Materials Science and Engineering (BMEE209L)

by

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Content

❑ Module: 4 Mechanical Behavior of Materials covers the following:

- Strengthening Mechanisms – Basics
- Types of Strengthening Mechanisms
- Mechanical Properties of Metals
- Type of Mechanisms lead to Failure
- Type of Mechanical Behaviour Phenomena
- Classification of Deformation Process
- Common Type of Deformation

Strengthening Mechanisms – Basics

- In pure state of some metals, the strength is not sufficient for specific engineering works.
- Important to the understanding of strengthening mechanisms is the relation between dislocation motion and mechanical behaviour of metals.
- Because macroscopic plastic deformation corresponds to the motion of large numbers of dislocations.
- The ability of a metal to plastically deform depends on the ability of dislocations to move.
- Hence, by reducing the mobility of dislocations, the mechanical strength may be enhanced; i.e., greater mechanical forces will be required to initiate plastic deformation.
- Virtually all strengthening techniques rely on this simple principle: Restricting or hindering dislocation motion renders a material harder and stronger.
- Variation of deformation processes with temperatures are; $T > 0.5\ T_m$ – Hot working (T_m is the absolute melting point of the metal), $T \sim 0.5\ T_m$ – Warm working, and $T < 0.5\ T_m$ – Cold working.

Types of Strengthening Mechanisms

- Material strength can be increased by hindering dislocation, which is responsible for plastic deformation.

- Different ways to hinder dislocation motion/Strengthening mechanisms:

- In single-phase materials:

  - Grain size reduction
  - Solid solution strengthening
  - Strain hardening

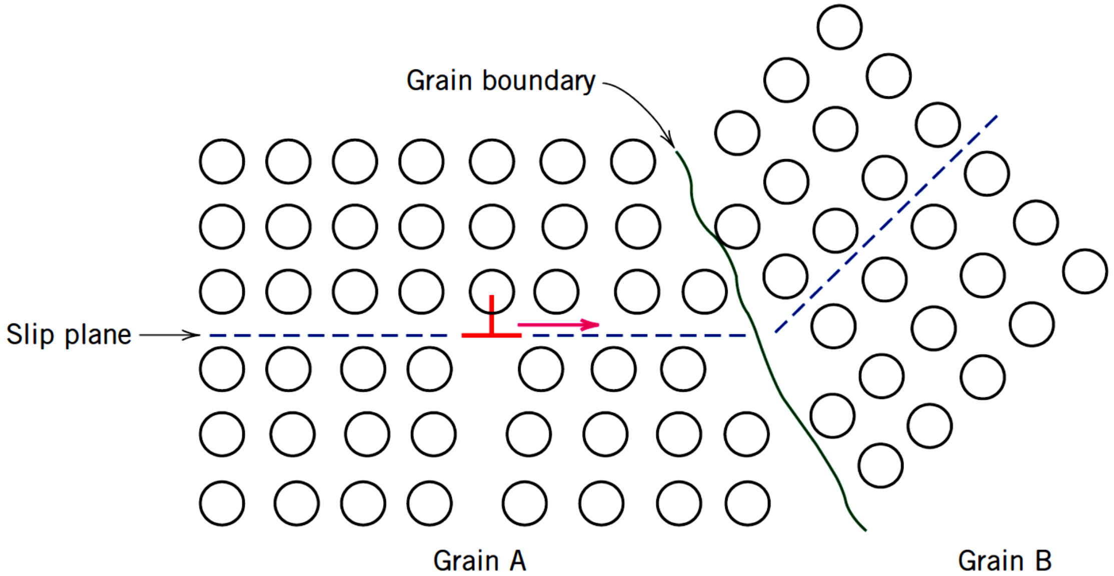
- In multi-phase materials:

  - Precipitation strengthening
  - Dispersion strengthening
  - Fiber strengthening
  - Martensite strengthening

Strengthening by Grain Size Reduction

- The size of the grains, or average grain diameter, in a polycrystalline metal influences the mechanical properties.
- Adjacent grains normally have different crystallographic orientations and, of course, a common grain boundary, as indicated in figure.

- During plastic deformation, slip or dislocation motion must take place across this common boundary—say, from grain A to grain B in figure.
- The grain boundary acts as a barrier to dislocation motion for two reasons:
  - Because the two grains are of different orientations, a dislocation passing into grain B will have to change its direction of motion; this becomes more difficult as the crystallographic mis-orientation increases.
  - The atomic disorder within a grain boundary region will result in a discontinuity of slip planes from one grain into the other.



The motion of a dislocation as it encounters a grain boundary, illustrating how the boundary acts as a barrier to continued slip. Slip planes are discontinuous and change directions across the boundary.

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- For high-angle grain boundaries, it is difficult for the dislocations to traverse grain boundaries during deformation; rather, dislocations tend to "pile up" (or back up) at grain boundaries.
- A fine-grained material (one that has small grains) is harder and stronger than one that is coarse grained, because the former has a greater total grain boundary area to impede dislocation motion.
- For many materials, the yield strength σ_y varies with grain size according to:

$$\sigma_y = \sigma_0 + k_y d^{-1/2}$$

- This expression is termed the Hall–Petch equation, where d is the average grain diameter, σ_0 and k_y are constants for a particular material.
- Note that the Hall–Petch equation is not valid for both very large (i.e., coarse) grain and extremely fine grain polycrystalline materials.
- Grain size may be regulated by the rate of solidification from the liquid phase, and also by plastic deformation followed by an appropriate heat treatment.
- grain size reduction improves not only strength, but also the toughness of many alloys.
- Boundaries between two different phases are also impediments to movements of dislocations; this is important in the strengthening of more complex alloys.
- The sizes and shapes of the constituent phases significantly affect the mechanical properties of multiphase alloys.

Solid-Solution Strengthening

- Another technique to strengthen and harden metals is alloying with elements that go into either substitutional or interstitial solid solution. Accordingly, this is called solid-solution strengthening.
- Impure foreign atoms in a single phase material produces lattice strains which can anchor the dislocations.
- Effectiveness of this strengthening depends on two factors – size difference and volume fraction of solute.
- Solute atoms interact with dislocations in many ways:
    - elastic interaction
    - modulus interaction
    - stacking-fault interaction
    - electrical interaction
    - short-range order interaction
    - long-range order interaction
- Alloys are stronger than pure metals because the alloying elements that go into solid solution ordinarily impose lattice strains (due to the different size of atoms) on the surrounding host atoms.
- Lattice strain field interactions between dislocations and these alloying elements result, and, consequently, dislocation movement is restricted.

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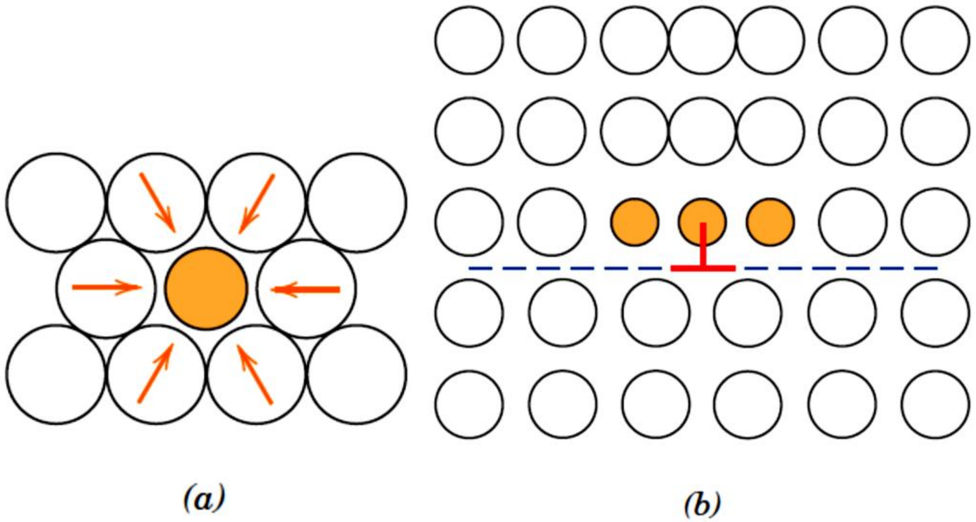
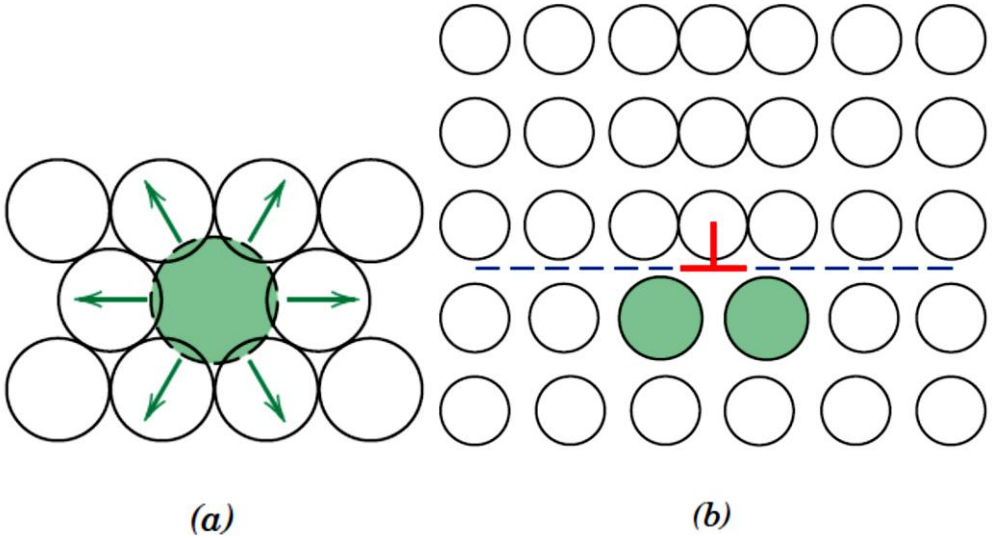
(a) Representation of tensile lattice strains imposed on host atoms by a smaller substitutional impurity atom.

(b) Possible locations of smaller impurity atoms relative to an edge dislocation such that there is partial cancellation of impurity–dislocation lattice strains.

(a) Representation of compressive strains imposed on host atoms by a larger substitutional impurity atom.

(b) Possible locations of larger impurity atoms relative to an edge dislocation such that there is partial cancellation of impurity–dislocation lattice strains.





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- These solute atoms tend to diffuse to and segregate around dislocations in a way so as to reduce the overall strain energy—i.e., to cancel some of the strain in the lattice surrounding a dislocation.

- To accomplish this, a smaller impurity atom is located where its tensile strain will partially nullify some of the dislocation's compressive strain.

- For the edge dislocation in figure (previous slide), this would be adjacent to the dislocation line and above the slip plane.

- A larger impurity atom would be situated as in figure (previous slide).

- The resistance to slip is greater when impurity atoms are present because the overall lattice strain must increase if a dislocation is torn away from them.

- A greater applied stress is necessary to first initiate and then continue plastic deformation for solid-solution alloys, as opposed to pure metals; this is evidenced by the enhancement of strength and hardness.

Strain Hardening

- **Strain hardening** is the phenomenon whereby a ductile metal becomes harder and stronger as it is plastically deformed.

- Sometimes it is also called **work hardening**, or, because the temperature at which deformation takes place is "cold" relative to the absolute melting temperature of the metal, cold working.

- Most metals strain harden at room temperature.

- It is sometimes convenient to express the degree of plastic deformation as percent (%) cold work rather than as strain.

- Percent cold work (%CW) is defined as:

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

- where A_o is the original area of the cross section that experiences deformation and A_d is the area after deformation.

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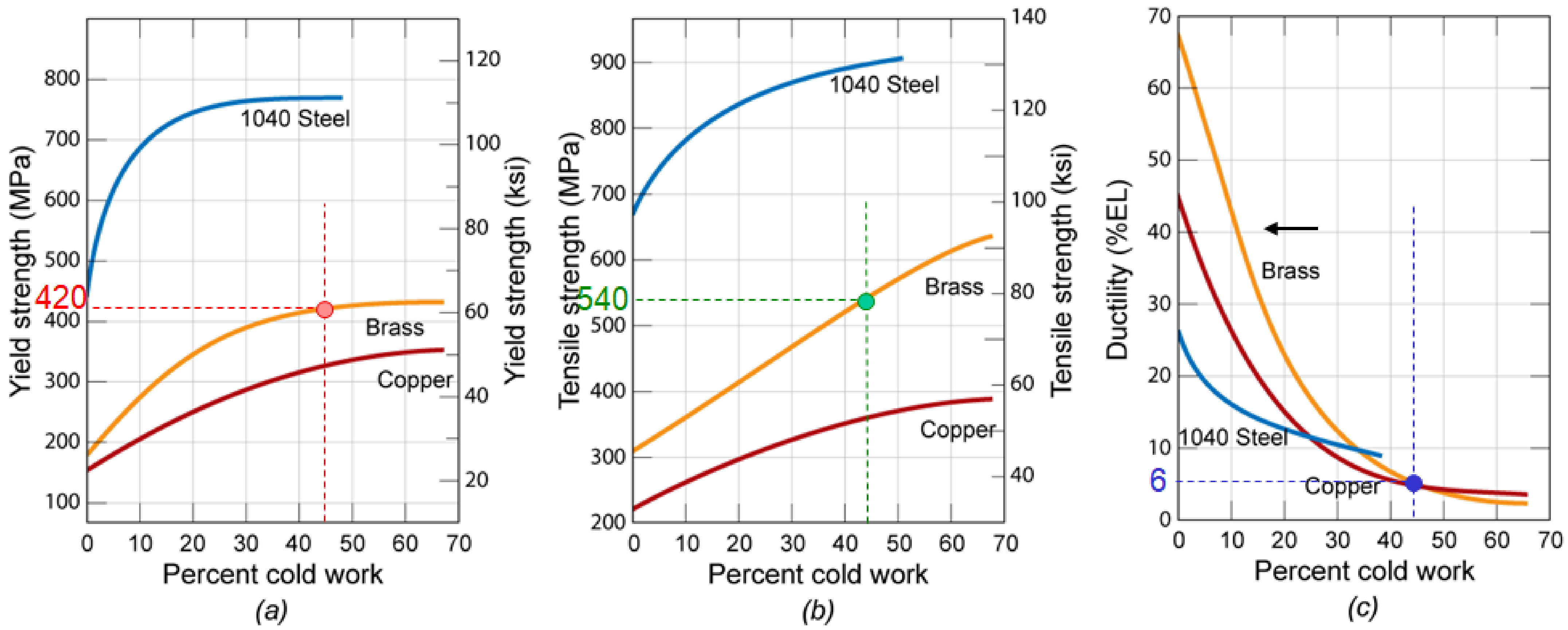
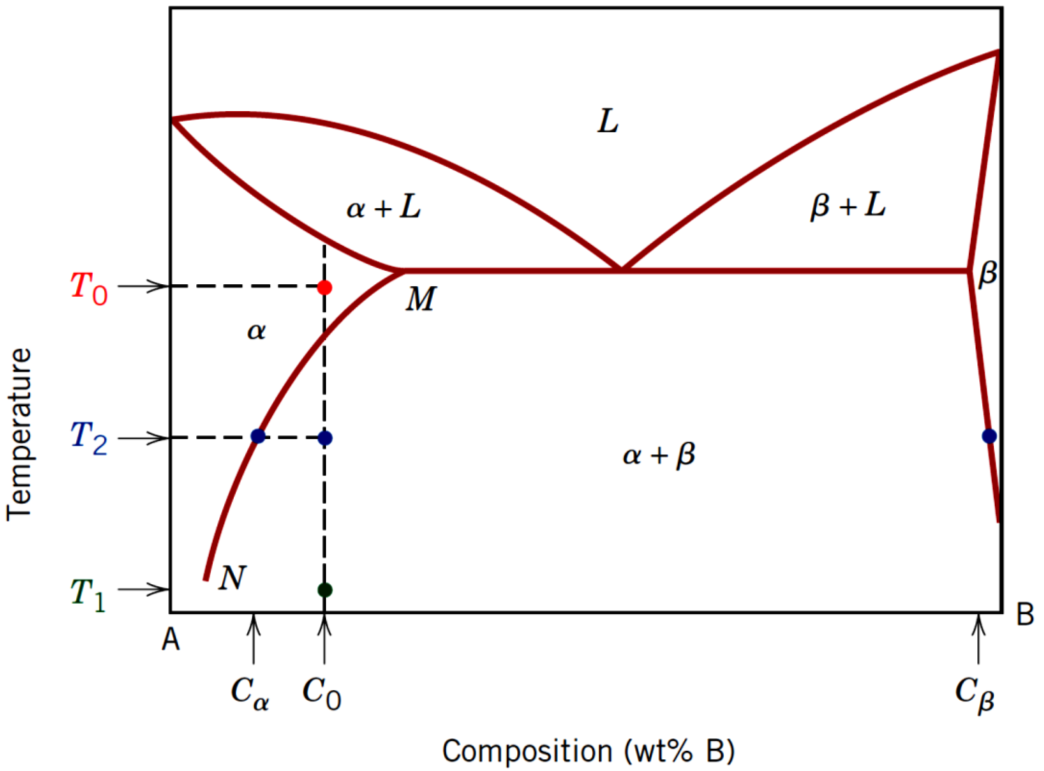


For 1040 steel, brass, and copper, (a) the increase in yield strength, (b) the increase in tensile strength, and (c) the decrease in ductility (%EL) with percent cold work.

Precipitation Hardening (Age Hardening)

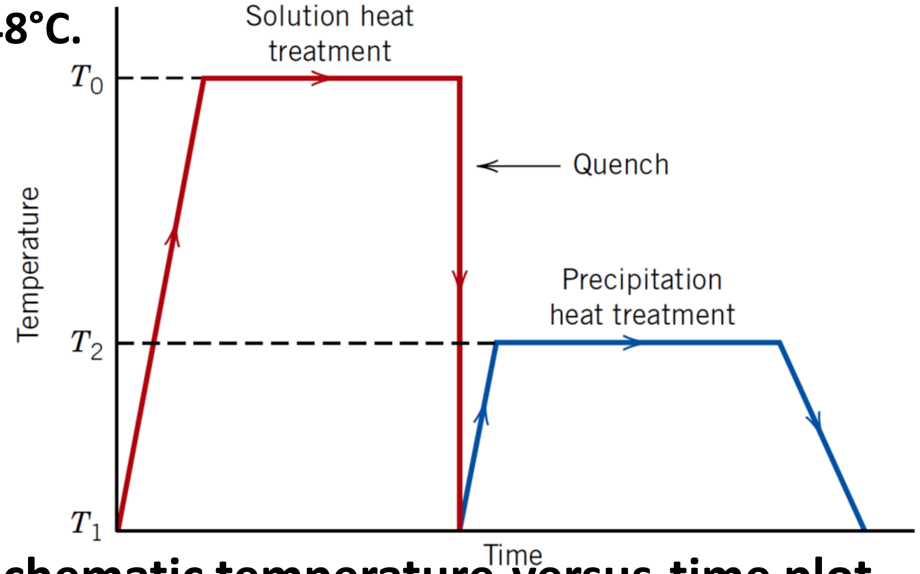
- Foreign particles can also obstructs movement of dislocations i.e. increases the strength of the material.
- Foreign particles can be introduced in two ways – precipitation and mixing-and-consolidation technique.
- The strength and hardness of some metal alloys may be enhanced by the formation of extremely small uniformly dispersed particles of a second phase within the original phase matrix; this must be accomplished by phase transformations that are induced by appropriate heat treatments.
- The process is called precipitation hardening because the small particles of the new phase are termed precipitates.
- Age hardening is also used to designate this procedure because the strength develops with time, or as the alloy ages.
- Requisite for precipitation hardening is that second phase must be soluble at an elevated temperature but precipitates upon quenching and aging at a lower temperature.
- E.g.: Al-alloys, Cu-Be alloys, Mg-Al alloys, Cu-Sn alloys.
- If aging occurs at room temperature – Natural aging.
- If material need to be heated during aging – Artificial aging.



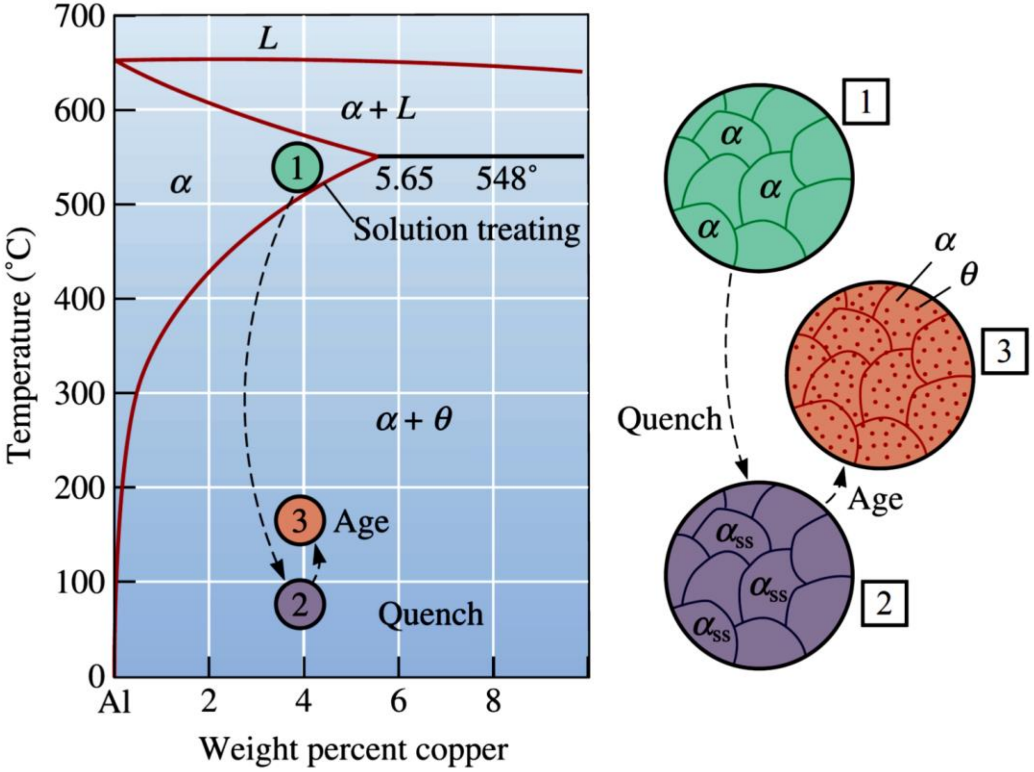
Hypothetical phase diagram for a precipitation-hardenable alloy of composition C_o.

Age–Hardened Alloys: Al–4% Cu

- The Al–4% Cu alloy is a classic example of an age-hardenable alloy.
- There are three steps in the age hardening heat treatment.
- Step 1: Solution Treatment
  - In the solution treatment, the alloy is first heated above the solvus temperature and held until a homogeneous solid solution is produced.
  - The Al–4% Cu alloy is solution treated between 500 and 548°C.



Schematic temperature-versus-time plot showing both solution and precipitation heat treatments for precipitation hardening



The Al–Cu phase diagram and the microstructures that may develop curing cooling of an Al–4% Cu alloy.

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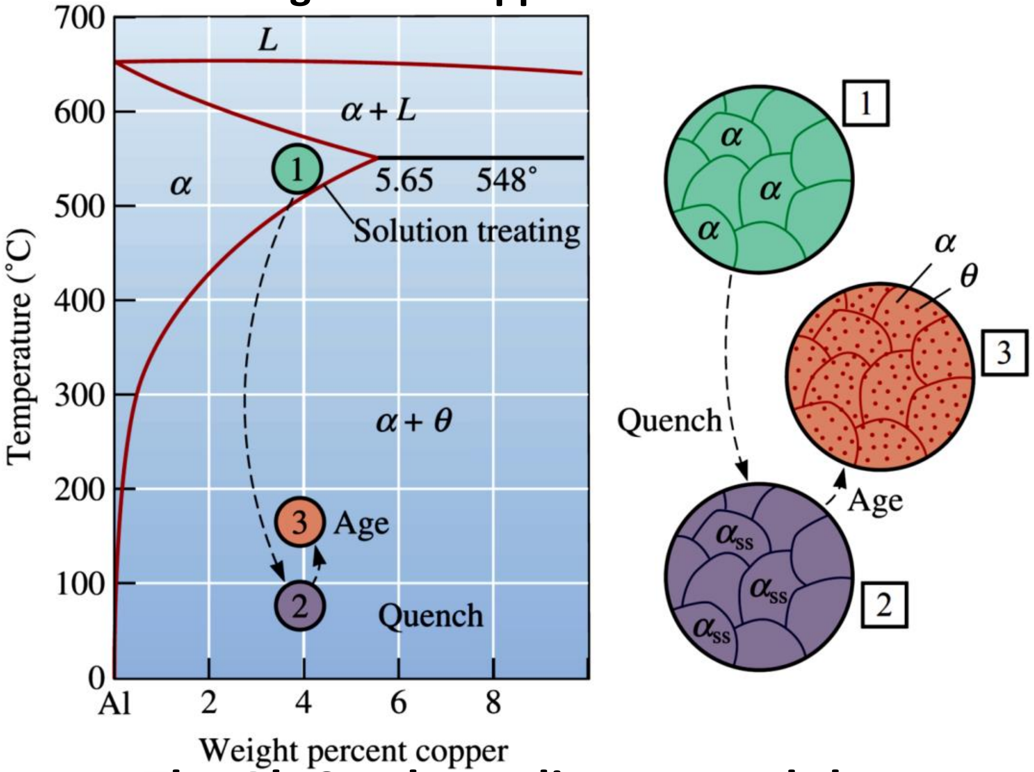
Step 2: Quench

- After solution treatment, the alloy, which contains only α in its structure, is rapidly cooled, or quenched.
- The atoms do not have time to diffuse to potential nucleation sites, so the θ does not form.
- After the quench, the structure is a supersaturated solid solution containing excess copper.

Step 3: Age

- Finally, the supersaturated α is heated at a temperature below the solvus temperature.
- At this aging temperature, atoms diffuse only short distances.
- Because the supersaturated is metastable, the extra copper atoms diffuse to numerous nucleation sites and precipitates grow.
- When we go through the three steps described previously, we produce the phase in the form of ultra-fine uniformly dispersed second-phase precipitate particles.
- This is what we need for effective precipitation strengthening.



The Al–Cu phase diagram and the microstructures that may develop curing cooling of an Al–4% Cu alloy.

Dispersion Hardening

- In dispersion hardening, fine second particles are mixed with matrix powder, consolidated, and pressed in powder metallurgy techniques.
- For dispersion hardening, second phase need to have very low solubility at all temperatures.
- E.g.: oxides, carbides, nitrides, borides, etc.
- Dislocation moving through matrix embedded with foreign particles can either cut through the particles or bend around and bypass them.
- Cutting of particles is easier for small particles which can be considered as segregated solute atoms.
- Effective strengthening is achieved in the bending process, when the particles are sub-microscopic in size.

Fiber Strengthening

- Second phase can be introduced into matrix in fiber form too.

- Requisite for fiber strengthening:

  - Fiber material – high strength and high modulus
  - E.g.: fiber material – Al_2O_3, boron, graphite, metal, glass etc.
  - Matrix material – ductile and non-reactive with fiber material
  - E.g.: matrix material – metals, polymers etc.

- Mechanism of strengthening is different from other methods.

- Higher modulus fibers carry load, ductile matrix distributes load to fibers.

- Interface between matrix and fibers thus plays an important role.

- Strengthening analysis involves application of continuum (develop predictive mathematical models of material behavior relating the applied forces to the material deformation and motion), not dislocation concepts as in other methods of strengthening.

Martensite Strengthening

- This strengthening method is based on formation of martensitic phase from the retained high temperature phase at temperatures lower then the equilibrium invariant transformation temperature.
- Martensite forms as a result of shearing of lattices.
- Martensite platelets assumes characteristic lenticular (double-convex) shape that minimizes the elastic distortion in the matrix.
- These platelets divide and subdivide the grains of the parent phase.
- Always touching but never crossing one another.
- Martensite platelets grow at very high speeds (1/3rd of sound speed) i.e. activation energy for growth is less.
- Thus volume fraction of martensite exist is controlled by its nucleation rate.

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- Martensite platelets attain their shape by two successive shear displacements:
  - First displacement is a homogeneous shear throughout the plate which occurs parallel to a specific plane in the parent phase known as the habit plane.
  - Second displacement, the lesser of the two, can take place by one of two mechanisms: slip as in Fe-C Martensite or twinning as in Fe-Ni Martensite.
- Martensite formation occurs in many systems.
- E.g.: Fe-C, Fe-Ni, Fe-Ni-C, Cu-Zn, Au-Cd, and even in pure metals like Li, Zr and Co.
- However, only the alloys based on Fe and C show a pronounced strengthening effect.
- High strength of Martensite is attributed to its characteristic twin structure and to high dislocation density.
- In Fe-C system, carbon atoms are also involved in strengthening.

Mechanical Properties of Metals

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

- Important mechanical properties are strength, hardness, ductility, and stiffness.
- These properties are ascertained by performing carefully designed laboratory experiments that replicate as nearly as possible the service conditions.
- Factors to be considered include the nature of the applied load and its duration, as well as the environmental conditions.

- It is possible for the load to be tensile, compressive, or shear, and its magnitude may be constant with time, or it may fluctuate continuously.
- Application time may be only a fraction of a second, or it may extend over a period of many years.
- Service temperature may be an important factor.

Type of Mechanisms lead to Failure

- If failure is considered as deterioration in desired performance, which could involve changes in properties and/or shape, then failure can occur by many mechanisms as below:

Mechanisms/methods by which a material can fail

- Elastic deformation
- Plastic deformation
  - Twinning
  - Slip
  - Etc.
- Fracture
- Fatigue
- Creep
- Microstructural changes
  - Twinning
  - Phase transformations
  - Grain growth
  - Particle coarsening
- Chemical / Electro-chemical degradation
  - Corrosion
  - Oxidation
- Physical degradation
  - Wear
  - Erosion

- **Fracture** is when something applies a load that exceeds the ultimate strength of a material.
- **Fatigue** is the failure of material due to rapidly stress.
- **Creep** is a time dependent deformation when material is under constant loading.

Type of Mechanical Behaviour Phenomena

- Phenomenologically mechanical behavior can be understood as in the flow diagram below.
- Multiple mechanisms may be associated with these phenomena (e.g., creep can occur by diffusion, grain boundary sliding etc.).
- These phenomena may lead to the failure of a material.
- Many of these phenomena may occur concurrently in a material.

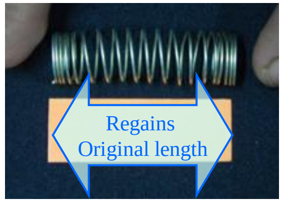
Mechanical Behaviour

A phenomenological classification *(not a mechanistic one)*

- **Elasticity** — Recoverable deformation

Pushing a spring

Release



- **Plasticity** — Permanent deformation

Bending of rod of metal

- **Fracture** — Propagation of cracks in a material

Crack Propagation

Crack Propagation

- **Fatigue** — Oscillatory loading
- **Creep** — Elongation at constant load/constant stress at 'high' temperatures

- Note: This is a broad classification for convenience.
- e.g., Creep is also leads to plastic deformation!

Classification of Deformation Process

- Deformation
  - Elastic (Recoverable)
    - Instantaneous
    - Time dependent
      - *Anelasticity*
      - *Viscoelasticity*
  - Plastic (Permanent)
    - Instantaneous
    - Time dependent
      - *Viscoplasticity*

- **Anelasticity**: Time-dependent, recoverable low strain with linear behavior and relatively low damping (any effect that tends to reduce the amplitude of vibrations) (recoverable deformation under load, e.g., results from internal friction and contributes to internal heating of the material specimen during deformation, particularly if high load frequencies are involved).
- **Viscoelasticity**: Time-dependent, recoverable higher strains with nonlinear behavior and higher damping (has a yield stress under any application of stress it will deform, e.g., metals at very high temperatures).
- **Viscoplasticity**: Time-dependent, non-recoverable strain with nonlinear behavior and higher damping (has a yield stress under which it will not deform, e.g., metals).

Common Type of Deformation

- From a macroscopic perspective we can deform a material in by applying external forces (or moments) in a few ways.
- The actual loading on a given component may be complex, involving combinations of these loading types:

  - Tension/Compression
  - Bending
  - Shear
  - Torsion

- The kind of loading employed is often dependent on the geometry of the sample (e.g. bending is done on thin long samples, while compression on short cylinders).

- The deformation mechanism involved at the microscopic level has to be separately analyzed.

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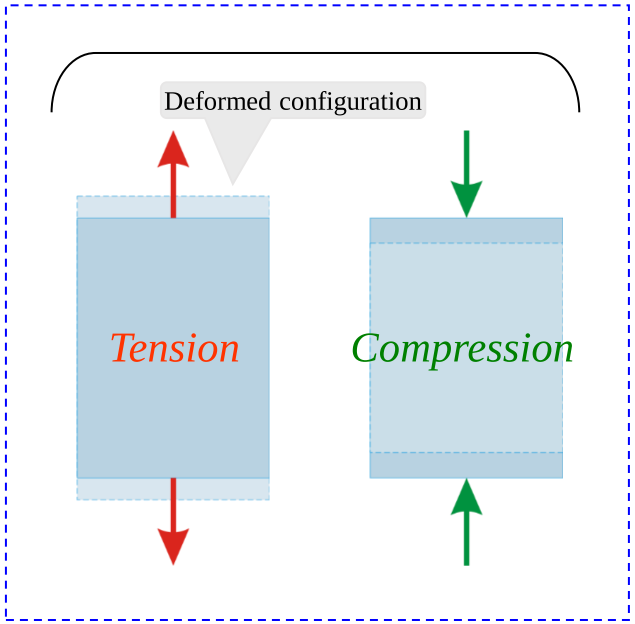
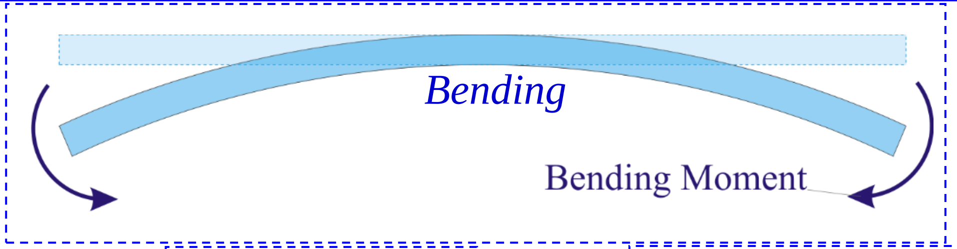
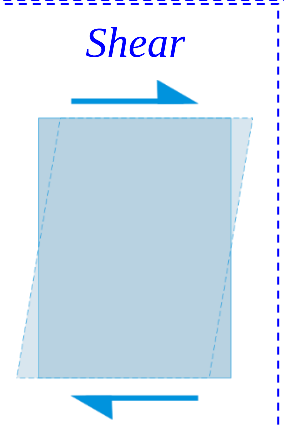
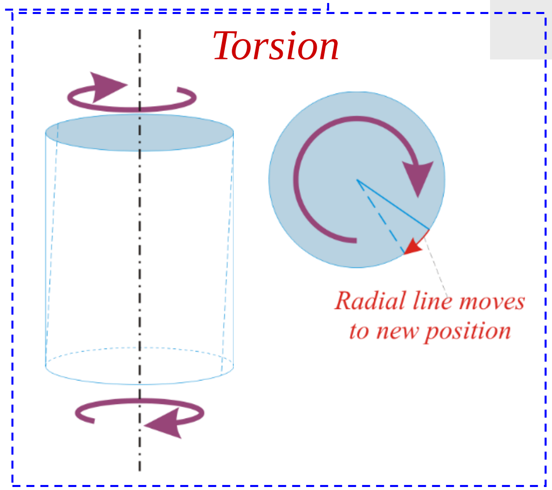
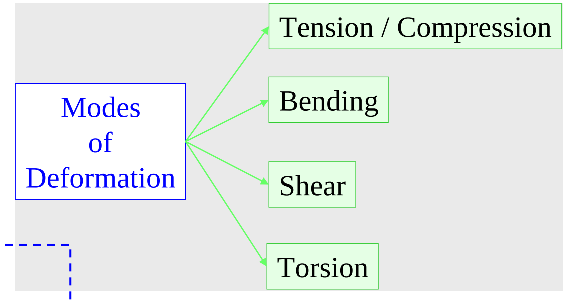




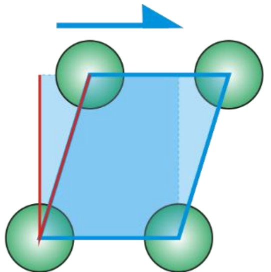




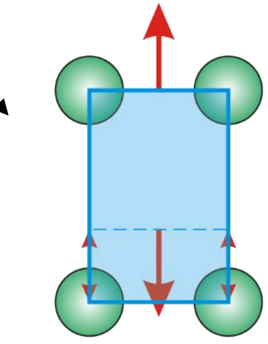


Deformation: a fundamental prospective:-

- At a more fundamental (material) level there are only two types of deformations:
- Tension/compression → where in bond length is increased/decreased
  - Usual tension/compression
  - During bending
- Shear → bond angle is distorted
  - Usual shear
  - Torsion



Change in bond angle



Change in bond length

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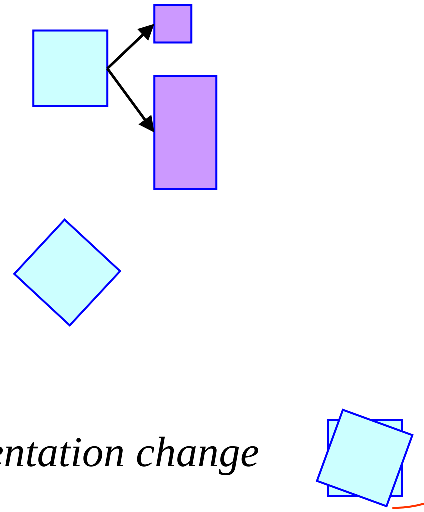
What can happen to a material body (solid) on the application of external loads/forces/constraints?

What can happen to a material body (solid) when we apply forces/constraints to the outside of the body

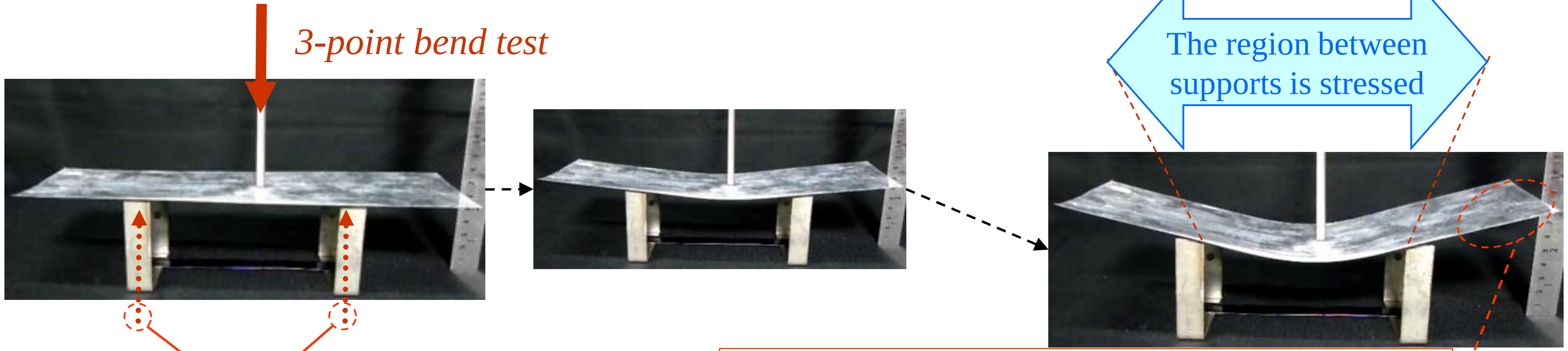
- Contraction/dilation — *Volume change*
- Shear — *Shape change*
- Rigid body rotation — *Orientation change*



Or a combination of these

Example showing how parts of a single body may have different responses to loading

3-point bend test



The region between supports is stressed

Normal reactions

The region outside the supports undergoes rigid body rotations and is not stressed

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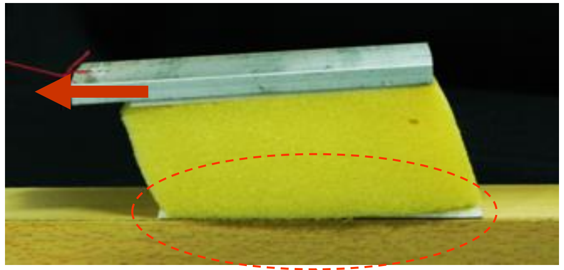
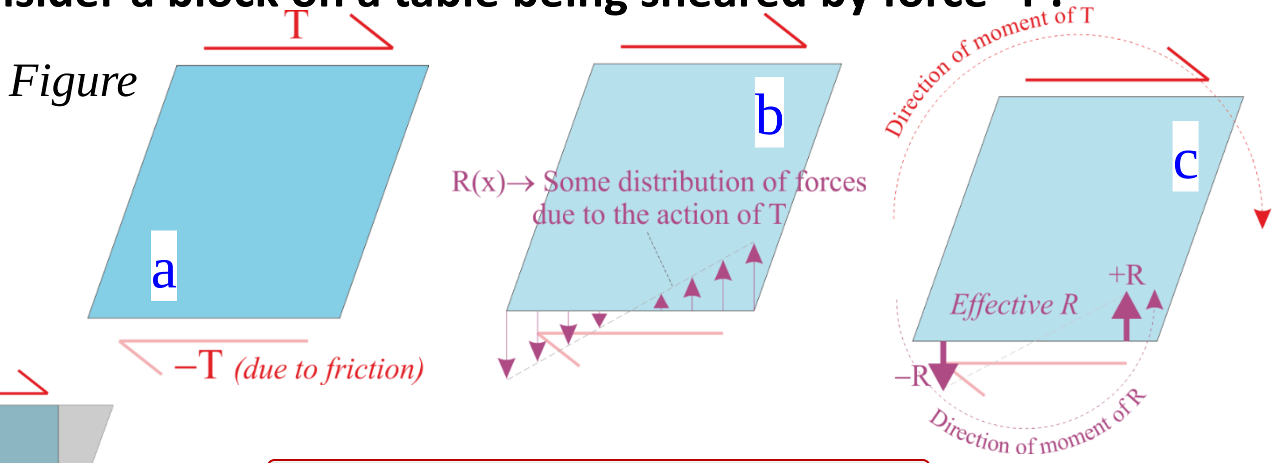
- Usually we apply **simple shear** forces on a body. Though this is called simple shear it is clear that with just two forces the body will not be in equilibrium (moment balance is not satisfied). This implies that there has to be additional 'hidden' forces (as shown in figure b). These forces ensure moment balance. To understand this let us consider a block on a table being sheared by force 'T'.



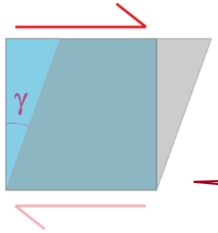
Note the bottom



- Friction provides the opposite force on bottom surface (–T).

- At the material level, pure shear can be considered as simple shear + rotation of γ/2 (for small shear).

For small deformations

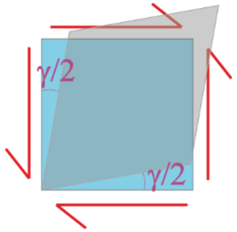


Usually we apply simple shear forces on a material

The way the diagram is drawn the body is not in equilibrium!

Shear → Simple Shear / Pure Shear

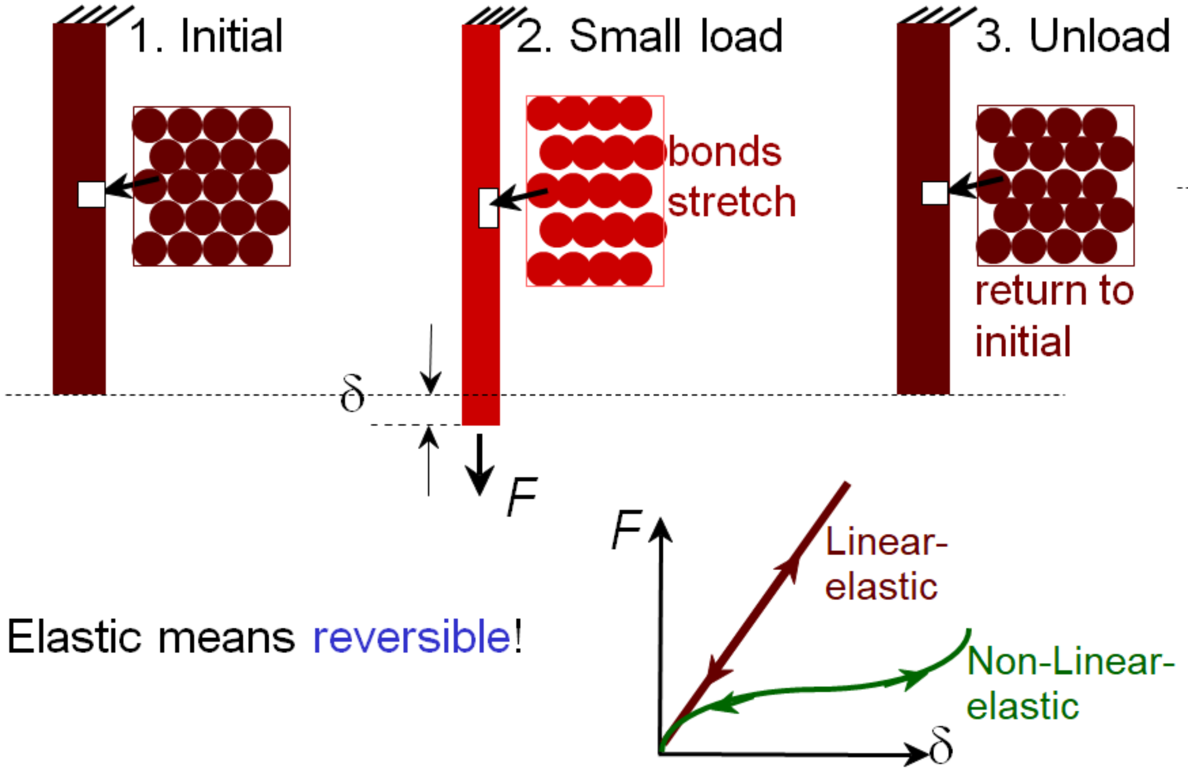
Pure shear of $\gamma/2$ = Simple shear of γ + Anti clock wise rotation of $\gamma/2$



OR

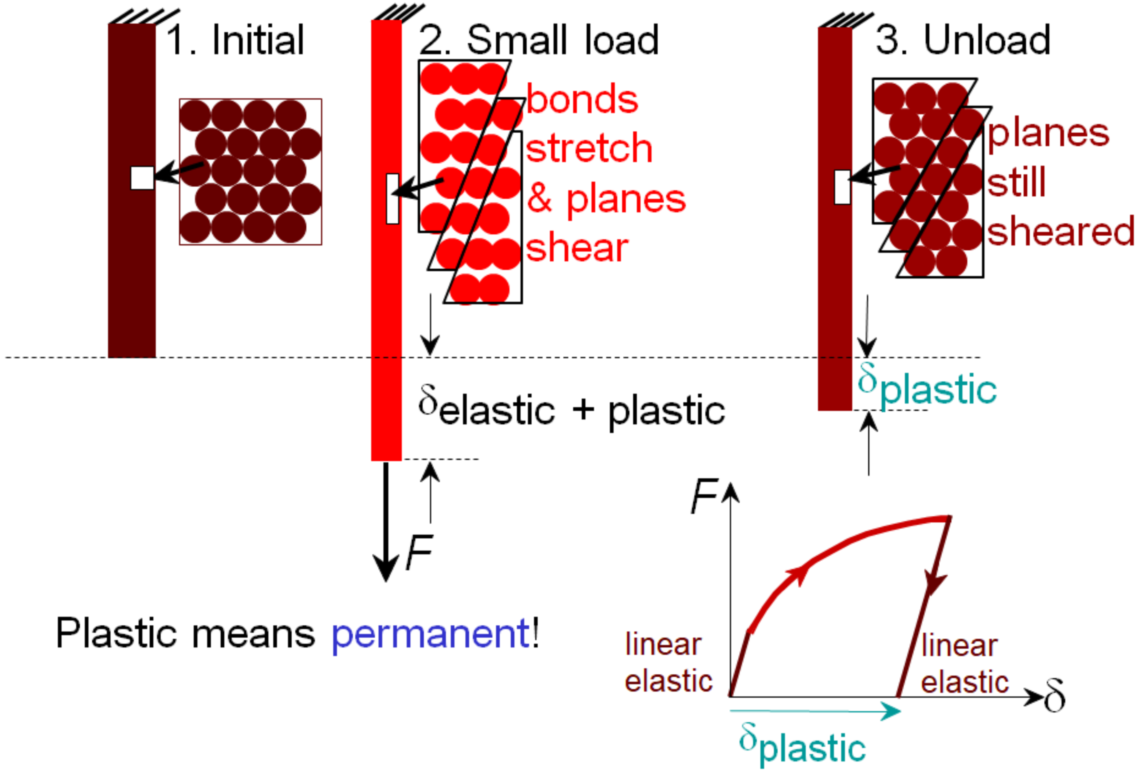
Simple shear of γ = Pure shear of $\gamma/2$ + Clock wise rotation of $\gamma/2$

Elastic and Plastic Deformation



Elastic means reversible!

Elastic Deformation

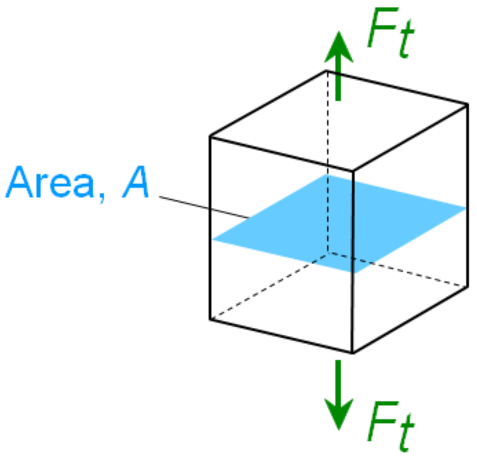


Plastic means permanent!

Plastic Deformation (Metals)

Engineering Stress and Strain

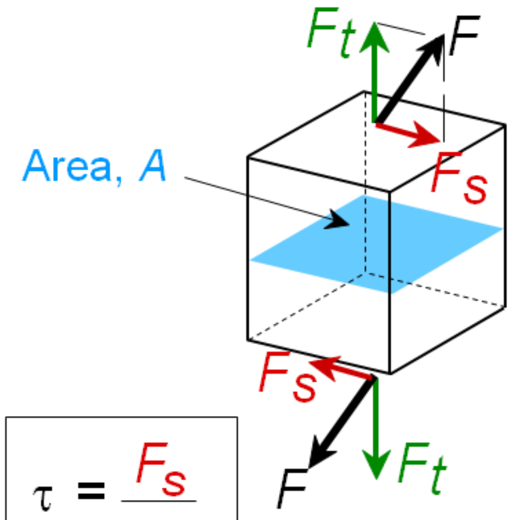
- Tensile stress, σ:



$$\sigma = \frac{F_t}{A_o} = \frac{lb_f}{in^2} \text{ or } \frac{N}{m^2}$$

original area before loading

- Shear stress, τ:



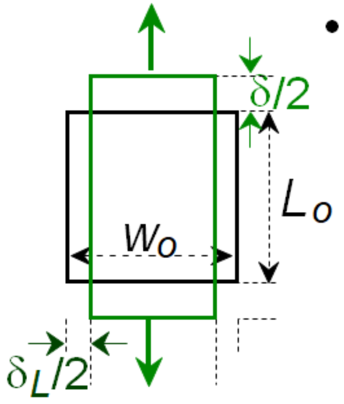
$$\tau = \frac{F_s}{A_o}$$

$\therefore$ Stress has units: N/m^2 or lb_f/in^2

Engineering Stress

- Tensile strain:

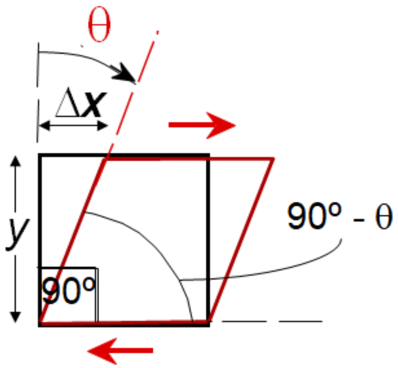
$$\varepsilon = \frac{\delta}{L_o}$$



- Lateral strain:

$$\varepsilon_L = \frac{-\delta_L}{w_o}$$

- Shear strain:



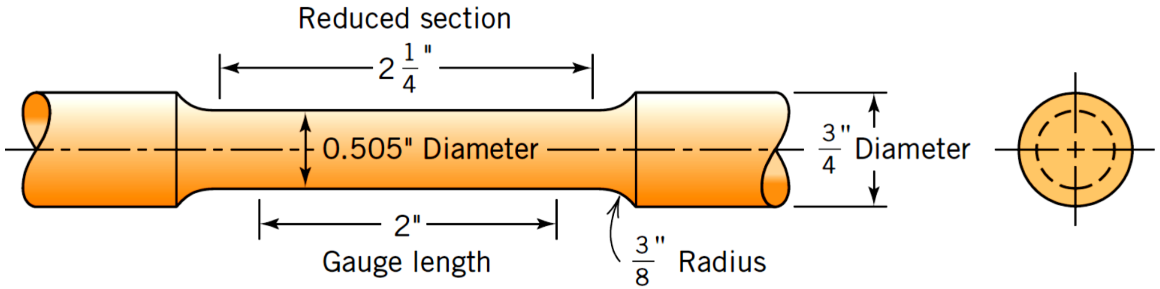
$$\gamma = \Delta x / y = \tan\theta$$

Strain is always dimensionless.

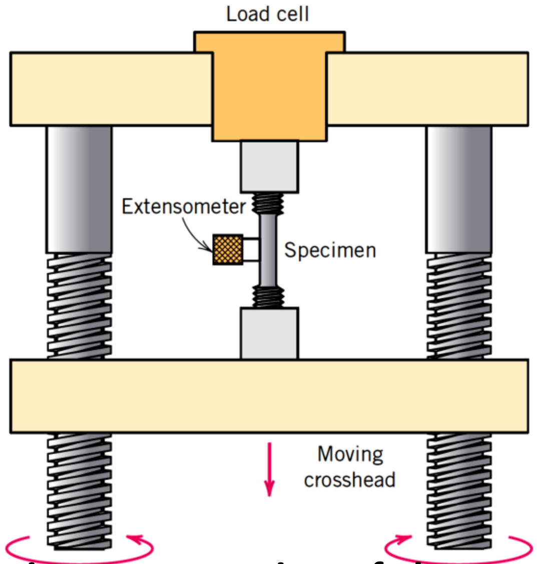
Engineering Strain

Tensile Properties of the Materials: Tension Test

- The tensile test measures the resistance of a material to a static or slowly applied force.
- The strain rates in a tensile test are very small.
- Information concerning the strength, Young's modulus, and ductility of a material can be obtained from such a tensile test.
- Typically, a tensile test is conducted on metals, alloys, and plastics.
- Tensile tests can be used for ceramics, however, the test is not very useful for ceramics because the sample often easily fractures while it is being aligned.



A standard tensile specimen with circular cross section



Schematic representation of the apparatus used to conduct tensile stress–strain tests. The specimen is elongated by the moving crosshead; load cell and extensometer measure, respectively, the magnitude of the applied load and the elongation.

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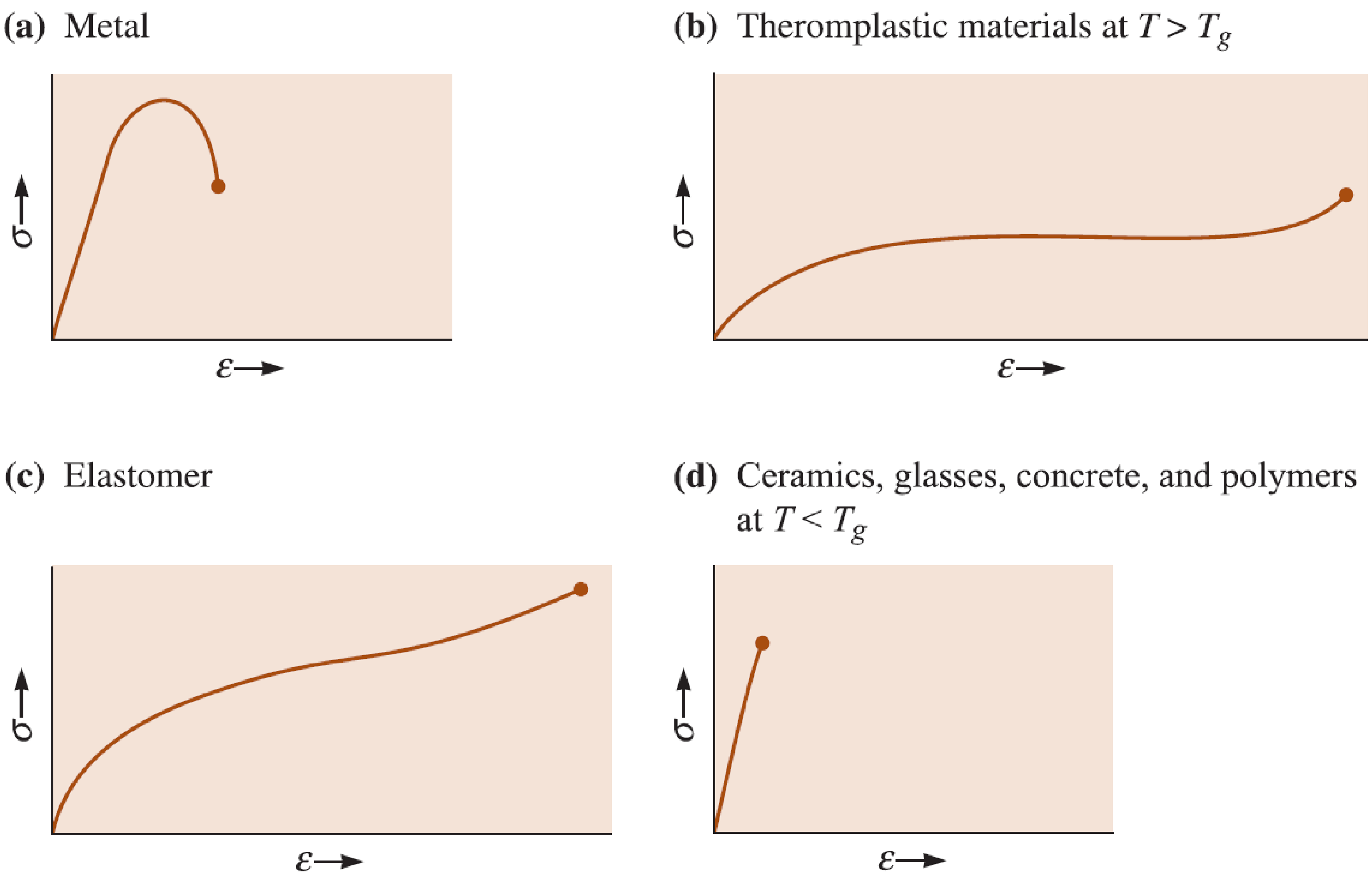


Tensile stress-strain curves for different materials (Note that these graphs are qualitative)

Elastic Deformation: Stress–Strain Behavior

- The degree to which a structure deforms or strains depends on the magnitude of an imposed stress.

- For most metals that are stressed in tension and at relatively low levels, stress and strain are proportional to each other through the relationship, $\sigma = E\varepsilon$

- This is known as Hooke's law, and the constant of proportionality E (GPa or psi) is the modulus of elasticity, or Young's modulus.

- For most typical metals, the magnitude of this modulus ranges between 45 GPa (6.5 X 10^6 psi), for Mg, and 407 GPa (59 X 10^6 psi), for W.

- Modulus of elasticity values for several metals at room temperature,

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

	Modulus of Elasticity		*Shear Modulus*		
Metal Alloy	*GPa*	*10^6 psi*	*GPa*	*10^6 psi*	*Poisson's Ratio*
Aluminum	69	10	25	3.6	0.33
Brass	97	14	37	5.4	0.34
Copper	110	16	46	6.7	0.34
Magnesium	45	6.5	17	2.5	0.29
Nickel	207	30	76	11.0	0.31
Steel	207	30	83	12.0	0.30
Titanium	107	15.5	45	6.5	0.34
Tungsten	407	59	160	23.2	0.28

Contd…

- Deformation in which stress and strain are proportional is called elastic deformation; a plot of stress (ordinate) vs. strain (abscissa) results in a linear relationship, as shown in figure.

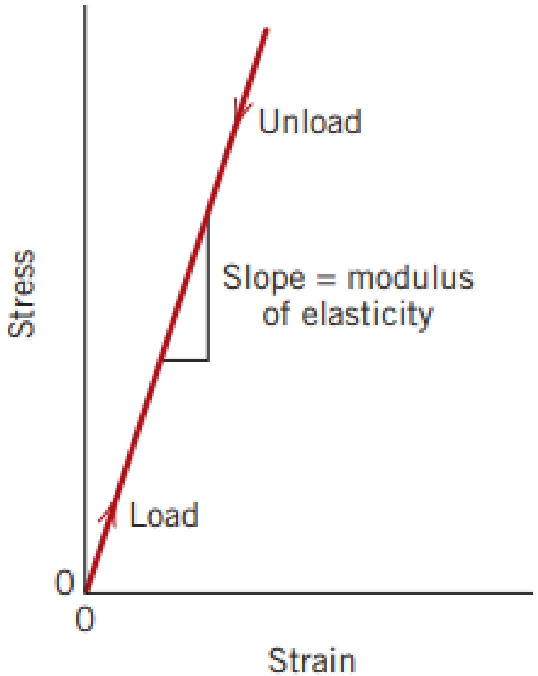
- The slope of this linear segment corresponds to the modulus of elasticity E and this modulus may be thought of as stiffness, or a material's resistance to elastic deformation.

- The greater the modulus, the stiffer the material, or the smaller the elastic strain that results from the application of a given stress.

- The modulus is an important design parameter for computing elastic deflections.

- Elastic deformation is nonpermanent, which means that when the applied load is released, the piece returns to its original shape.

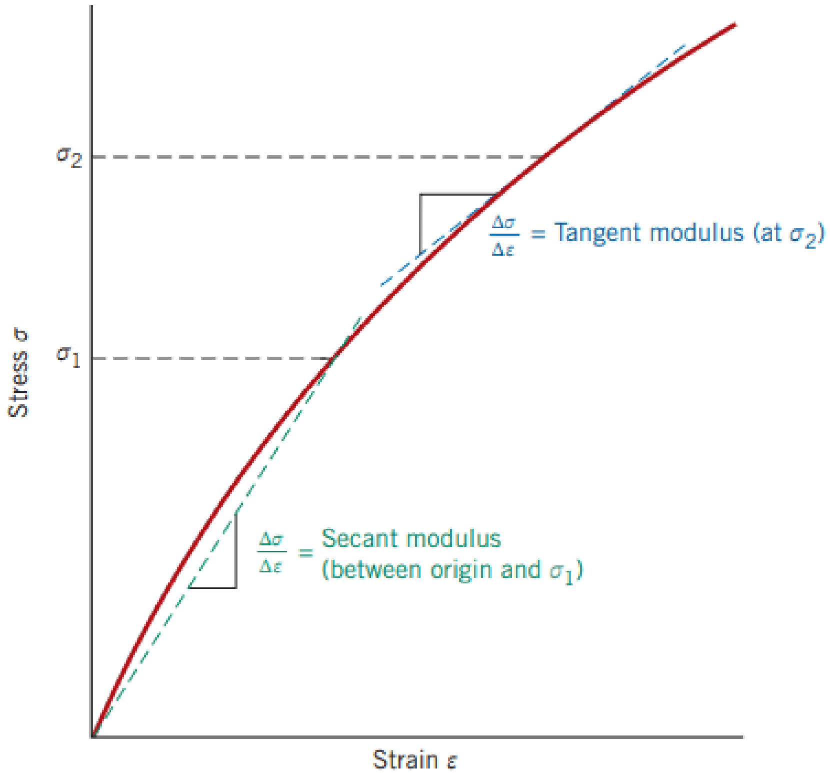
- As shown in the stress–strain plot, application of the load corresponds to moving from the origin up and along the straight line and upon release of the load, the line is traversed in the opposite direction, back to the origin.



Schematic stress–strain diagram showing linear elastic deformation for loading and unloading cycles

Contd…

- There are some materials (i.e., gray cast iron, concrete, and many polymers) for which this elastic portion of the stress–strain curve is not linear as shown in figure.
- Hence, it is not possible to determine a modulus of elasticity as described earlier.
- For this nonlinear behavior, either the tangent or secant modulus is normally used.
- The tangent modulus is taken as the slope of the stress–strain curve at some specified level of stress.
- Whereas the secant modulus represents the slope of a secant drawn from the origin to some given point of the σ-ε curve.
- The determination of these moduli is illustrated in figure.



Schematic stress–strain diagram showing nonlinear elastic behavior and how secant and tangent moduli are determined

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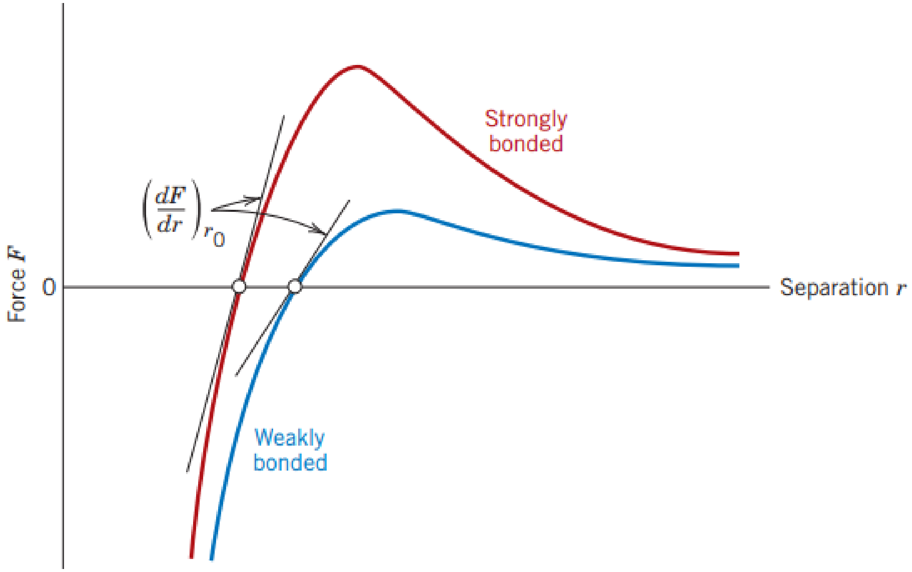
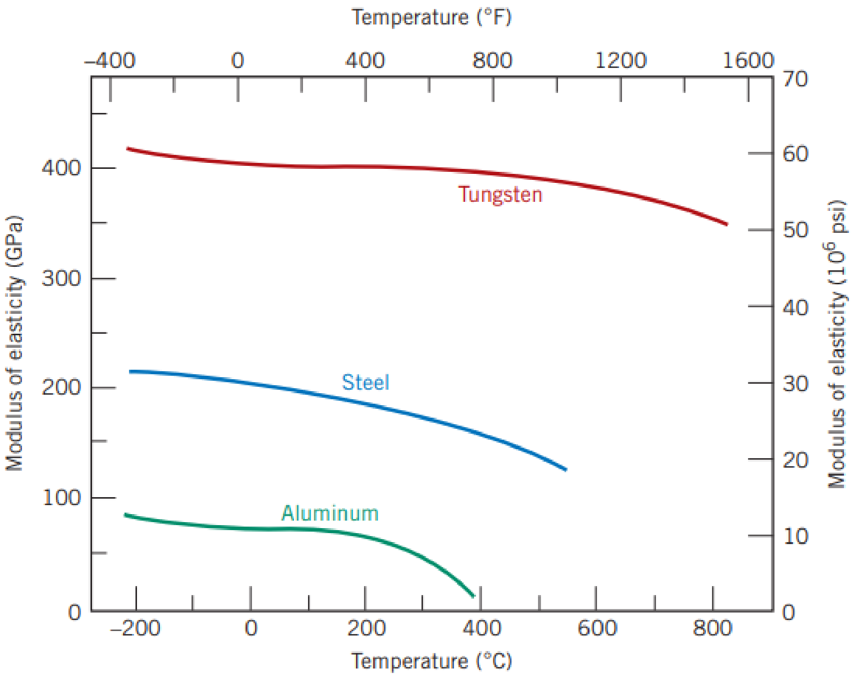


Force vs. interatomic separation for weakly and strongly bonded atoms. The magnitude of the modulus of elasticity is proportional to the slope of each curve at the equilibrium interatomic separation r_0.



Plot of modulus of elasticity vs. temperature for W, steel, and Al

- Shear stress and strain are proportional to each other through the expression,

$$\tau = G\gamma$$

- where, G is the shear modulus, the slope of the linear elastic region of the shear stress–strain curve.

Example – 1

- A piece of copper originally 305 mm (12 in.) long is pulled in tension with a stress of 276 MPa (40,000 psi). If the deformation is entirely elastic, what will be the resultant elongation?

- Solution:
- Because the deformation is elastic, strain is dependent on stress.

- Furthermore, the elongation Δ*l* is related to the original length l_0.

$$\sigma = \varepsilon E = \left(\frac{\Delta l}{l_0}\right) E$$

$$\Delta l = \frac{\sigma l_0}{E}$$

- The values of σ and l_0 are given as 276 MPa and 305 mm, respectively, and the magnitude of E for Cu from earlier table is 110 GPa (16 X 10^6 psi).

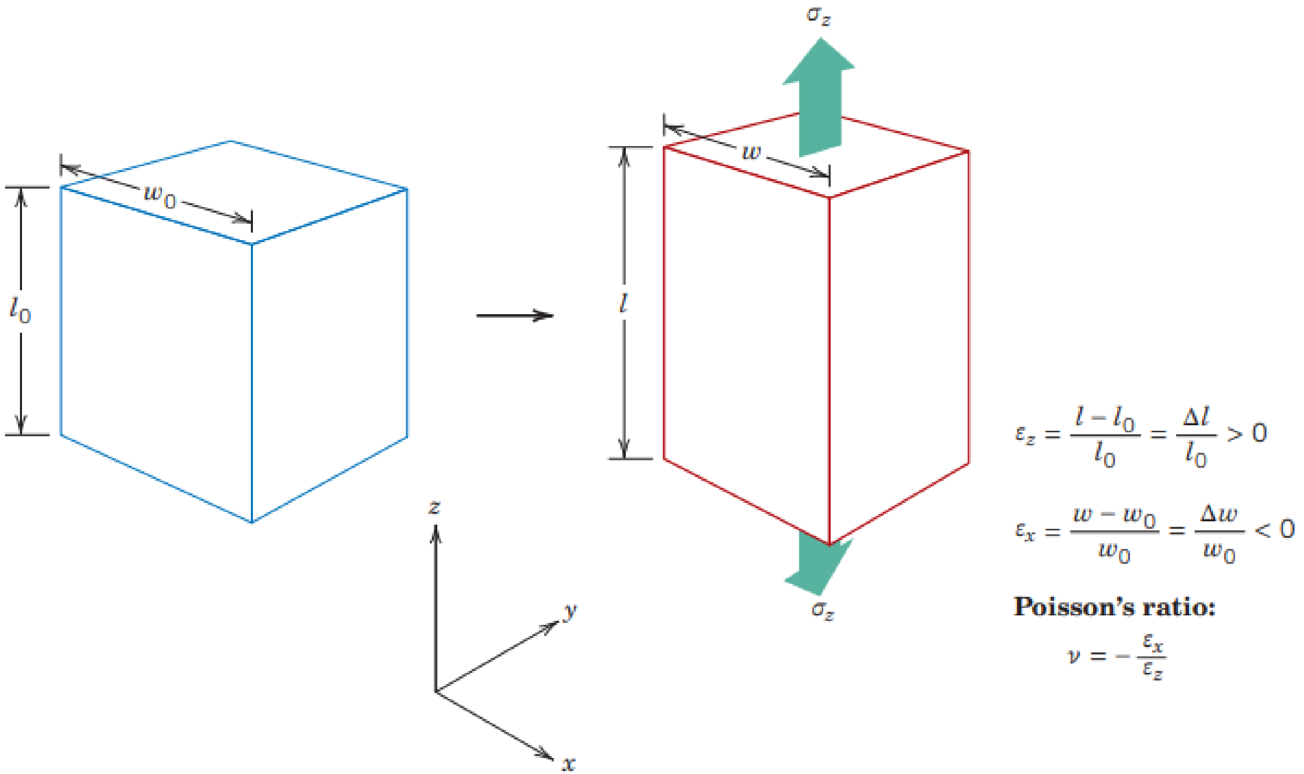
- Elongation is obtained by substitution into the preceding expression as,

$$\Delta l = \frac{(276\ \text{MPa})(305\ \text{mm})}{110 \times 10^3\ \text{MPa}} = 0.77\ \text{mm}\ (0.03\ \text{in.})$$

Elastic Properties of Materials

- 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 (arbitrarily taken to be the z direction).
- 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.
- 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 ν is defined as the ratio of the lateral and axial strains, or,

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



Schematic illustration showing axial (z) elongation (+ve strain, ε_z) and the lateral (x) contraction (–ve strain, ε_x) that result from the application of an axial tensile stress (σ_z)

- 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 0.4E)

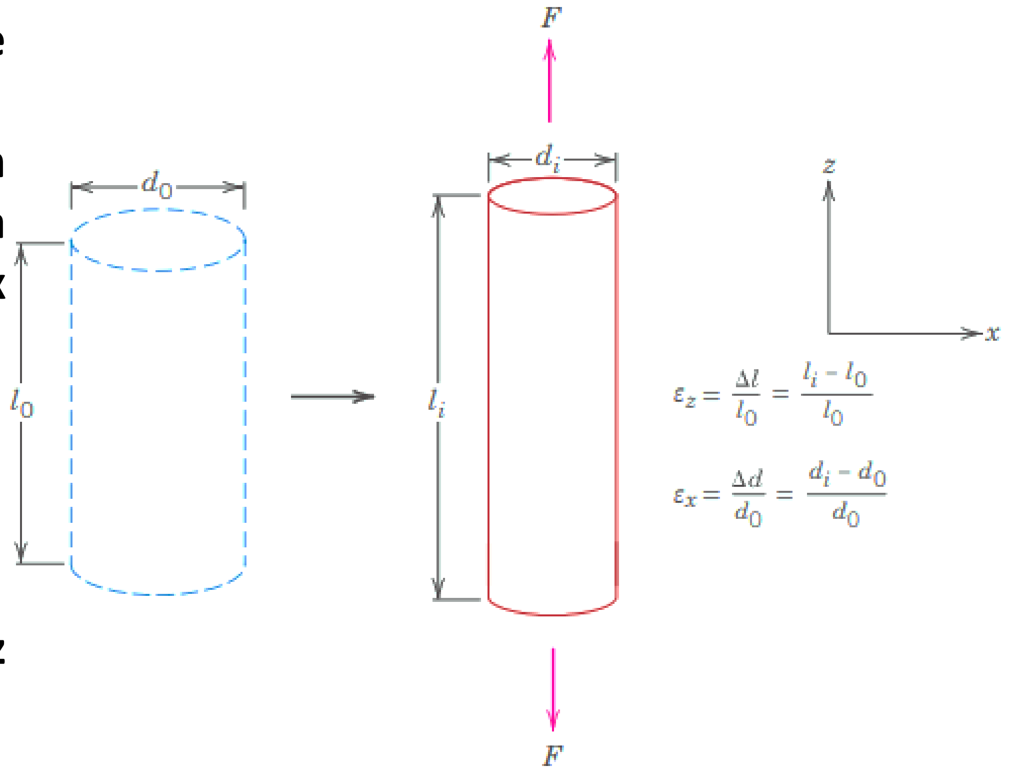
Example – 2

- A tensile stress is to be applied along the long axis of a cylindrical brass rod that has a diameter of 10 mm (0.4 in.). Determine the magnitude of the load required to produce a 2.5 X 10^{-3}-mm (10^{-4}-in.) change in diameter, if the deformation is entirely elastic.
- **Solution**: This deformation situation is represented in the accompanying drawing.
- When the force F is applied, the specimen will elongate in the z direction and at the same time experience a reduction in diameter, Δd, of 2.5 X 10^{-3} mm in the x direction.
- For the strain in the x direction,

$$\varepsilon_x = \frac{\Delta d}{d_0} = \frac{-2.5 \times 10^{-3}\ \text{mm}}{10\ \text{mm}} = -2.5 \times 10^{-4}$$

- which is negative because the diameter is reduced.
- It next becomes necessary to calculate the strain in the z direction.
- The value for Poisson's ratio for brass is 0.34 (Table), thus,

$$\varepsilon_z = -\frac{\varepsilon_x}{\nu} = -\frac{(-2.5 \times 10^{-4})}{0.34} = 7.35 \times 10^{-4}$$



Contd…

- The applied stress may now be computed and the modulus of elasticity, given in Table as 97 GPa (14 X 10^6 psi), as:

$$\sigma = \varepsilon_z E = (7.35 \times 10^{-4})(97 \times 10^3 \text{ MPa}) = 71.3 \text{ MPa}$$

- Finally, the applied force may be determined as,

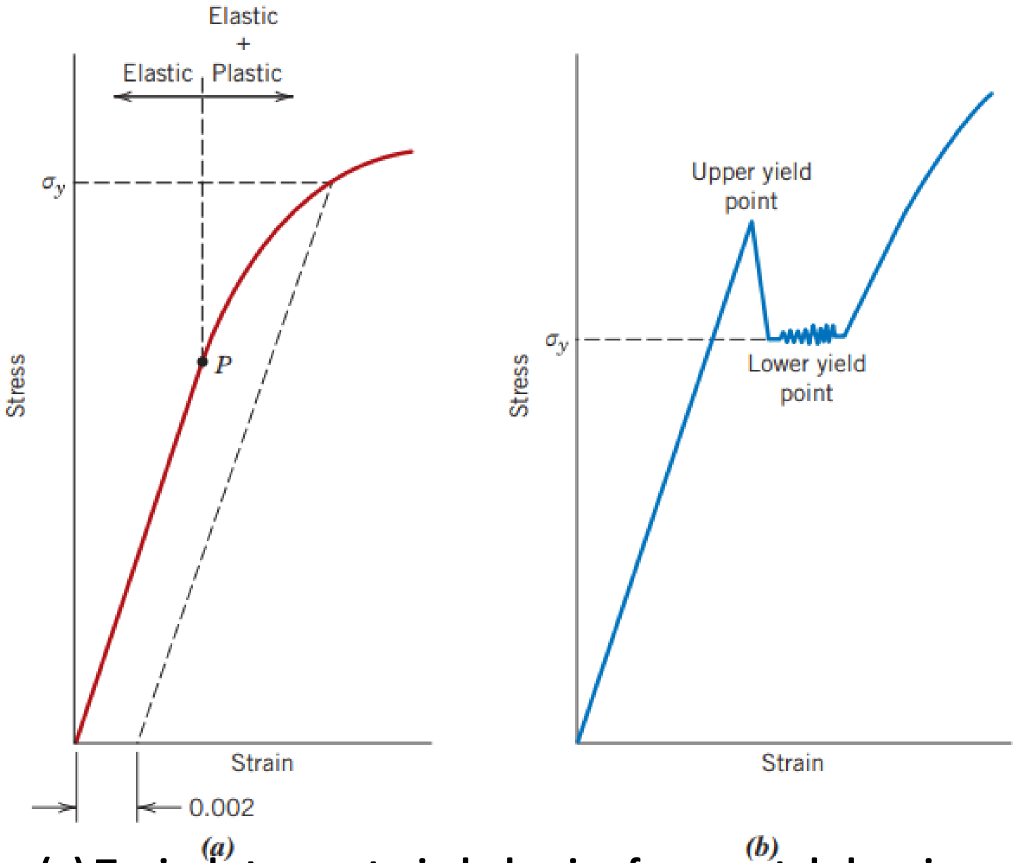
$$F = \sigma A_0 = \sigma \left(\frac{d_0}{2}\right)^2 \pi$$

$$= (71.3 \times 10^6 \text{ N/m}^2)\left(\frac{10 \times 10^{-3} \text{ m}}{2}\right)^2 \pi = 5600 \text{ N } (1293 \text{ lb}_f)$$

Plastic Deformation: Stress–Strain Behavior

- A structure or component that has plastically deformed—or experienced a permanent change in shape—may not be capable of functioning as intended.
- It is therefore desirable to know the stress level at which plastic deformation begins or where the phenomenon of yielding occurs.
- For metals that experience this gradual elastic–plastic transition, the point of yielding may be determined as the initial departure from linearity of the stress–strain curve; this is sometimes called the proportional limit P, and represents the onset of plastic deformation on a microscopic level.
- The position of this point P is difficult to measure precisely.

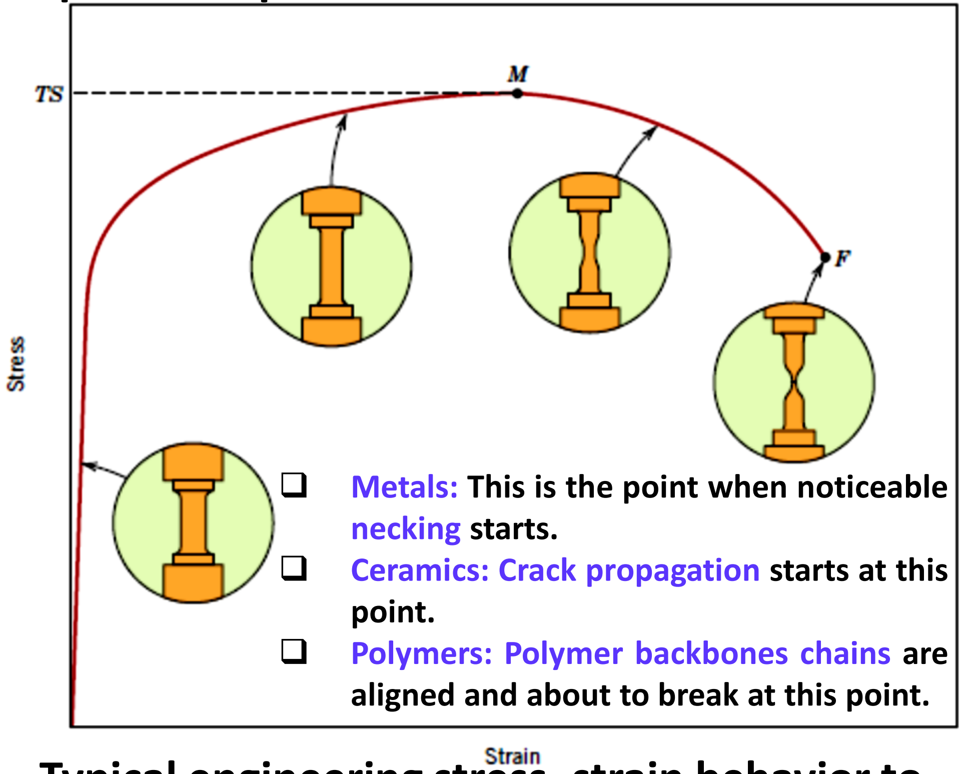
- A convention has been established by which a straight line is constructed parallel to the elastic portion of the stress–strain curve at some specified strain offset of 0.002.
- The stress corresponding to the intersection of this line and the stress–strain curve as it bends over in the plastic region is defined as the yield strength σ_y.



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

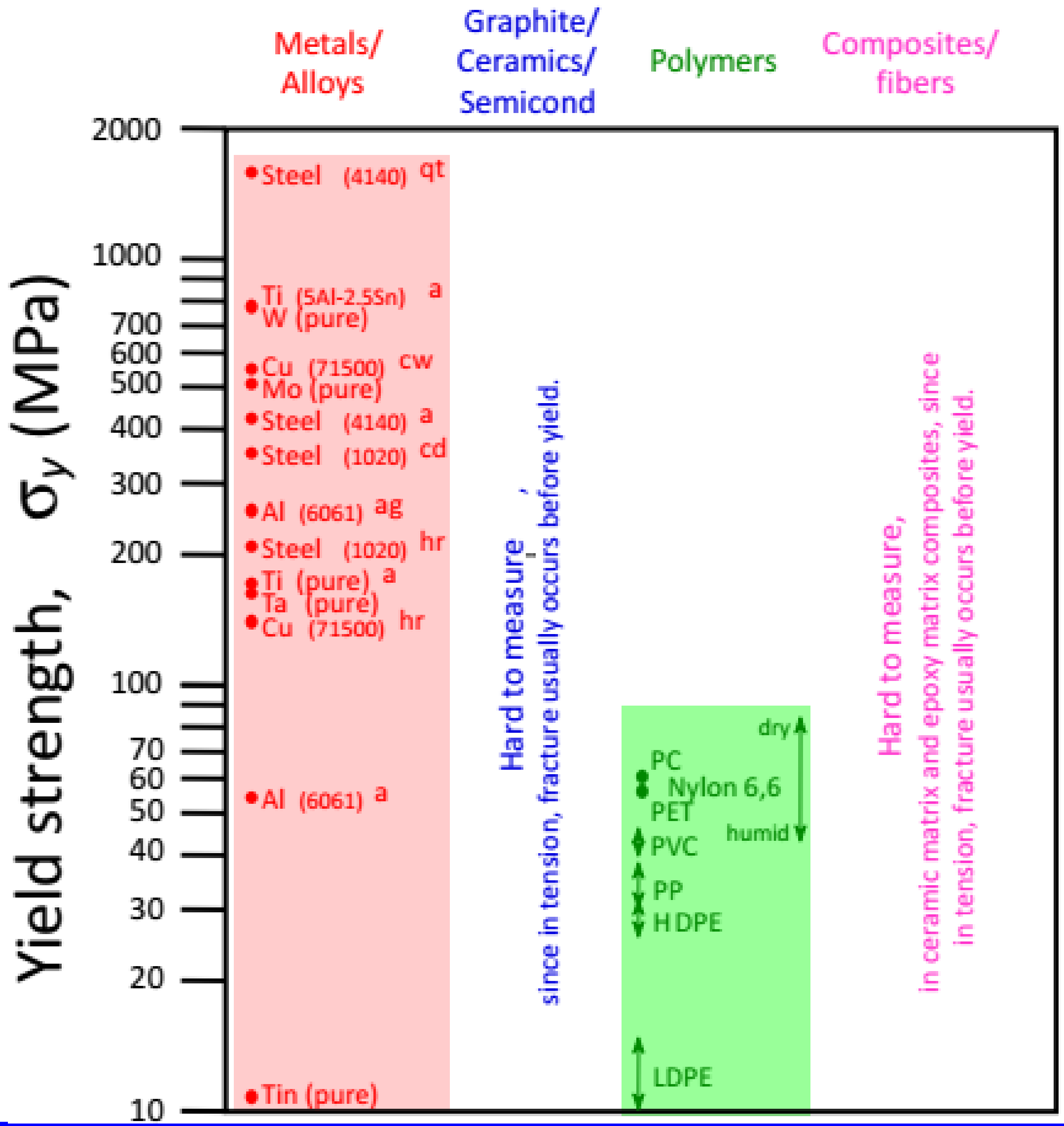
Contd…

- For materials having a nonlinear elastic region, use of the strain offset method is not possible, and the usual practice is to define the yield strength as the stress required to produce some amount of strain (e.g., $\varepsilon = 0.005$).
- After yielding, the stress necessary to continue plastic deformation in metals increases to a maximum, point M.
- Then decreases to the eventual fracture, point F.
- The tensile strength TS (MPa or psi) is the stress at the maximum on the engineering stress–strain curve.
- This corresponds to the maximum stress that can be sustained by a structure in tension; if this stress is applied and maintained, fracture will result.
- All deformation to this point is uniform throughout the narrow region of the tensile specimen.
- However, at this maximum stress, a small constriction or neck begins to form at some point, and all subsequent deformation is confined at this neck and this phenomenon is termed necking and fracture ultimately occurs at the neck.
- The fracture strength corresponds to the stress at fracture.



Typical engineering stress–strain behavior to fracture, point F. The tensile strength TS is indicated at point M. The circular insets represent the geometry of the deformed specimen at various points along the curve.

Yield Strength: Comparison

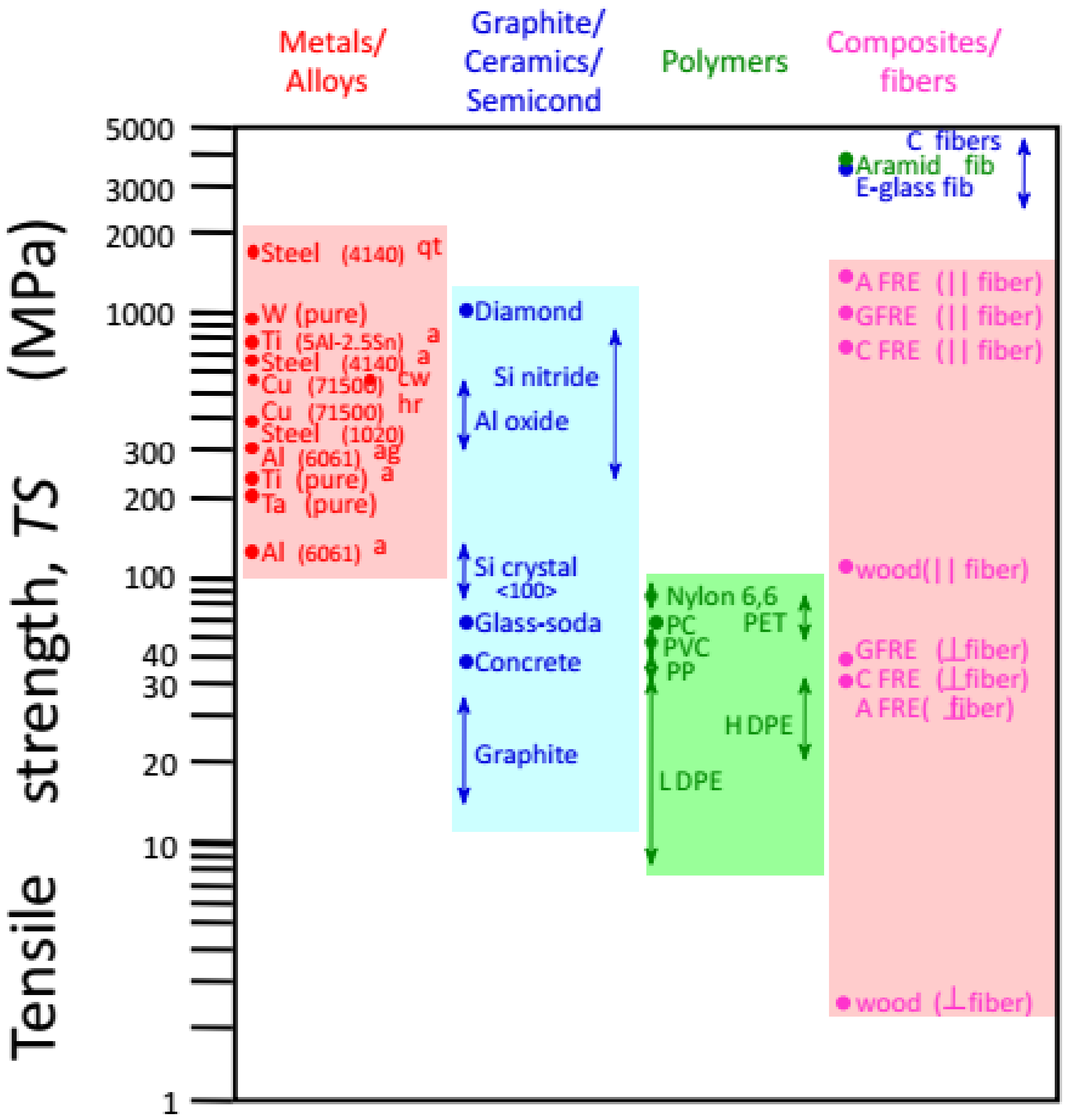


Room T values

a = annealed
hr = hot rolled
ag = aged
cd = cold drawn
cw = cold worked
qt = quenched & tempered

σ_y(ceramics) >> σ_y(metals) >> σ_y(polymers)

Tensile Strength: Comparison



Room T values

a = annealed
hr = hot rolled
ag = aged
cd = cold drawn
cw = cold worked
qt = quenched & tempered
AFRE, GFRE, & CFRE = aramid, glass, & carbon fiber-reinforced epoxy composites, with 60 vol% fibers.

Example – 3

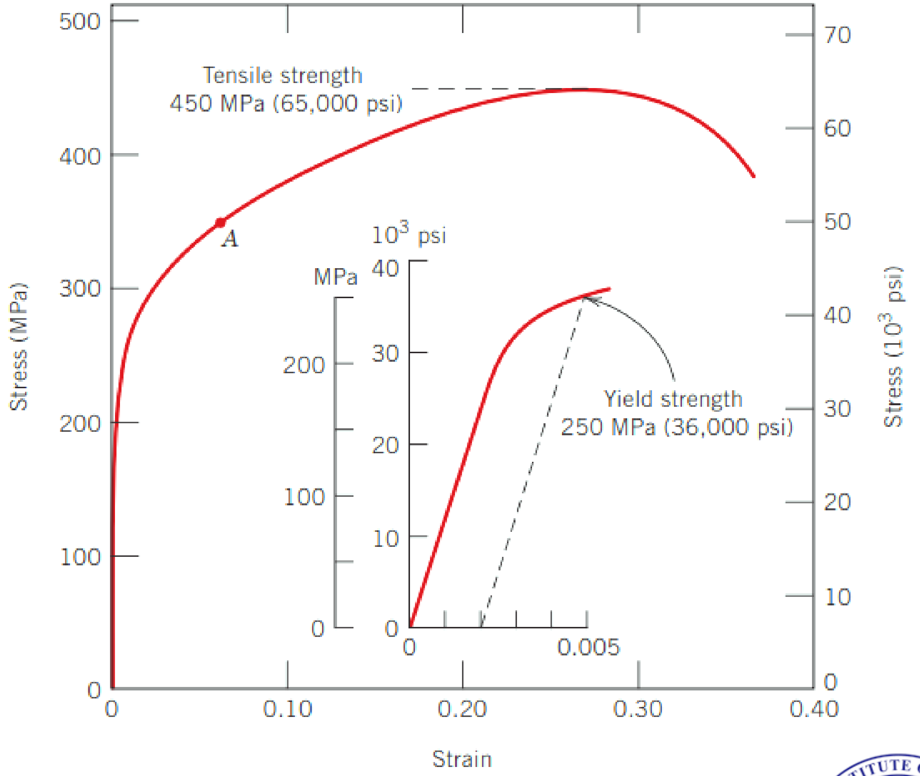
- From the tensile stress–strain behavior for the brass specimen shown in figure, determine the following: (a) The modulus of elasticity (b) The yield strength at a strain offset of 0.002 (c) The maximum load that can be sustained by a cylindrical specimen having an original diameter of 12.8 mm (0.505 in.) (d) The change in length of a specimen originally 250 mm (10 in.) long that is subjected to a tensile stress of 345 MPa (50,000 psi).
- Solution: (a) The modulus of elasticity is the slope of the elastic or initial linear portion of the stress– strain curve.
- The strain axis has been expanded in the inset of figure to facilitate this computation.
- The slope of this linear region is the rise over the run, or the change in stress divided by the corresponding change in strain; in mathematical terms,

$$E = \text{slope} = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1}$$

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

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

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



The stress–strain behavior for the brass specimen

Contd…

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

- (c) The maximum load that can be sustained by the specimen is calculated in which σ is taken to be the tensile strength, from the figure, 450 MPa (65,000 psi).

- Solving for F, the maximum load yields,

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

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

- (d) To compute the change in length, Δl, it is first necessary to determine the strain that is produced by a stress of 345 MPa.

- This is accomplished by locating the stress point on the stress–strain curve, point A, and reading the corresponding strain from the strain axis, which is approximately 0.06.

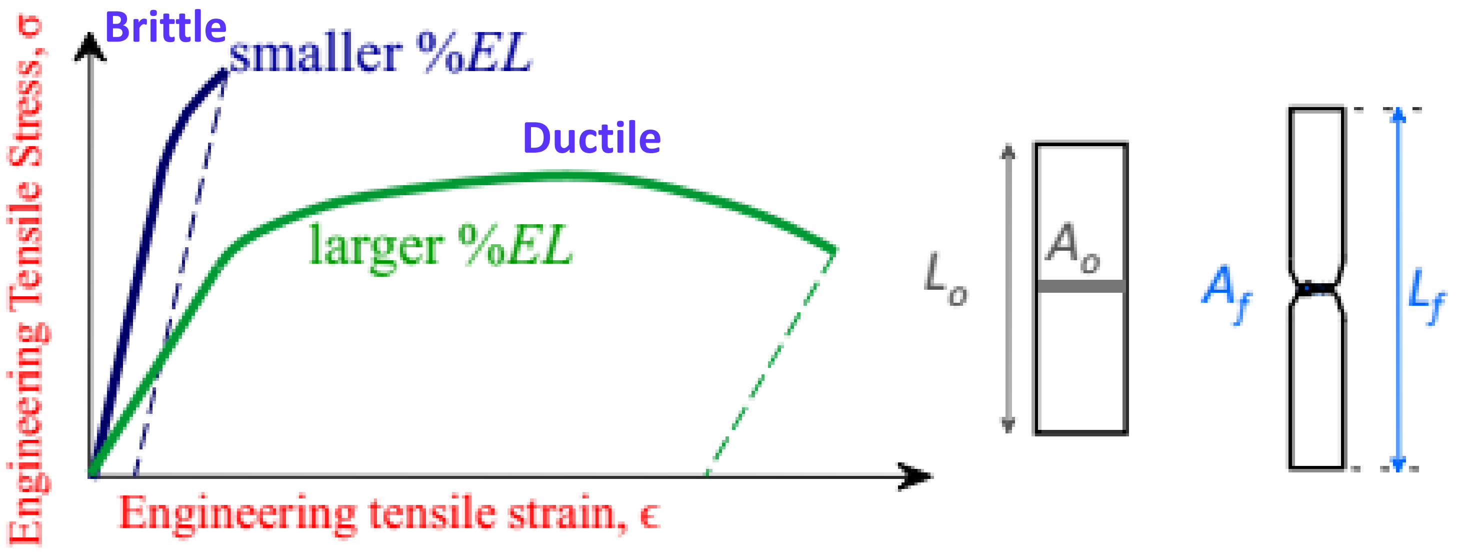
- Inasmuch as l_0 = 250 mm, we have,

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

Ductility, %Elongation

- Ductility may be expressed quantitatively as either percent elongation or percent reduction in area.

- The percent elongation (%EL) is the percentage of plastic strain at fracture: $\%EL = \frac{L_f - L_o}{L_o} \times 100$



- Another ductility measure: $\%RA = \frac{A_o - A_f}{A_o} \times 100$

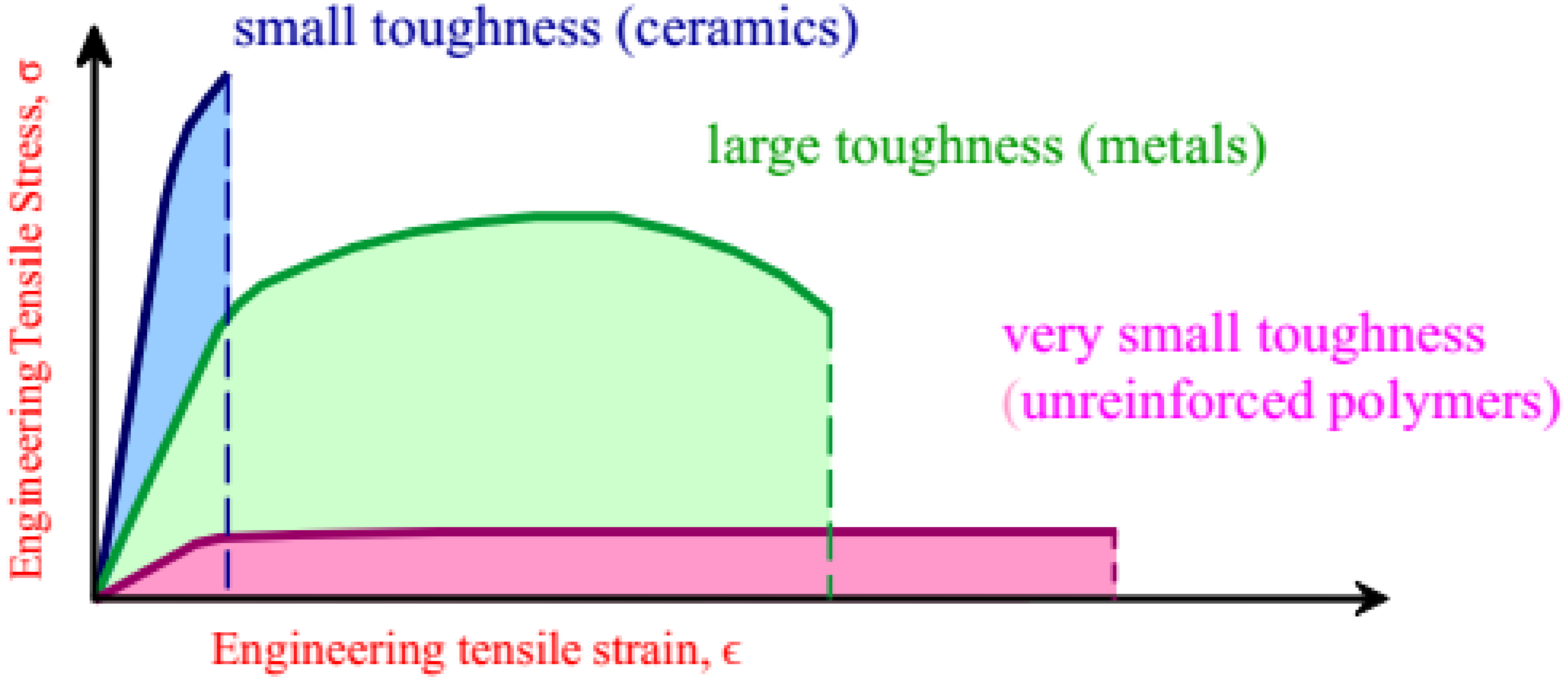
Contd…

Typical Mechanical Properties of Several Metals and Alloys in an Annealed State

Metal Alloy	*Yield Strength, MPa (ksi)*	*Tensile Strength, MPa (ksi)*	*Ductility, %EL [in 50 mm (2 in.)]*
Aluminum	35 (5)	90 (13)	40
Copper	69 (10)	200 (29)	45
Brass (70Cu–30Zn)	75 (11)	300 (44)	68
Iron	130 (19)	262 (38)	45
Nickel	138 (20)	480 (70)	40
Steel (1020)	180 (26)	380 (55)	25
Titanium	450 (65)	520 (75)	25
Molybdenum	565 (82)	655 (95)	35

Toughness

- Energy required to break a unit volume of material.
- It can be approximated by the area under the stress-strain curve up to the point of fracture.

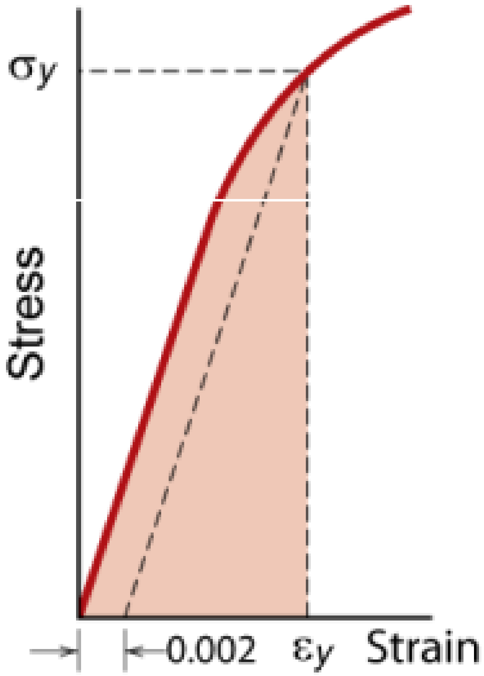


- For brittle fracture: elastic energy
- For ductile fracture: elastic + plastic energy

Resilience, U_r

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

- **Modulus of resilience** is the strain energy per unit volume required to stress a material from an unloaded state up to the point of yielding.



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

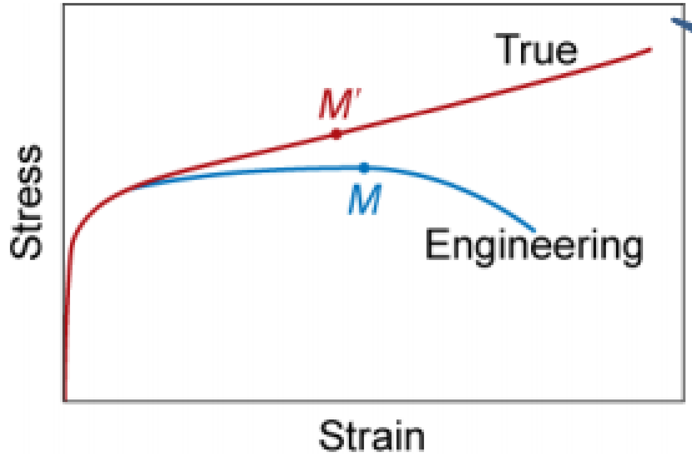
If we assume a linear stress-strain curve this simplifies to

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

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

True Stress and Strain

- True stress: $\sigma_{True} = \dfrac{F}{A_i}$
- If no volume change occurs during deformation $A_i l_i = A_0 l_0$
- True strain: $\varepsilon_{True} = \ln \dfrac{l_i}{l_o}$
- The relationship with engineering stress and engineering strain is: $$\sigma_T = \sigma(1+\varepsilon)$$ $$\varepsilon_T = \ln(1+\varepsilon)$$
- **Necking** begins at point M on the engineering curve, which corresponds to on the true curve.
- The **corrected true stress–strain curve** takes into account the complex stress state within the neck region.



A comparison of typical tensile engineering stress–strain and true stress–strain behaviors

Contd…

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

$$\sigma_T = K\varepsilon_T^n$$

- In this expression, K and n are constants; these values vary from alloy to alloy and also depend on the condition of the material (whether it has been plastically deformed, heat-treated, etc.).

- The parameter n is often termed the strain-hardening exponent and has a value less than unity.

- Values of n and K for several alloys are given in the below table.

The n and K Values for Several Alloys

Material	*n*	*K* (*MPa*)	*K* (*psi*)
Low-carbon steel (annealed)	0.21	600	87,000
4340 steel alloy (tempered @ 315°C)	0.12	2650	385,000
304 stainless steel (annealed)	0.44	1400	205,000
Copper (annealed)	0.44	530	76,500
Naval brass (annealed)	0.21	585	85,000
2024 aluminum alloy (heat-treated—T3)	0.17	780	113,000
AZ-31B magnesium alloy (annealed)	0.16	450	66,000

Example – 4

- A cylindrical specimen of steel having an original diameter of 12.8 mm (0.505 in.) is tensile-tested to fracture and found to have an engineering fracture strength σ_f of 460 MPa (67,000 psi). If its cross-sectional diameter at fracture is 10.7 mm (0.422 in.), determine (a) The ductility in terms of percentage reduction in area and (b) The true stress at fracture.
- Solution: (a) Ductility is computed, as:

$$\%\,\mathrm{RA} = \frac{\left(\frac{12.8\text{ mm}}{2}\right)^2 \pi - \left(\frac{10.7\text{ mm}}{2}\right)^2 \pi}{\left(\frac{12.8\text{ mm}}{2}\right)^2 \pi} \times 100$$

$$= \frac{128.7\text{ mm}^2 - 89.9\text{ mm}^2}{128.7\text{ mm}^2} \times 100 = 30\%$$

- (b) True stress is defined by the below equation, where, in this case, the area is taken as the fracture area A_f.
- However, the load at fracture must first be computed from the fracture strength as:

$$F = \sigma_f A_0 = (460 \times 10^6\text{ N/m}^2)(128.7\text{ mm}^2)\left(\frac{1\text{ m}^2}{10^6\text{ mm}^2}\right) = 59{,}200\text{ N}$$

- Thus, the true stress is calculated as:

$$\sigma_T = \frac{F}{A_f} = \frac{59{,}200\text{ N}}{(89.9\text{ mm}^2)\left(\frac{1\text{ m}^2}{10^6\text{ mm}^2}\right)}$$

$$= 6.6 \times 10^8\text{ N/m}^2 = 660\text{ MPa } (95{,}700\text{ psi})$$

Example – 5

- Compute the strain-hardening exponent n for an alloy, in which a true stress of 415 MPa (60,000 psi) produces a true strain of 0.10; assume a value of 1035 MPa (150,000 psi) for K.
- Solution: This requires some algebraic manipulation, so that n becomes the dependent parameter.
- We first take the logarithm of both sides as follows: $\log \sigma_T = \log(K\varepsilon_T^n) = \log K + \log(\varepsilon_T^n)$
- Which leads to, $\log \sigma_T = \log K + n \log \varepsilon_T$
- Rearrangement of this expression yields, $n \log \varepsilon_T = \log \sigma_T - \log K$
- And when solving for n, the following results:

$$n = \frac{\log \sigma_T - \log K}{\log \varepsilon_T}$$

- We now solve for the value of n by insertion of σ_T (415 MPa), K (1035 MPa) and ε_T (0.10) provided in the problem statement as follows:

$$n = \frac{\log(415\ \text{MPa}) - \log(1035\ \text{MPa})}{\log(0.1)} = 0.40$$

Hardness

- **Hardness is a measure of a material's resistance to localized plastic deformation (e.g., a small dent or a scratch).**

- **Hardness tests are performed more frequently than any other mechanical test for several reasons:**

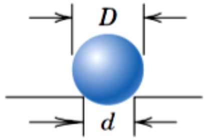
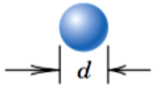
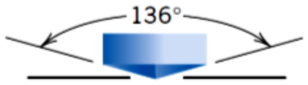
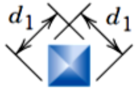
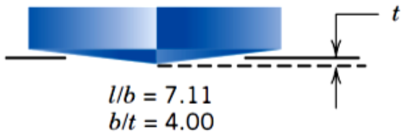
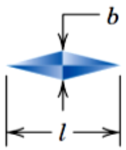
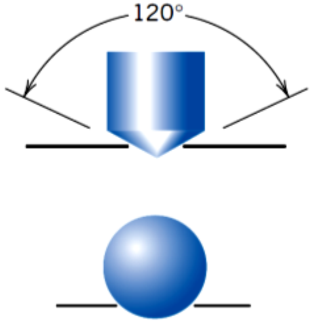
  - **They are simple and inexpensive—ordinarily no special specimen need be prepared, and the testing apparatus is relatively inexpensive.**

  - **The test is relatively non-destructive—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 Testing Techniques

- ❑ Resistance to permanently indenting the surface.
- ❑ Large hardness means:
  - ○ Resistance to plastic deformation or cracking in compression
  - ○ Better wear properties

Test	Indenter	Shape of Indentation: Side View	Shape of Indentation: Top View	Load	Formula for Hardness Number[a]
Brinell	10-mm sphere of steel or tungsten carbide			P	$HB = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
Vickers microhardness	Diamond pyramid			P	$HV = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid			P	$HK = 14.2P/l^2$
Rockwell and superficial Rockwell	Diamond cone; $\frac{1}{16}$-, $\frac{1}{8}$-, $\frac{1}{4}$-, $\frac{1}{2}$- in.-diameter steel spheres			60 kg, 100 kg, 150 kg } Rockwell 15 kg, 30 kg, 45 kg } Superficial Rockwell	

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Scale Symbol	Indenter	Major Load (kg)
A	Diamond	60
B	$\frac{1}{16}$-in. ball	100
C	Diamond	150
D	Diamond	100
E	$\frac{1}{8}$-in. ball	100
F	$\frac{1}{16}$-in. ball	60
G	$\frac{1}{16}$-in. ball	150
H	$\frac{1}{8}$-in. ball	60
K	$\frac{1}{8}$-in. ball	150

Rockwell hardness scales

Scale Symbol	Indenter	Major Load (kg)
15N	Diamond	15
30N	Diamond	30
45N	Diamond	45
15T	$\frac{1}{16}$-in. ball	15
30T	$\frac{1}{16}$-in. ball	30
45T	$\frac{1}{16}$-in. ball	45
15W	$\frac{1}{8}$-in. ball	15
30W	$\frac{1}{8}$-in. ball	30
45W	$\frac{1}{8}$-in. ball	45

Superficial Rockwell hardness scales

Fracture of Metals

- Simple fracture is the separation of a body into two or more pieces in response to an imposed stress that is static (i.e., constant or slowly changing with time) and at temperatures that are low relative to the melting temperature of the material.

- Fracture can also occur from fatigue (when cyclic stresses are imposed) and creep (time-dependent deformation, normally at elevated temperatures).

- Although applied stresses may be tensile, compressive, shear, or torsional (or combinations of these), the topic will be confined to fractures that result from uniaxial tensile loads.

- For metals, two fracture modes are possible: ductile and brittle.

- Classification is based on the ability of a material to experience plastic deformation.

    - Ductile metals typically exhibit substantial plastic deformation with high energy absorption before fracture.
    - However, brittle fracture normally exhibit little or no plastic deformation with low energy absorption.

Contd…

- Ductile and brittle are relative terms; whether a particular fracture is one mode or the other depends on the situation.
- Ductility may be quantified in terms of percent elongation and percent reduction in area.
- Ductility is a function of temperature of the material, the strain rate, and the stress state.
- Any fracture process involves two steps—crack formation and propagation—in response to an imposed stress.
- The mode of fracture is highly dependent on the mechanism of crack propagation.
- Ductile fracture is characterized by extensive plastic deformation in the vicinity of an advancing crack.
- The process proceeds relatively slowly as the crack length is extended and such a crack is often said to be stable, i.e., it resists any further extension unless there is an increase in the applied stress.

Contd…

- In addition, there typically is evidence of appreciable gross deformation at the fracture surfaces (e.g., twisting and tearing).

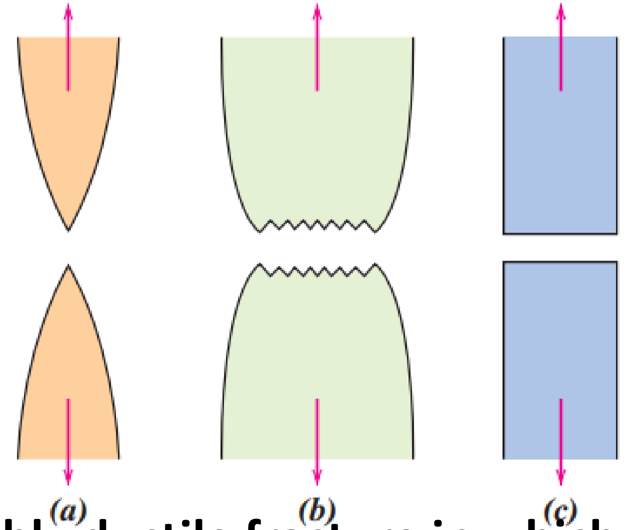
- However, for brittle fracture, cracks may spread extremely rapidly with very little accompanying plastic deformation.

- Such cracks may be said to be unstable, and crack propagation once started, continues spontaneously without an increase in magnitude of the applied stress.

- Ductile fracture is almost always preferred to brittle fracture for two reasons:
  - First, brittle fracture occurs suddenly and catastrophically without any warning; this is a consequence of the spontaneous and rapid crack propagation.
  - In ductile fracture, the presence of plastic deformation gives warning that failure is imminent, allowing preventive measures to be taken.
  - Second, more strain energy is required to induce ductile fracture in as much as these materials are generally tougher.
  - Under the action of an applied tensile stress, many metal alloys are ductile, whereas ceramics are typically brittle, and polymers may exhibit a range of behaviors.

Ductile Fracture

- Ductile fracture surfaces have distinctive features on both macroscopic and microscopic levels.
- The figure shows schematic representations for two characteristic macroscopic fracture profiles.
- The configuration shown in figure a is found for extremely soft metals, such as pure gold and lead at room temperature, and other metals, polymers, and inorganic glasses at elevated temperatures.
- These highly ductile materials neck down to a point fracture, showing virtually 100% reduction in area.
- The most common type of tensile fracture profile for ductile metals is that represented in figure b, where fracture is preceded by only a moderate amount of necking.

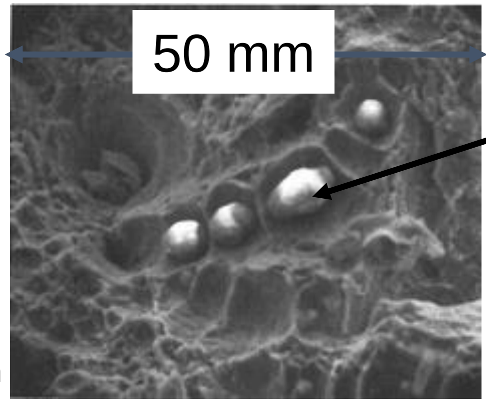


(a) Highly ductile fracture in which the specimen necks down to a point (b) Moderately ductile fracture after some necking. (c) Brittle fracture without any plastic deformation

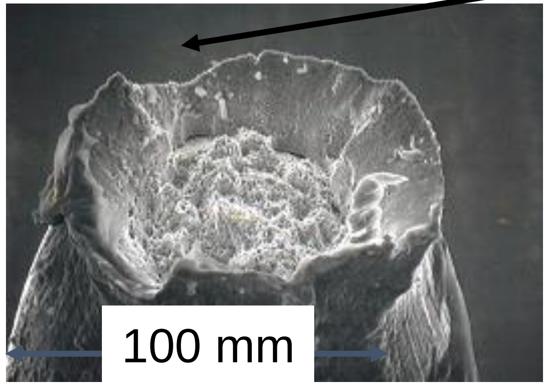
Contd…

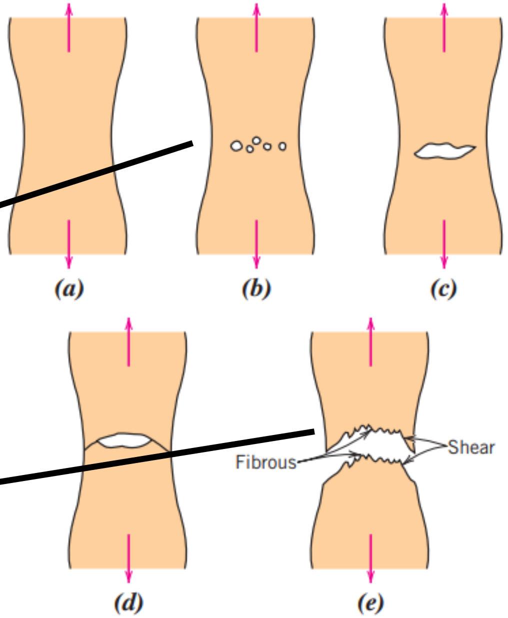
- The fracture process normally occurs in several stages as shown in figure.
- First, after necking begins (figure a) , small cavities, or micro-voids, form in the interior of the cross section, as indicated in figure b.
- Next, as deformation continues, these micro-voids enlarge, come together, and coalesce to form an elliptical crack, which has its long axis perpendicular to the stress direction.
- The crack continues to grow in a direction parallel to its major axis by this micro-void coalescence process as shown in figure c.
- Finally, fracture ensues by the rapid propagation of a crack around the outer perimeter of the neck as shown in figure d by shear deformation at an angle of about 45° with the tensile axis—the angle at which the shear stress is a maximum.
- Sometimes a fracture with this characteristic surface contour is termed a cup-and-cone fracture because one of the mating surfaces is in the form of a cup and the other like a cone.

Resulting fracture surfaces (steel)



particles serve as void nucleation sites





Stages in the cup-and-cone fracture. (a) Initial necking (b) Small cavity formation (c) Coalescence of cavities to form a crack (d) Crack propagation (e) Final shear fracture at a 45° angle relative to the tensile direction

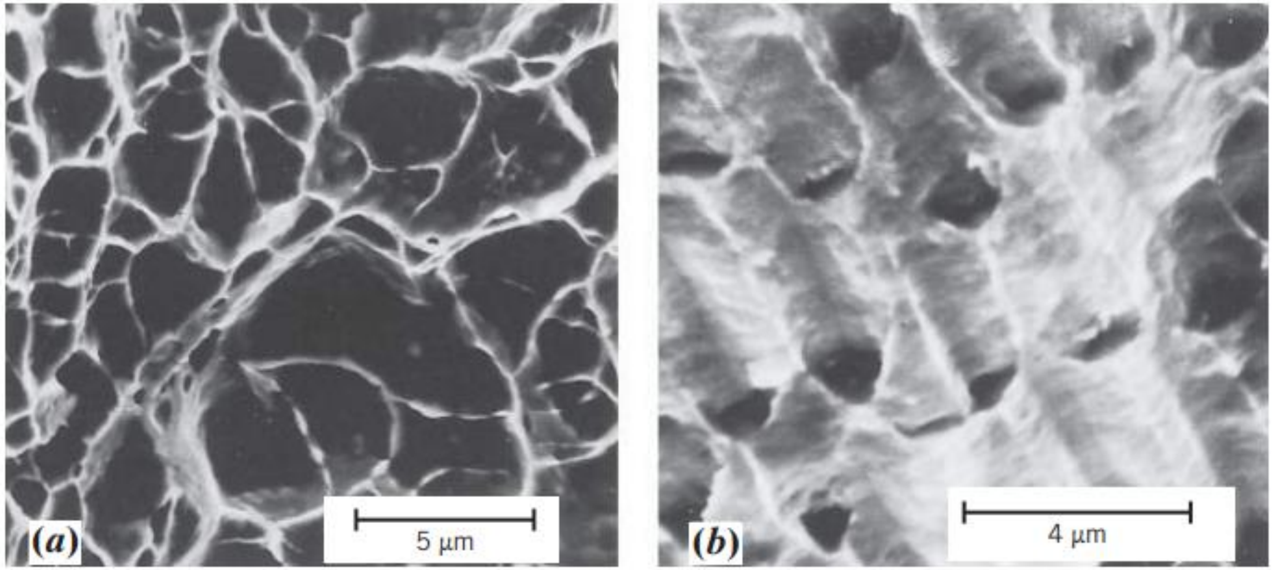
Contd…

- In this type of fractured specimen shown in figure a, the central interior region of the surface has an irregular and fibrous appearance, which is indicative of plastic deformation.

(a)

(b)

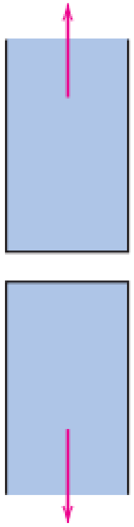
(a) Cup-and-cone fracture in aluminum and (b) Brittle fracture in gray cast iron



(a) Scanning electron fractograph showing spherical dimples characteristic of ductile fracture resulting from uniaxial tensile loads. 3300X and (b) Scanning electron fractograph showing parabolic-shaped dimples characteristic of ductile fracture resulting from shear loading. 5000X

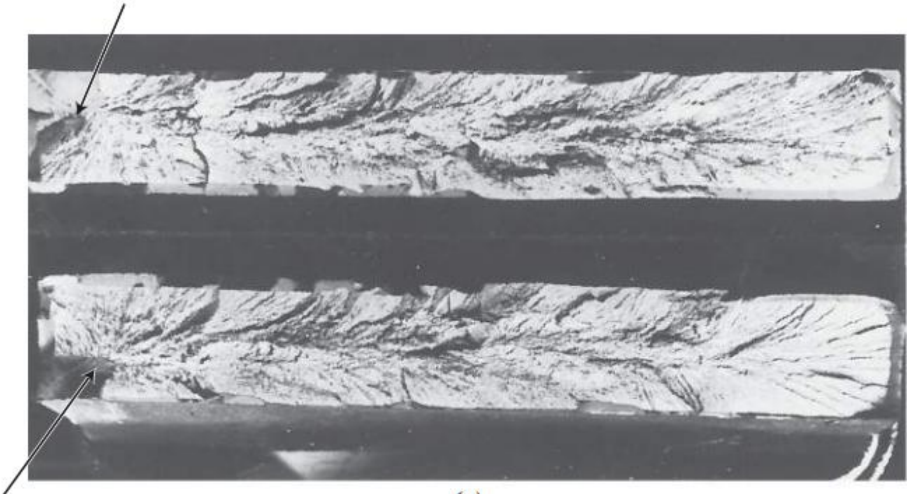
Brittle Fracture

- Brittle fracture takes place without any appreciable deformation and by rapid crack propagation.
- The direction of crack motion is very nearly perpendicular to the direction of the applied tensile stress and yields a relatively flat fracture surface, as indicated in figure c.
- Fracture surfaces of materials that fail in a brittle manner have distinctive patterns; any signs of gross plastic deformation are absent.
- For example, in some steel pieces, a series of V-shaped "chevron" markings may form near the center of the fracture cross section that point back toward the crack initiation site as shown in figure a.



(c)

Arrows indicate point at which failure originated



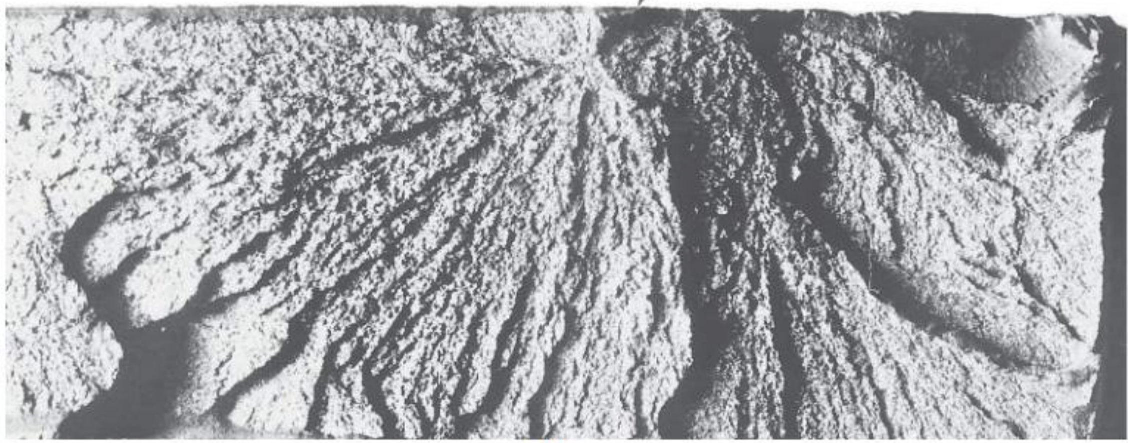
(a)

(a) Photograph showing V-shaped "chevron" markings characteristic of brittle fracture. Arrows indicate origin of crack. Approximate actual size.

Contd…

- Other brittle fracture surfaces contain lines or ridges that radiate from the origin of the crack in a fanlike pattern shown in figure b.
- Often, both of these marking patterns are sufficiently coarse to be discerned with the naked eye.
- For very hard and fine-grained metals, there is no discernible fracture pattern.
- Brittle fracture in amorphous materials, such as ceramic glasses, yields a relatively shiny and smooth surface.

Arrows indicate point at which failure originated



(b)

(b) Photograph of a brittle fracture surface showing radial fan-shaped ridges. Arrow indicates origin of crack. Approximately 2X.

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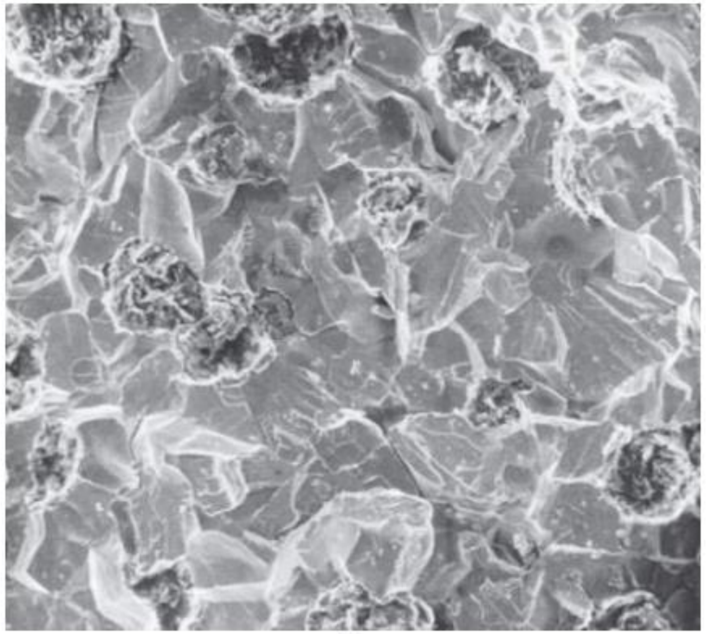
- For most brittle crystalline materials, crack propagation corresponds to the successive and repeated breaking of atomic bonds along specific crystallographic planes shown in figure a; such a process is termed cleavage.

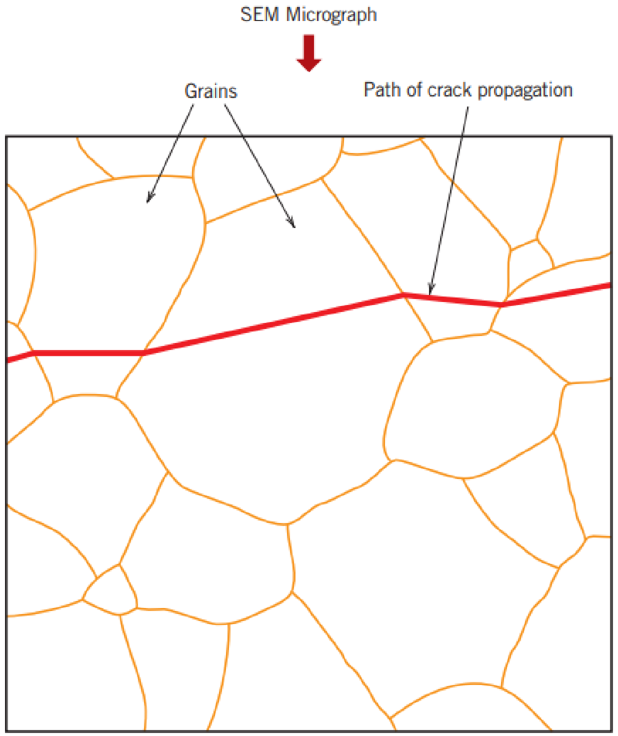


(b)

(b) Scanning electron fractograph of ductile cast iron showing a transgranular fracture surface

- This type of fracture is said to be transgranular (or transcrystalline) because the fracture cracks pass through the grains.

- Macroscopically, the fracture surface may have a grainy or faceted texture shown in figure b as a result of changes in orientation of the cleavage planes from grain to grain.



(a)

(a) Schematic cross-section profile showing crack propagation through the interior of grains for transgranular fracture

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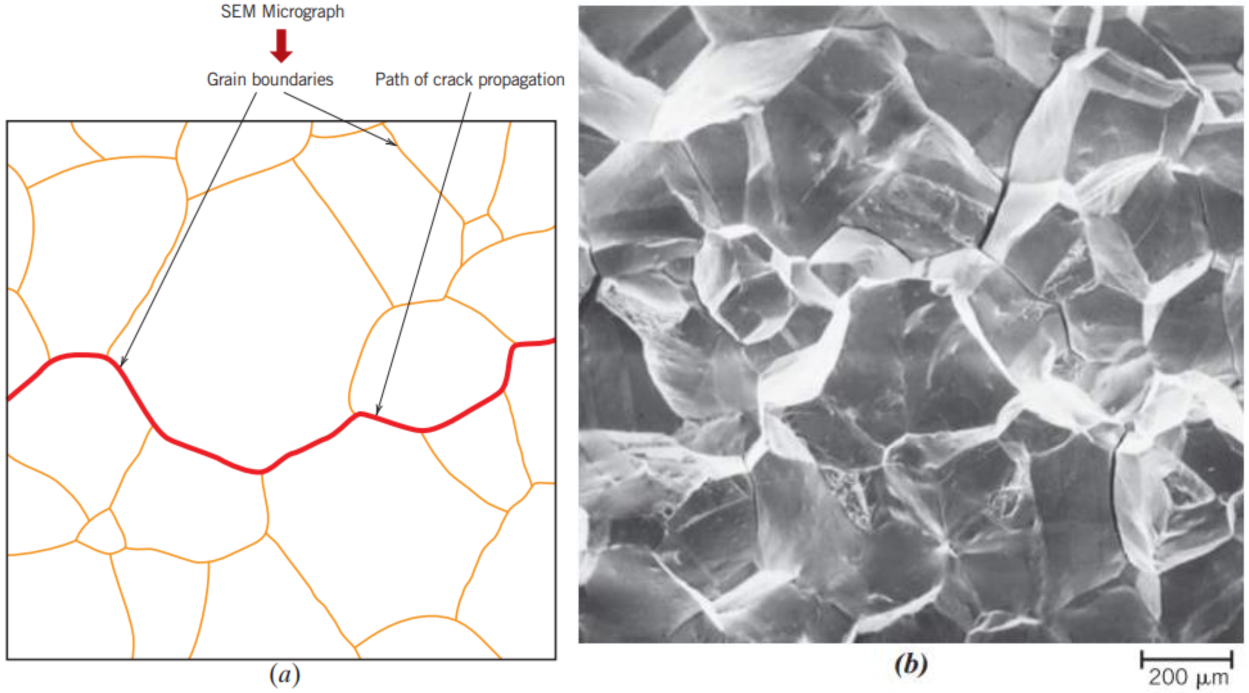
- In some alloys, crack propagation is along grain boundaries as shown in figure a; this fracture is termed intergranular.
- Figure b is a scanning electron micrograph showing a typical intergranular fracture, in which the three-dimensional nature of the grains may be seen.
- This type of fracture normally results subsequent to the occurrence of processes that weaken or embrittle grain boundary regions.



(a) Schematic cross-section profile showing crack propagation along grain boundaries for intergranular fracture and (b) Scanning electron fractograph showing an intergranular fracture surface. 50X.