechanical stresses

- Properties include elastic modulus, ductility, hardness, and various measures of strength

- Dilemma: mechanical properties desirable to the designer, such as high strength, usually make manufacturing more difficult
  - The manufacturing engineer should appreciate the design viewpoint
  - And the designer should be aware of the manufacturing viewpoint

Stress-Strain Relationships

Three types of static stresses to which materials can be subjected:

1. Tensile - tend to stretch the material
2. Compressive - tend to squeeze it
3. Shear - tend to cause adjacent portions of material to slide against each other

- Stress-strain curve - basic relationship that describes mechanical properties for all three types

Tensile Test

- Most common test for studying stress-strain relationship, especially metals
- In the test, a force pulls the material, elongating it and reducing its diameter

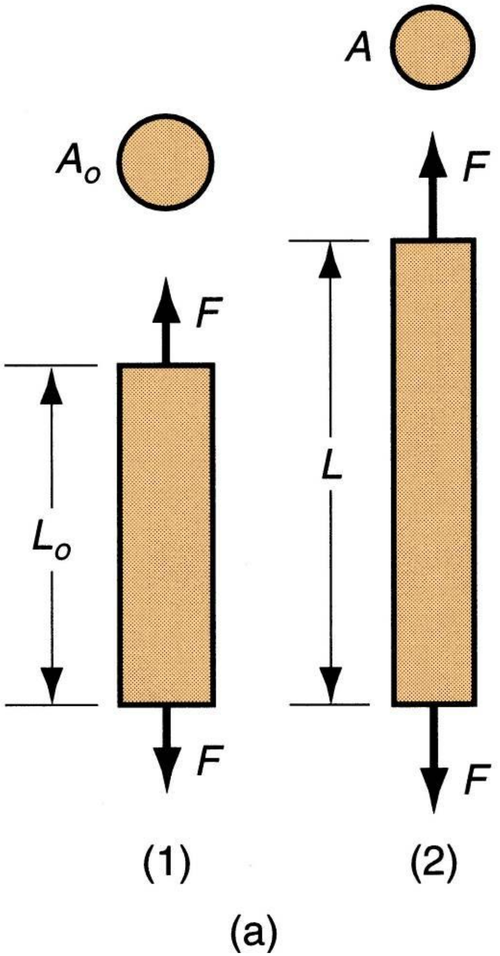


Figure 3.1 Tensile test: (a) tensile force applied in (1) and (2) resulting elongation of material

Tensile Test Specimen

ASTM (American Society for Testing and Materials) specifies preparation of test specimen

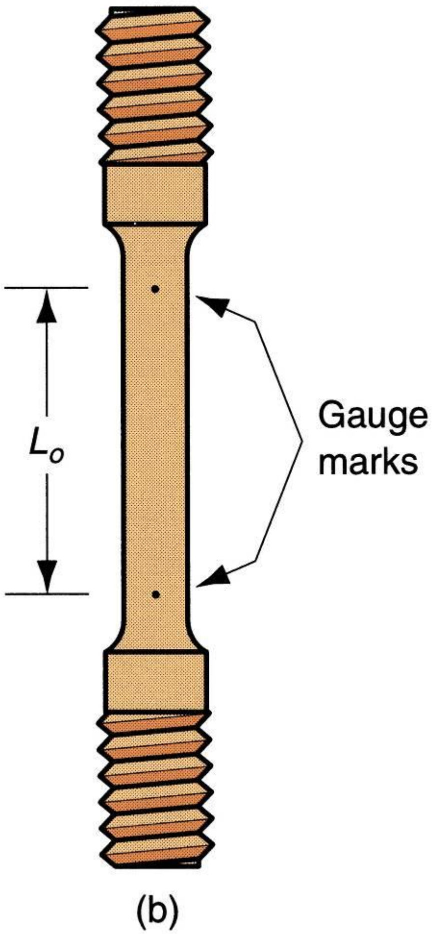
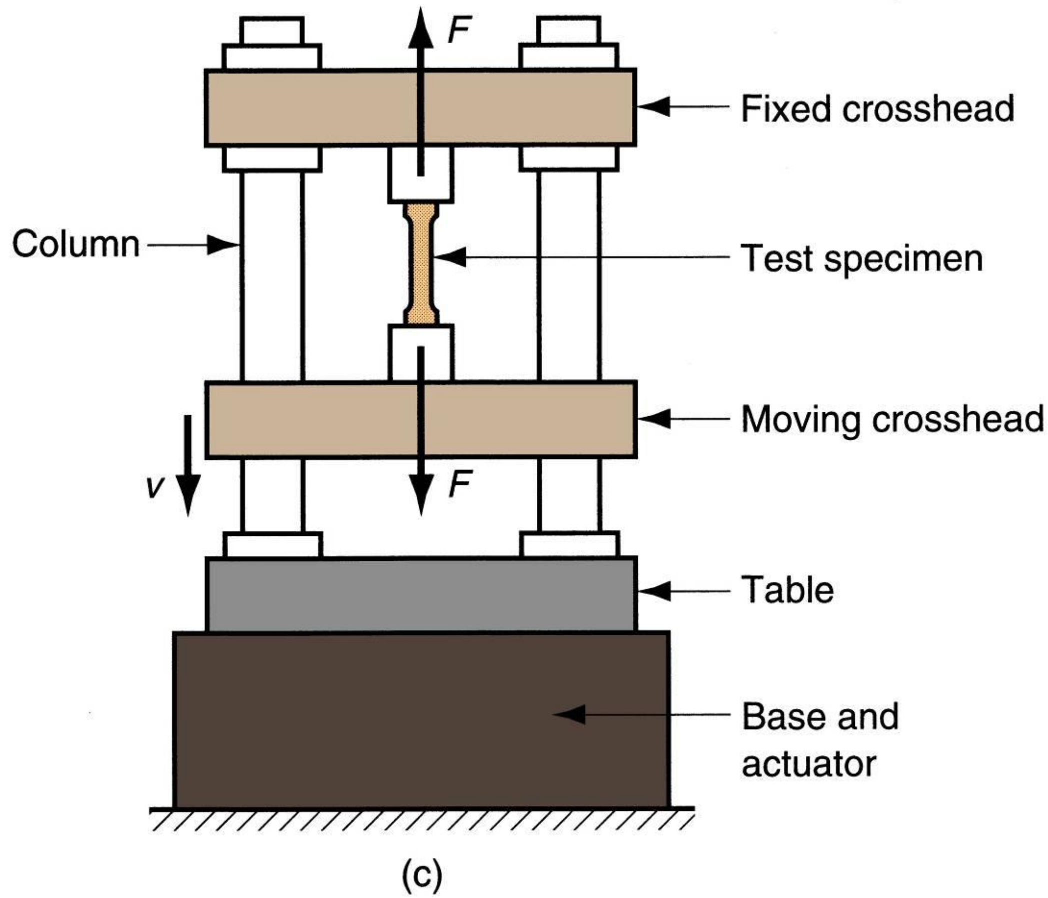


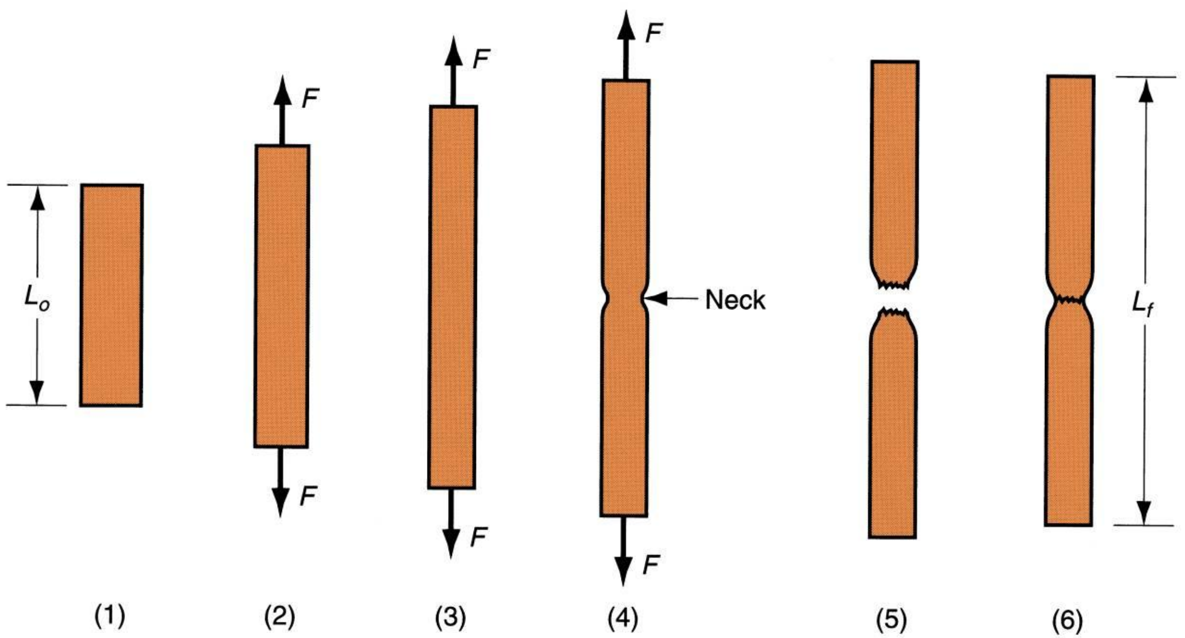
Figure 3.1 Tensile test: (b) typical test specimen

Tensile Test Setup



Tensile Test Sequence

Figure 3.2 Typical progress of a tensile test: (1) beginning of test, no load; (2) uniform elongation and reduction of cross-sectional area; (3) continued elongation, maximum load reached; (4) necking begins, load begins to decrease; and (5) fracture. If pieces are put back together as in (6), final length can be measured.



Engineering Stress

Defined as force divided by original area:

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

where σ_e = engineering stress, F = applied force, and A_o = original area of test specimen

Engineering Strain

Defined at any point in the test as

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

where e = engineering strain; L = length at any point during elongation; and L_o = original gage length

Typical Engineering Stress-Strain Plot

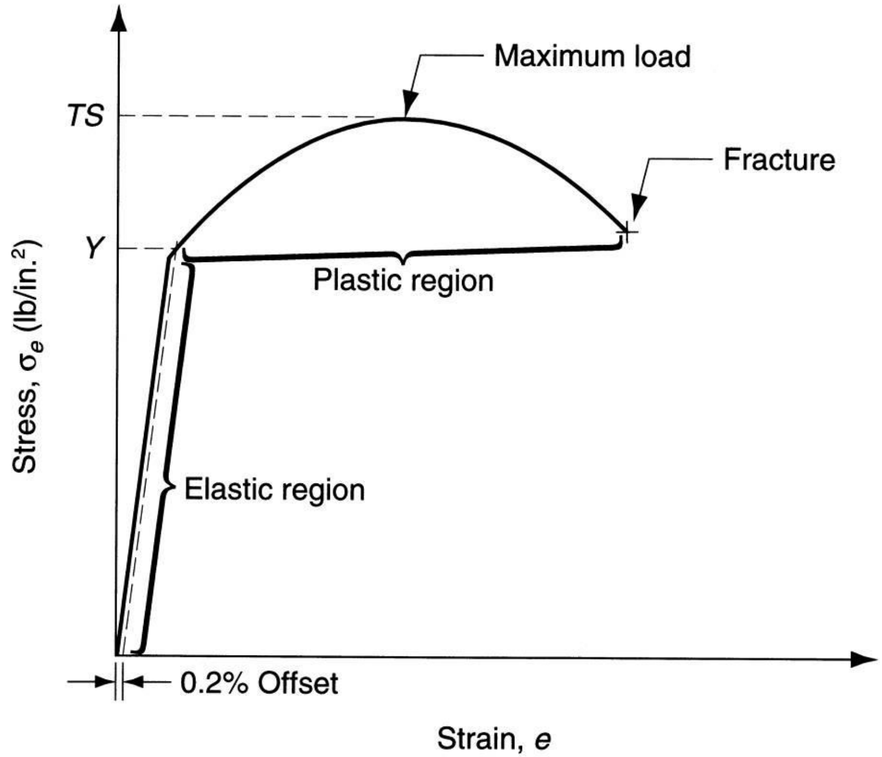


Figure 3.3 Typical engineering stress-strain plot in a tensile test of a metal.

Two Regions of Stress-Strain Curve

The two regions indicate two distinct forms of behavior:

1. Elastic region – prior to yielding of the material
2. Plastic region – after yielding of the material

Elastic Region in Stress-Strain Curve

- Relationship between stress and strain is linear
- Material returns to its original length when stress is removed

  Hooke's Law: $\sigma_e = E\, e$

  where E = *modulus of elasticity*
- *E* is a measure of the inherent stiffness of a material
- Its value differs for different materials

Yield Point in Stress-Strain Curve

- As stress increases, a point in the linear relationship is finally reached when the material begins to yield
  - *Yield point Y* can be identified by the change in slope at the upper end of the linear region
  - *Y* = a strength property
  - Other names for yield point = yield strength, yield stress, and elastic limit

Plastic Region in Stress-Strain Curve

- Yield point marks the beginning of plastic deformation
- The stress-strain relationship is no longer guided by Hooke's Law
- As load is increased beyond *Y*, elongation proceeds at a much faster rate than before, causing the slope of the curve to change dramatically

Tensile Strength in Stress-Strain Curve

- Elongation is accompanied by a uniform reduction in cross-sectional area, consistent with maintaining constant volume
- Finally, the applied load *F* reaches a maximum value, and engineering stress at this point is called the *tensile strength TS* (a.k.a. ultimate tensile strength)

$$TS = \frac{F_{\text{max}}}{A_o}$$

Ductility in Tensile Test

Ability of a material to plastically strain without fracture

- Ductility measure = elongation *EL*

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

where EL = elongation; L_f = specimen length at fracture; and L_o = original specimen length

L_f is measured as the distance between gage marks after two pieces of specimen are put back together

True Stress

Stress value obtained by dividing the instantaneous area into applied load

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

where σ = true stress; F = force; and A = actual (instantaneous) area resisting the load

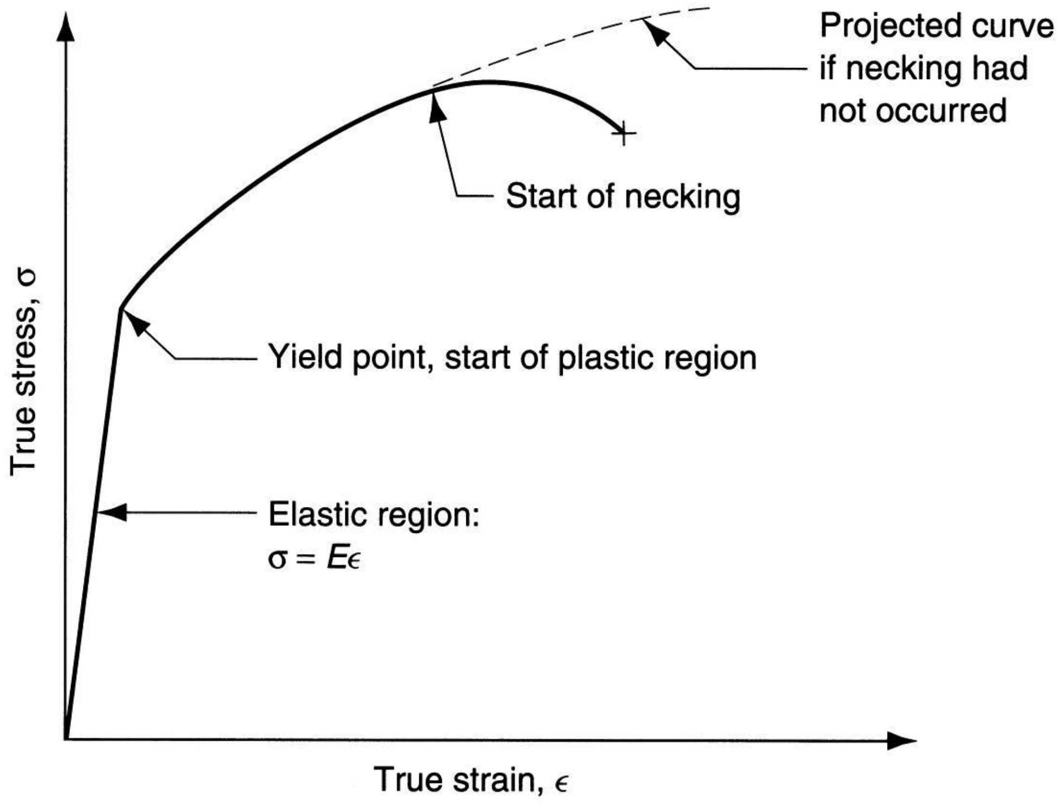
True Strain

Provides a more realistic assessment of "instantaneous" elongation per unit length

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

True Stress-Strain Curve

Figure 3.4 - True stress-strain curve for the previous engineering stress-strain plot in Figure 3.3.



Strain Hardening in Stress-Strain Curve

- Note that true stress increases continuously in the plastic region until necking
  - In the engineering stress-strain curve, the significance of this was lost because stress was based on an incorrect area value
- It means that the metal is becoming stronger as strain increases
  - This is the property called *strain hardening*

True Stress-Strain in Log-Log Plot

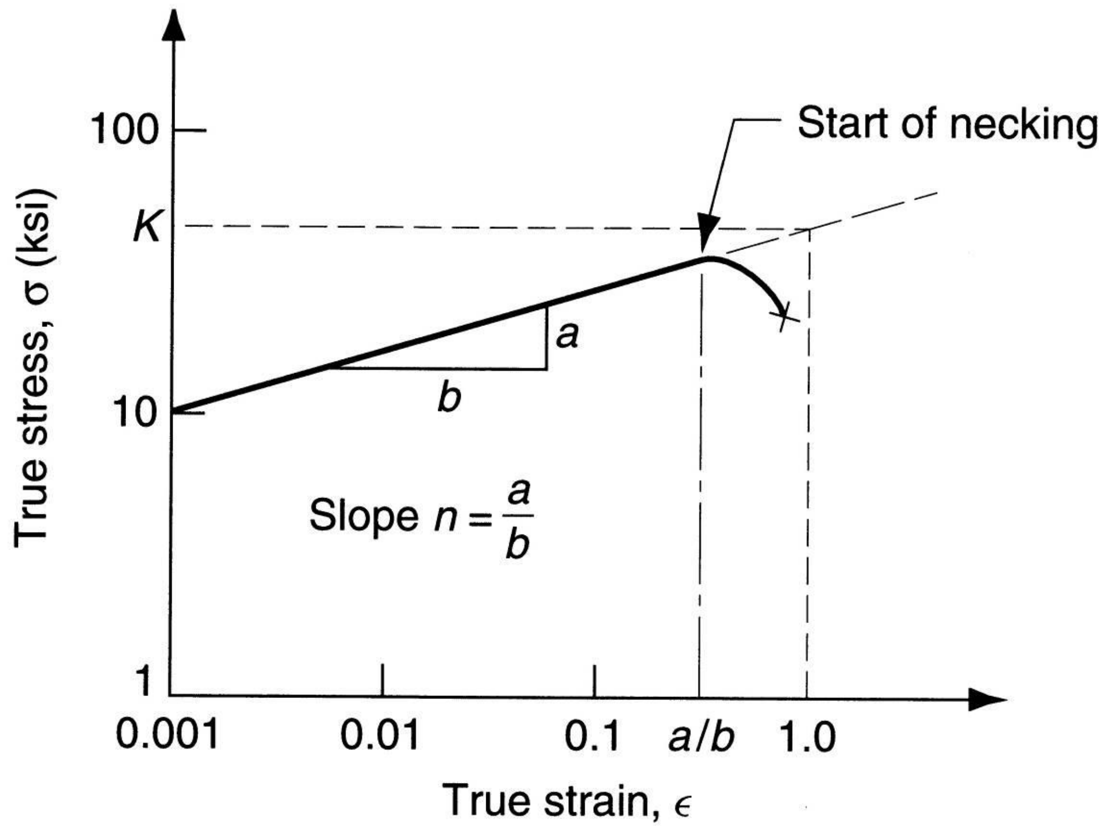


Figure 3.5 True stress-strain curve plotted on log-log scale.

Flow Curve

Because it is a straight line in a log-log plot, the relationship between true stress and true strain in the plastic region is

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

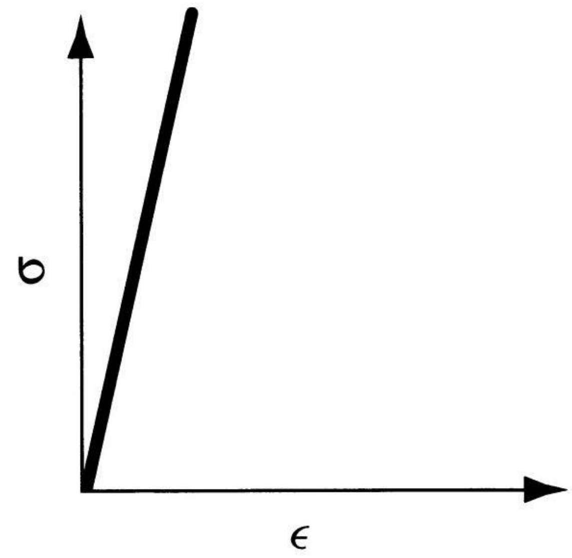
where K = *strength coefficient;* and n = *strain hardening exponent*

Categories of Stress-Strain Relationship

- Perfectly elastic
- Elastic and perfectly plastic
- Elastic and strain hardening

Perfectly Elastic

- Behavior is defined completely by modulus of elasticity *E*
- Fractures rather than yielding to plastic flow
- Brittle materials: ceramics, many cast irons, and thermosetting polymers



(a)

Figure 3.6 Three categories of stress-strain relationship: (a) perfectly elastic.

Elastic and Perfectly Plastic

- Stiffness defined by *E*
- Once *Y* reached, deforms plastically at same stress level
- Flow curve: $K = Y$, $n = 0$
- Metals behave like this when heated to sufficiently high temperatures (above recrystallization)

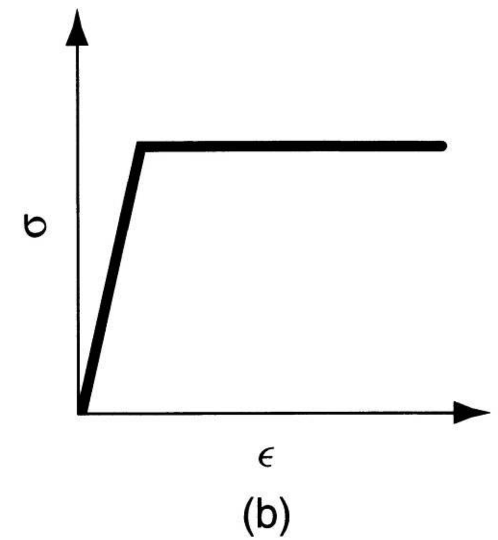


Figure 3.6 Three categories of stress-strain relationship: (b) elastic and perfectly plastic.

Elastic and Strain Hardening

- Hooke's Law in elastic region, yields at Y
- Flow curve: $K > Y$, $n > 0$
- Most ductile metals behave this way when cold worked

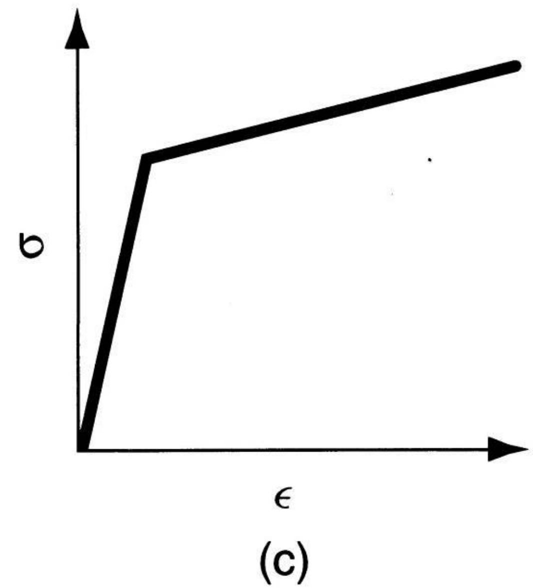


Figure 3.6 Three categories of stress-strain relationship: (c) elastic and strain hardening.

Compression Test

Applies a load that squeezes the ends of a cylindrical specimen between two platens

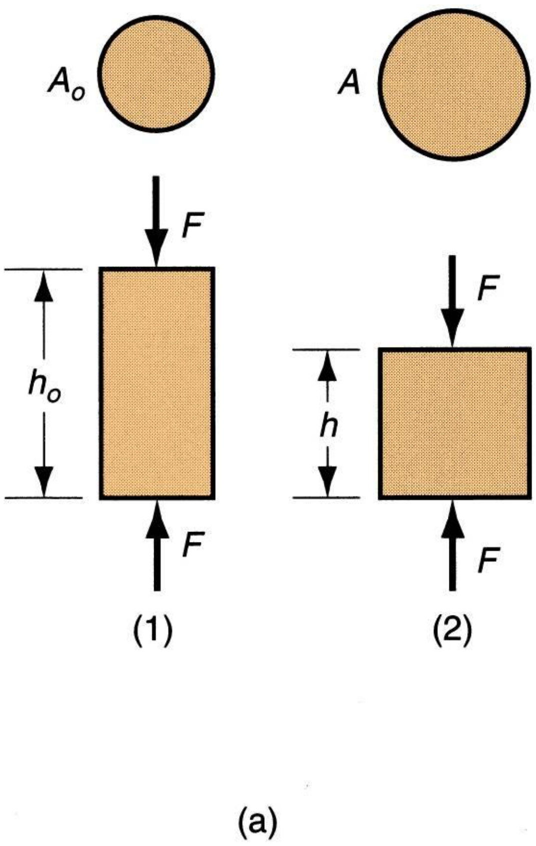
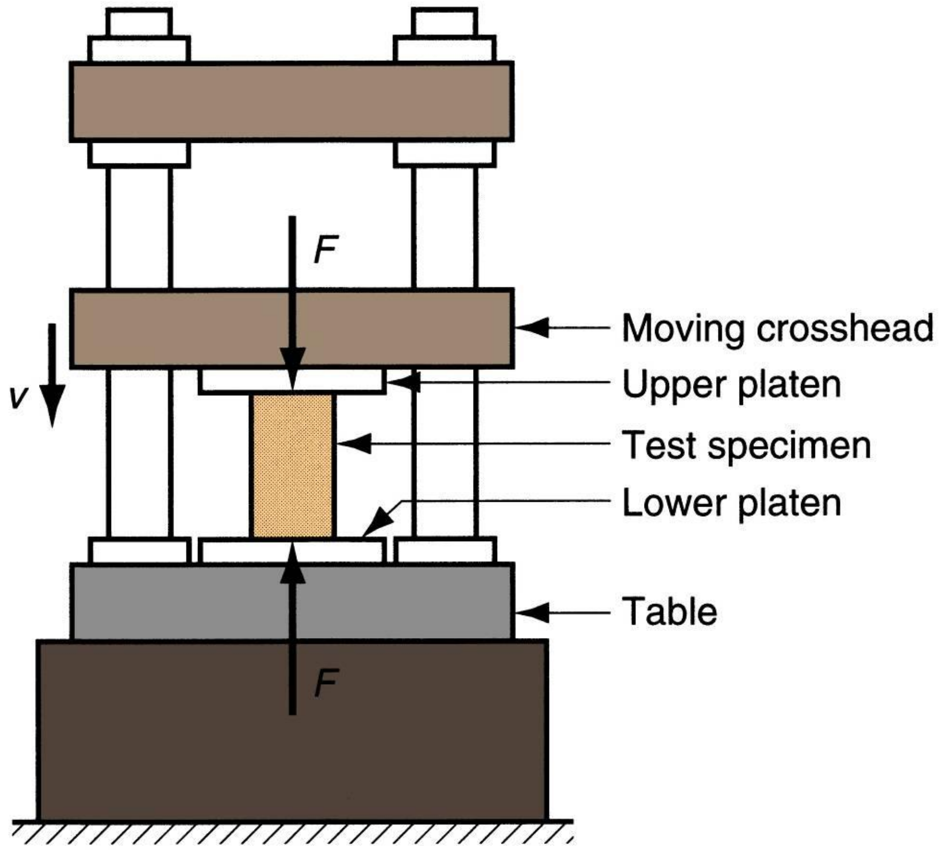


Figure 3.7 Compression test:

(a) compression force applied to test piece in (1) and (2) resulting change in height.

Compression Test Setup



(b)

Engineering Stress in Compression

As the specimen is compressed, its height is reduced and cross-sectional area is increased

$$\sigma_e = -\frac{F}{A_o}$$

where A_o = original area of the specimen

Engineering Strain in Compression

Engineering strain is defined

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

Since height is reduced during compression, value of *e* is negative (the negative sign is usually ignored when expressing compression strain)

Stress-Strain Curve in Compression

- Shape of plastic region is different from tensile test because cross section increases
- Calculated value of engineering stress is higher

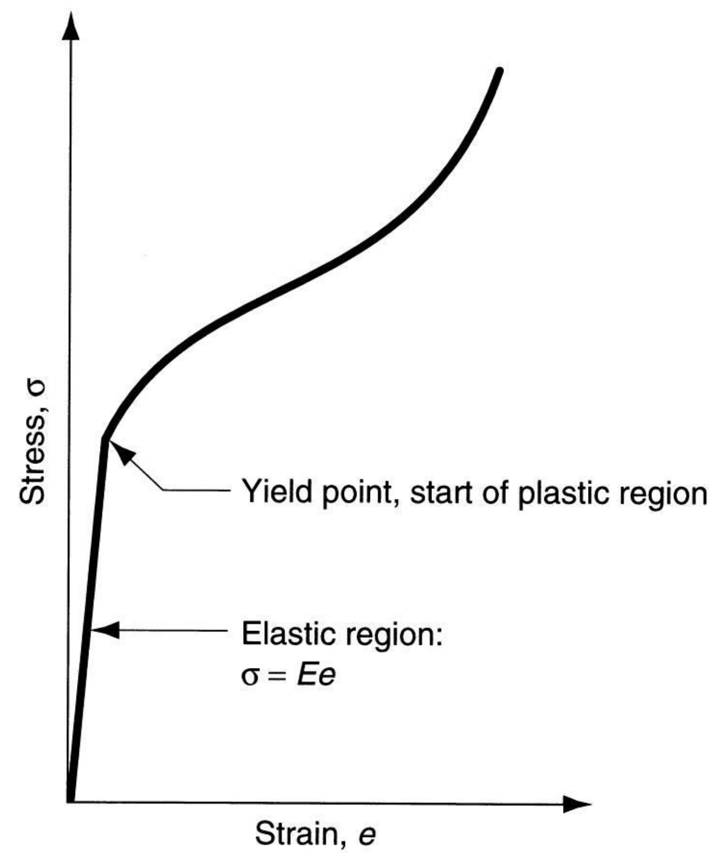


Figure 3.8 Typical engineering stress-strain curve for a compression test.

Tensile Test vs. Compression Test

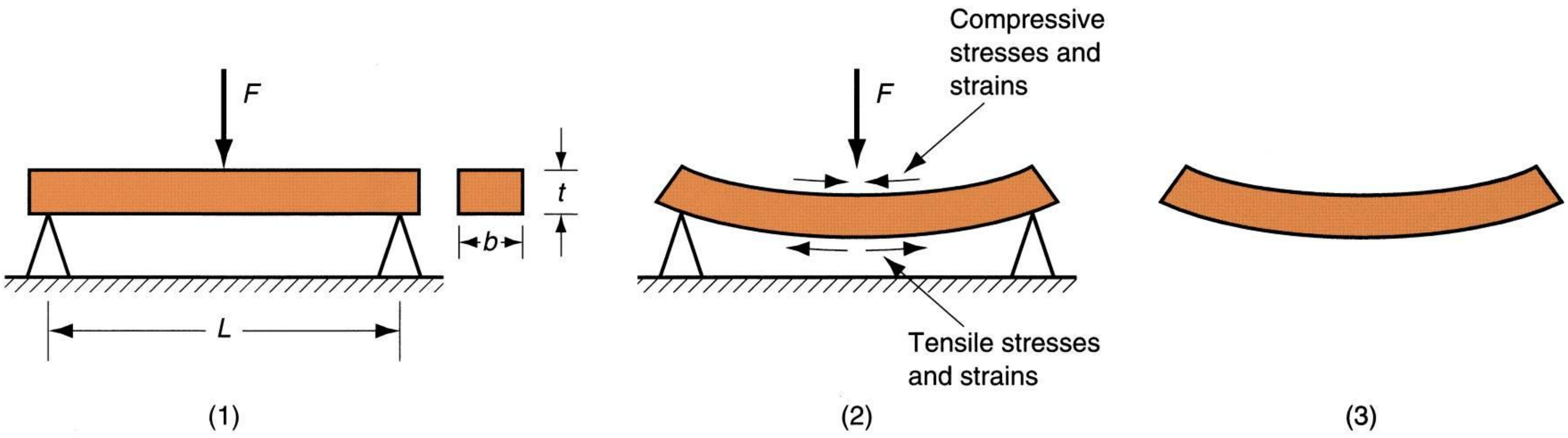
- Although differences exist between engineering stress-strain curves in tension and compression, the true stress-strain relationships are nearly identical
- Since tensile test results are more common, flow curve values (*K* and *n*) from tensile test data can be applied to compression operations
- When using tensile *K* and *n* data for compression, ignore necking, which is a phenomenon peculiar to straining induced by tensile stresses

Testing of Brittle Materials

- Hard brittle materials (e.g., ceramics) possess elasticity but little or no plasticity
- Often tested by a *bending test* (also called *flexure test*)
  - Specimen of rectangular cross-section is positioned between two supports, and a load is applied at its center

Bending Test

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.



Testing of Brittle Materials

- 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

Shear Properties

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

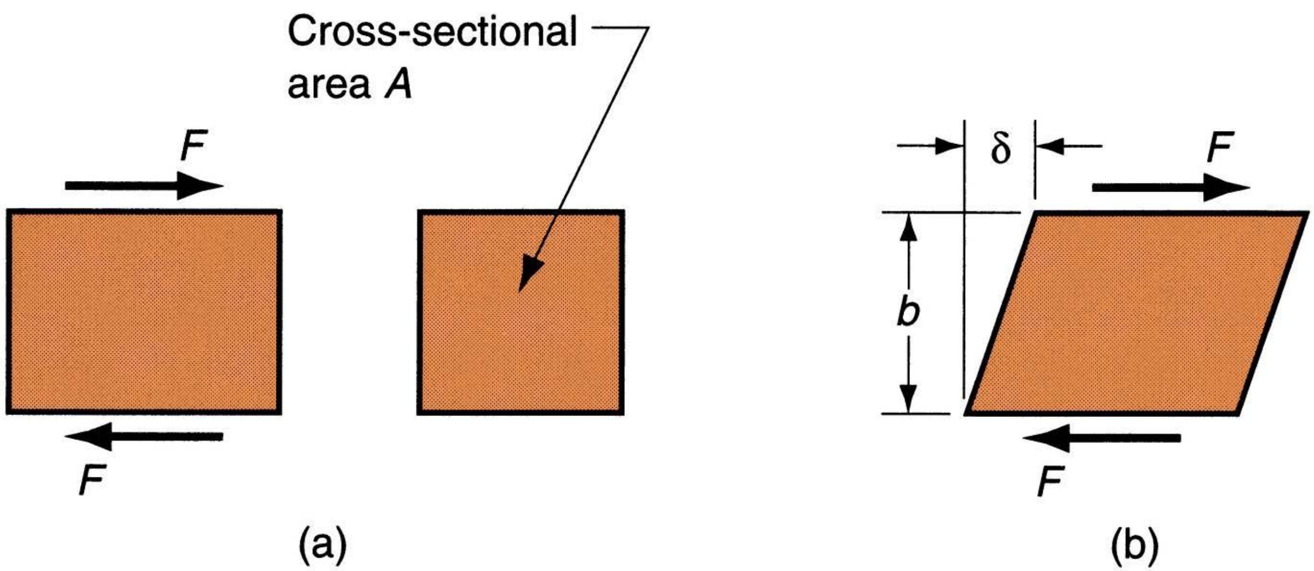


Figure 3.11 Shear (a) stress and (b) strain.

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

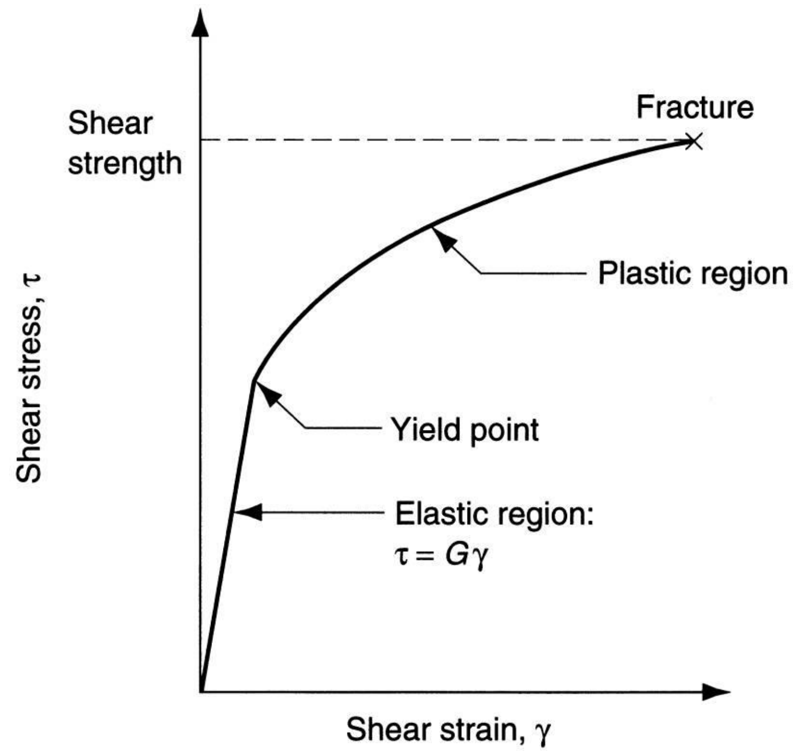


Figure 3.13 Typical shear stress-strain curve from a torsion test.

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 $\cong$ true stress-strain curve

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

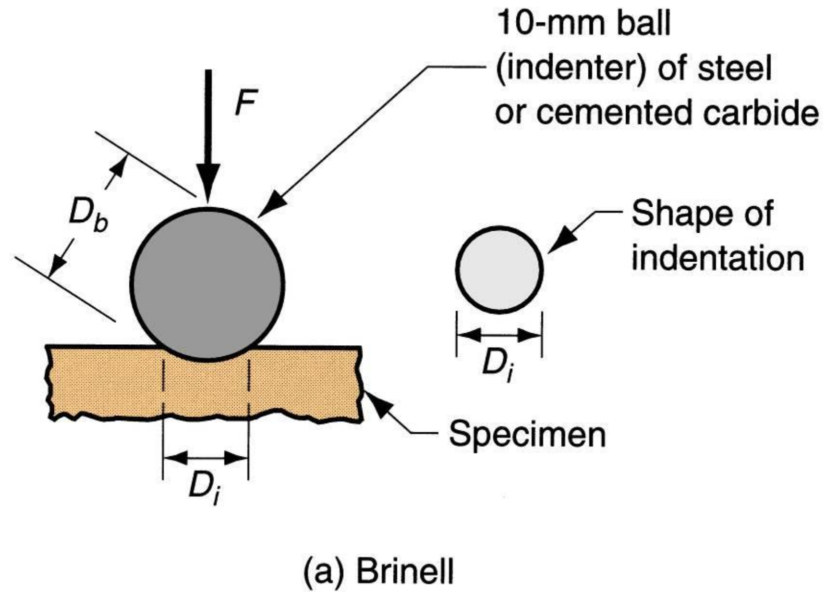


Figure 3.14 Hardness testing methods: (a) Brinell

Brinell Hardness Number

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

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

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

Rockwell Hardness Test

- 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

Rockwell Hardness Test

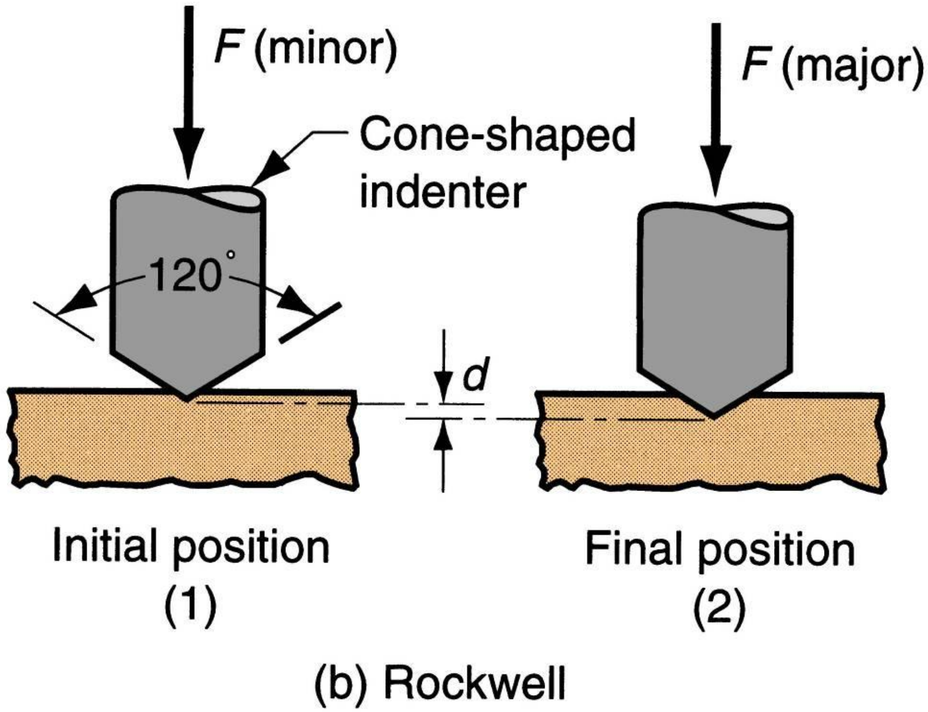


Figure 3.14 Hardness testing methods: (b) Rockwell: (1) initial minor load and (2) major load.

Effect of Temperature on Properties

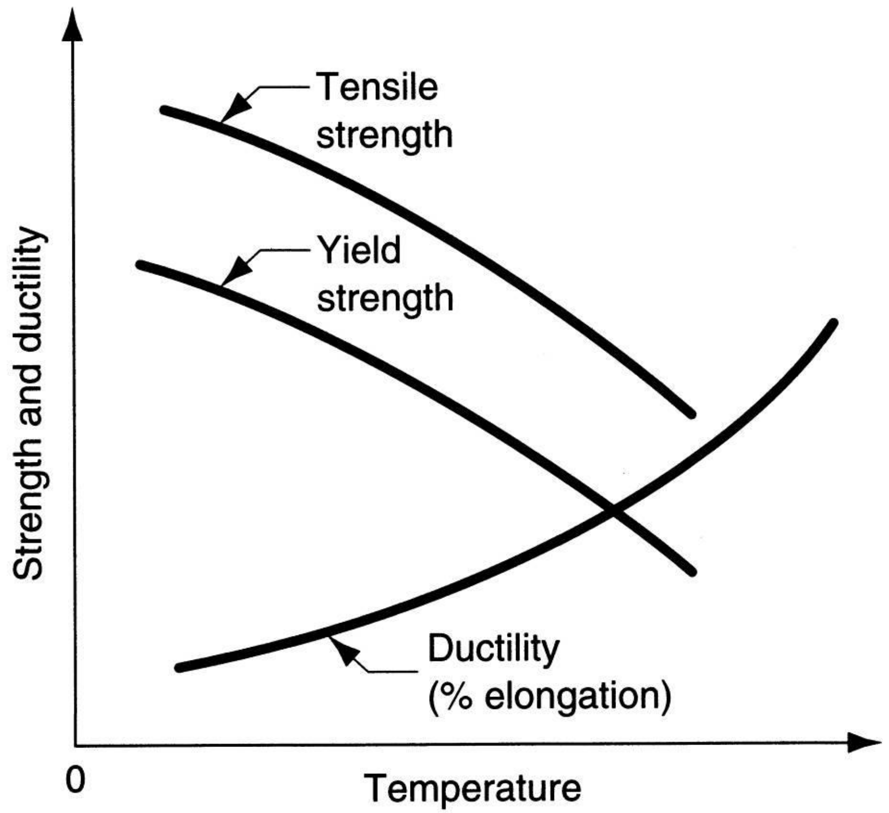


Figure 3.15 General effect of temperature on strength and ductility.

Hot Hardness

Ability of a material to retain hardness at elevated temperatures

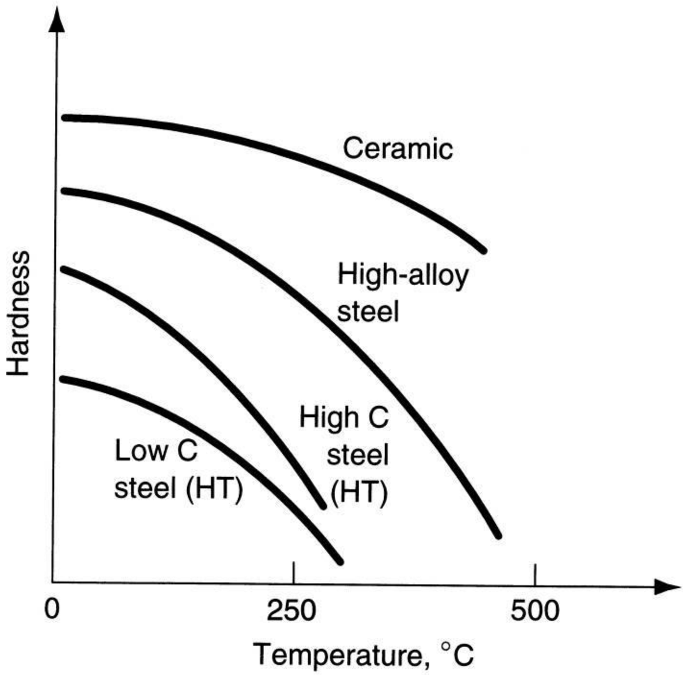


Figure 3.16 Hot hardness - typical hardness as a function of temperature for several materials.

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 one hour

Recrystallization and Manufacturing

- Recrystallization can be exploited in 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

- 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

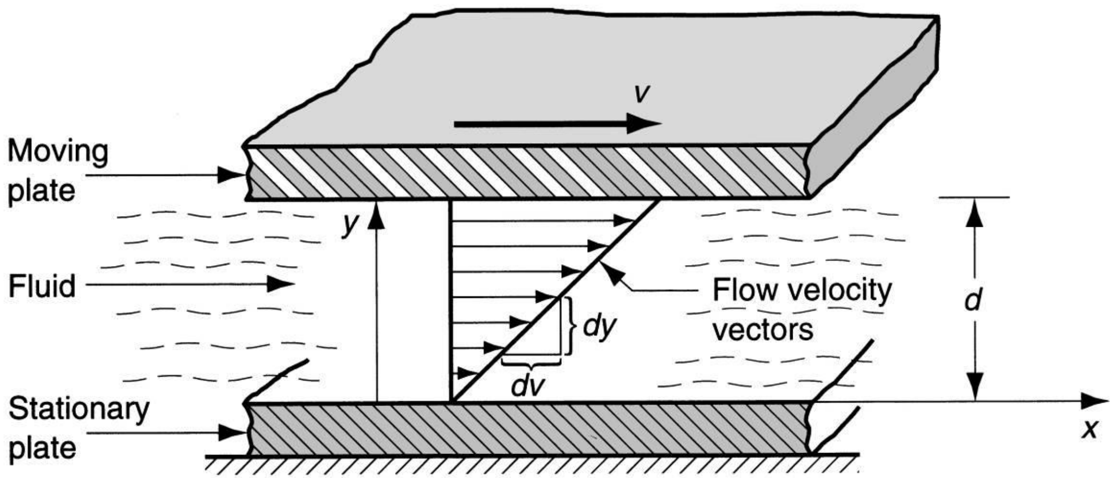


Figure 3.17 Fluid flow between two parallel plates, one stationary and the other moving at velocity *v*

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*

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

where $\dot{\gamma}$ = shear rate, 1/s; *dv* = change in velocity, m/s; and *dy* = change in distance *y*, m

Shear rate = velocity gradient perpendicular to flow direction

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

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, coefficient of viscosity can be expressed:

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

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

Viscosity of Polymers and Flow Rate

- Viscosity of 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

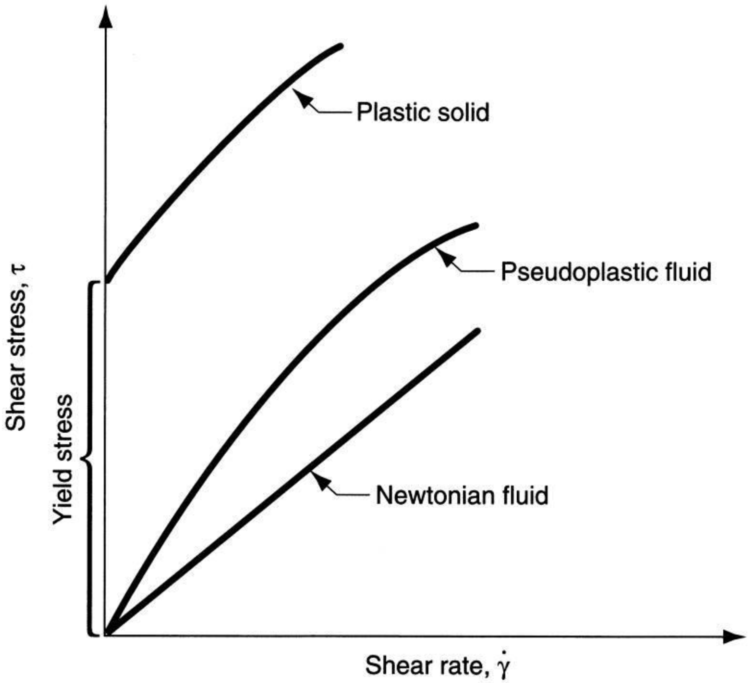


Figure 3.18 Viscous behaviors of Newtonian and pseudoplastic fluids. Polymer melts exhibit pseudoplastic behavior. For comparison, the behavior of a plastic solid material is shown.

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

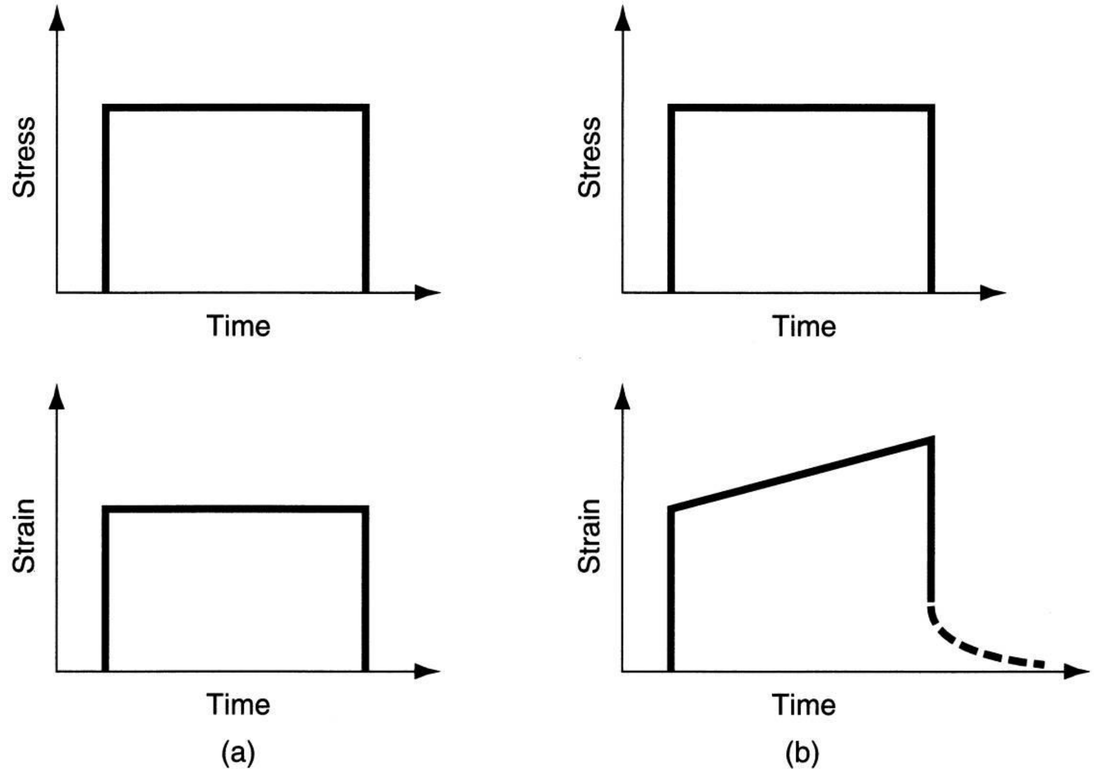


Figure 3.19 (a) perfectly elastic response of material to stress applied over time; and (b) response of a viscoelastic material under same conditions. The material in (b) takes a strain that is a function of time and temperature.

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