# Introduction to Materials Engineering

- In this course we will be covering topics such as:

    - Atomic structure and Bonding, Microstructures, & Crystalline Structures.

    - Phase Diagrams and Phase Transformations.

    - Mechanical, Physical, Electrical, & Magnetic Properties.

    - Metals, Ceramics, Polymers, & Composites.

    - And the degradation of materials or Corrosion.

# Types of Materials

- *Metals* – Al, Cu, Iron (Fe), Steel, Alloys
- *Ceramics* – $Al_2O_3$, $Fe_3C$, $YBa_2Cu_3O_7$, Glasses
- *Polymers* – Polyethylene, PVC, Teflon, Elastomers
- *Composites* – Fiberglass, Carbon Fiber, Concrete
- Other Categories:
  – Semiconductors
  – Biomaterials
  – Advanced

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# Materials in History

- *Stone Age* – Naturally available materials
- *Bronze Age* – Man made material (alloy)
- *Iron Age* – Stronger man made material
- *Industrial Revolution* – Cheep Steel
- *Nuclear Age* – Cheep power (???)
- *Space Age* – Transportation advances
- *??? Age* – The next big discovery
- Advances in Materials often precede advances in technology and or society.

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# Materials in the future

- ***Information Age*** – Semiconductors are allowing almost everyone access to more and more information everyday!!!

- ***Smart Materials*** – Materials that sense and respond to changes in their environment.

- ***Nanotechnology*** – The study and design of materials on the atomic scale.

- ***Superconductors*** – materials that have no electrical resistivity and completely exclude magnetic fields.

# Summary

- Materials Engineering covers a broad range of materials topics such as:
    - The structure of materials.
    - The different types of materials.
    - Materials properties and their relation to the microstructure.
- Materials have played a major role in shaping parts of our history.
- In the future, advances in Materials will allow for unimaginable advances in technology and our societies.

# Atomic Structure & Bonding

*Issues to cover…*

- Structure of an atom

- Atomic mass & Avogadros number

- Importance of Valence electrons

- Atomic bonding

- Binding Energy

# Atomic Structure

- The structure of atoms is important to Materials Engineers because it influences the way atoms bond together which in turn helps us to categorize the materials that they form.

- The atomic structure and bonding also allows us to formulate some general conclusions on the mechanical and physical properties of the material.

# The Structure of an Atom

- **Nucleus:** Particle Mass ~ $1.67 \times 10^{-24}$ g
  - **Proton:** Positive Charge ($+1.60 \times 10^{-19}$ C)
  - **Neutron:** Neutral Charge

- **Electron:** Mass ~ $9.11 \times 10^{-28}$ g

  Negatively Charged ($-1.60 \times 10^{-19}$ C)

A normal atom has equal numbers of protons and electrons.

The Atomic Number of an atom is the number of protons it has in it's nucleus.

# Atomic Mass

- The atomic mass of an element is the mass of one mole of the element (g/mol).

- Avogadros number $(N_A = 6.02 \times 10^{23} \text{ atoms}/\text{mole})$

- An Atomic Mass Unit (AMU) is $^1/_{12}$ the mass of a carbon 12 atom.

# Example Problem

✓ How many Cu atoms are needed to coat a post 1983 (Zinc core) penny with a Cu layer 0.15 mm thick?

| | |
|---|---|
| Diameter = 1.90 cm | Density of Cu = 8.93 g/cm$^3$ |
| Thickness = 0.14 cm | Atomic mass of Cu = 63.55 g/mol |

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# Valence Electrons

- Valence electrons are the electrons in the outermost orbital or shell.

- They are the electrons that participate in bonding (ionic, covalent, metallic).

- They also play major roles in most of the physical properties of the material (eg. electrical conductivity, thermal conductivity, magnetism, …).

# Atomic Bonding

- **Metallic Bond** - sea of electrons
- **Covalent Bond** - sharing of electrons
- **Ionic Bond** - one atom giving up electrons to another atom
  - Cation - positive charge (the donor atom)
  - Anion - negative charge (the receptor atom)
- **Van der Waals Bond** - electrostatic attraction (secondary bond)

# Binding Energy

The inter atomic spacing is governed by the balance of attractive and repulsive forces.

Some of the properties that can be related to these are Modulus of Elasticity and Coefficient of Thermal Expansion

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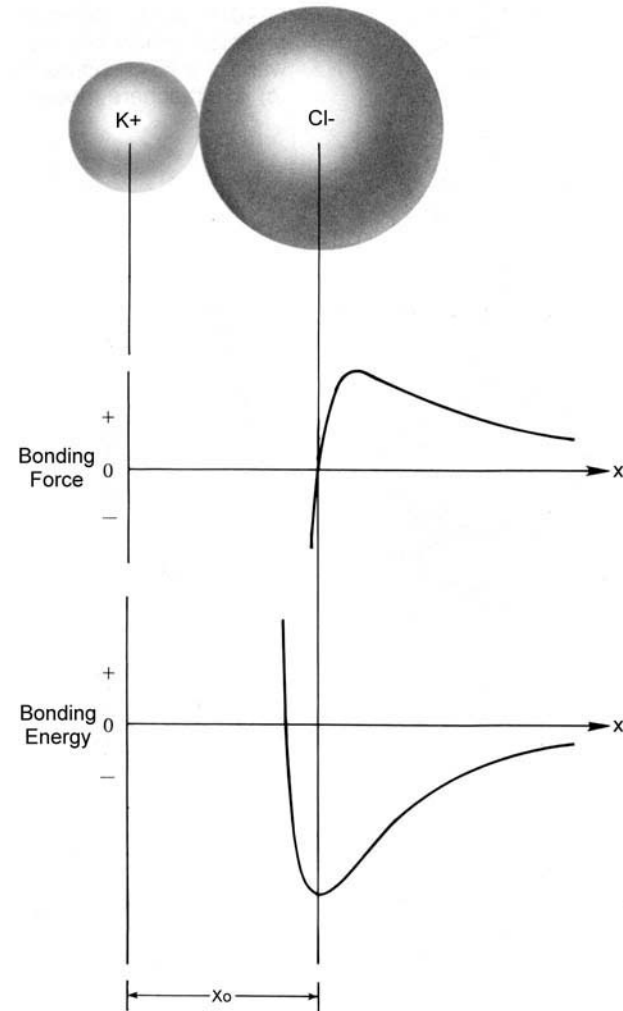
# Summary

- Atomic mass of an element is either in Atomic Mass Units (AMU) or g/mol. We will be using g/mol.

- Valence electrons play an important role in bonding. They also play a major role in other properties such as electrical and thermal conductivity

- Graphs of Bonding Energy and Bonding Force display property traits such as Coefficient of Thermal Expansion and Elastic Modulus (E).

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# Crystalline Structures

*Issues to cover…*

- What are Crystalline Structures

- Points, Directions, and Planes in Unit Cells

- Lattice Parameters

- Close Packed Directions/Planes
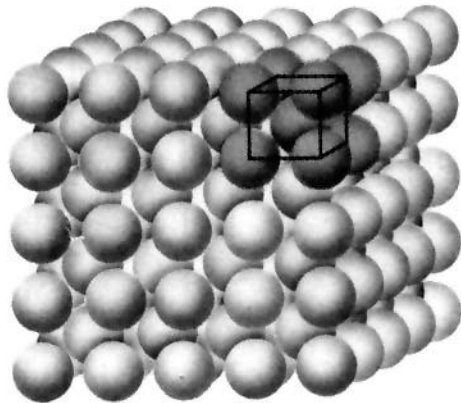
- Unit Cells

- Interstitial

# Crystalline Structures

- The atomic arrangement or crystalline structure of a material is important in determining the behavior and properties of a solid material.

- We use the Atomic Hard Sphere Model when describing the crystalline structures.

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# Order: Short vs. Long Range

- **No Order** - atoms or molecules are in random order

- **Short Range Order** - atoms or molecules are only arranged with there closest neighbors

- **Long Range Order** - atoms or molecules are arranged in a regular repetitive pattern or lattice.

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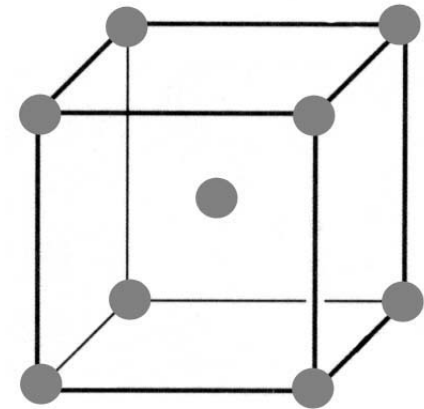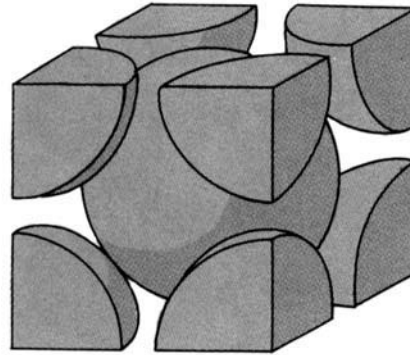
# Unit Cells



- Unit Cells are the smallest part of a crystalline structure that display the repeating structure.

- 14 Types of unit cells also know as Bravais lattices. These are grouped into 7 different crystalline structures.

# Coordinates of Points

- Use a right-handed coordinate system.

- Written as three distances, with commas separating the numbers (*x, y, z*).

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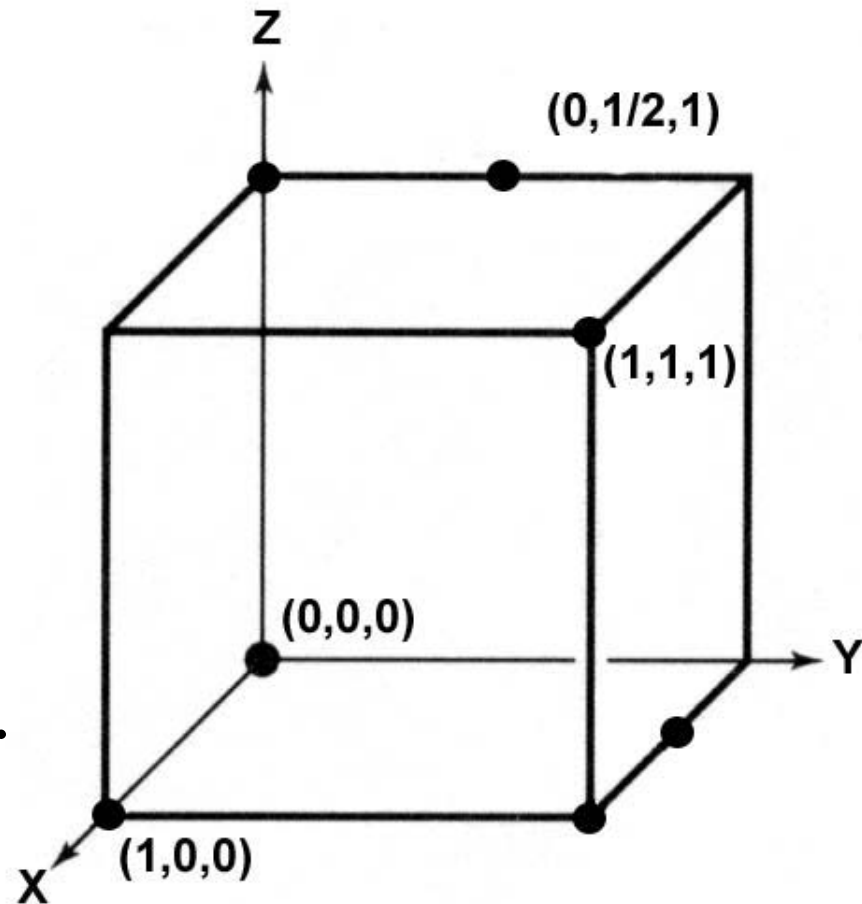
# Directions in the Unit Cell

- Miller indices are used to describe the directions.

- **Procedure:** subtract the coordinates of the "tail" from the "head". Clear fractions and reduce.

- A direction is written as three numbers enclosed in square brackets [*xyz*], with a line over a number if it is a negative.

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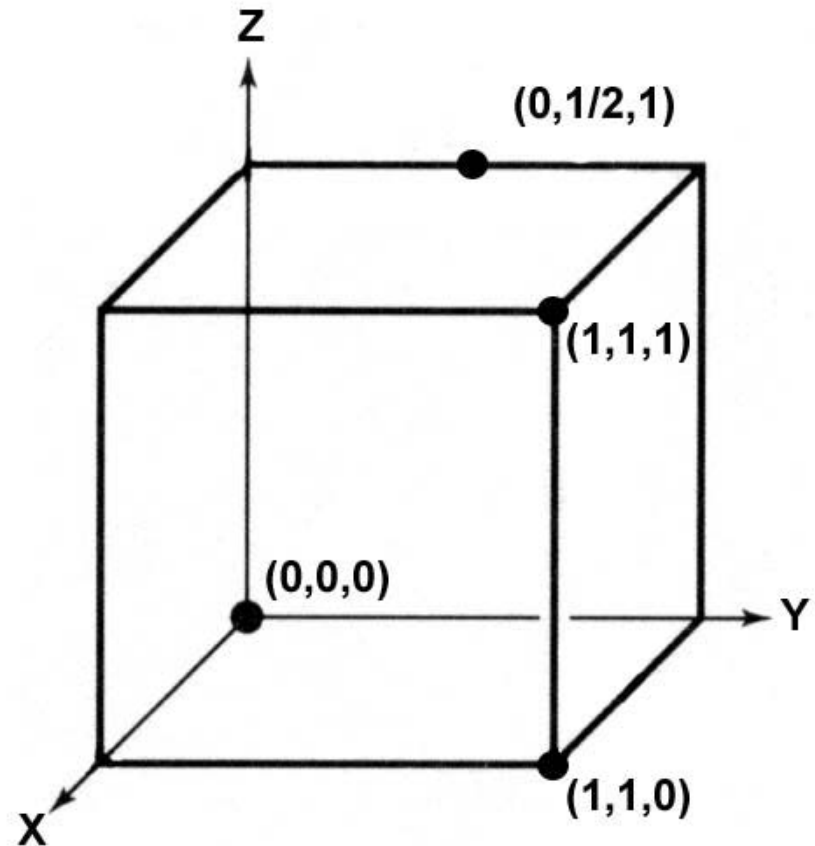
# Planes in the Unit Cell

- **Procedures:** identify where the plane intercepts the *x*, *y*, and *z* axis. If it passes through the origin then it must be moved. Take reciprocals of these intercepts. Clear fractions but do not reduce.

- Planes are written as three numbers enclosed in parentheses (*xyz*). Again with a line over a number if it is a negative

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# Example

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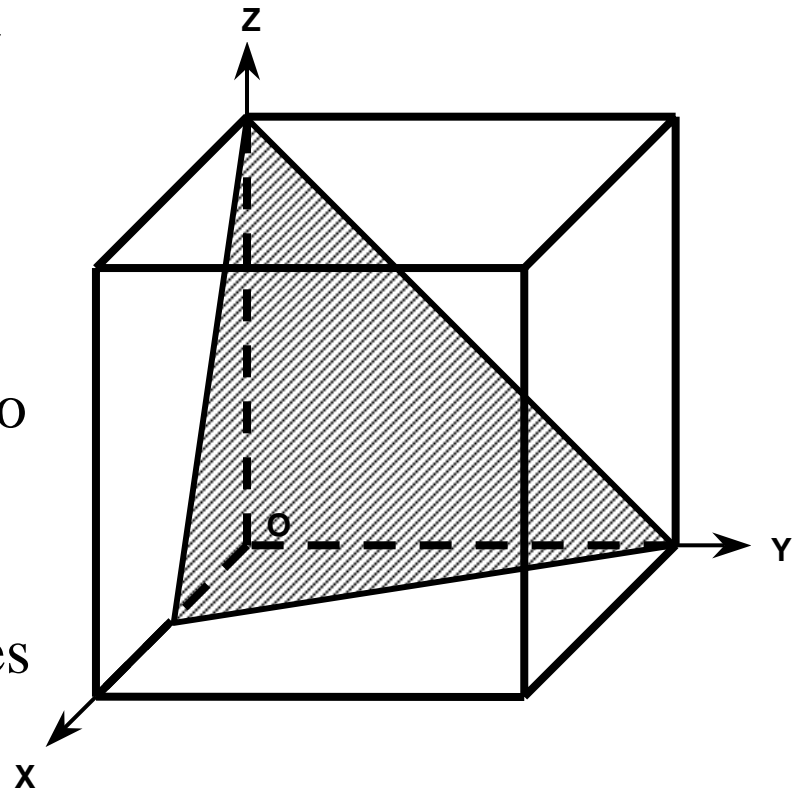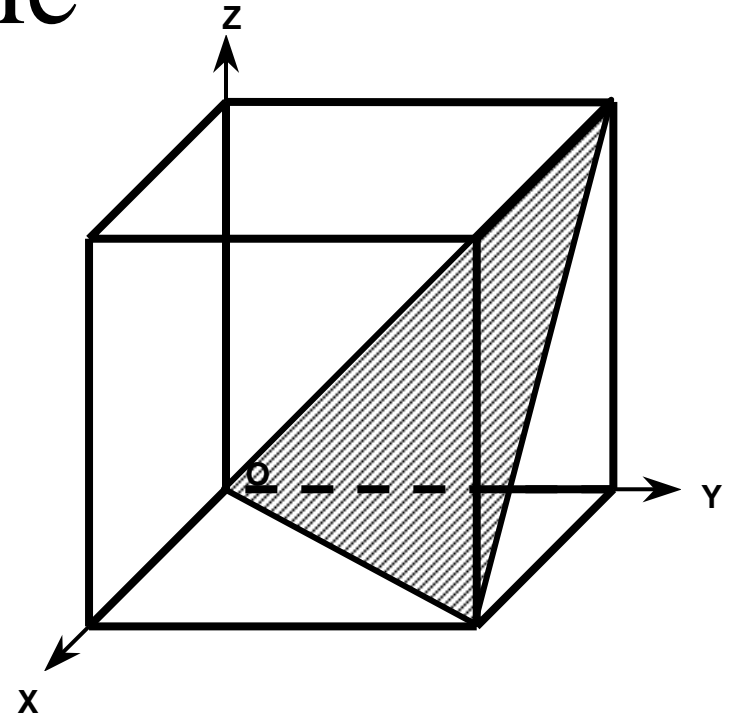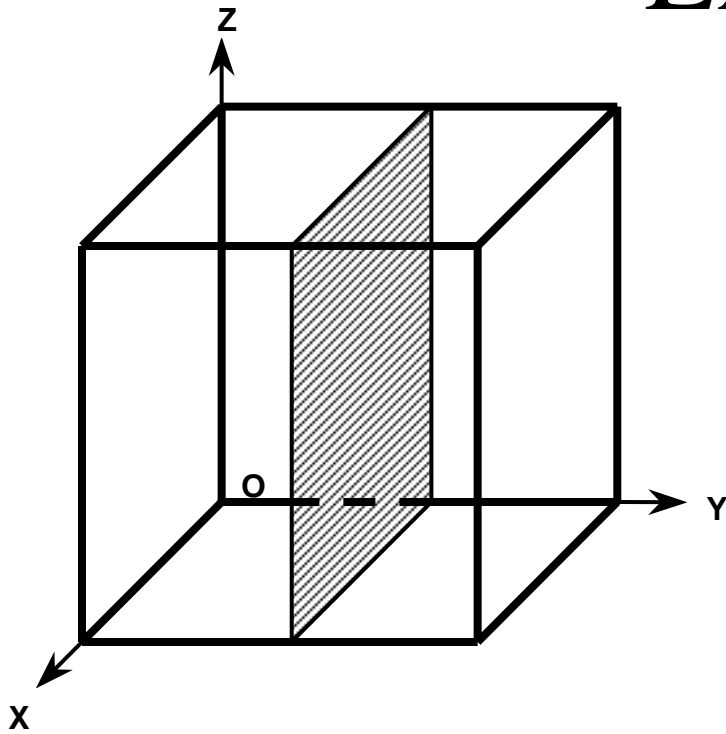
# Lattices

- Lattice Point - The points that make up the unit cell.

- Lattice Parameters - are the length of the sides of a unit cell and/or the angle between the sides.

- Packing Factor - is the volume occupied by the atoms in a unit cell.

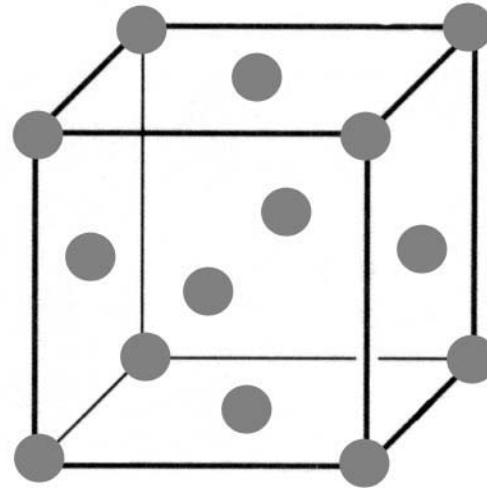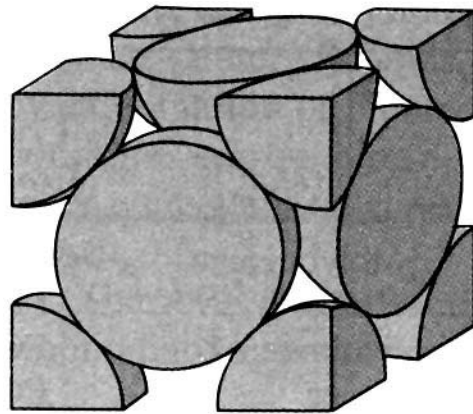$$P.F. = \frac{(\#\,\text{of atoms/cell})(\text{volume of each atom})}{\text{volume of unit cell}}$$

# Close Packed Direction

- Direction in which all atoms are touching.

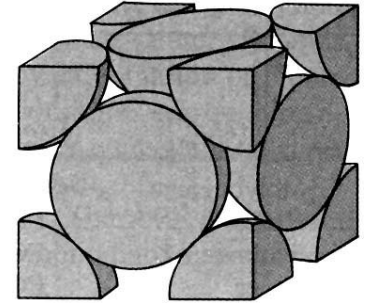- Close Packed Plane is a plane in which all the atoms are touching

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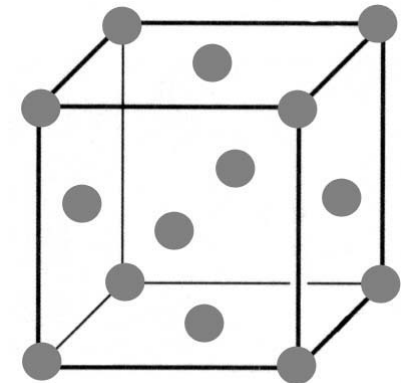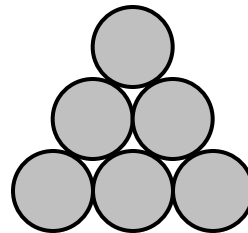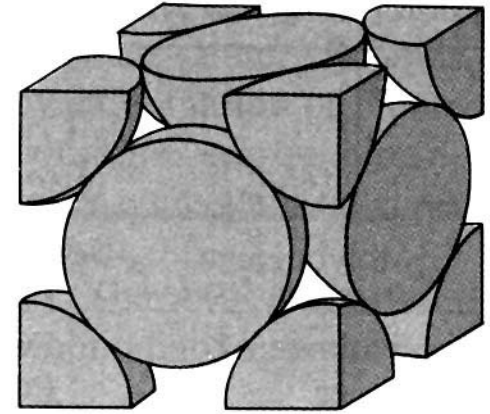
# Face Centered Cubic (FCC)



- 4 atoms per unit cell, 6 $^1/_2$ atoms on each face and 8 $^1/_8$ atoms at the corners.

- Close-packed direction <110>, diagonal from opposite corners on a face. $a_o = \dfrac{4r}{\sqrt{2}}$

# Example

- What is the lattice parameter $a_o$ of Aluminum (FCC structure)

  Atomic Radius = 0.143 nm

# Body Centered Cubic (BCC)
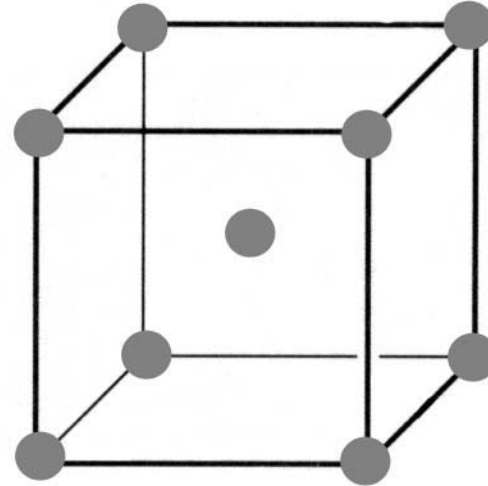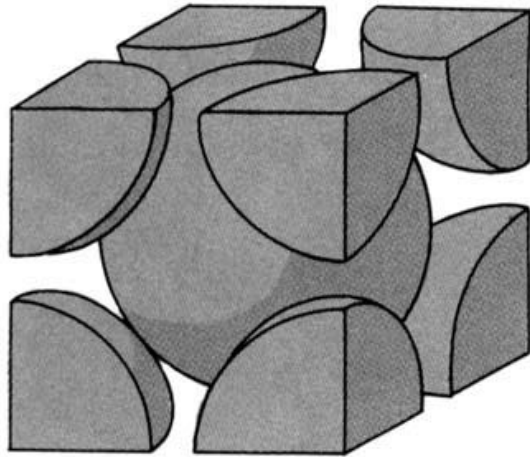
- Two atoms per unit cell, one in the center and $^1/_8$ of each of the 8 corner atoms.

- Close-packed direction <111>, diagonal from opposite corners going through the center.

$$a_o = \frac{4r}{\sqrt{3}}$$

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# Example

- Packing Factor of BCC
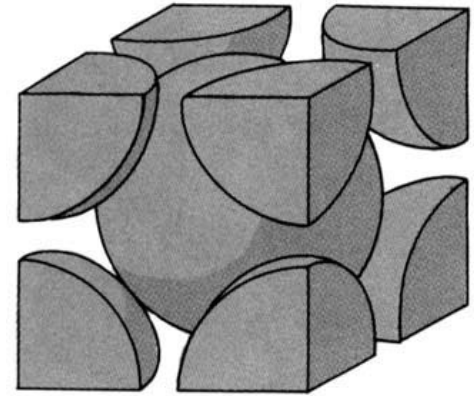
# Crystalline Transformation

- **Polymorphic** - a material that can have more then one crystalline structure.

- **Allotropic -** same as polymorphic but reserved for use when referring to a pure element.

These transformations usually are associated with changes in temperatures. Iron has a BCC structure at low temp but FCC at higher temperatures.

# Behavior and Crystallographic Direction

- **Anisotropic** - Physical properties depend on the crystallographic direction.

- **Isotropic** - Physical properties are independent of the crystallographic direction

**Polycrystalline** materials are made up of many small crystals or grains which are randomly oriented.

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# Interstitial Sites

- Interstitial Sites are the small holes between atoms in the crystalline structures.

- Interstitial atoms will only go into interstitial sites that are smaller then they are.

Linear

Center of Triangle
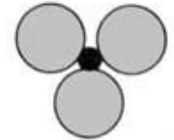
Center of Tetrahedron
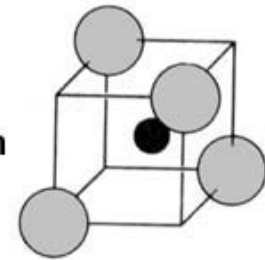
Center of Octahedron

Center of Cube

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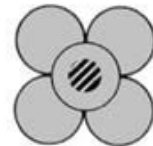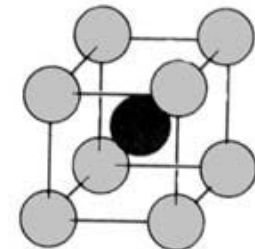
# Summary

- Points, Directions, and Planes in a Unit Cell

- Lattice Parameter and Packing Factor

- Close Packed Directions and Planes

- Face Centered Cubic (FCC)

- Body Centered Cubic (BCC)

- Anisotropic / Isotropic

- Interstitial Sites

# Defects in Crystalline Structures

*Issues to cover*

❑The effect of defects in crystalline structures

❑Point Defects

❑Linear Defects

❑Slip and Slip Planes

❑Surface Defects

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# Defects in the Crystalline Structure

- Defects in the crystalline structure can have an tremendous effect on a materials behavior.

- We can modify and improve many of the physical, electrical, magnetic, and optical properties of crystalline materials by controlling the imperfections in their lattice structure.

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# Defects

- **Point Defects** - Vacancies, Interstitial, and Substitutional

- **Line Defects (Dislocations)** - Edge and Screw dislocations

- **Surface Defects** - Grain Boundaries and Material Surface

# Vacancy Defects

- A vacancy defect is formed when an atom is missing from a normal atomic site in a crystalline structure.

- The number of vacancies present in a material increases exponentially as the temperature increases.
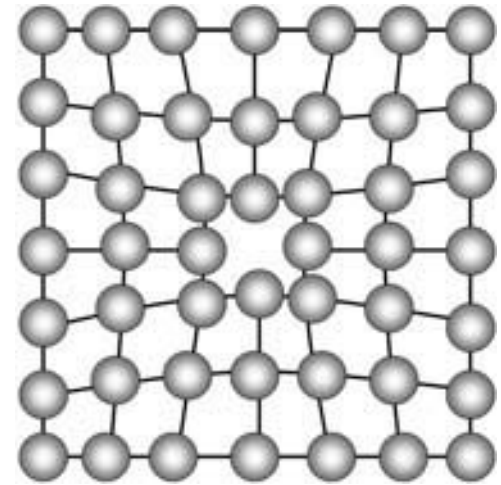
$$n_v = n \exp\left(\frac{-Q}{kT}\right)$$

# Example

How many vacancies per cubic centimeter are there in Silicon (Si) at room temperature?

**Activation Energy (Q) = 0.867 eV/atom**
**Atomic Weight = 28.09 g/mol**
**Density = 2.33 g/cm³**

$$n_v = n \exp\left(\frac{-Q}{kT}\right)$$

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# Interstitial Defects

- An Interstitial defect is formed when an extra atom occupies a normally unoccupied site (interstitial site).

- Since the interstitial atoms are larger then the interstitial sites the surrounding lattice is in compression.

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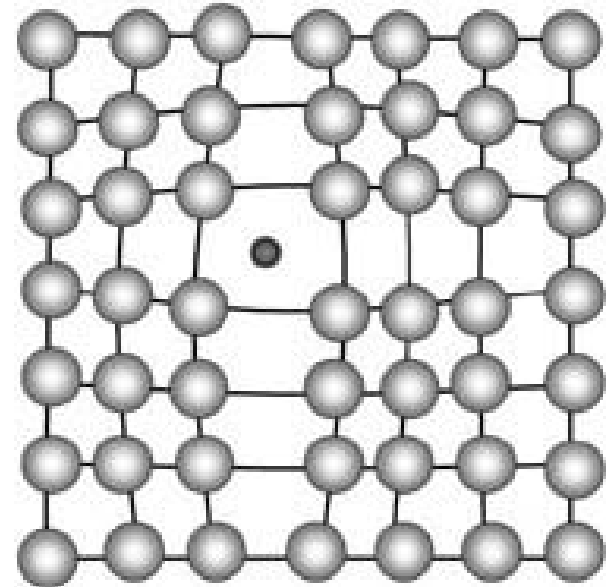
# Substitutional Defects

- Substitutional defects are produced when one atom is replaced by a different type of atom.

- If the substitutional atom is smaller then the original atom then the lattice is in tension.

- If the substitutional atom is larger then the original atom then the lattice is in compression.

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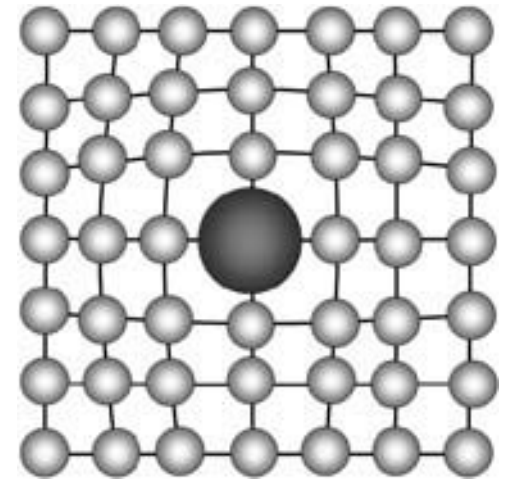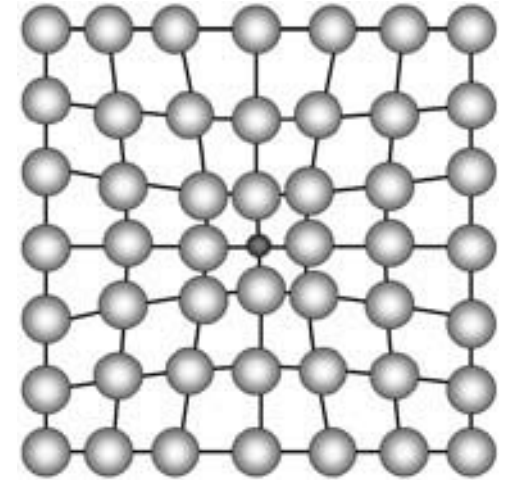
# Compositions

- Weight Percent -  $C_1 = \dfrac{m_1}{m_1 + m_2} \times 100$

- Atomic Percent -  $C_1' = \dfrac{n_{m_1}}{n_{m_1} + n_{m_2}} \times 100$

## Solid Solution

$$n_{m_1} = \text{Number of moles of } m_1 = \dfrac{m_1}{A_1}$$

$$n_{m_2} = \text{Number of moles of } m_2 = \dfrac{m_2}{A_2}$$

$$C_1 + C_2 = 100\%$$

$$C_1' + C_2' = 100\%$$

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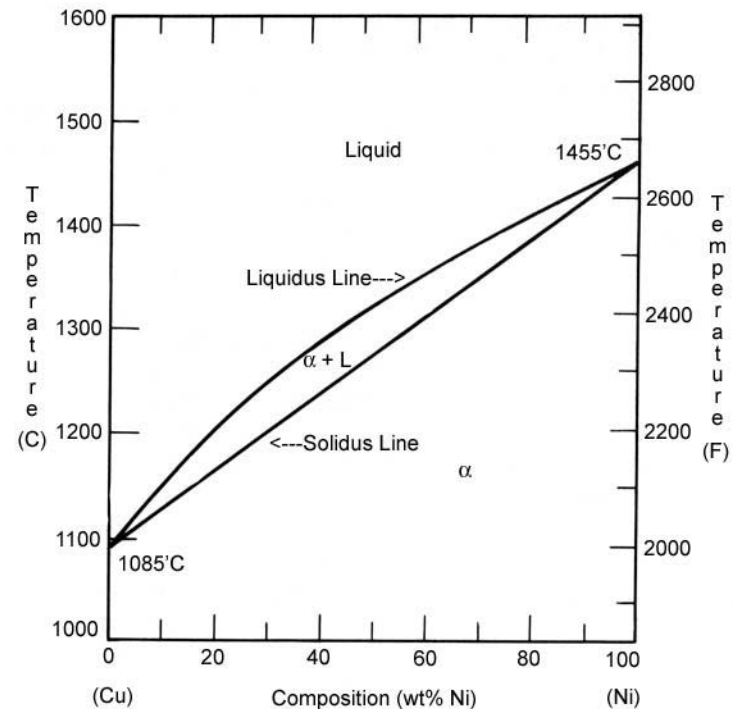
# Example

What is the weight percent & atomic percent of Cu in a Brass that has 57g of Cu and 82g of Zn?

Atomic Mass:    Zn = 65.38 g/mol    Cu = 63.55 g/mol

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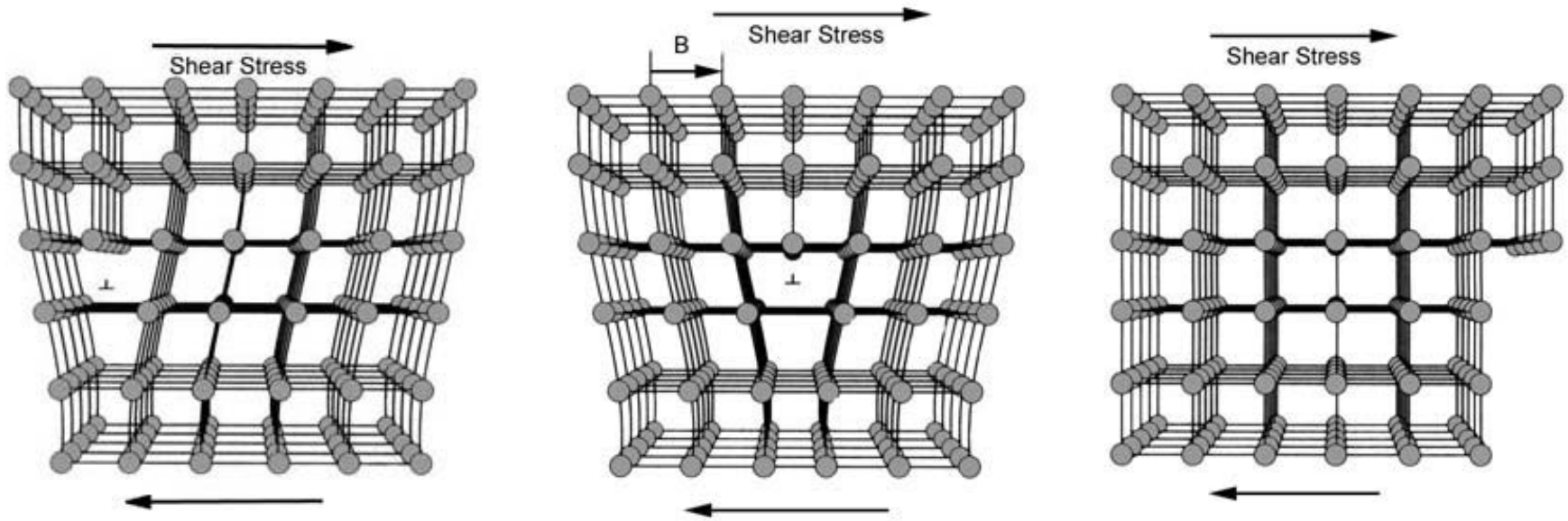
# Edge Dislocations

- Extra ½ plane of atoms inserted into the lattice.
- The Burgers Vector is parallel to deformation.

## *Dislocations are how metals deform!!!*

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# Screw Dislocations



**Screw Dislocation Movement**

B

Screw

Edge

b

b
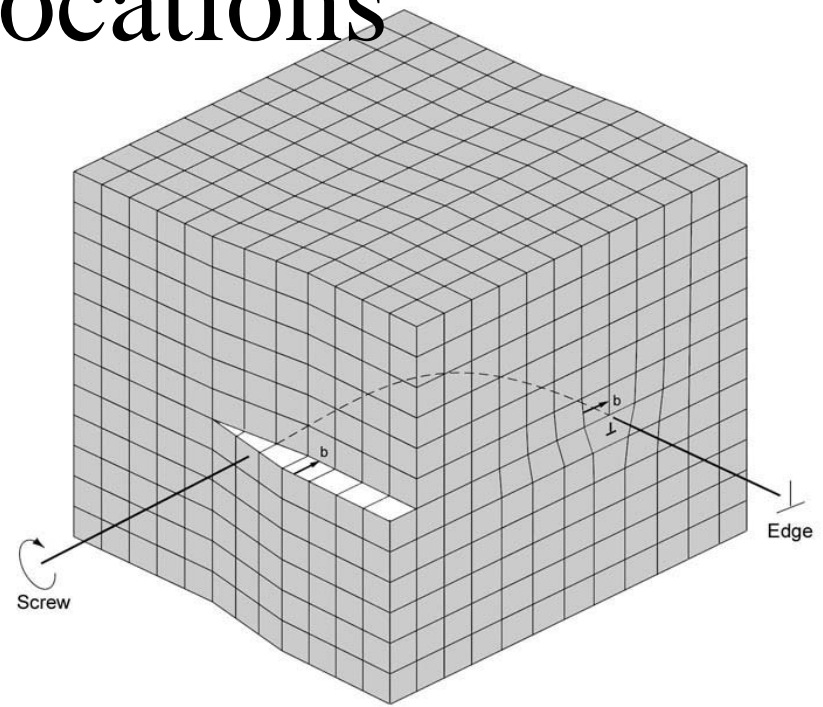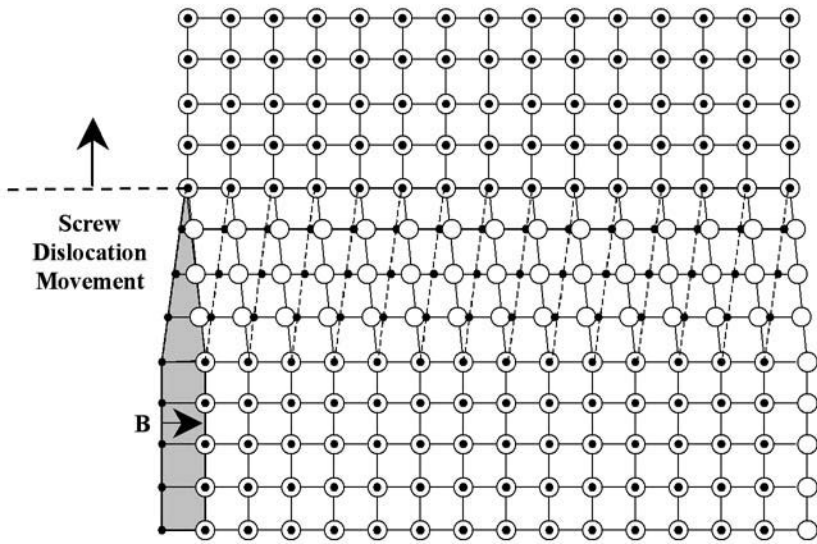
- The name Screw, is derived from the spiral path that is traced around the dislocation line.

- Most dislocation are a mixture of Edge & Screw.

## *Dislocations are how metals deform!!!*

# Slip

- Slip - The process by which a dislocation moves and deforms a material.

- Slip direction - The direction in which a dislocation moves.

- Slip Planes - The plane formed by the dislocation and the Burgers vector.

- Slip Systems - The combination of the slip direction and slip plane make up the slip system.

# Grain Boundaries

- The crystalline structure of each grain is identical but there orientations are not

- The grain boundaries is a narrow zone where the atoms are not properly spaced
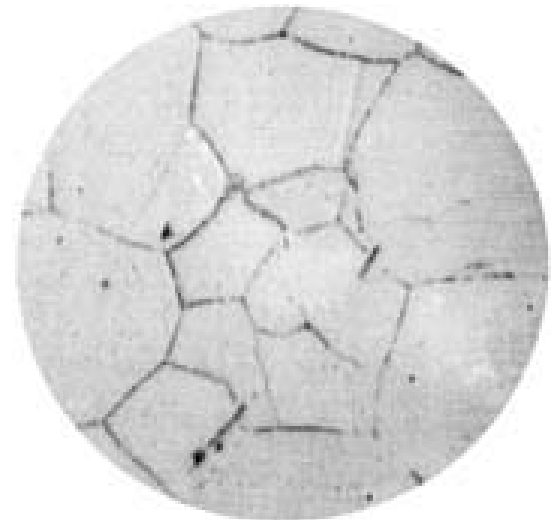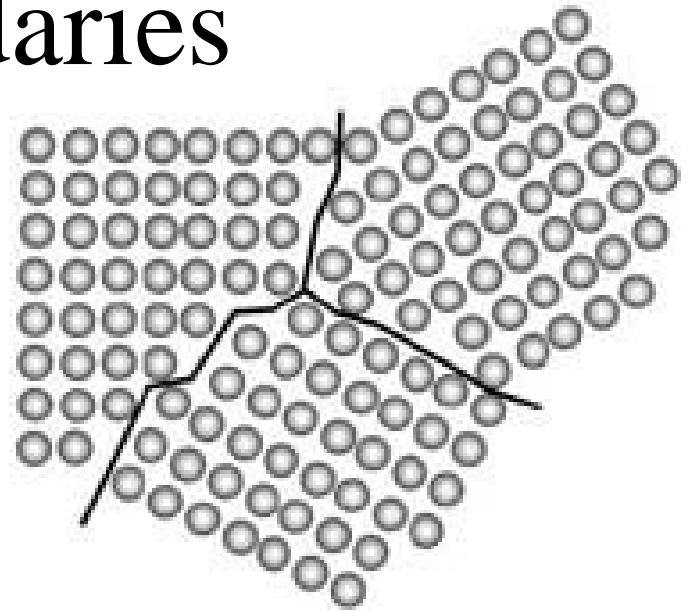
# Material Surface

- This surface defect is the exterior of the material. The crystalline structure ends abruptly.

- The atoms on the exterior surface do not have the proper coordination number so they are more reactive then the bulk material.

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# Summary

- All crystalline structures have defects in them.

- Types of defects: Point – Linear – Surface

- Composition (weight percent): $m_1/(m_{1+}\, m_2)$

- ***Dislocations are how metals deform!!!***

- Dislocations move along slip planes in metals.

- Grain boundaries stop dislocations.

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# Diffusion

*Issues to cover*

❑What is Diffusion and what controls it?

❑Diffusion Mechanisms

❑Fick's First Law of Diffusion

❑Fick's Second Law of Diffusion

❑Error Function

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# Diffusion

- The movement of atoms in a material from high concentrations to lower concentrations.

- Temperature has a large effect on diffusion, as temperature increases so does the rate at which the diffusion proceeds.

- Time is the other factor that effects diffusion. More time = More diffusion

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# Diffusion Mechanisms

- Vacancy Diffusion - the movement of an atom from a normal lattice position to a vacancy

Host or substitutional atom motion

Vacancy

Vacancy

- Interstitial Diffusion - the movement of an interstitial atom from one interstitial site to another

Interstitial atom position before diffusion

Interstitial atom position after diffusion
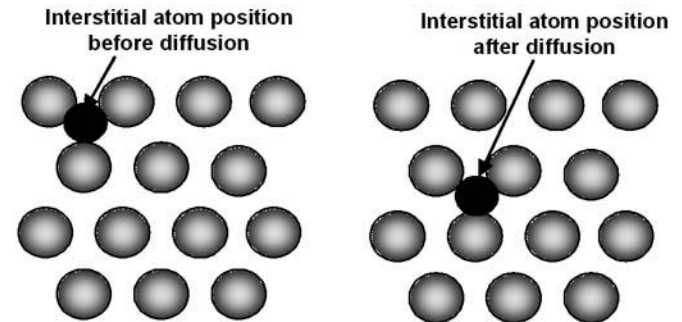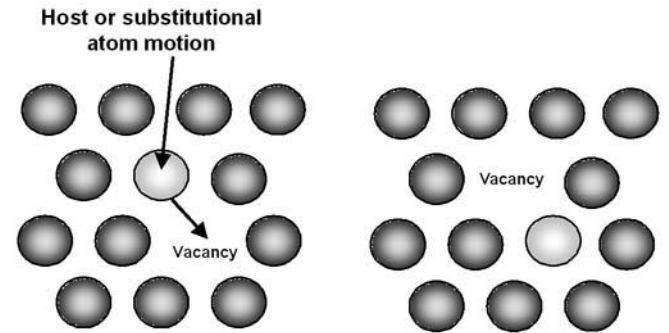
# Steady-State Diffusion
## (Fick's First Law)

- Diffusion is a time dependent process and the rate of mass transfer is the ***diffusion flux*** (J).

- In a steady-state condition the concentration gradient is constant.

- Fick's First law:    $J = -D\dfrac{\Delta c}{\Delta x}$

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# Diffusion Coefficient

$$D = D_o \exp\left(\frac{-Q}{RT}\right)$$

**D** is the diffusion coefficient ($cm^2$/s).

$D_o$ = a temperature-independent pre-exponential ($m^2$/s)

Q = the activation energy for diffusion (J/mol, cal/mol, or eV/atom)

R = the gas constant, 8.31 J/mol-K, 1.987 cal/mol-K, or $8.62 \times 10^{-5}$ eV/atom-K)

T = absolute temperature (K)

# Example

How thick does a BCC iron membrane at 973 K have to be to only allow $2.5 \times 10^{15}$ Nitrogen atoms/cm$^2$s to pass through, if the concentration difference between sides is $43 \times 10^{18}$ N atoms/cm$^3$?

From Tables: $D_o = 0.0047$ cm$^2$/s          $Q = 18,300$ cal/mol

# Nonsteady-State Diffusion
## (Fick's Second Law)

| $\dfrac{x}{2\sqrt{Dt}}$ | $erf\,\dfrac{x}{2\sqrt{Dt}}$ |
|:---:|:---:|
| **0** | **0** |
| **0.10** | **0.1125** |
| **0.20** | **0.2227** |
| **0.30** | **0.3286** |
| **0.40** | **0.4284** |
| **0.50** | **0.5205** |
| **0.60** | **0.6039** |
| **0.70** | **0.6778** |
| **0.80** | **0.7421** |
| **0.90** | **0.7970** |
| **1.00** | **0.8427** |
| **1.50** | **0.9661** |
| **2.00** | **0.9953** |

- Most diffusion situations are nonsteady-state. The concentration gradient at some point will change with time.

- Fick's Second Law.

$$\frac{c_s - c_x}{c_s - c_o} = \text{erf}\left(\frac{x}{2\sqrt{Dt}}\right)$$

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# Error Function

| z | erf(z) | z | erf(z) | z | erf(z) |
|---|--------|---|--------|---|--------|
| 0 | 0 | 0.55 | 0.5633 | 1.30 | 0.9340 |
| 0.025 | 0.0282 | 0.60 | 0.6039 | 1.40 | 0.9523 |
| 0.05 | 0.0564 | 0.65 | 0.6420 | 1.50 | 0.9661 |
| 0.10 | 0.1125 | 0.70 | 0.6778 | 1.60 | 0.9763 |
| 0.15 | 0.1680 | 0.75 | 0.7112 | 1.70 | 0.9838 |
| 0.20 | 0.2227 | 0.80 | 0.7421 | 1.80 | 0.9891 |
| 0.25 | 0.2763 | 0.85 | 0.7707 | 1.90 | 0.9928 |
| 0.30 | 0.3286 | 0.90 | 0.7970 | 2.00 | 0.9953 |
| 0.35 | 0.3794 | 0.95 | 0.8209 | 2.20 | 0.9981 |
| 0.40 | 0.4284 | 1.00 | 0.8427 | 2.40 | 0.9993 |
| 0.45 | 0.4755 | 1.10 | 0.8802 | 2.60 | 0.9998 |
| 0.50 | 0.5205 | 1.20 | 0.9103 | 2.80 | 0.9999 |

$$\frac{z - L_z}{U_z - L_z} = \frac{erf(z) - L_{erf(z)}}{U_{erf(z)} - L_{erf(z)}} \qquad \text{Where,} \quad z = \left(\frac{x}{2\sqrt{Dt}}\right)$$

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# Example

How long does an iron-carbon alloy with an initial carbon concentration of 0.30 wt%C have to be carburized at 1000°C to have a carbon concentration of 0.60 wt%, 3mm below the surface? The surface concentration will remain at 1.50 wt% C.

D = 1.93 x 10⁻¹¹ m²/s

# Materials Processing

- Grain Growth - The movement of atoms across a grain boundary causing some grains to grow at the expense of others.

- Diffusion Bonding - The bonding of two materials by diffusion. Pressure and high temperatures are required.

- Sintering - The bonding of particles and the reduction of the voids between them.

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# Summary

- Diffusion is ***TIME*** and ***TEMPERATURE*** dependent.

- Diffusion Coefficient $D = D_o \exp\left(\dfrac{-Q}{RT}\right)$

- Fick's First Law (steady state)

- Fick's Second Law (non-steady state)

- Error Function

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# Mechanical Properties

*Issues to cover*

❑ What is a Tensile Test and what does it tell us?

❑ How to read a Stress Strain Curve.

❑ What is Fracture Toughness?

❑ Fatigue

❑ Creep

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# Mechanical Properties

- The mechanical properties of materials are important to engineers allowing the selection of the proper material and design of part in order to avoid or at least minimize failure.

- These mechanical properties are determined by carefully designed and performed laboratory experiments.

**Materials Engineering**

# Tensile Test

- Yield Strength - Is the force at which a materials begins to yield and plastic deformation is evident.

- Tensile Strength - Is the highest force applied to a material during a tensile test.

- Modulus of Elasticity (E) - Is a measure of the stiffness of a material. It is the slope of the stress-strain curve in the elastic region.

- Ductility - A measurement of the amount a material can deform before it breaks.

# Stress-Strain Curve
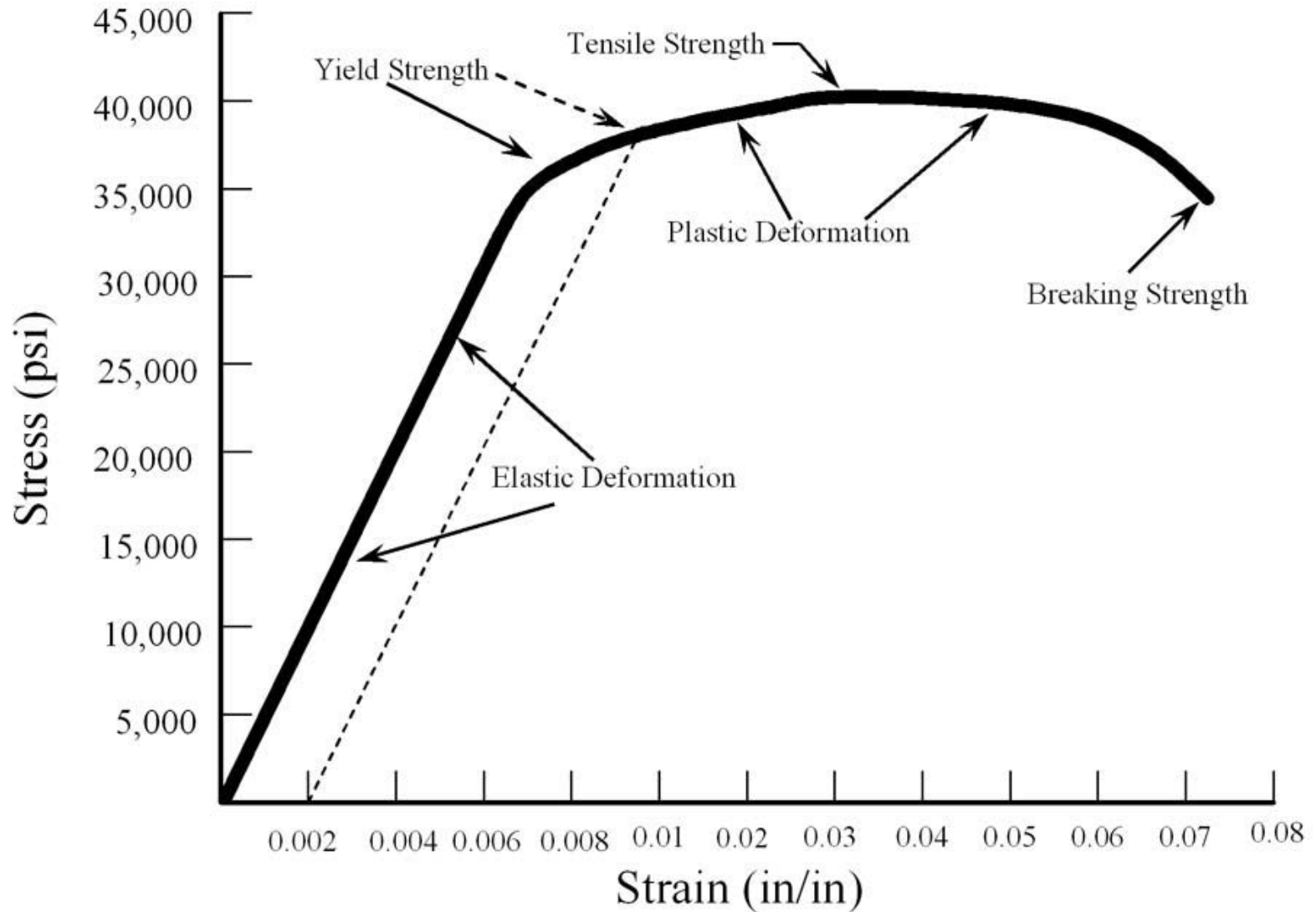
# Example

What is the Yield point, Tensile Strength, and Elastic Modulus of the previous Stress Strain curve?

**Materials Engineering**
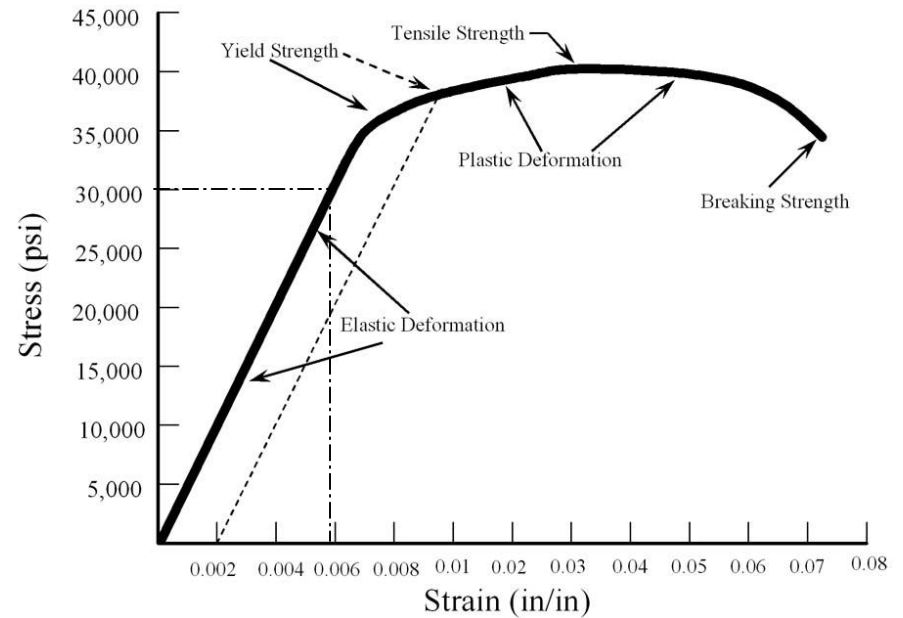
# Hardness Test

- Hardness is a measure of a materials resistance to localized deformation.

- ***Rockwell*** - Most common, numerous scales to test the full rage of materials from soft to hard.

- ***Brinell*** - Uses a 10 mm diameter ball and standard loads between 500 & 3000 kg.

- ***Microhardness Test*** - Vickers & Knoop. These test utilize smaller loads and a diamond tip and must use a microscope to measure the indent.

**Materials Engineering**

# Charpy Impact Test

- A Charpy Impact test measures the amount of energy absorbed by the material from a sudden intense blow and is used to evaluate the its brittleness.

- ***Toughness*** - A materials ability to withstand an impact blow.

- ***Transition Temperature*** - The temperature at which a material changes from brittle to ductile failure.

- ***Notch Sensitivity*** - Notches concentrate stresses and reduces a materials toughness.

**Materials Engineering**

# Fracture Toughness

- ***Fracture Toughness*** ($K_c$) is a measurement of a materials ability to withstand an applied load while containing a flaw.

$$K = f\sigma\sqrt{\pi a}$$

- $K_{Ic}$ - Is the plane strain fracture toughness.
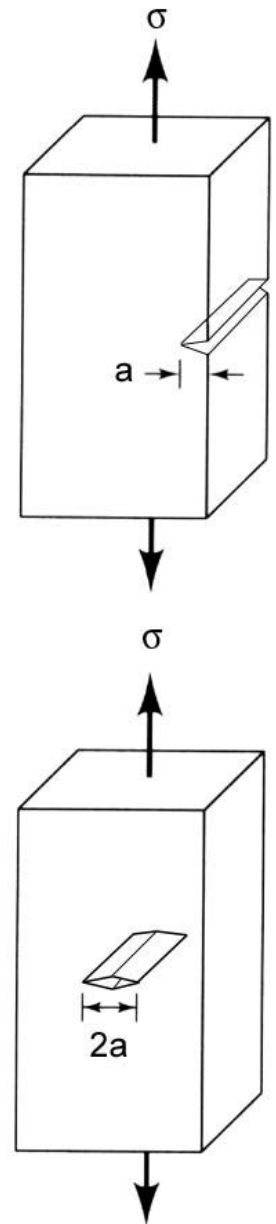
# Example

What is the minimum crack size that can be present in a large steel plate exposed to a stress of 65,000psi.

Fracture toughness $= 80,000 \, \text{psi} \, \sqrt{\text{in}}$

**Materials Engineering**

# Fatigue Test
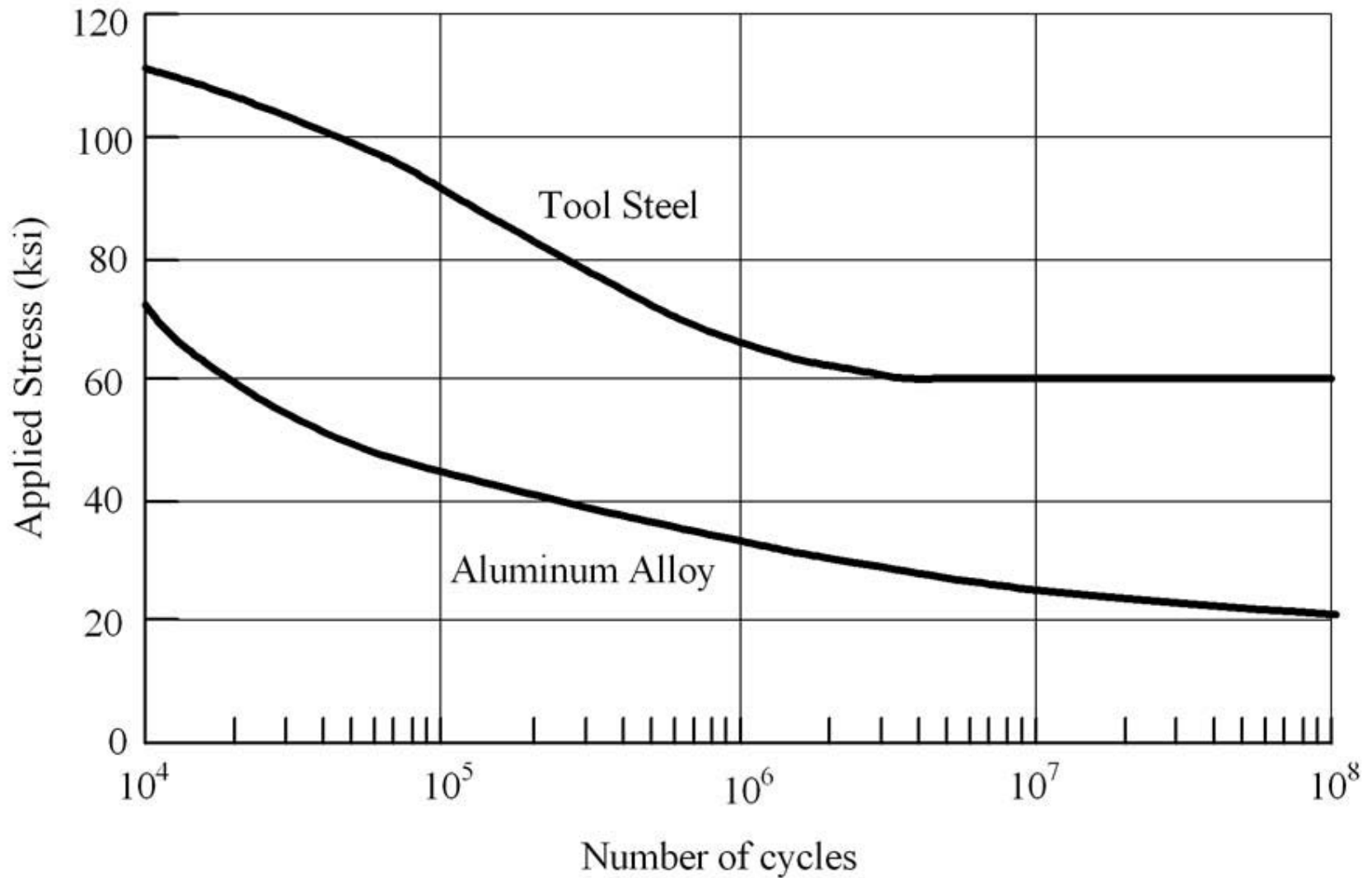
# Creep Test

- Creep is the plastic deformation of a material at high temperatures and applied load lower then the yield strength.



Constant Stress
Constant Temperature

Rupture

$\frac{\Delta \varepsilon}{\Delta t}$ = Creep Rate

Strain

$\varepsilon_o$ = Elastic Strain

First Stage

Second Stage (steady state)

Third Stage

Time

Rupture Time
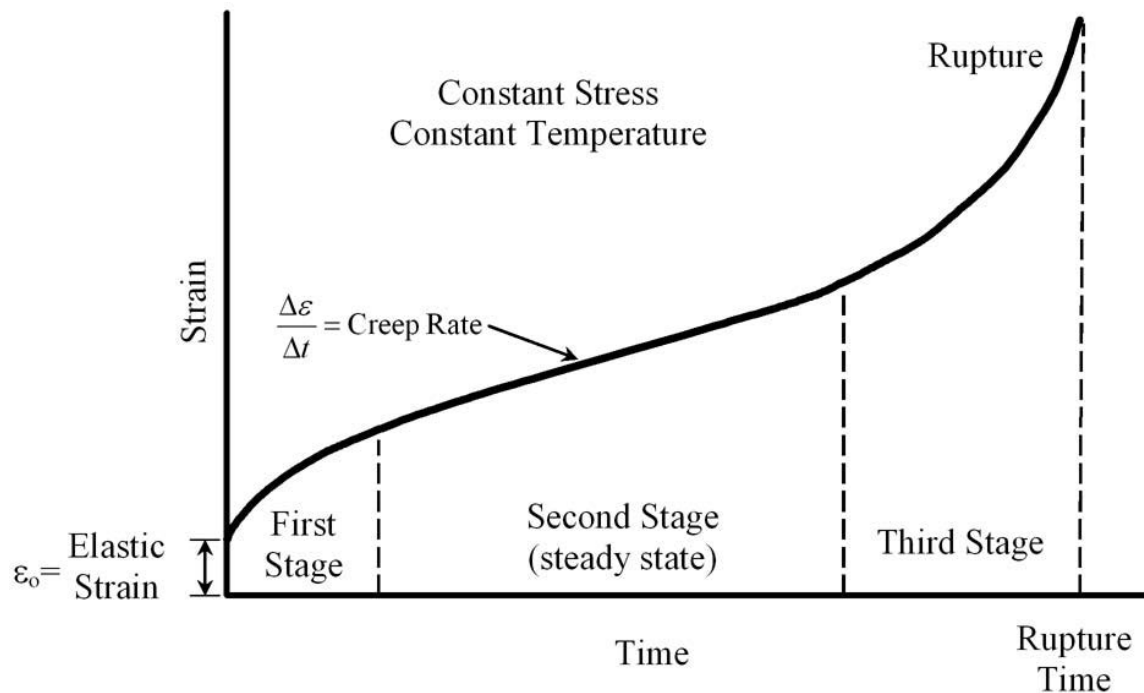
# Summary

- Tensile Test / Stress Strain Curve give us – Elastic Modulus, Yield Strength, Tensile Strength

- Hardness Test - Rockwell

- Charpy Impact Test

- Fracture Toughness ($K_{Ic}$)

- Fatigue Test – Endurance Limit

- Creep – Creep rate during second stage (steady state)

**Materials Engineering**

# Strain Hardening and Annealing

*Issues to cover*

❑ What does Strain Hardening and Cold Working mean?

❑ Cold Working effects on Stress Strain Curve.

❑ What are some Strain-Hardening mechanisms?

❑ How Cold Working effects Material Properties.

❑ What is Annealing and what are it's effects?

# Strain Hardening and Annealing

- Cold Working - deforming of a metal at low temperatures and strengthening by dislocation formation.

- Hot Working - deforming a metal at high temperatures (above the metals recrystallization temperature). No strengthening.

- Annealing - a heat treatment that eliminates the effects of cold working.

# Stress-Strain Curve & Cold Working

- Strain-Hardening - occurs when the applied stress exceeds the original yield strength.
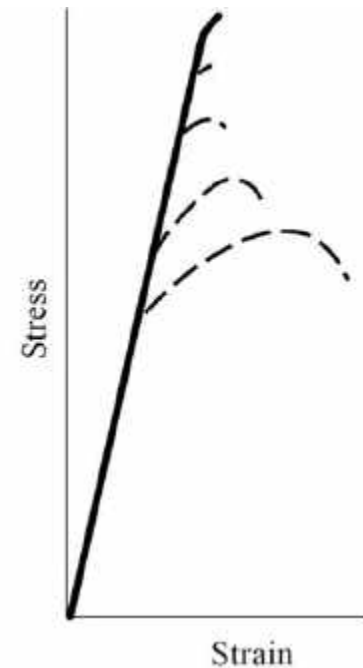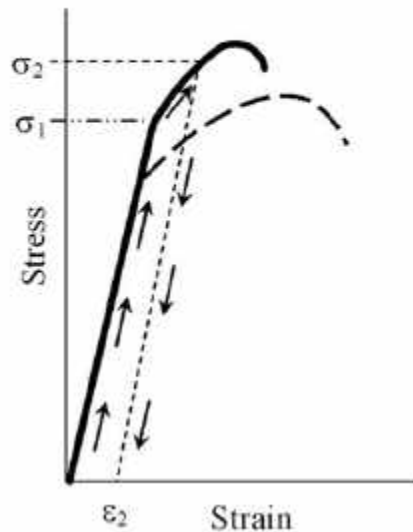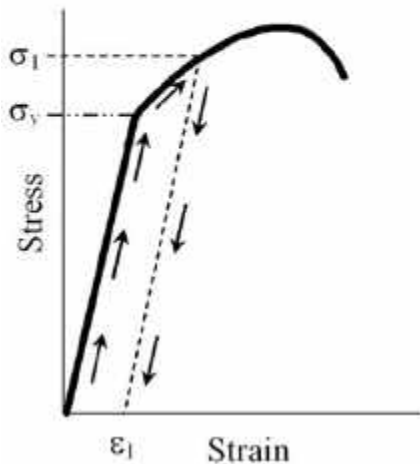
# Strain-Hardening Mechanisms

- The strengthening of a metal during deformation is a result of the increase in dislocations.

- Dislocations formed during cold working strengthen a metal by storing some of the energy applied, in the form of residual stress.

- Frank-Read source is a dislocation generating mechanism.

# Edge Dislocations
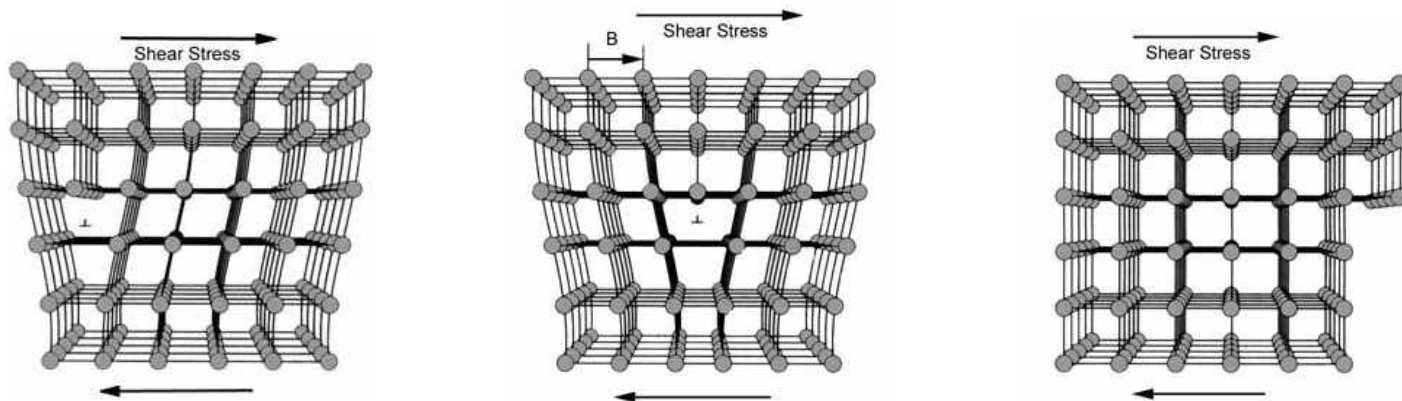


# Screw Dislocations
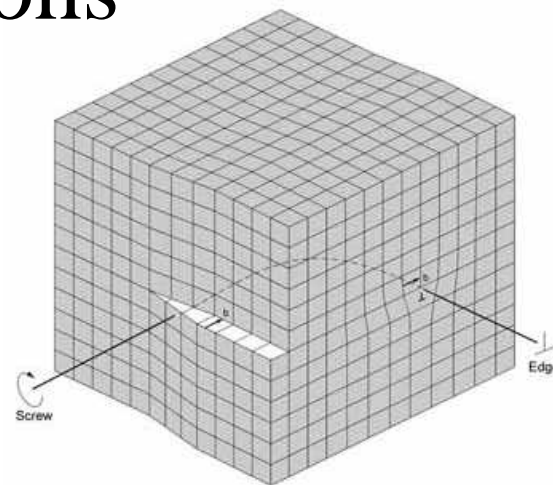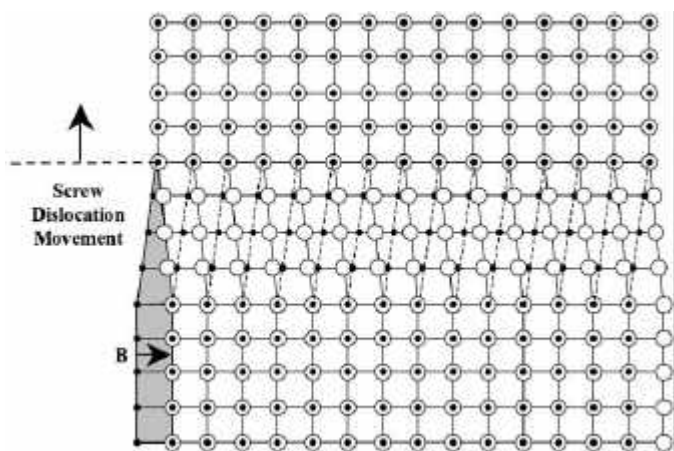
# Amount of Cold Working

- The amount of cold working done to a sample is usually given in a percentage and is determined by the change in cross sectional area.

- It is very important to note that the original cross sectional area of the sample before any cold working was done needs to be used in all further calculations of the percent cold worked.

- When a sample is Cold-Rolled it only get thinner and does not get wider so the cross sectional area is only changing by the decrease in the thickness.

$$\text{Percent cold work} = \frac{A_o - A_f}{A_o} \times 100$$

# Example

- A Copper strip previous cold rolled 25% is 1.50in thick. It is then cold rolled further to 0.75in thick. Calculate the total percent cold worked.

**Note:** during this rolling process the width of the sample does not change, only the thickness decreases.

**Materials Engineering**

# Material Properties & Cold Working

## As the percent of Cold Working increases:

*Tensile strength* - **increases**

*Yield strength* - **increases**

*Ductility* - **decreases**

*Corrosion resistance* - **decreases**

*Electrical conductivity* - **decreases**

**Materials Engineering**
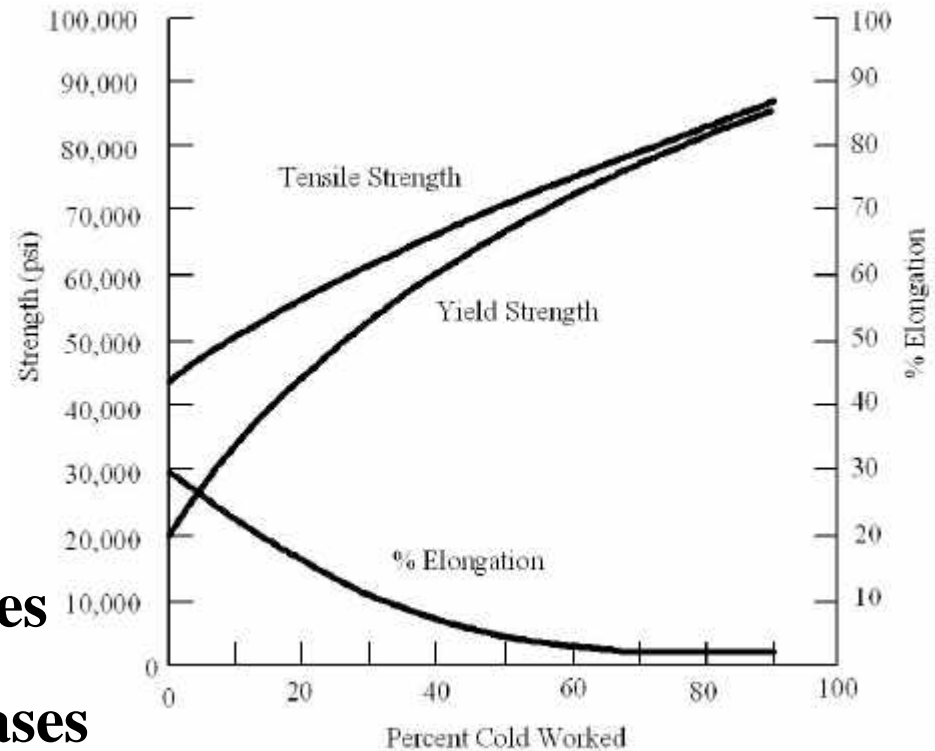
# Example

What is the Tensile Strength and Yield Strength of a 50% cold worked sample?
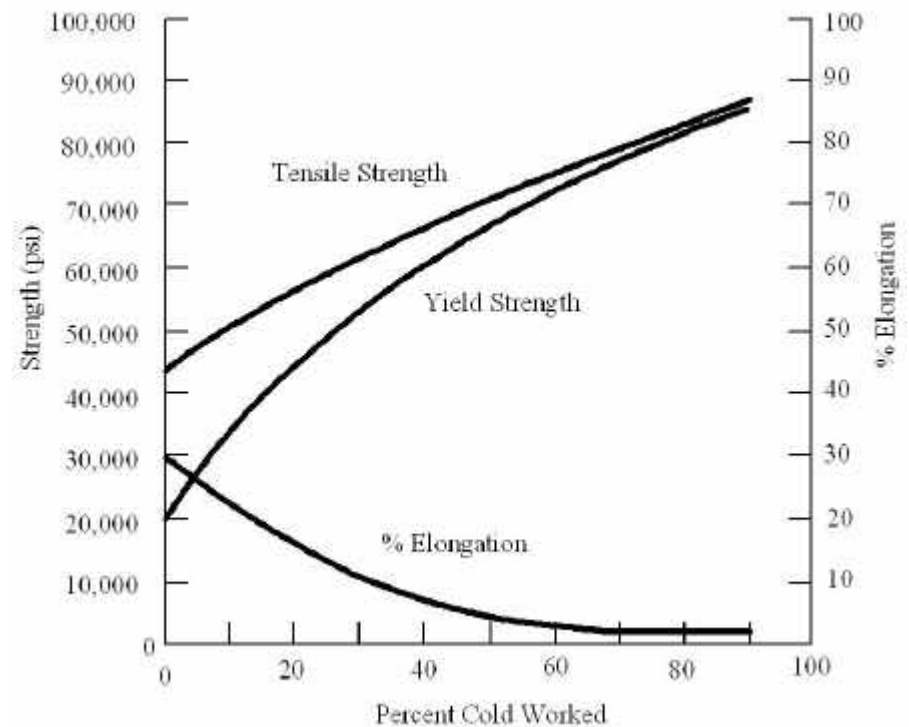
# Hot Working

- Deformation is performed above a metals recrystallization temperature.

- Continuous recrystallization occurs during hot working.

- No strengthening occurs during deformation by hot working.

**Materials Engineering**

# Annealing

The elimination of the effects of cold working by heat treatment
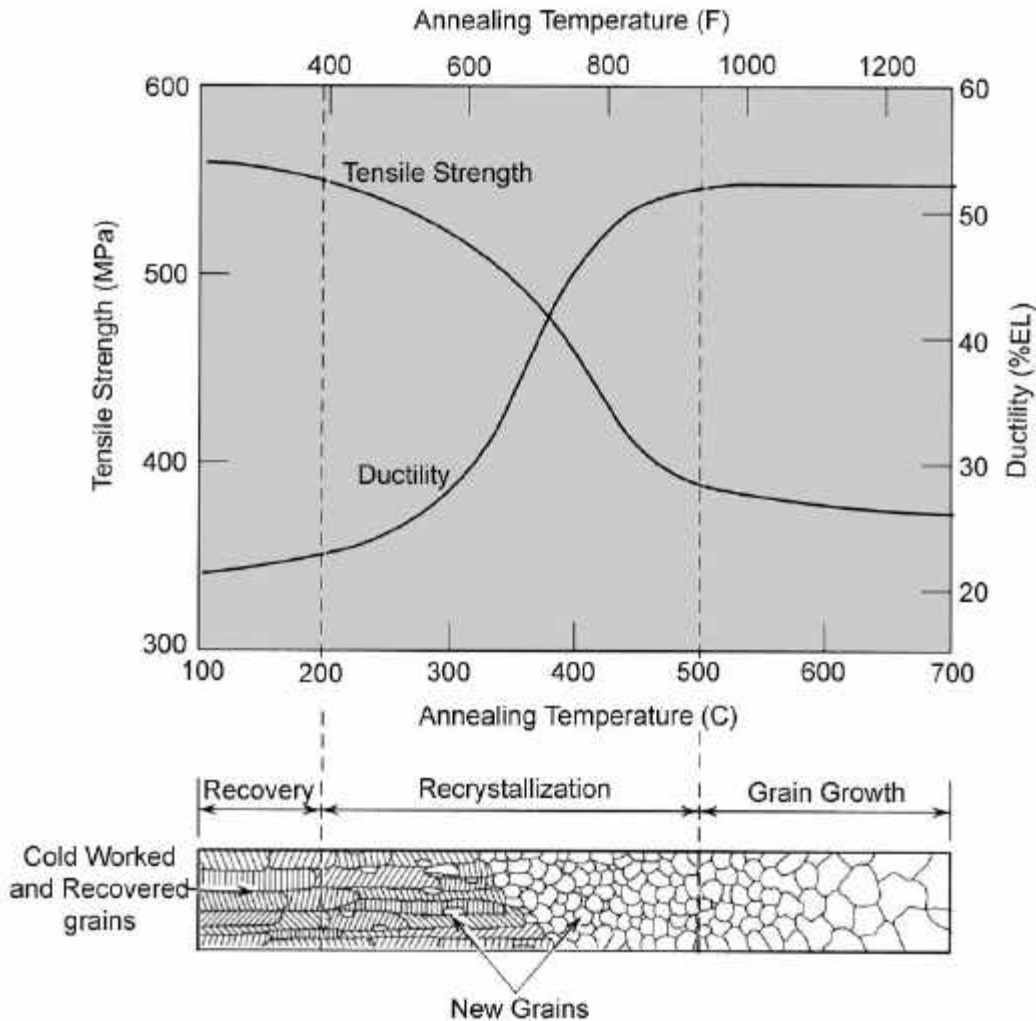
- Recovery
- Recrystallization
- Grain Growth

# Summary

- Strain Hardening is the increase in strength due to plastic deformation.

- Metals deform by dislocation formation and movement which also strengthens the metal.

- When ever the applied stress exceeds the Yield point a new Yield point is set at the maximum applied stress.

- Cold Working increases the Tensile and Yield Strength but lowers the Ductility and Electrical Conductivity.

- Annealing removes the effects of Cold Working by allowing recrystallization.

Materials Engineering

# Phase Diagrams

_Issues to cover_

❑ What are Phase Diagrams and what information can we get from them?

❑ Solid Solution and its strengthening mechanics.

❑ What is the Lever Law and how to use it.

❑ Eutectics and Binary Eutectic systems.

**Materials Engineering**

# Phase Diagrams

- Phase Diagrams are a road map for the Materials Engineer.

- Phase diagrams help in determining properties of different alloying systems.

- A Phase is a portion of a system that is homogeneous with uniform chemical compositions and physical properties.

- Phase diagrams are your friends.

**Materials Engineering**

# Solid Solutions
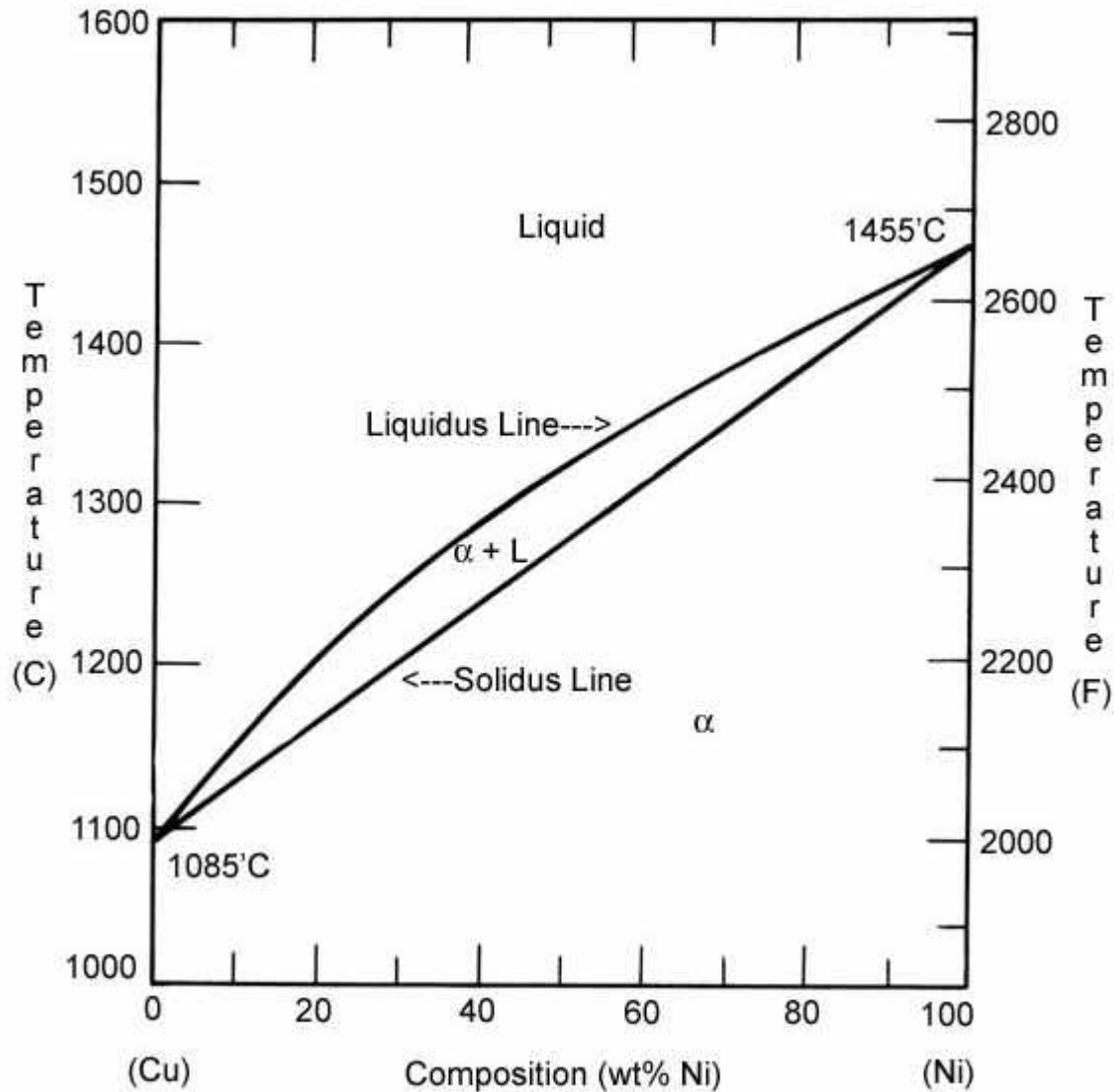
# Lever Law

- In order to determine the amount of a phase present at a given temperature and composition we must use the Lever Law.

- Tie Line is the line drawn connecting one phase to the other through the two phased region.

- The Arms are the portions of the Tie Line extending from the overall alloy composition to each phase.

$$\text{Percent of Phase} = \frac{\text{opposite arm}}{\text{Tie Line}} \times 100$$

# Example

For a 50 gram sample of a 60% Ni alloy at 1325°C what are the compositions of the phases present and what is the amount of each?

**Materials Engineering**
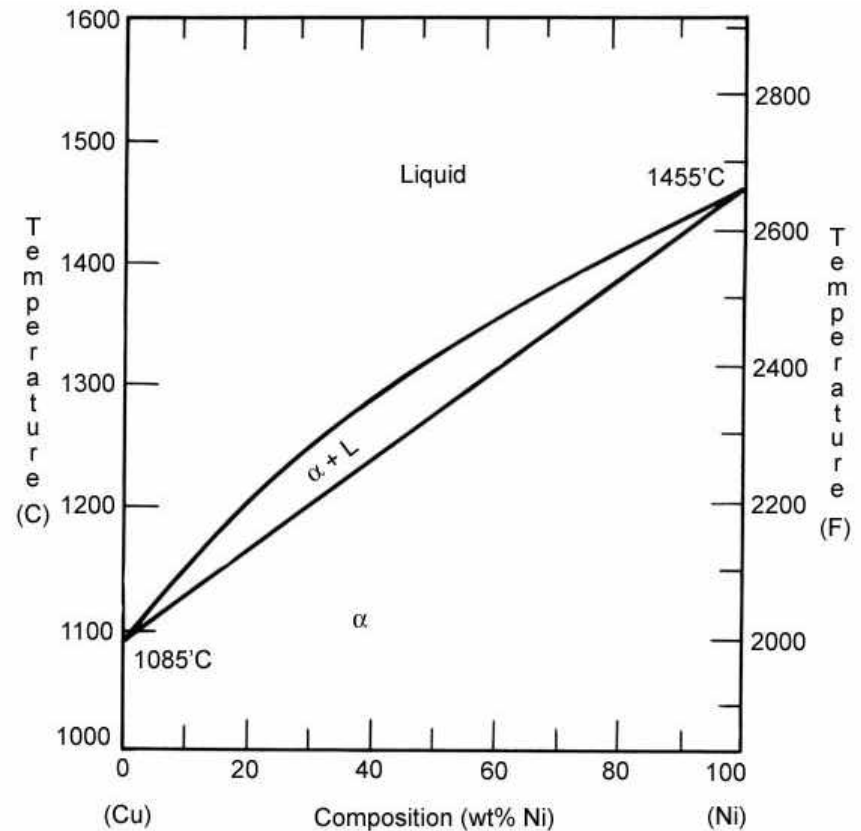
# Solid Solution Strengthening

- The yield strength, tensile strength, and hardness of the alloy are higher

- The ductility of the alloy is usually lower

- The electrical conductivity of the alloy is much lower

- The resistance to creep, or loss of strength at higher temperatures is improved

Materials Engineering
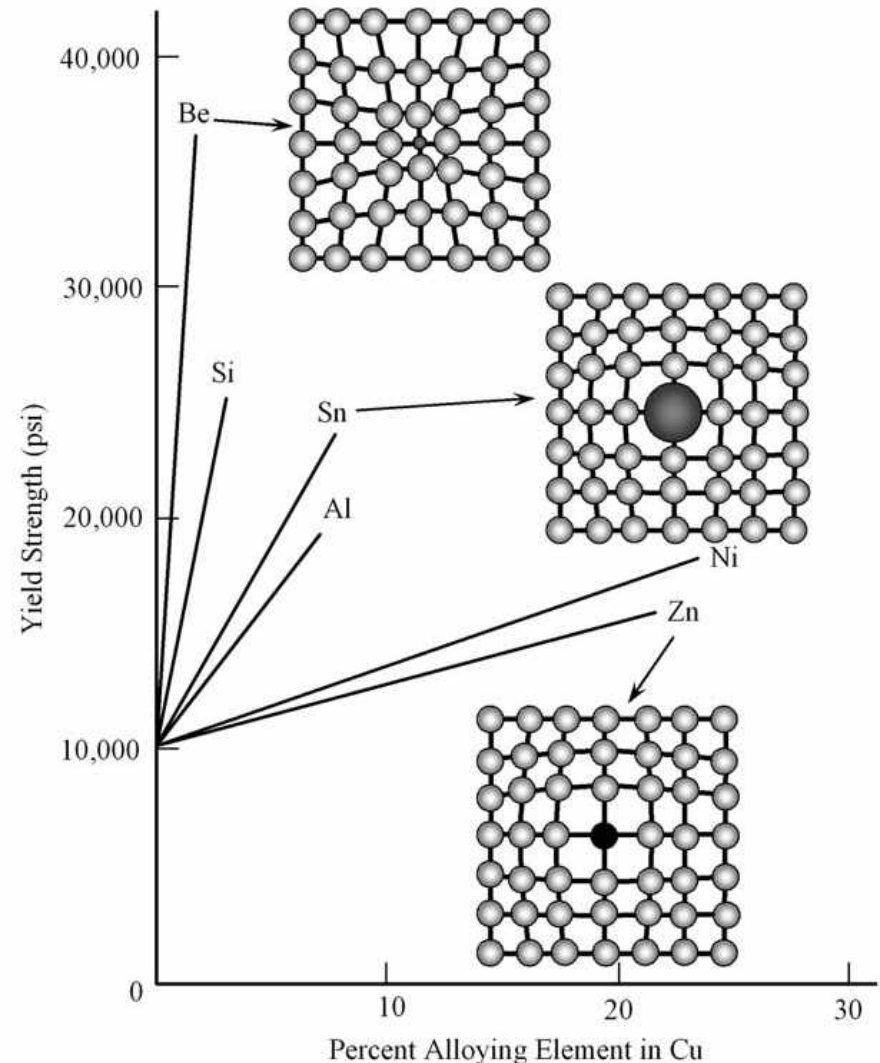
# Binary Eutectic Systems

# Eutectic Alloys



α$_{19\%Sn}$

β$_{97.5\%Sn}$

α$_{19\%Sn}$

β$_{97.5\%Sn}$

α$_{19\%Sn}$

β$_{97.5\%Sn}$

Pb

Sn

Pb

Materials Engineering
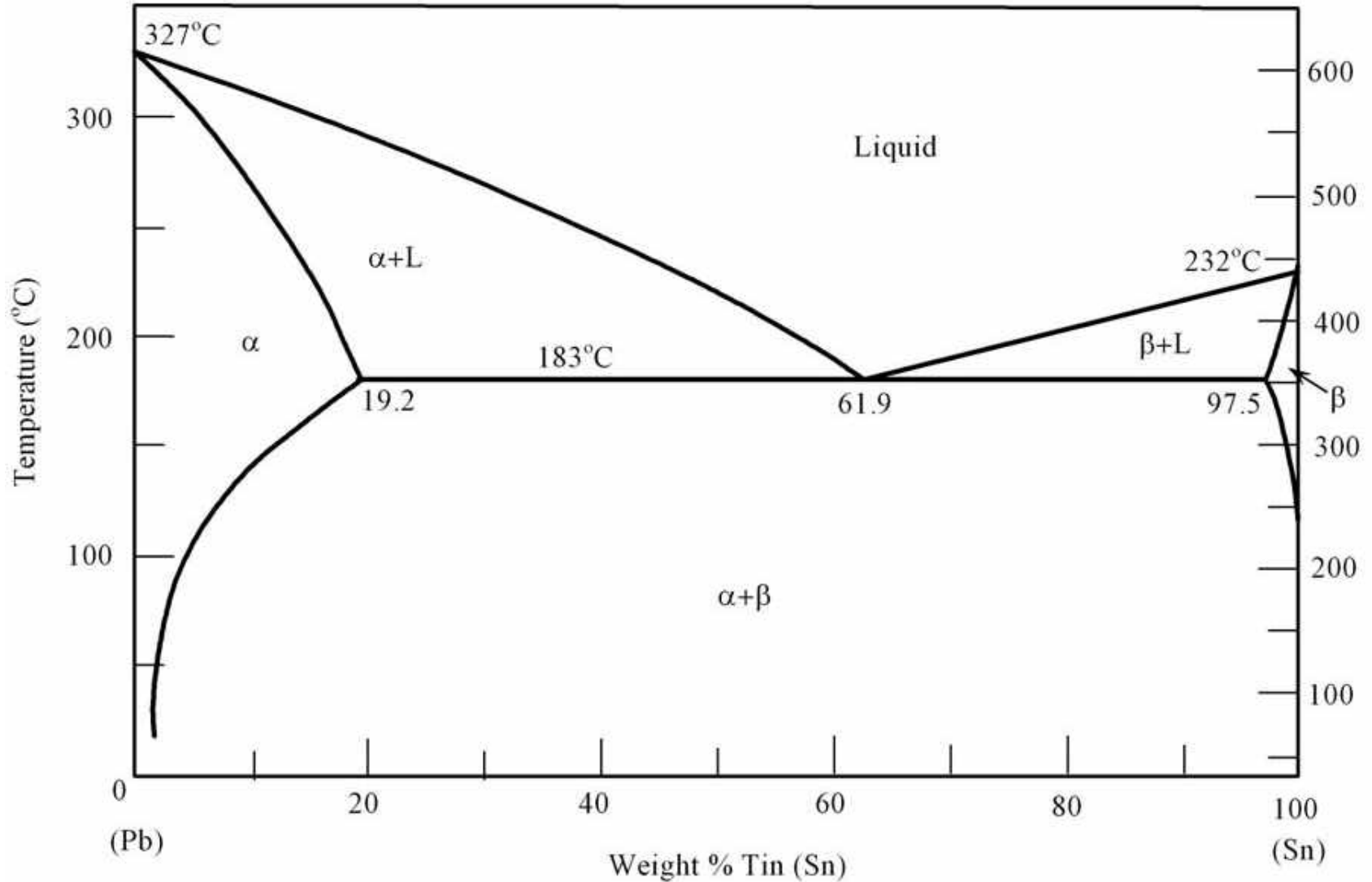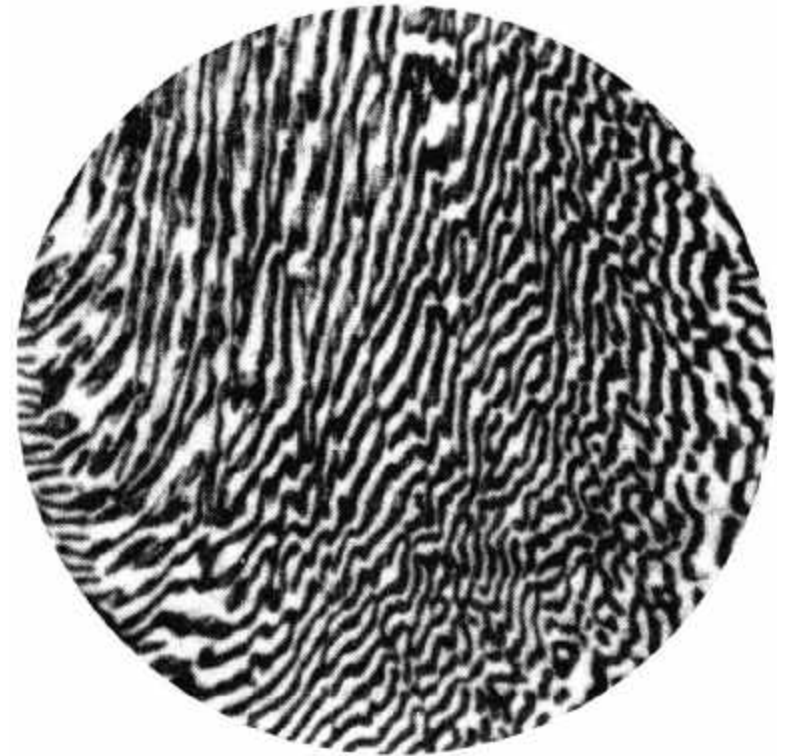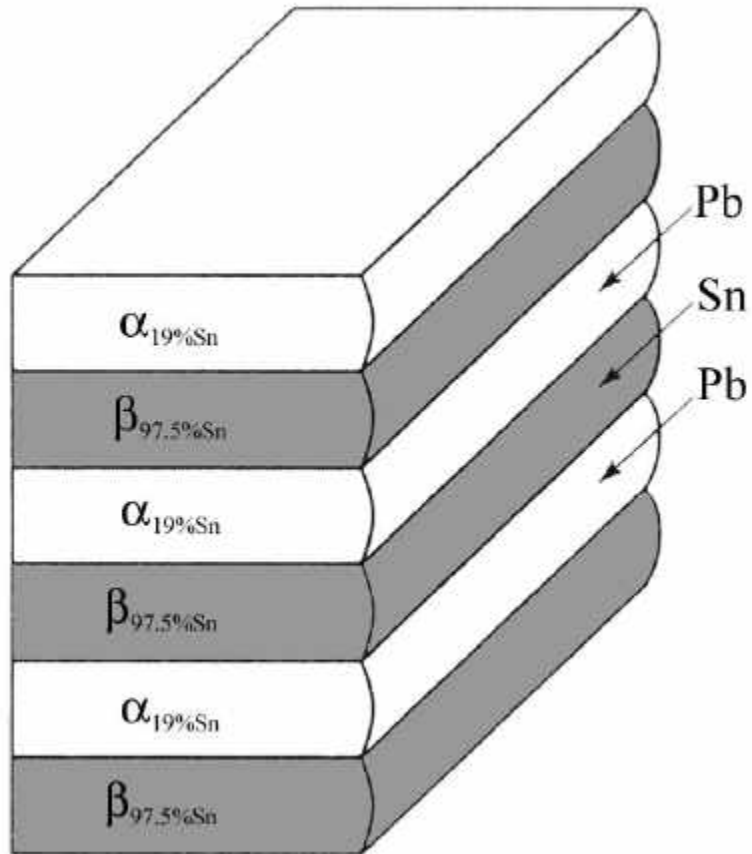
# Example

For a 40%Sn alloy at 200ºC what phases are present, what is their composition, and what is the amount of each?
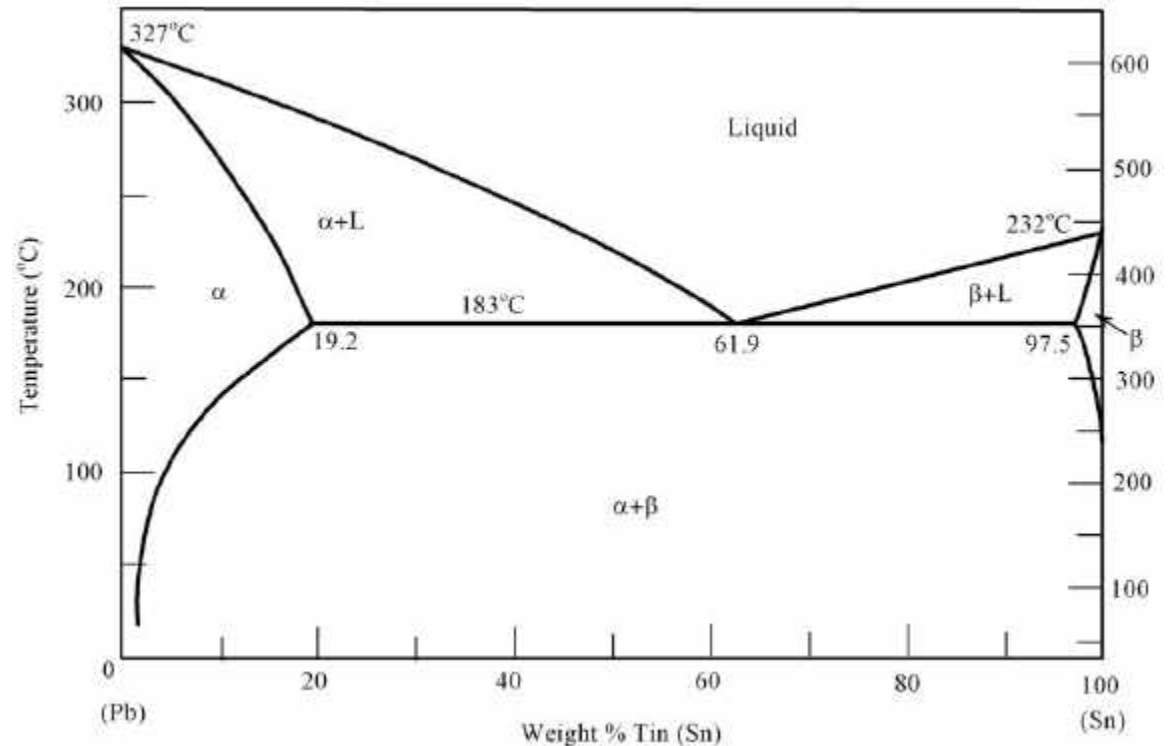
# Eutectoid System (Steel)
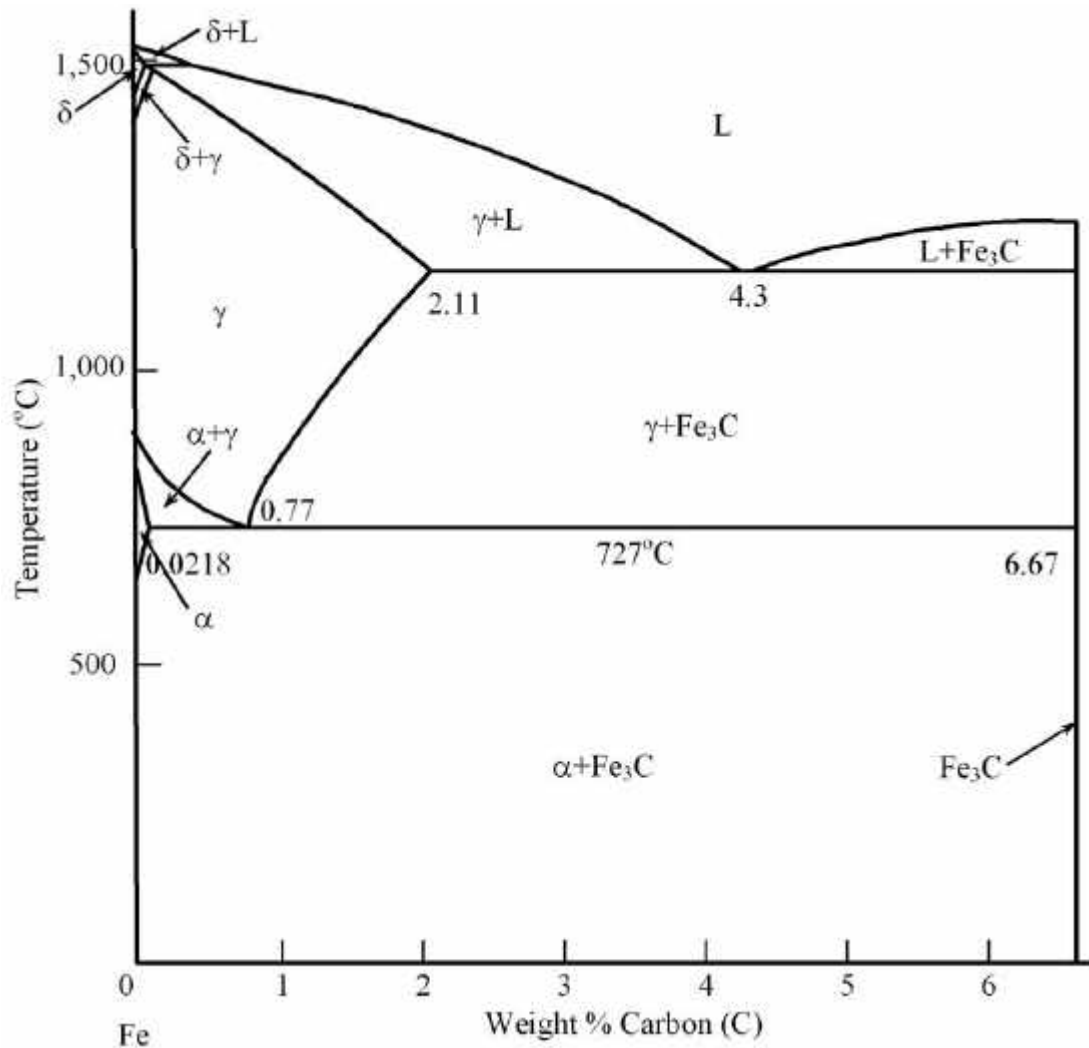


γ = Austenite

α = Ferrite

Fe₃C = Cementite

**Materials Engineering**

# Example

For a 0.3%C Steel at 800ºC what phases are present, what is their composition, and what is the amount of each?

**Materials Engineering**
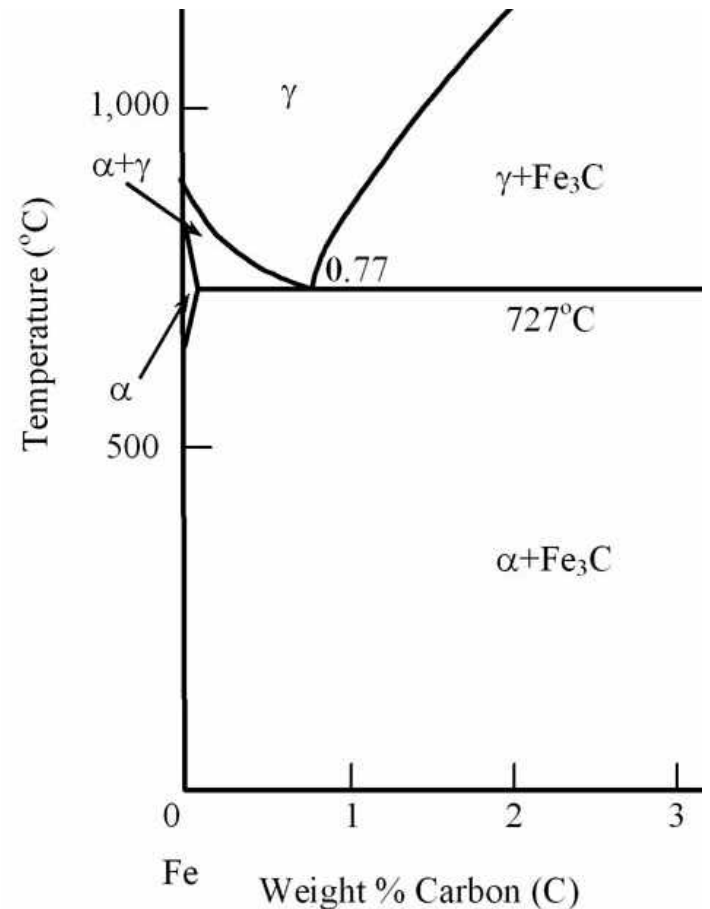
# Summary

- Phase Diagrams tell us what phases are present in a given alloy at a given temperature.

- Solid Solution is uniform mixing of elements.

- The Lever Law allows the calculation of the amounts of each phase.

- Eutectic is a layered structure that forms when an alloy is cooled from a single phase liquid into a two phase solid.

- The Iron-C phase diagram has specific names for each of the phases (eg. Ferrite, Pearlite, Austenite,…)

Materials Engineering

# Phase Transformations

*Issues to cover*

❑Why phase diagrams don't always reflect the real world

❑What are Isothermal Transformation (IT) Diagrams and what do they tell us?

❑The mechanics behind Dispersion Strengthening.

❑How and why is Age Hardening done.

# Phase Transformations

- Regular phase diagrams are for equilibrium conditions.

- Phase transformations are **_time_** and **_temperature_** dependent.

- Mechanical properties depend on the microstructure which can vary due to the phase transformation.

**Materials Engineering**

# Eutectoid Reaction

- Austenite is a single phase *solid* that transforms to a two phased *solid*.

- In order for this transformation to occur diffusion has to take place.

- Diffusion takes time!

**Materials Engineering**
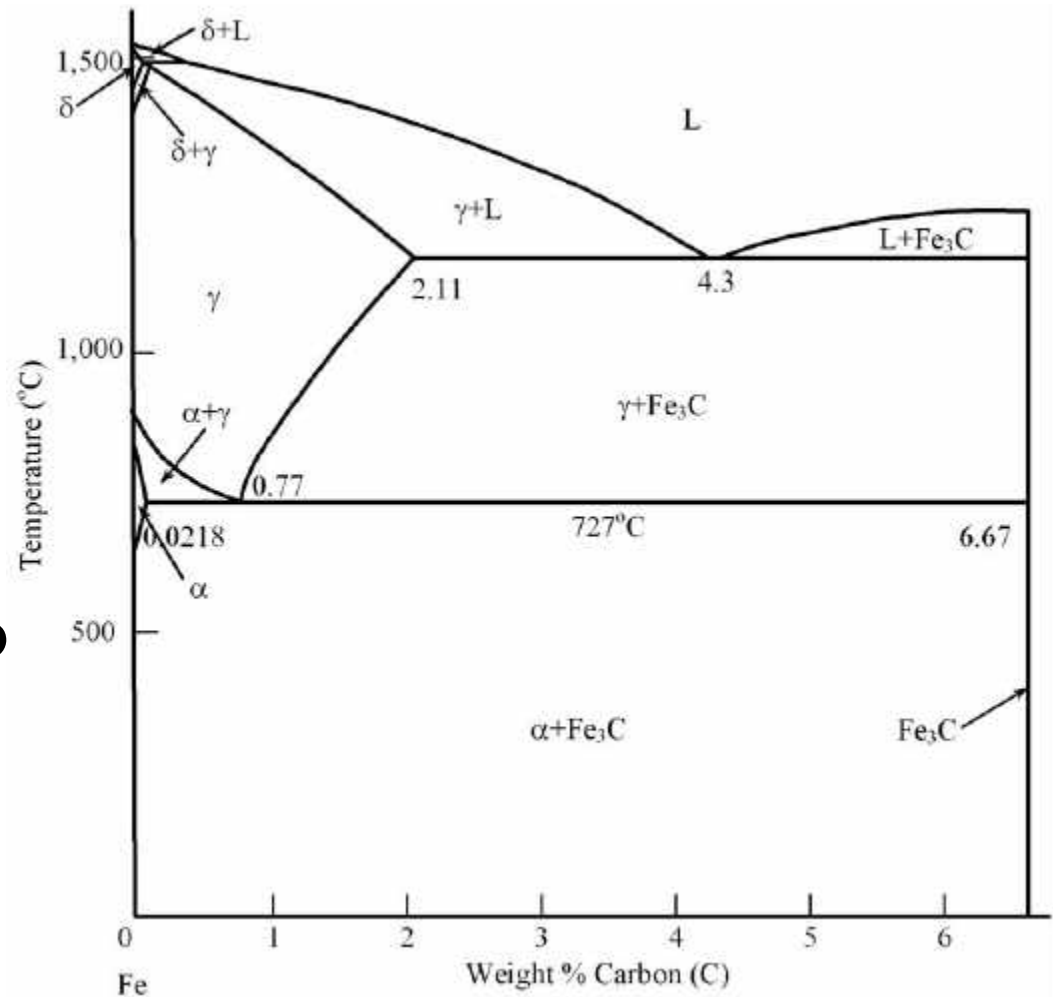
# Isothermal Transformation (IT) Diagram

- The transformation of Austenite to Pearlite takes time.

- Martensite forms during a diffusionless transformation from Austenite.

- Cooling times
  - Water Quench ~ 2s
  - Oil Quench ~ 30s
  - Air Cool ~ 1200s



1080 Steel

$\gamma$ = Austenite (Fe + C)

$P_s$

50% Transformation

$P_f$

$P + \gamma_u$

$P$ = Pearlite (Fe + Fe$_3$C)

$\gamma_u$

$M_s$

$M_f$

$M$

$M$ = Martensite (Fe + C)

Temperature (°C)

Time (s)

727°C

**Materials Engineering**
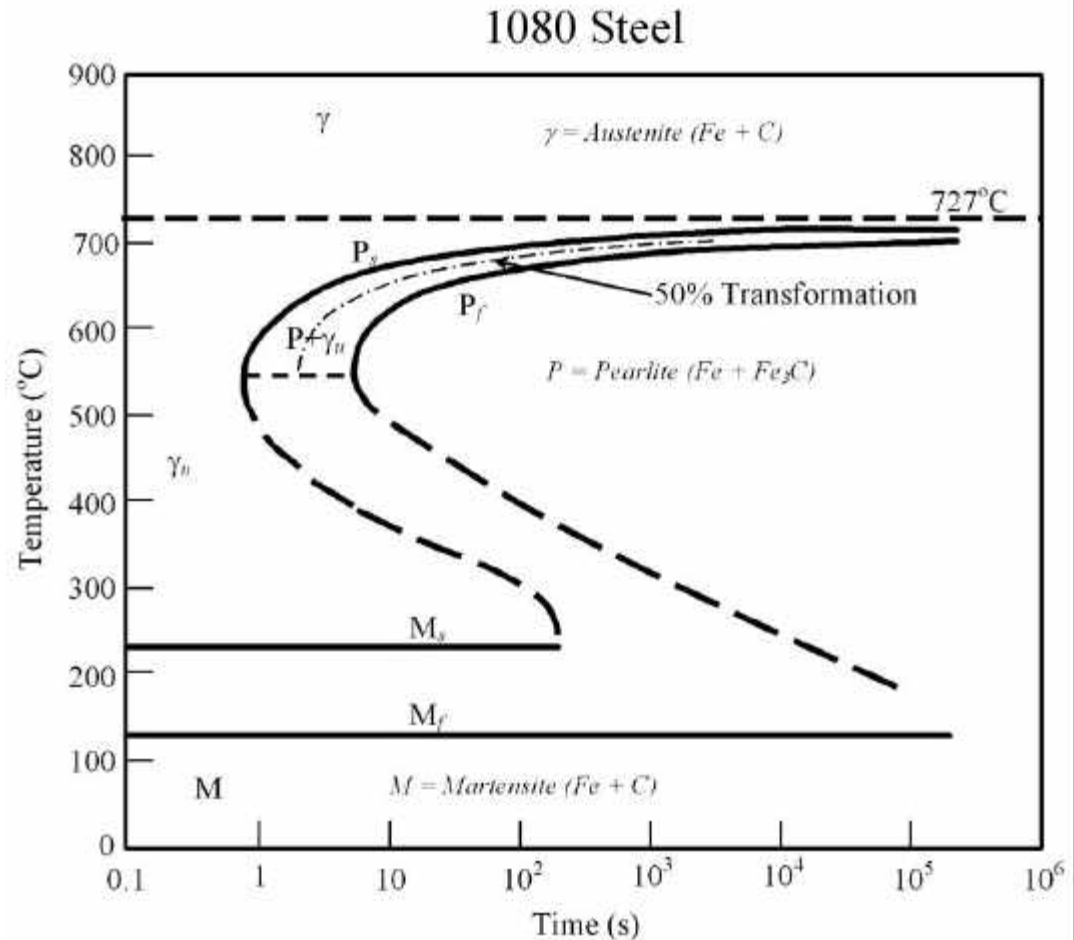
# Example

What are the resulting microstructures from a water quenched, oil quenched and an air cooled samples?



4340 Steel

**Materials Engineering**
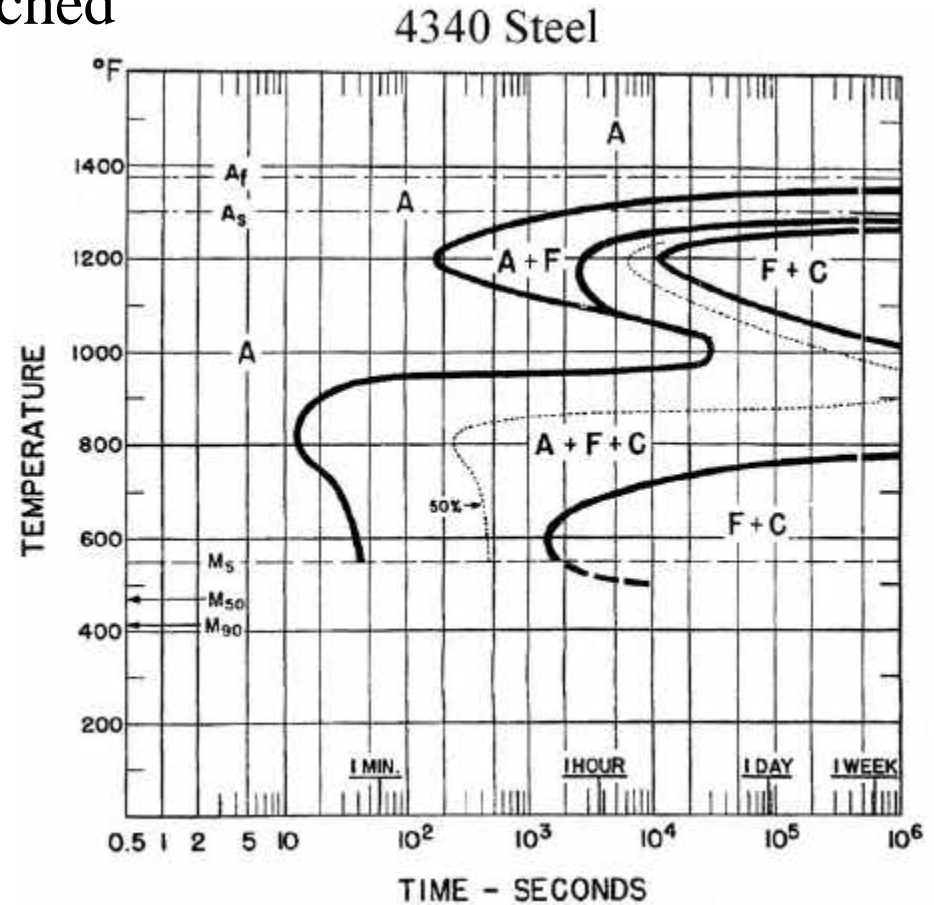
# Heat Treatment and Dispersion Strengthening

- Heat Treatment allow us to control solid-state transformation processes and the resultant properties.

- The most desirable dispersion strengthening characteristics are a soft ductile matrix encompassing a hard strong precipitate which should be small, round, discontinuous, and numerous.

# Nucleation and Growth

- **<u>Nucleation</u>** – Needs a critical size or critical radius for nucleation to occur. In order to minimize the surface energy, precipitate nucleate at existing grain boundaries.

- **<u>Growth</u>** - the growth of the precipitate occurs by long-range diffusion and the rate at which diffusion proceeds is effected by temperature.

# Precipitates



- **Shape** - a sphere has the lowest surface energy but precipitates don't always form spheres.

- **Coherent Precipitate** - the atomic lattice of precipitate is continuous with the lattice of the matrix.

**Materials Engineering**
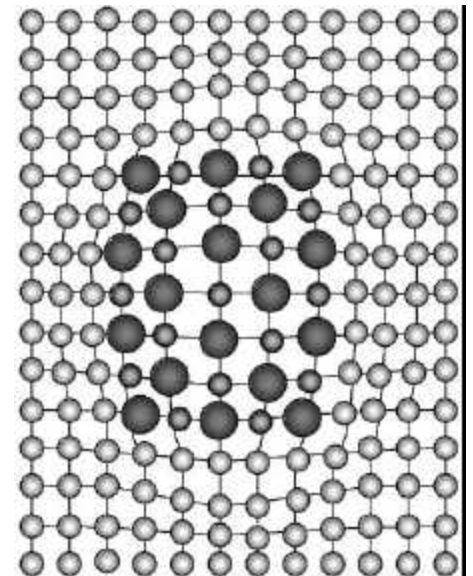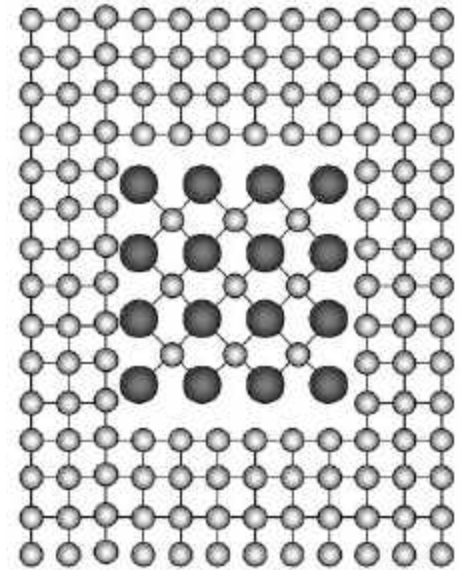
# Age or Precipitation Hardening

- First step is to heat the sample until all one single solution.

- Second step is to quench sample so the solid is super saturated.

- Third step is to let the sample age at a slightly elevated temperature.



Aluminum – Copper Alloy

**Materials Engineering**
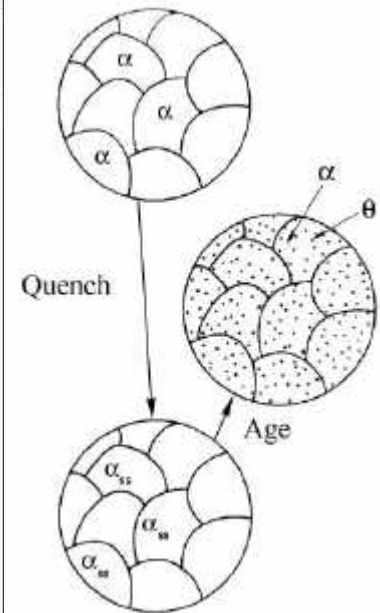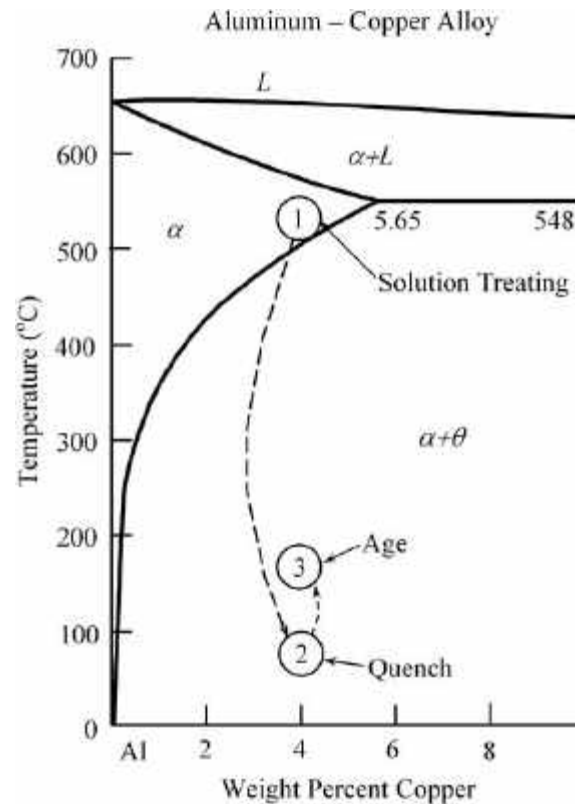
# Aging Temperature & Time
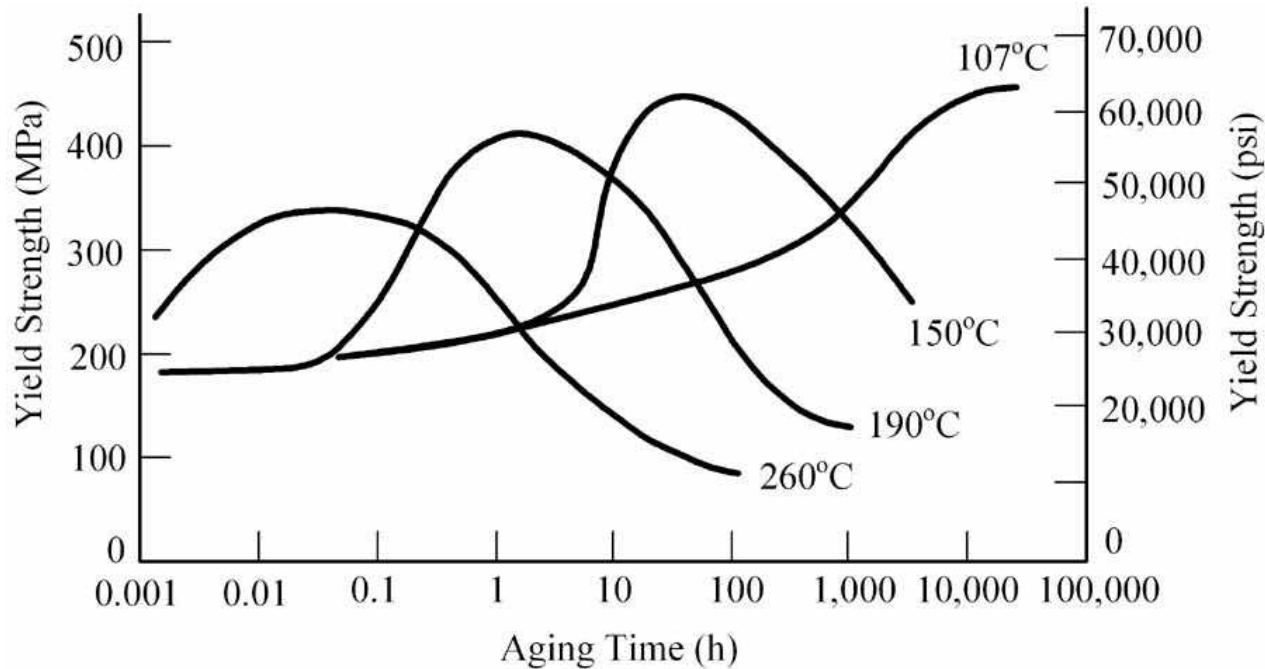


- The higher the temperature the shorter the time needed to get to maximum yield strength.

- The lower the temperature the higher the possible yield strength.

- Remember, diffusion is time and temperature dependent.

# Example

What are the steps (including approximate temperatures) involved in age hardening an Al – Cu alloy to a yield strength of 400 Mpa?



Al – Cu Alloy

**Materials Engineering**
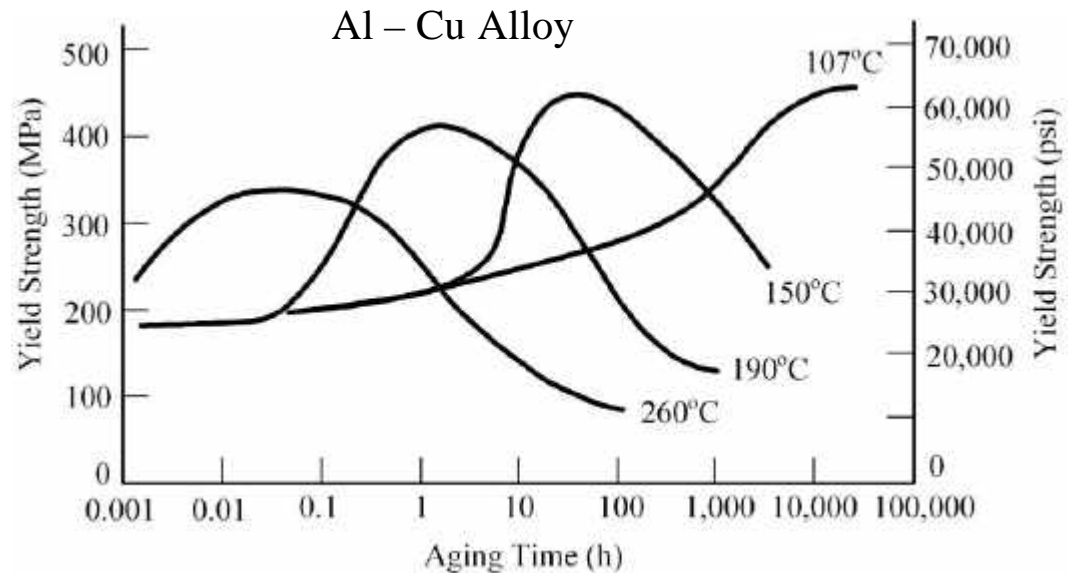
# Summary

- Phase transformations are ***Time*** and ***Temperature*** dependent.

- Regular phase diagrams are for equilibrium conditions.

- Isothermal Transformation (IT) Diagrams display phase transformation in relation to cooling rate.

- Precipitates should be small, round, hard, discontinuous, and numerous.

- Age Hardening steps are:
    1) Solution treat.
    2) Quench.
    3) Age at elevated temperature and quench.

**Materials Engineering**

# Ferrous and Nonferrous Alloys

*Issues to cover*

❑ What are Ferrous Alloys?

❑ What are the AISI-SAE number designations for steel?

❑ What is the difference between Steel, Stainless Steels, and Cast Iron?

❑ What are Nonferrous Alloys?

❑ How can we rate metals based on weight and strength?

❑ Important properties of some Nonferrous alloys.

**Materials Engineering**

# Ferrous Alloys

- Iron is the primary element in Ferrous alloys, this includes steels and cast iron.

- The properties of steels are determined by dispersion strengthening which depend on the amount, size, shape, and distribution of cementite ($Fe_3C$).

- These factors are controlled by alloying and heat treatment.

# Steel Production

Iron ore,
coke (carbon),
and limestone

Gases

**Basic Oxygen Furnace**

Oxygen

## Old Big Steel Mills
(iron ore processing)

**Blast
Furnace**

Steel

## vs.

Air
(oxygen)

Pig iron

Liquid
Metal

**Electric Arc Furnace**

Carbon electrodes

## The New Mini-Mills
(recycling)

Steel
scrap

Steel

**Materials Engineering**
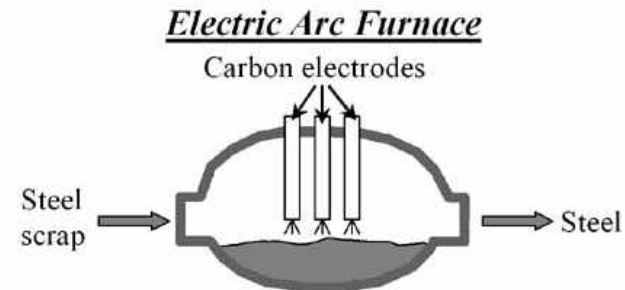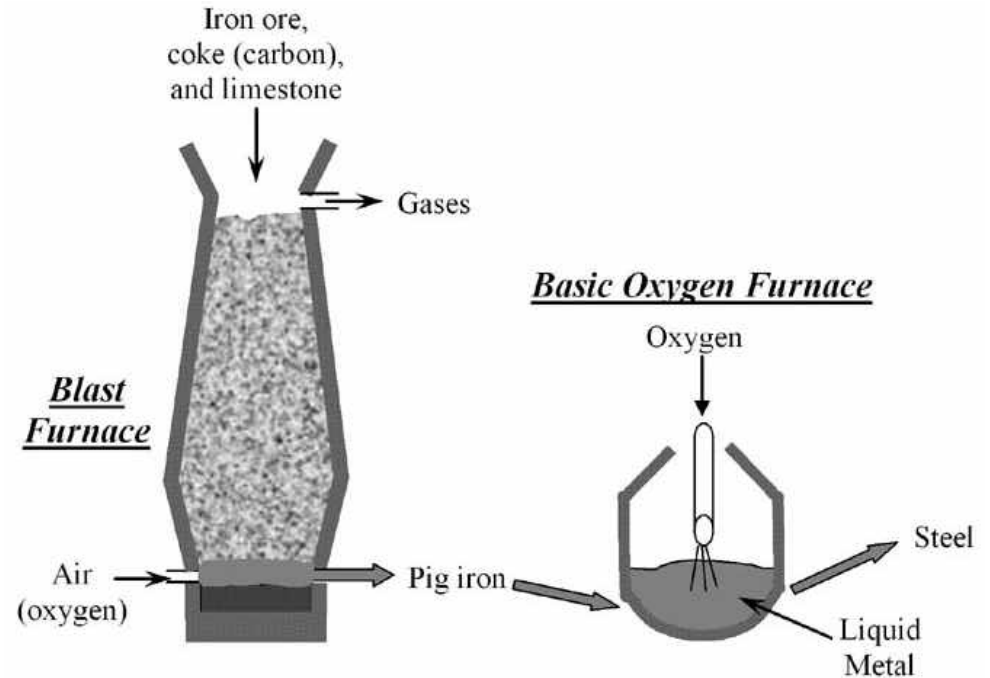
# AISI-SAE Steel Designations

| AISI-SAE Number | % C | % Mn | % Si | % Ni | % Cr | Other |
|---|---|---|---|---|---|---|
| 1020 | 0.18 - 0.23 | 0.30 - 0.60 | | | | |
| 1040 | 0.37 - 0.44 | 0.60 - 0.90 | | | | |
| 1060 | 0.55 - 0.65 | 0.60 - 0.90 | | | | |
| 1080 | 0.75 - 0.88 | 0.60 - 0.90 | | | | |
| 1095 | 0.90 - 1.03 | 0.30 - 0.50 | | | | |
| 1140 | 0.37 - 0.44 | 0.70 - 1.00 | | | | 0.08 - 0.13% S |
| 4140 | 0.38 - 0.43 | 0.70 - 1.00 | 0.15 - 0.30 | | 0.80 - 1.10 | 0.15 - 0.25% Mo |
| 4340 | 0.38 - 0.43 | 0.60 - 0.80 | 0.15 - 0.30 | 1.65 - 2.00 | 0.70 - 0.90 | 0.20 - 0.30% Mo |
| 4620 | 0.17 - 0.22 | 0.45 - 0.65 | 0.15 - 0.30 | 1.65 - 2.00 | | 0.20 - 0.30% Mo |
| 52100 | 0.98 - 1.10 | 0.25 - 0.45 | 0.15 - 0.30 | | 1.30 - 1.60 | |
| 8620 | 0.18 - 0.23 | 0.70 - 0.90 | 0.15 - 0.30 | 0.40 - 0.70 | 0.40 - 0.60 | 0.15 - 0.25% V |
| 9260 | 0.56 - 0.34 | 0.75 - 1.00 | 1.80 - 2.20 | | | |

- If the first two numbers are "10" then it is a plain carbon steel, otherwise it is an alloy steel.

- The last set of numbers are the carbon content (eg. 1040 steel has 0.4% C)

**Materials Engineering**

# Amount of Phases in a Steel

- By knowing how much carbon is in a slow cooled steel we can determine the amount of each phase present.

- A **_Hypo_**eutectoid steel will have **_Ferrite_** and **_Pearlite_**.

- A **_Hyper_**eutectoid steel will have **_Cementite_** and **_Pearlite_**.

**Hypoeutectoid Steels:**

$$\text{Amount of Carobon} = Ferrite(0\%\,C) + Pearlite(0.8\%\,C)$$

**Hypereutectoid Steels:**

$$\text{Amount of Carobon} = Cementite(6.67\%\,C) + Pearlite(0.8\%\,C)$$

Materials Engineering

# Example

What phases are present in a slow cooled 1090 steel?  How much of each of these phases are present?

Materials Engineering

# Surface Treatments

- **Surface Heat Treatment** - The surface is quickly heated, quenched, and then tempered

- **Carburizing** - diffusion of carbon into the surface to increase the carbon at the surface

- **Nitriding** - Similar to Carburizing but nitrogen (N) is substituted for carbon

- **Shot Peening** – Compressive stresses introduced at the surface by bombardment of steel shot.

# Stainless Steels

- Ferritic Stainless Steels (BCC)- Up to 30% Cr and less then 0.12% C. Good corrosion resistance.

- Martensitic Stainless Steels - Cr < 17%. Heat treatable with the ability to form martensite among other phases.

- Austenitic Stainless Steels (FCC)- High Ni concentration because Ni is an austenite stabilizing element.

Materials Engineering

# Cast Iron

- Grey Cast Iron - Interconnected graphite flakes in pearlite matrix. Good vibration damping.

- White Cast Iron – Rapidly cool so most of the carbon is in cementite not graphite. Used for their high hardness and wear resistance.

- Malleable Cast Iron - Heat treated to form clusters of graphite. It is an unalloyed 3% carbon white cast iron.

- Nodular Cast Iron - The addition of magnesium (Mg) to Grey Cast Iron causes the graphite to grow spheroidal in shape instead of flakes.

Materials Engineering

# Nonferrous Alloys

- Non Iron based alloys.

- Wide range of structures, physical, mechanical, and electrical properties, cost, and strengthening mechanisms.

- $$ Cost. $$

- Selecting the right material to fit the application.

Materials Engineering

# Specific Strength

| Metal | Density (lb/in$^3$) | Tensile Strength (psi) | ~Cost per lb ($) |
|---|---|---|---|
| Aluminum | 0.097 | 83,000 | $9.00 |
| Beryllium | 0.067 | 55,000 | $300.00 |
| Copper | 0.322 | 150,000 | $5.50 |
| Lead | 0.41 | 10,000 | $1.25 |
| Magnesium | 0.063 | 55,000 | $7.00 |
| Nickel | 0.321 | 180,000 | $20.00 |
| Titanium | 0.163 | 160,000 | $80.00 |
| Tungsten | 0.695 | 150,000 | $95.00 |
| Zinc | 0.257 | 75,000 | $2.00 |
| Iron | 0.284 | 200,000 | $2.00 |

- Allows the comparison of metal on the bases of strength to weight.

$$\text{Specific Strength} = \frac{\text{Tensile Strength}}{\text{Density}}$$

**Materials Engineering**

# Example

Rank these metal in decreasing Specific Strength: Al, Mg, Ti, Zn.

**Materials Engineering**

# Aluminum Alloys

- Second most plentiful metal on earth

- Hall-Heroult process - electrolytic reduction of $Al_2O_3$ to liquid metal

- One-third the density of Steel

- Aluminum alloys can be up to 30 times stronger then pure Aluminum

- Al - Li Alloys

Materials Engineering

# Magnesium Alloys

- Extracted electrolytically from concentrated magnesium chloride in seawater

- Density = $1.74 \text{g/cm}^3$ (lighter then Al)

- Specific strength comparable to Al

- Poor corrosion resistance in a marine environment

Materials Engineering

# Beryllium Alloys

- Modulus of Elasticity = 42 x 10$^6$ psi (stiffer then steel)

- Density = 1.848 g/cm$^3$ (light then Al)

- Very expensive $$$$$, due to complicated production.

- It can be toxic, BeO is a carcinogenic material for some people.

Materials Engineering

# Copper Alloys

- Heavier then Steel, lower specific strength then Aluminum

- Many copper alloys are excellent electrical conductors

- Brass - Copper-Zinc alloys w/ < 40% Zn

- Bronze - Copper-Tin alloys w/ < 10% Sn

- Copper-Beryllium alloys are non-sparking

**Materials Engineering**

# Nickel Alloys

- High temperature alloys.

- Great corrosion resistance.

- Supperalloys - Nickel, iron-nickel, and cobalt. (high strength at high temperatures)

- Solid solution, dispersion strengthening and precipitation hardening

# Titanium Alloys

- The Kroll process - conversion of $TiO_2$ to $TiCl_4$ which is then reduced to titanium metal.

- Higher specific strength then aluminum

- excellent corrosion resistance and high temperature properties

- Alpha ($\alpha$) and Beta ($\beta$) titanium alloys

Materials Engineering

# Refractory Metals

- Exceptionally high melting temperatures

- **Tungsten (W)** - 3,410$^o$C

- **Molybdenum (Mo)** - 2,610$^o$C

- **Tantalum (Ta)** - 2,996$^o$C

- **Niobium or Columbium (Nb)** - 2,468$^o$C

**Materials Engineering**

# Summary

- Ferrous alloys are iron based.

- Steels can be designated by their AISI-SAE number and are made up of Ferrite, Cementite, and Pearlite.

- Three types of stainless steels are: Ferritic, Martensitic, and Austenitic.

- Cast iron has excess carbon that is in the form of graphite.

- Non-Ferrous alloys include all non-iron based alloys.

- Specific strength allows the raking of metal by their strength to weight ratio, which is important for transportation industry.

- Non-Ferrous alloys have a huge range of properties so it allows the selection of the best metal for a given application.
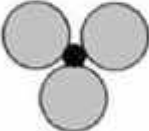
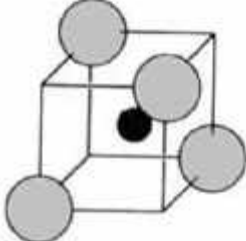Materials Engineering

# Ceramics

## *Issues to cover*
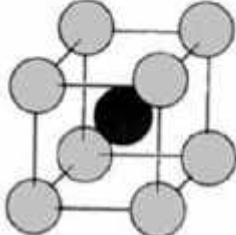
❑ What are Ceramics and what are their typical properties?

❑ Ceramic crystalline structure.

❑ Defects in ceramics and their effect on Fracture Toughness.

❑ Porosity and its effects on Mechanical properties.

❑ What are Glasses and what are their typical properties?

❑ What is Sintering and why is it important?

Materials Engineering

# Ceramics

- Ceramics are compounds of metallic and nonmetallic elements.

- Ceramics have predominately ionic bonding.

- They are typically hard, stiff, brittle, wear and thermal resistant.

- Can be: Insulators (electrical and thermal), Semiconductor, Superconductors, or Magnetic.

- Glasses are similar to ceramics but are amorphous in structure.

# Ceramic Structure

- The Coordination Number is the number of nearest neighbors for a cation.

- Coordination geometry is similar to interstitial sites.

- Cation have to be as big or larger then their site to be stable.

- Cations like to have as many nearest neighbors as possible.

- The overall charge has to be balanced.

| Coordination Number | Coordination Geometry |
| --- | --- |
| 2 | |
| 3 | |
| 4 | |
| 5 | |
| 6 | |

**Materials Engineering**

# Defects

- Some of the defect in ceramics are similar to metals but they can behave quite differently due to the strong ionic bonding.

- Remember that the charge must be balanced.

- Point Defect - Frenkel, Shottky, Impurities

- Linear Defects – Dislocations

- Surface Defects – Grain Size, Cracks

- Porosity

Materials Engineering

# Point Defects

- Frenkel defect – Cation moved from normal position to an interstitial site.

- Schottky defect – Missing cation & anion pair.

- Impurity – Both substitutional and interstitial.

- Remember Charge must be balanced.

Frenkel Defect

Schottky Defect

Materials Engineering
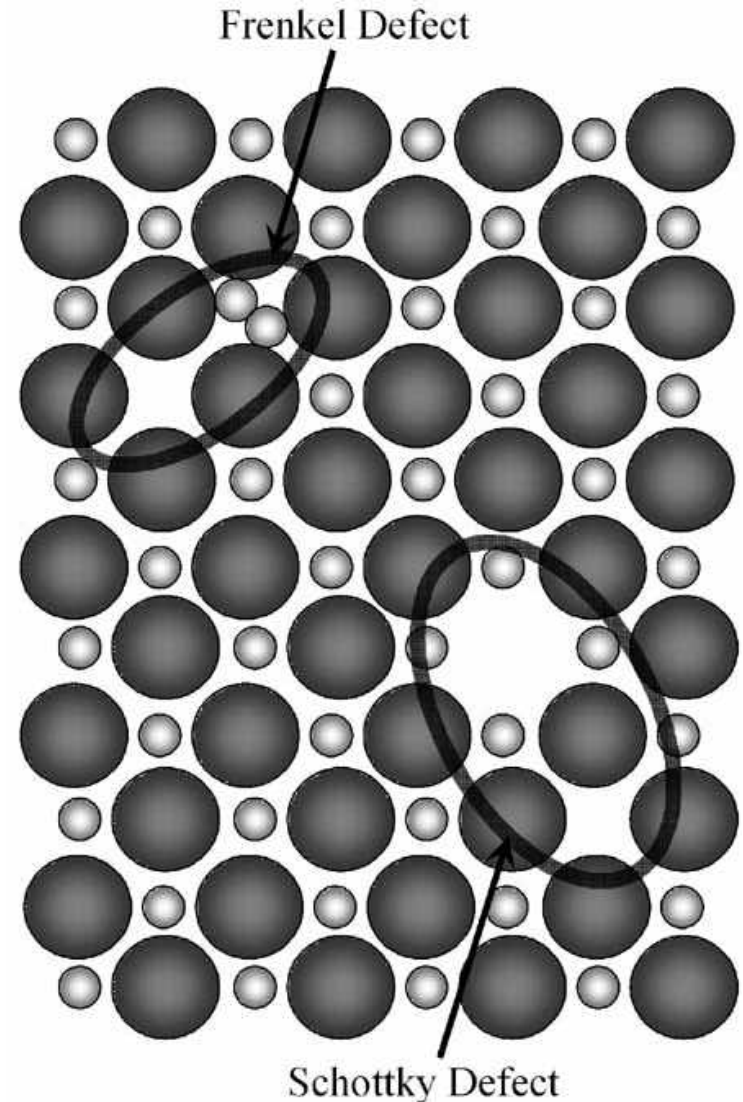
# Linear Defects

- Dislocations are present in the ceramic crystalline structure but are unable to move due to the high strength of the ionic bonds holding the atoms together.

- Before such a large force could be applied to cause dislocation movement, other defect would be overloaded and cause the ceramic to fail.

- Some ceramics may deform by viscous flow at high temperatures.

**Materials Engineering**

# Surface Defects

- Improper Coordination number / Missing bonding.

- Surface scratches (cracks):

$$K_{IC} = Y s \sqrt{p a}$$

- Geometric Shape – Y is a geometric factor due to stress concentration of different shapes (e.g.. sharp corners, rounded fillets)
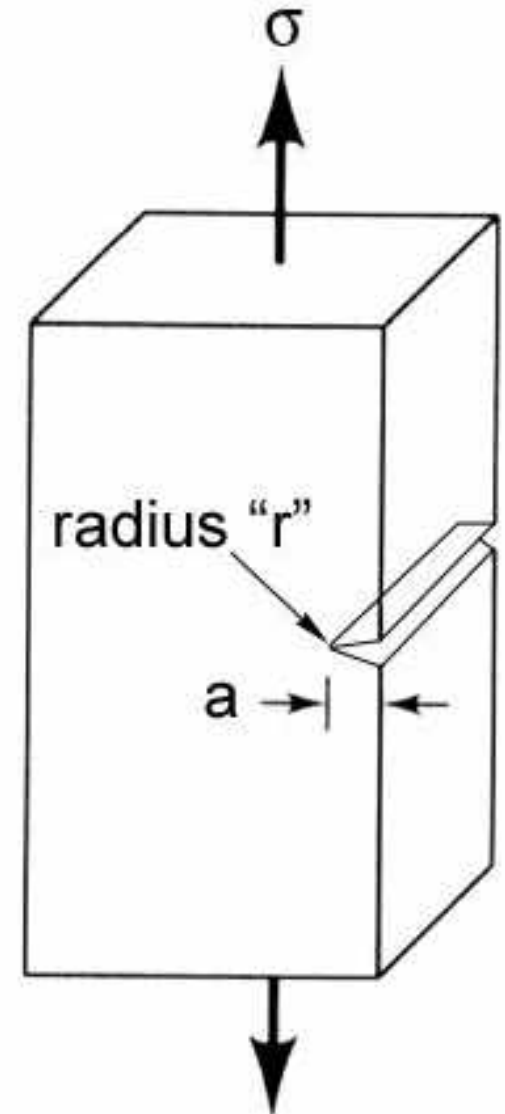
# Example

A structural component in the form of a wide plate is to be fabricated from a steel alloy that has a plane strain fracture toughness of 77 MPa. The flaw size resolution limit of the Ultrasonic Inspection tool that will be used to detect flaws in this structure is 2.0mm. If the design stress is 1200 MPa and the value of Y is 1.0, determine: What the maximum flaw size is and whether a critical flaw for this plate be detected?

# Porosity

- Porosity are voids in the bulk ceramic material usually introduced during fabrication.

- Porosity lowers the Modulus of Elasticity and Flexural Strength.

- Modulus of Elasticity – $E = E_O \left(1 - 1.9P + 0.9P^2\right)$

- Flexural Strength – $\sigma_{fs} = \sigma_O \exp\left(-nP\right)$

# Example

The modulus of elasticity for boron carbide ($B_4C$) having 20 vol% porosity is 210 Gpa. Compute the modulus of elasticity for the nonporous material and at what volume percent porosity will the modulus of elasticity be 290 Gpa?

# Mechanical Properties

- Failure Modes (Brittle)

- Flexural Strength

  ➢ $$s = \frac{3FL}{2bd^2} = \frac{FL}{pR^3}$$

Possible cross sections

F

Support

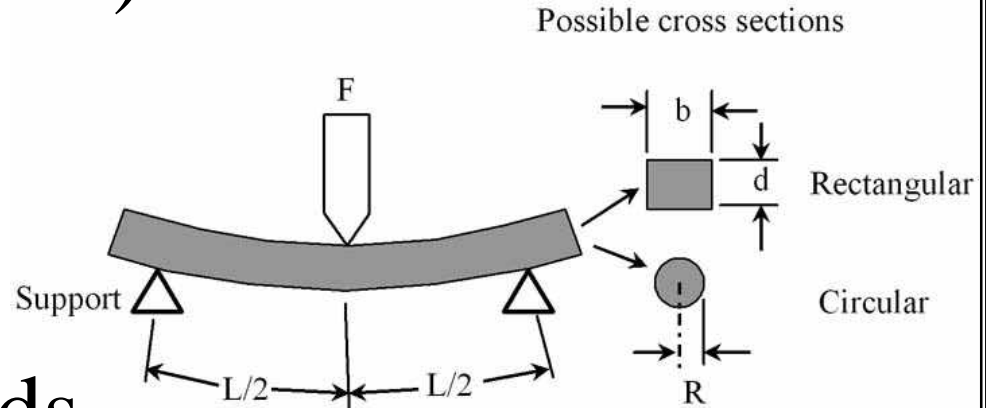L/2 — L/2

b

d Rectangular

Circular

R

- Toughening Methods

  ➢ Cermet (tough matrix / hard ceramic particle)

  ➢ Ceramic Matrix Composite (interface block cracks)

  ➢ Transformation-Toughened

  ➢ Improving Processing (fine grain, pure, dense)

**Materials Engineering**

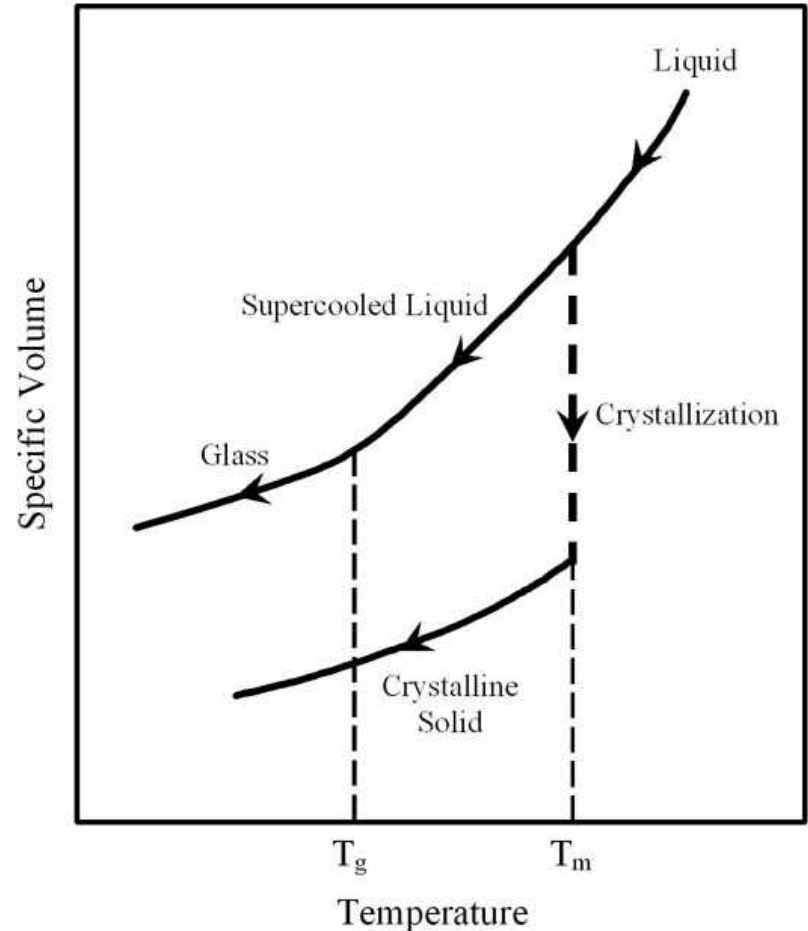# Example

A rectangular cross section glass sample, with the height d = 4mm and the width b = 6mm, is subjected to a three point bend test with the spacing between support points of 50mm. Calculate the flexural strength if the load at fracture is 100N

Materials Engineering

# Glasses

- Glasses vs Crystalline Structures

- Glasses are amorphous.

- Glass Transition Temperature is where the glass goes from a supercooled liquid to a rigid glass.

- Glass Modifiers ($Na_2O$, CaO)

- Heat Treatment – Annealing and Tempering



Liquid

Specific Volume

Supercooled Liquid

Crystallization

Glass

Crystalline Solid

$T_g$     $T_m$

Temperature

**Materials Engineering**
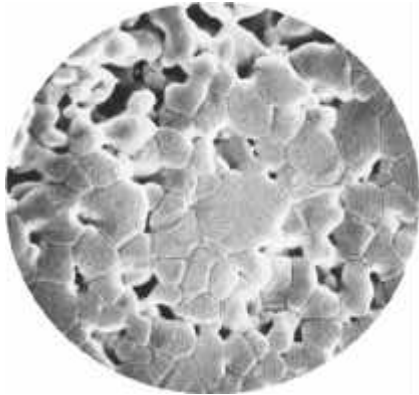
# Glass Properties

- **Melting Point** – Glass is Liquid.

- **Working Point** – Above this point glass is too easily deformed.

- **Softening Point** – Below this point no significant deformation.

- **Annealing Point** – At this point residual stresses are removed.

- **Strain Point** – Below this point glass will fracture before any plastic deformation.



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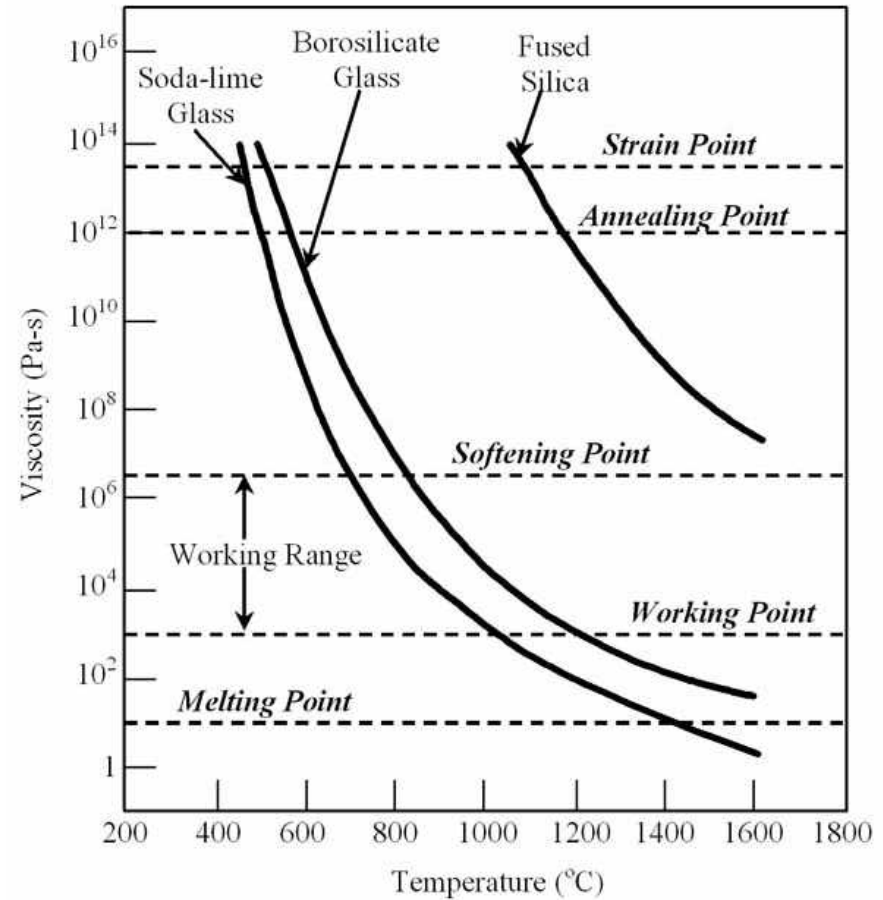
# Sintering

- Sintering is the diffusion across grain boundaries bonding particles together.

- Sintering is typically done at high temperature and pressure.

- Decrease porosity with increase in sintering.

Neck
Pore
Grain Boundary

1

2

3

**Materials Engineering**
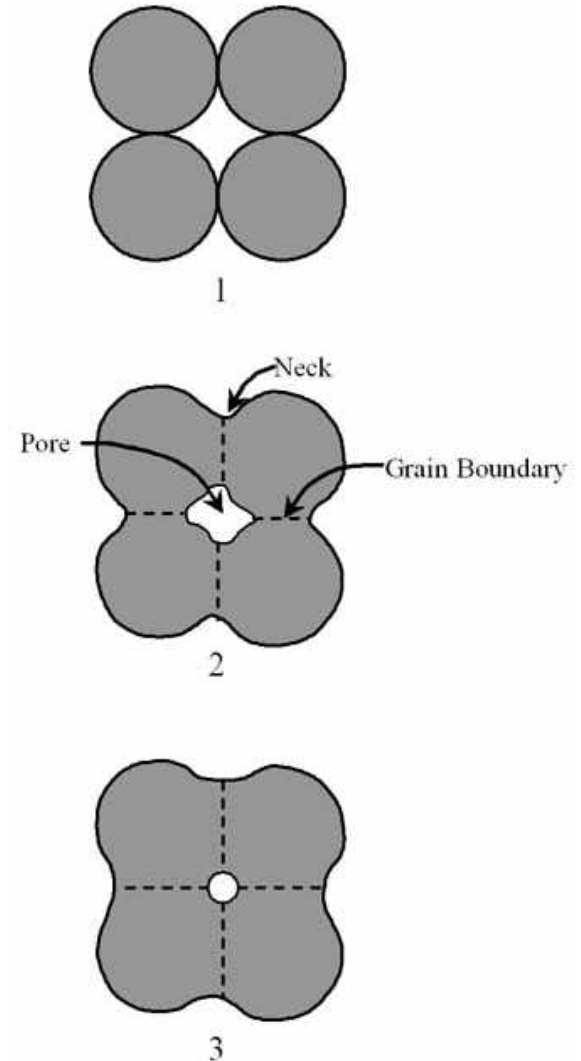
# Summary

- Ceramics are typically hard, stiff, brittle, wear resistant, and thermal resistant.

- The Coordination Number is the number of nearest neighbors for a cation.

- Point defects - charge must be balanced.

- Fracture toughness - $K_{IC} = Y\boldsymbol{s}\sqrt{\boldsymbol{p}a}$

- Porosity lowers the Modulus of Elasticity and Flexural Strength.

- Glass Transition Temperature is where the glass goes from a supercooled liquid to a rigid glass.

- Sintering is the diffusion across grain boundaries bonding particles together.

Materials Engineering

# Polymers

## *Issues to cover*

❑ What are Polymers and why can only some of them be recycled easily?

❑ What is the microstructure of polymers and how does it effect properties?

❑ Mechanical behavior of polymers (time & temperature effects).

❑ Glass Transition Temperature and why it is important for polymers

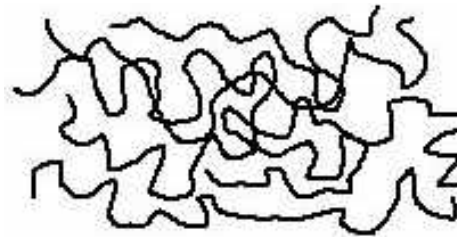❑ Elastomers (Rubber) and why they are Vulcanized.

# Polymers
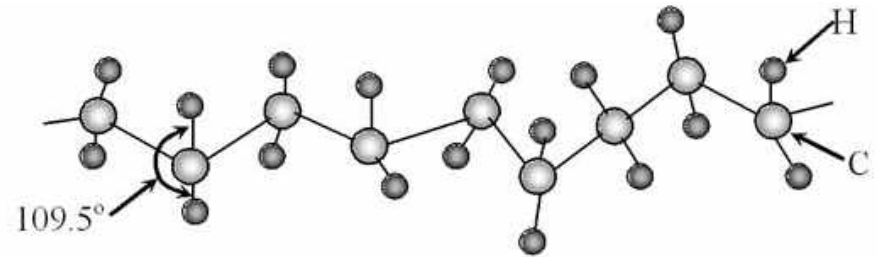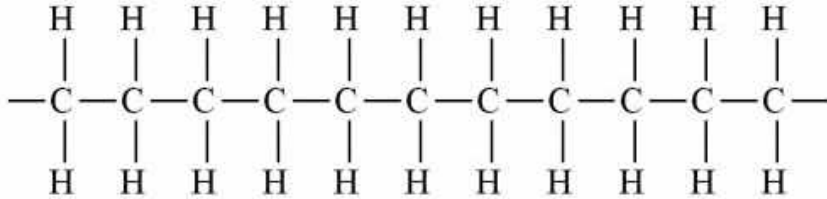


- The word polymer is derived from the combination of:
  - *Poly* – which means "many"
  - *Mer* – which means "single unit"

- Some natural polymers – Latex, Silk, Wood, Leather.

- Some synthetic polymers – Polypropylene, Kevlar, Teflon.

**Materials Engineering**

# Types of Polymers

- Thermoplastics:
    - Little or no cross linking.
    - Ductile.
    - Soften when heated and will melt.
    - Polyethylene, polypropylene, polycarbonate, polystyrene.

- Thermosets:
    - Have large amounts of cross linking (10 to 50% of mers).
    - Hard and brittle.
    - They do NOT soften when heated
    - epoxies, polyester resin, phenolic resin

- Elastomers:
    - Have small amounts of cross linking.
    - Can experience large reversible elastic deformation.
    - Vulcanized rubber, Latex.

**Thermoplastic**
Flexible linear chains
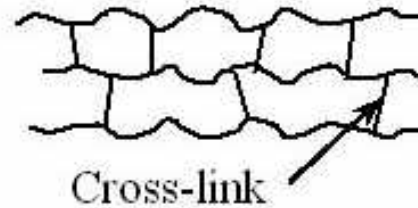
**Thermosetting**
Rigid 3D network
Cross-link
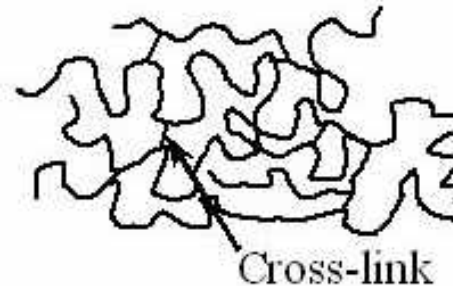
**Elastomers**
Linear cross-linked chains
Cross-link

**Materials Engineering**

# Polymer Microstructures
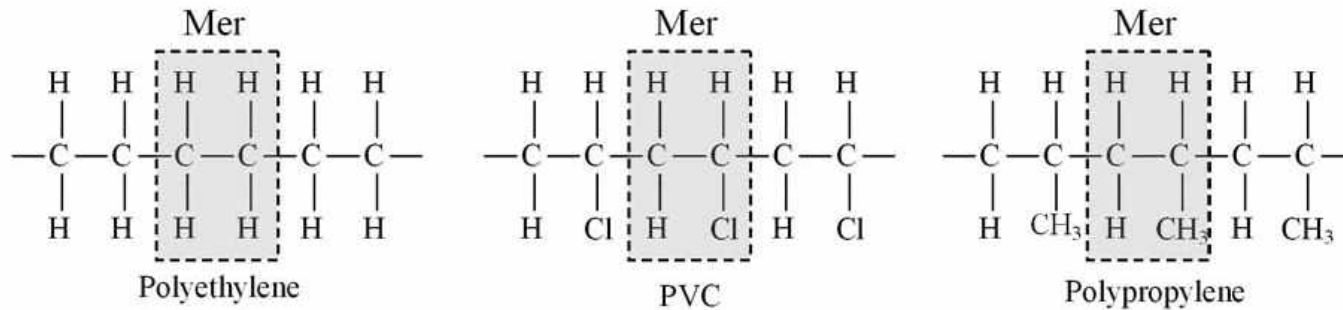


- The larger the Pendent Groups the higher the yield strength and glass transition temperature.

- The different types of covalent chain configurations effects the polymers relative strength.

**Materials Engineering**
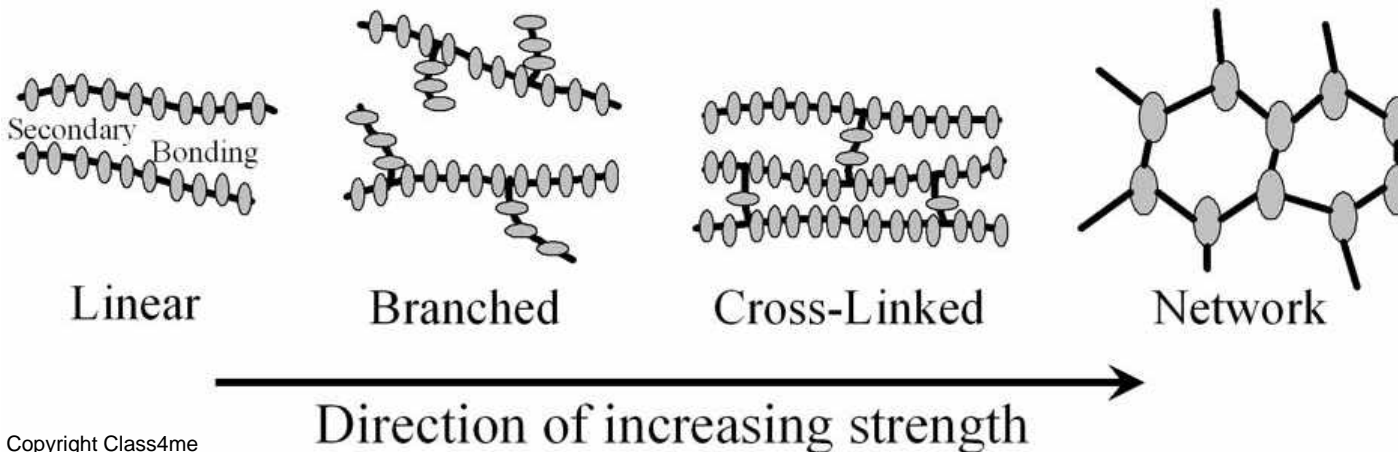
# Molecular Weight

- Degree of Polymerization $n_w$ – The average number of mers in a chain.

- Molecular weight, $M_w$ - The mass of a mole of chains.

- Mer Molecular Weight, $m$ – The mass of a single mer.

- Tensile strength (TS) - Often increases with $M_w$ due to the longer chains being better entangled (anchored) together.

$$n_w = \frac{\overline{M}_w}{\overline{m}}$$

Smaller $M_w$

Larger $M_w$

**Materials Engineering**
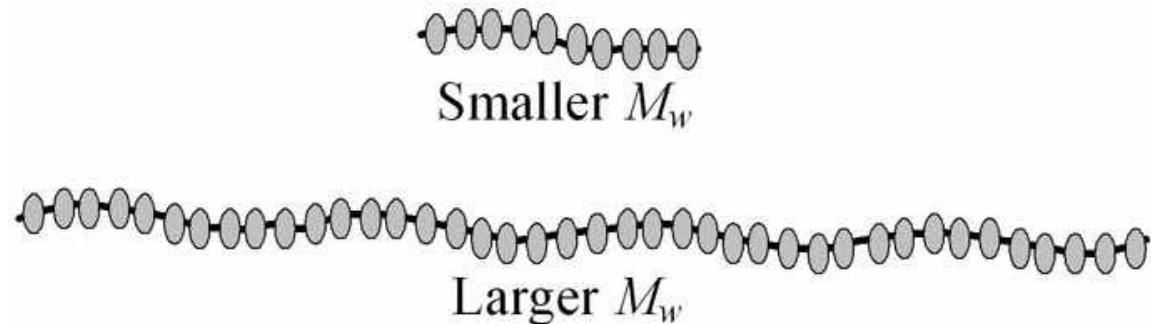
# Example

A polyethylene rod weighs 4.0g/cm. If the number-average degree of polymerization is 6000, calculate the average number of polyethylene chains (molecules) in a 35cm length of rod (Hint: $6.023 \times 10^{23}$ molecules/mol).

# Crystallinity

- There are different types of crystallinity: Fringed-Micelles, Chain-folded model, Spherulites.

- % Crystallinity: % of material that is crystalline.

  - Tensile Strength and Elastic Modulus often increase with % crystallinity.

  - Annealing causes crystalline regions to grow and % crystallinity to increases.



Crystalline Region        Amorphous Region

**Materials Engineering**
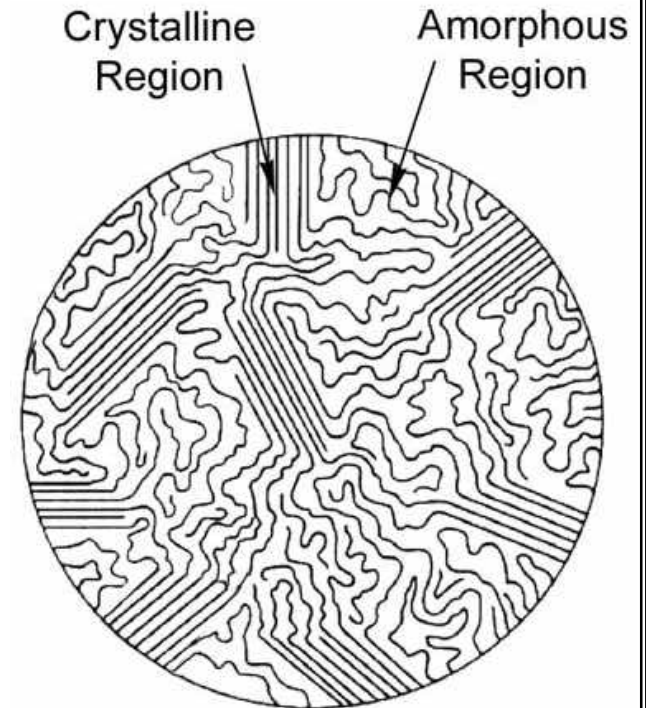
# Mechanical Behavior

- This Stress-Strain graph displays the stress-strain curves of a brittle polymer, a ductile polymer, and an elastomer.

- Mechanical behavior of polymers is also dependent on:

  - Time - viscoelasticity
  - Strain rate
  - Temperature effects (e.g. $T_g$, creep)

**Materials Engineering**
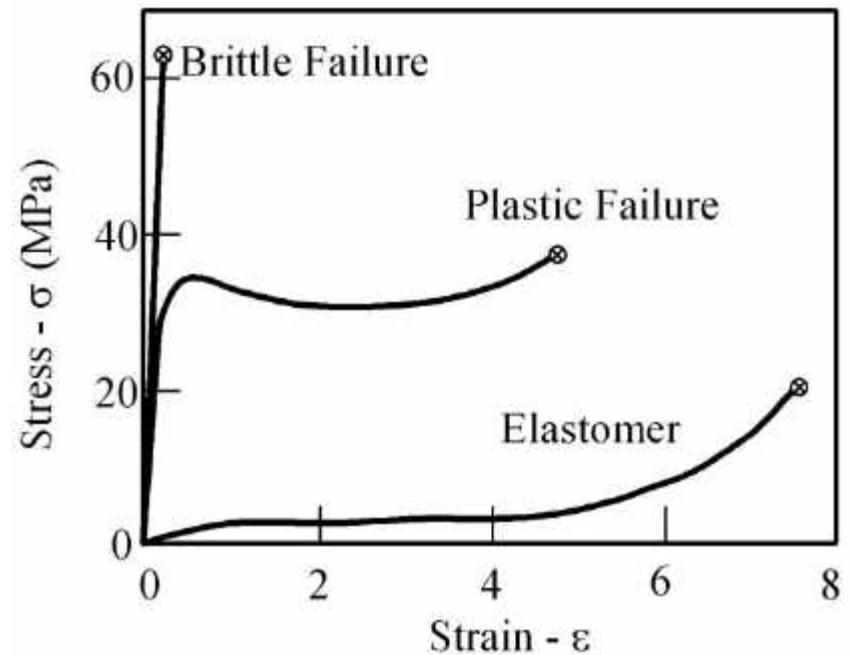
# Time Dependent Deformation

- Viscoelastic Deformation is the delay in deformation when a stress is applied or removed.

- Stress relaxation test:
  a) Strain to $\varepsilon_o$ and hold.
  b) Observe decrease in stress with time.
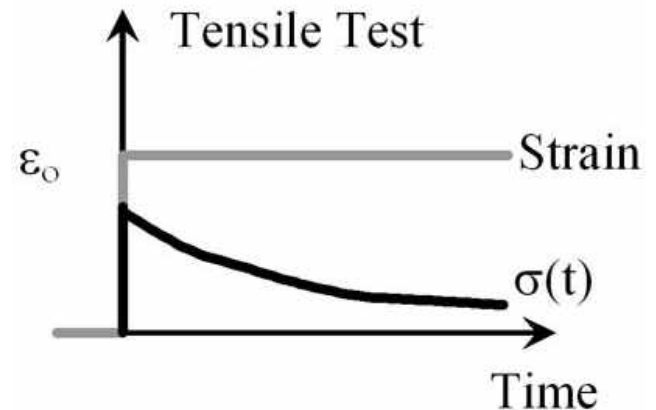
- Relaxation modulus: $E_r(t) = \dfrac{\sigma(t)}{\varepsilon_o}$

- Increasing strain rate causes polymers to behave more like a brittle material.

- Viscoelastic Creep is the deformation over time even with very small applied loads.

**Materials Engineering**

# Temperature Dependent Deformation

- Increasing the Temperature: increases the average distance between the chains due to the increase in vibration. This increase in spacing allows the chains to slide past each other easier (interference of pendent groups is diminished).

- Decreasing T has the same effects as increasing strain rate:
  - Increases Elastic Modulus
  - Increases Tensile Strength
  - Decreases %Elongation

PMMA (Plexiglass)
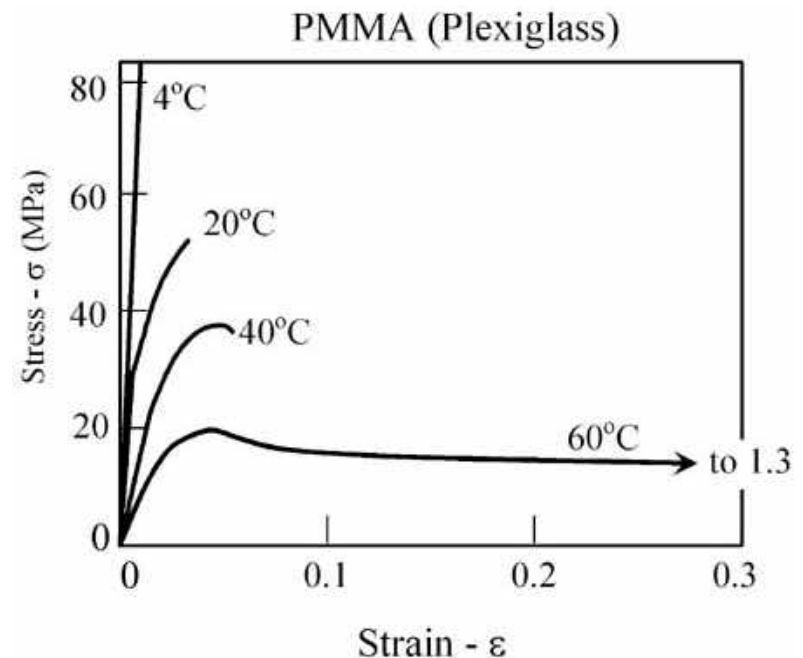
# Melting and Glass Transition

- When thermoplastic polymers are heated to high temperatures the chain spacing grows until the secondary bonds are too weak to hold the chains together, and it melts.

- The Glass Transition Temperature ($T_g$): is where the cooling polymer transforms from a rubbery to a rigid state.

- Above the Glass Transition temperature a polymer is not able to take a load without deforming.

# Fracture
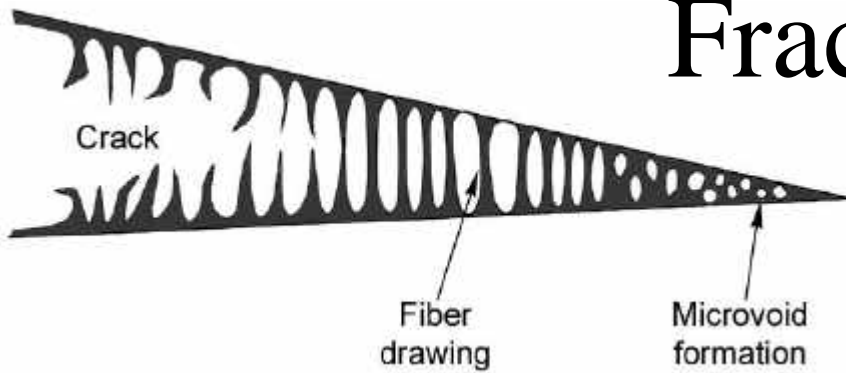


- Crazing precedes fracture in some glassy thermoplastic polymers.

- Localized yielding in these crazed regions causes the formation of small (micro) voids.

- The areas between these voids are drawn into fibers with the chains becoming oriented.

- Finally the fibers between the voids rupture and the Microvoids coalesce.

- Difference between crazes and cracks is a craze supports a load across its face and absorbs energy as the microvoids coalesce and it grows.

**Materials Engineering**

# Elastomers (Rubber)

- The Cross-linking in rubbers is done by a process called Vulcanization which is the addition of sulfur at high temperature and pressure to cause this cross-linking.

- Elastomers are above their Glass Transition temperature ($T_g$) at room temperature.

- Elastomers are non-crystalline in nature.
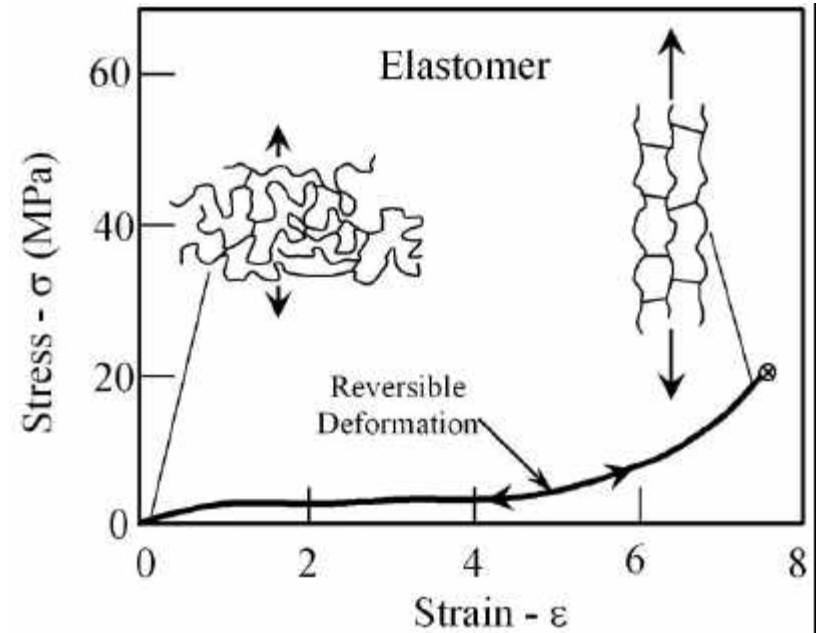


a. Initially the amorphous chains are kinked and heavily cross-linked.

b. Finally the chains straighten out but are still cross-linked.

**Materials Engineering**

# Forming Techniques

- Compression Molding – Polymer and additives are placed in heated mold that compress mixture until it flows.

- Injection Molding – Melted polymer is injected into mold cavity.

- Extrusion – Viscous polymer is forced through an open ended die.

- Blow Molding – a polymer tube is extruded and then inflated inside a two piece mold to conform to the inside of that mold.

- Casting – molten or liquid plastics are poured into a mold and allowed to harden.

# Summary

- Polymers are long chains of repeating mers.

- 3 different types of polymers with different properties:
  - Thermoplastics (PE, PS, PP, PC):
    - Will melt so easier to form and recycle.
    - Smaller E, $\sigma_y$, $T_{app}$, larger $K_c$
  - Elastomers (rubber):
    - Large reversible strains!
    - Vulcanized
  - Thermosets (epoxies, polyesters):
    - Will not melt
    - Larger E, $\sigma_y$, $T_{app}$, smaller $K_c$

- General drawbacks to polymers:
  - E, $\sigma_y$, $K_c$, $T_{app}$ are generally small.
  - Deformation is often Temperature and time dependent.

**Materials Engineering**

# Composites

## *Issues to cover*

❑What are Composites and what are their typical properties?

❑What are the classes and types of composites?

❑How does each type of composite take advantage of its constituents?

❑How do we estimate composite stiffness & strength?

**Materials Engineering**

# Composites

- Composites are multiphase materials containing a *Matrix* and a *Dispersed phase*, with significant proportions of each phase.

- The *Matrix* is the continuous phase and its purpose is to:
  - transfer stress to the dispersed phases.
  - protect the dispersed phases from the environment.
  - ➢ Types of matrix materials:  Metal, Ceramic, Polymer.

- The *Dispersed phase* is encased in the matrix and it:
  - enhances the properties of the matrix.
  - ➢ Classification of phases:  particle, fiber, structural.

# Classes and Type

- In this course: ***Classes*** of composites refers to the dispersed phase (particle, fiber, structural) where as ***Type*** of composites refers to the type of matrix material (metal, ceramic,or polymer).

- ***<u>Classes</u>*** of composites include:
  - Particle – small discontinuous particle dispersed in a matrix
  - Fiber – fibers encased in a matrix.
  - Structural – sandwiched panels or layered sheets.

- ***<u>Types</u>*** of composites include:
  - Metal Matrix Composite (MMC):  increase $\sigma_y$, TS, creep resist.
  - Ceramic Matrix Composits (CMC):  increase Kc
  - Polymer Matrix Composite (PMC):  increase E, $\sigma_y$, TS, creep resist.
  - ➢ Purpose: enhance matrix properties.

Materials Engineering

# Particle Reinforced

- Particle reinforced composites contain discontinuous particles encompassed by the matrix and can be classified as either *Large-particle* or *Dispersion-strengthened* composites.

- *Large particle* composites tend to have harder stiffer particle that bear some of the load.

  ➢ Examples: Concrete, WC/Co (abrasive material).

- *Dispersion-strengthened* composites tend to have very small particles that hinder deformation on an atomic scale.

  ➢ Examples: Carbon black in auto tires, aged hardened Aluminum alloy.

Materials Engineering
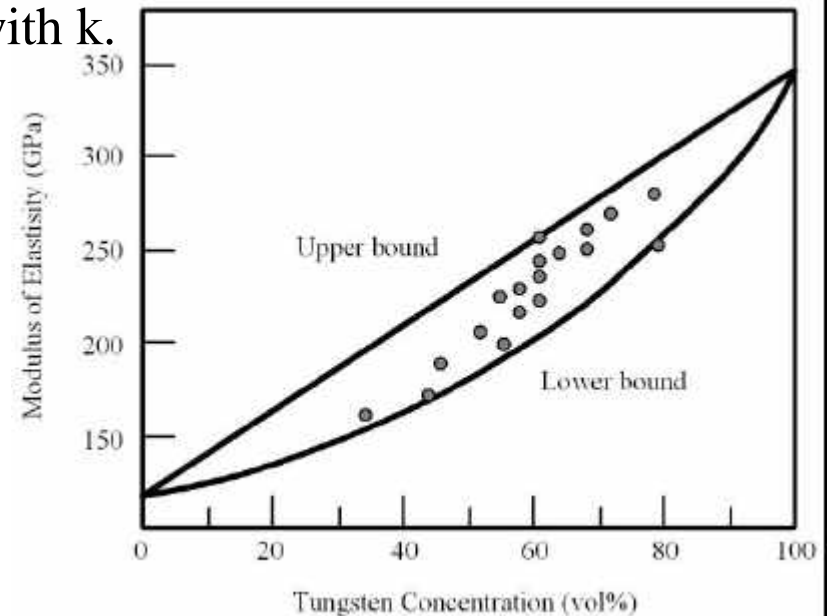
# Particle (Properties)

- The Elastic modulus ($E_c$) of particle composites is found experimentally to have a range in values bound by an upper and lower limit.

- Application to other properties:
  - Electrical conductivity ($\sigma_e$):  replace E with $\sigma_e$.
  - Thermal conductivity (k):  replace E with k.

**Upper Limit:**

$$E_c(u) = E_m V_m + E_p V_p$$

**Lower Limit:**

$$E_c(l) = \frac{E_m E_p}{E_m V_p + E_p V_m}$$

# Example

A 40% concentration of Tungsten particle is dispersed in a Cu matrix, determine the upper and lower bonds of this composites Elastic Modulus.

$E_W$=407 Gpa         $E_{cu}$=110 GPa

# Fiber Reinforced

- Fiber reinforced composites are usually designed with high strength and or high stiffness to weight ratios.

- Aligned Continuous fibers:
  - Long strong fibers encased in a ductile matrix.
  - Can be woven and or wound for optimal load bearing.
  - Examples: Fiberglass, Carbon Fiber bike frames, packing tape, radial auto tires (steel belted).

- Discontinuous, random 3D fibers
  - Short random fibers dispersed in a ductile matrix.
  - Easier to manufacture (injection molding).
  - Example: Surfboard fin, Carbon-Carbon (used on disk brakes).

- Other variations:
  - Discontinuous, aligned short fibers.

**Materials Engineering**

# Fiber Critical Length

- The interface between the fiber and matrix has to be strong enough to transmit the load without failure.

- Critical fiber length ($l_c$) is needed to transmit the applied load from the matrix on to the fiber in order for effective stiffening & strengthening.

$$\text{Critical fiber length}(l_c) = \frac{s_f d}{2t_c}$$

- Fibers lengths > ~15($l_c$) will behave like continuous fibers.

**Materials Engineering**
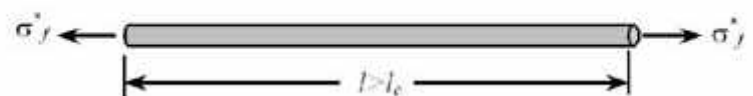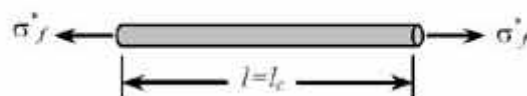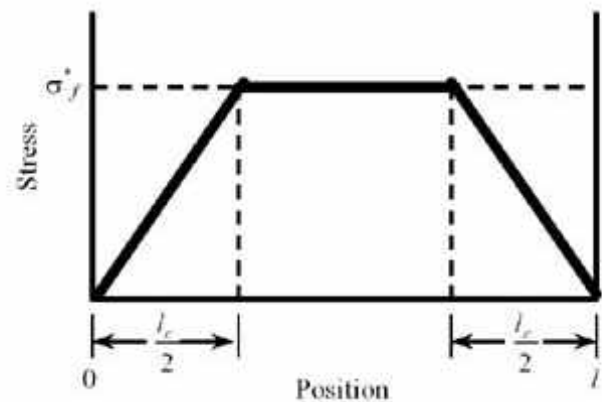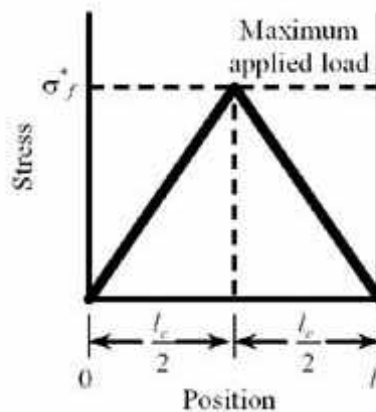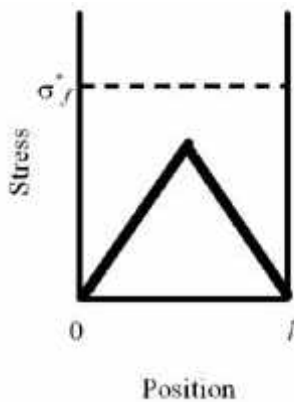
# Example

A Nylon 6,6 matrix composite has Silicon Carbide fibers 65mm in length and with a diameter d = 200μm. Determine if the fibers in this composite are greater then the critical fiber length. If they are, can they be considered continuous?

Silicon Carbide fiber $\sigma_f$ = 3.9 GPa        Nylon 6,6 $\tau_c$ = 60 MPa

**Materials Engineering**

# Fiber (Properties)

- Estimation of Elastic modulus ($E_c$) and Tensile Strength ($\sigma_{cl}$) are valid when: Fiber Length $> 15 \dfrac{\sigma_f d}{\tau_c}$

- $E_c$ <u>in fiber direction</u>: $E_c = E_m V_m + K E_f V_f$

  - K is an efficiency factor dependent on fiber orientation:
    - aligned 1D: K = 1    (anisotropic)
    - random 2D: K = 3/8 (2D isotropy)
    - random 3D: K = 1/5 (3D isotropy)

- $\sigma_{cl}$ <u>in fiber direction</u>: $\sigma_{cl} = \sigma'_m V_m + \sigma_f V_f$

  - $\sigma'_m$ is the stress in the matrix at fiber failure.

# Example

In an aligned and continuous fiber-reinforced composite, the Epoxy matrix has a tensile strength of 10.3 MPa and an elastic modulus of 2.41 GPa, and the E glass fibers have a tensile strength of 3.45 GPa and an elastic modulus of 72.5 GPa. What vol% fibers are required to insure that the fibers carry 65% of the longitudinal applied load? What will the tensile strength of this composite? Assume that the matrix stress at fiber failure is 32 MPa.

$$\frac{F_f}{F_m} = \frac{E_f V_f}{E_m V_m}$$

# Structural

- There are two main types of Structural Composites, *Layered* and *Sandwiched*.

- *Layered*: fiber-reinforced sheets are stacked on top of one another.
  - stacking sequence: e.g., 0/90
  - benefit: balanced, in-plane stiffness

- *Sandwich* panels: face sheets are adhered to both sides of a honeycomb layer.
  - low density, due to honeycomb core.
  - benefit: very light weight, large bending stiffness.

Face Sheet

Adhesive Layer

Honeycomb

**Materials Engineering**
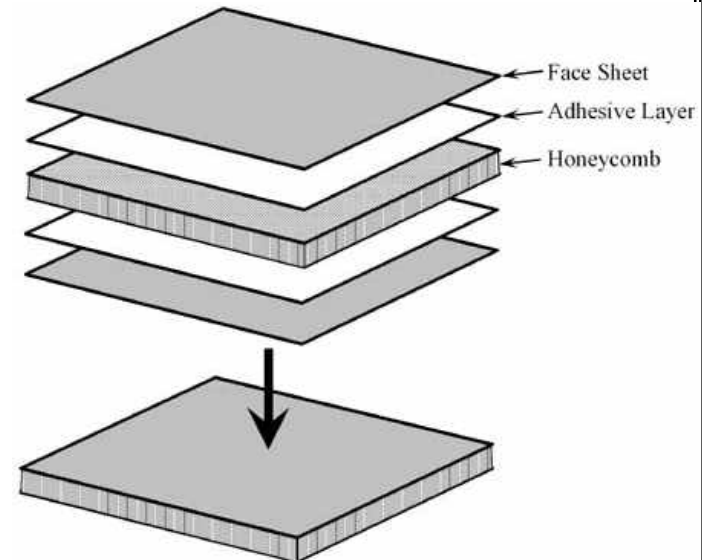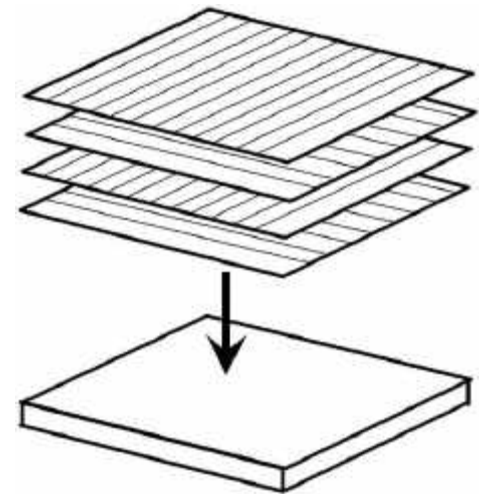
# Benefits of Composite Types

- ***Ceramic Matrix Composites*** (CMC) typically have increased Fracture Toughness ($K_c$) as a result of the addition of the dispersed phase.

- ***Polymer Matrix Composites*** (PMC) typically have increased E, $\sigma_y$, $\sigma_{TS}$, and creep performance as a result of the addition of fibers.

- ***Metal Matrix Composites*** (MMC) typically have increased $\sigma_y$, $\sigma_{TS}$, creep resistance and or abrasive properties as a result of the addition of the dispersed phase.

**Materials Engineering**

# Summary

- Composites are classified according to:
  - *Classes* of reinforcement geometry (particles, fibers, layers).
  - *Types* of matrix material (e.g. CMC, MMC, PMC)

- Particulate-reinforced:
  - Elastic modulus can be estimated within a range.
  - Properties are isotropic.

- Fiber-reinforced:
  - Elastic modulus and $\sigma_{TS}$ can be estimated in the direction of the fibers.
  - Properties can be isotropic or anisotropic depending on fiber size and orientation.

- Structural:
  - These are typically stiff light weight panels.
  - Properties are based on build-up of sandwiches in layered form.

- Matrix properties are enhanced in composites:
  - MMC: enhance $\sigma_y$, $\sigma_{TS}$, creep performance
  - CMC: enhance $K_c$
  - PMC: enhance E, $\sigma_y$, $\sigma_{TS}$, creep performance

**Materials Engineering**

# Electrical Properties

*Issues to cover*

❑What is Ohm's Law?

❑Band theory.

❑Conductivity in Metals.

❑Conductivity in Semiconductors.

❑What are Superconductors?

**Materials Engineering**

# Electrical Conductivity

- **Ohm's Law** is the relationship between Voltage (V), Current (I), and Resistance (R).

$$V = IR \Rightarrow \text{V(volts)},\ \text{I(amps)},\ \text{R}(\Omega)$$

- **Resistivity** ($\rho$) is independent of specimen geometry and is the inverse of Electrical Conductivity ($\sigma$).

$$\rho = \frac{1}{\sigma} = \frac{RA}{l} \Rightarrow\ \rho(\Omega \bullet \text{cm}),\ \sigma(\Omega^{-1} \bullet \text{cm}^{-1})$$

- **Power** (P) is the energy consumed as current flows through a resistance.
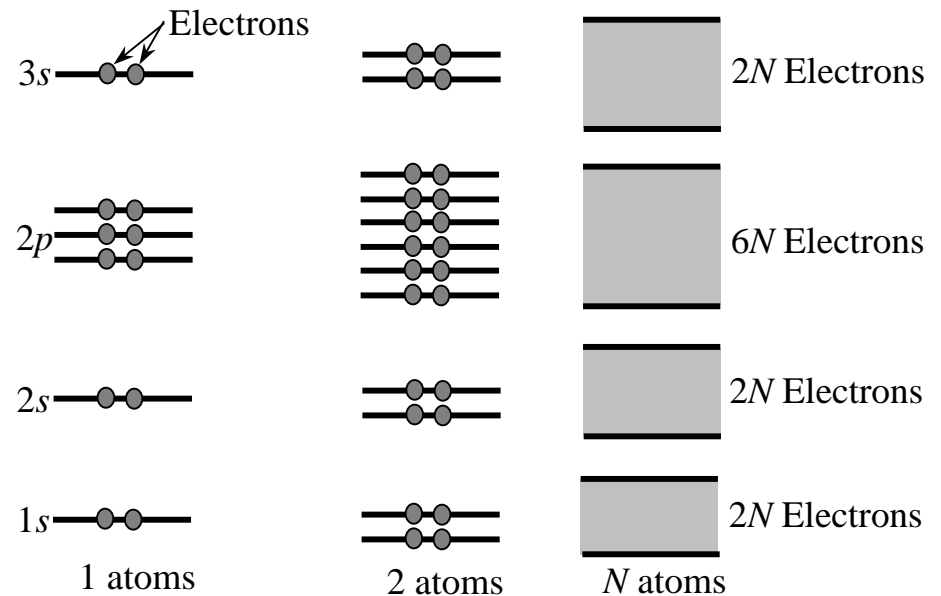
$$P = VI = I^2 R \Rightarrow \text{P}\left(\text{watts}\right)$$
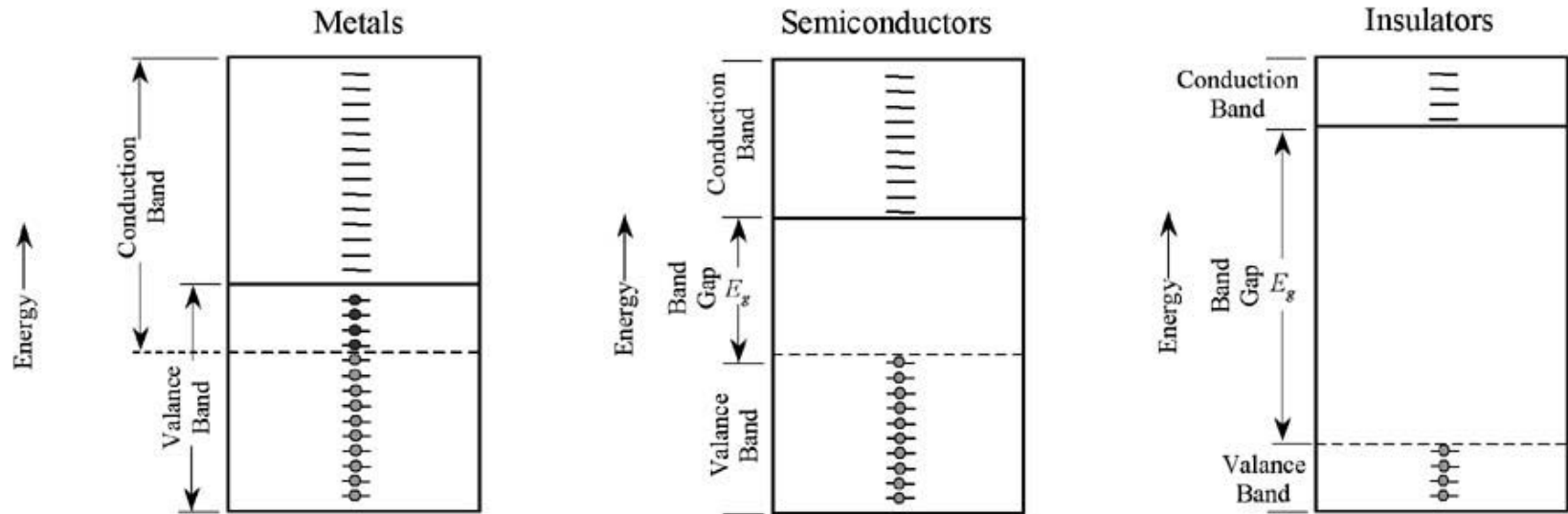
**Materials Engineering**

# Example

A Gold wire 10mm long must not experience a voltage drop of more then 2.5 mV went a 500 milliamp current passes through it. Calculate the minimum diameter of the wire.      $\sigma_{Au} = 4.3 \times 10^7 \, (\Omega m)^{-1}$

# Band Theory

- Pauli Exclusion Principle - Each energy level can only contain two electrons.

- When N atoms come together each energy level can only contain 2 electrons so these energy levels spread out into energy bands.

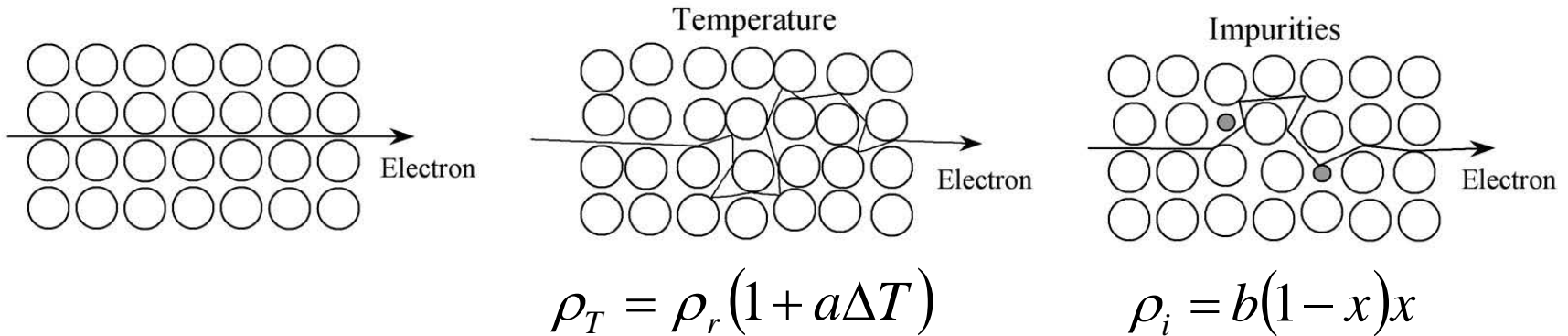- The electrons in the highest energy band are the valance electrons.



3s — Electrons

3s

2p

2s

1s

1 atoms          2 atoms          N atoms

2N Electrons

6N Electrons

2N Electrons

2N Electrons

# Conduction in Terms of Bands

Metals    Semiconductors    Insulators

- For ***Metals*** the Conduction and Valance bands overlap.

- For ***Semiconductors*** there is a small "Gap" between the Valance and Conduction bands.

- For ***Insulators*** there is a large "Gap" between the Valance and Conduction bands,

**Materials Engineering**

# Resistivity of Metals

Temperature

Electron

Impurities

Electron

Electron

$$\rho_T = \rho_r(1 + a\Delta T)$$

$$\rho_i = b(1-x)x$$

- Metals are good conductors to begin with so any disruption will increase the ***Resistivity***.

- The ***Resistivity*** ($\rho$), of a metal is a combination of the resistivity due to Temperature ($\rho_T$), Impurities ($\rho_i$), and plastic Deformation ($\rho_d$).

$$\rho_{Total} = \rho_T + \rho_i + \rho_d$$

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# Example

How much will the resistivity increase in a Cu wire if the temperature increases by 100°C from room temperature? What is the percent increase in total resistivity due to the temperature increase?

$$\rho_r = 1.67 \times 10^{-6} \text{ (ohm-cm)} \qquad\qquad a_{Cu} = 0.0068 \text{(ohm-cm/°C)}$$
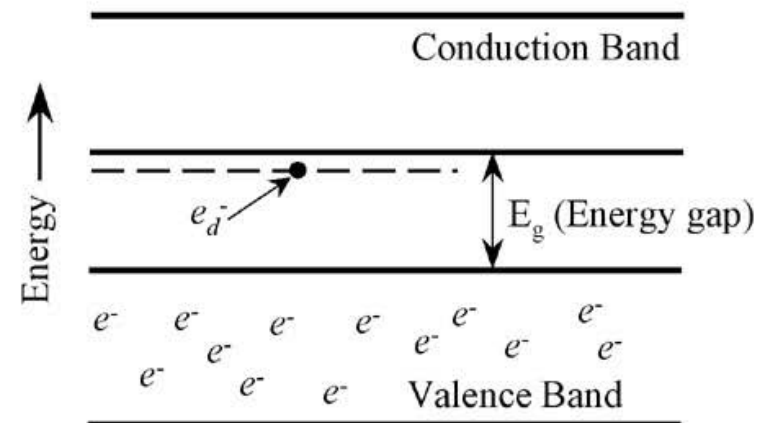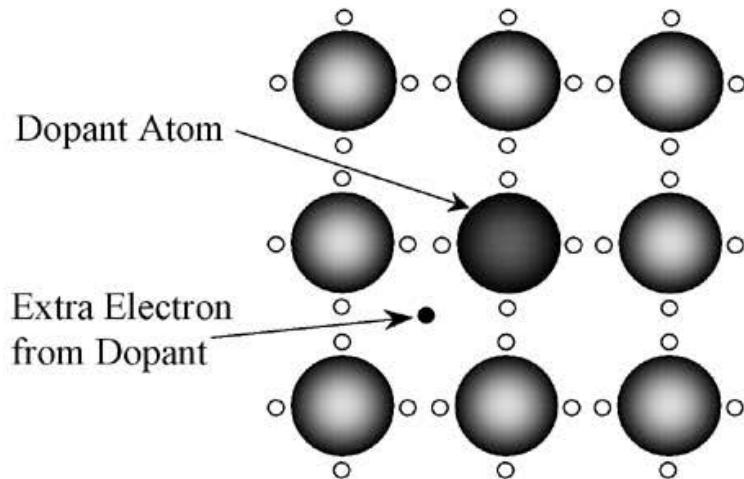
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# Intrinsic Semiconductors

- An ***Intrinsic Semiconductor*** is a pure material whose electrical properties are determined only by the temperature and the Energy Gap ($E_g$).

- Example: silicon or germanium which have a small Energy Gap so thermal energy allows some electrons to jump into the conduction band.
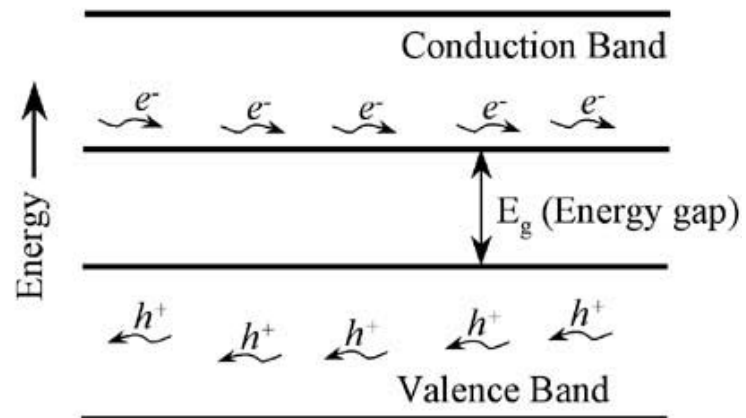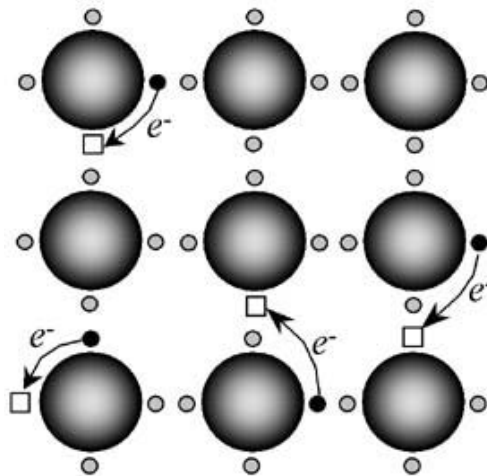
# Extrinsic Semiconductors

- An ***Extrinsic Semiconductor*** is a doped material whose electrical properties are determined by the amount of impurities.

- **_n_ - Type Semiconductors**: are doped with impurity atoms that have an extra valence electron which become the main charge carriers.

Dopant Atom

Extra Electron from Dopant

Conduction Band

Energy

$e_d^-$

$E_g$ (Energy gap)

$e^-$ $e^-$ $e^-$ $e^-$ $e^-$ $e^-$ $e^-$ $e^-$ $e^-$ $e^-$ $e^-$ $e^-$ $e^-$

Valence Band

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# Extrinsic Semiconductors

- ***p* - Type Semiconductors**: are doped with impurity atoms that are lacking a valence electron which leaves an electron "hole" which can be filled by a near by electron in the same energy band.



Dopant Atom

Hole due to Dopant

Conduction Band

Energy

$E_h$

$e^-$

$E_g$ (Energy gap)

$e^-$  $e^-$  $e^-$  $e^-$  $e^-$  $e^-$  $e^-$  $e^-$  $e^-$  $e^-$  $e^-$  $e^-$  $e^-$

Valence Band
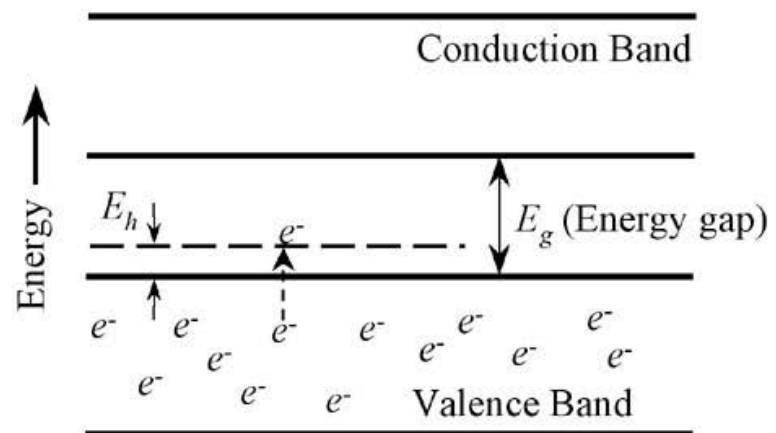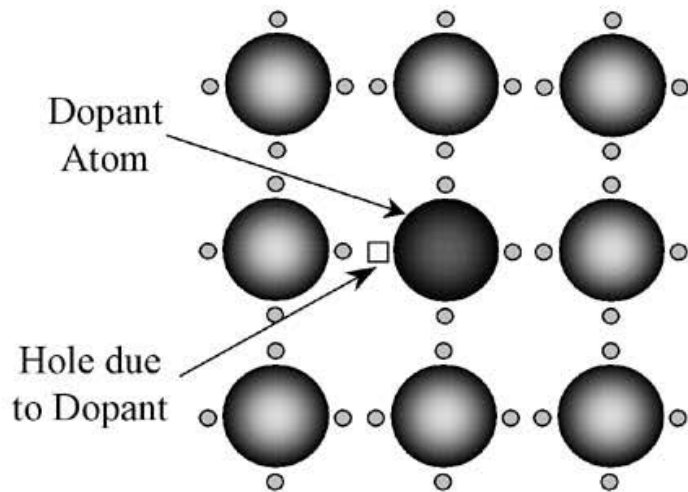
# Charge Carrier Mobility

- ***Charge Carrier Mobility*** is the ease at which electrons or holes are able to move through the structure.

- Temperature and impurities hinder ***Charge Carrier Mobility*** in semiconductors just as they do in metals.

- Electrons mobility is larger then hole mobility.

- Conductivity is a function of the ***Charge Carrier Mobility***.

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# Superconductivity

- ***Superconductivity*** is a state in which a material has no resistance to the flow of an electrical current.

- When certain materials are cooled below their Critical Temperature (Tc) they become superconductive.

**Materials Engineering**
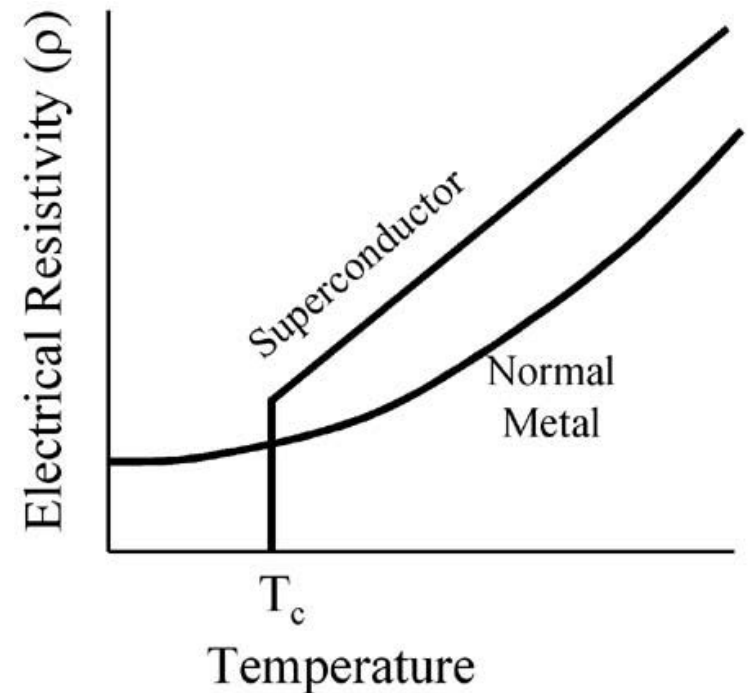
# Summary

- Ohms Law: $V = IR \Rightarrow$ V(volts), I(amps), R($\Omega$)

- Conduction in Terms of Bands:
  - Metals – Conduction and Valance bands overlap.
  - Semiconductors – small gap ($E_g$) between bands.
  - Insulators – Large gap between bands.

- Semiconductors:
  - Intrinsic – pure material.
  - n-Type – electron are the predominate charge carrier.
  - p-Type – holes are the predominate charge carrier.

- Charge Carrier Mobility: temperature and impurities hinder movement of Charge Carriers.

- Superconductivity: a state in which the material looses all of its electrical resistivity.

**Materials Engineering**

# Magnetic Properties

*Issues to cover*

☐ What is Magnetism and where does it come from?

☐ How do materials respond to a magnetic field?

☐ What are Magnetic Moments and Domains?

☐ What are Hysteresis Loops and what do they tell us?

**Materials Engineering**
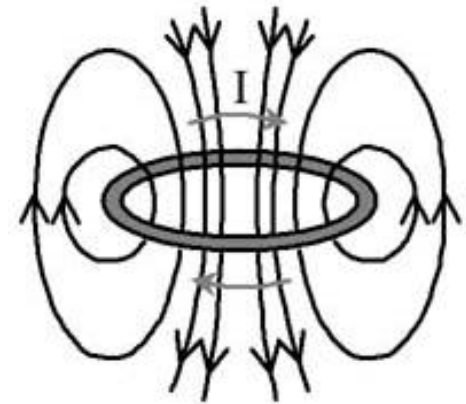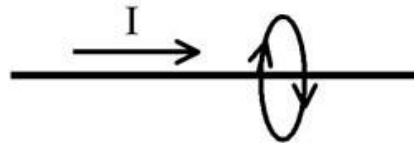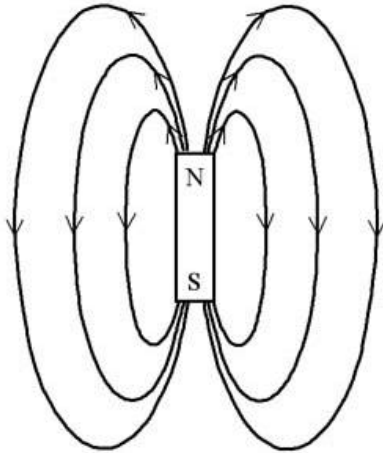
# Magnetism

- Magnetism is the attractive or repulsive force asserted by some materials on other materials.

- Magnetic force can be generated when a current flows through a conductor.

- Some materials naturally exhibit magnetic properties.

- We think of magnetic force or fields as leaving the North pole and reentering the South pole of a bar magnet or we use the right hand rule when determining the magnetic field due to current flow.

Materials Engineering
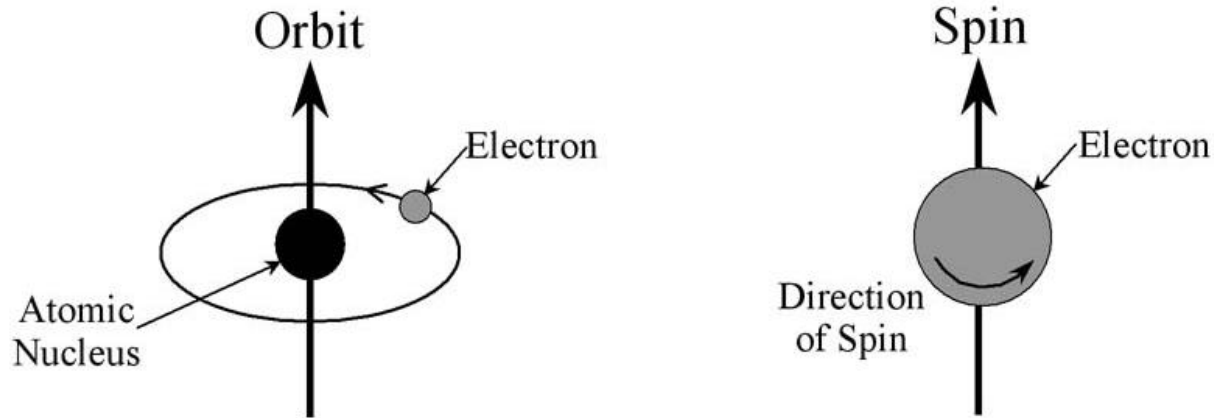
# Magnetic Moments



- Magnetic properties of materials are due to the electrons producing magnetic moments.

- Magnetic Moments in electrons come from two sources:
  - Electron Orbit – the orbital path around the nucleus (moving charge).
  - Electron Spin – the spin around it axis (either up or down).

- Net magnetic moment is the sum of all electron moments

# Applied Magnetic Field

- An Applied Magnetic Field (H) is created when current flows through a coil.

$$H = \frac{NI}{l}$$
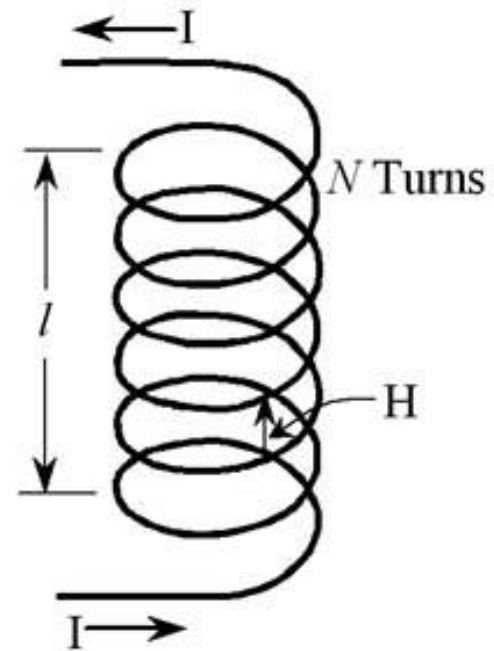
- Applied Magnetic Field (H) units = (ampere-turns/m)

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# Example

How much current (I) must be passed through a coil that has 125 turns and is 5cm long to produce a magnetic field (H) that is at least $12.5 \times 10^3$ (ampere·turn/m)?

**Materials Engineering**

# Response to a Magnetic Field
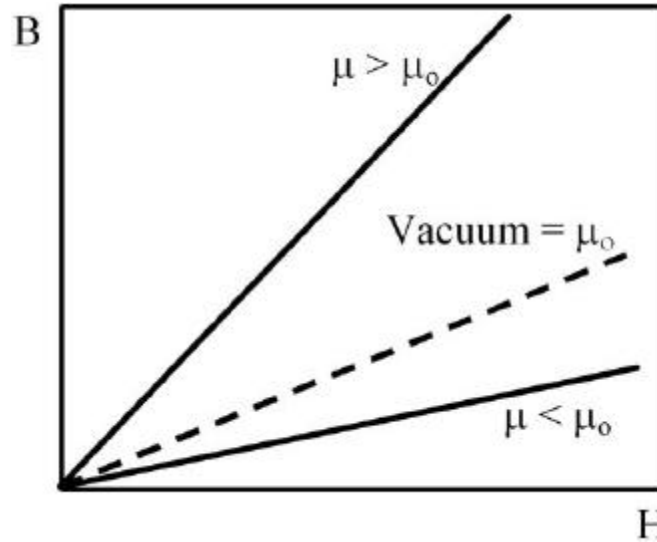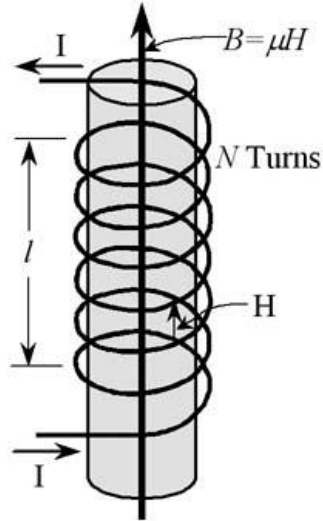


- Magnetic Induction (B) in the material is a result of the Applied Magnetic Field (H):  $B=mH$

-  μ is the Permeability of the material placed in the Applied Magnetic Field.

-  $\mu_o$ is the Permeability of a Vacuum and is a universal constant.

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# 3 Types of Magnetism
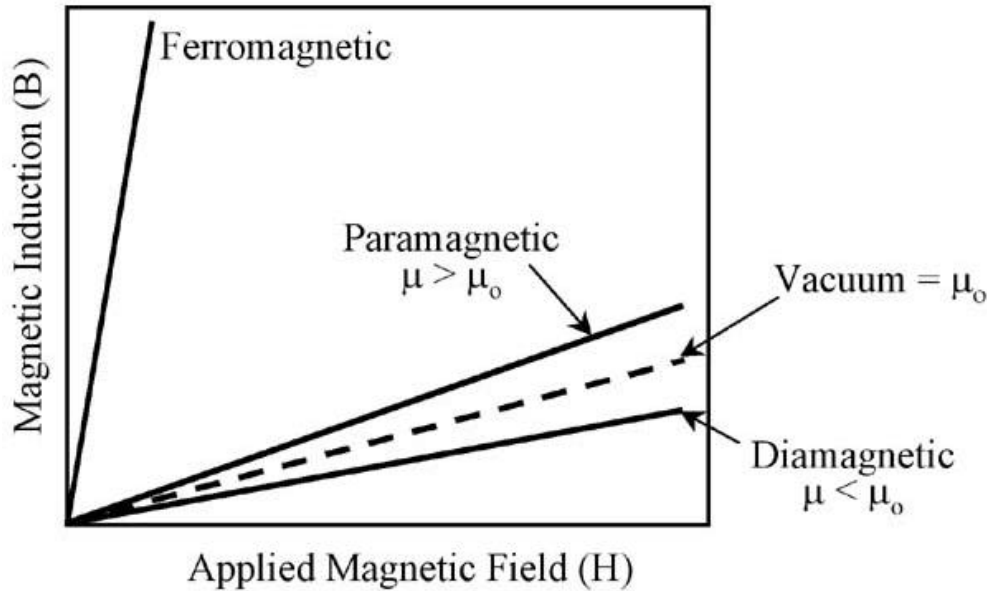


$$B = \textbf{\textit{m}}H$$

- Ferromagnetic – Ferrite ($\alpha$), Co, Ni, Gd
  - Ferrimagnetic – $Fe_3O_4$, $NiFe_2O_4$

- Paramagnetic – Al, Ti, Cr, Mo, Na

- Diamagnetic – Cu, Ag, Au, Si, $Al_2O_3$,

# Magnetic Moment Behavior
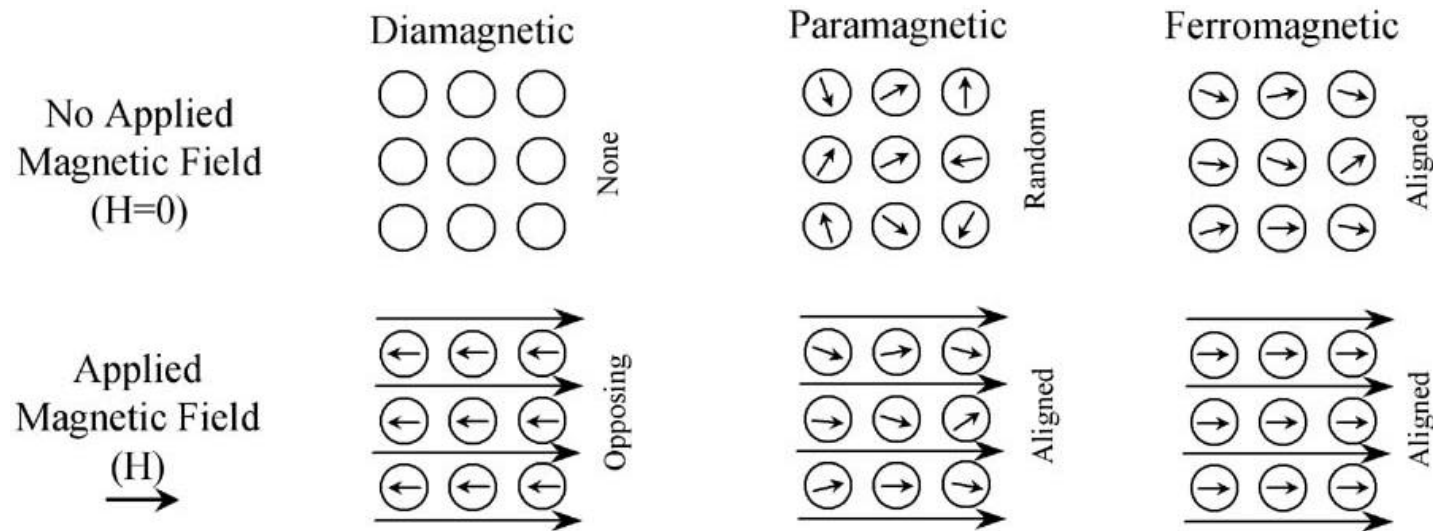


- **_Diamagnetic_** – atomic magnetic moments line-up opposing applied field (H).

- **_Paramagnetic_** – atomic moments generally align with field.

- **_Ferromagnetic_** – atomic moments completely align with field.

# Domains
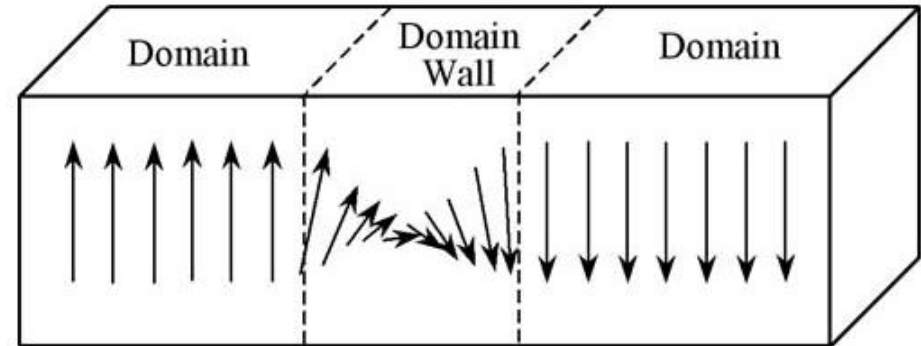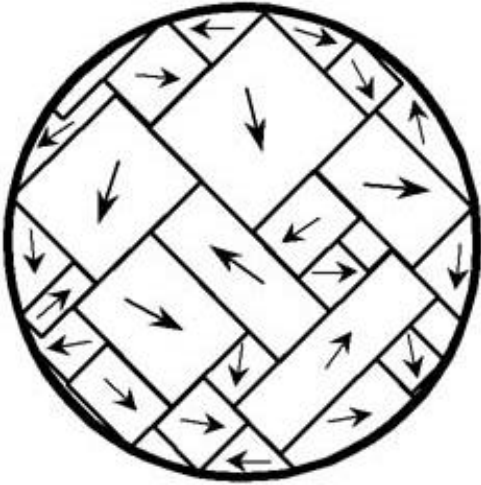


- Domains are areas in Ferromagnetic materials where all of the magnetic moments align with each other.

- Domains are separated by domain (Bloch) walls.

- Domains walls are like magnetic grains boundaries.

**Materials Engineering**

# Ferro-Magnetic Materials

- As the Applied Magnetic Field (H) increases the domains align with H.

- Domains that are aligned with the Applied Magnetic Field grow at the expense of poorly aligned domains.

- Saturation is when all domains align with the applied magnetic field and coalesce into large domains.
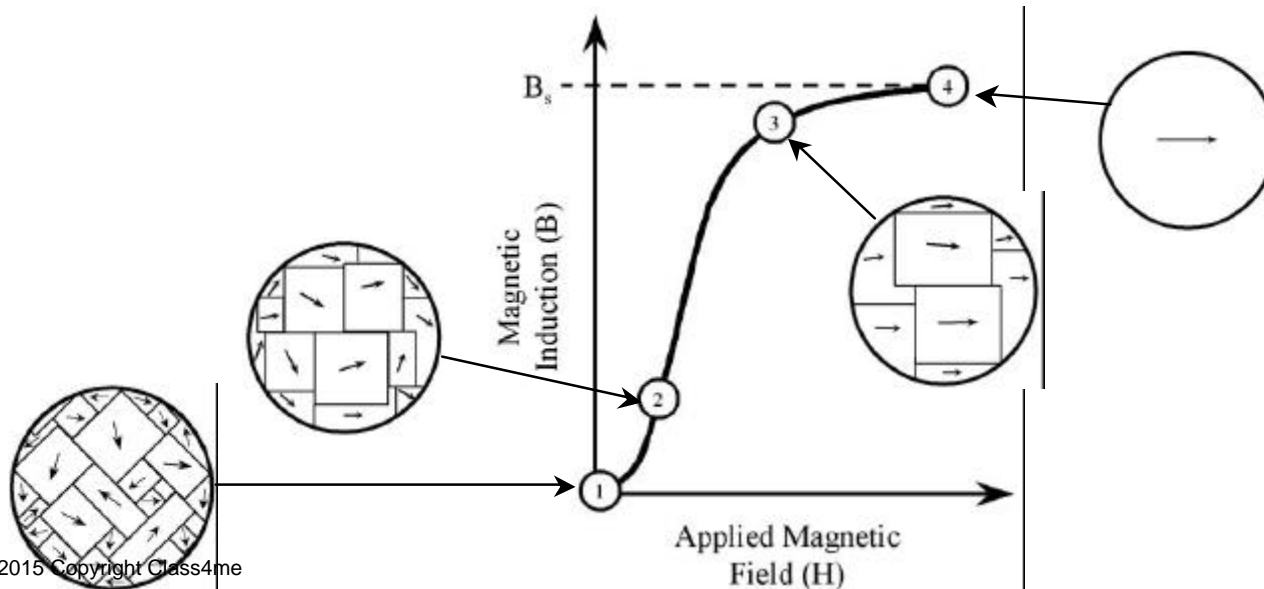
# Hysteresis Loops
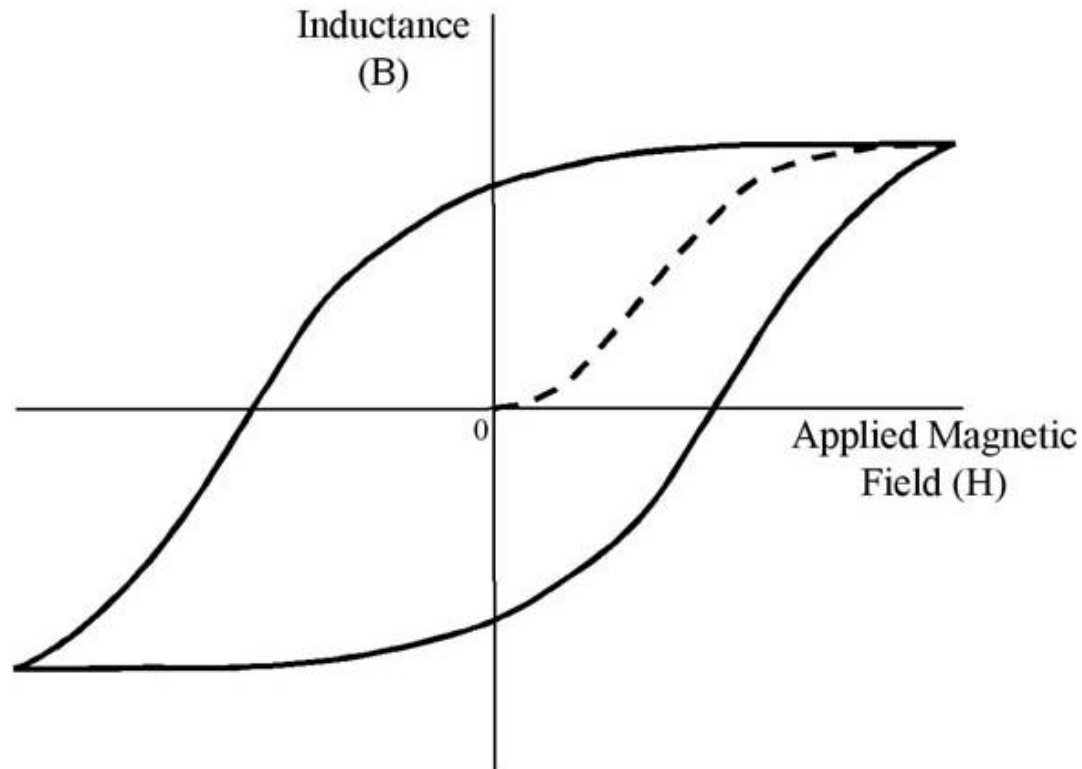


- Alternating the applied magnetic field will trace out the ***Hysteresis Loop***.

- The area inside the loop represents the energy consumed during one complete cycle.

Materials Engineering

# Types of Magnetic Materials

- ***Hard Magnets*** – Strong permanent magnets.

- ***Soft Magnets*** – Electrical applications where magnetic field is to do work.

- ***Small Square Loop*** – Computer applications such as information storage.

- ***Particulate:*** needle-shaped $\gamma$-$Fe_2O_3$. magnetic moment along axis. (tape, floppy)

- ***Thin film:*** CoPtCr or CoCrTa alloy. Domains are ~ 10-30nm! (hard drive)



Inductance (B)

Soft Magnet

Square Loop (computer applications)

Applied Magnetic Field (H)

Hard Magnet

**Materials Engineering**
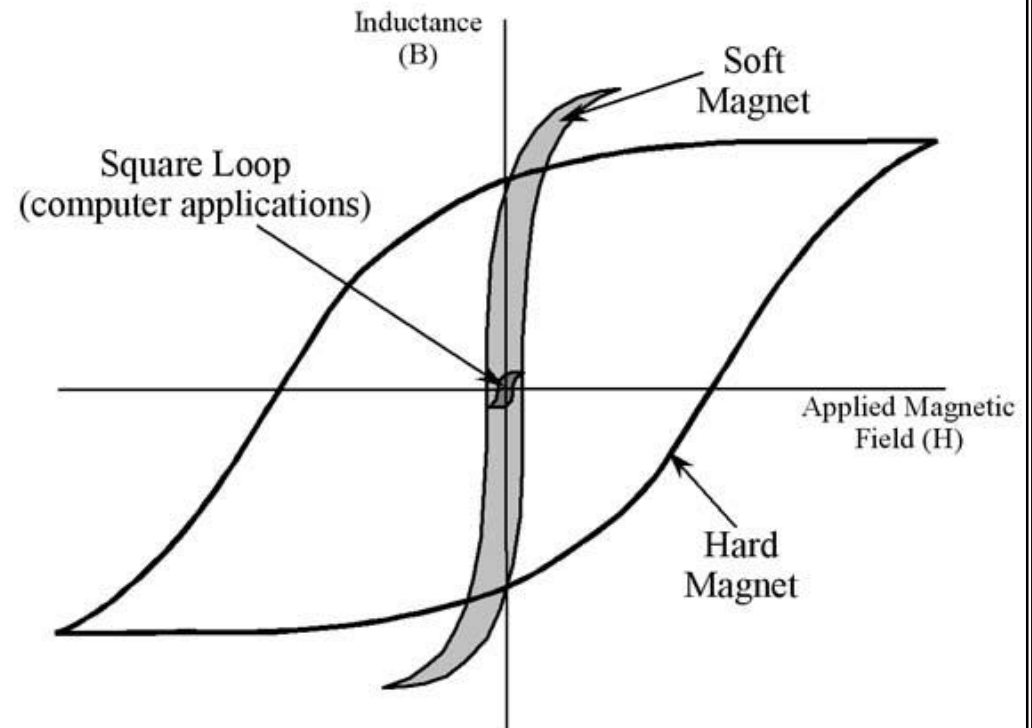
# The Effects of Temperature
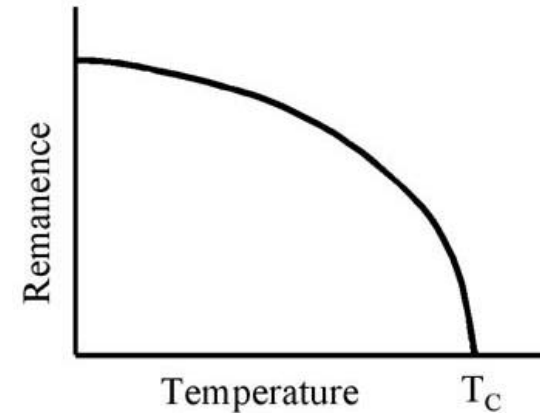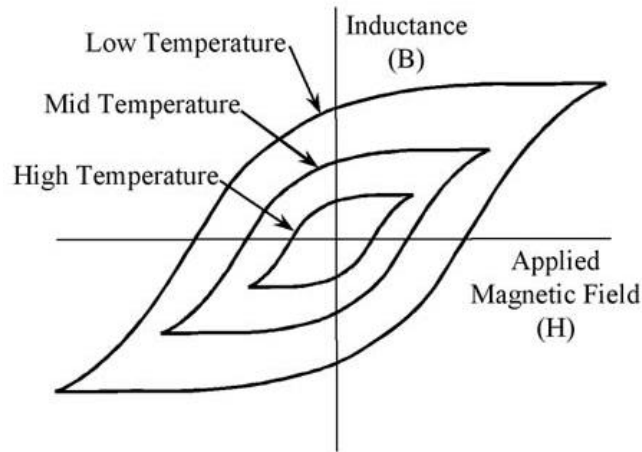


- Hysteresis Loops – As the temperature increases the hysteresis loops shrink (saturation magnetism & remanence decrease).

- Curie Temperature ($T_C$) – The temperature above which ferromagnetic behavior is no longer observed and the material displays paramagnetic behavior.

Materials Engineering

# Summary

- A magnetic field is produced when a current flows through a conductor.

- Magnetic induction is a change in magnetic moment of electrons and it occurs when a material is subjected to a magnetic field.

- Types of magnetic moment behavior to a magnetic field are:
  - Ferri- or Ferro-Magnetic (large magnetic induction)
  - Paramagnetic (small magnetic induction)
  - Diamagnetic (opposing magnetic moment)

- Domains are areas where all magnetic moments are aligned.

- Types of Magnetic materials are:
  - Hard magnets: large remanence, large hysteresis loop.
  - Soft magnets: small remanence, small hysteresis loop.
  - Magnetic storage media: small square hysteresis loop.
    - particulate $\gamma$-$Fe_2O_3$ (needles) in a polymeric film (tape or floppy)
    - thin film CoPtCr or CoCrTa on glass disk (hard drive)

Materials Engineering

# Corrosion

- What is Corrosion?

- The 4 elements needed for corrosion.

- The Galvanic Series.

- Corrosion Penetration Rate (CPR).

- The 8 types of corrosion.

- Degradation of ceramics.

- Degradation of Polymers.

**Materials Engineering**

# Corrosion

- Corrosion is the destructive result of a chemical reaction between metal (or alloy) and it's environment.

- The same energy needed to extract metal from it's ore is emitted by the chemical reaction during corrosion. It returns the metal to the minerals that they were extracted from.

- Cost of Corrosion is 4 to 5% of the Gross National Product (GNP) or just over ~$400 billion/yr. *(Data from 1985 & 1998)*

- Examples of Corrosion Protection:
  - Paint (cars, equipment)                          - Passivation (anodizing)
  - Sacrificial Anode (boats, fence post)            - Alloy

**Materials Engineering**

# How Corrosion Works
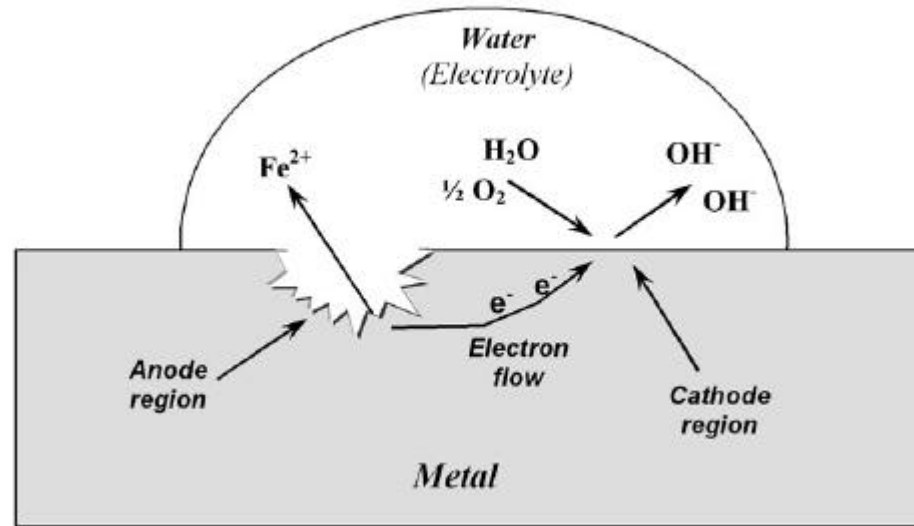


- ***Anode*** – Oxidation (electron release)

- ***Cathode*** – Reduction (electron distribution)

- ***Electrical Connection*** – (electron exchange)

- ***Electrolyte*** – conductive medium (ion exchange)

- Remove any of the above and corrosion can not happen.

**Materials Engineering**

# Galvanic Series

- Lists metals and alloys in order of their relative reactivities.

- Metals at the top of this list are more reactive and will become the **Anode** and corrode.

- Metals at the bottom of the list are less reactive and will become the **Cathode** if galvanically coupled with a metal higher on the list.

- Seawater is the electrolyte used for the Galvanic Series.

Magnesium - ***Anodic***
Zinc
Aluminum (pure)
Cadmium
Aluminum alloys
Iron & Steel
Cast iron
Stainless Steels (active)
Lead
Tin
Nickel (active)
Brasses
Copper
Bronzes
Nickel (passive)
Stainless steels (passive)
Silver
Titanium
Graphite
Gold
Platinum - ***Cathodic***

**Materials Engineering**

# Corrosion Rate

- Corrosion Penetration Rate (CPR) is the thickness of material lost per unit of time given in mpy (mils per year) or mm/yr (millimeters per year)

- $W$ – weight lost after time $t$ [milligrams]
- $t$ – time [hours]
- $r$ – density [g/cm$^3$]
- $A$ – exposed area [in$^2$ or cm$^2$]
- $K$ – constant (exposed area unit dependent)
  - 534 – for exposed area with units of **in$^2$**
  - 87.6 – for exposed area with units of **cm$^2$**

$$CPR = \frac{KW}{rAt}$$

**Materials Engineering**

# Example

- A Cu plate that was originally 20 in$^2$ submerged in sea water was found to have lost approximately 1.2 kg to corrosion. Assuming a CPR of 90 mpy estimate how many years the Cu plate has been submerged.        $\rho_{Cu} = 8.94$ g/cm$^3$

# Effects on Corrosion

- pH of the environment can cause metal to become active or passive

- Protective layer formation protects underlying metal

- Size of Cathode effect the rate at witch corrosion will happen

- Stress can alter the corrosion potential

- Alloy composition and phase distribution can influence Anode and Cathode formation

- 8 different types of corrosion

# Uniform Attack

- Oxidation / Reduction occurs randomly across surface.

- Variations in alloy composition or other defects can cause areas to be more reactive and become the anode.

- *Example:*
  - Rusting of steel or iron
  - Tarnishing of silverware

- *Prevention:*
  - Protective coating

**Materials Engineering**

# Galvanic Corrosion
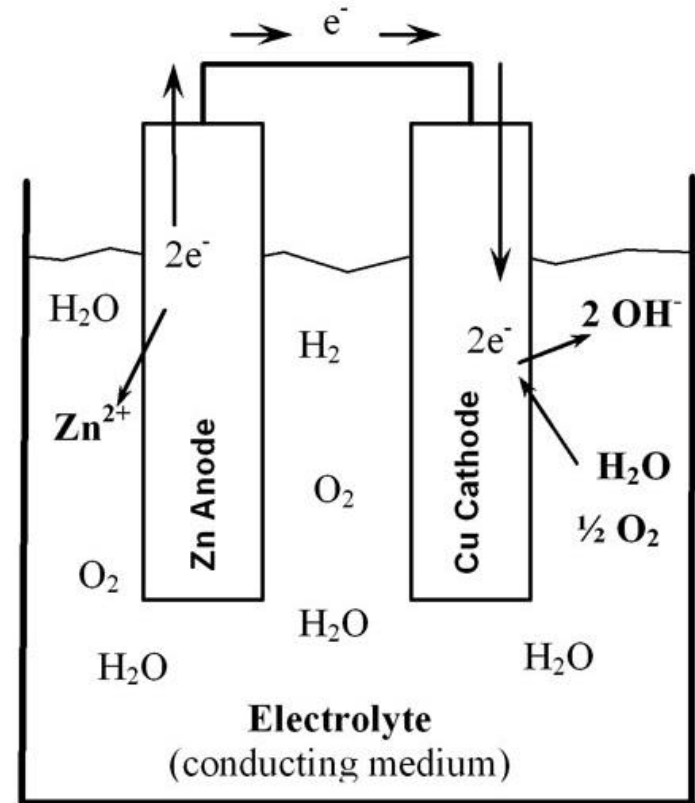
- 2 different metals electrically connected in an electrolyte.

- The more active metal (from Galvanic series) will be the Anode and the other will be the Cathode.

- *Example:*
  - –Cu & Steel plumbing
  - –Sacrificial anode

- *Prevention:*
  - –Remove electrical connection
  - –Selection of metals close on Galvanic series
  - –Large Anode with a small Cathode

**Materials Engineering**
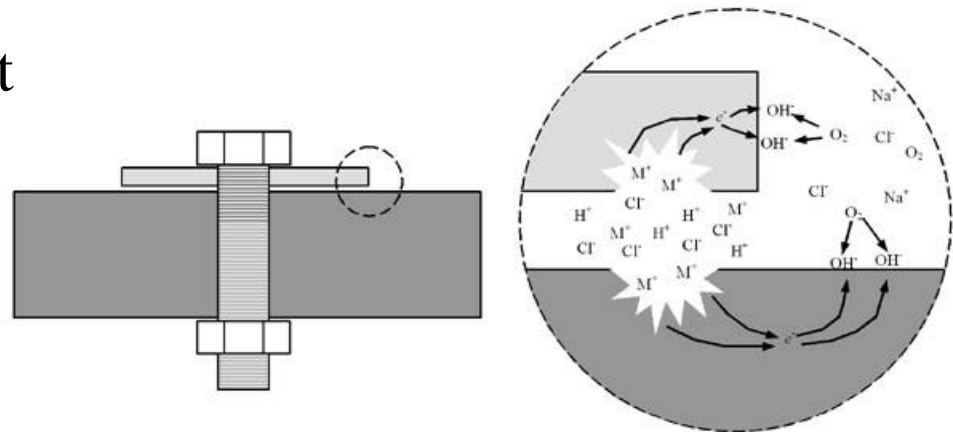
# Crevice Corrosion

- Solution in crevice is stagnant and oxygen is depleted this causes concentration differences of dissolved gasses or ions and a change in the pH.

- Crevice becomes a small anode and surrounding area is a large cathode.

- *Example:*
  - A washer between a bolt and the surface.

- *Prevention:*
  - Non-absorbing gasket
  - Weld the pieces
  - Complete drainage

# Pitting Corrosion

- Will typically start at some localized defect on the surface.

- Typically this form of corrosion happens from the top surface down with gravity causing the corrosion to be driven down.

- It's processes are similar to Crevice corrosion where the solution at the bottom of the pit is stagnant.

- *Example:*
  - Aluminum soap dish.

- *Prevention:*
  - Polishing the surface improves resistance.
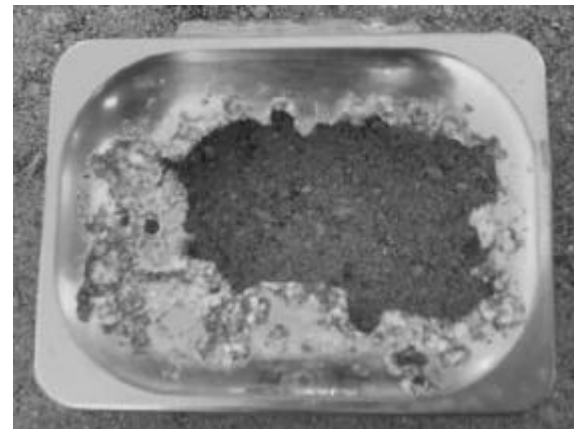
# Intergranular Corrosion

- Small precipitates can form at certain temperatures removing one alloying element causing the depleted areas to become anodic.

- Occurs along grain boundaries (areas of high energy).

- It is also known as Weld Decay as it happens in the Heat Affected Zone (HAZ).

- *Example:*
  - Weld decay in the HAZ of some welded Stainless Steels.

- *Prevention:*
  - High temp heat treatment to redissolve particles.
  - Lower C concentration in Stainless Steels.
  - Alloy with metals that will preferentially form precipitate.



Precipitate

Grain Boundary

Depleted Zone

**Materials Engineering**
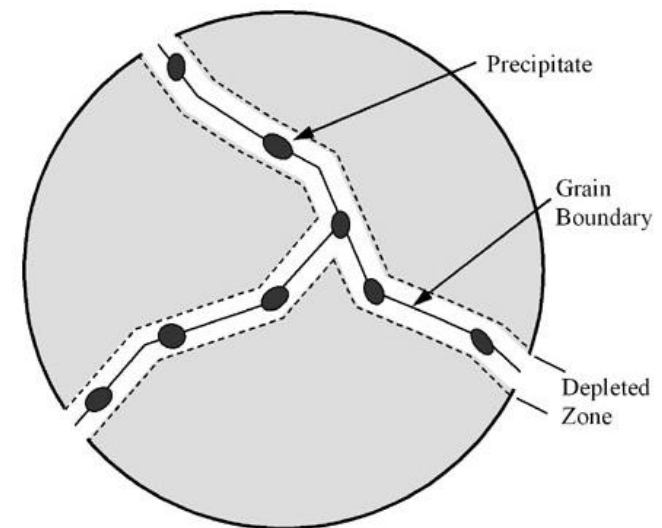
# Selective Leaching

- In solid solution alloys when one element is corroded leaving a porous shell of the other element.

- Happens when the solute element is more active then the solvent element.

- *Example:*
  - Dezincification, Zinc corrodes leaving pure Copper.
  - Graphitic corrosion where the iron corrodes out of the Cast Iron leaving graphite (buried cast iron pipe).

- *Prevention:*
  - Select different alloy
  - For graphitic corrosion, graphite must be continuous.

# Erosion Corrosion

- Combined action of corrosion and mechanical abrasion.

- Surface films are eroded away exposing underlying metal to further corrosion.

- All metals are susceptible to this type of corrosion especially metals with passivation layers.

- *Example:*
  - A pipe elbow in your home plumbing.
  - Slurry delivery tubing in lapping and polishing tools.

- *Prevention:*
  - Redesign to minimize fluid turbulence.
  - Remove particulates or bubbles from the fluid stream.

**Materials Engineering**

# Stress Corrosion

- Happens only when both a stress and a corrosive environment are present.

- The stress can be residual stress or stresses due to thermal cycling.

- Small cracks will form and grow perpendicular to the applied stress.

- This usually ends up with a brittle type fracture.

- *Example:*
  – Brass will become susceptible in an ammonia solution
  – Stainless Steels will become susceptible in solution with Cl ions

- *Prevention:*
  – Reduce applied stress
  – Anneal part to remove residual stresses.

**Materials Engineering**

# Hydrogen Embrittlement

- Atomic Hydrogen (H not $H_2$) present interstitially in the metal.

- This reduces the ductility and tensile strength and causes brittle fracture due to rapid crack growth.

- Concentration as low as several parts per million can cause failure.

- *Example:*
  - Arc welding with damp (flux coated) welding rods.
  - Electroplating in presences of a Hydrogen environment.

- *Prevention:*
  - Remove source of Hydrogen.
  - Baking at high temperatures to remove the Hydrogen.
  - Annealing to reduce tensile strength.

# Scale Formation

$$P - B\ ratio = \frac{A_o\, r_m}{A_m\, r_o}$$

- Pilling – Bedworth ratio is a ratio of the volume of the metal to the volume of the oxide.

- Scale Types:

  <1 Volume smaller, porous, ***unprotective***

  1-2 Volume similar, film w/ compressive stresses, ***protective***

  >2 Volume greater, large compressive stresses cause cracking and flaking of oxide film, ***unprotective***

# Degradation of Ceramics

- Since ceramics are compounds of metals and nonmetals it is like they are already corroded.

-  Because of this ceramics are basically immune to corrosion in most all environment.

- If anything ceramics could be dissolved by simple chemical dissolution.

- Ceramics are very wear resistant.

# Degradation of Polymers

- Do not really corrode but can deteriorate with interaction with the environment.

- Bond rupture due to heat, radiation, or chemistry:
  - Bond rupture by radiation (UV, X-ray, e⁻ beam) is caused by the radiation energy ionizing atoms causing them to loose a bond.
  - $O_2$ and $O_3$ can react with double bonds.
  - Bonds can break due to added thermal energy.

- Swelling and Dissolution:
  - Swelling degrades a polymers properties by the liquid absorbing into the polymer structure, squeezing between molecules (chains) and increasing spacing between molecules and weakening the secondary bonding. This also lowers the Glass Transition temperature $T_{g.}$
  - Dissolving is just swelling taken to the point where the liquid absorption causes the chains to completely separate.

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# Summary

- Corrosion costs us $$$$$$ every year.

- Needed for corrosion: ***Anode***, ***Cathode***, ***electrical connection***, and an ***electrolyte***.

- Galvanic series – more reactive will be anode.

- CPR – mpy or mm/yr (mixed units)

- 8 types of corrosion (+ Hydrogen Embrittlement)

- Scale formation (passivation – protective layer)

- Ceramics don't corrode.

- Polymers don't corrode but can degrade by swelling (dissolution) or bond rupture.

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