AMME1362 - Materials

Introduction to Materials (Chapter 1)

Material Classification	Properties [chemical bonding, conductivity, application, grain sizes]
Metals	• Metallic bonding • Strong, ductile • high thermal & electrical conductivity • opaque, reflective.
Polymers/plastics	• Covalent bonding (sharing of e's) • Soft, ductile, low strength, low density • thermal & electrical insulators • Optically translucent or transparent.
Ceramics	• ionic bonding (refractory) – compounds of metallic & non-metallic elements (oxides, carbides, nitrides, sulfides) • Brittle, glassy, elastic • non-conducting (insulators)
Composites	• Composed of at least 2 different types of materials • Produces a new material with enhanced properties such as hardness, tensile strength etc.

The Materials Selection Process

1. Pick Application → Determine required Properties

   Properties: mechanical, electrical, thermal, magnetic, optical, deteriorative.

2. Properties → Identify candidate Material(s)

   Material: structure, composition.

3. Material → Identify required Processing/Synthesis

   Processing: changes ***structure*** and **overall *shape*** ex: casting, sintering, vapor deposition, doping forming (for semiconductors), joining, annealing.

   - [changing cooling rate of steel changes hardness, faster cooling greater hardness]
   - [adding impurities such as Ni to Copper and deforming Cu increases its resistivity]

PROCESSING/SYNTHESIS -----> MATERIAL -----> PROPERTIES -----> PERFORMANCE/APPLICATION

Mechanical Properties of Metals (Chapter 6)

6.2, 6.4, 6.10, 6.21,6.30, 6.42, 6.43, 6.60,

KEYWORDS	DEFINITION
Stress & strain	These are size-independent measures of load and displacement, respectively
Elastic behavior	This reversible behavior often shows a linear relation between stress and strain. To minimize deformation, select a material with a large elastic modulus (*E* or *G*).
Plastic behavior	This permanent deformation behavior occurs when the tensile (or compressive) uniaxial stress reaches σ_y
Toughness	Energy needed to break a unit volume of material.
Ductility	The plastic strain at failure

DEFORMATION

- On an atomic level, elastic deformation of a material corresponds to the stretching of interatomic bonds and corresponding slight atomic displacements.
-

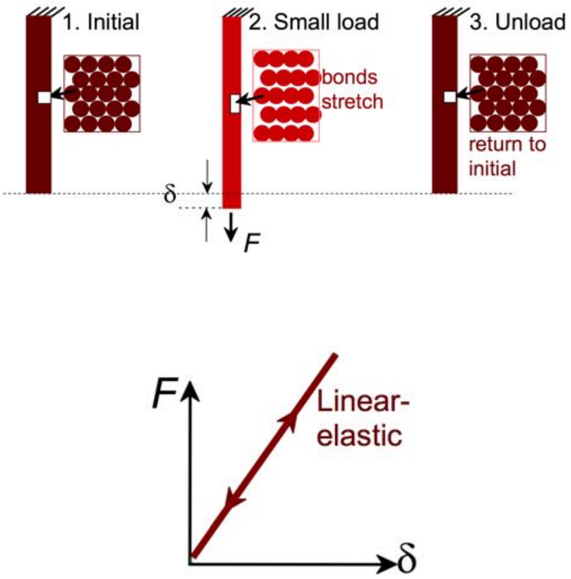
<table>
<tr><th>Elastic Deformation</th><th>Plastic Deformation (METALS)</th></tr>
<tr><td>

- Elastic = reversible
- Non-permanent (i.e. returns back to its own shape when applied load is released)

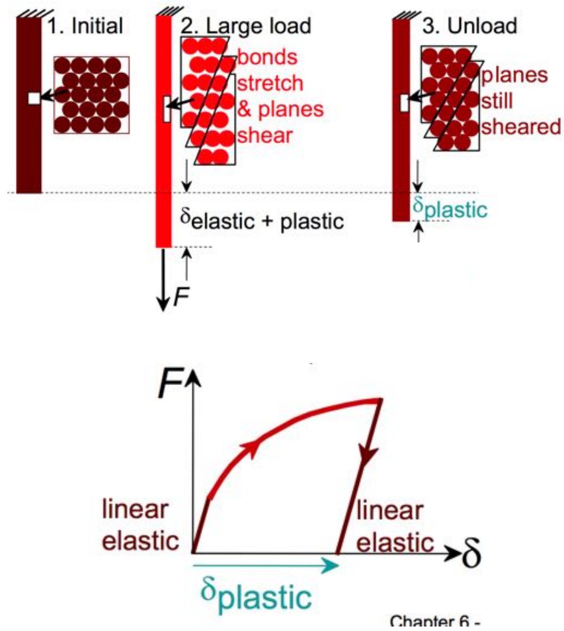
</td><td>

- Plastic = permanent

</td></tr>
<tr><td>



</td><td>



1. A material that is stressed first undergoes elastic, or nonpermanent, deformation.
2. Elastic + Plastic deformation at larger stress
3. Permanent (plastic) after load is removed

</td></tr>
</table>

ENGINEERING STRESS

Engineering stress σ is defined as the instantaneous load divided by the original specimen cross-sectional area

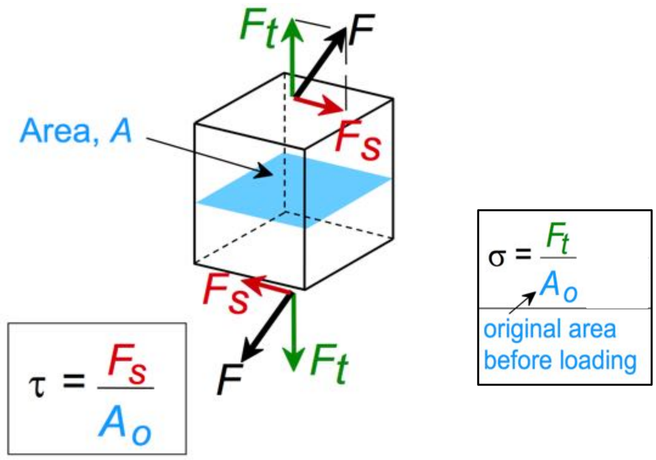
Stress Type

Tensile ($\sigma > 0$)

PERPENDICULAR to Plane

Shear (τ) – scissors

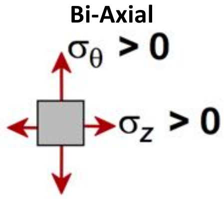
ON THE PLANE



Compressive ($\sigma < 0$)

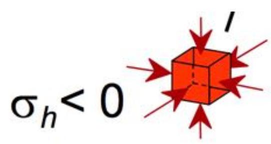
Torsion [form of shear] – TWIST

Bi-Axial

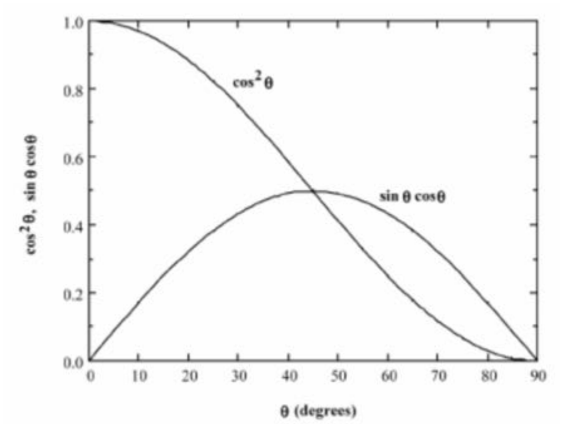


e.g. Pressurized Tank

Hydrostatic Compression



e.g. Fish in Water

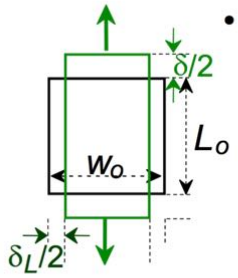
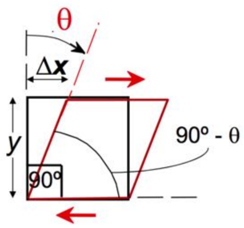


The maximum normal stress at $\theta = 0°$.

The maximum shear stress at $\theta = 45°$

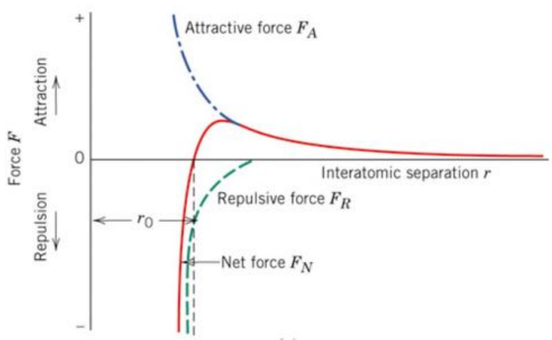
ENGINEERING STRAIN – NO UNITS/DIMENSIONS

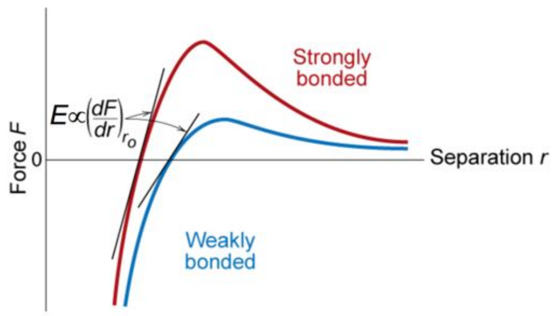
Engineering strain ε is expressed as the Δ in length (in the direction of load application) divided by the original length

Tensile strain	$\varepsilon = \frac{\delta}{L_o}$	
Lateral strain	$\varepsilon_L = \frac{-\delta_L}{w_o}$	
Shear strain (γ)	$\gamma = \frac{\Delta x}{y} = tan\theta$	

For shear elastic deformations, shear stress (τ) and shear strain (γ) are proportional to one another. The constant of proportionality is the shear modulus (G).

MECHANICAL PROPERTIES





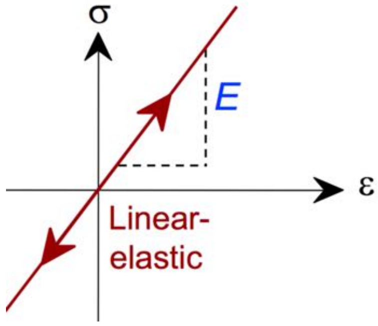
- **Slope of stress strain plot (∝ young's elastic modulus)** depends on bond strength of metal
- As atoms get closer, there is greater electrostatic repulsion. There is a point of balance where the net force is zero → the **gradient** determines how strong the bonding between atoms is.

LINEAR ELASTIC PROPERTIES

- The degree to which a structure deforms or strains depends on the **magnitude of an imposed stress.** For tensile and compressive loading, the slope of the linear elastic region of the stress–strain curve is the **modulus of elasticity (E, stiffness),** per Hooke's law.
- When most materials are deformed **elastically** [due to reduced load size], stress and strain are proportional— that is, a plot of stress versus strain is linear.

Hooke's Law:

$$\sigma = E\varepsilon$$



Hooke's Law is the relationship between engineering stress and engineering strain for elastic deformation (tension and compression)

E - measure of interatomic bonding force (*GPa or psi*) or stiffness

σ - stress placed on material (Nm^{-2})

ε - epsilon

ANELASTICITY

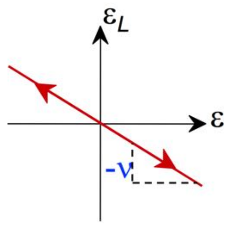
Elastic deformation that is dependent on time is termed *anelastic [e.g. carbon nanotubes]*

DIFFERENCES BETWEEN PLASTIC, ELASTIC & ANELASTICITY

Plastic deformation is permanent whereas elastic and anelasticity deformation results in the material returning to its original shape completely. However elastic deformation is immediate whereas anelastic deformation takes time

POISSON'S RATIO

$$\nu\ (no\ units) = -\frac{\varepsilon_L\ (lateral\ strain - GPa\ or\ psi)}{\varepsilon\ (actual\ strain)}$$



<u>**NOTE**</u>: If object becomes longer under stress, the width (lateral dimension) will decrease

- v > 0.50	Density increases
- v < 0.50	Density decreases → voids form (i.e. widening of the material)

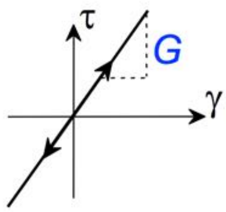
metals: ν ~ 0.33
ceramics: ν ~ 0.25
polymers: ν ~ 0.40

RELATIONSHIP AMONG MODULI AND POISSON RATIO

For shear elastic deformations, shear stress (τ) and shear strain (γ) are proportional to one another. The constant of proportionality is the shear modulus (*G*).

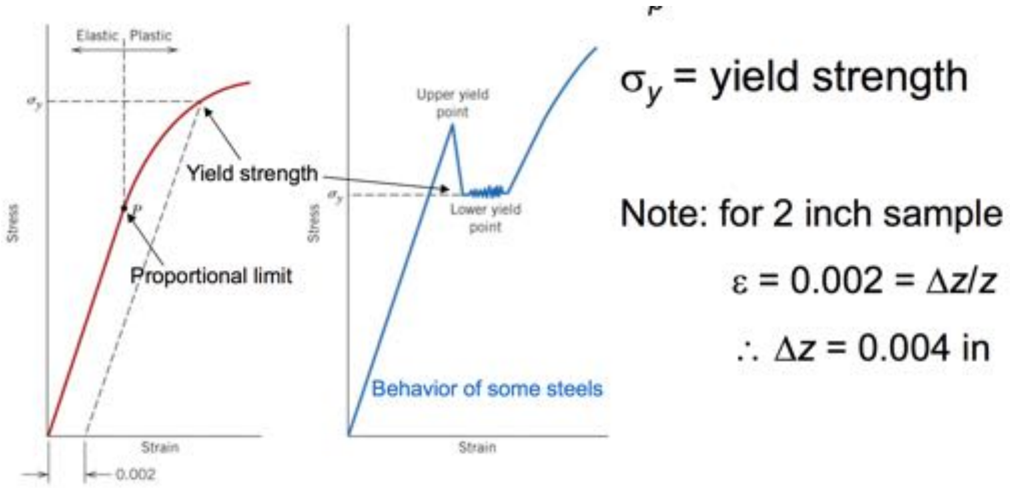
Elastic Shear modulus, *G*:

$$\tau = G\gamma$$



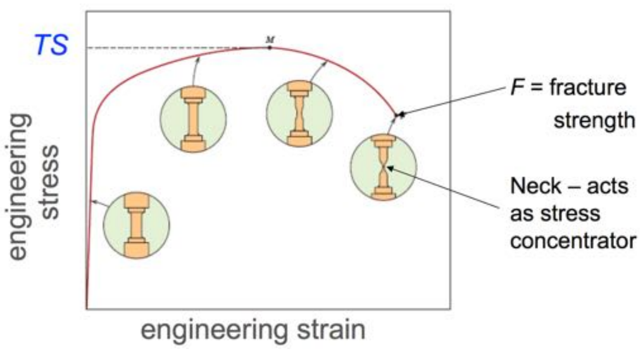
YIELD STRENGTH, σ_y

The minimum stress required for plastic deformation of 0.002 (0.2%)



TENSILE STRENGTH

Maximum stress on engineering stress-strain curve.



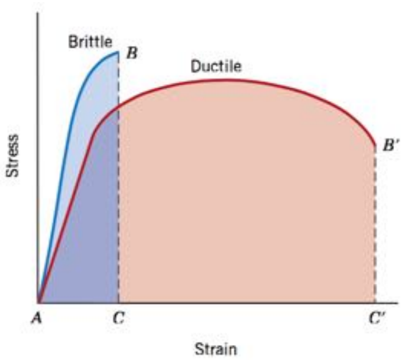
Metals: occurs when noticeable necking starts.

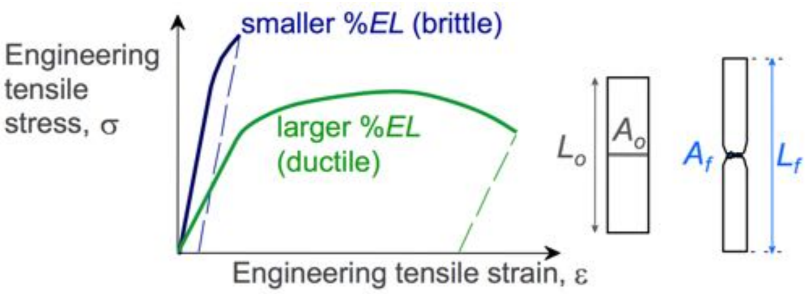
Polymers: occurs when polymer backbone chains are aligned and about to break.

DUCTILITY

Measure of the degree of plastic deformation that has been sustained at fracture. A metal that experiences **very little or no plastic deformation upon fracture** is termed *brittle*

$$\%EL = \frac{L_f - L_o}{L_o} \times 100 \qquad \%RA = \frac{A_o - A_f}{A_o} \times 100$$



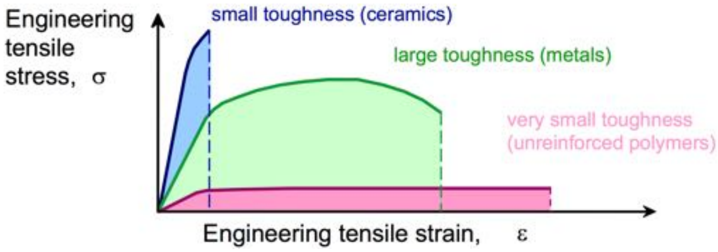


Brittle fracture: Elastic Energy

Ductile fracture: elastic + plastic energy

TOUGHNESS (or fracture toughness)

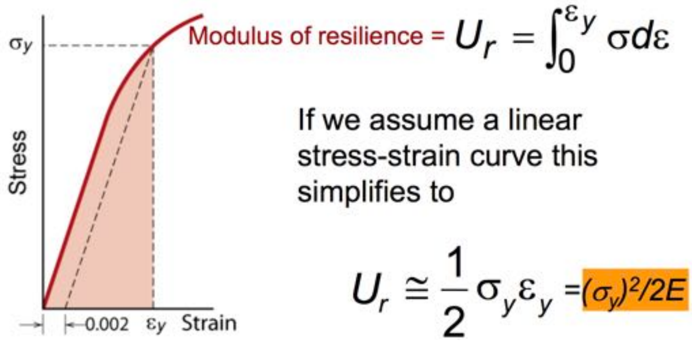
- Energy to break a unit volume of material calculated by area under stress-strain curve
- Measure of material's resistance to fracture when a crack (or other stress-concentrating defect) is present



- The **greater the product of tensile stress and tensile strain**, the greater the toughness
- Metals absorb most amount of energy, hence is used in cars

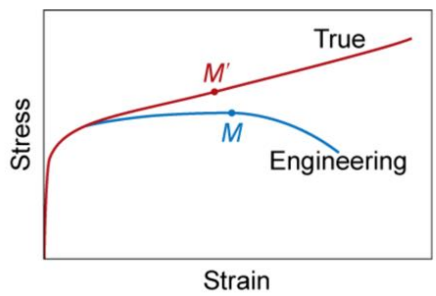
RESILIENCE, U_r

- **Material's ability to store energy for elastic deformation**
- Modulus of resilience – the strain energy per unit volume for stress up to the point of yielding



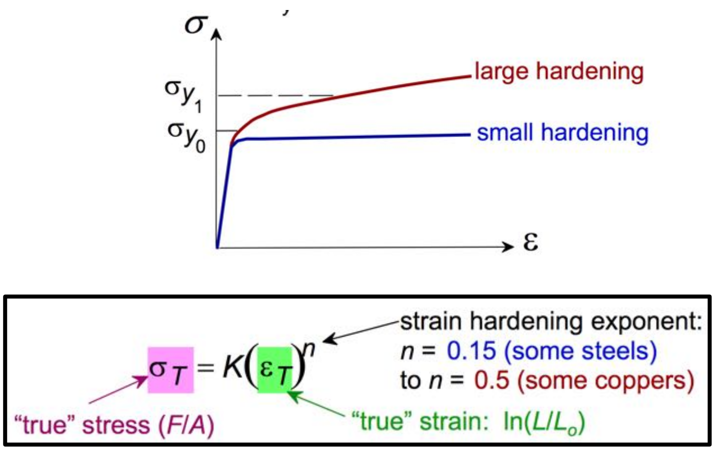
TRUE STRESS & TRUE STRAIN

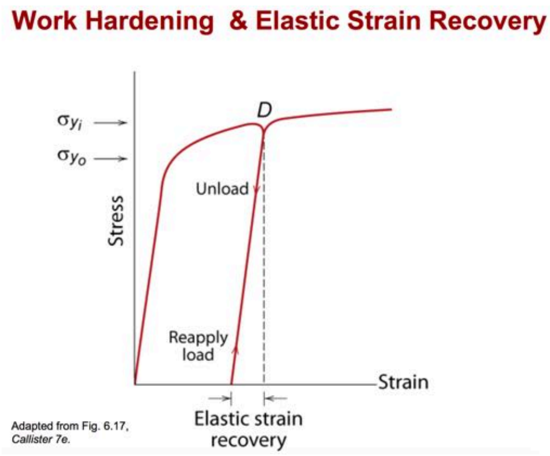
- The true stress and true strain are both instantaneous measurements (instantaneous cross-sectional area, length and elongation of length) unlike engineering stress and strain.
- It is a measure taken **BEFORE NECKING** and **ASSUMING THAT THERE IS NO CHANGE IN VOLUME** [i.e. $A_o l_o = A_i l_i$]



WORK HARDENING

Work hardening is the **increase in the yield strength** of a material due to plastic deformation [new material has higher yield strength compared to its initial undeformed state]





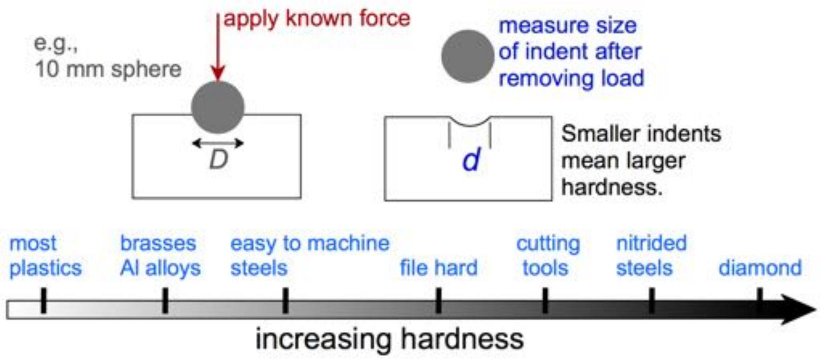
HARDNESS

Resistance to permanently indenting the surface. Although it is not a well-defined property, it is the property tested most because it is:

- Inexpensive & simple
- Non destructive – causes small indentation
- Able to be approximately converted to other properties (e.g. tensile strength)

Large hardness means:

- resistance to plastic deformation or cracking in compression.
- better wear properties.



- ✓ Smaller Indent = Large Hardness
- ✓ **Hardness is inversely proportional to toughness** (i.e. greater hardness, less toughness)

There are many methods to measure hardness such as:

- Rockwell Method → uses a scale up to 130 (useful only 20-100)
  - Uses a minor (10kg) and major load (A,B,C) to give value
  - If value is <20 or > 100, different major load should be used
  - Hardness Specification 80 HRB → 80 Rockwell hardness on the B scale
- Brinell Test (HB = Brinell Hardness)
- Vickers/Knoll Microhardness

COMPARISON OF DIFFERENT HARDNESS SCALES:

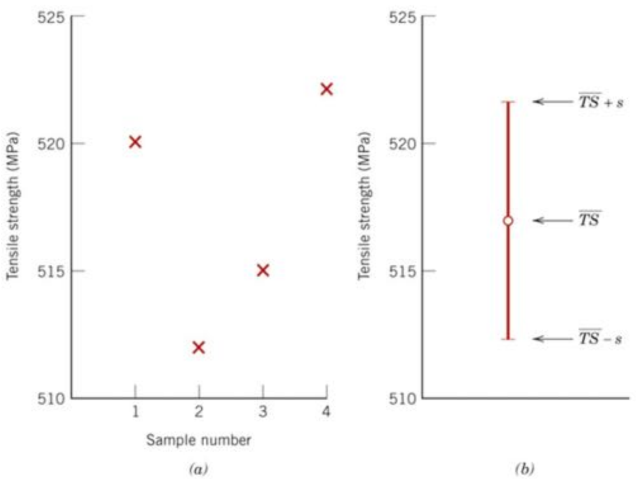
- Comprehensive conversion scheme not available
- Conversion data depend on materials
- Most reliable data exist for steels

Variability in Material Properties

- Elastic modulus is material property (unique)
- Critical properties depend largely on sample flaws (defects, etc.). Large sample to sample variability.
- Hence we use statistic to acknowledge this variation between specimens

Scatter in experimental data

- Test method
- Inhomogeneity
- Slight structural difference
- Operator bias



Structure of Crystalline Solids (Chapter 3)

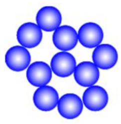
SUMMARY

1. Materials can be single crystals or polycrystalline. Material properties generally vary with single crystal orientation (i.e., they are anisotropic), but are generally non-directional (i.e., they are isotropic) in polycrystals with randomly oriented grains.
2. Some materials can have more than one crystal structure. This is referred to as polymorphism (or allotropy).
3. X-ray/electron diffraction is used for crystal structure and interplanar spacing determinations

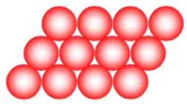
ENERGY AND PACKING

Dense, ordered packed structures tend to have lower energies, HENCE more stable.

Non-Dense Random Packing



Dense Ordered Packing

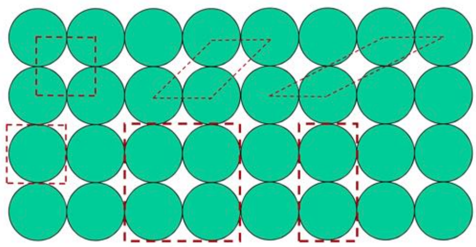


MATERIAL AND PACKING

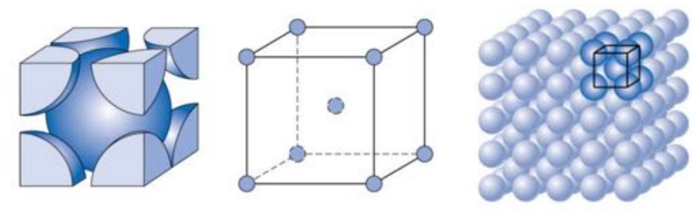
CRYSTALLINE	➢ atoms pack in periodic 3D arrays ➢ typical of: all metals, most ceramics, some polymers
NON-CRYSTALLINE = AMORPHOUS	➢ No periodic packing ➢ Typical of: complex structures, rapid cooling

CRYSTAL SYSTEMS (TERMINOLOGY)

Unit crystal systems: Smallest repetitive volume with the highest symmetry, which contains the complete lattice pattern of a crystal

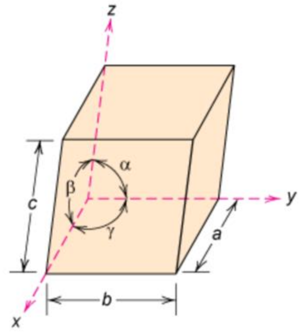


Atomic hard sphere model, in which atoms/ions are solid sphere with well-defined diameters, is used to describe crystalline structures



(a) a hard sphere unit cell (b) a reduced-sphere unit cell (c)

CRYSTAL PARAMETERS - IMPORTANT



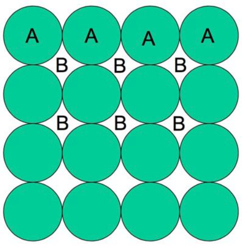
- **Lattice Parameters**: a, b, c (edge lengths),α, β, and γ (inter-axial angles)
- **Coordination Number** – no. of nearest neighbour/touching atoms
- **Atomic Packing Factor** ($AFP = \frac{Volume\ of\ atoms\ in\ unit\ cell}{Total\ Unit\ Cell\ Volume}$)

METALLIC CRYSTAL STRUCTURES

1. Tend to be densely packed because --
   a. Usually one element is present, so all atomic radii are the same.
   b. Metallic bonding is not directional → **allows atoms to be closely packed**
   c. Nearest neighbor distances tend to be small in order to lower bond energy
   d. Electron cloud shields cores from each other
2. Have the simplest crystal structures.

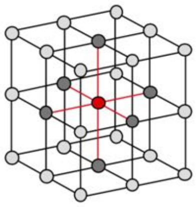
The 4 main structures of metallic crystals are:

Simple cubic



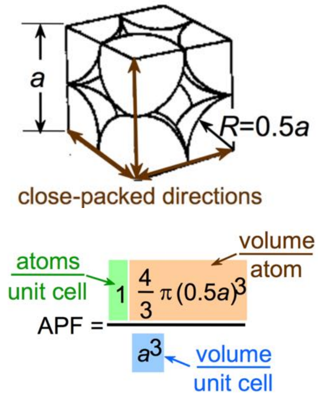
SC

- Rare due to low packing density (only Po has this structure)
- Close-packed directions are cube edges.

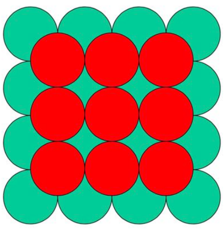


No. of atoms in unit cell:1

Coordinate No: 6

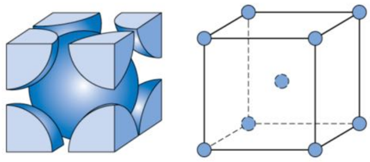


Body-centered cubic (BCC)



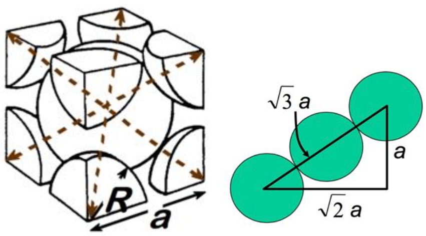
BCC

- Atoms touch each other along **cube diagonals**
- ex: Cr, W, Fe (α), Mo

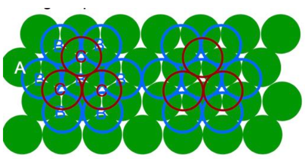


No. of atoms in unit cell: 2

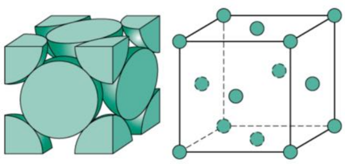
Coordinate No: 8



Face-centered cubic (FCC)



- Atoms touch each other along **face diagonals**.
- Stacking Sequence = ABCABC..
- ex: Al, Cu, Au, Pb, Ni, Pt, Ag



No. of atoms in unit cell: 4

Coordinate No: 12