

Engineering Materials and their Properties



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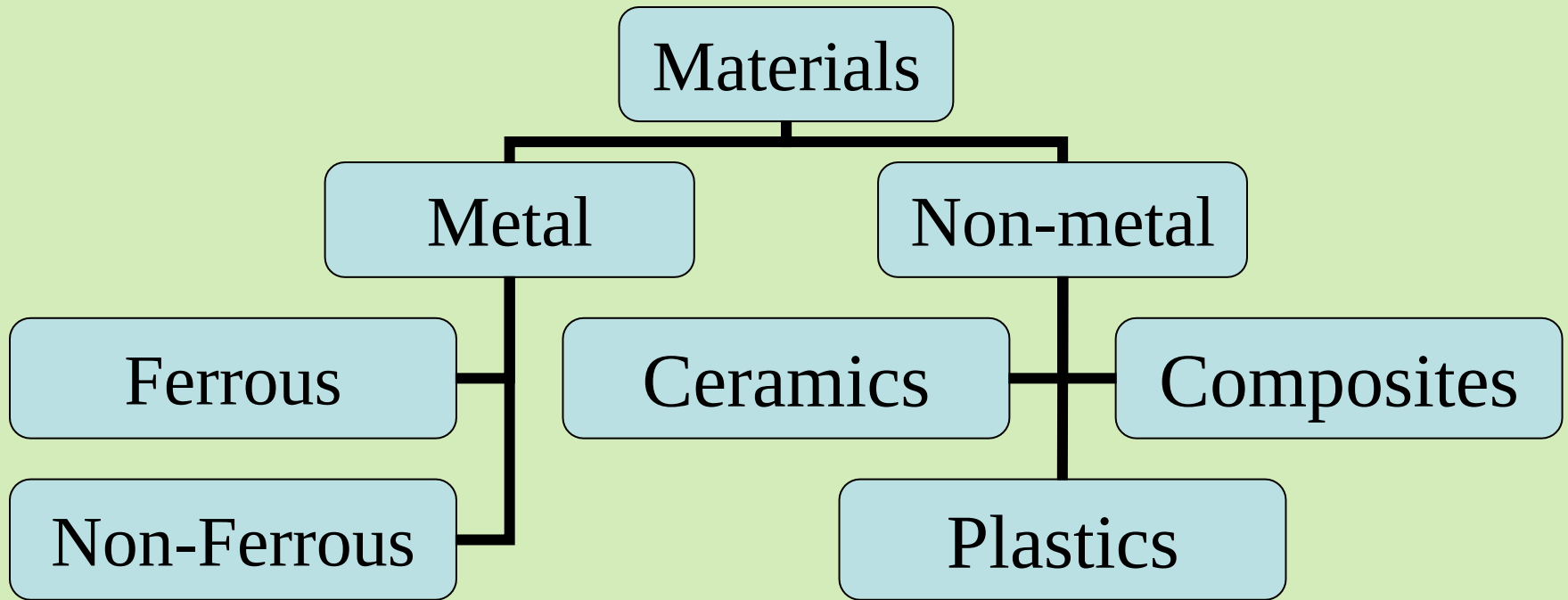
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Ferrous Metals

Cast Iron

Manufacture

- Product that comes out of the BF is Pig Iron
 - Composition: 3-4 % C, 1.5-2.5 % Mn , 1-3 % Si + S and P
- When it is cast directly it is called Cast Iron

Properties

- Good in compression, bad in tension
- Brittle

- Good corrosion resistance
 - Corrodes readily under atmospheric conditions, then protective film will form
 - Used in water pipes.
- Good vibration damping capacity
 - More than 100 times better than steel and 2000 times better than Al
 - Fatigue resistant
- Machinability: Good to bad

Usage

Engine blocks

Machine frames

Steels

Manufacture

- Formed by reducing C , Si , Mn , P in pig iron

Classification

- Plain C steels
- Alloy steels

Plain C Steels

Classification

- Low C steel: $< 0.3\%$ C
- Medium C Steel: $0.3 - 0.8\%$ C
- High C Steel: $> 0.8\%$ C

Small amounts of other elements (0.4% Mn, 0.05% S, 0.04% P)

↑ C content ↑ hardness and ↓ ductility

- Lowest cost steels
- Form the major proportion of steel produced

Alloy Steels

Definition

- Alloy of iron and carbon containing high amount of alloying element other than elements in carbon steels.

Properties

- Gives better strength , ductility and toughness compared to plain carbon steels.

- Effect of alloying elements
 - Mn improves strength and hardness
 - Cr improves corrosion resistance, strength, wear resistance, hot hardness
 - Ni improves strength, toughness
 - Mo increases tensile and creep strength at high temperature

Types of alloy steels

- Stainless steel
 - Large family of steel containing at least 11.5 % Cr . Corrosion resistance due to formation of Cr_2O_3
 - Most stainless steels show good short time strength up to 1100°C compared to plain C steels, which lose their usefulness above 510°C .
 - Thermal conductivity of stainless steels are poor. Copper cladding is often used in cooking utensils for distributing heat.

- Tool steels
 - Contains elements such as C (0.8-1.3 %), Mn (0.2-1.6 %) , Cr , W , Va , Mo , Co .
 - A class of high C alloy steels that is both shock and wear resistant.
 - Withstand high temperatures.

- Steel for electrical and magnetic applications
 - Contains 0.5 – 5% Si.
 - Increases electrical conductivity and permeability.
 - Used in electric motors generators and transformers.
 - Reduces power loss associated heat problems .

Non-Ferrous Metals

Aluminium

- Predominantly used in aerospace industry (80.0% weight / commercial aircraft) in the form of Al/Al alloy
- Al has emerged as a valuable source of metal for the automobile industry .

Properties of Al/Al alloys

- High strength /weight ratio
- Ease of machining and forming
- Resistance to (i) atmospheric corrosion and (ii) attack by certain chemicals.
- High electrical conductivity.

Al-Li alloys

- Each % of Li (up to 4%) reduces weight by 3 % and increases stiffness by 6%
- Greater fatigue resistance
- Will reduce weight of commercial aircraft by 10-15%.

Titanium

- Properties between those of steel and Al.
- Strong, lightweight, corrosion resistance.
- Mechanical properties are retained up to 535°C.
- Problems with Ti:
 - Chemically very active in molten state, absorbing O₂ or N₂ from air with ruinous capacity.
 - Difficult and costly to produce.

High Temperature Metals/Alloys

- Jet engines, gas turbines, rocket and nuclear applications require materials
 - high strength,
 - creep resistance
 - corrosion resistance

at temperatures in excess of 1100°C .

- Future jet engine temperatures may be well above 1400°C

Superalloys

- Ni, Fe, Ti and Co form the base of these materials
 - Aerospace: Ti- based superalloys (Al, C, Mo, V)
 - Turbine blades are Ni-based (Fe, Cr)

Refractory Metals

- Nb (2470°C), Mo (2610°C), Tantalum (3000°C), W (3410°C).

Ceramics

- Compounds of metallic and non-metallic elements. Often in the form of oxides, carbides and nitrides

Characteristics

- Very high M.P ($>1500^{\circ}\text{C}$)
- Compressive strength can be 5 to 10 times of tensile strength.
- Very Brittle and lack of ductility. Some ceramics like SiC and SiN offer moderate toughness.

- E higher than steels. Very stiff and considerably harder .
 - Especially useful as wear-resistant parts and for abrasive (grinding wheel) and cutting tools (Co bonded WC).

Applications

- SiC and SiN work well in high-stress, high-temperature applications such as turbine blades.
 - May replace Ni or Co based superalloys
 - SiN is one-half the weight of stainless steel

- Sialon(Si-Al-O-N) : It is stronger than steel extremely hard and as light as aluminium
 - Good resistance to wear and thermal shock
 - Electrical insulator
 - Retains good tensile and compressive strength up to 1400°C
- Ceramics engine blocks
- Refractory materials in furnaces and high temperature reactors

- Heating elements for furnaces e.g. SiC
- Substitutes for joints/bones, dental implants.

SiAlONs are ceramics based on the elements silicon (Si), aluminium (Al), oxygen (O) and nitrogen (N). They are solid solutions of silicon nitride (Si_3N_4), where Si–N bonds are partly replaced with Al–N and Al–O bonds.

Composite Materials

- Heterogeneous solid consisting of two or more different materials that are mechanically or metallurgically bonded

Advantages

- Can combine conflicting properties such as ductility and strength/hardness, resulting in a new material with a unique combination of:
 - Low weight
 - Stiffness, strength and creep resistance

- Corrosion resistance
- Hardness
- Conductivity

Classification

- Laminar/layer composites
 - Plywood: layers of wood bonded together with their grain orientations at different angles
 - Improves strength and fracture resistance
 - Reduces swelling and shrinkage
 - Safety glasses(wind shield): Adhesive layer placed between two pieces of glass
 - Retains fragments when glass is broken

- Particulate Composites
 - Discrete particles of one material surrounded by matrix. Common example is concrete
 - Hard particles-soft matrix
 - Pronounced strengthening, better creep resistance, toughness

Examples

- Cemented carbides that are used as tools
 - WC, TaC, or TiC dispersed in a metal matrix, generally cobalt.
 - Hard, stiff carbides can withstand high cutting temperatures, but is extremely brittle
 - Toughness imparted by cobalt matrix

- Properties depend on
 - Size of the particles
 - Volume fraction of particles
 - Mechanical properties of particles and matrix
- Fibre Composites
 - Most popular composite
 - Matrix provides ductility and toughness
 - Fibre carries the load
 - Graphite and kevlar most popular fibres
 - Kevlar: Low ρ (1/2 of Al), High UTS (4 -5 times that of steel, Al)
 - Glass fibres most widely used in polymers

- SiC and Al_2O_3 main fibre materials for ceramics
- Polymeric matrix used for low temperature (< 300°C) applications
- Metal matrix used for high temperature applications

Examples

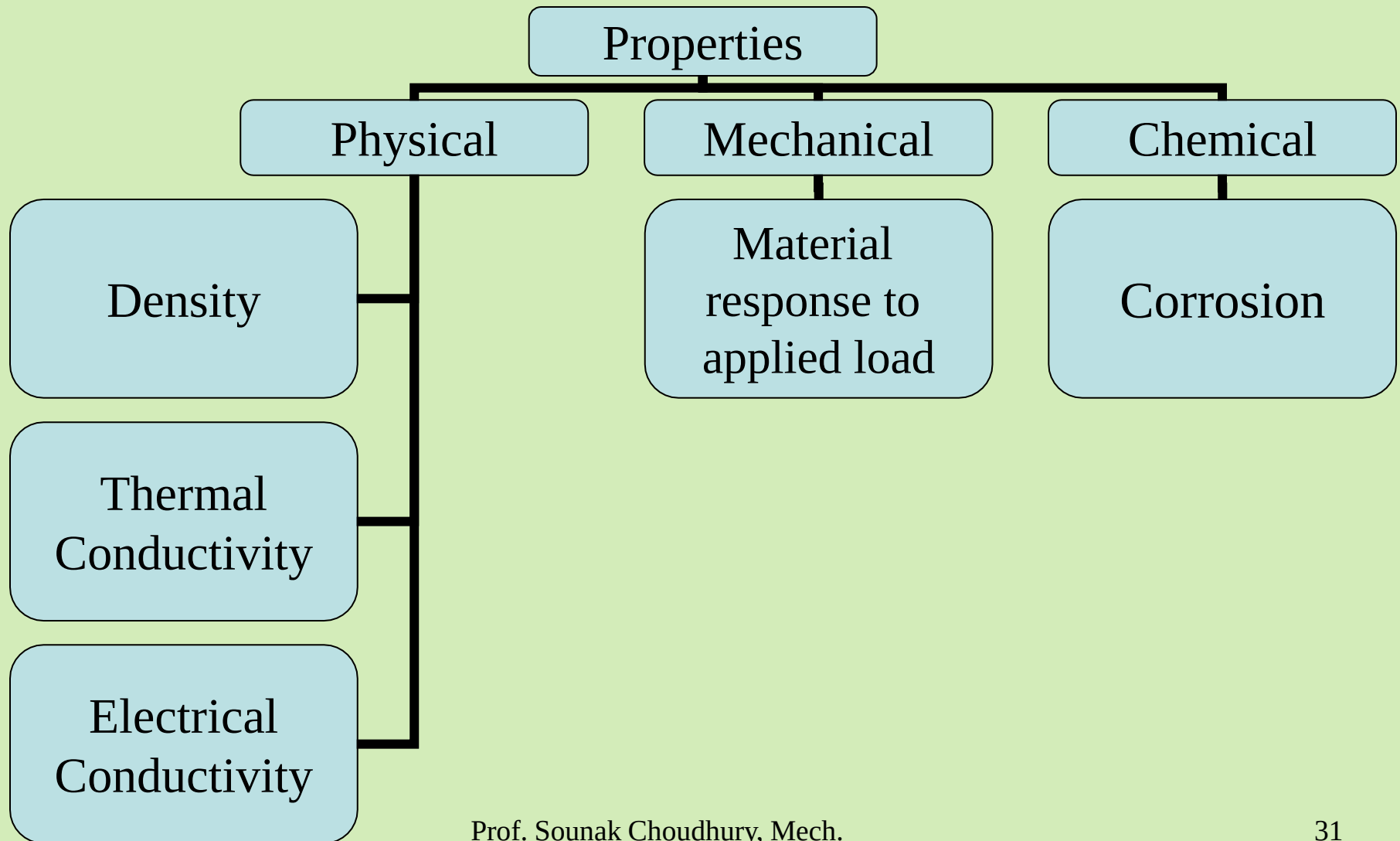
- Steel-reinforced concrete
- Nylon-reinforced tyres
- Glass fibre-reinforced plastics for car bodies, furnitures
- Boron-reinforced aluminium composites for aircraft and rocket components

- Sporting equipment such as tennis rackets, skis, fishing rods

Properties depend on

- Properties of fibres
- Volume fraction of fibres
- Aspect ratio of fibres
- Orientation of fibres
- Degree of bonding between matrix and fibres
- Properties of matrix

Properties of Materials



Properties

Ductility

- Ability of a material to be deformed plastically without fracture.
- Elongation up to the point of necking (uniform elongation) is taken as a measure of ductility.
- Useful in metal forming operations.

Brittleness

- Opposite of ductility
- Fracture and yield points similar
- Indicates lack of significant plasticity, but not strength
- Yield strength can be very high

Toughness

- Ability of a material to absorb energy in the plastic range without fracturing.
- Sustains shock loading.
- Area under the stress – strain curve is a measure of toughness.
- Desired in parts such as railways tracks, train couplings, gears, crane hooks, cutting tools.

Hardness

- Resistance to indentation
- In general implies resistance to plastic deformation
- High hardness implies higher yield strength
- Two popular scales: Rockwell, Brinell
 - New Rado watch: VHN10000, can only be scratched by high purity diamond, Rs. 1.93 lakhs.
- Used in cutting tools

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

Engineering Stress

Defined as force divided by original area:

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

where σ_e = engineering stress [MPa],

F = applied force [N], and

A_o = original area of test specimen [mm²]

Engineering Strain

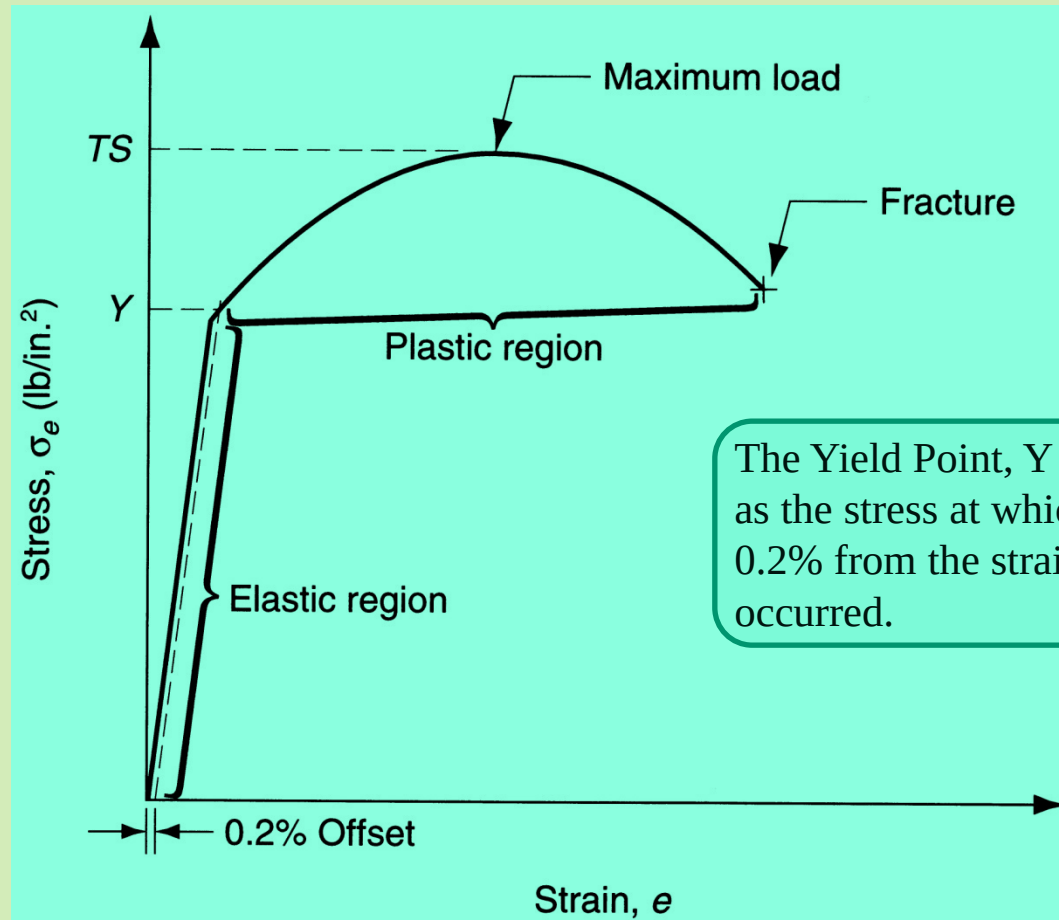
Defined at any point in the test as

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

where e = engineering strain [mm/mm];

L = length at any point during elongation [mm]; and

L_o = original gauge length [mm]



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

Elastic Region in Stress-Strain Curve

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

The Stress-Strain relationship in the elastic region is defined by:

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

where $E = \text{modulus of elasticity [MPa]}$

- 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* or *ultimate tensile strength* of the material

$$TS = \frac{F_{\max}}{A_0}$$

TABLE 3.1 Elastic modulus for selected materials.

Metals	Modulus of Elasticity		Ceramics and polymers	Modulus of Elasticity	
	MPa	lb/in ²		MPa	lb/in ²
Aluminum and alloys	69×10^3	10×10^6	Alumina	345×10^3	50×10^6
Cast iron	138×10^3	20×10^6	Diamond ^a	1035×10^3	150×10^6
Copper and alloys	110×10^3	16×10^6	Plate glass	69×10^3	10×10^6
Iron	209×10^3	30×10^6	Silicon carbide	448×10^3	65×10^6
Lead	21×10^3	3×10^6	Tungsten carbide	552×10^3	80×10^6
Magnesium	48×10^3	7×10^6	Nylon	3.0×10^3	0.40×10^6
Nickel	209×10^3	30×10^6	Phenol formaldehyde	7.0×10^3	1.00×10^6
Steel	209×10^3	30×10^6	Polyethylene (low density)	0.2×10^3	0.03×10^6
Titanium	117×10^3	17×10^6	Polyethylene (high density)	0.7×10^3	0.10×10^6
Tungsten	407×10^3	59×10^6	Polystyrene	3.0×10^3	0.40×10^6

TABLE 3.2 Yield strength and tensile strength for selected metals.

Metal	Yield Strength		Tensile Strength		Metal	Yield Strength		Tensile Strength	
	MPa	lb/in ²	MPa	lb/in ²		MPa	lb/in ²	MPa	lb/in ²
Aluminum, annealed	28	4,000	69	10,000	Nickel, annealed	150	22,000	450	65,000
Aluminum, CW ^a	105	15,000	125	18,000	Steel, low C ^a	175	25,000	300	45,000
Aluminum alloys ^a	175	25,000	350	50,000	Steel, high C ^a	400	60,000	600	90,000
Cast iron ^a	275	40,000	275	40,000	Steel, alloy ^a	500	75,000	700	100,000
Copper, annealed	70	10,000	205	30,000	Steel, stainless ^a	275	40,000	650	95,000
Copper alloys ^a	205	30,000	410	60,000	Titanium, pure	350	50,000	515	75,000
Magnesium alloys ^a	175	25,000	275	40,000	Titanium alloy	800	120,000	900	130,000

Ductility in Tensile Test

Ability of a material to plastically strain without fracture

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

where EL = elongation, in percent;

L_f = specimen length at fracture [mm]; and

L_o = original specimen length [mm]

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

Ductility of Various Engineering Materials

TABLE 3.3 Ductility as % elongation (typical values) for various selected materials.

Material	Elongation	Material	Elongation
<i>Metals</i>		<i>Metals, continued</i>	
Aluminum, annealed	40%	Steel, low C ^a	30%
Aluminum, cold worked	8%	Steel, high C ^a	10%
Aluminum alloys, annealed ^a	20%	Steel, alloy ^a	20%
Aluminum alloys, heat treated ^a	8%	Steel, stainless, austenitic ^a	55%
Aluminum alloys, cast ^a	4%	Titanium, nearly pure	20%
Cast iron, gray ^a	0.6%	Zinc alloy	10%
Copper, annealed	45%	<i>Ceramics</i>	0 ^b
Copper, cold worked	10%	<i>Polymers</i>	
Copper alloy: brass, annealed	60%	Thermoplastic polymers	100%
Magnesium alloys ^a	10%	Thermosetting polymers	1%
Nickel, annealed	45%	Elastomers (e.g., rubber)	1% ^c

True Stress

Stress value obtained by dividing the instantaneous area into applied load

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

where σ = true stress [MPa];

F = force [N]; and

A = actual (instantaneous) area resisting the load [mm²]

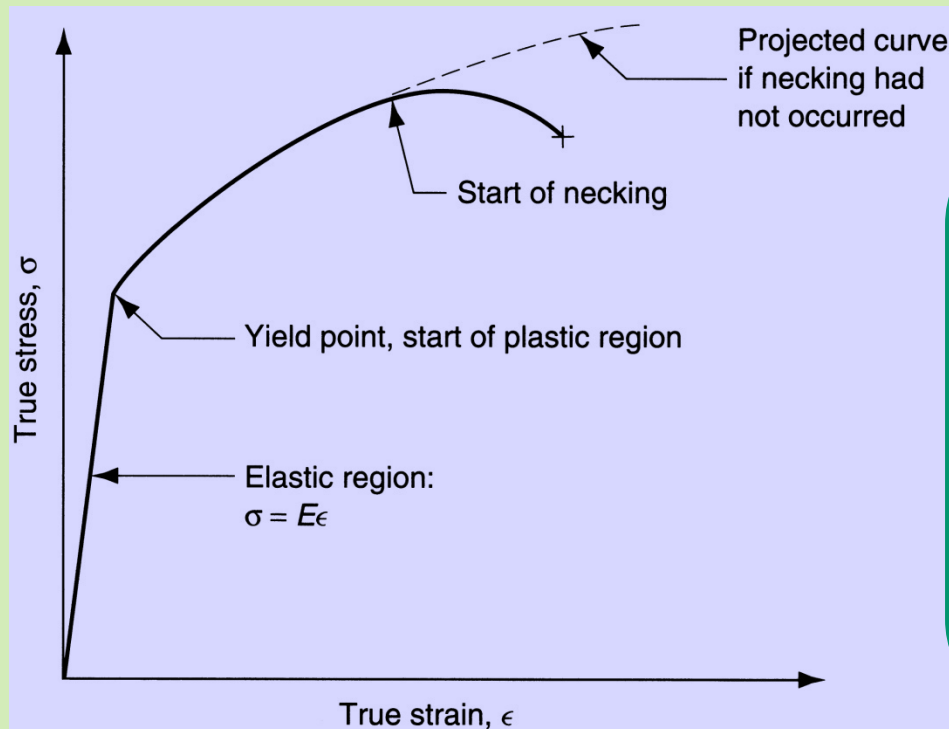
True Strain

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

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

Logarithmic strains are additive in sequential processes, which is not true of linear strains. A bar is strained from L_0 to L_1 , then the true strain, $e_1 = \ln(L_1/L_0)$. If the bar is further extended to L_2 , the strain will be $e_2 = \ln(L_2/L_1)$. The total strain is then, $e = e_1 + e_2 = \ln(L_1/L_0) + \ln(L_2/L_1) = \ln(L_2/L_0)$.

If previous engineering stress-strain curve were plotted using true stress and strain values



In the elastic region, there is almost no change. Strain values are small, and true strain is nearly equal to Engineering Strain. The reason is that the cross sectional area of the test specimen is not significantly reduced in the elastic region.

True stress-strain curve for the previous engineering stress-strain plot

Difference between true stress-strain and Engineering curves

- The difference between the true stress-strain curve and its Engineering counterpart lies in the plastic region. The stress values are higher in the plastic region because the instantaneous cross-sectional area of the specimen, which has been continuously reduced during elongation, is now used in the computation.

As strain becomes significant in the plastic region, the values of true strain and engineering strain diverge. True strain can be related to the corresponding engineering strain by

$$\epsilon = \ln(1 + e) \quad (3.8)$$

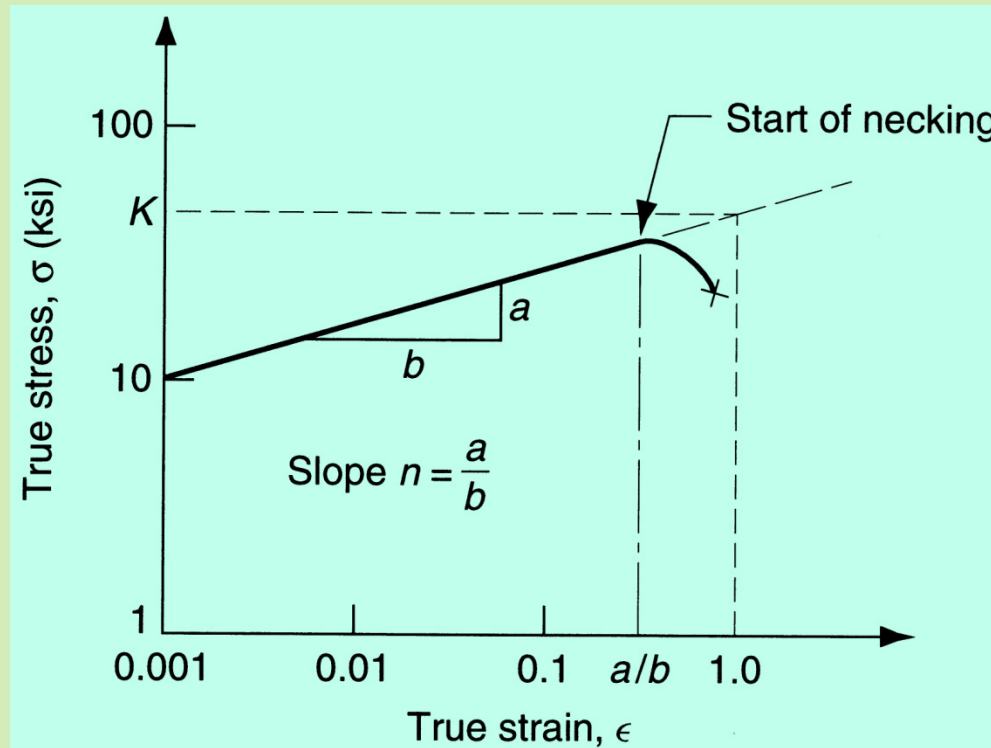
Similarly, true stress and engineering stress can be related by the expression

$$\sigma = \sigma_e(1 + e) \quad (3.9)$$

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
- What it means is that the metal is becoming stronger as strain increases
 - This is the property called *strain hardening*
(*material being able to withstand the increased load despite the uniform reduction in the cross-sectional area*)

When the plastic region of the true stress-strain curve is plotted on a log-log scale, it becomes linear



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 [MPa]*; and n = *strain hardening exponent*

K equals the value of true stress at a true strain value equal to one.

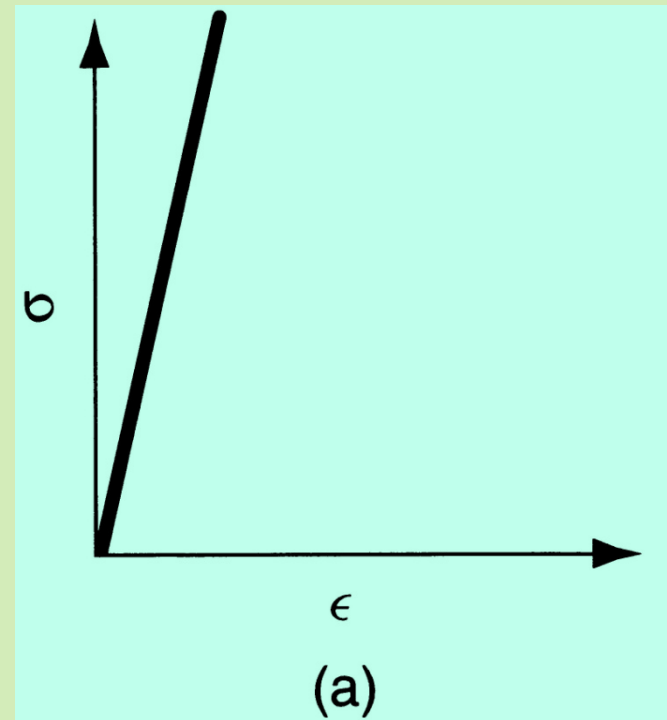
Categories of Stress-Strain Relationship

1. Perfectly elastic
2. Elastic and perfectly plastic
3. Elastic and strain hardening

Perfectly Elastic

Behavior is defined completely by modulus of elasticity E

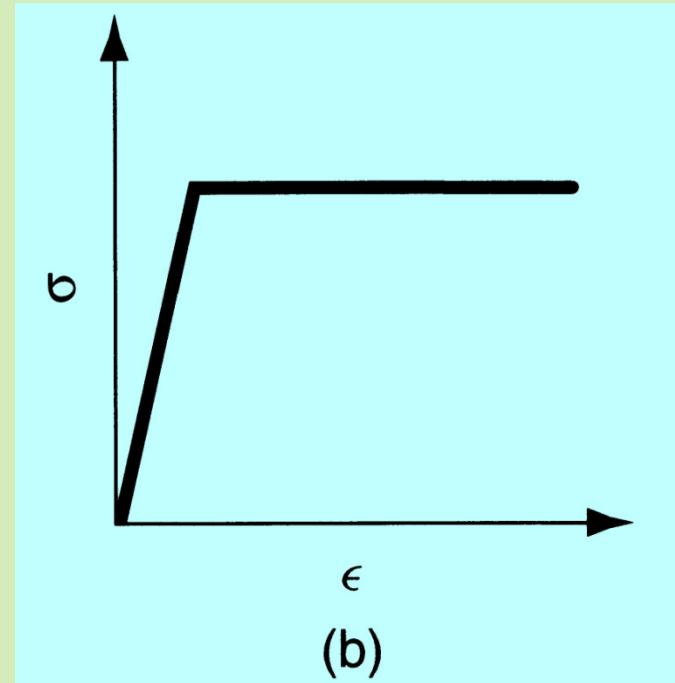
- It fractures rather than yielding to plastic flow
- Brittle materials: ceramics, many cast irons, and thermosetting polymers



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

Elastic and Perfectly Plastic

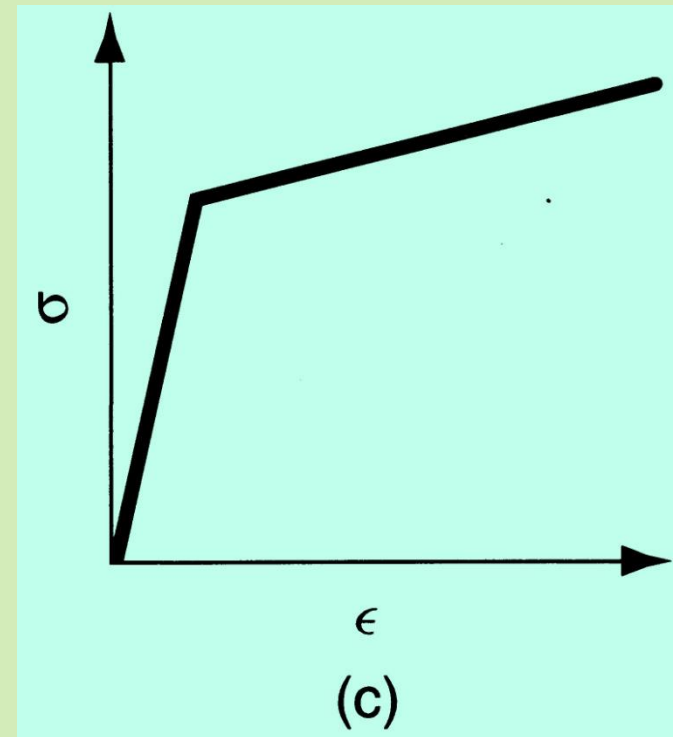
- Stiffness defined by E
- Once Y reached, deforms plastically at same stress level
- Flow curve: $K = Y, n = 0$
- Metals behave like this when heated to sufficiently high temperatures (above recrystallization)



(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



(c) elastic and strain hardening

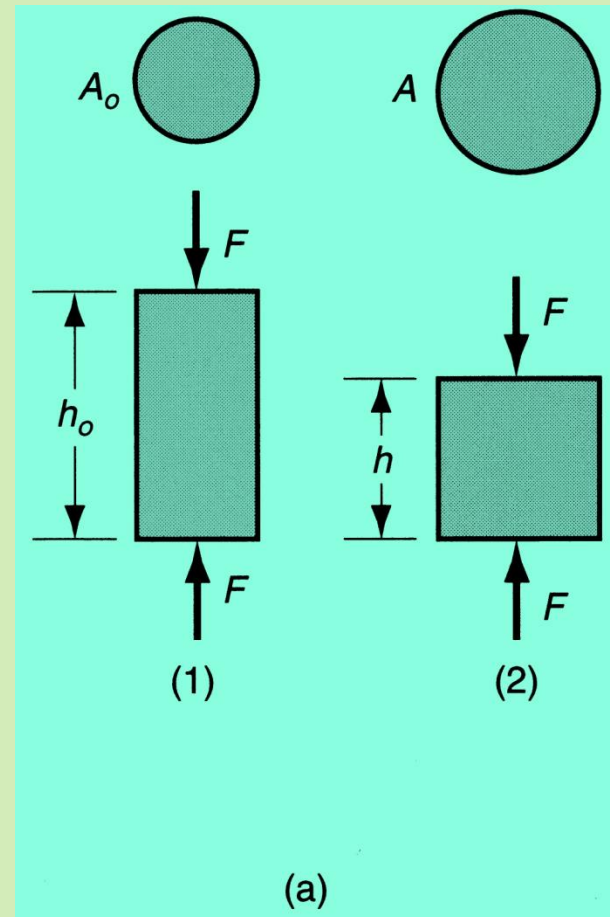
Typical values of 'K' and 'n'

TABLE 3.4 Typical values of strength coefficient K and strain hardening exponent n for selected metals.

Material	Strength Coefficient, K		Strain Hardening Exponent, n
	MPa	lb/in ²	
Aluminum, pure, annealed	175	25,000	0.20
Aluminum alloy, annealed ^a	240	35,000	0.15
Aluminum alloy, heat treated	400	60,000	0.10
Copper, pure, annealed	300	45,000	0.50
Copper alloy: brass ^a	700	100,000	0.35
Steel, low C, annealed ^a	500	75,000	0.25
Steel, high C, annealed ^a	850	125,000	0.15
Steel, alloy, annealed ^a	700	100,000	0.15
Steel, stainless, austenitic, annealed	1200	175,000	0.40

Compression Test

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



Compression test:

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

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

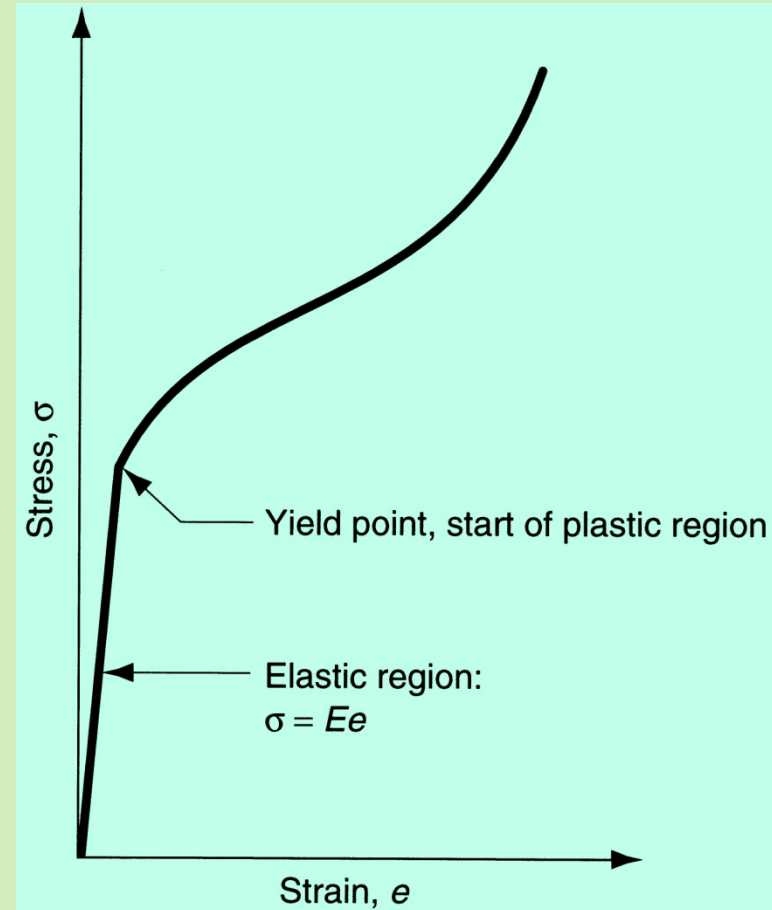
Engineering Strain in Compression

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)

- Shape of plastic region is different from tensile test because cross-section increases
- Since the load increases more rapidly than previously, the calculated value of engineering stress is higher



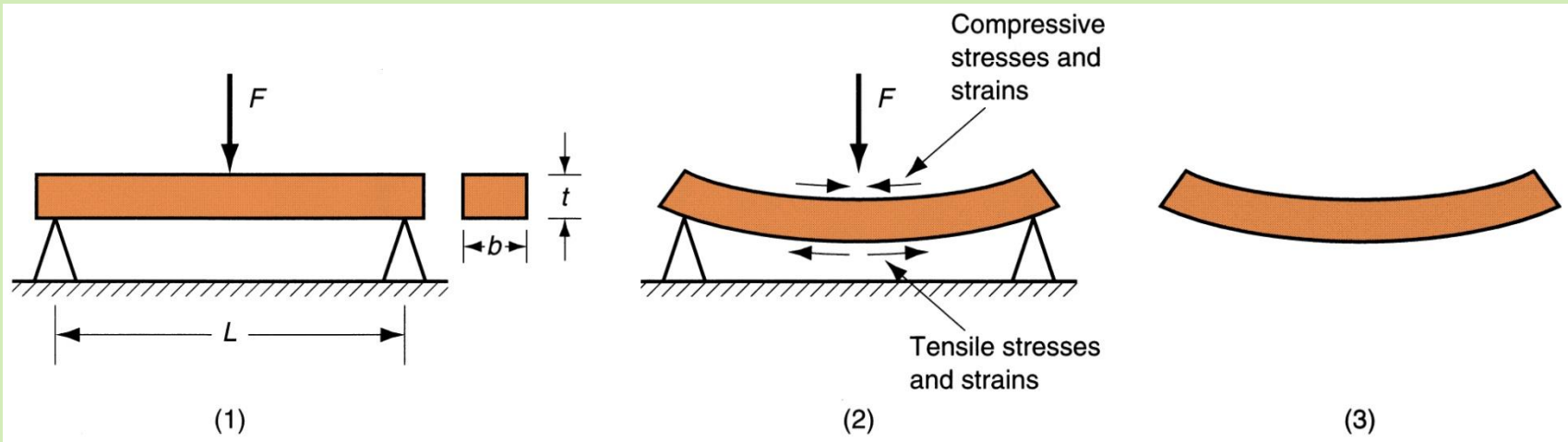
Typical engineering stress-strain curve for a compression test

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 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

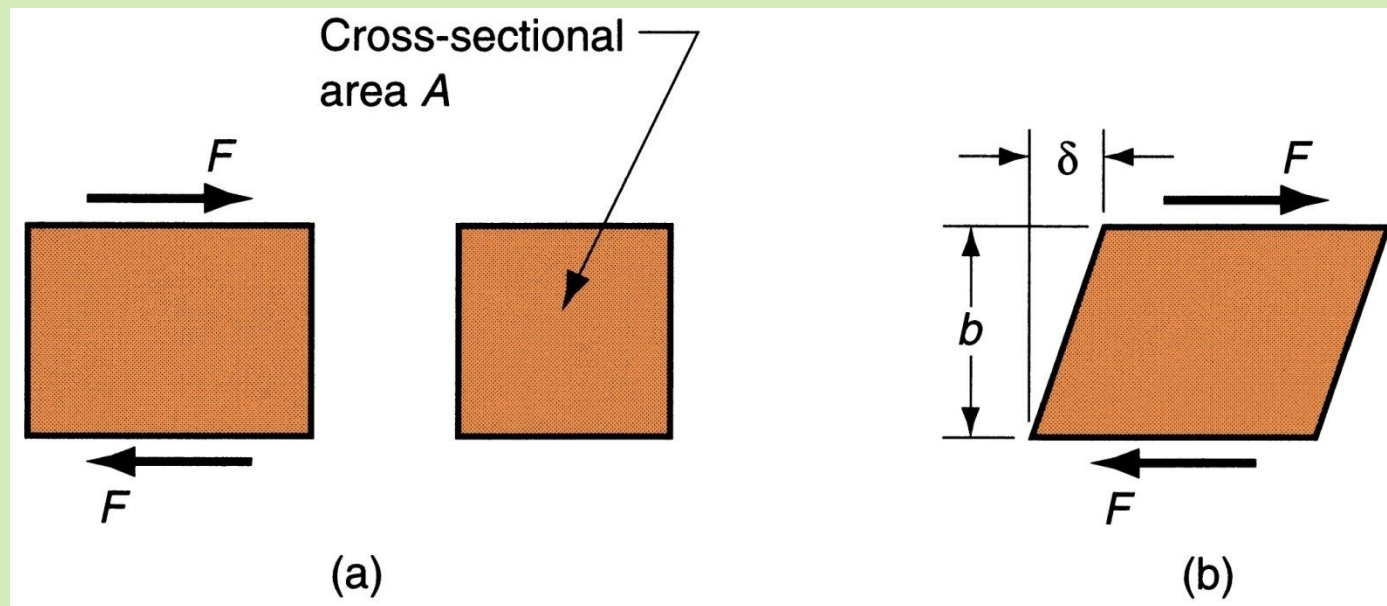
The strength value derived from the bending test:

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

where TRS = transverse rupture strength [MPa]; F = applied load at fracture [N]; L = length of specimen between supports [mm]; and b and t are dimensions of cross-section [mm]

Shear Properties

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



Shear (a) stress and (b) strain

Shear Stress and Strain

Shear stress defined as

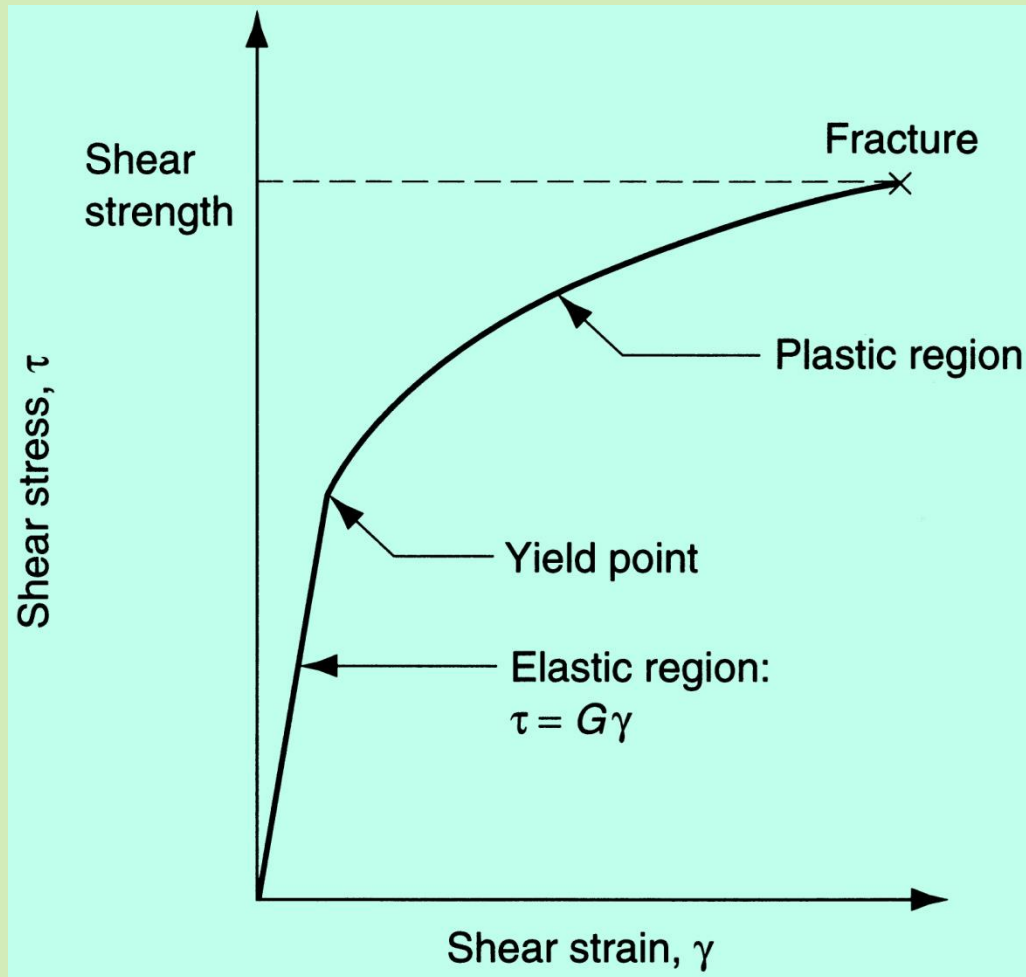
$$\tau = \frac{F}{A}$$

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

Shear strain defined as

$$\gamma = \frac{\delta}{b}$$

where δ = deflection of the element; and
 b = distance over which deflection occurs



In the plastic region, the material strain hardens to cause the applied torque to continue to increase until fracture occurs

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
- 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

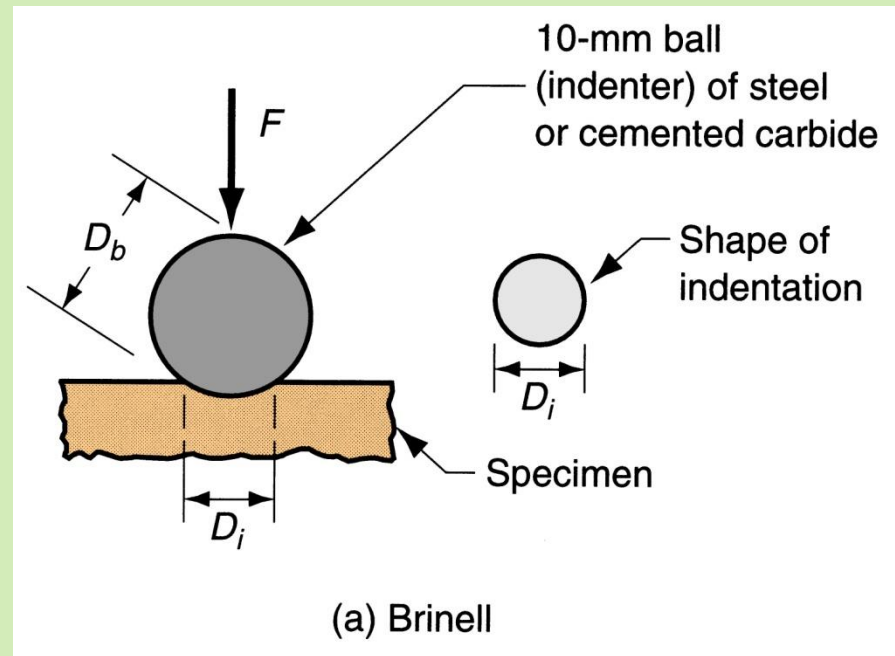
Hardness Tests

- 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

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



Hardness testing methods: (a) Brinell

Brinell Hardness Number

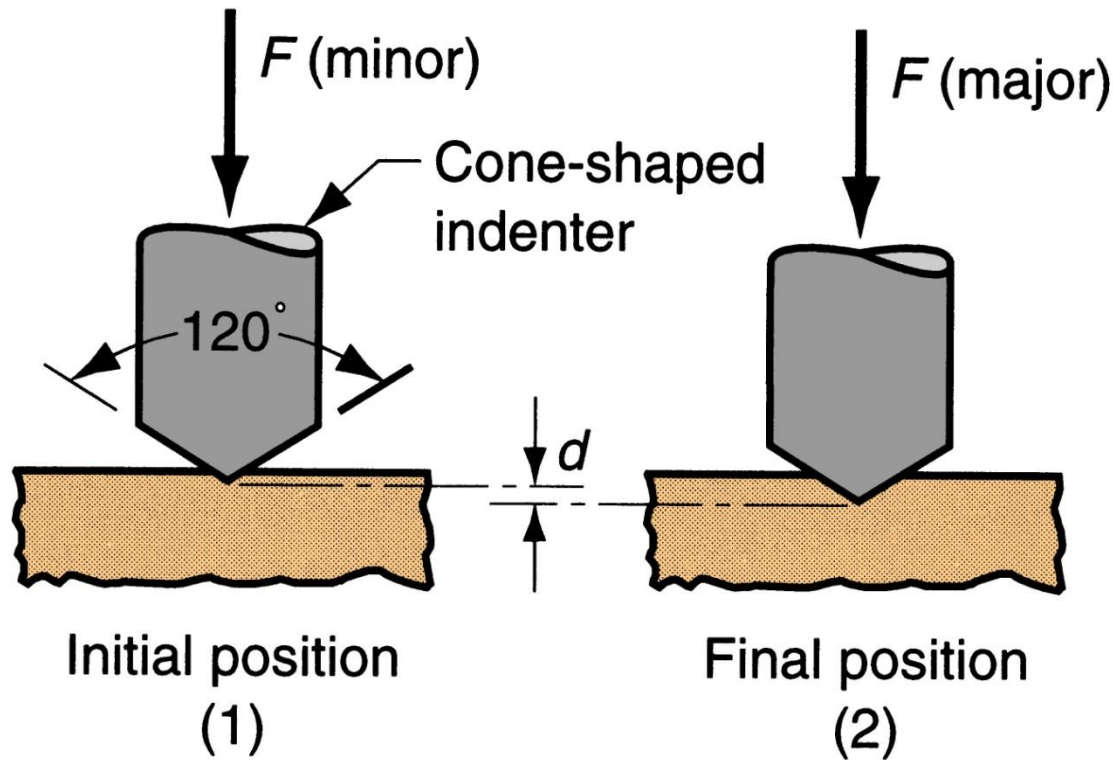
Load divided into indentation area = Brinell Hardness Number (BHN)

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

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

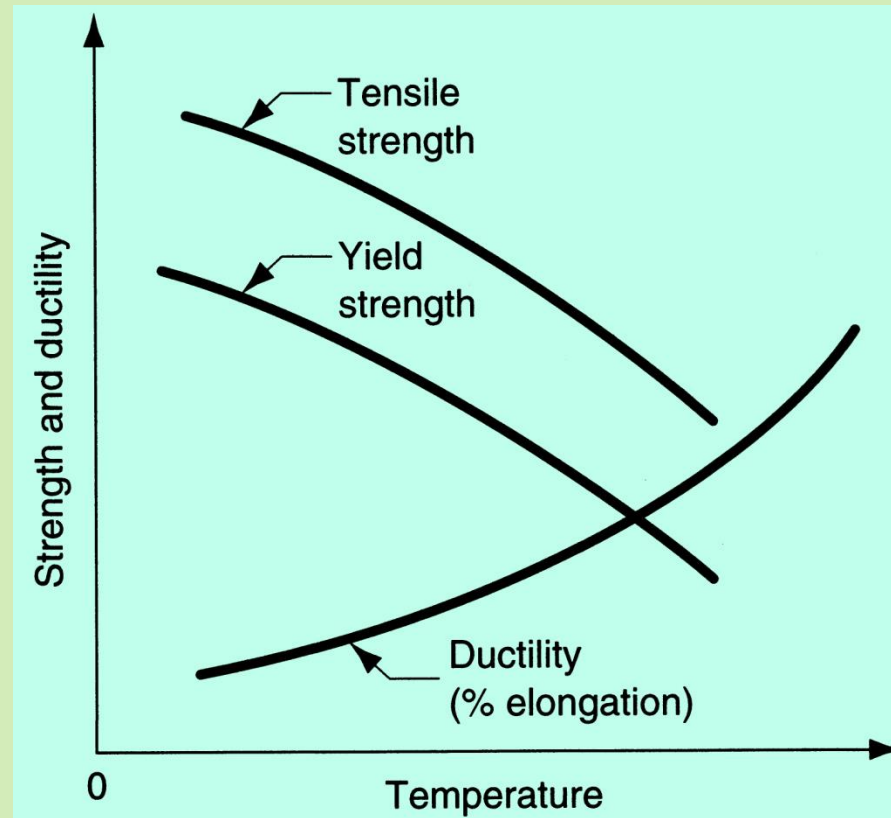
- Another widely used test
- A cone shaped indenter is pressed into specimen using a minor load of 10 kg, thus seating indenter in material
- Then, a major load of 150 kg is applied, causing indenter to penetrate beyond its initial position
- Additional penetration distance d is converted into a Rockwell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



(b) Rockwell

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

Effect of Temperature on Properties

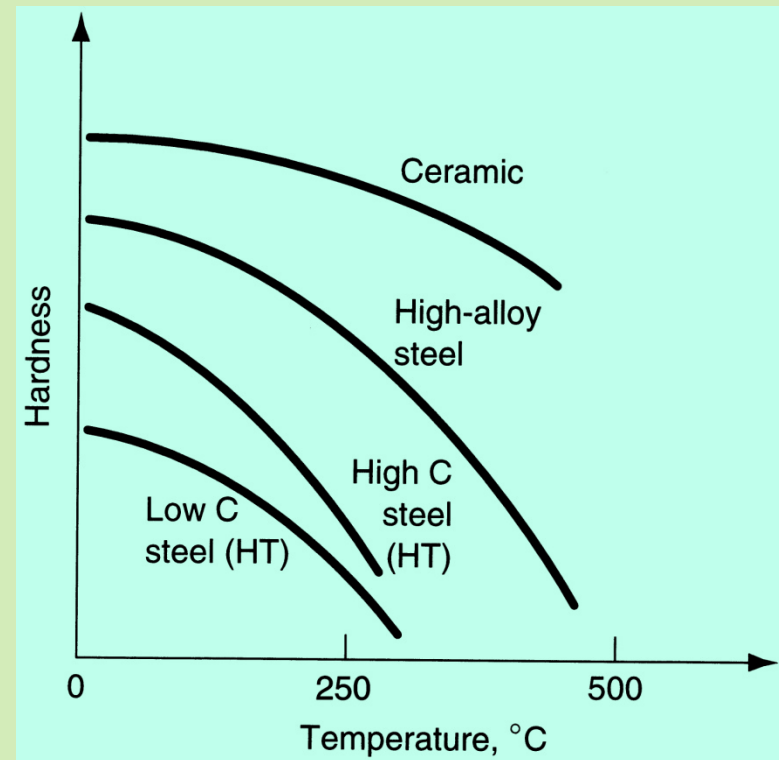


General effect of temperature on strength and ductility

Hot Hardness

Ability of a material to retain hardness at elevated temperatures

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 to endure 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*

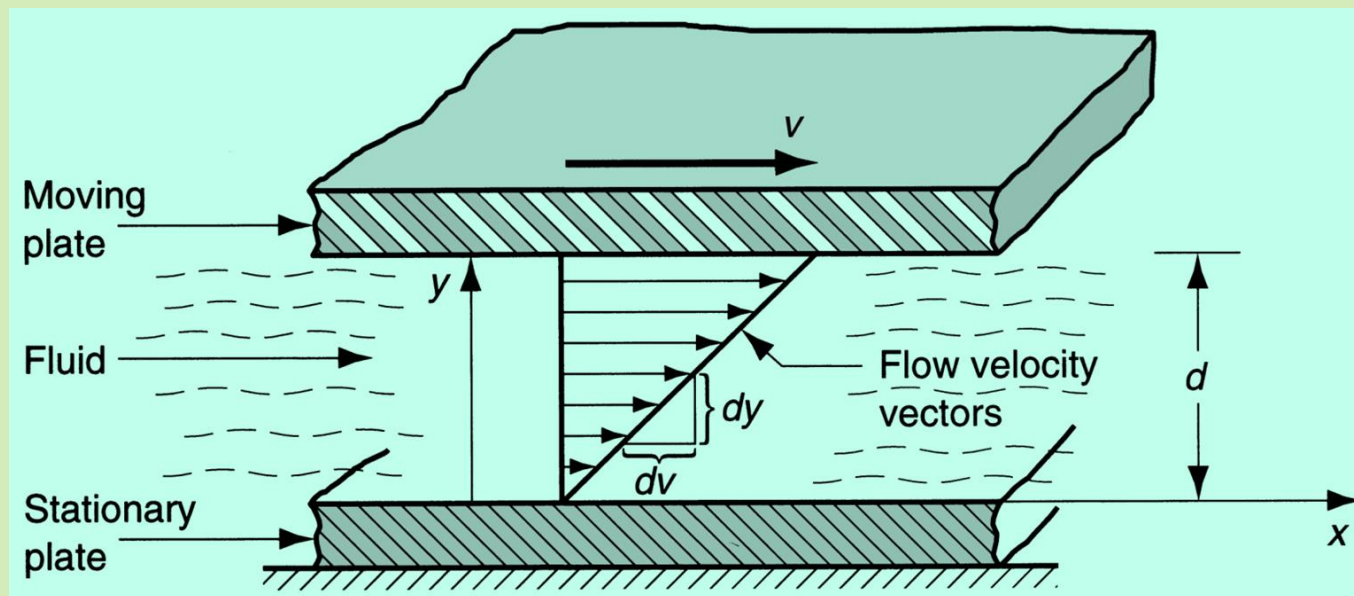
Fluid Properties and Manufacturing

- 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
- Examples:
 - Metals are cast in molten state
 - Glass is formed in a heated and highly fluid state
 - Polymers are almost always shaped as thick fluids

Viscosity in Fluids

- Flow is a defining characteristic of fluids, but the tendency to flow varies for different fluids
- Viscosity is the resistance to flow that is characteristic of a given fluid
- 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 can be defined using two parallel plates separated by a distance d
- A fluid fills the space between the two plates.



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 stress τ is in Pa or N/m²

Shear Rate

Shear stress is related to *shear rate*, which is 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,

$$\frac{F}{A} = \eta \frac{dv}{dy} \quad \text{or} \quad \tau = \eta \dot{\gamma}$$

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:

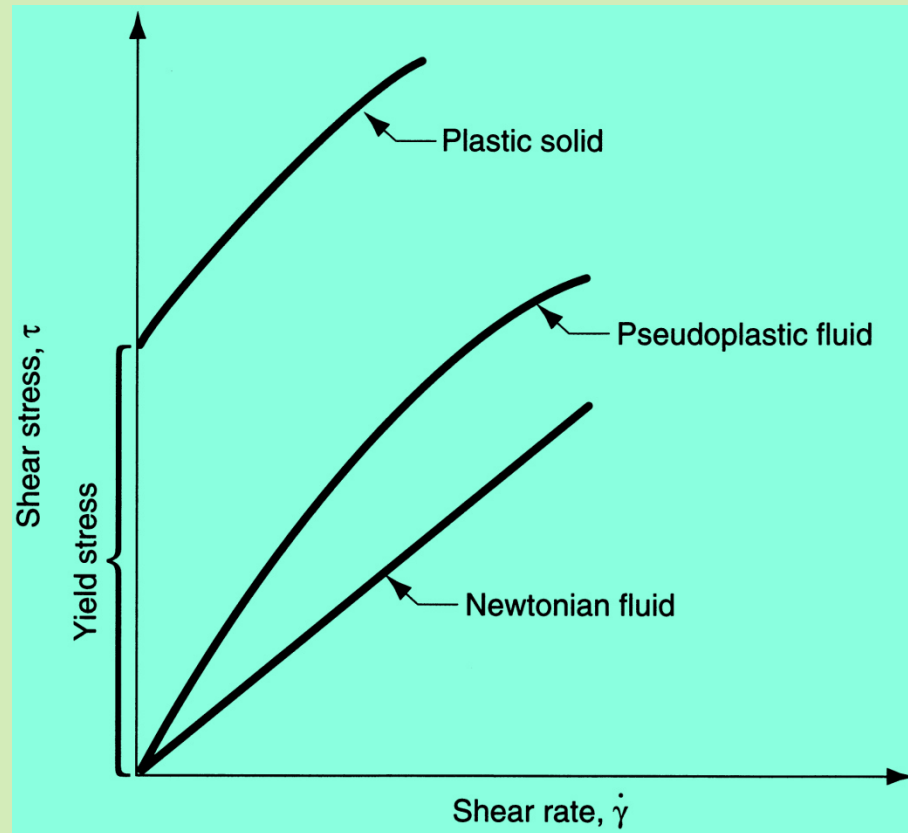
$$\eta = \frac{\tau}{\dot{\gamma}}$$

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

- Unit of Viscosity is: N-s/m² or Pascal-Seconds

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

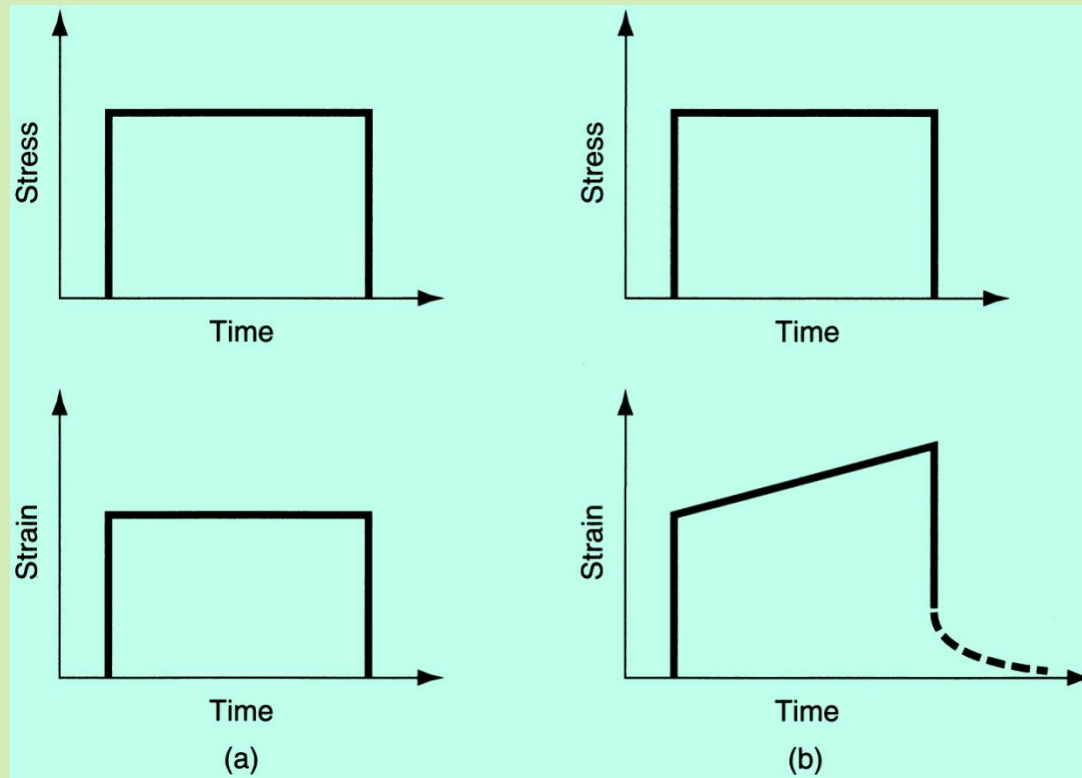


Viscous behaviors of Newtonian and pseudoplastic fluids. Polymer melts exhibit pseudoplastic behavior. For comparison, the behavior of a plastic solid material is shown.

Viscoelastic Behavior

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

- Combination of viscosity and elasticity



Comparison of elastic and viscoelastic properties:

(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 common 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
 - It “remembers”

PHYSICAL PROPERTIES OF MATERIALS

- Volumetric and Melting Properties
- Thermal Properties

Physical Properties Defined

Properties that define the behavior of materials in response to physical forces other than mechanical

- Includes: volumetric, thermal, electrical, and electrochemical properties
- Components in a product must do more than simply withstand mechanical stresses
- They must conduct electricity (or prevent conduction), allow heat to transfer (or allow its escape), transmit light (or block transmission), and satisfy many other functions

Physical Properties in Manufacturing

- Important in manufacturing because they often influence process performance
- Examples:
 - In machining, thermal properties of the work material determine the cutting temperature, which affects how long tools can be used before failure
 - In microelectronics, electrical properties of silicon and how these properties can be altered by chemical and physical processes is the basis of semiconductor manufacturing

Volumetric and Melting Properties

Properties related to the volume of solids and how the properties are affected by temperature

- Includes:
 - Density
 - Thermal expansion
 - Melting point

Density Defined

Weight per unit volume

- Typical units are g/cm^3
- Determined by atomic number and other factors such as atomic radius, and atomic packing

Specific gravity = density of a material relative to density of water and is a ratio with no units

Why Density is Important

Important consideration in material selection for a given application, but it is generally not the only property of interest

- Strength is also important, and the two properties are often related in a *strength-to-weight ratio*, which is tensile strength divided by its density
 - Useful ratio in comparing materials for structural applications in aircraft, automobiles, and other products where weight and energy are of concern

Thermal Expansion

- Density of a material is a function of temperature
 - In general, density decreases with increasing temperature
 - Volume per unit weight increases with increasing temperature
 - Thermal expansion is the name for this effect of temperature on density
 - Measured by *coefficient of thermal expansion* α

Coefficient of Thermal Expansion

Change in length per degree of temperature, such as mm/mm/°C

- Length ratio rather than volume ratio because this is easier to measure and apply

Change in length for a given temperature change is:

$$L_2 - L_1 = \alpha L_1 (T_2 - T_1)$$

where α = coefficient of thermal expansion; L_1 and L_2 are lengths corresponding respectively to temperatures T_1 and T_2

Thermal Expansion in Manufacturing

- Thermal expansion is used in *shrink fit* and *expansion fit* assemblies
 - Part is heated to increase size or cooled to decrease size to permit insertion into another part
 - When part returns to ambient temperature, a tightly-fitted assembly is obtained
- Thermal expansion can be a problem in *heat treatment* and *welding* due to thermal stresses that develop in material during these processes

Melting Characteristics for Elements

Melting point T_m of a pure element = temperature at which it transforms from solid to liquid state

- The reverse transformation occurs at the same temperature and is called the *freezing point*

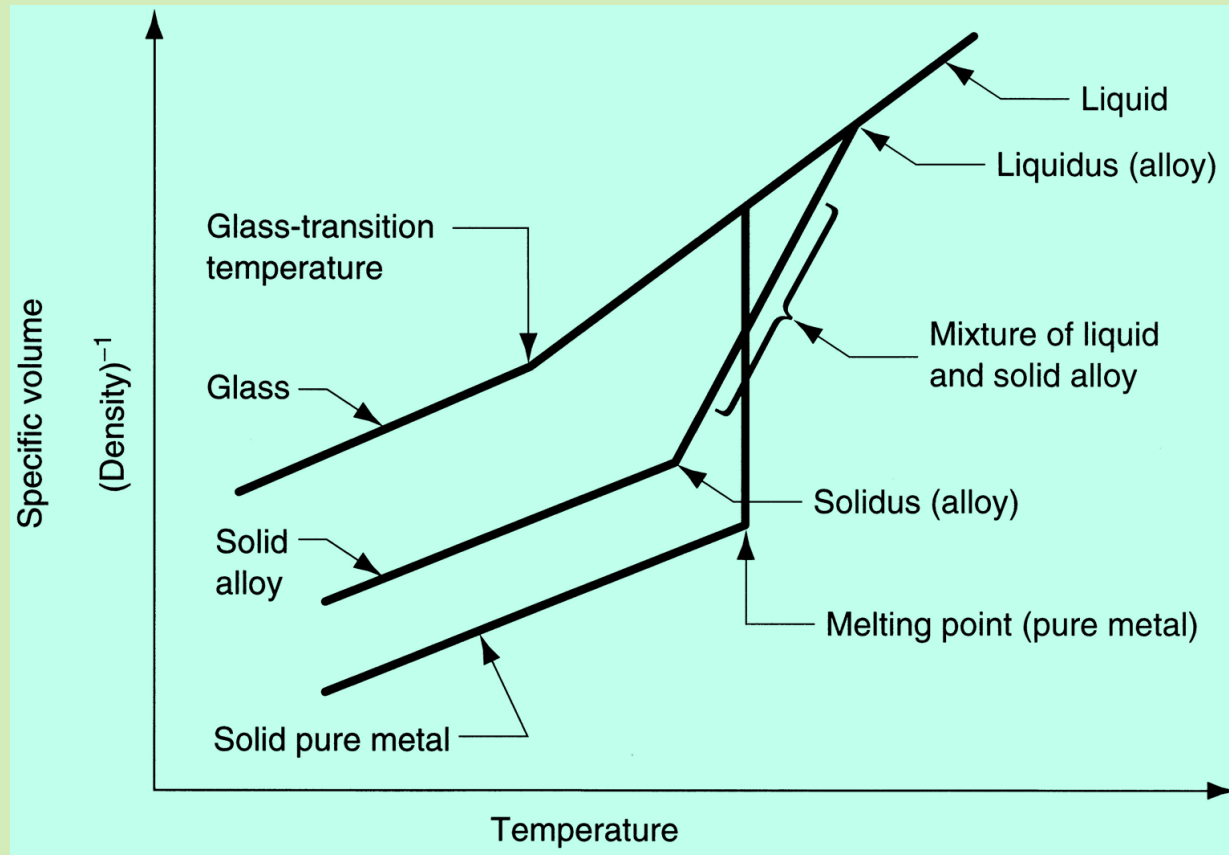
Heat of fusion = heat energy required at T_m to accomplish transformation from solid to liquid

Melting of Metal Alloys

- Unlike pure metals, most alloys do not have a single melting point
- Instead, melting begins at a temperature called the *solidus* and continues as temperature increases until converting completely to liquid at a temperature called the *liquidus*
 - Between the two temperatures, the alloy is a mixture of solid and molten metals
 - Exception: *eutectic alloys* melt (and freeze) at a single temperature

Melting of Noncrystalline Materials

- In noncrystalline materials (glasses), a gradual transition from solid to liquid states occurs
- The solid material gradually softens as temperature increases, finally becoming liquid at the melting point
- During softening, the material has a consistency of increasing plasticity (increasingly like a fluid) as it gets closer to the melting point



Changes in volume per unit weight ($1/\text{density}$) as a function of temperature for a hypothetical pure metal, alloy, and glass; all exhibiting similar thermal expansion and melting characteristics

Importance of Melting in Manufacturing

- *Metal casting* - the metal is melted and then poured into a mold cavity
 - Metals with lower melting points are generally easier to cast
- *Plastic molding* - melting characteristics of polymers are important in nearly all polymer shaping processes
- *Sintering of powdered metals* - sintering does not melt the material, but temperatures must approach the melting point in order to achieve the required bonding of powders

Thermal Properties

- Thermal expansion, melting, and heat of fusion are thermal properties because temperature determines the thermal energy level of the atoms, leading to the changes in materials
- Additional thermal properties:
 - Specific heat
 - Thermal conductivity
 - These properties relate to the storage and flow of heat within a substance

Specific Heat

The quantity of heat energy required to increase the temperature of a unit mass of material by one degree

To determine the energy to heat a certain weight of metal to a given elevated temperature:

$$H = C W (T_2 - T_1)$$

where

H = amount of heat energy;

C = specific heat of the material;

W = its weight; and

$(T_2 - T_1)$ = change in temperature

Volumetric Specific Heat

The quantity of heat energy required to raise the temperature of a unit volume of material by one degree

- Density ρ multiplied by specific heat C
- *Volumetric specific heat* = ρC

Thermal Conductivity

Thermal conduction - transfer of thermal energy within a material from molecule to molecule by purely thermal motions; no transfer of mass

Thermal conductivity of a material = capability to transfer heat through itself by this physical mechanism

- Measured by *coefficient of thermal conductivity* k .
Units: J/s mm °C (Btu/in hr °F)
- Coefficient of thermal conductivity is generally high in metals, low in ceramics and plastics

Thermal Diffusivity

The ratio of thermal conductivity to volumetric specific heat is frequently encountered in heat transfer analysis

$$K = \frac{k}{\rho C}$$

Thermal Properties in Manufacturing

- Important in manufacturing because heat generation is common in so many processes
 - In some cases, heat is the energy that accomplishes the process
 - *Examples: heat treating, sintering of powder metals and ceramics*
 - In other cases, heat is generated as a result of the process
 - *Examples: cold forming and machining of metals*