

METALLURGICAL AND MATERIAL SCIENCE

**B.TECH III SEMESTER
Mechanical Engineering
Course Code: AME005 (IARE - R16)**

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UNIT I

Structure of metals: Crystallography, Miller indices, packing efficiency, Density calculations, Grains and grain boundaries, Effect of grain size on the properties, Determination of grain size by different methods.

Constitution of alloys: Necessity of alloying, Types of solid solutions, Hume- Rothery's rules, Intermediate alloy phases

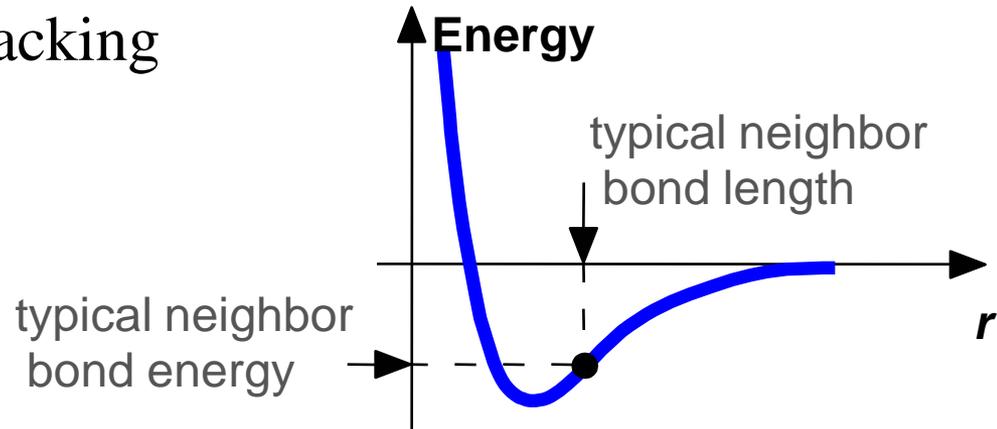
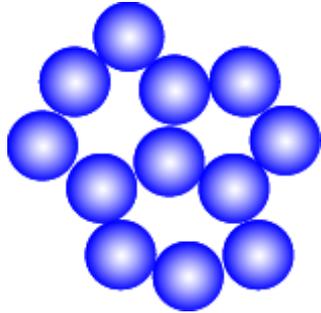
CRYSTAL STRUCTURE

Overview

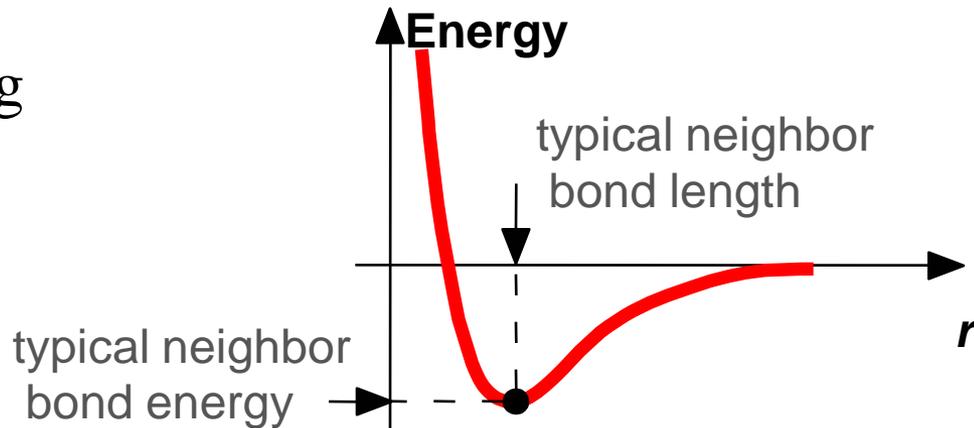
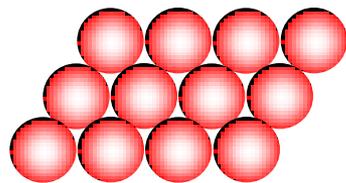
- Crystal Structure – matter assumes a periodic shape
 - Non-Crystalline or Amorphous “structures” exhibit no long range periodic shapes
 - Xtal **Systems** – not structures but potentials
 - FCC, BCC and HCP – common Xtal Structures for metals
- Point, Direction and Planer ID'ing in Xtals
- X-Ray Diffraction and Xtal Structure

Energy and Packing

- Non dense, **random** packing



- Dense, **ordered** packing



Dense, ordered packed structures tend to have lower energies & thus are more stable.

CRYSTAL STRUCTURES

Crystal Structure

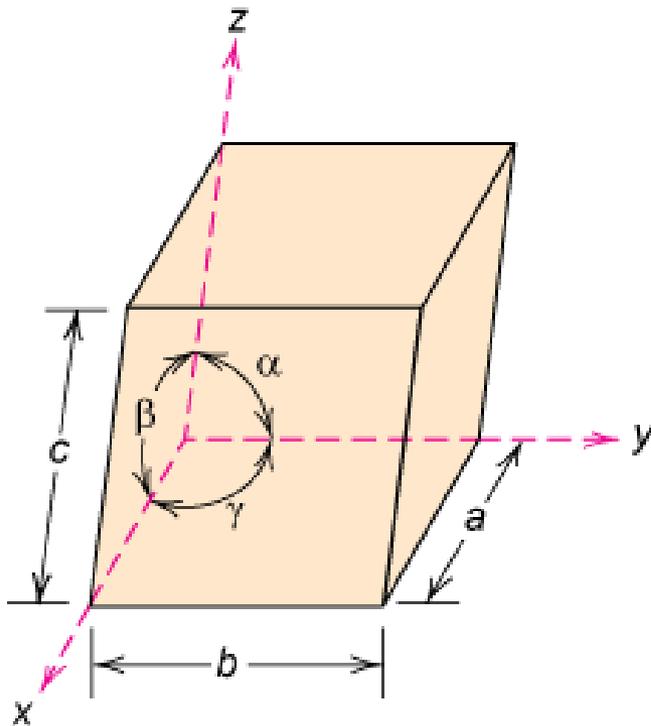
Means: *PERIODIC ARRANGEMENT OF ATOMS/IONS OVER LARGE ATOMIC DISTANCES*

→ Leads to structure displaying
LONG-RANGE ORDER that is
Measurable and Quantifiable

All metals, many ceramics, and some polymers exhibit this “High Bond Energy” and a More Closely Packed Structure

Crystal Systems – Some Definitional information

Unit cell: smallest repetitive volume which contains the complete *lattice pattern* of a crystal.



7 crystal systems of varying symmetry are known

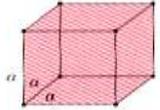
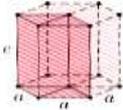
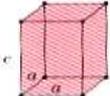
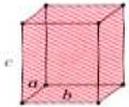
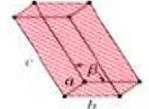
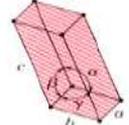
These systems are built by changing the lattice parameters:

a , b , and c are the edge lengths
 α , β , and γ are inter axial angles

Crystal Systems

Crystal structures are divided into groups according to unit cell geometry (symmetry).

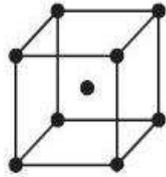
Table 3.2 Lattice Parameter Relationships and Figures Showing Unit Cell Geometries for the Seven Crystal Systems

<i>Crystal System</i>	<i>Axial Relationships</i>	<i>Interaxial Angles</i>	<i>Unit Cell Geometry</i>
Cubic	$a = b = c$	$\alpha = \beta = \gamma = 90^\circ$	
Hexagonal	$a = b \neq c$	$\alpha = \beta = 90^\circ, \gamma = 120^\circ$	
Tetragonal	$a = b \neq c$	$\alpha = \beta = \gamma = 90^\circ$	
Rhombohedral	$a = b = c$	$\alpha = \beta = \gamma \neq 90^\circ$	
Orthorhombic	$a \neq b \neq c$	$\alpha = \beta = \gamma = 90^\circ$	
Monoclinic	$a \neq b \neq c$	$\alpha = \gamma = 90^\circ \neq \beta$	
Triclinic	$a \neq b \neq c$	$\alpha \neq \beta \neq \gamma \neq 90^\circ$	

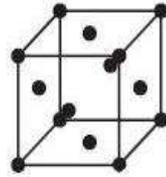
The 14 Crystal (Bravais) Lattices



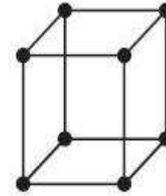
Simple cubic



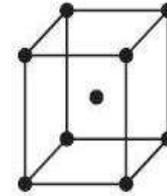
Body-centered cubic



Face-centered cubic



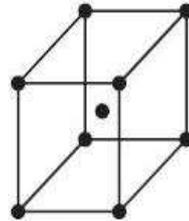
Simple tetragonal



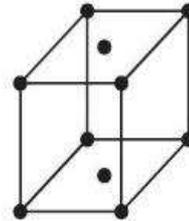
Body-centered tetragonal



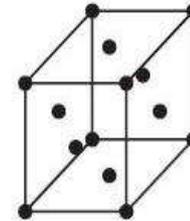
Simple orthorhombic



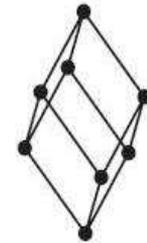
Body-centered orthorhombic



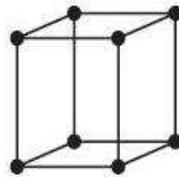
Base-centered orthorhombic



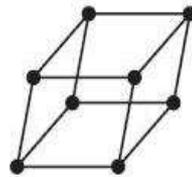
Face-centered orthorhombic



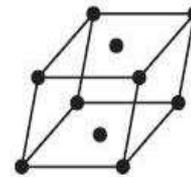
Rhombohedral



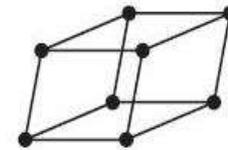
Hexagonal



Simple monoclinic



Base-centered monoclinic



Triclinic

Metallic Crystal Structures

- Tend to be densely packed
- Reasons for dense packing:
 - Typically, only one element is present, so all atomic radii are the same.
 - Metallic bonding is not directional.
 - Nearest neighbor distances tend to be small in order to lower bond energy.
 - Electron cloud shields cores from each other
- Have the simplest crystal structures

We will examine three such structures (those of engineering importance) called: FCC, BCC and HCP – with a nod to Simple Cubic

Crystal Structure of Metals

Atomic Radii and Crystal Structures for 16 Metals

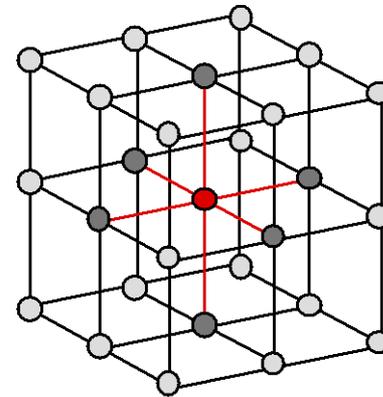
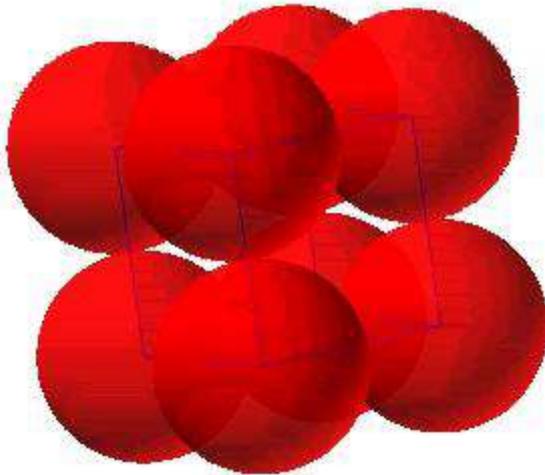
<i>Metal</i>	<i>Crystal Structure^a</i>	<i>Atomic Radius^b</i> (nm)	<i>Metal</i>	<i>Crystal Structure</i>	<i>Atomic Radius</i> (nm)
Aluminum	FCC	0.1431	Molybdenum	BCC	0.1363
Cadmium	HCP	0.1490	Nickel	FCC	0.1246
Chromium	BCC	0.1249	Platinum	FCC	0.1387
Cobalt	HCP	0.1253	Silver	FCC	0.1445
Copper	FCC	0.1278	Tantalum	BCC	0.1430
Gold	FCC	0.1442	Titanium (α)	HCP	0.1445
Iron (α)	BCC	0.1241	Tungsten	BCC	0.1371
Lead	FCC	0.1750	Zinc	HCP	0.1332

^a FCC = face-centered cubic; HCP = hexagonal close-packed; BCC = body-centered cubic.

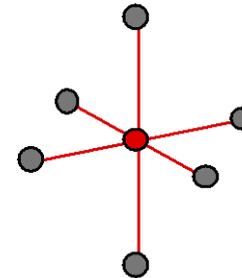
^b A nanometer (nm) equals 10^{-9} m; to convert from nanometers to angstrom units (\AA), multiply the nanometer value by 10.

Simple Cubic Structure (SC)

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



- Coordination No. = 6
(# nearest neighbors) for each atom as seen

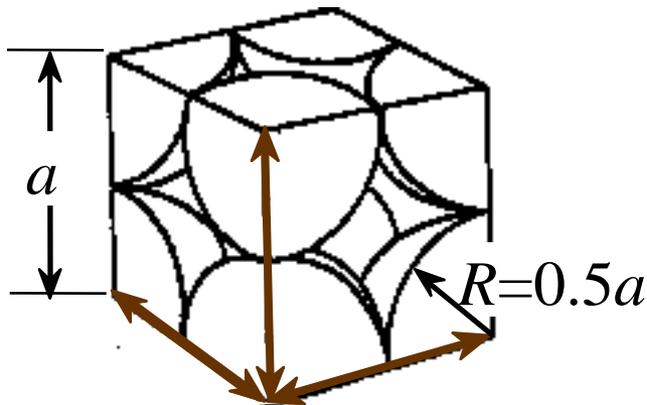


Atomic Packing Factor (APF)

$$\text{APF} = \frac{\text{Volume of atoms in unit cell}^*}{\text{Volume of unit cell}}$$

*assume hard spheres

- APF for a simple cubic structure = 0.52



close-packed directions

contains $(8 \times 1/8) =$

1 atom/unit cell

Adapted from Fig. 3.23,
Callister 7e.

$$\text{APF} = \frac{\text{atoms/unit cell} \times \frac{4}{3} \pi (0.5a)^3}{a^3}$$

Labels in the diagram:
 - 'atoms/unit cell' points to the '1' in the numerator.
 - 'volume atom' points to the $\frac{4}{3} \pi (0.5a)^3$ term in the numerator.
 - 'volume unit cell' points to the a^3 term in the denominator.

Here: $a = R_{\text{at}} * 2$

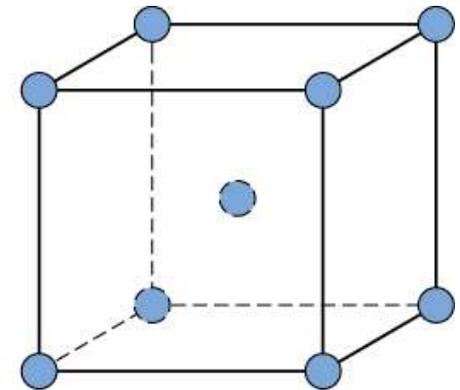
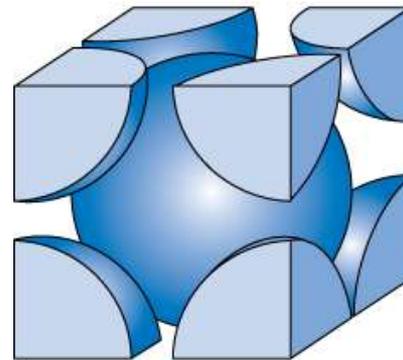
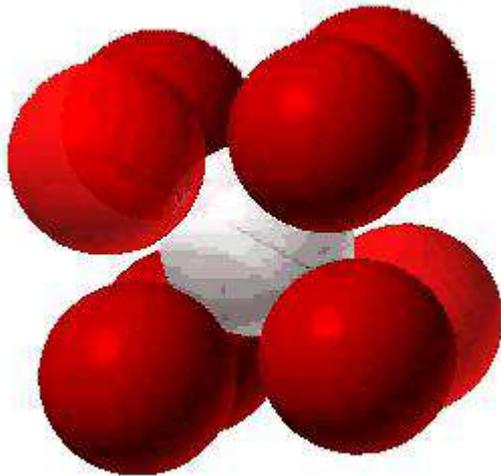
Where R_{at} is the 'handbook'
atomic radius

Body Centered Cubic Structure (BCC)

- Atoms touch each other along *cube diagonals within a unit cell*.

--Note: All atoms are identical; the center atom is shaded differently only for ease of viewing.

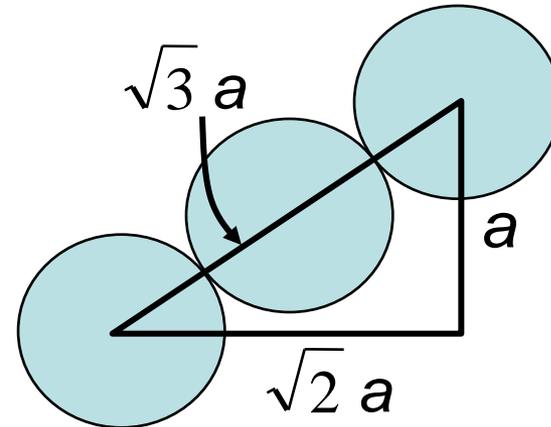
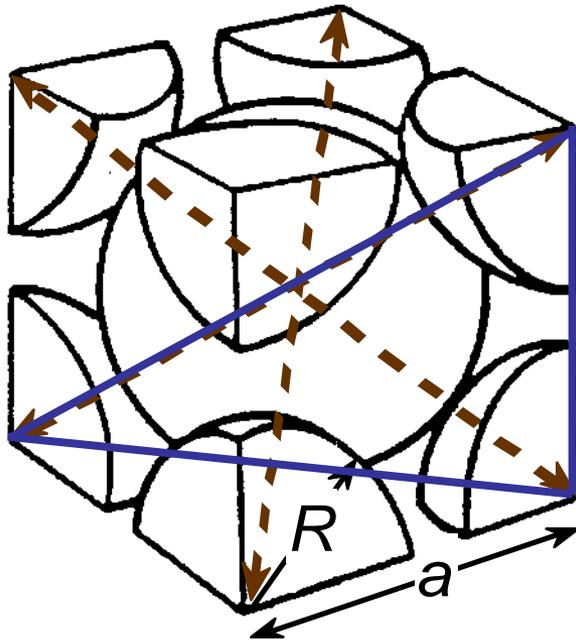
ex: Cr, W, Fe (α), Tantalum, Molybdenum



- Coordination # = 8

2 atoms/unit cell: (1 center) + (8 corners x 1/8)

Atomic Packing Factor: BCC



Close-packed directions:

$$\text{length} = 4R = \sqrt{3} a$$

$$\text{APF} = \frac{\text{unit cell} \rightarrow 2 \cdot \frac{4}{3} \pi (\frac{\sqrt{3}a}{4})^3 \leftarrow \frac{\text{volume}}{\text{atom}}}{a^3 \leftarrow \frac{\text{volume}}{\text{unit cell}}}$$

Adapted from
Fig. 3.2(a), Callister 7e.

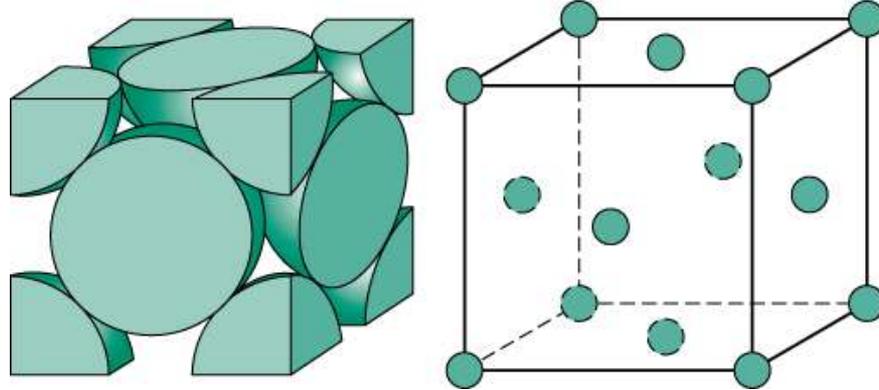
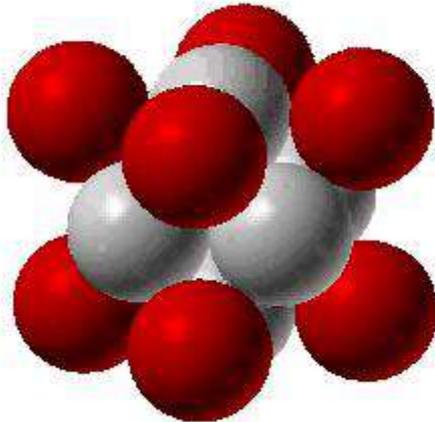
- APF for a body-centered cubic structure = 0.68

Face Centered Cubic Structure (FCC)

- Atoms touch each other along *face diagonals*.
--Note: All atoms are identical; the face-centered atoms are shaded differently only for ease of viewing.

ex: Al, Cu, Au, Pb, Ni, Pt, Ag

- Coordination # = 12

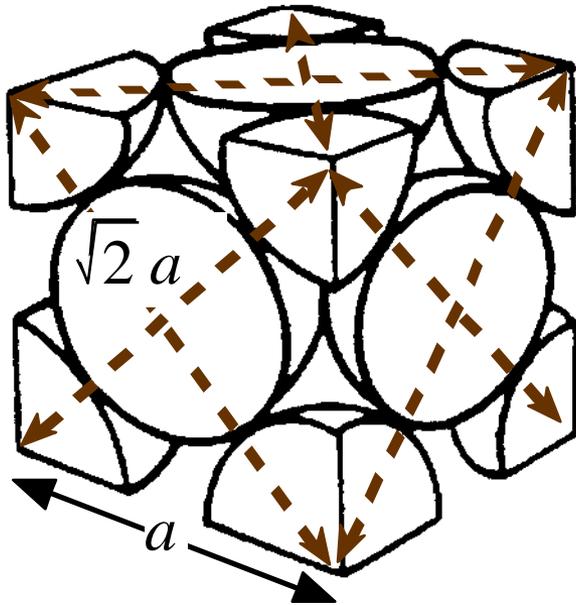


Adapted from Fig. 3.1, *Callister 7e*.

4 atoms/unit cell: $(6 \text{ face} \times \frac{1}{2}) + (8 \text{ corners} \times \frac{1}{8})$

Atomic Packing Factor: FCC

- APF for a face-centered cubic structure = 0.74



The maximum achievable APF!

Close-packed directions:

$$\text{length} = 4R = \sqrt{2} a$$

$$(a = 2\sqrt{2}R)$$

Unit cell contains:

$$6 \times 1/2 + 8 \times 1/8$$

$$= 4 \text{ atoms/unit cell}$$

Adapted from
Fig. 3.1(a),
Callister 7e.

$$\text{APF} = \frac{\text{atoms/unit cell} \times \frac{4}{3} \pi \left(\frac{\sqrt{2}a}{4}\right)^3}{a^3}$$

atoms
unit cell

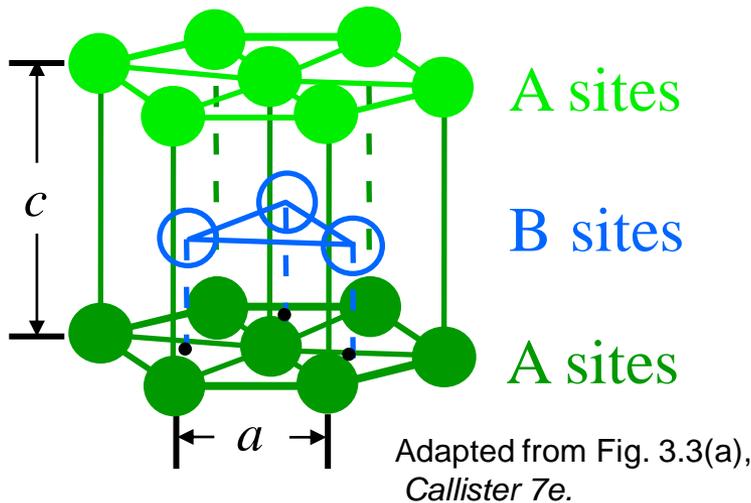
volume
atom

volume
unit cell

Hexagonal Close-Packed Structure (HCP)

ex: Cd, Mg, Ti, Zn

- ABAB... Stacking Sequence
- 3D Projection



- 2D Projection



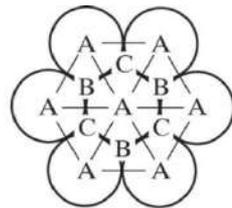
- Coordination # = 12

6 atoms/unit cell

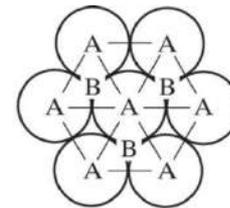
- APF = 0.74

• $c/a = 1.633$ (*ideal*)

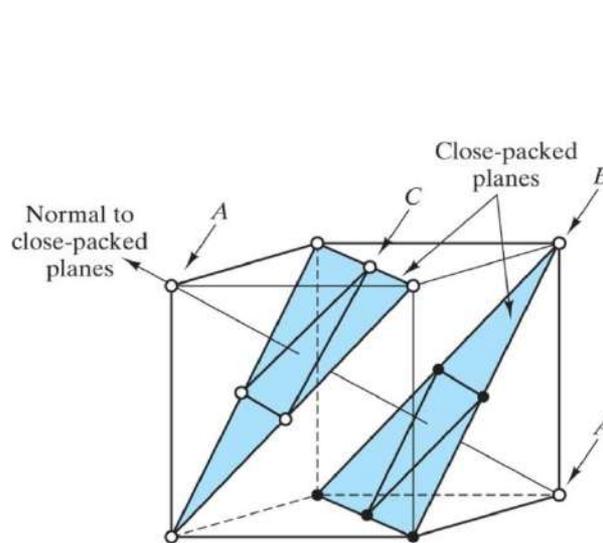
We find that both FCC & HCP are highest density packing schemes (APF = .74) – this illustration shows their differences as the closest packed planes are “built-up”



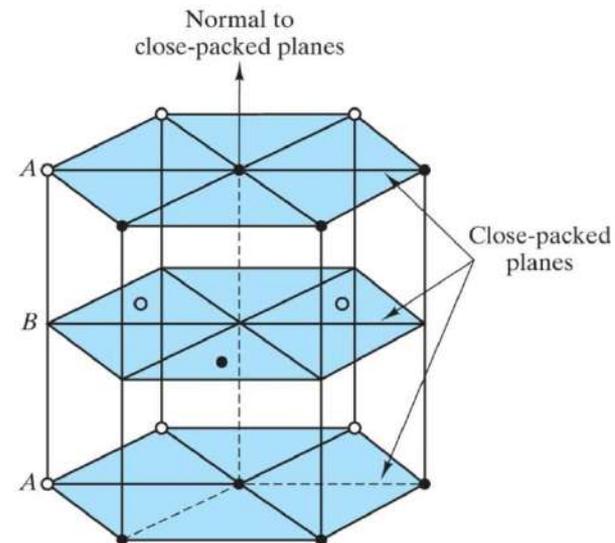
(a) Stacking of close-packed planes



(b) Stacking of close-packed planes



(c) Face-centered cubic



(d) Hexagonal close packed

Theoretical Density, ρ

$$\text{Density} = \rho = \frac{\text{Mass of Atoms in Unit Cell}}{\text{Total Volume of Unit Cell}}$$

$$\rho = \frac{nA}{V_C N_A}$$

where

n = number of atoms/unit cell

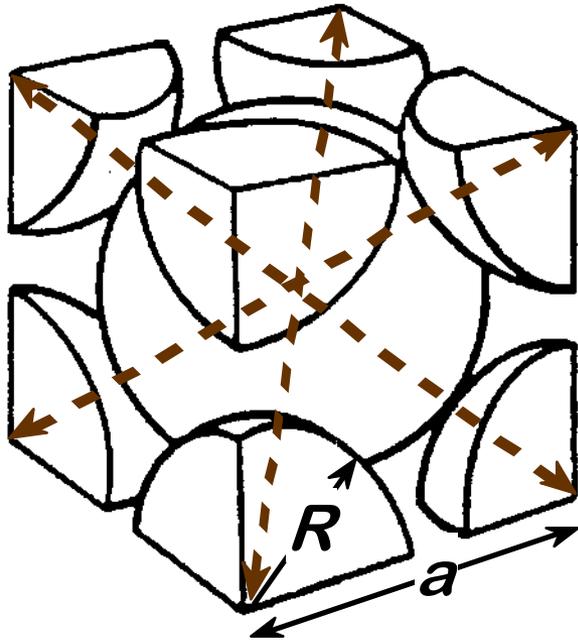
A = atomic weight

V_C = Volume of unit cell = a^3 for cubic

N_A = Avogadro's number

= 6.023×10^{23} atoms/mol

Theoretical Density, ρ



- Ex: Cr (BCC)

$$A = 52.00 \text{ g/mol}$$

$$R = 0.125 \text{ nm}$$

$$n = 2$$

$$\therefore a = 4R/\sqrt{3} = 0.2887 \text{ nm}$$

$$\frac{\text{atoms}}{\text{unit cell}} \rightarrow \begin{array}{|c|c|} \hline 2 & 52.00 \\ \hline \end{array}$$

$\frac{\text{g}}{\text{mol}}$

$$\rho_{\text{theoretical}} = 7.18 \text{ g/cm}^3$$

$$r_{\text{actual}} = 7.19 \text{ g/cm}^3$$

$\rho =$

$$\frac{\begin{array}{|c|c|} \hline a^3 & 6.023 \times 10^{23} \\ \hline \end{array}}$$

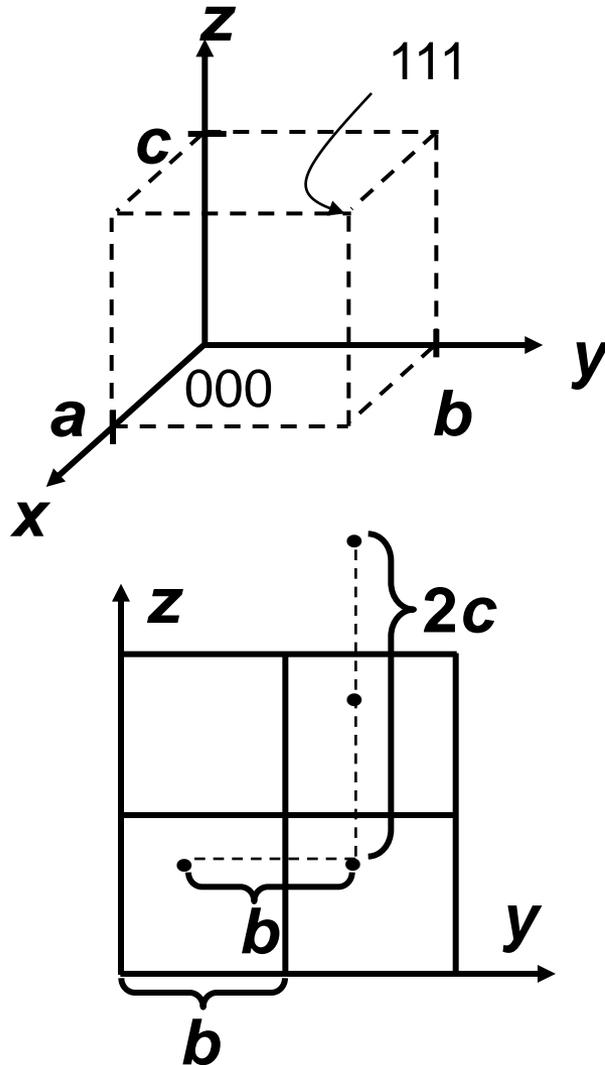
$\frac{\text{volume}}{\text{unit cell}}$

$\frac{\text{atoms}}{\text{mol}}$

$\frac{\text{unit cell}}{\text{mol}}$

$\frac{\text{mol}}{\text{mol}}$

Locations in Lattices: Point Coordinates



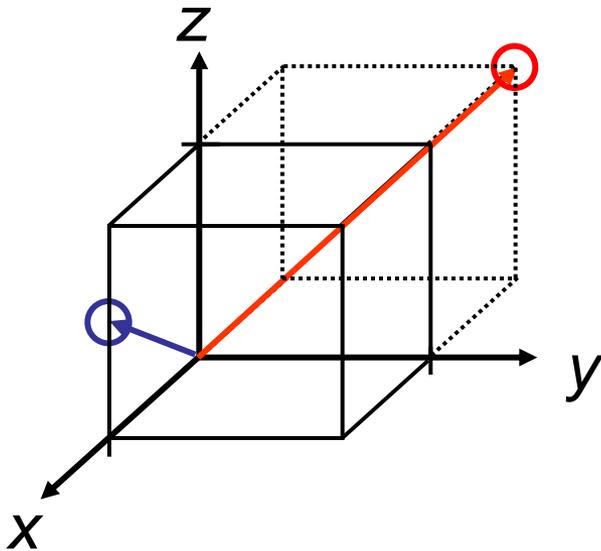
Point coordinates for unit cell center are

$$a/2, b/2, c/2 \quad \frac{1}{2}\frac{1}{2}\frac{1}{2}$$

Point coordinates for unit cell (body diagonal) corner are 111

Translation: integer multiple of lattice constants \rightarrow identical position *in another unit cell*

Crystallographic Directions



Algorithm

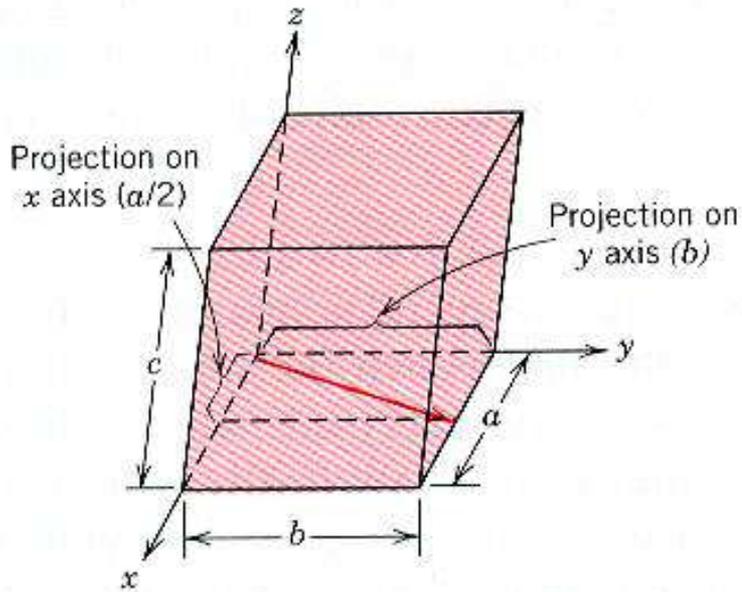
1. Vector is repositioned (if necessary) to *pass through the Unit Cell origin*.
2. Read off line projections (to principal axes of U.C.) in terms of unit cell dimensions a , b , and c
3. Adjust to smallest **integer values**
4. Enclose in square brackets, *no commas*

$[uvw]$

ex: $1, 0, \frac{1}{2} \Rightarrow 2, 0, 1 \Rightarrow [201]$

$-1, 1, 1 \Rightarrow [\bar{1}11]$ where 'overbar' represents a negative index

families of directions $\langle uvw \rangle$



What is this *Direction* ?????

Projections:

Projections in terms of a,b and c:

Reduction:

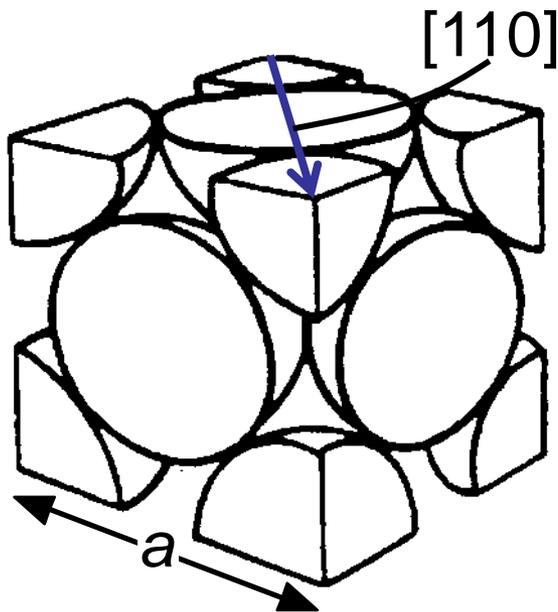
Enclosure [brackets]

<u>x</u>	<u>y</u>	<u>z</u>
a/2	b	0c
1/2	1	0
1	2	0

[120]

Linear Density

- Linear Density of Atoms \equiv LD = $\frac{\text{Number of atoms}}{\text{Unit length of direction vector}}$



ex: linear density of Al in $[110]$ direction

$$a = 0.405 \text{ nm}$$

$$\text{LD} = \frac{\text{\# atoms}}{\text{length}} = \frac{2}{\sqrt{2}a} = 3.5 \text{ nm}^{-1}$$

The number 2 is highlighted in a green box, and the term $\sqrt{2}a$ is highlighted in a blue box. The final result, 3.5 nm^{-1} , is highlighted in a yellow box.

atoms **CENTERED** on the direction of interest!

Length is of the **direction** of interest **within** the Unit Cell

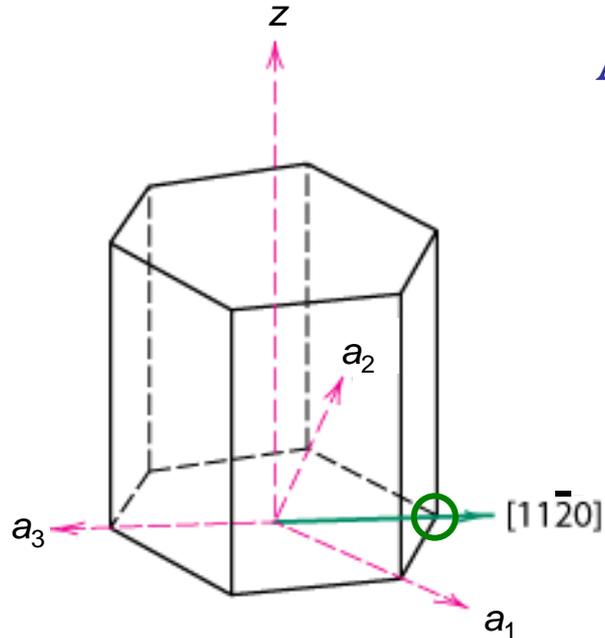
Determining Angles Between Crystallographic Direction:

$$\theta = \text{Cos}^{-1} \left[\frac{u_1 u_2 + v_1 v_2 + w_1 w_2}{\sqrt{(u_1^2 + v_1^2 + w_1^2) \cdot (u_2^2 + v_2^2 + w_2^2)}} \right]$$

Where u_i 's , v_i 's & w_i 's are the “Miller Indices” of the directions in question

– also (for information) If a direction has the same Miller Indices as a plane, it is NORMAL to that plane

HCP Crystallographic Directions



Adapted from Fig. 3.8(a), Callister 7e.

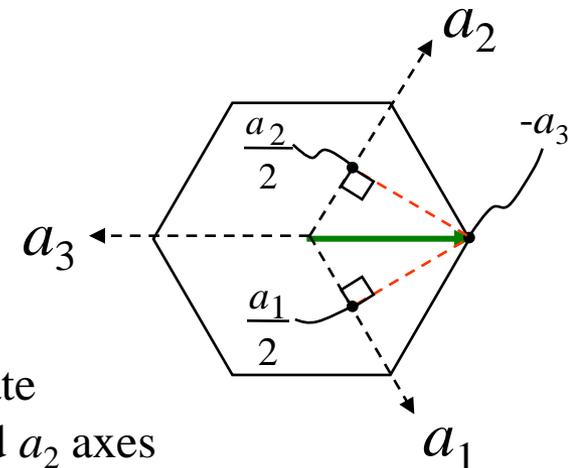
ex: $\frac{1}{2}, \frac{1}{2}, -1, 0 \Rightarrow [11\bar{2}0]$

Algorithm

1. Vector repositioned (if necessary) to pass through origin.
2. Read off projections in terms of unit cell dimensions a_1, a_2, a_3 , or c
3. Adjust to smallest integer values
4. Enclose in square brackets, no commas

$[uvw]$

dashed red lines indicate projections onto a_1 and a_2 axes



HCP Crystallographic Directions

- Hexagonal Crystals

- 4 parameter Miller-Bravais lattice coordinates are related to the direction indices (i.e., $u'v'w'$) in the '3 space' Bravais lattice as follows.

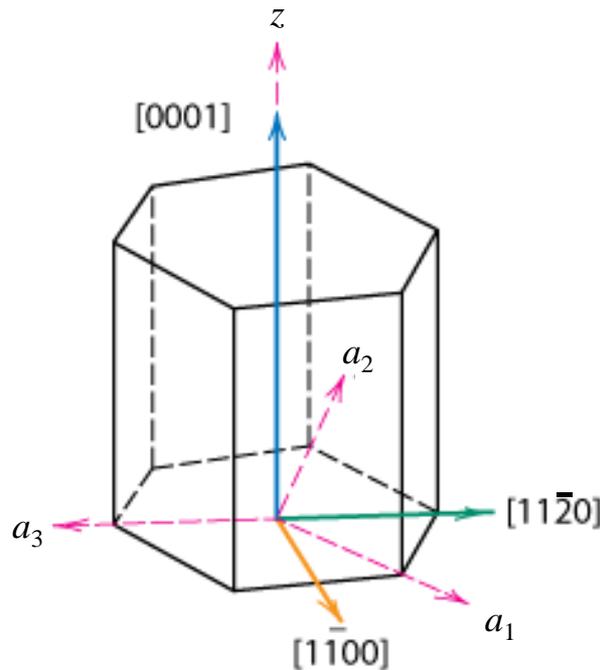


Fig. 3.8(a), Callister 7e.

$$[u'v'w'] \textcircled{R} [uvw]$$

$$u = \frac{1}{3}(2u' - v')$$

$$v = \frac{1}{3}(2v' - u')$$

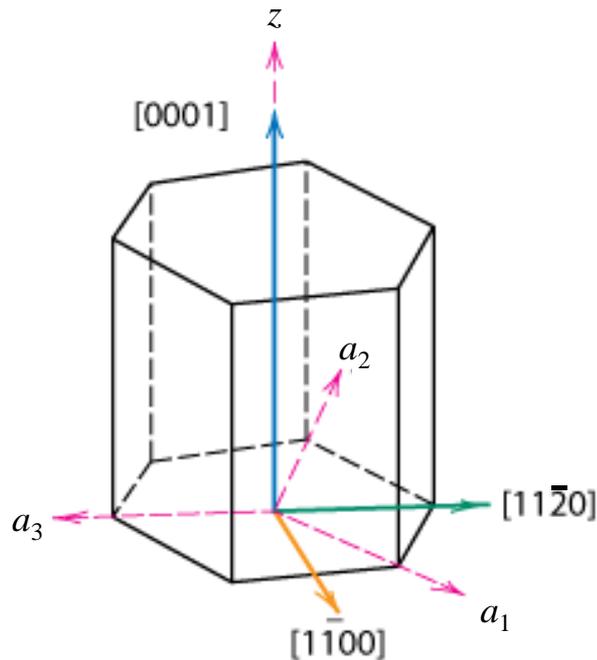
$$t = -(u + v)$$

$$w = w'$$

Computing HCP Miller- Bravais Directional Indices (an alternative way):

We confine ourselves to the bravais parallelopiped in the hexagon: a_1 - a_2 - Z and determine: (u', v', w')

Here: $[1\ 1\ 0]$ - so now apply the models to create M-B Indices



$$u = \frac{1}{3} (2u' - v') = \frac{1}{3} (2 * 1 - 1) = \frac{1}{3} \rightarrow 1$$

$$v = \frac{1}{3} (2v' - u') = \frac{1}{3} (2 * 1 - 1) = \frac{1}{3} \rightarrow 1$$

$$t = -(u + v) = -\left(\frac{1}{3} + \frac{1}{3}\right) = -\frac{2}{3} \rightarrow -2$$

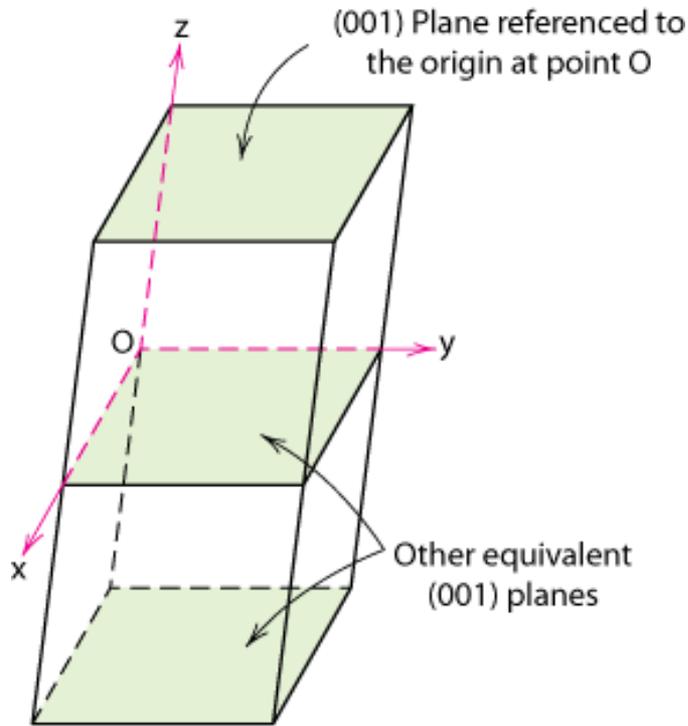
$$w = w' = 0$$

$$\text{M-B Indices: } [1\ 1\ \bar{2}\ 0]$$

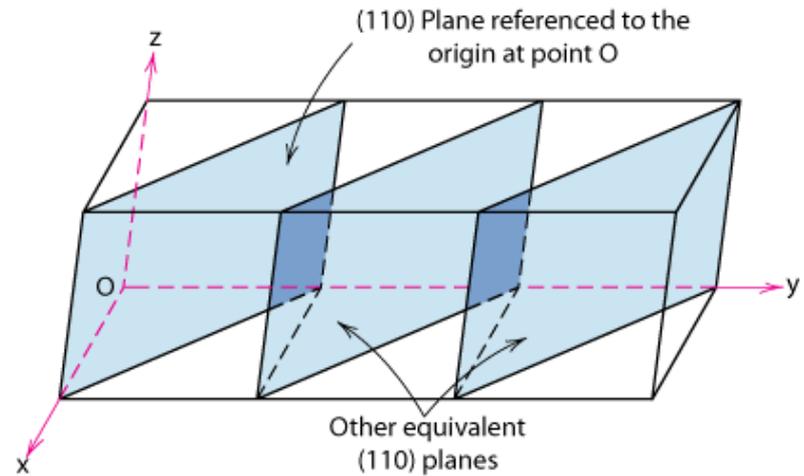
Defining Crystallographic Planes

- Miller Indices: Reciprocals of the (three) axial intercepts for a plane, cleared of fractions & common multiples. All parallel planes have same Miller indices.
- Algorithm (in cubic lattices this is direct)
 1. Read off intercepts of plane with axes in terms of a, b, c
 2. Take reciprocals of intercepts
 3. Reduce to smallest integer values
 4. Enclose in parentheses, no commas i.e., (hkl) → families $\{hkl\}$

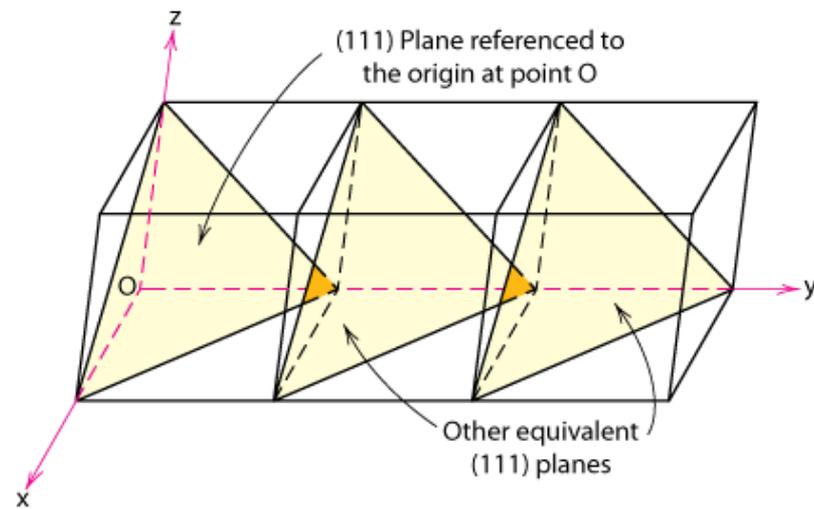
Crystallographic Planes -- families



(a)



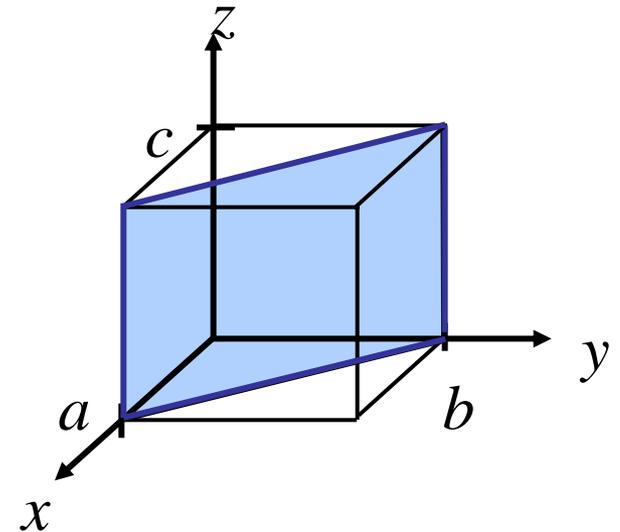
(b)



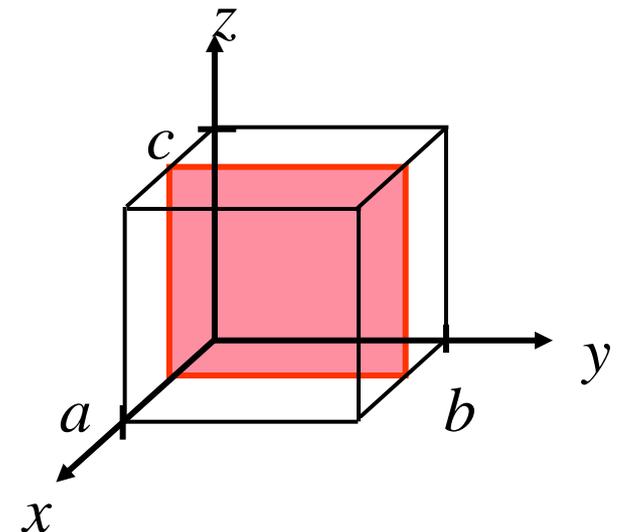
(c)

Crystallographic Planes

<u>example</u>	<i>a</i>	<i>b</i>	<i>c</i>
1. Intercepts	1	1	∞
2. Reciprocals	1/1	1/1	1/ ∞
	1	1	0
3. Reduction	1	1	0
4. Miller Indices	(110)		

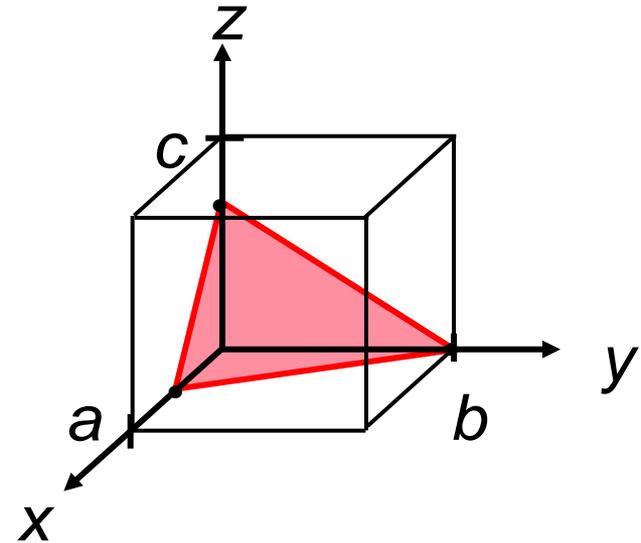


<u>example</u>	<i>a</i>	<i>b</i>	<i>c</i>
1. Intercepts	1/2	∞	∞
2. Reciprocals	1/1/2	1/ ∞	1/ ∞
	2	0	0
3. Reduction	2	0	0
4. Miller Indices	(100)		



Crystallographic Planes

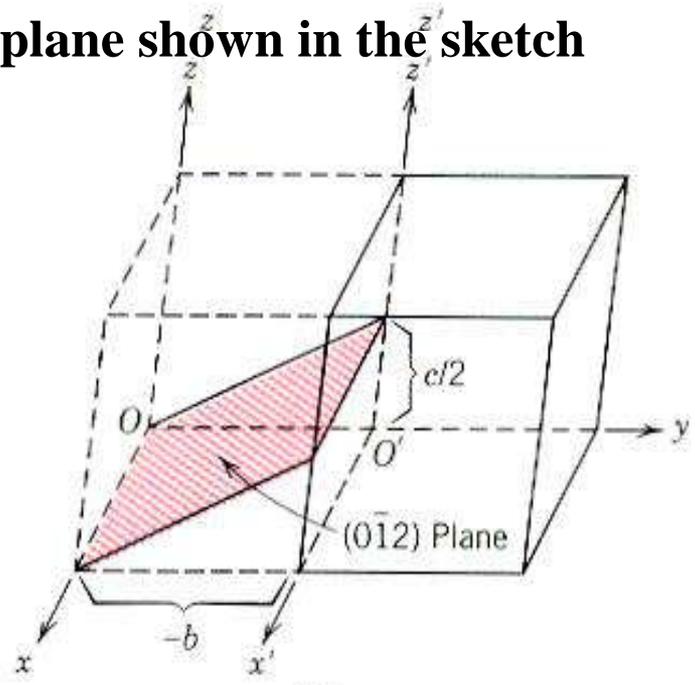
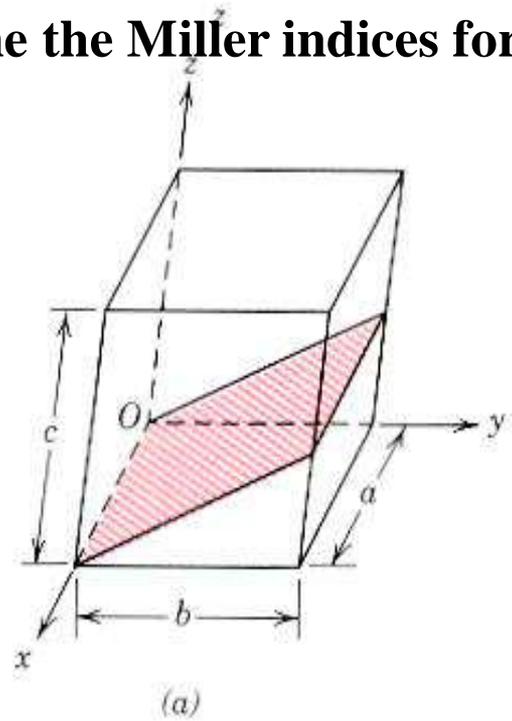
<u>example</u>	<i>a</i>	<i>b</i>	<i>c</i>
1. Intercepts	1/2	1	3/4
2. Reciprocals	1/1/2	1/1	1/3/4
	2	1	4/3
3. Reduction	6	3	4
4. Miller Indices	(634)		



Family of Planes $\{hkl\}$

Ex: $\{100\} = (100), (010), (001), (\bar{1}00), (0\bar{1}0), (00\bar{1})$

Determine the Miller indices for the plane shown in the sketch



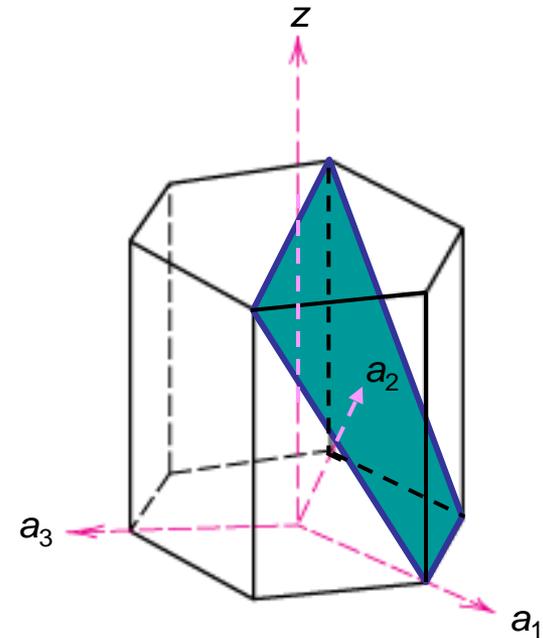
- Intercepts
- Intercept in terms of lattice parameters
- Reciprocals
- Reductions
- Enclosure

$\frac{1}{x}$	y	z
$\propto a$	-b	c/2
\propto	-1	1/2
0	-1	2
	—	N/A
	(0\bar{1}2)	

Crystallographic Planes (HCP)

- In hexagonal unit cells the same idea is used

<u>example</u>	a_1	a_2	a_3	c
1. Intercepts	1	∞	-1	1
2. Reciprocals	1	$1/\infty$	-1	1
	1	0	-1	1
3. Reduction	1	0	-1	1
4. Miller-Bravais Indices	$(10\bar{1}1)$			



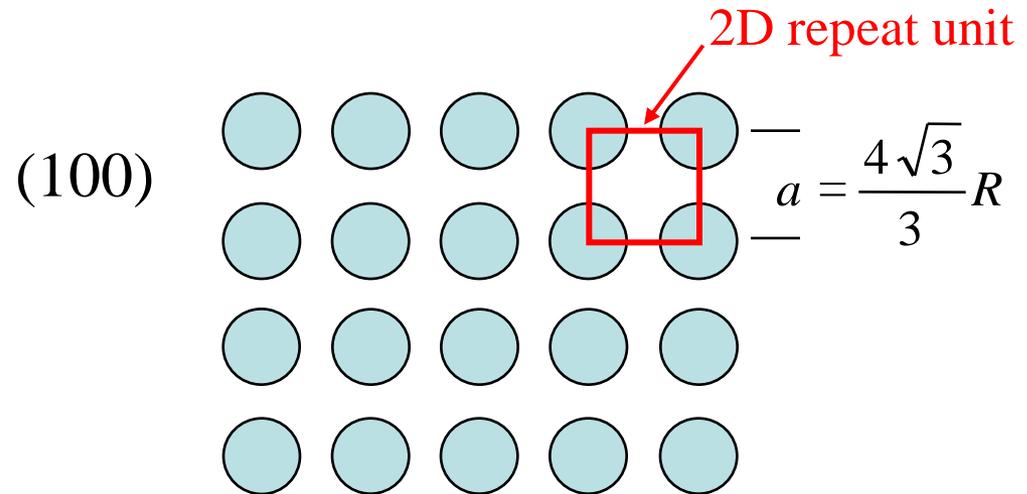
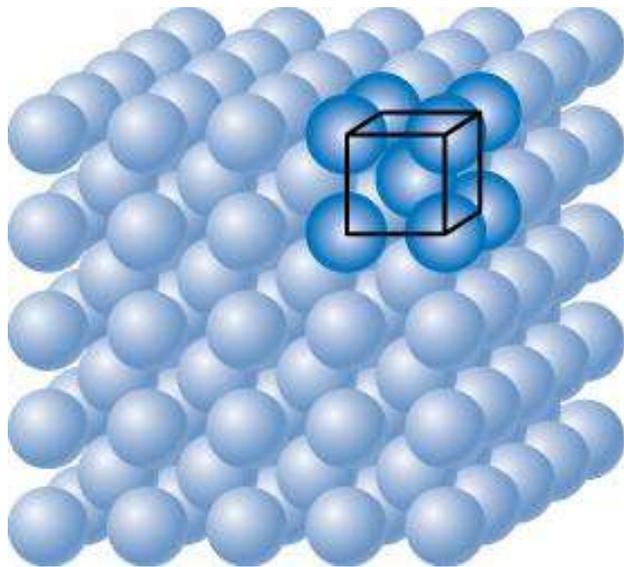
Adapted from Fig. 3.8(a), Callister 7e.

Crystallographic Planes

- We want to examine the atomic packing of crystallographic planes – those with the same packing are equivalent and part of families
- Iron foil can be used as a catalyst. The atomic packing of the exposed planes is important.
 - a) Draw (100) and (111) crystallographic planes for Fe.
 - b) Calculate the planar density for each of these planes.

Planar Density of (100) Iron

Solution: At $T < 912^\circ\text{C}$ iron has the BCC structure.



Radius of iron $R = 0.1241 \text{ nm}$

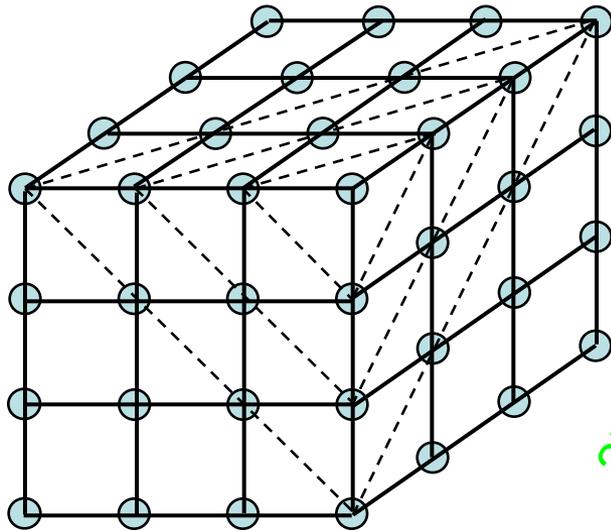
$$\text{Planar Density} = \frac{\text{atoms}}{\text{area}} = \frac{1}{\left(\frac{4\sqrt{3}}{3}R\right)^2} = 12.1 \frac{\text{atoms}}{\text{nm}^2} = 1.2 \times 10^{19} \frac{\text{atoms}}{\text{m}^2}$$

The diagram includes labels for the terms in the equation: "atoms" is labeled above the numerator, "2D repeat unit" is labeled below the numerator, "area" is labeled below the denominator, and "2D repeat unit" is labeled below the denominator's square term.

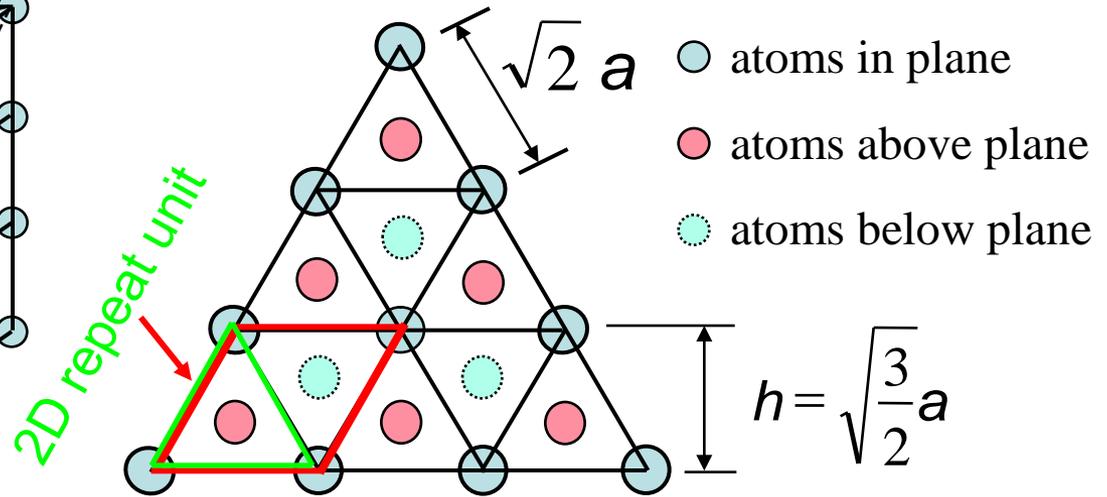
Atoms: wholly contained and centered in/on plane within U.C., area of plane in U.C.

Planar Density of (111) Iron

Solution (cont): (111) plane



1/2 atom centered on plane/ unit cell



Area 2D Unit: $\frac{1}{2} hb = \frac{1}{2} * [(\sqrt{3}/2)a][(\sqrt{2})a] = \frac{1}{2}(\sqrt{3})a^2 = 8R^2/(\sqrt{3})$

atoms

2D repeat unit

area

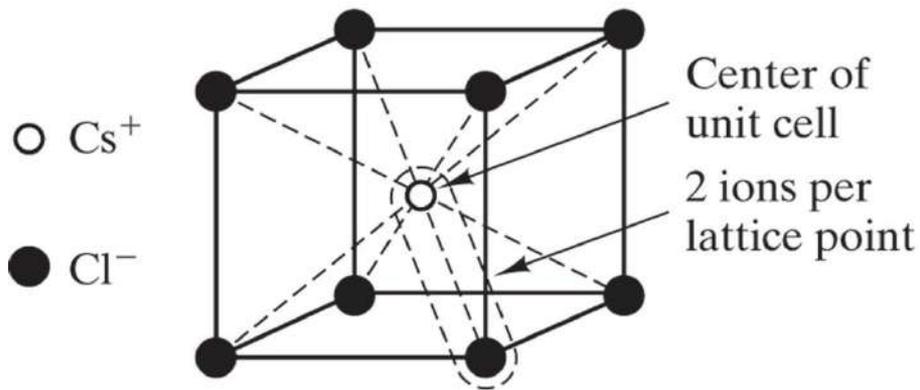
2D repeat unit

$$\text{Planar Density} = \frac{3 * \frac{1}{6}}{\frac{8R^2}{\sqrt{3}}} = 7.0 \frac{\text{atoms}}{\text{nm}^2} = 0.70 \times 10^{19} \frac{\text{atoms}}{\text{m}^2}$$

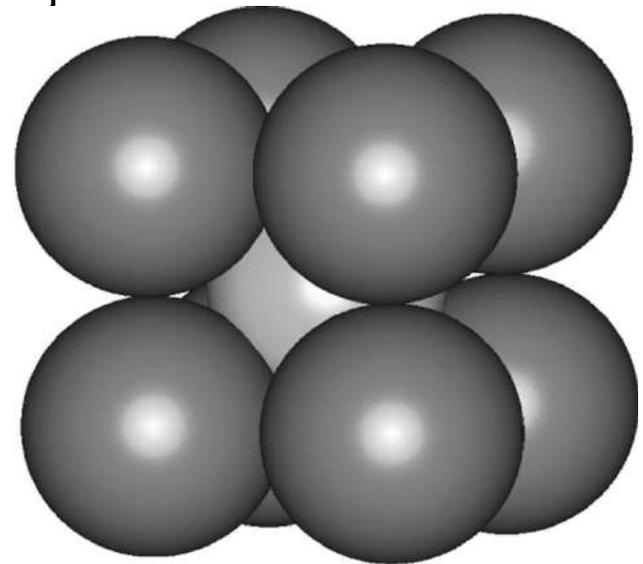
Looking at the Ceramic Unit Cells

Adding Ionic Complexities

Cesium chloride (CsCl) unit cell showing (a) ion positions and the two ions per lattice point and (b) full-size ions. Note that the $\text{Cs}^+\text{-Cl}^-$ pair associated with a given lattice point is not a molecule because the ionic bonding is nondirectional and because a given Cs^+ is equally bonded to eight adjacent Cl^- , and vice versa. [Part (b) courtesy of Accelrys, Inc.]



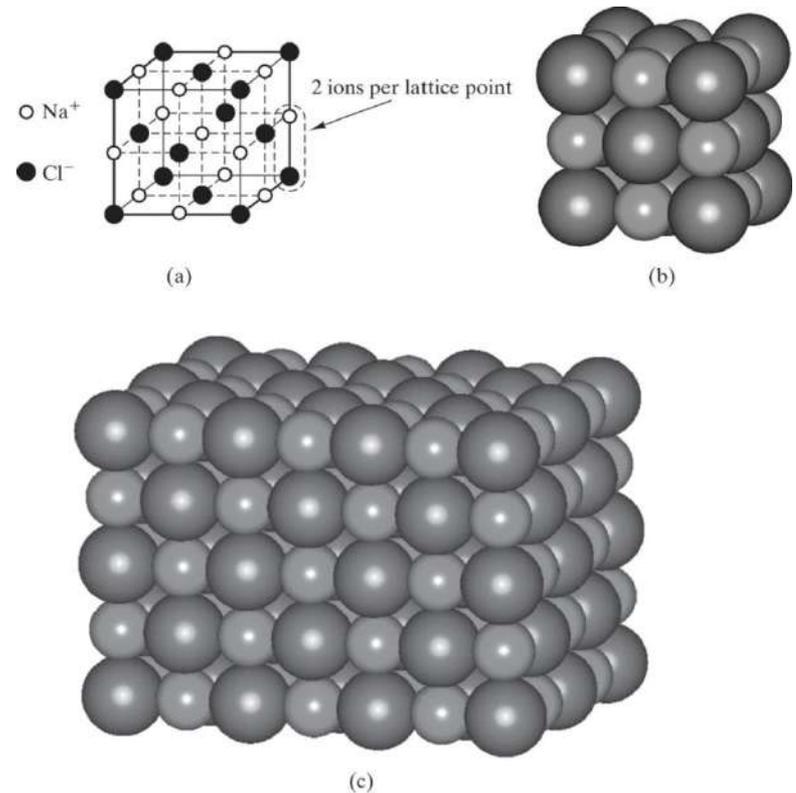
(a)



(b)

Structure: CsCl type
Bravais lattice: simple cubic
Ions/unit cell: $1\text{Cs}^+ + 1\text{Cl}^-$

Sodium chloride (NaCl) structure showing (a) ion positions in a unit cell, (b) full-size ions, and (c) many adjacent unit cells. [Parts (b) and (c) courtesy of Accelrys, Inc.]

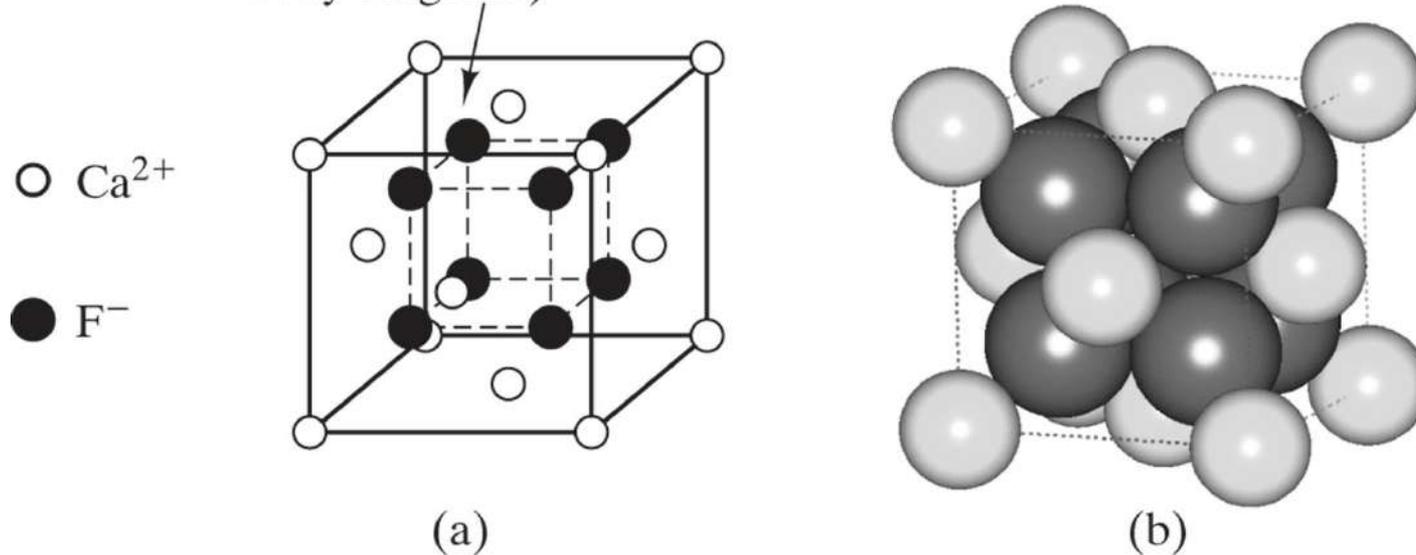


Structure: NaCl type
Bravais lattice: fcc
Ions/unit cell: $4\text{Na}^+ + 4\text{Cl}^-$
Typical ceramics: MgO, CaO, FeO, and NiO

Fluorite (CaF_2) unit cell showing (a) ion positions and (b) full-size ions.

[Part (b) courtesy of Accelrys, Inc.]

F^- ions located at corners of a cube (at one-quarter of the distance along the body diagonal)



Structure: fluorite (CaF_2) type

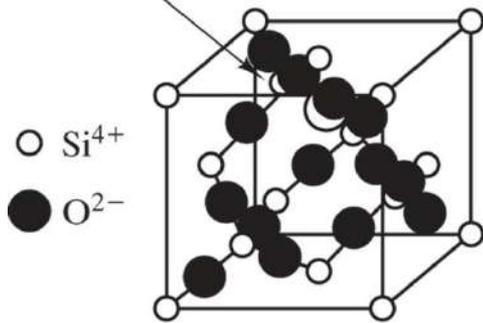
Bravais lattice: fcc

Ions/unit cell: $4\text{Ca}^{2+} + 8\text{F}^-$

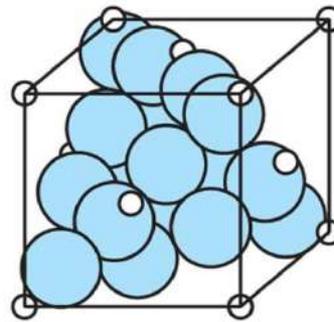
Typical ceramics: UO_2 , ThO_2 , and TeO_2

Figure 3.11 The cristobalite (SiO_2) unit cell showing (a) ion positions, (b) full-size ions, and (c) the connectivity of SiO_4^{4-} tetrahedra. In the schematic, each tetrahedron has a Si^{4+} at its center. In addition, an O^{2-} would be at each corner of each tetrahedron and is shared with an adjacent tetrahedron. [Part (c) courtesy of Accelrys, Inc.]

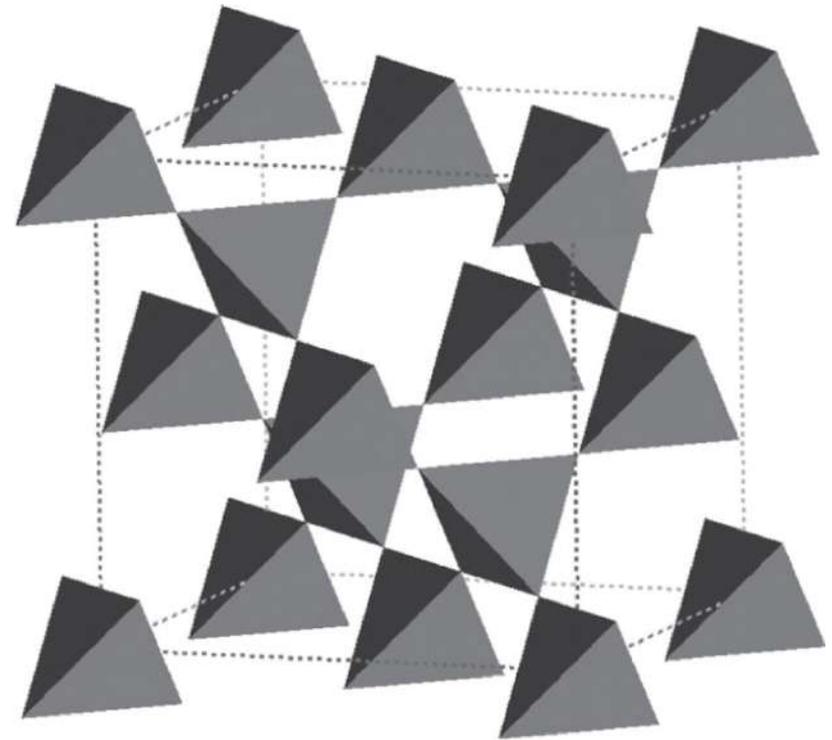
Interior Si^{4+} located at positions one-quarter of the distance along the body diagonal



(a)



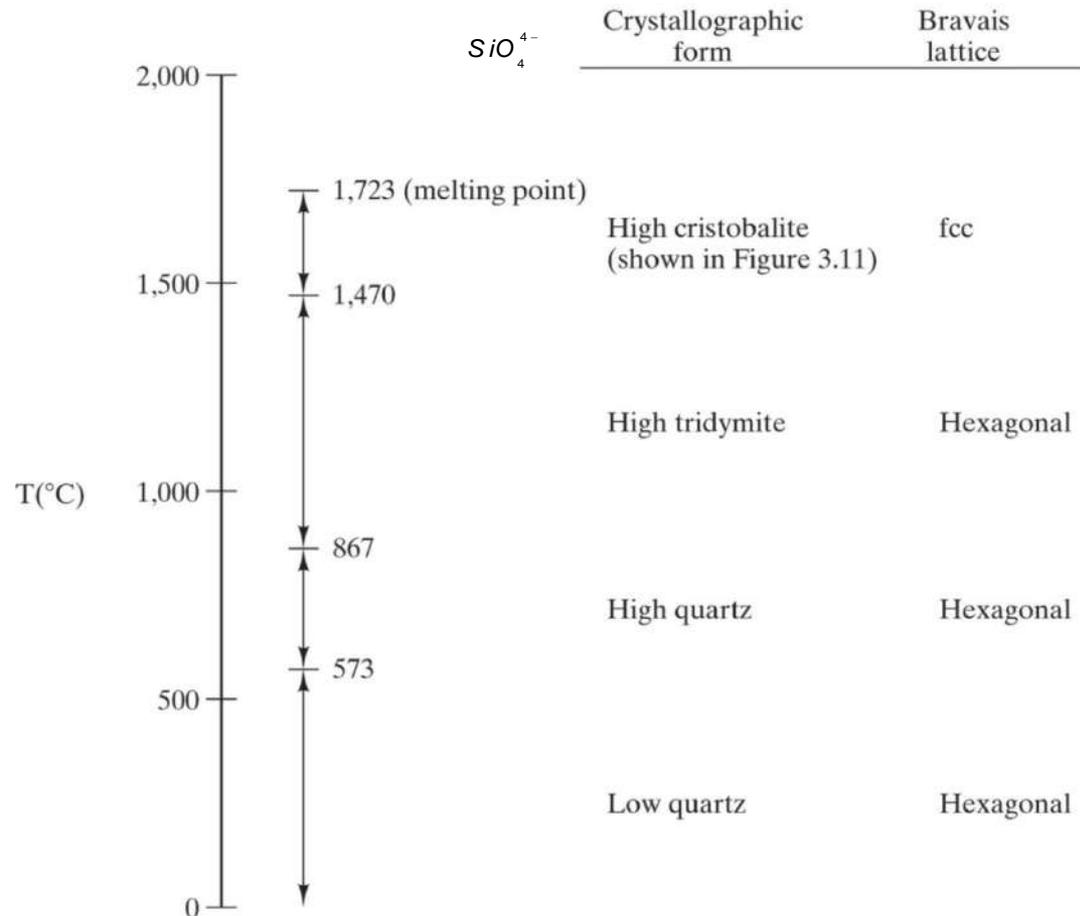
(b)



(c)

Structure: cristobalite (SiO_2) type
 Bravais lattice: fcc
 Ions/unit cell: $8\text{Si}^{4+} + 16\text{O}^{2-}$

Many crystallographic forms of SiO_2 are stable as they are heated from room temperature to melting temperature. Each form represents a different way to connect adjacent SiO_4^{4-} tetrahedra.



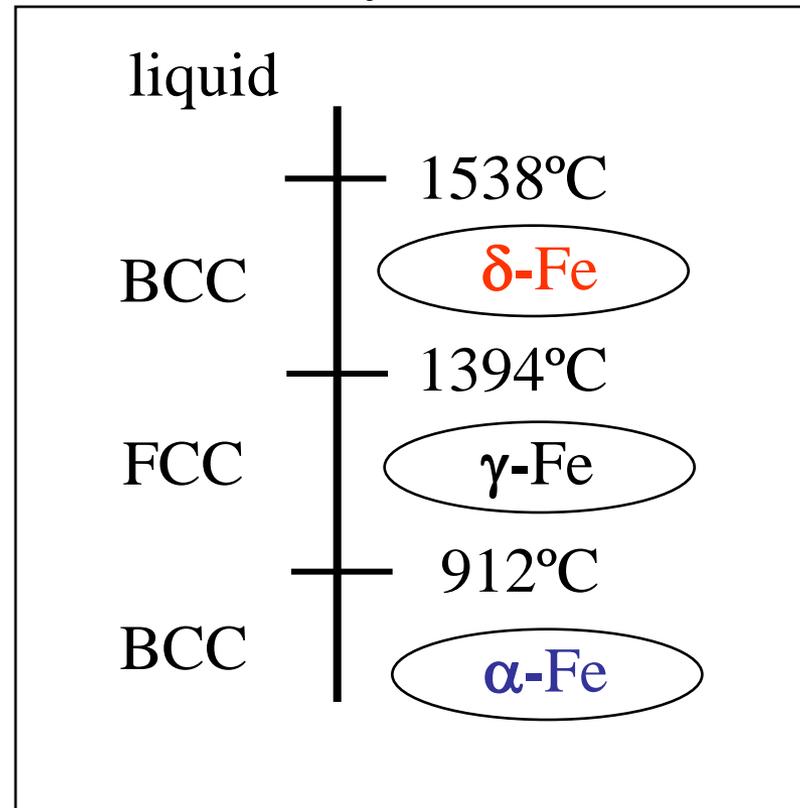
Polymorphism: Also in Metals

- Two or more **distinct crystal structures** for the same material (allotropy/polymorphism)

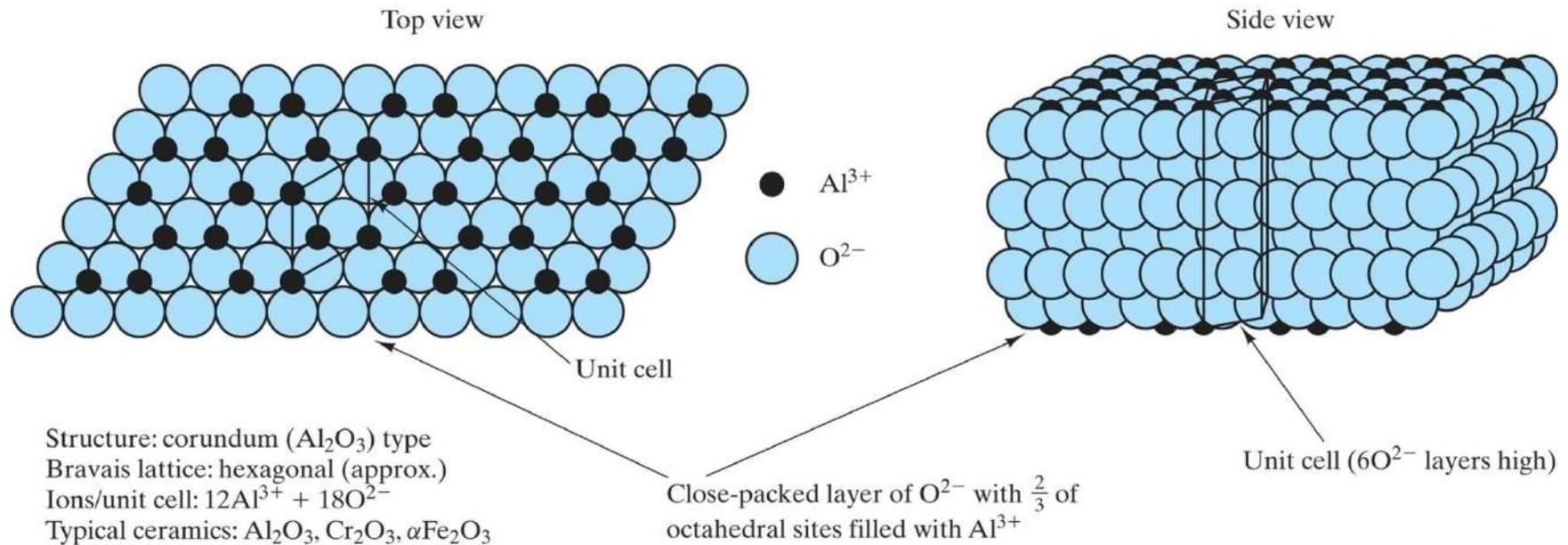
titanium
 α (HCP), β (BCC)-Ti

carbon:
diamond, graphite

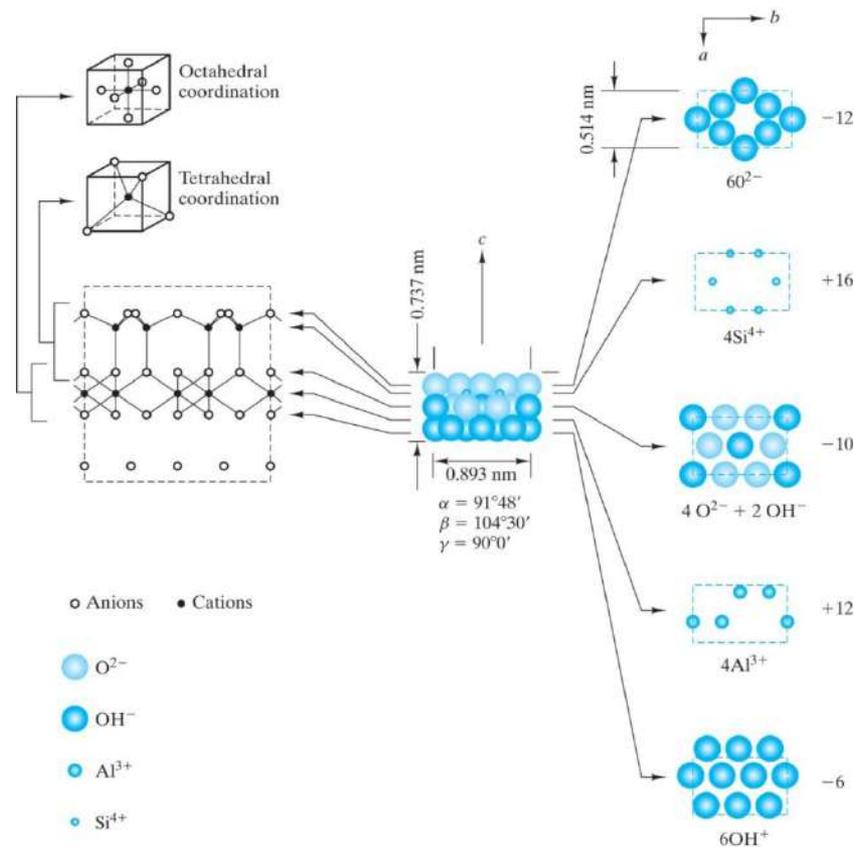
iron system:



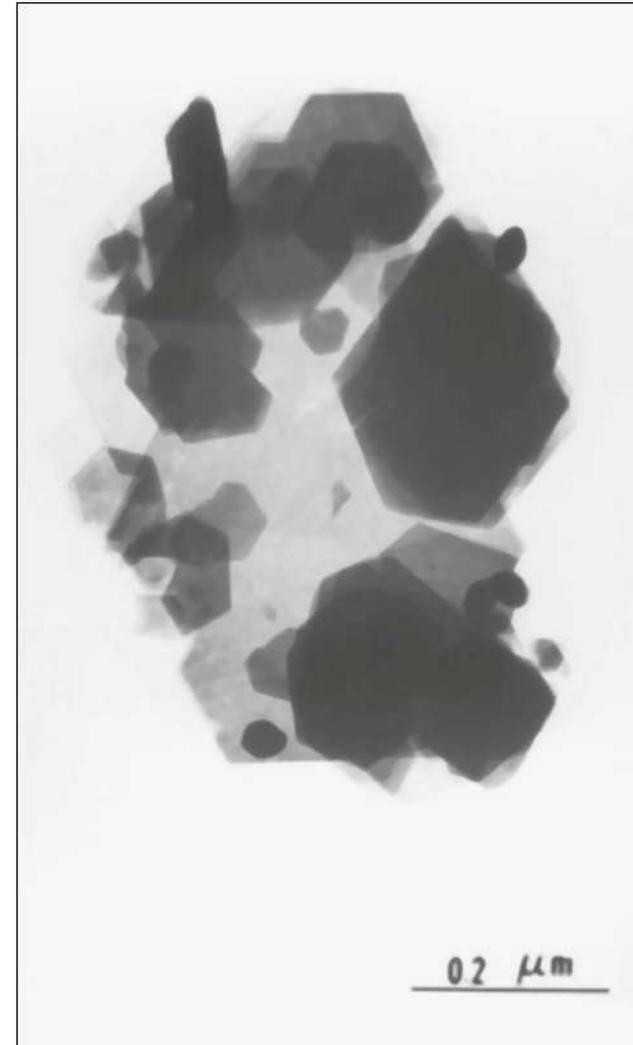
The corundum (Al_2O_3) unit cell is shown superimposed on the repeated stacking of layers of close-packed O^{2-} ions. The Al^{3+} ions fill two-thirds of the small (octahedral) interstices between adjacent layers.



Exploded view of the kaolinite unit cell, $2(\text{OH})_4\text{Al}_2\text{Si}_2\text{O}_5$. (From F. H. Norton, Elements of Ceramics, 2nd ed., Addison-Wesley Publishing Co., Inc., Reading, MA, 1974.)

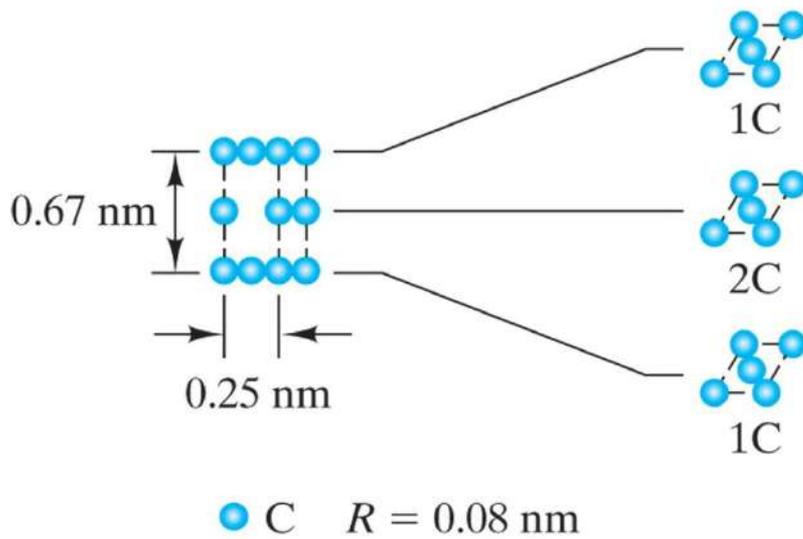


Transmission electron micrograph of the structure of clay platelets. This microscopic-scale structure is a manifestation of the layered crystal structure shown in the previous slide. (Courtesy of I. A. Aksay.)

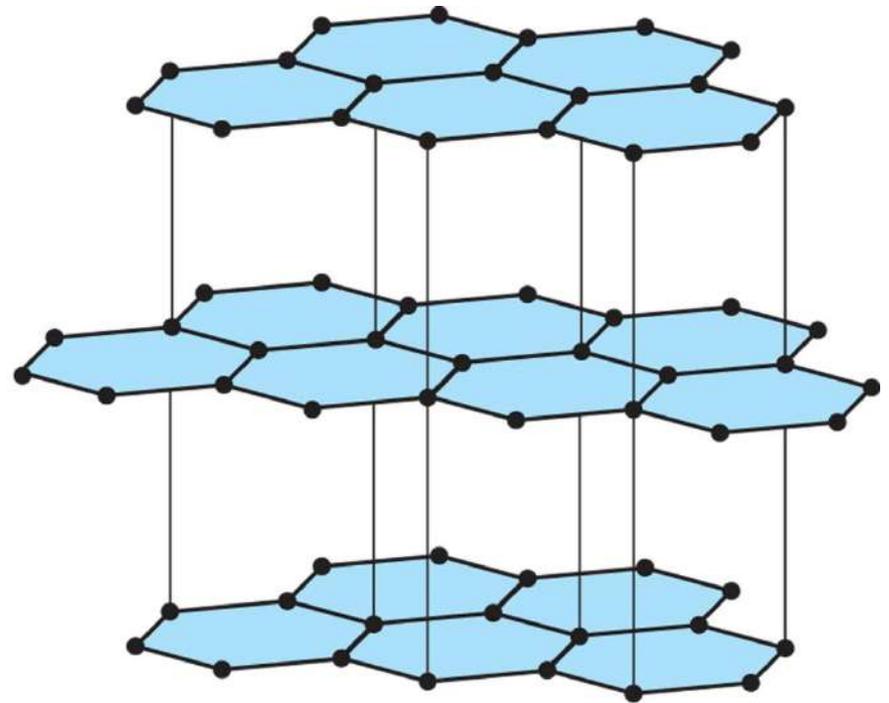


(a) An exploded view of the graphite (C) unit cell.

(b) A schematic of the nature of graphite's layered structure.

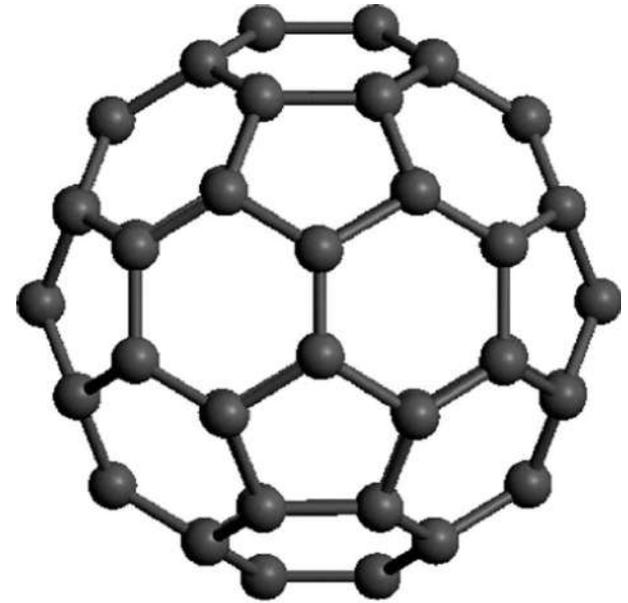


(a)

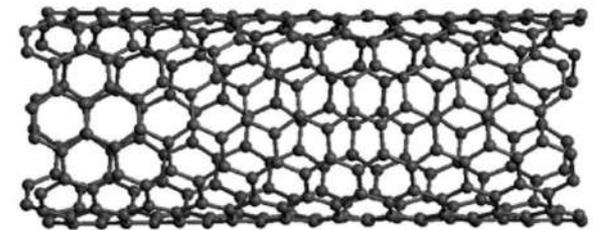


(b)

- (a) C_{60} molecule, or buckyball.
(b) Cylindrical array of hexagonal rings of carbon atoms, or buckytube.
(Courtesy of Accelrys, Inc.)

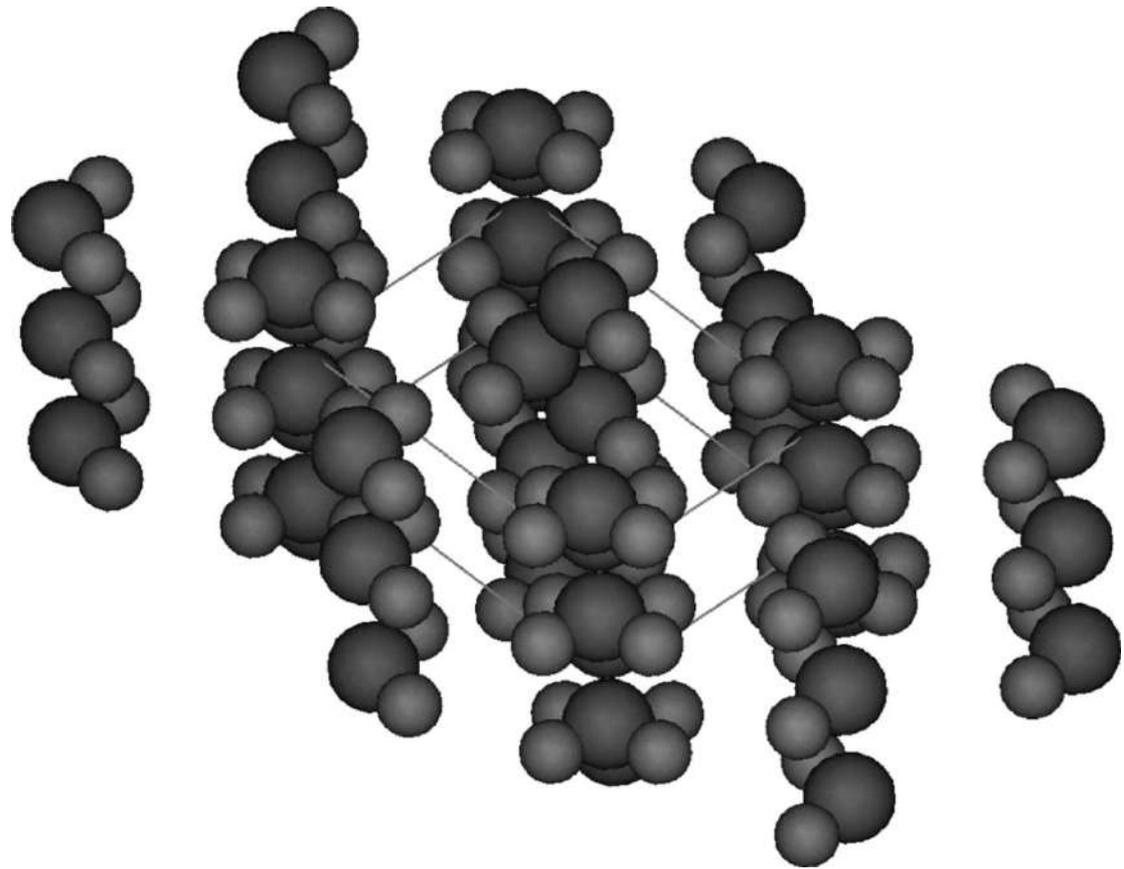


(a)

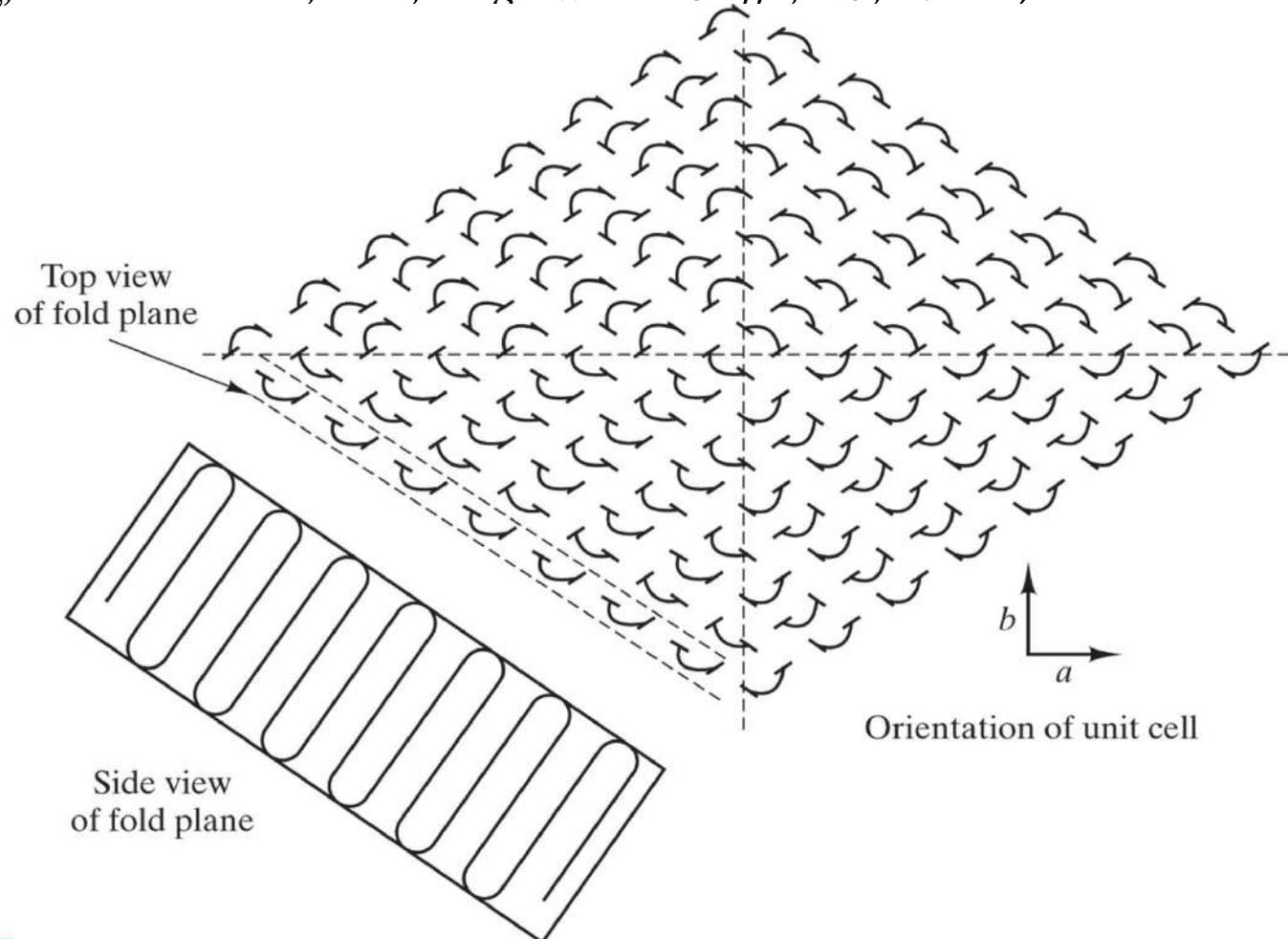


(b)

Arrangement of polymeric chains in the unit cell of polyethylene. The dark spheres are carbon atoms, and the light spheres are hydrogen atoms. The unit-cell dimensions are $0.255 \text{ nm} \times 0.494 \text{ nm} \times 0.741 \text{ nm}$. (Courtesy of Accelrys, Inc.)



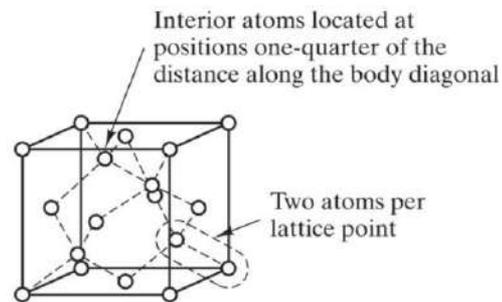
Weaving-like pattern of folded polymeric chains that occurs in thin crystal platelets of polyethylene. (From D. J. Williams, Polymer Science and Engineering, Prentice Hall, Inc., Englewood Cliffs, NJ, 1971.)



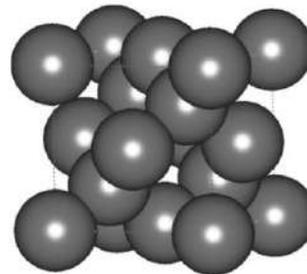
Diamond cubic unit cell showing

(a) atom positions. There are two atoms per lattice point (note the outlined example). Each atom is tetrahedrally coordinated.

(b) The actual packing of full-size atoms associated with the unit cell.



(a)



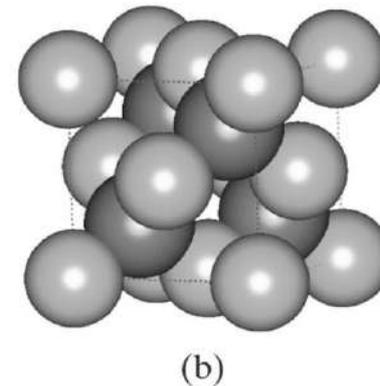
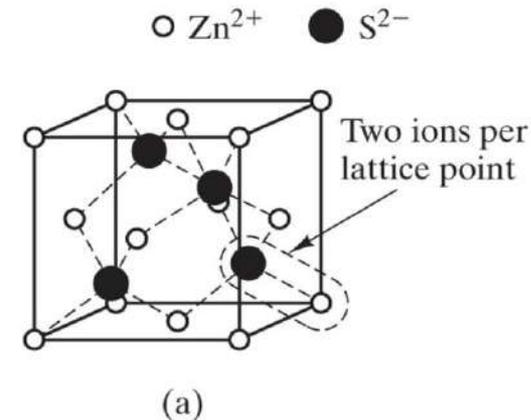
(b)

Structure: diamond cubic
Bravais lattice: fcc
Atoms/unit cell: $4 + 6 \times \frac{1}{2} + 8 \times \frac{1}{8} = 8$
Typical semiconductors: Si, Ge, and gray Sn

Zinc blende (ZnS) unit cell showing

(a) ion positions. There are two ions per lattice point (note the outlined example). Compare this structure with the diamond cubic structure

(b) The actual packing of full-size ions associated with the unit cell.



Structure: Zinc blende (ZnS) type

Bravais lattice: fcc

Ions/unit cell: $4\text{Zn}^{2+} + 4\text{S}^{2-}$

Typical semiconductors:

GaAs, AlP, InSb (III-V compounds),

ZnS, ZnSe, CdS, HgTe (II-VI compounds)

Densities of Material Classes

In general

$$\rho_{\text{metals}} > \rho_{\text{ceramics}} > \rho_{\text{polymers}}$$

Why?

Metals have...

- close-packing (metallic bonding)
- often large atomic masses

Ceramics have...

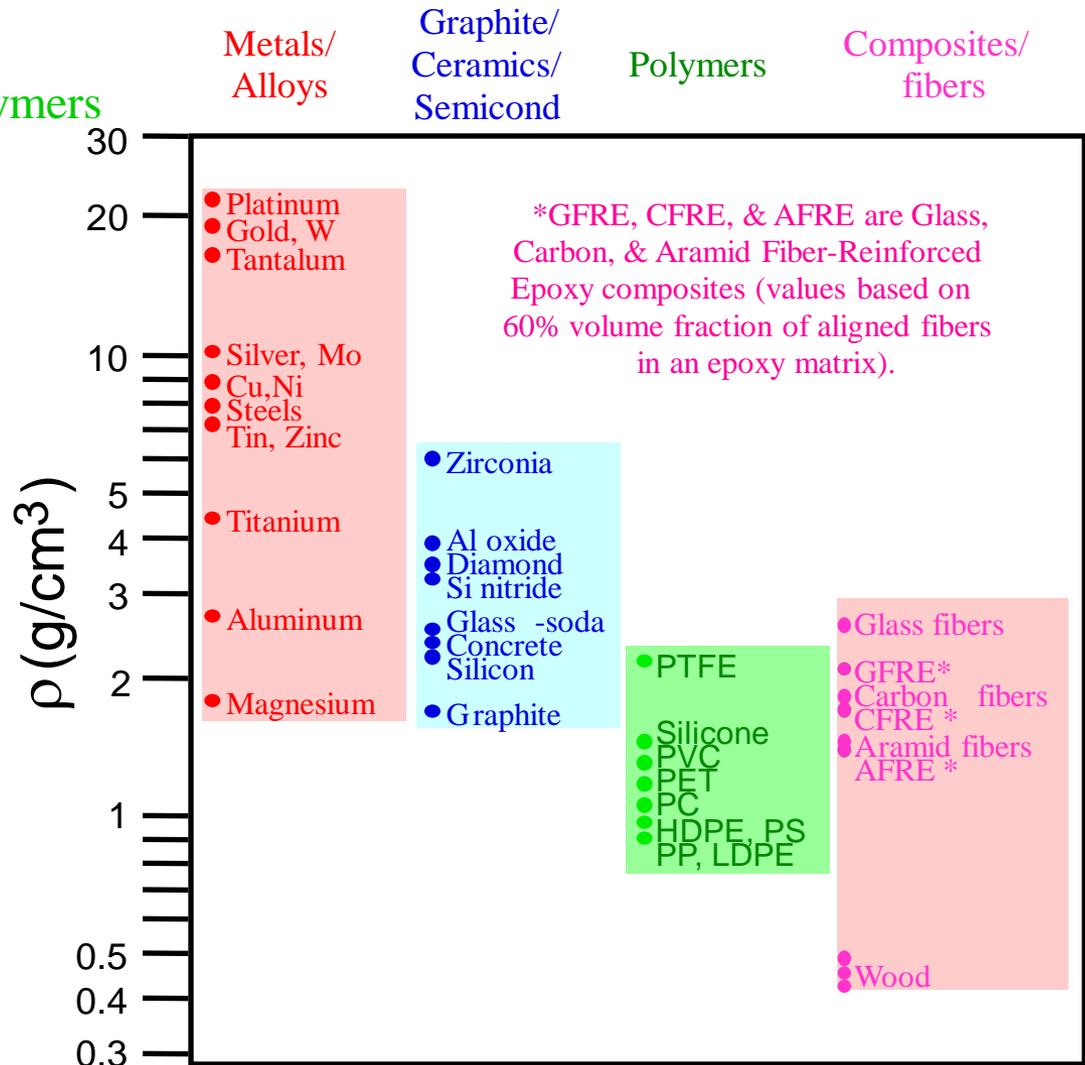
- less dense packing
- often lighter elements

Polymers have...

- low packing density (often amorphous)
- lighter elements (C,H,O)

Composites have...

- intermediate values



Crystals as Building Blocks

- *Some* engineering applications require single crystals:

- diamond single crystals for abrasives



- turbine blades



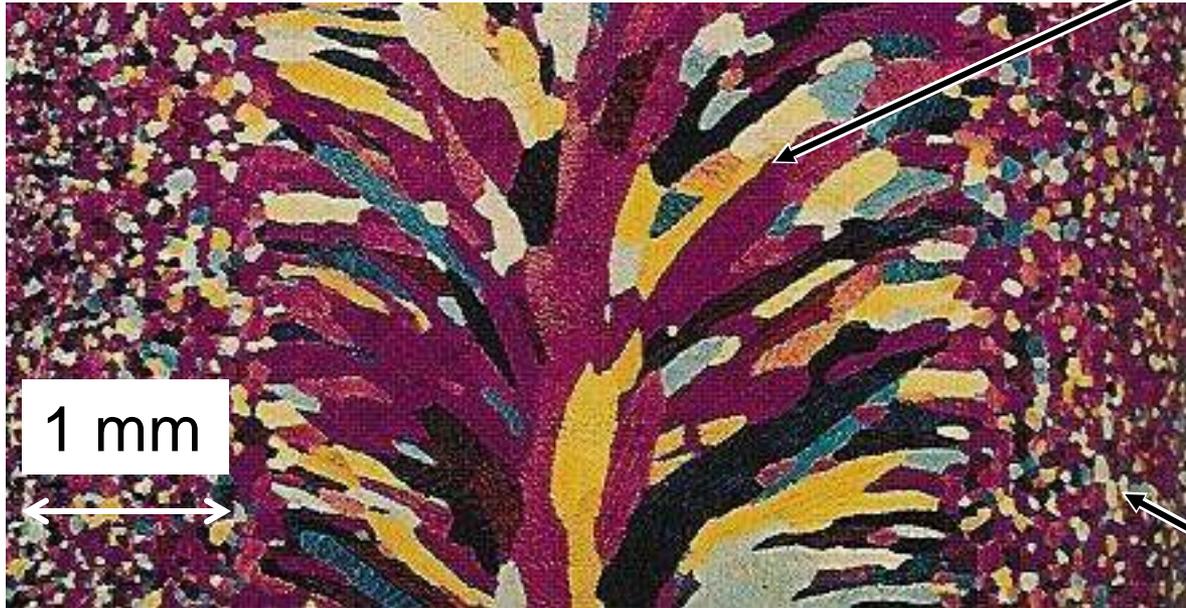
- Properties of crystalline materials often related to crystal structure.

- Ex: Quartz fractures more easily along some crystal planes than others.



Polycrystals

- *Most* engineering materials are polycrystals.



Anisotropic

Adapted from Fig. K, color inset pages of *Callister 5e*. (Fig. K is courtesy of Paul E. Danielson, Teledyne Wah Chang Albany)

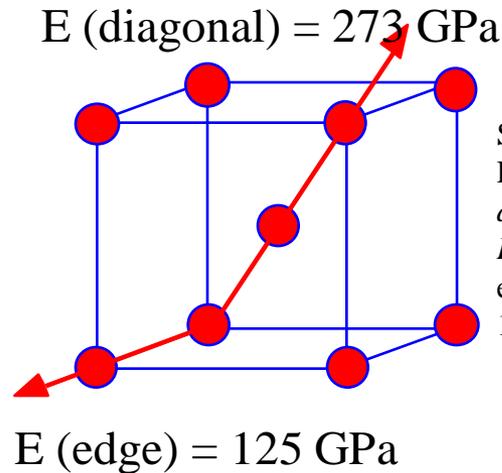
Isotropic

- Nb-Hf-W plate with an electron beam weld.
- Each "grain" is a single crystal.
- If grains are randomly oriented, overall component properties are not directional.
- Grain sizes typ. range from 1 nm to 2 cm (i.e., from a few to millions of atomic layers).

Single vs Polycrystals

- Single Crystals

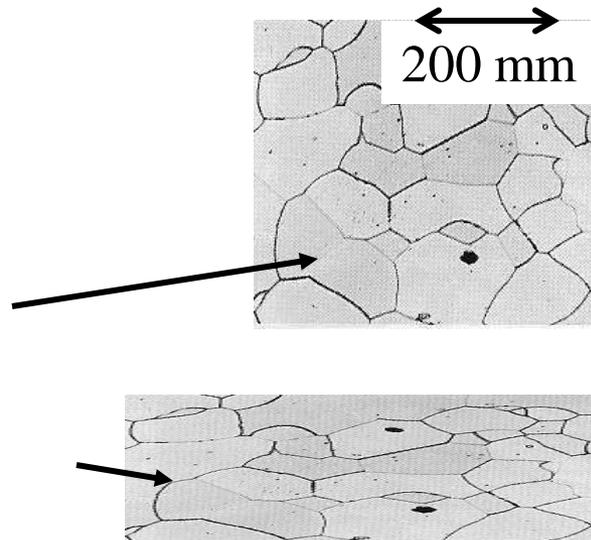
- Properties vary with direction: **anisotropic**.
- Example: the modulus of elasticity (E) in BCC iron:



Source of data is R.W. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 3rd ed., John Wiley and Sons, 1989.

- Polycrystals

- Properties may/may not vary with direction.
- If grains are randomly oriented: **isotropic**. ($E_{\text{poly iron}} = 210 \text{ GPa}$)
- If grains are **textured**, anisotropic.



courtesy of L.C. Smith and C. Brady, the National Bureau of Standards, Washington, DC [now the National Institute of Standards and Technology, Gaithersburg, MD].

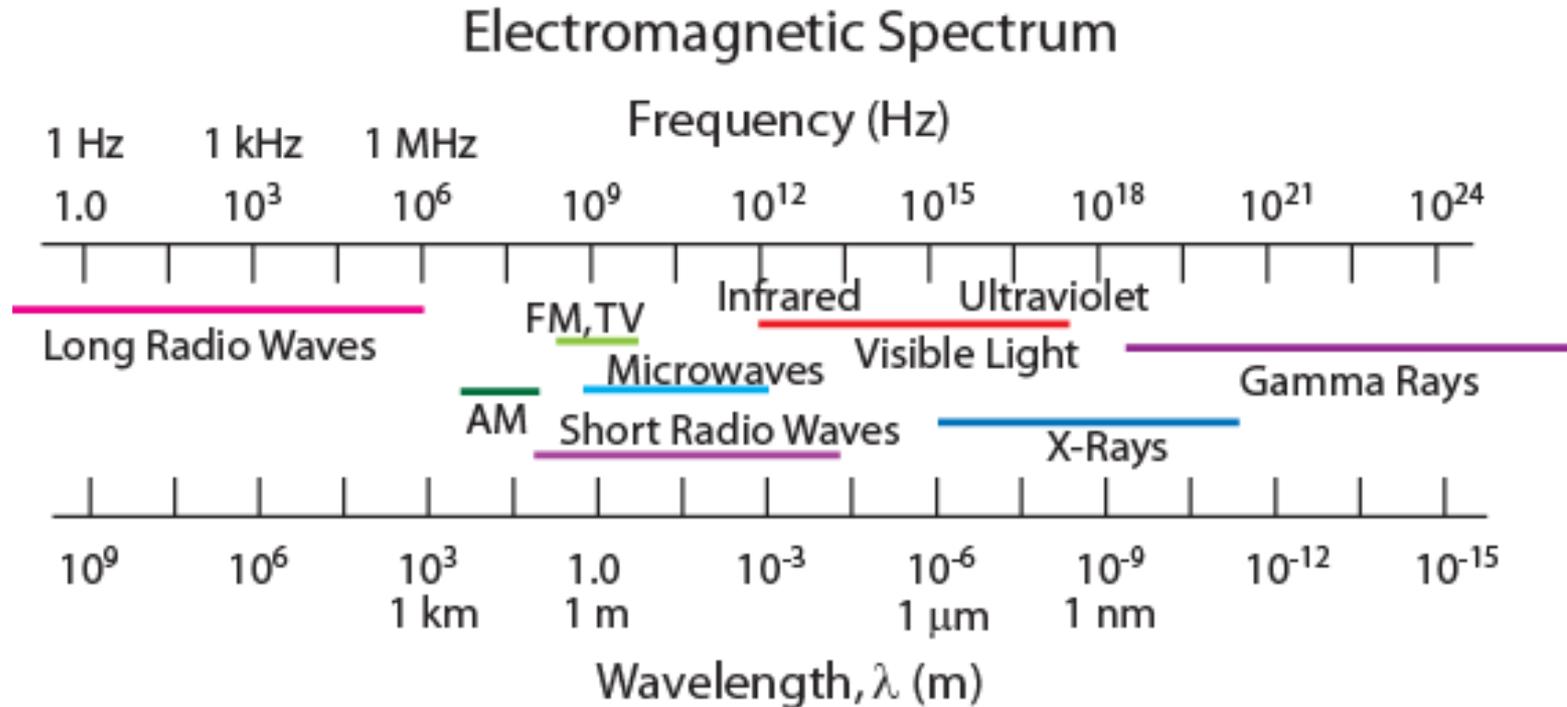
Effects of Anisotropy:

Table 3.3 Modulus of Elasticity Values for Several Metals at Various Crystallographic Orientations

<i>Metal</i>	<i>Modulus of Elasticity (GPa)</i>		
	<i>[100]</i>	<i>[110]</i>	<i>[111]</i>
Aluminum	63.7	72.6	76.1
Copper	66.7	130.3	191.1
Iron	125.0	210.5	272.7
Tungsten	384.6	384.6	384.6

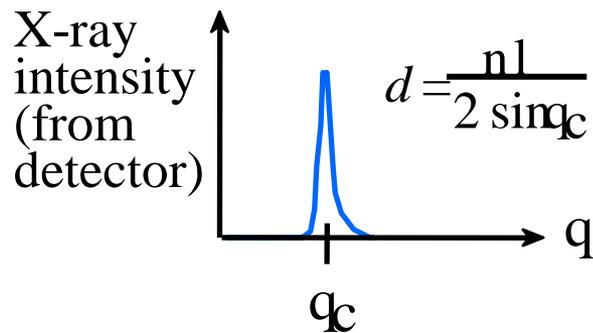
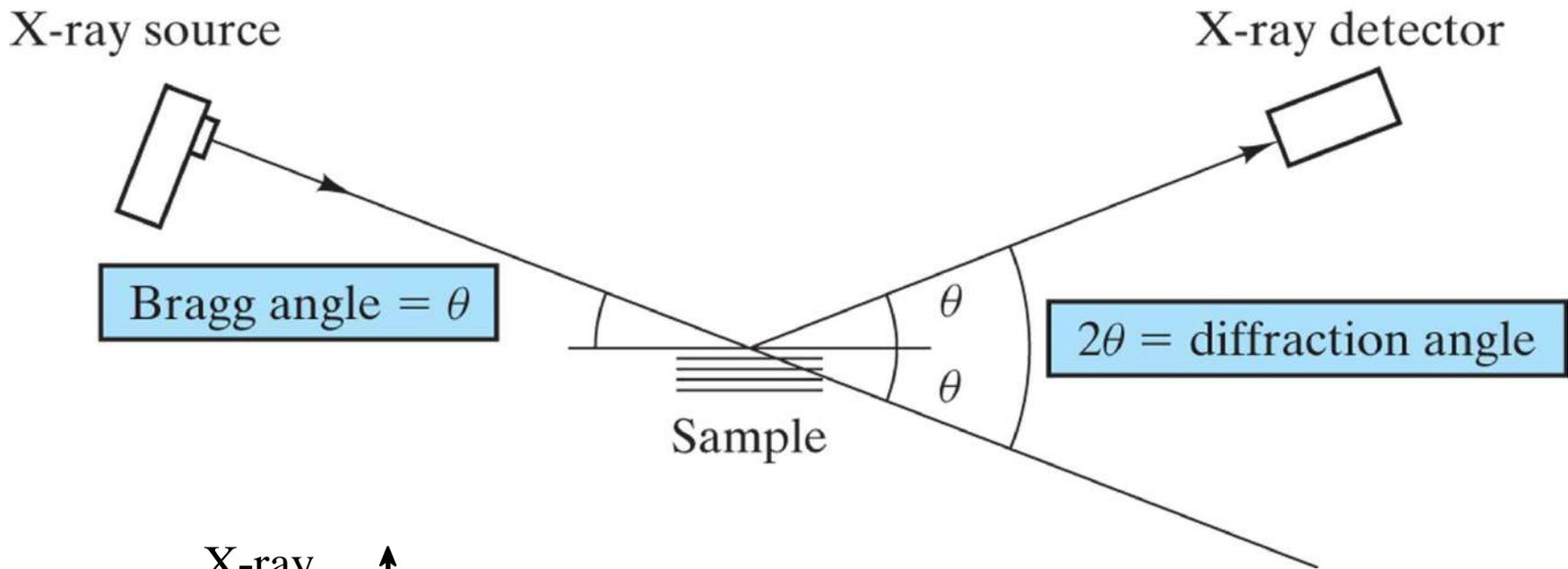
Source: R. W. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 3rd edition. Copyright © 1989 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.

X-Ray Diffraction



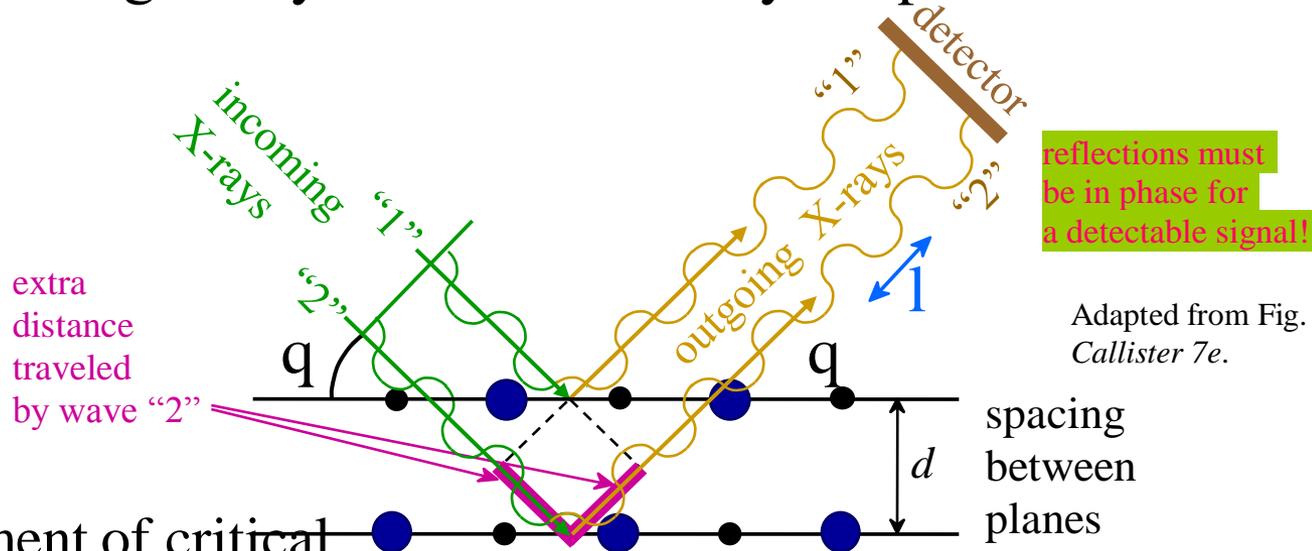
- Diffraction gratings must have spacings comparable to the wavelength of diffracted radiation.
- Can't resolve spacings $< \lambda$
- Spacing is the distance between parallel planes of atoms.

Relationship of the Bragg angle (θ) and the experimentally measured diffraction angle (2θ).



X-Rays to Determine Crystal Structure

- Incoming X-rays diffract from crystal planes.



Adapted from Fig. 3.19, Callister 7e.

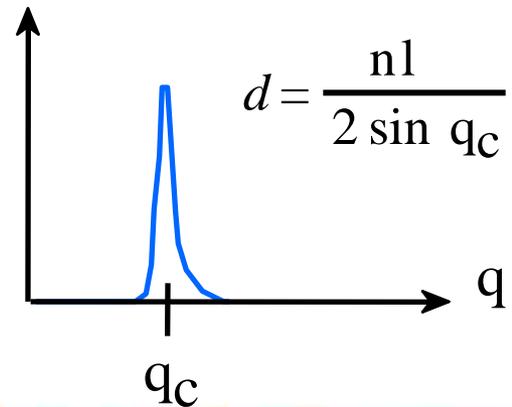
Measurement of critical angle, q_c , allows computation of planar spacing, d .

For Cubic Crystals:

$$d_{hkl} = \frac{a}{\sqrt{h^2 + k^2 + l^2}}$$

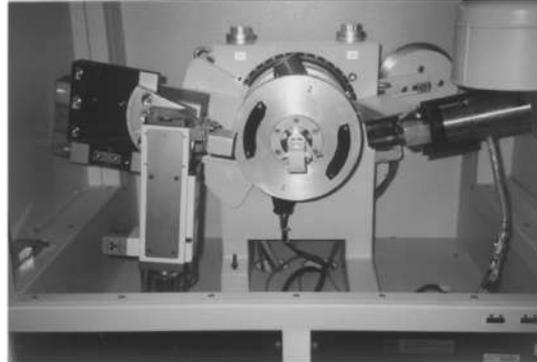
h, k, l are Miller Indices

X-ray intensity (from detector)

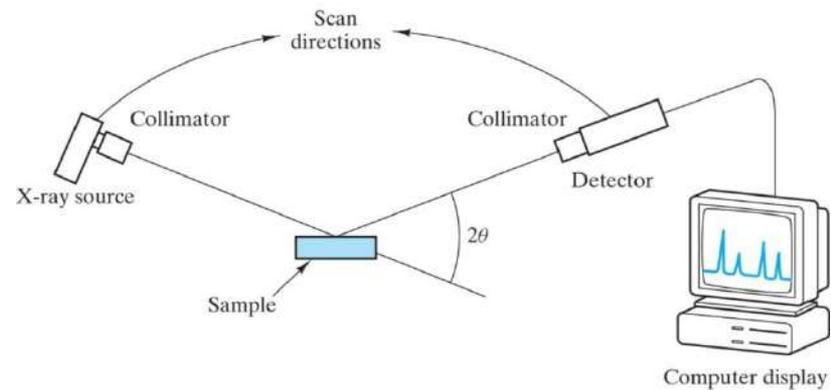


(a) An x-ray diffractometer

(b) A schematic of the experiment.

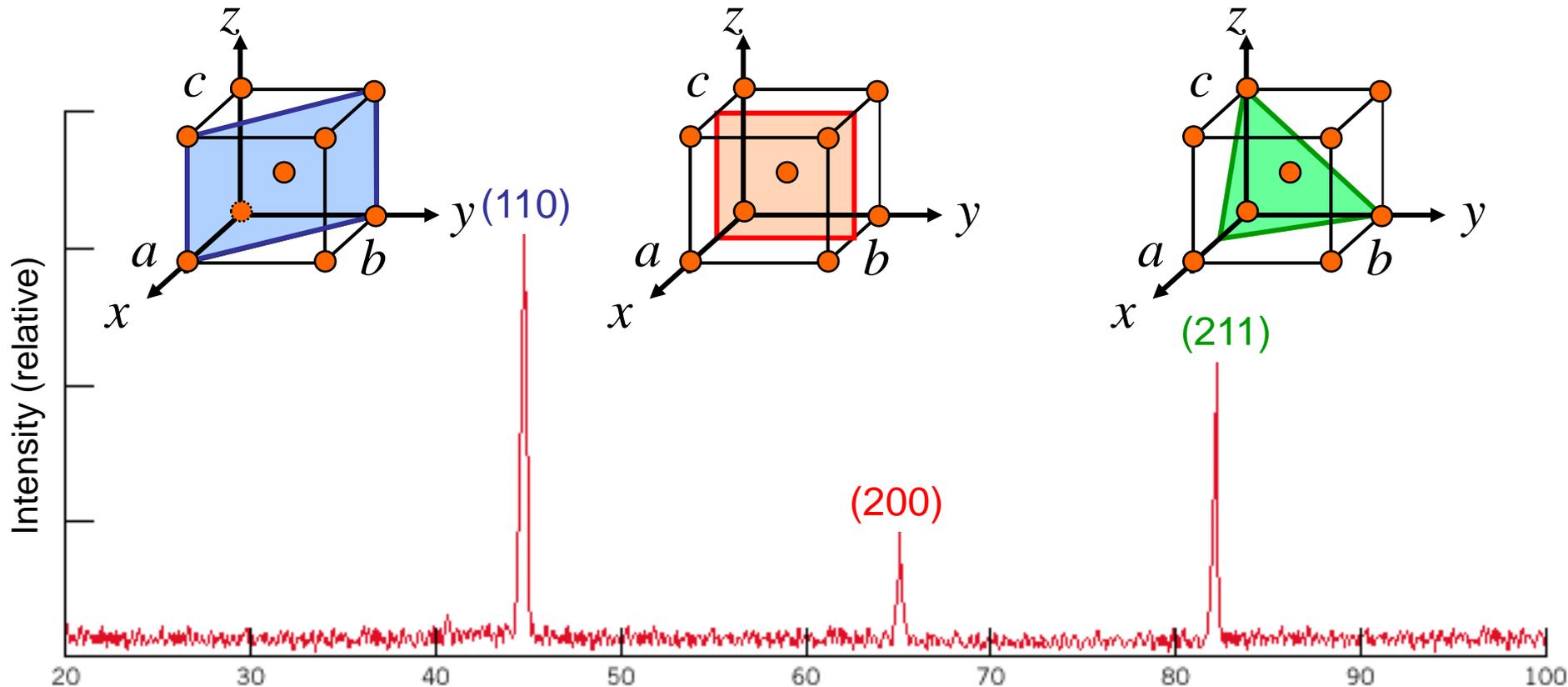


(a)



(b)

X-Ray Diffraction Pattern



Diffraction angle 2θ
Diffraction pattern for polycrystalline α -iron.

Diffraction pattern for polycrystalline α -iron (BCC)

Diffraction in Cubic Crystals:

TABLE 3.4

Reflection Rules of X-Ray Diffraction for the Common Metal Structures

Crystal structure	Diffraction does not occur when	Diffraction occurs when
Body-centered cubic (bcc)	$h + k + l = \text{odd number}$	$h + k + l = \text{even number}$
Face-centered cubic (fcc)	h, k, l mixed (i.e., both even and odd numbers)	h, k, l unmixed (i.e., are all even numbers or all are odd numbers)
Hexagonal close packed (hcp)	$(h + 2k) = 3n, l \text{ odd}$ (n is an integer)	All other cases

SUMMARY

- Atoms may assemble into **crystalline** or **amorphous** structures.
- Common metallic crystal structures are **FCC**, **BCC**, and **HCP**. **Coordination number** and **atomic packing factor** are the same for both FCC and HCP crystal structures.
- We can predict the **density** of a material, provided we know the **atomic weight**, **atomic radius**, and **crystal geometry** (e.g., FCC, BCC, HCP).
- **Crystallographic points**, **directions** and **planes** are specified in terms of indexing schemes.
Crystallographic directions and planes are related to **atomic linear densities** and **planar densities**.

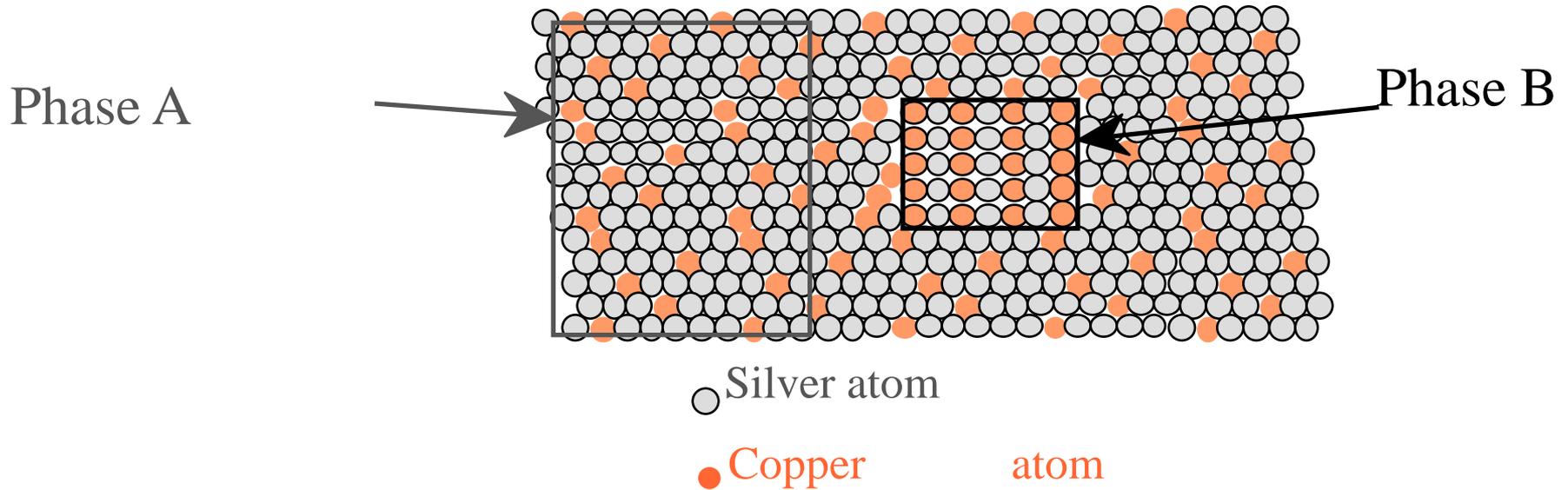
SUMMARY

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

UNIT II

- **Phase Diagrams:** Construction and interpretation of phase diagrams, Phase rule, Lever rule. Binary phase diagrams, Isomorphous, Eutectic and Eutectoid transformations with examples

PHASE DIAGRAMS



- When we combine two elements...
what equilibrium state do we get?
- In particular, if we specify...
 - a composition (e.g., wt% Cu - wt% Ag), and
 - a temperature (T)

THE SOLUBILITY LIMIT

- **Solubility Limit:**
Max concentration for which only a solution occurs.
(No precipitate)
- Ex: Phase Diagram: Water-Sugar System

Question: What is the solubility limit at 20C?

Answer: 65wt% sugar.

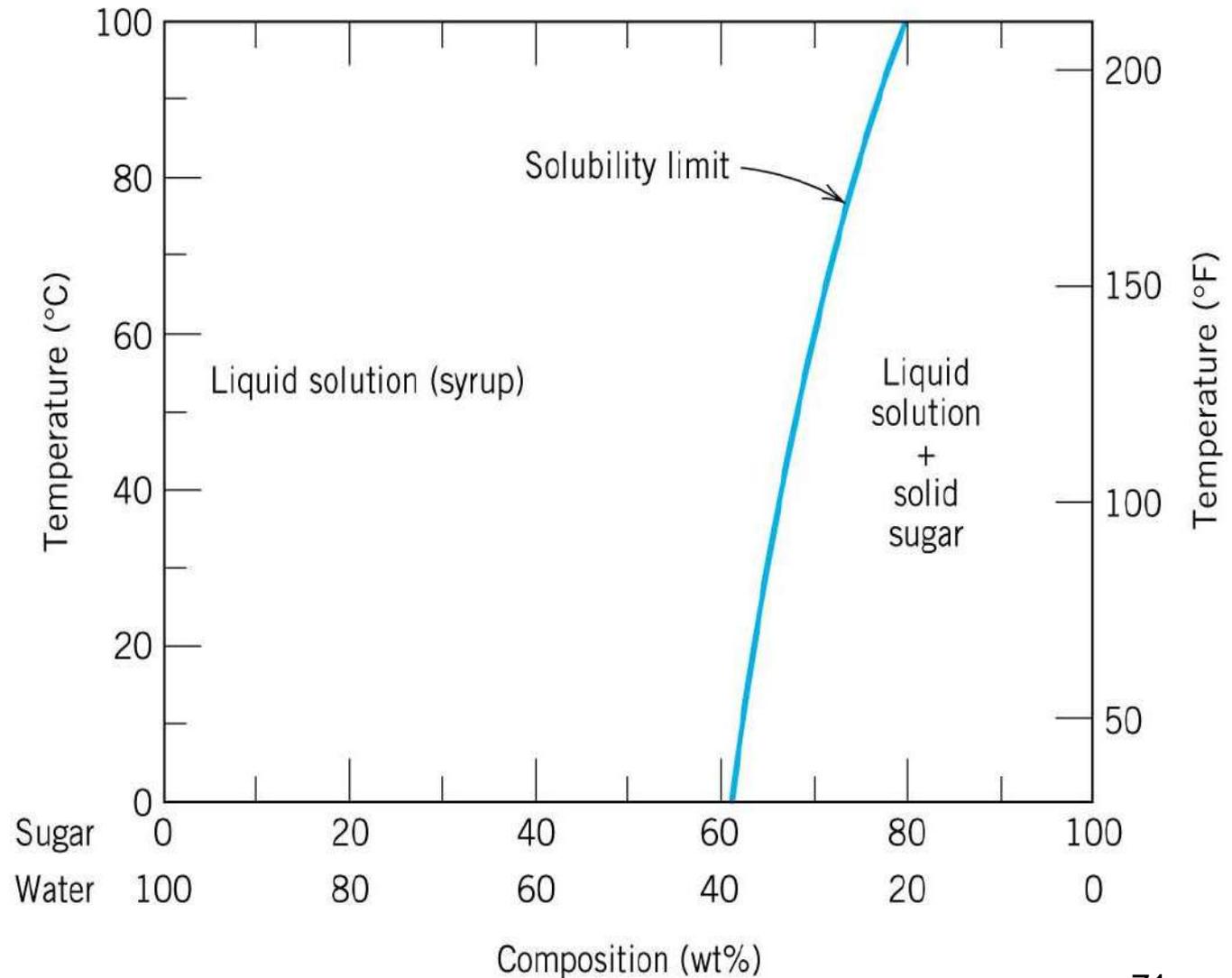
If Comp < 65wt% sugar: syrup

If Comp > 65wt% sugar: syrup + sugar coexist

- Solubility limit increases with T:
e.g., if T = 100C, solubility limit = 80wt% sugar.

Solubility Limit

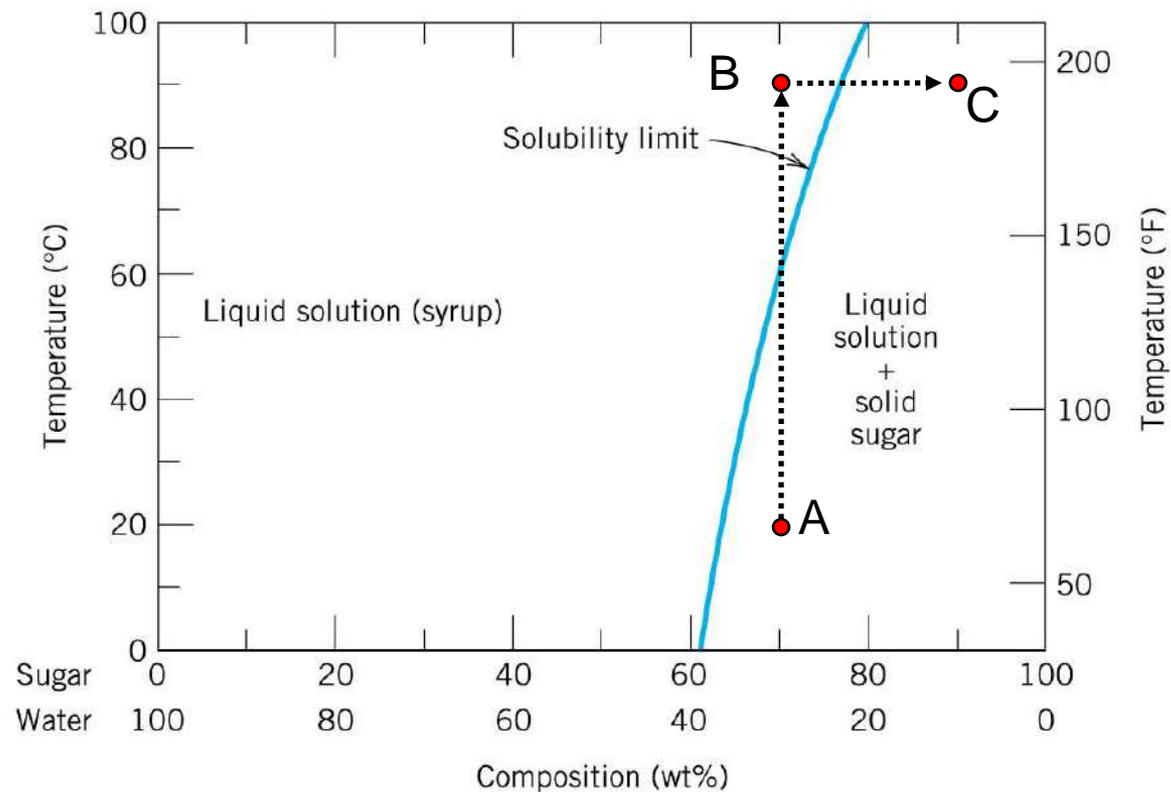
The solubility of sugar in a sugar water syrup



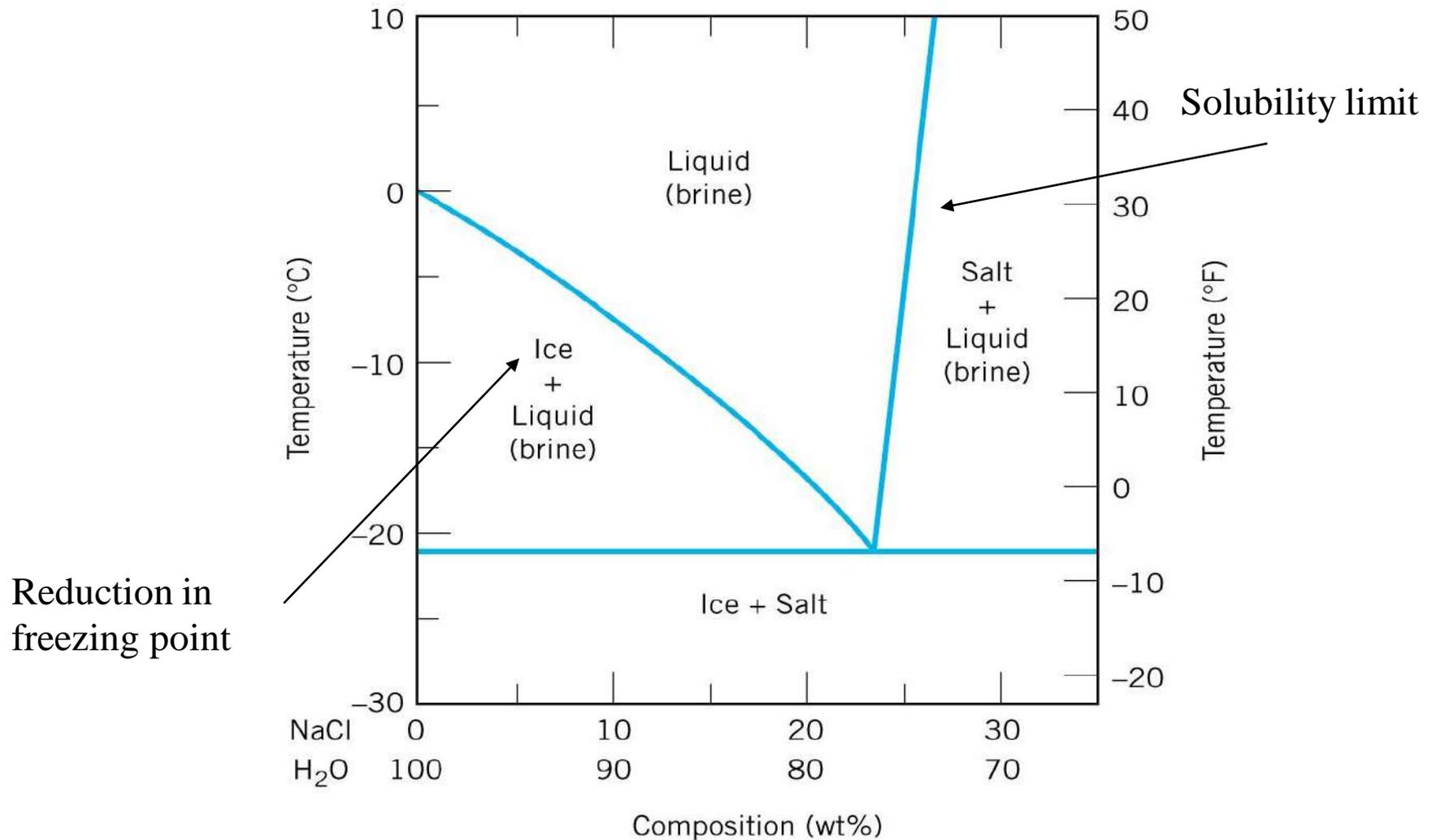
EFFECT OF T & COMPOSITION (C_0)

- Each point on this phase diagram represents equilibrium
- Changing T can change # of phases: path **A** to **B**
- Changing C_0 can change # of phases: path **B** to **C**

The solubility of sugar ($C_{12}H_{22}O_{11}$) in a sugar-water syrup.



WATER-SALT PHASE DIAGRAM



COMPONENTS AND PHASES

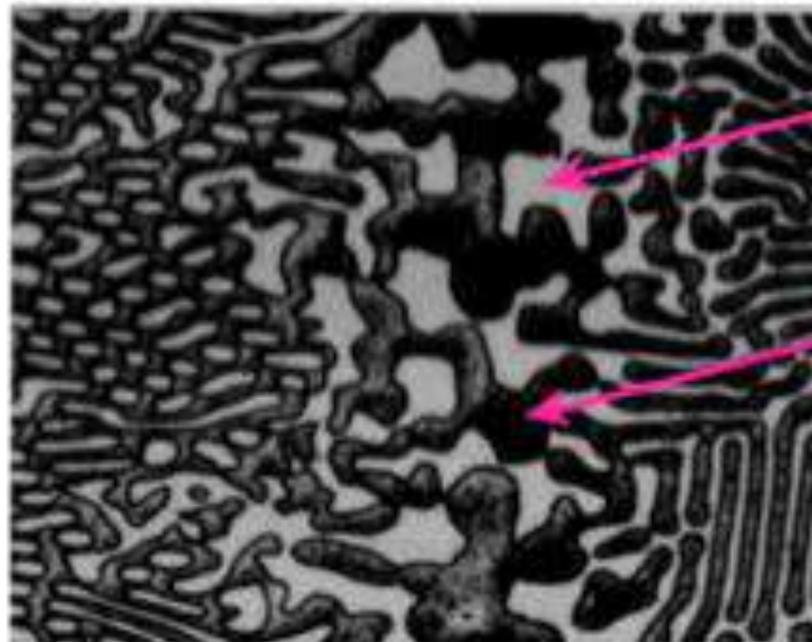
- **Components:**

The elements or compounds which are mixed initially
(e.g., Al and Cu, or water and sugar)

- **Phases:**

The physically and chemically distinct material regions
that result (e.g., α and β , or syrup and sugar)

Aluminum-
Copper
Alloy



β (lighter
phase)

α (darker
phase)

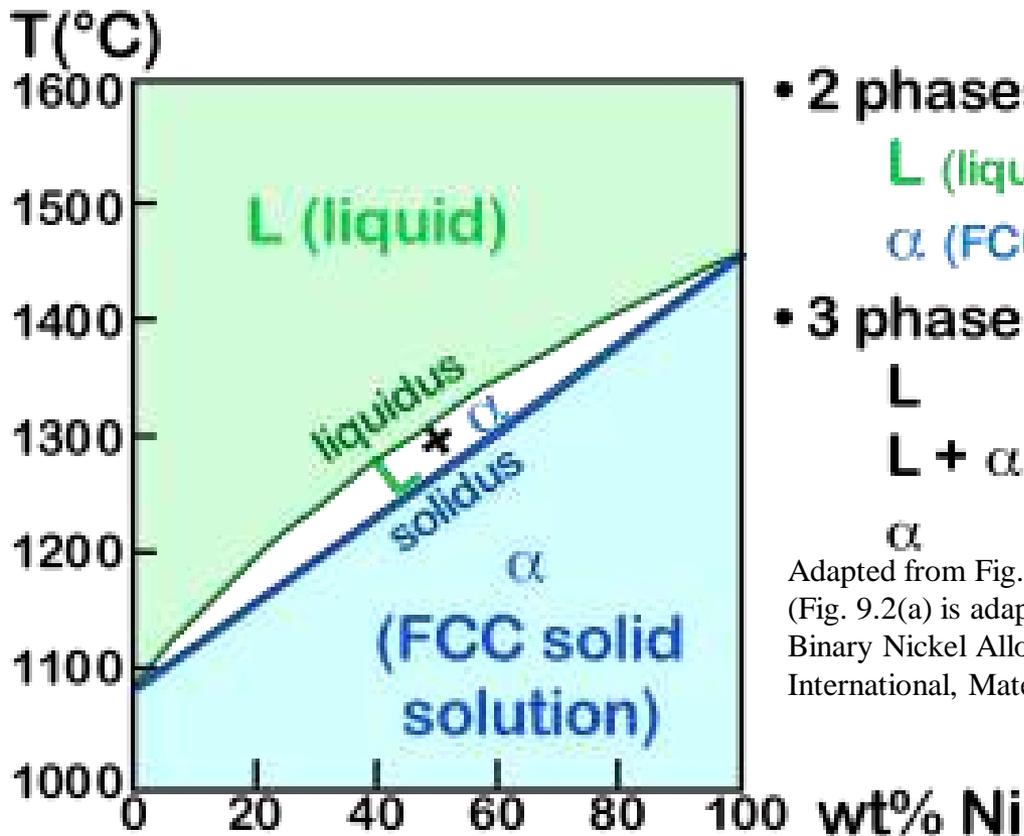
Adapted from Fig.
9.0,
Callister 3e.

PHASE DIAGRAMS

- Tell us about phases as function of T , C_o , P
- For this course:
 - binary systems: just 2 components.
 - independent variables: T and C_o ($P = 1$ atm is always used)

- **Phase Diagram**
for Cu-Ni system

- Isomorphous system: i.e., complete solubility of one component in another



- **2 phases:**

- L (liquid)

- α (FCC solid solution)

- **3 phase fields:**

- L

- L + α

- α

Adapted from Fig. 9.2(a), Callister 6e.
(Fig. 9.2(a) is adapted from Phase Diagrams of Binary Nickel Alloys, P. Nash (Ed.), ASM International, Materials Park, OH (1991).

Note change in
melting point

PHASE DIAGRAMS: # and types of phases

- Rule 1: If we know T and C_o , then we know:
--the # and types of phases present.

- Examples:

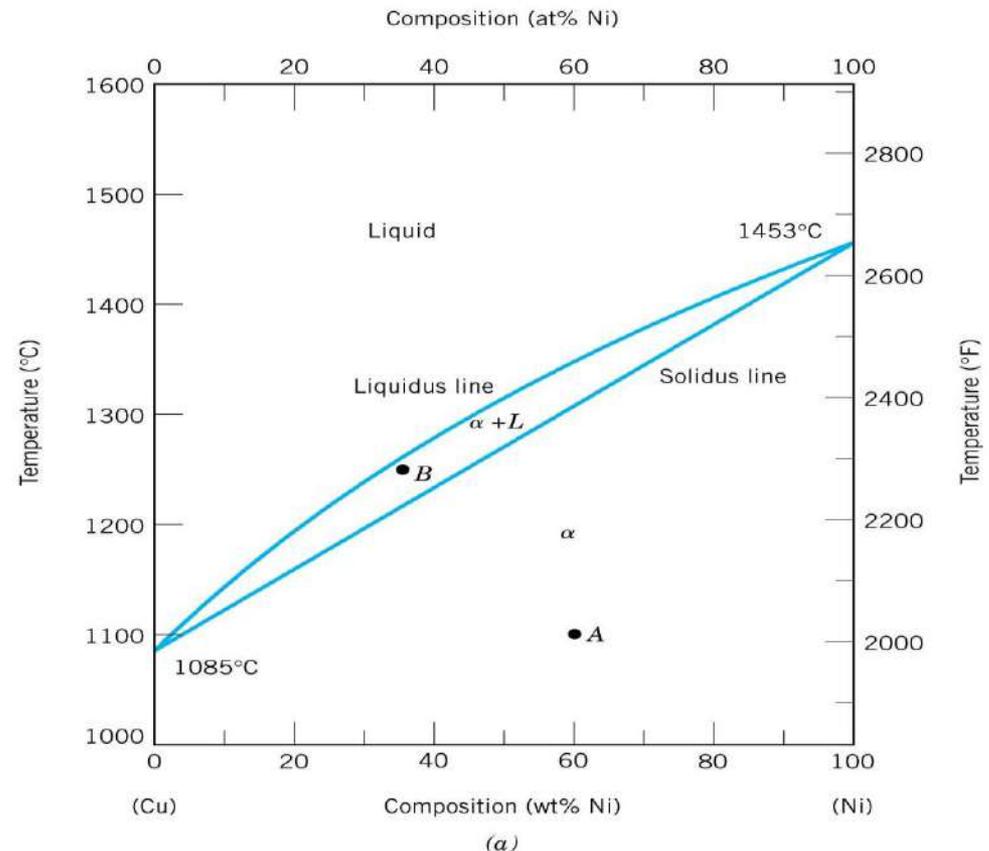
A:

1 phase (α)

B:

2 phases ($L + \alpha$)

Cu-Ni
phase
diagram

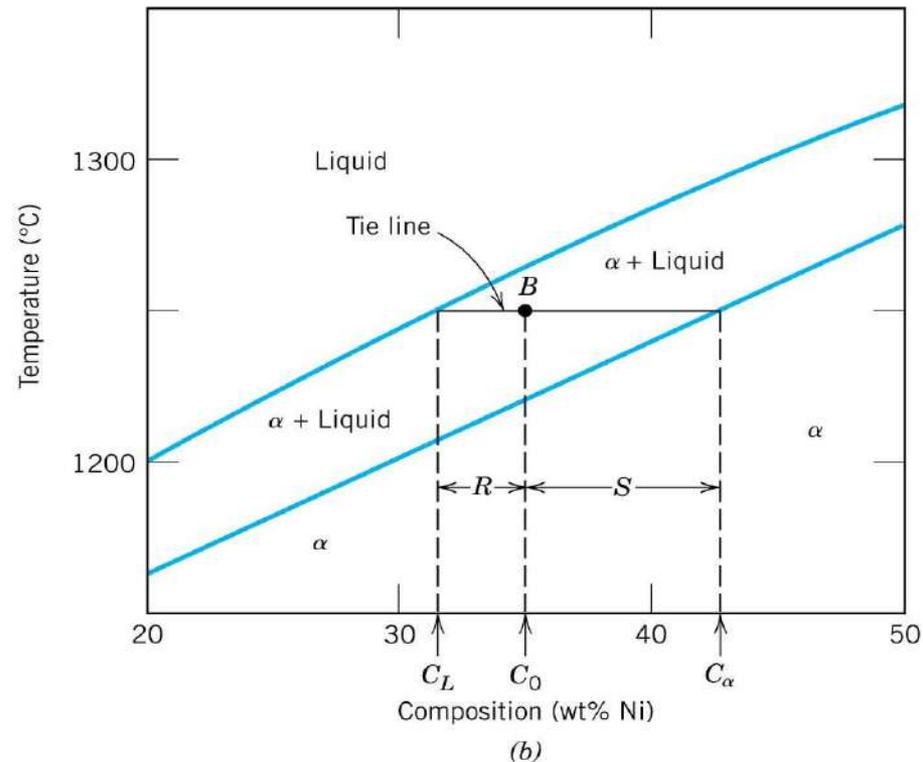


PHASE DIAGRAMS: weight fractions of phases

- Rule 3: If we know T and C_0 , then we know:
 - the amount of each phase (given in wt%).

- $C_0 = 35$ wt% Ni
- At 1300 C:
 - Only liquid (L)
 - $W_L = 100$ wt%, $W_\alpha = 0$ wt%
- At 1150 C:
 - Only solid (α)
 - $W_L = 0$ wt%, $W_\alpha = 100$ wt%
- At T_B :
 - Both α and L
 - $W_L = S/(R+S) = (43-35)/(43-32) = 73$ wt%
 - $W_\alpha = R/(R+S) = (35-32)/(43-32) = 27$ wt%

Cu-Ni
system



The lever rule

THE LEVER RULE: A PROOF

- Sum of weight fractions:
- Conservation of mass (Ni):
- Combine above equations:

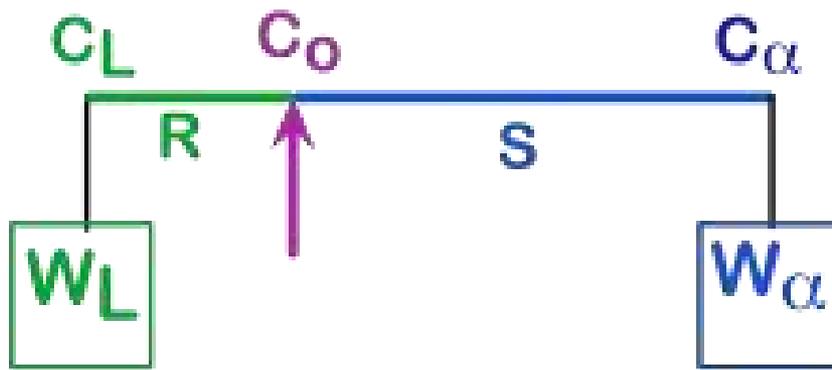
$$W_L + W_\alpha = 1$$

$$C_O = W_L C_L + W_\alpha C_\alpha$$

$$W_L = \frac{C_\alpha - C_O}{C_\alpha - C_L} = \frac{S}{R + S}$$

$$W_\alpha = \frac{C_O - C_L}{C_\alpha - C_L} = \frac{R}{R + S}$$

- A geometric interpretation:



moment equilibrium:

$$W_L R = W_\alpha S$$

$$1 - W_\alpha$$

solving gives Lever Rule

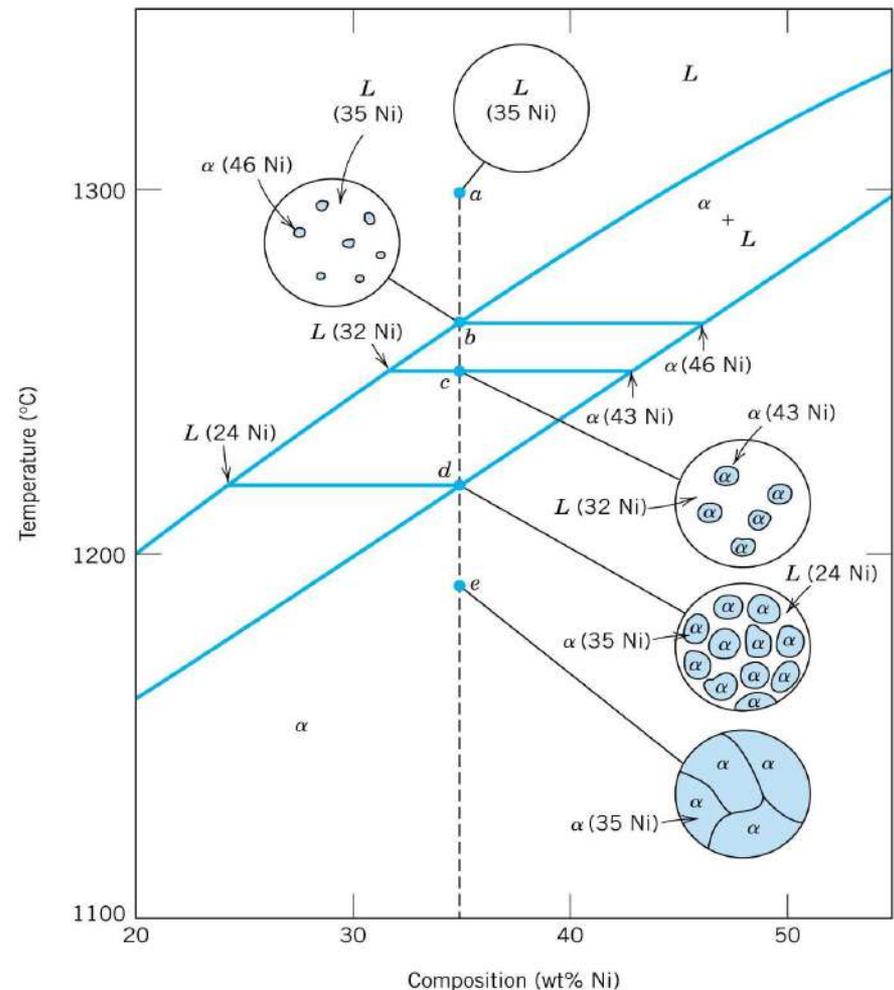
COOLING A Cu-Ni BINARY

- System is:
- **binary** i.e., 2 components: Cu and Ni.
- **isomorphous** i.e., complete solubility of one component in another; α phase field extends from 0 to 100wt% Ni.

Consider

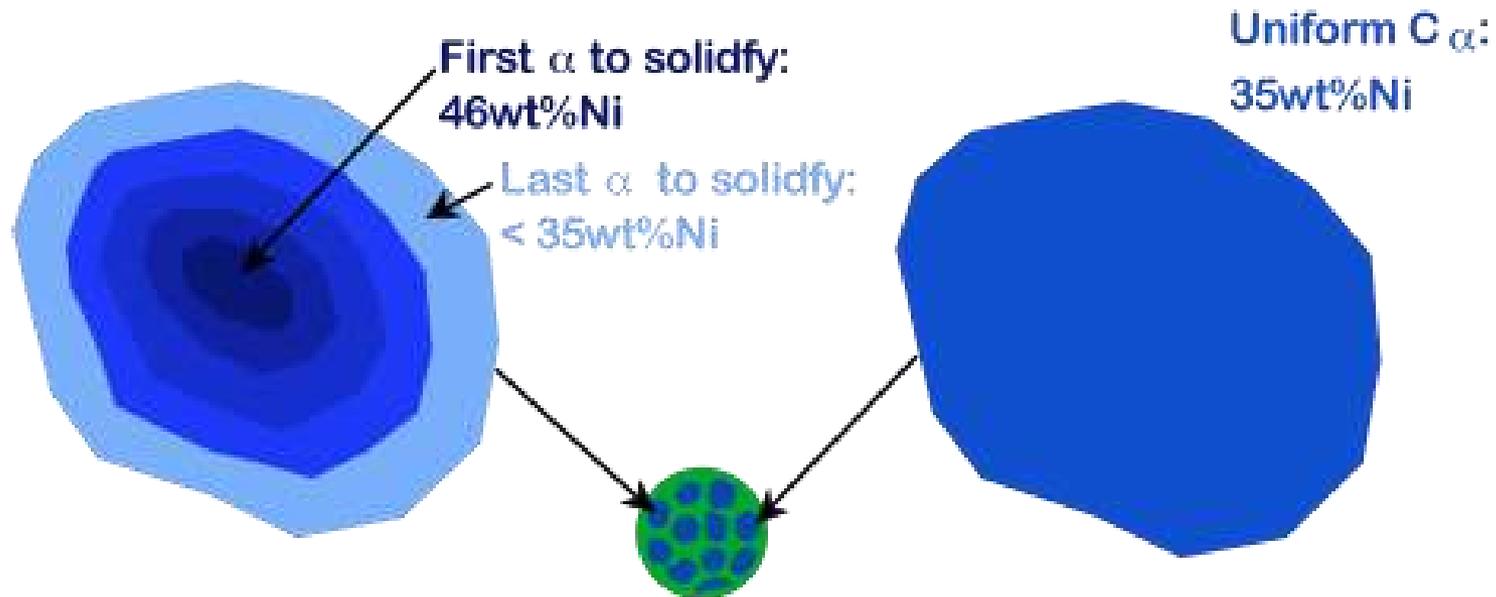
- $C_0 = 35\text{wt}\% \text{Ni}$.
- Equilibrium cooling

Schematic Representation of the development of microstructure during the equilibrium solidification of a 35 wt% Ni – 65 wt % Cu alloy



NON-EQUILIBRIUM PHASES

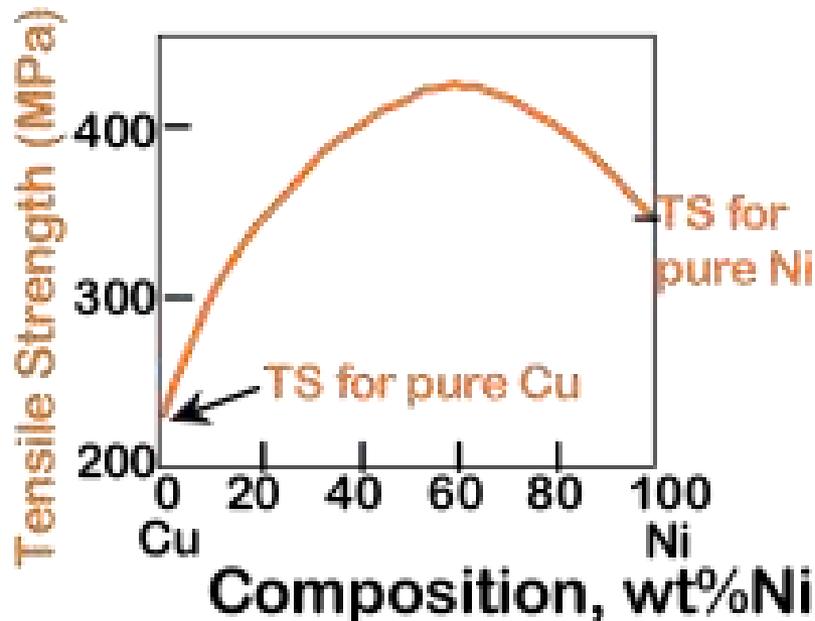
- C_α changes as we solidify.
- Cu-Ni case: First α to solidify has $C_\alpha = 46\text{wt}\% \text{Ni}$.
Last α to solidify has $C_\alpha = 35\text{wt}\% \text{Ni}$.
- Fast rate of cooling:
Cored structure
- Slow rate of cooling:
Equilibrium structure



MECHANICAL PROPERTIES: Cu-Ni System

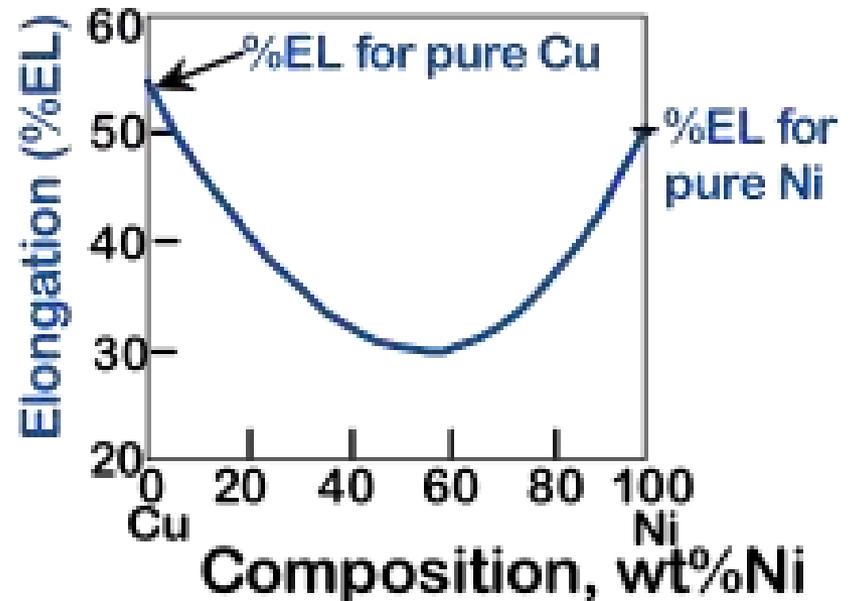
- Effect of solid solution strengthening on:

--Tensile strength (TS)



Adapted from Fig. 9.5(a), Callister 6e.

--Ductility (%EL,%AR)



Adapted from Fig. 9.5(b), Callister 6e.

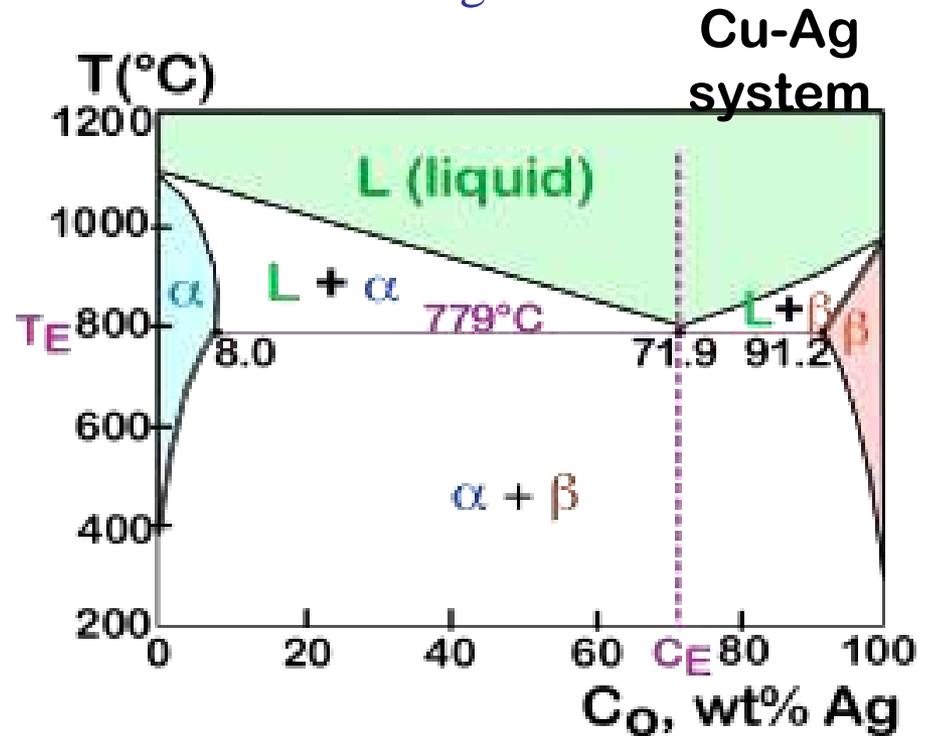
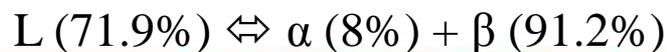
BINARY-EUTECTIC SYSTEMS

2 components

has a special composition with a min. melting T.

Ex.: Cu-Ag system

- 3 single phase regions (L, α , β)
- Limited solubility:
 - α : FCC, mostly Cu
 - β : FCC, mostly Ag
- T_E : No liquid below T_E
- C_E : Min. melting T composition
- 3 two phase regions
- Cooling along dotted line:



Adapted from Fig. 9.6, Callister 6e. (Fig. 9.6 adapted from Binary Phase Diagrams, 2nd ed., Vol. 1, T.B. Massalski (Editor-in-Chief), ASM International, Materials Park, OH, 1990.)

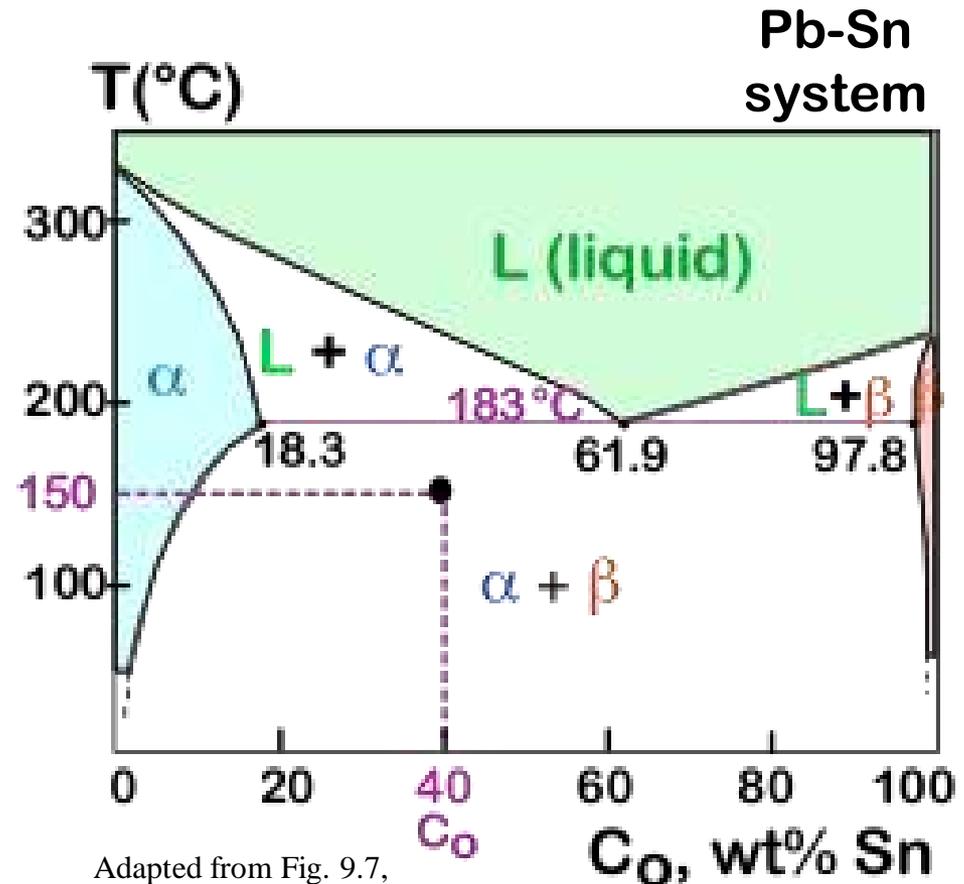
EX: Pb-Sn EUTECTIC SYSTEM (1)

- For a 40wt%Sn-60wt%Pb alloy at 150C, find...

--the phases present

--the compositions of the phases

--the relative amounts of each phase

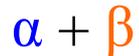


Adapted from Fig. 9.7, Callister 6e. (Fig. 9.7 adapted from Binary Phase Diagrams, 2nd ed., Vol. 3, T.B. Massalski (Editor-in-Chief), ASM International, Materials Park, OH, 1990.)

EX: Pb-Sn EUTECTIC SYSTEM (2)

- For a 40wt%Sn-60wt%Pb alloy at 150C, find...

--the phases present:



--the compositions of the phases:

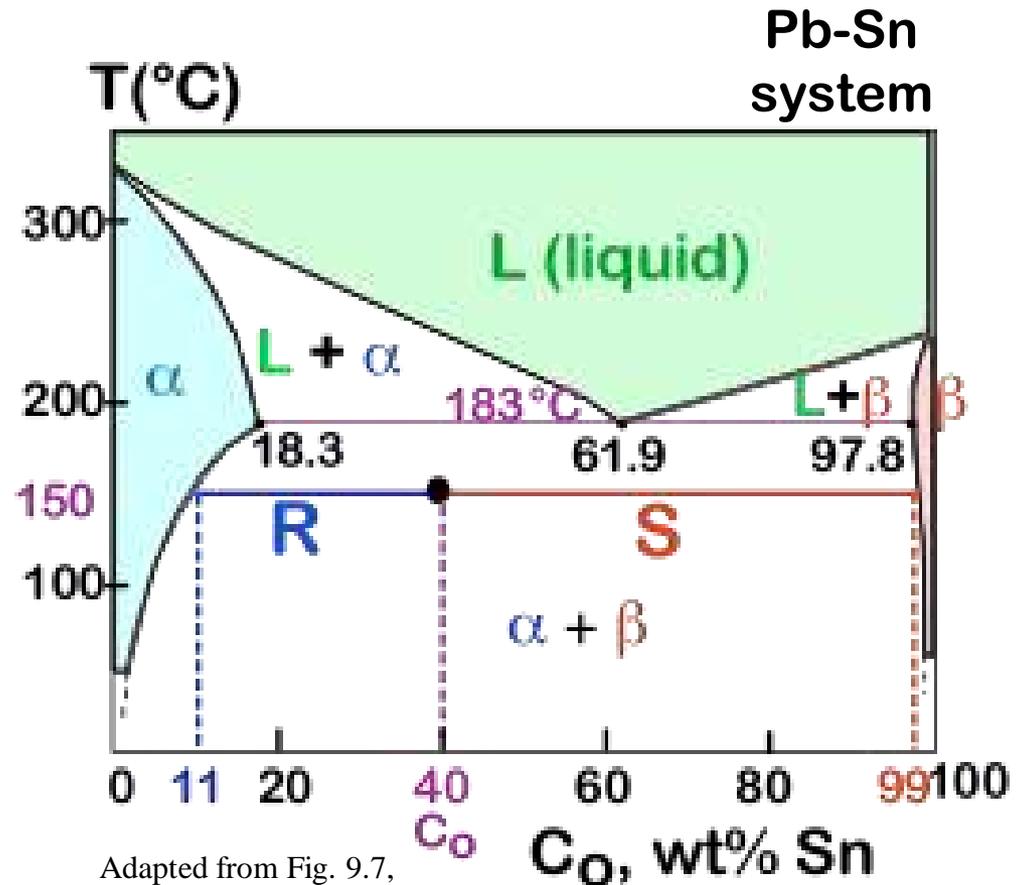
$$C_{\alpha} = 11\text{wt\% Sn}$$

$$C_{\beta} = 99\text{wt\% Sn}$$

--the relative amounts of each phase:
(lever rule)

$$W_{\alpha} = \frac{59}{88} = 67\text{wt\%}$$

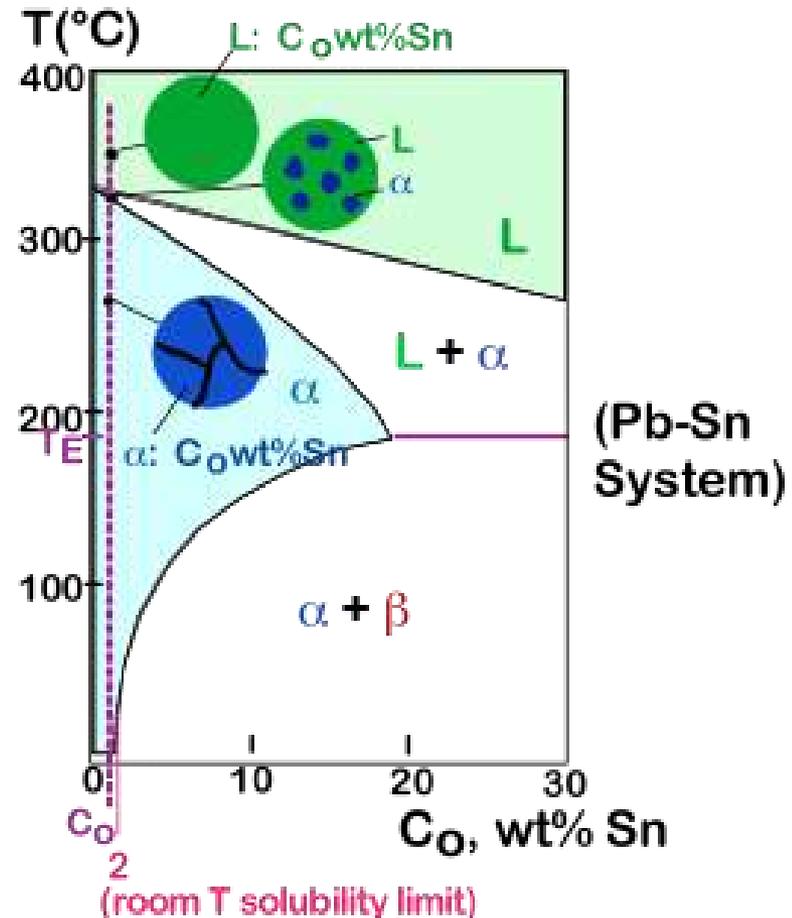
$$W_{\beta} = \frac{29}{88} = 33\text{wt\%}$$



Adapted from Fig. 9.7, Callister 6e. (Fig. 9.7 adapted from Binary Phase Diagrams, 2nd ed., Vol. 3, T.B. Massalski (Editor-in-Chief), ASM International, Materials Park, OH, 1990.)

MICROSTRUCTURES IN EUTECTIC SYSTEMS-I

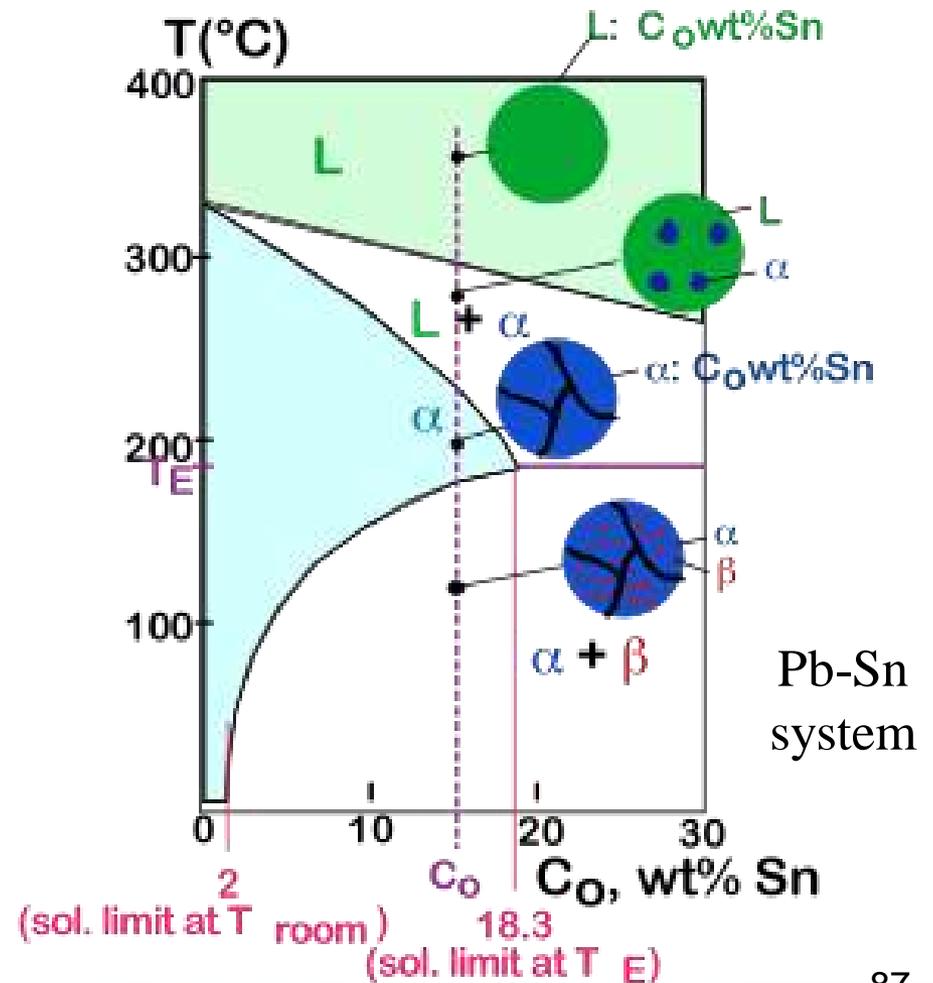
- $C_0 < 2\text{wt}\% \text{Sn}$
- Result:
--polycrystal of α grains.



Adapted from Fig. 9.9,
Callister 6e.

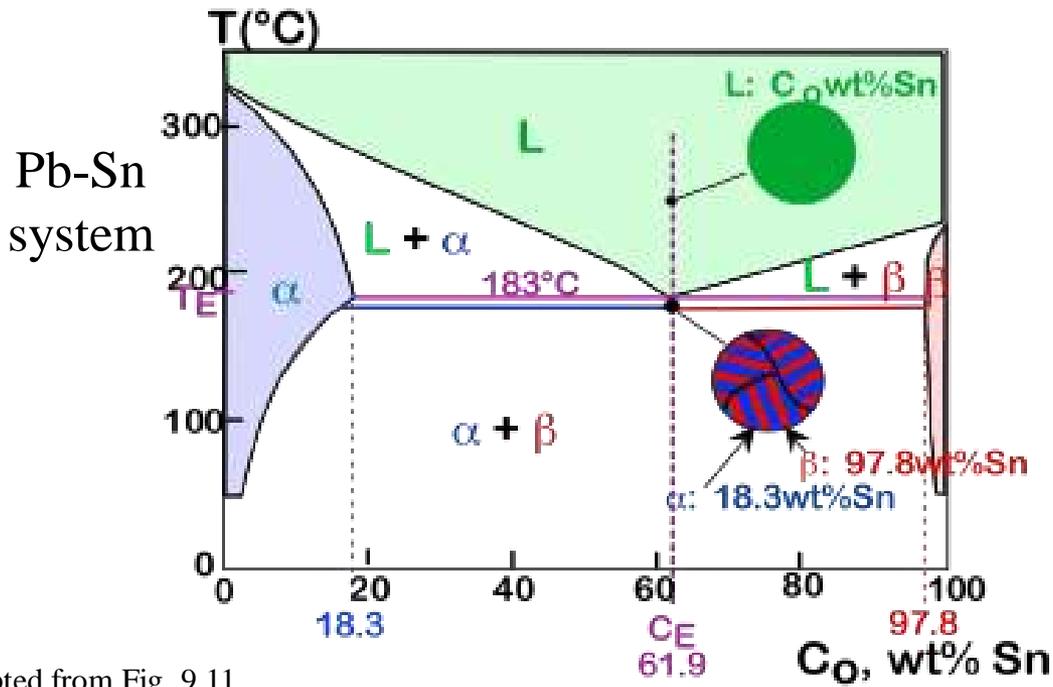
MICROSTRUCTURES IN EUTECTIC SYSTEMS-II

- $2\text{wt}\% \text{Sn} < C_0 < 18.3\text{wt}\% \text{Sn}$
- Result:
 - α polycrystal with fine β crystals.



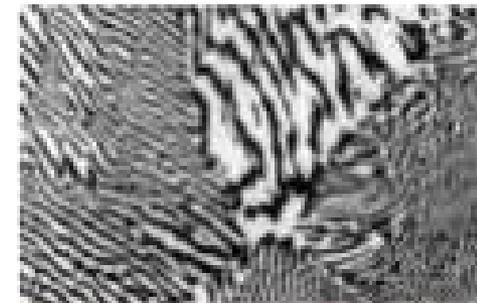
MICROSTRUCTURES IN EUTECTIC SYSTEMS-III

- $C_0 = C_E$ (Eutectic composition)
- Result: Eutectic microstructure
--alternating layers of α and β crystals.



Adapted from Fig. 9.11,
Callister 6e.

Micrograph of Pb-Sn
eutectic
microstructure



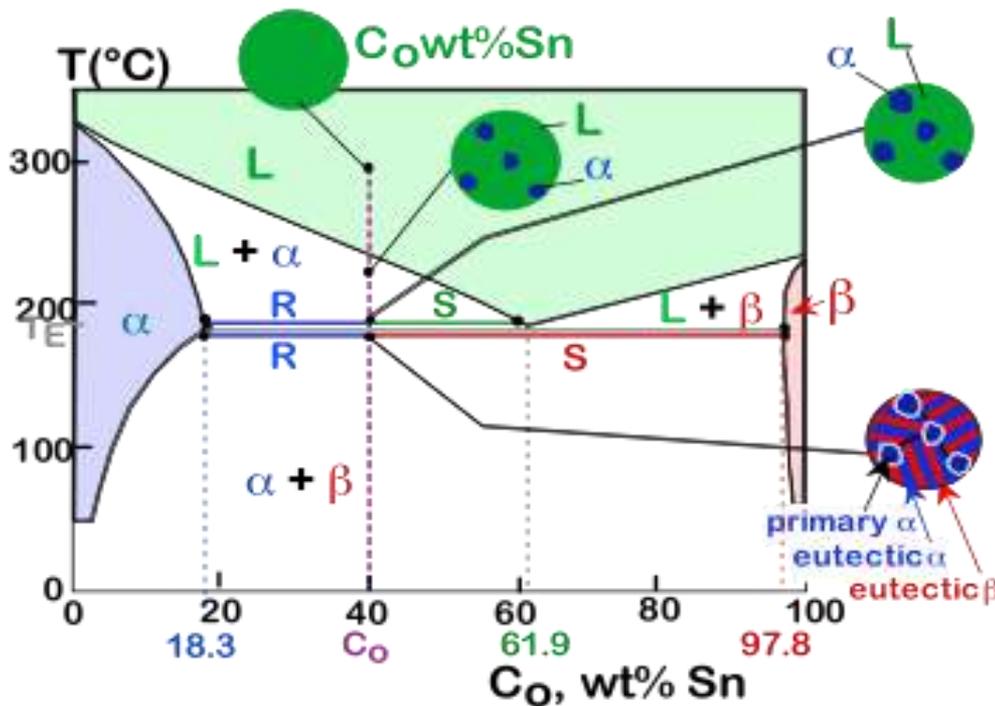
160 μm

Adapted from Fig. 9.12, Callister 6e. (Fig. 9.12 from Metals Handbook, Vol. 9, 9th ed., Metallography and Microstructures, American Society for Metals, Materials Park, OH, 1985.)

MICROSTRUCTURES IN EUTECTIC SYSTEMS-IV

- $18.3\text{wt}\% \text{Sn} < C_0 < 61.9\text{wt}\% \text{Sn}$
- Result: α crystals and a eutectic microstructure

Pb-Sn system



- Just above T_E :

$$C_\alpha = 18.3\text{wt}\% \text{Sn}$$

$$C_L = 61.9\text{wt}\% \text{Sn}$$

$$W_\alpha = \frac{S}{R+S} = 50\text{wt}\%$$

$$W_L = (1 - W_\alpha) = 50\text{wt}\%$$

- Just below T_E :

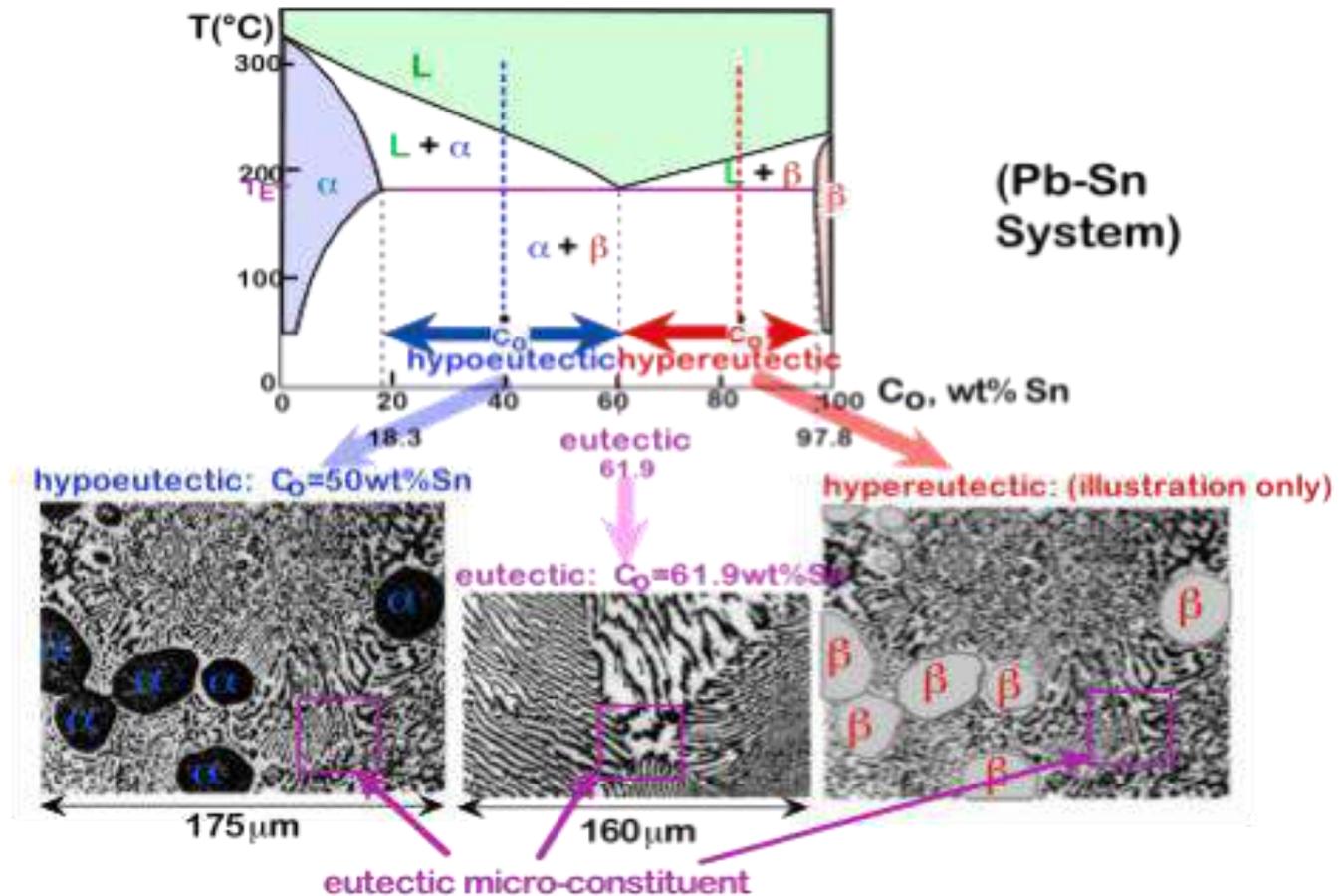
$$C_\alpha = 18.3\text{wt}\% \text{Sn}$$

$$C_\beta = 97.8\text{wt}\% \text{Sn}$$

$$W_\alpha = \frac{S}{R+S} = 73\text{wt}\%$$

$$W_\beta = 27\text{wt}\%$$

HYPOEUTECTIC & HYPEREUTECTIC



COMPLEX PHASE DIAGRAMS: Cu-Zn

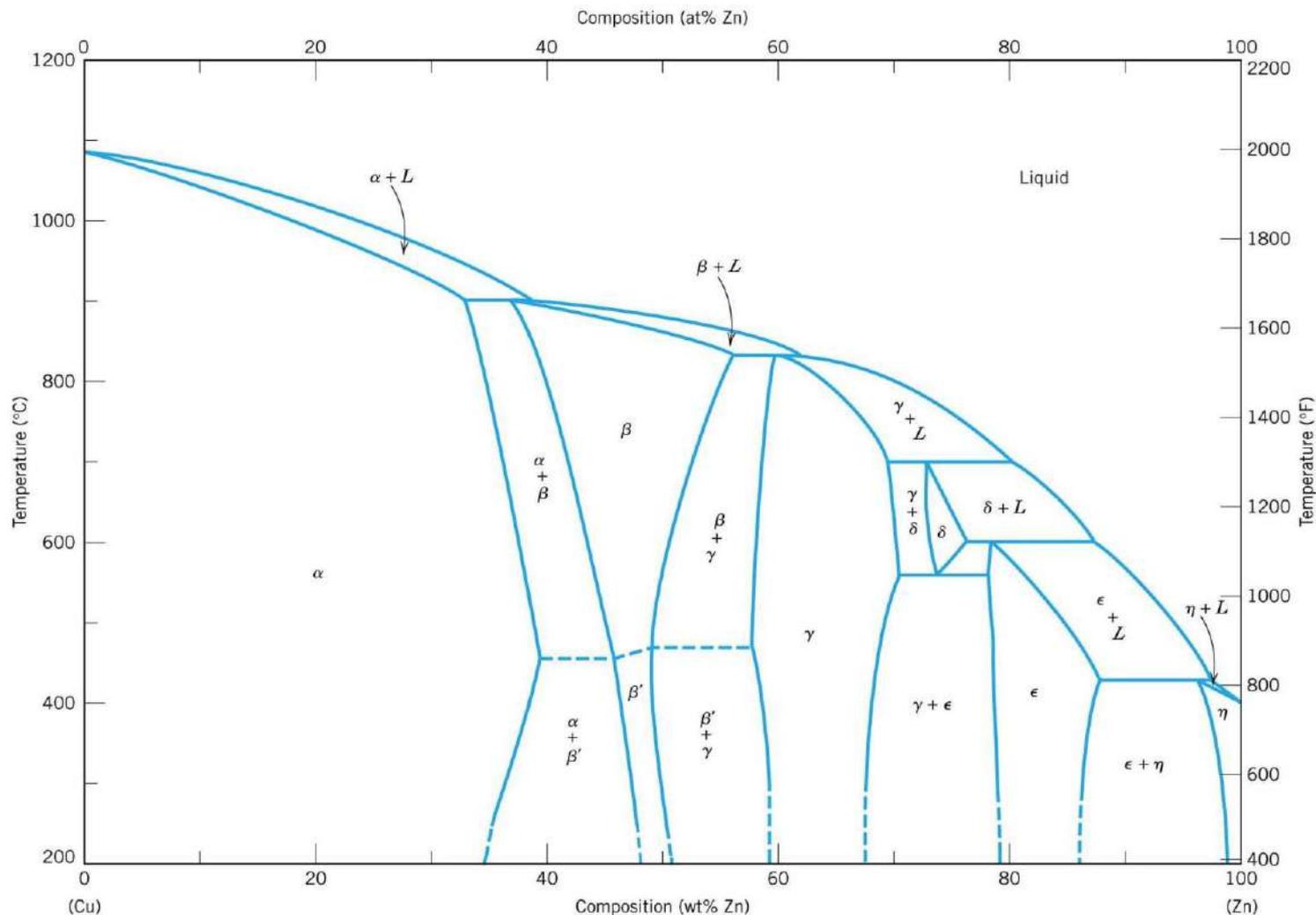


FIGURE 9.17 The copper–zinc phase diagram. [Adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 2, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

IRON-CARBON (Fe-C) PHASE DIAGRAM

- Pure iron: 3 solid phases
 - BCC ferrite (α)
 - FCC Austenite (γ)
 - BCC δ
- Beyond 6.7% C
 → cementite (Fe_3C)
- Eutectic: 4.3% C
 - $L \rightleftharpoons \gamma + \text{Fe}_3\text{C}$
 - ($L \rightleftharpoons \text{solid} + \text{solid}$)
- Eutectoid: 0.76% C
 - $\gamma \rightleftharpoons \alpha + \text{Fe}_3\text{C}$
 - ($\text{solid} \rightleftharpoons \text{solid} + \text{solid}$)

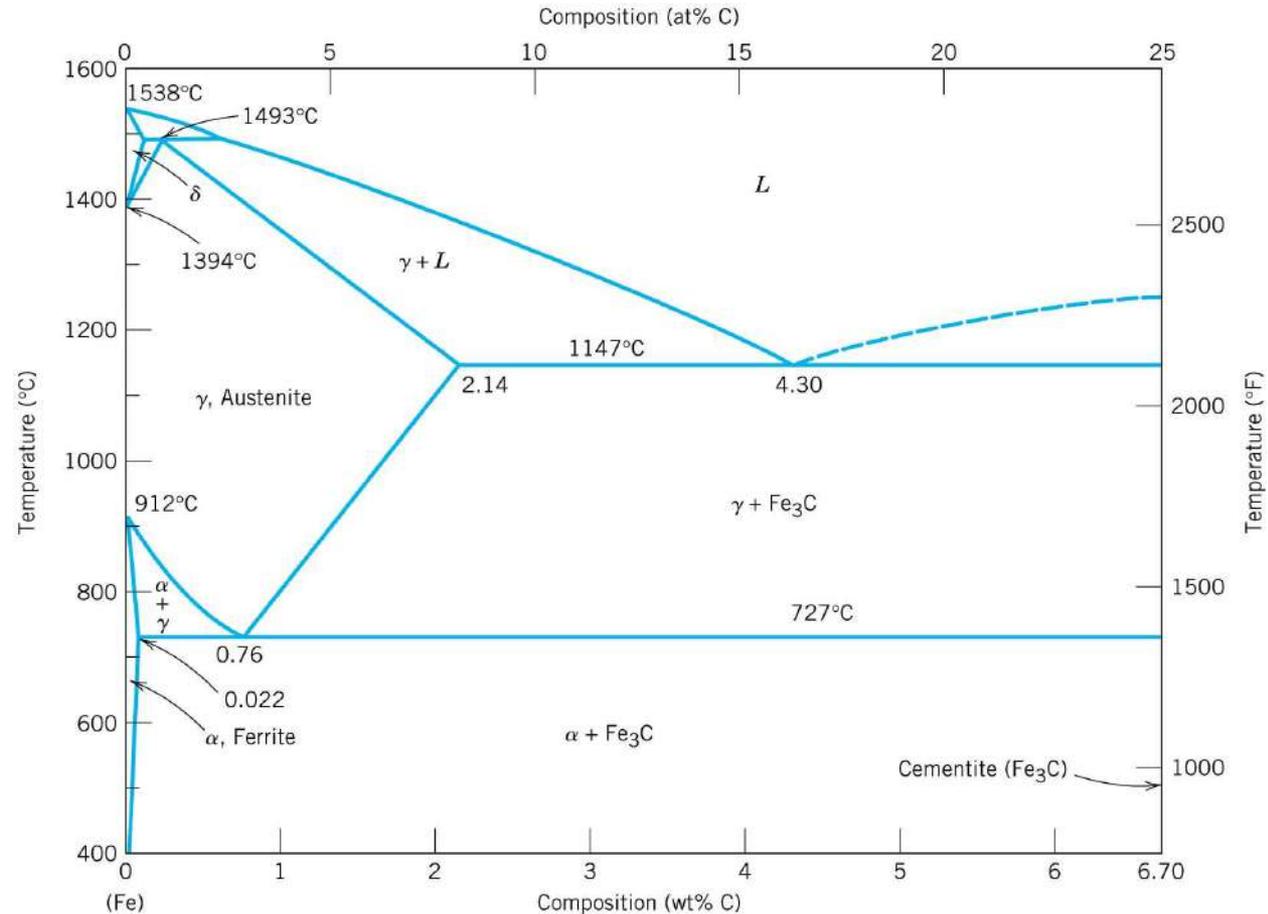


FIGURE 9.21 The iron-iron carbide phase diagram. [Adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

Fe-C PHASE DIAGRAM: EUTECTOID POINT

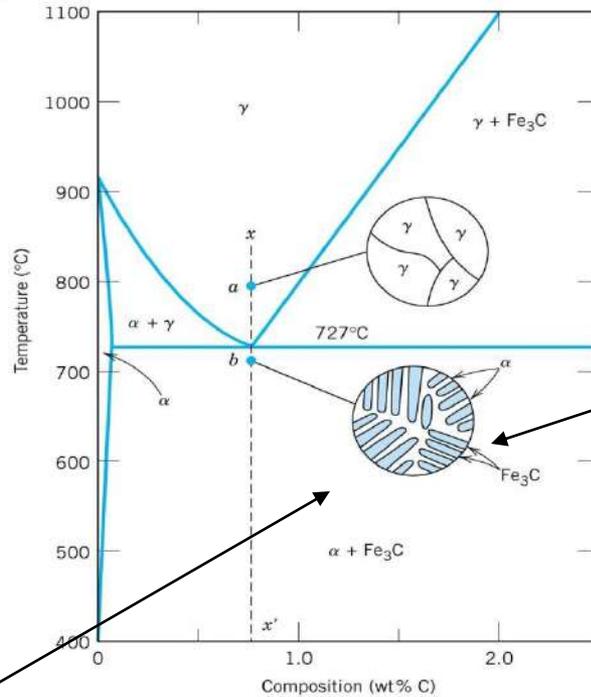


FIGURE 9.23 Schematic representations of the microstructures for an iron-carbon alloy of eutectoid composition (0.76 wt% C) above and below the eutectoid temperature.

Pearlite microstructure:
Just below the eutectoid point

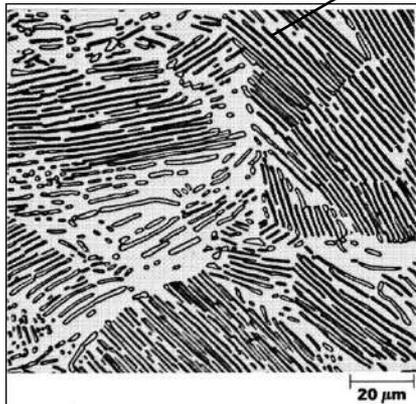


FIGURE 9.24 Photomicrograph of a eutectoid steel showing the pearlite microstructure consisting of alternating layers of α ferrite (the light phase) and Fe_3C (thin layers most of which appear dark). 500 \times . (Reproduced with permission from *Metals Handbook*, 9th edition, Vol. 9, *Metallography and Microstructures*, American Society for Metals, Materials Park, OH, 1985.)

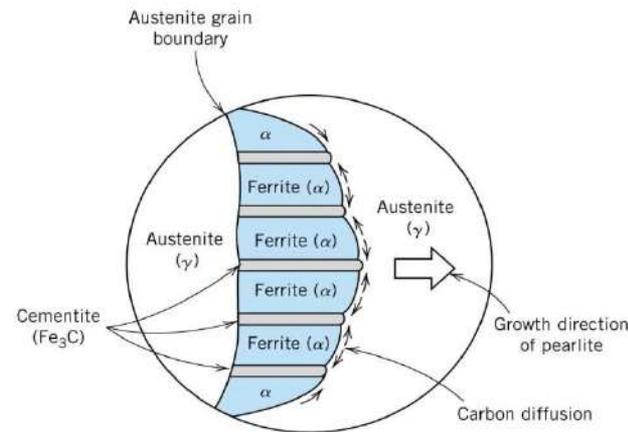


FIGURE 9.25 Schematic representation of the formation of pearlite from austenite; direction of carbon diffusion indicated by arrows.

EUTECTOID POINT: LEVER RULE

- Just below the eutectoid point:

- $W_{\alpha} = (6.7 - 0.76) / (6.7 - 0.022) = 89\%$

- $W_{\text{Fe}_3\text{C}} = (0.76 - 0.022) / (6.7 - 0.022) = 11\%$

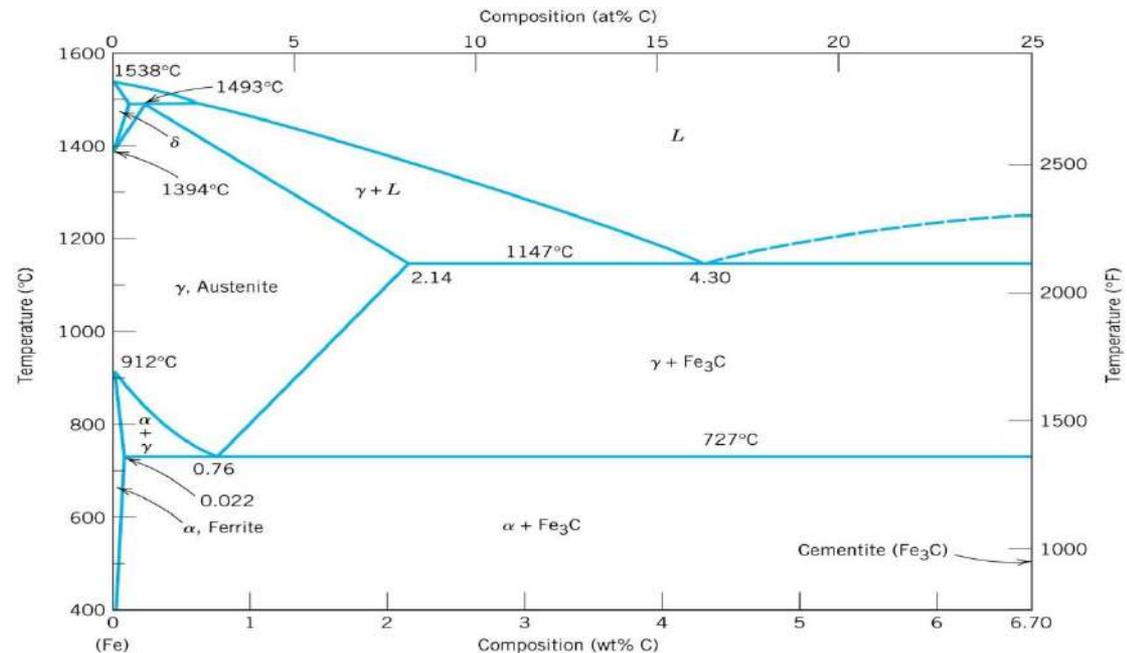


FIGURE 9.21 The iron–iron carbide phase diagram. [Adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

HYPOEUTECTOID STEEL

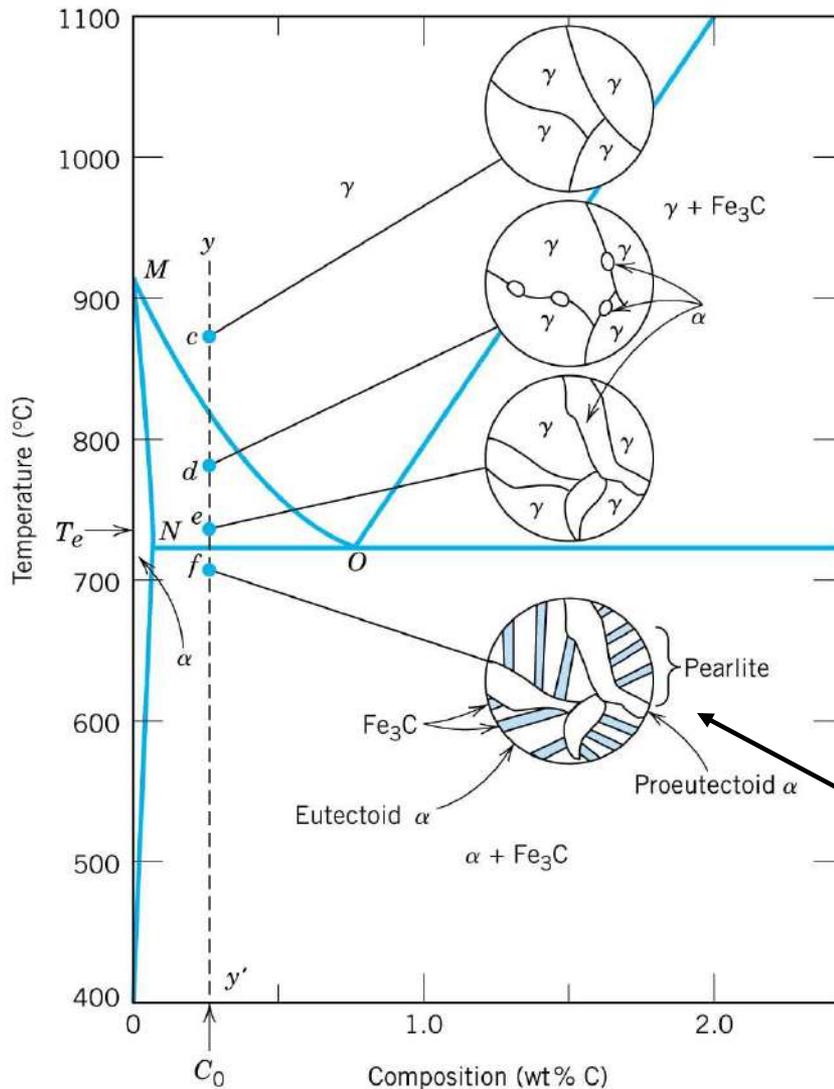
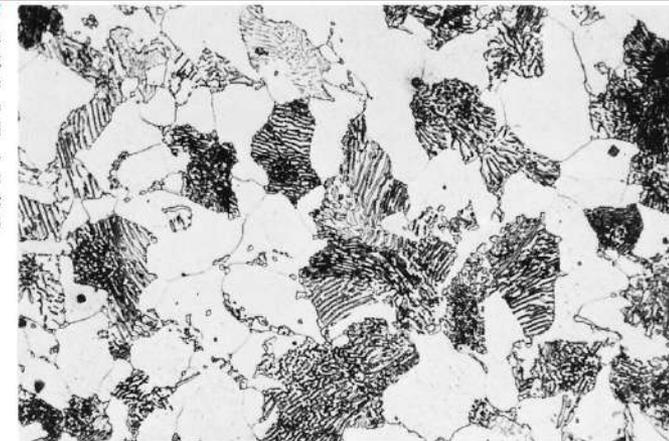


FIGURE 9.26 Schematic representations of the microstructures for an iron-carbon alloy of hypoeutectoid composition C_0 (containing less than 0.76 wt% C) as it is cooled from within the austenite phase region to below the eutectoid temperature.

Proeutectoid α :
 α phase formed at $T > T_{\text{eutectoid}}$

FIGURE 9.27 Photomicrograph of a 0.38 wt% C steel having a microstructure consisting of pearlite and proeutectoid ferrite. 635 \times . (Photomicrograph courtesy of Republic Steel Corporation.)



HYPEREUTECTOID STEEL

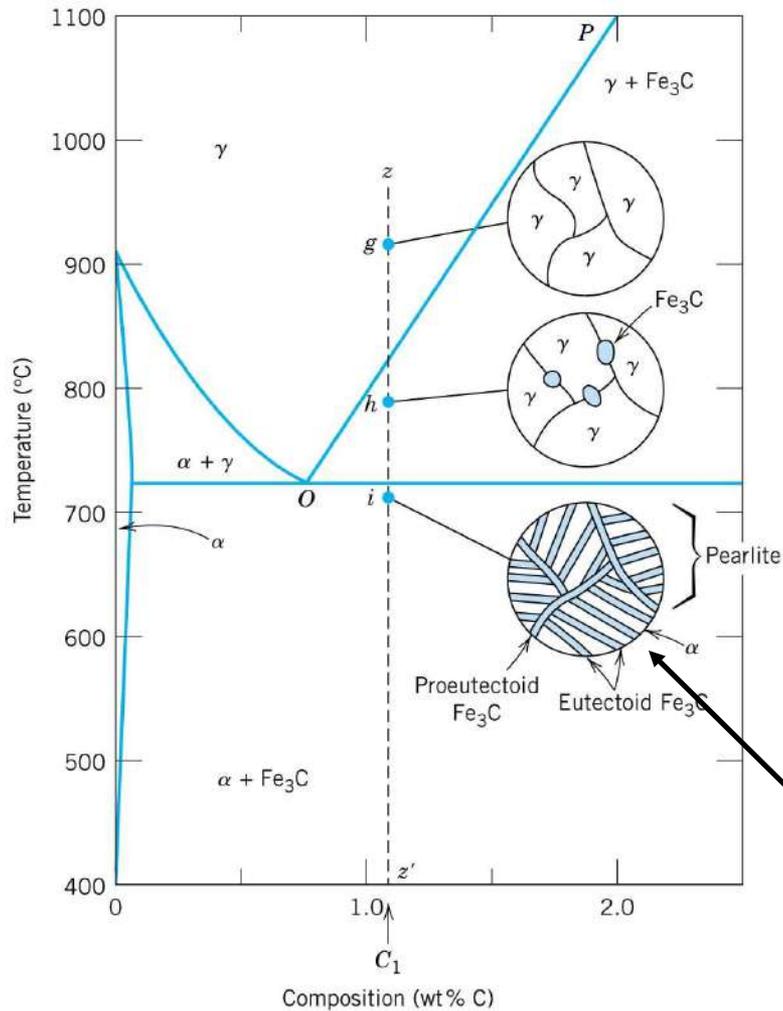


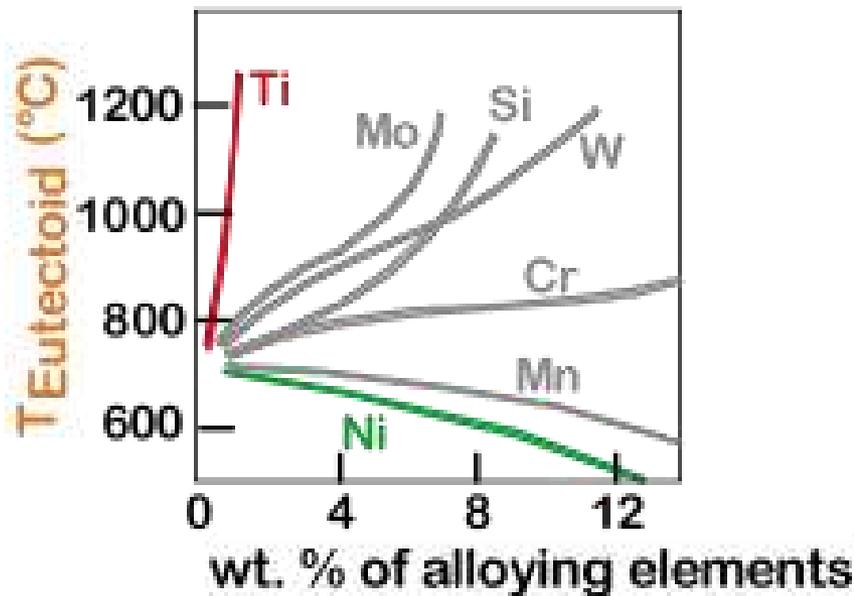
FIGURE 9.29 Schematic representations of the microstructures for an iron-carbon alloy of hypereutectoid composition C_1 (containing between 0.76 and 2.14 wt% C), as it is cooled from within the austenite phase region to below the eutectoid temperature.



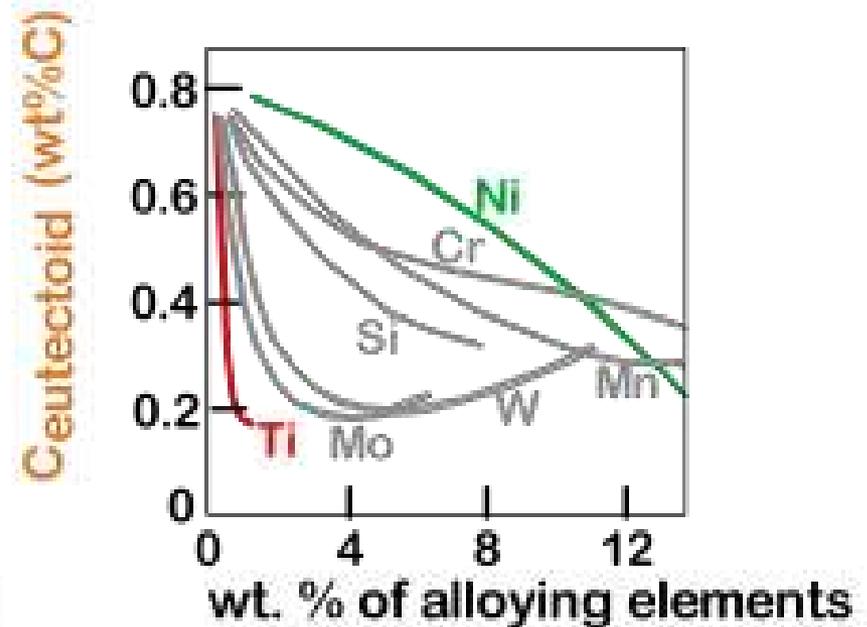
FIGURE 9.30 Photomicrograph of a 1.4 wt% C steel having a microstructure consisting of a white proeutectoid cementite network surrounding the pearlite colonies. 1000 \times . (Copyright 1971 by United States Steel Corporation.)

ALLOYING STEEL WITH MORE ELEMENTS

- $T_{\text{eutectoid}}$ changes:



- $C_{\text{eutectoid}}$ changes:



SUMMARY

- **Phase diagrams** are useful tools to determine:
 - the number and types of phases,
 - the wt% of each phase,
 - and the **composition** of each phasefor a given T and composition of the system.
- Alloying to produce a solid solution usually
 - increases the tensile strength (TS)
 - decreases the ductility.
- Binary **eutectics** and binary **eutectoids** allow for a range of microstructures.

UNIT III

- **Engineering Materials-I Steels:** Iron –Carbon phase diagram and heat treatment: Study of iron-iron carbide phase diagram, Construction of TTT diagrams, Annealing, Normalizing, Hardening and Tempering of steels, Hardenability, Alloy steels.

HEAT TREATMENT

Fundamentals

Fe-C equilibrium diagram. Isothermal and continuous cooling transformation diagrams for plain carbon and alloy steels. Microstructure and mechanical properties of pearlite, bainite and martensite. Austenitic grain size. Hardenability, its measurement and control.

Processes

Annealing, normalising and hardening of steels, quenching media, tempering. Homogenisation. Dimensional and compositional changes during heat treatment. Residual stresses and decarburisation.

Surface Hardening

Case carburising, nitriding, carbonitriding, induction and flame hardening processes.

Special Grade Steels

Stainless steels, high speed tool steels, maraging steels, high strength low alloy steels.

Cast irons

White, gray and spheroidal graphitic cast irons

Nonferrous Metals

Annealing of cold worked metals. Recovery, recrystallisation and grain growth. Heat treatment of aluminum, copper, magnesium, titanium and nickel alloys. Temper designations for aluminum and magnesium alloys.

Controlled Atmospheres

Oxidizing, reducing and neutral atmospheres.

Definition of heat treatment

Heat treatment is an operation or combination of operations involving heating at a specific rate, soaking at a temperature for a period of time and cooling at some specified rate. The aim is to obtain a desired microstructure to achieve certain predetermined properties (physical, mechanical, magnetic or electrical).

Objectives of heat treatment (heat treatment processes)

The major objectives are

- to increase strength, hardness and wear resistance (**bulk hardening, surface hardening**)
- to increase ductility and softness (**tempering, recrystallization annealing**)
- to increase toughness (**tempering, recrystallization annealing**)
- to obtain fine grain size (**recrystallization annealing, full annealing, normalising**)
- to remove internal stresses induced by differential deformation by cold working, non-uniform cooling from high temperature during casting and welding (**stress relief annealing**)

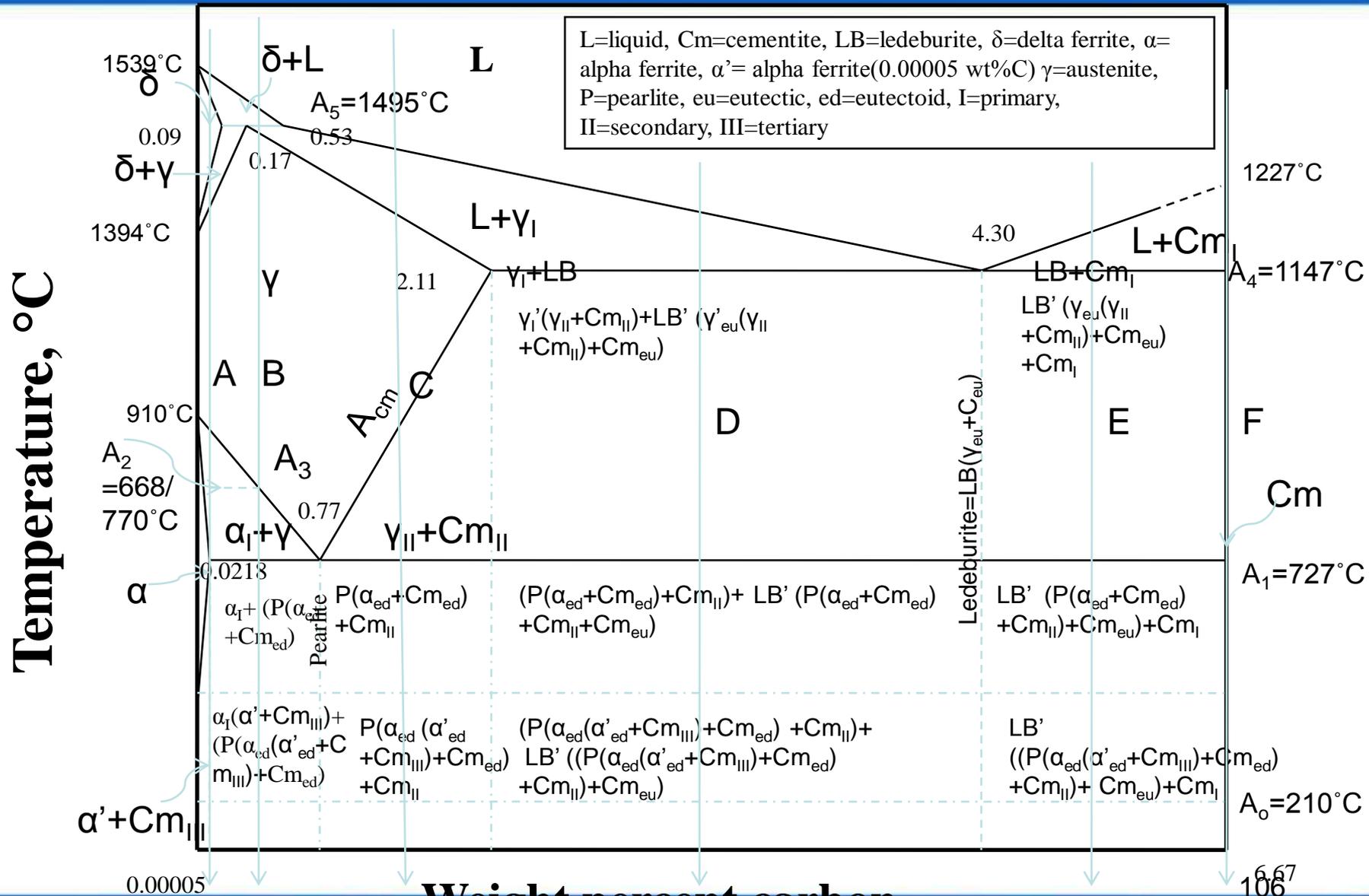
Objectives of heat treatment (heat treatment processes)

- to improve machineability (**full annealing and normalising**)
- to improve cutting properties of tool steels (**hardening and tempering**)
- to improve surface properties (**surface hardening, corrosion resistance-stabilising treatment and high temperature resistance-precipitation hardening, surface treatment**)
- to improve electrical properties (**recrystallization, tempering, age hardening**)
- to improve magnetic properties (**hardening, phase transformation**)

Fe-cementite metastable phase diagram (**Fig.1**) consists of phases liquid iron(L), δ -ferrite, γ or austenite, α -ferrite and Fe_3C or cementite and phase mixture of pearlite (interpenetrating bi-crystals of α ferrite and cementite)(P) and ledeburite (mixture of austenite and cementite)(LB).

Solid phases/phase mixtures are described here.

Fe-Cementite metastable phase diagram (microstructural)



δ ferrite:

Interstitial solid solution of carbon in iron of body centred cubic crystal structure (**Fig .2(a)**) (δ iron) of higher lattice parameter (2.89\AA) having solubility limit of 0.09 wt% at 1495°C with respect to austenite. The stability of the phase ranges between $1394\text{-}1539^{\circ}\text{C}$.

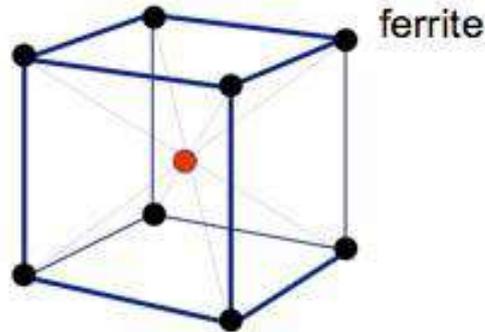
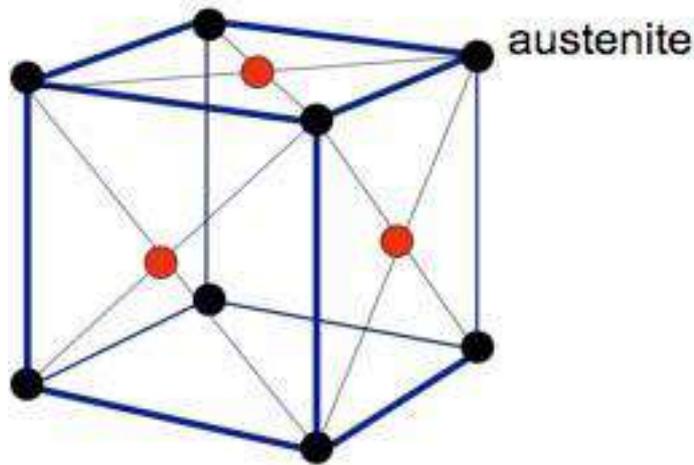


Fig.2(a): Crystal structure of ferrite

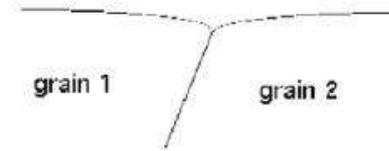
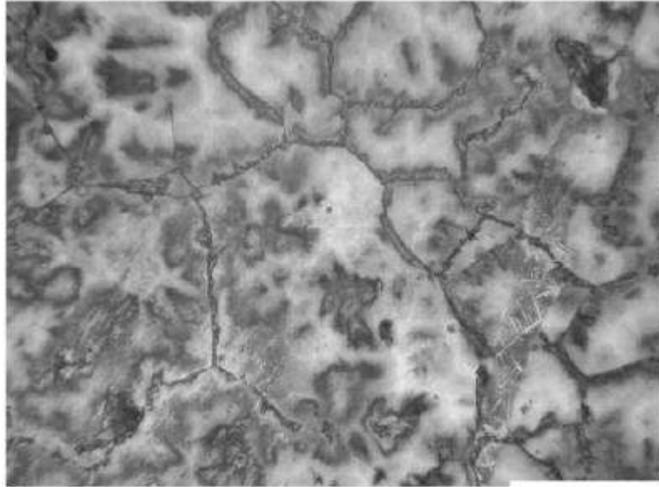
This is not stable at room temperature in plain carbon steel. However it can be present at room temperature in alloy steel specially duplex stainless steel.

γ phase or austenite:

Interstitial solid solution of carbon in iron of face centred cubic crystal structure (**Fig.3(a)**) having solubility limit of 2.11 wt% at 1147°C with respect to cementite. The stability of the phase ranges between $727\text{-}1495^{\circ}\text{C}$ and solubility ranges $0\text{-}0.77$ wt% C with respect to alpha ferrite and $0.77\text{-}2.11$ wt% C with respect to cementite, at 0 wt% C the stability ranges from $910\text{-}1394^{\circ}\text{C}$.



Crystal structure of austenite is shown at right side.



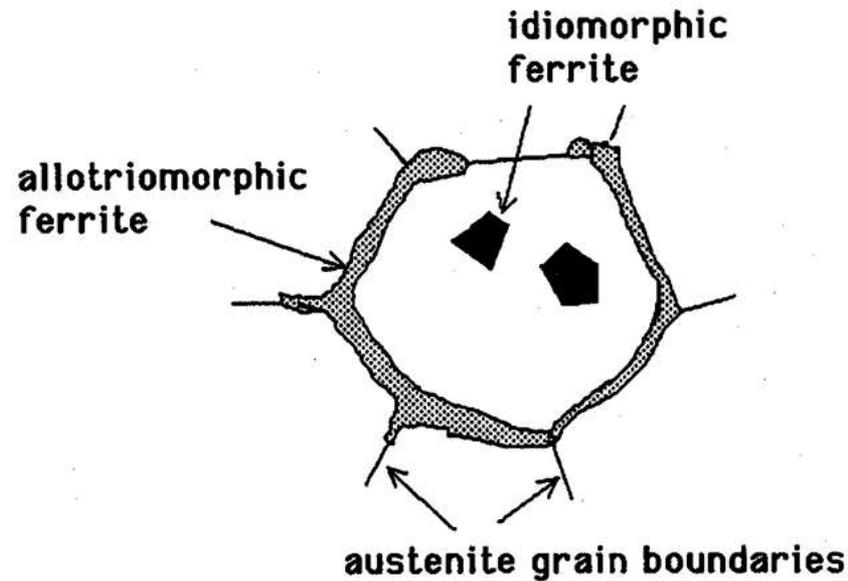
Polished sample held at austenitisation temperature. Grooves develop at the prior austenite grain boundaries due to the balancing of surface tensions at grain junctions with the free surface. Micrograph courtesy of *Saurabh Chatterjee*.

α -ferrite:

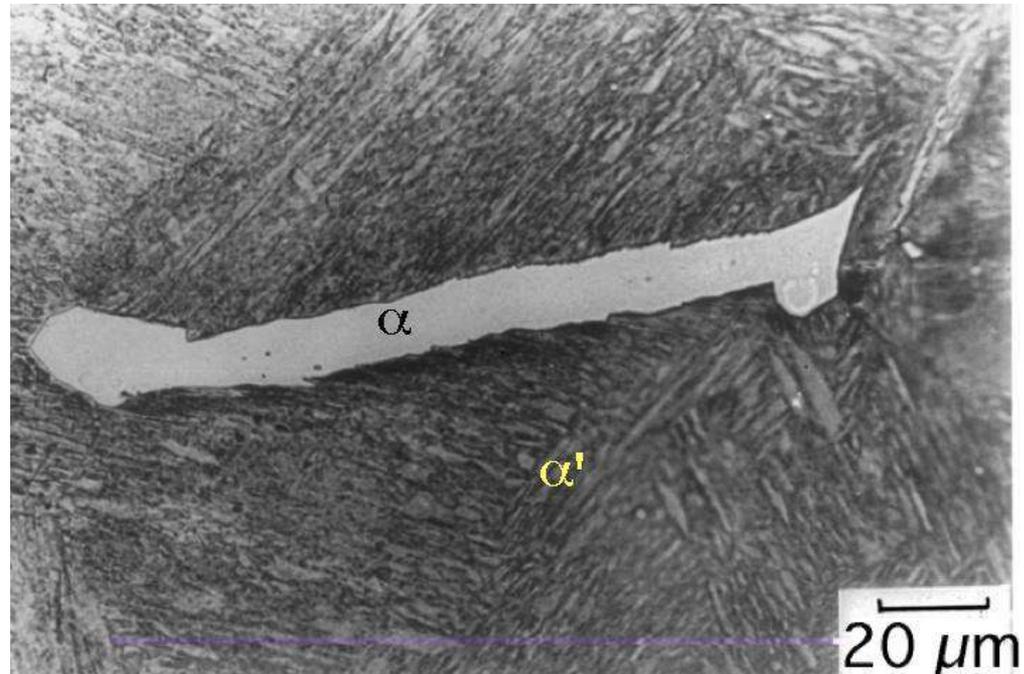
Interstitial solid solution of carbon in iron of body centred cubic crystal structure (α iron) (same as **Fig. 2(a)**) having solubility limit of 0.0218 wt % C at 727°C with respect to austenite.

The stability of the phase ranges between low temperatures to 910°C, and solubility ranges 0.00005 wt % C at room temperature to 0.0218 wt% C at 727°C with respect to cementite.

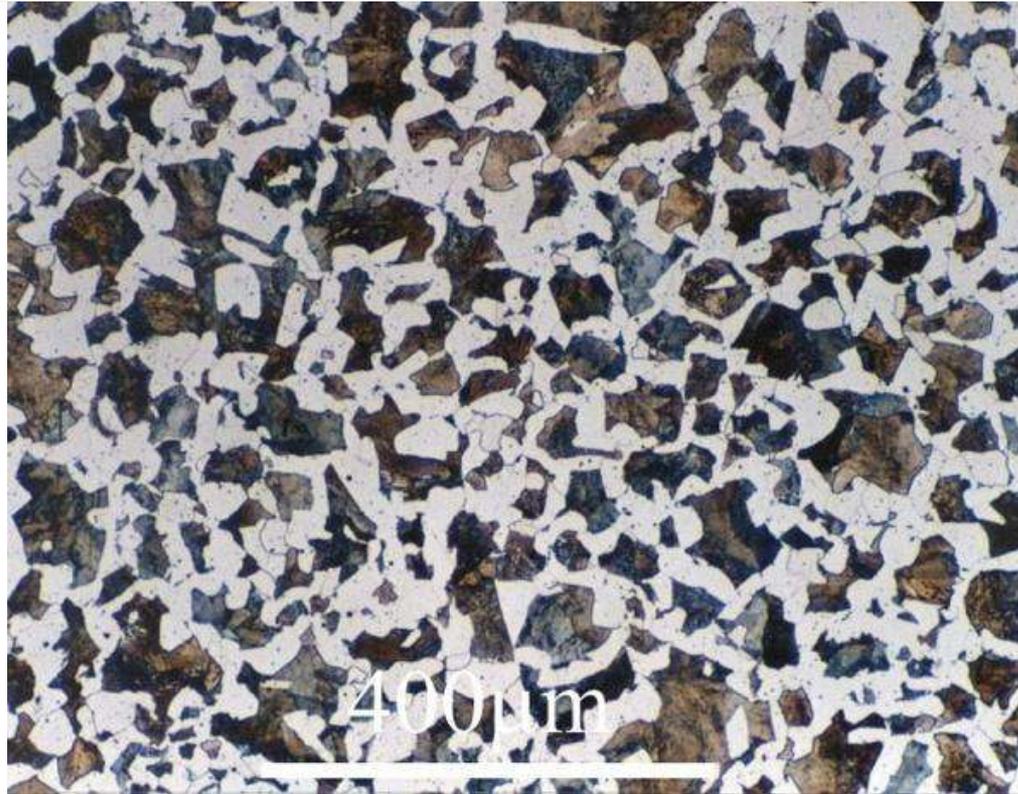
There are two morphologies can be observed under equilibrium transformation or in low under undercooling condition in low carbon plain carbon steels. These are intergranular allotriomorphs (α) (**Fig. 4-7**) or intragranular idiomorphs (α_I) (**Fig. 4, Fig. 8**)



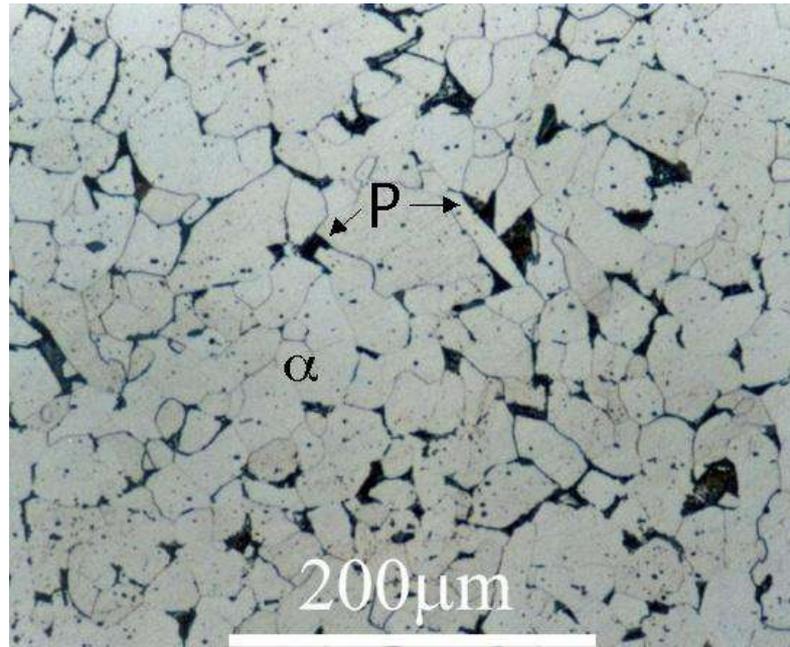
Schematic diagram of grain boundary allotriomorphic ferrite, and intragranular idiomorphic ferrite.



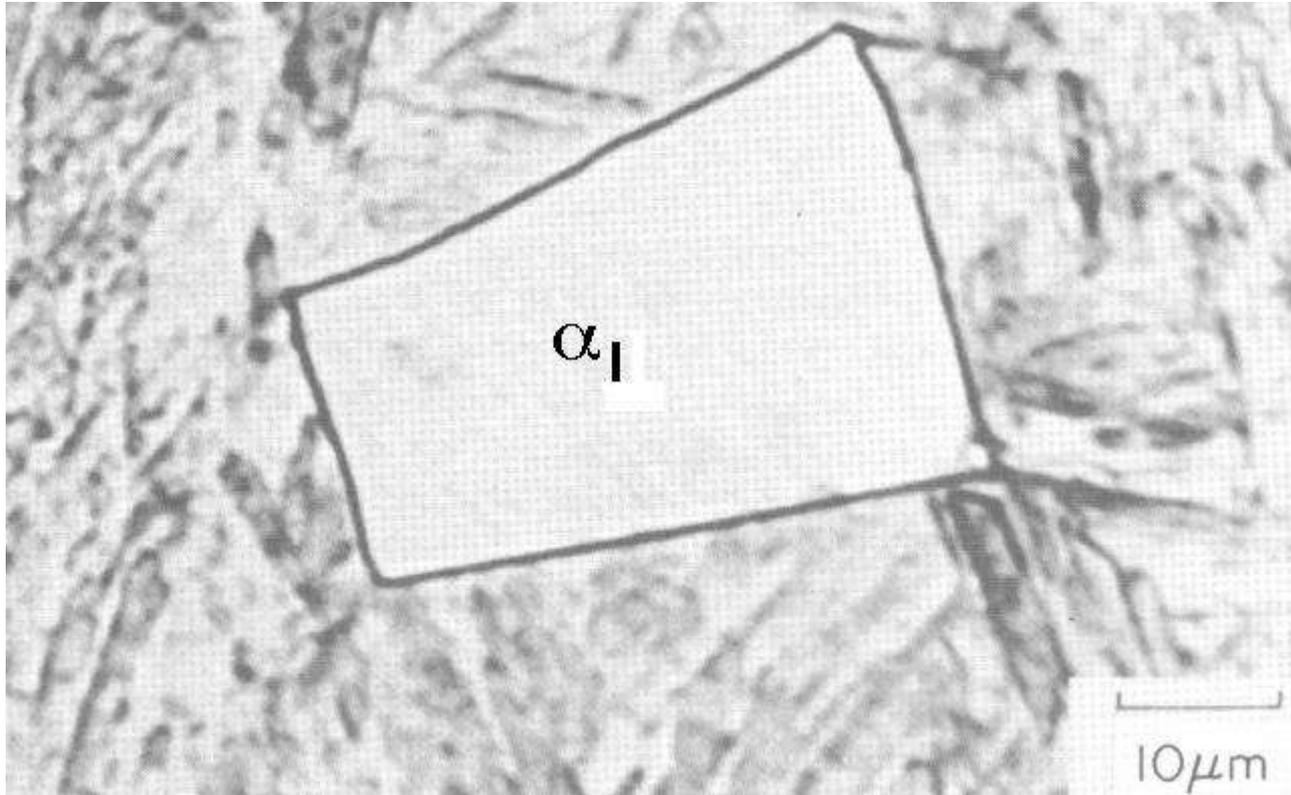
An allotriomorph of ferrite in a sample which is partially transformed into α and then quenched so that the remaining γ undergoes martensitic transformation. The allotriomorph grows rapidly along the austenite grain boundary (which is an easy diffusion path) but thickens more slowly.



Allotriomorphic ferrite in a Fe-0.4C steel which is slowly cooled; the remaining dark-etching microstructure is fine pearlite. Note that although some α -particles might be identified as idiomorphs, they could represent sections of allotriomorphs. Micrograph courtesy of the *DOITPOMS* project.



The allotriomorphs have in this slowly cooled low-carbon steel have consumed most of the austenite before the remainder transforms into a small amount of pearlite. Micrograph courtesy of the DoITPOMS project. The shape of the ferrite is now determined by the impingement of particles which grow from different nucleation sites.



An idiomorph of ferrite in a sample which is partially transformed into α and then quenched so that the remaining γ undergoes martensitic transformation. The idiomorph is crystallographically faceted.

There are three more allotropes for pure iron that form under different conditions

ϵ -iron:

The iron having hexagonal close packed structure. This forms at extreme pressure, 110 kbars and 490°C. It exists at the centre of the Earth in solid state at around 6000°C and 3 million atmosphere pressure.

FCT iron:

This is face centred tetragonal iron. This is coherently deposited iron grown as thin film on a {100} plane of copper substrate

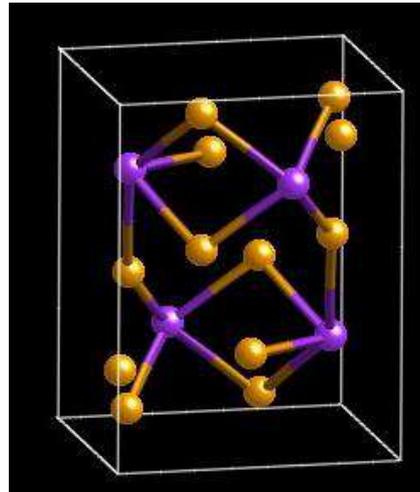
Trigonal iron:

Growing iron on misfitting {111} surface of a face centred cubic copper substrate.

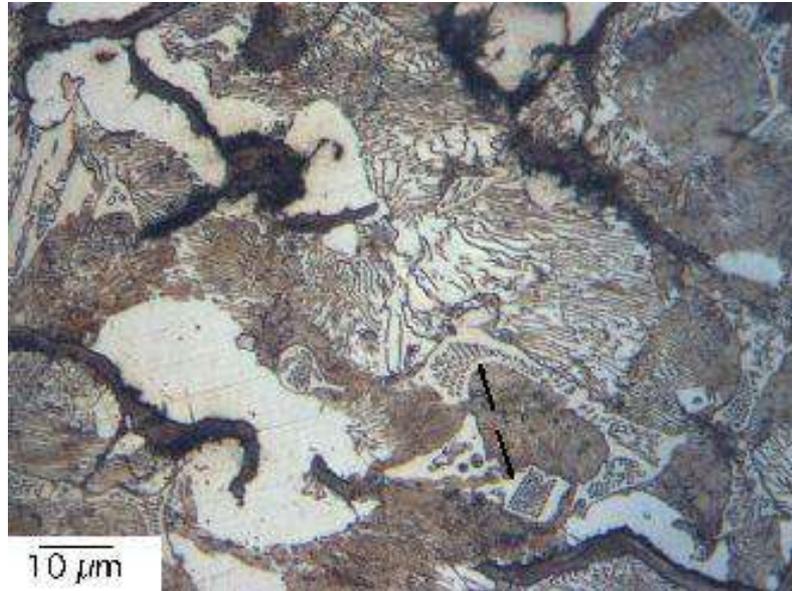
Fe_3C or cementite:

Interstitial intermetallic compound of C & Fe with a carbon content of 6.67 wt% and orthorhombic structure consisting of 12 iron atoms and 4 carbon atoms in the unit cell.

Stability of the phase ranges from low temperatures to 1227°C



Orthorhombic crystal structure of cementite. The purple atoms represent carbon. Each carbon atom is surrounded by eight iron atoms. Each iron atom is connected to three carbon atoms.



The pearlite is resolved in some regions where the sectioning plane makes a glancing angle to the lamellae. The lediburite eutectic is highlighted by the arrows. At high temperatures this is a mixture of austenite and cementite formed from liquid. The austenite subsequently decomposes to pearlite.

Courtesy of *Ben Dennis-Smith, Frank Clarke and Mohamed Sherif*

Critical temperatures:

$A = \textit{arret}$ means arrest

A_0 = a subcritical temperature ($< A_1$) = Curie temperature of cementite = 210°C

A_1 = Lower critical temperature = eutectoid temperature = 727°C

A_2 = Curie temperature of ferrite = $768/770^\circ\text{C}$

A_3 = upper critical temperature = $\gamma + \alpha / \gamma$ phase field boundary
= composition dependent = $910-727^\circ\text{C}$

A_4 = Eutectic temperature = 1147°C

A_5 = Peritectic temperature = 1495°C

$A_{cm} = \gamma/\gamma + \text{cementite}$ phase field boundary = composition dependent = 727-1147°C

In addition the subscripts c or r are used to indicate that the temperature is measured during heating or cooling respectively.

c = *chaffauge* means heating, A_c

r = *refroidissement* means cooling, A_r

Types/morphologies of phases in Fe-Fe₃C system

Cementite = primary (Cm_I), eutectic (Cm_{eu}), secondary (Cm_{II}) (grain boundary allotriomorphs, idiomorphs), eutectoid (Cm_{ed}) and tertiary (Cm_{III}).

Austenite = austenite (γ) (equiaxed), primary (γ_I), eutectic (γ_{eu}), secondary (γ_{II}) (proeutectoid),

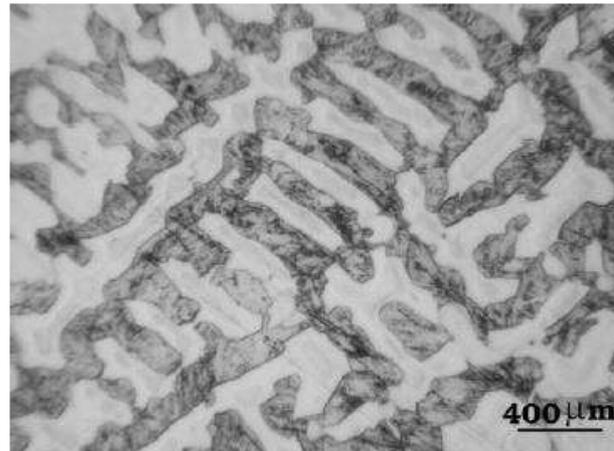
α -ferrite = ferrite (α) (equiaxed), proeutectoid or primary (grain boundary allotriomorphs and idiomorphs) (α_I), eutectoid (α_{eu}) and ferrite (lean in carbon) (α').

Phase mixtures

Pearlite (P) and ledeburite (LB)

Important Reactions

Peritectic reaction



δ -ferrite in dendrite form in as-cast Fe-0.4C-2Mn-0.5Si-2Al0.5Cu, Courtesy of *S. Chatterjee et al. M. Muruganath, H. K. D. H. Bhadeshia*

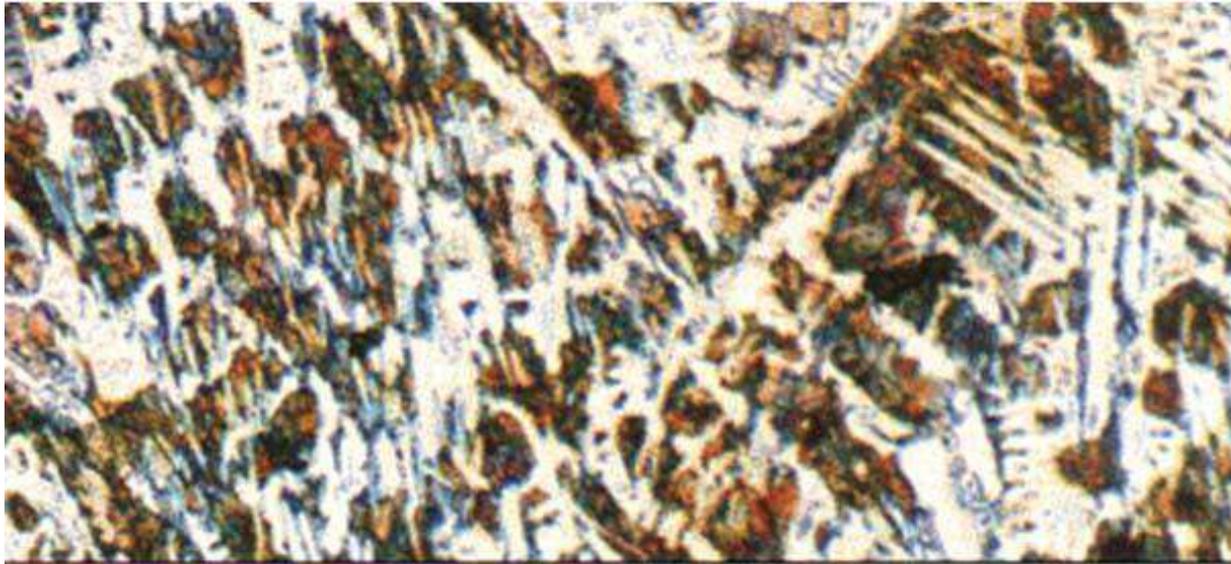
EUTECTIC REACTION

Liquid \leftrightarrow Solid₁ + Solid₂

Liquid (4.3wt%C) \leftrightarrow γ (2.11wt%C) + Fe₃C (6.67wt%C) at 1147°C

Liquid-100 wt% \rightarrow 51.97wt% γ + Fe₃C (48.11wt%)

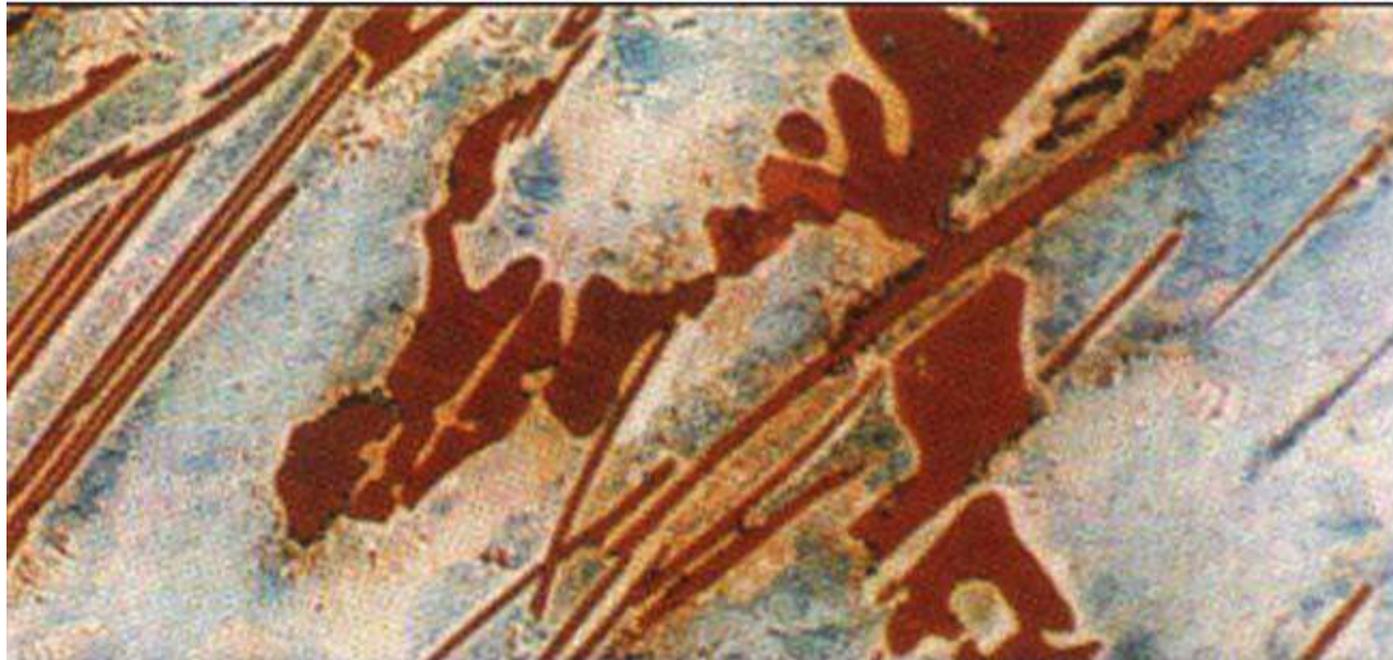
The phase mixture of austenite and cementite formed at eutectic temperature is called ledeburite.



Microstructure of white cast iron containing massive cementite (white) and pearlite etched with 4% nital, 100x. After Mrs. Janina Radzikowska, Foundry Research Institute in Kraków, Poland



High magnification view (400x) of the white cast iron specimen shown in Fig. 11, etched with 4% nital. After *Mrs. Janina Radzikowska, Foundry Research Institute in Kraków, Poland*



High magnification view (400x) of the white cast iron specimen shown in Fig. 11, etched with alkaline sodium picrate. After *Mrs. Janina Radzikowska, Foundry Research Institute in Kraków, Poland*

Eutectoid reaction



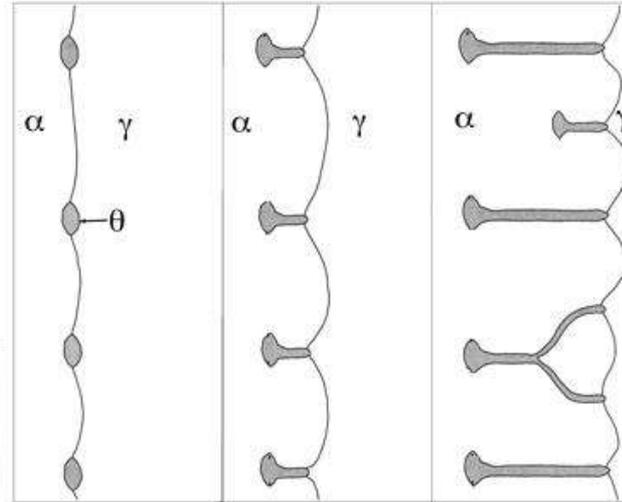
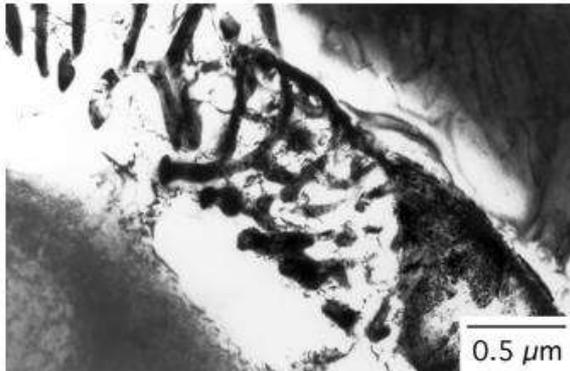
Typical density

$$\alpha \text{ ferrite} = 7.87 \text{ gcm}^{-3}$$

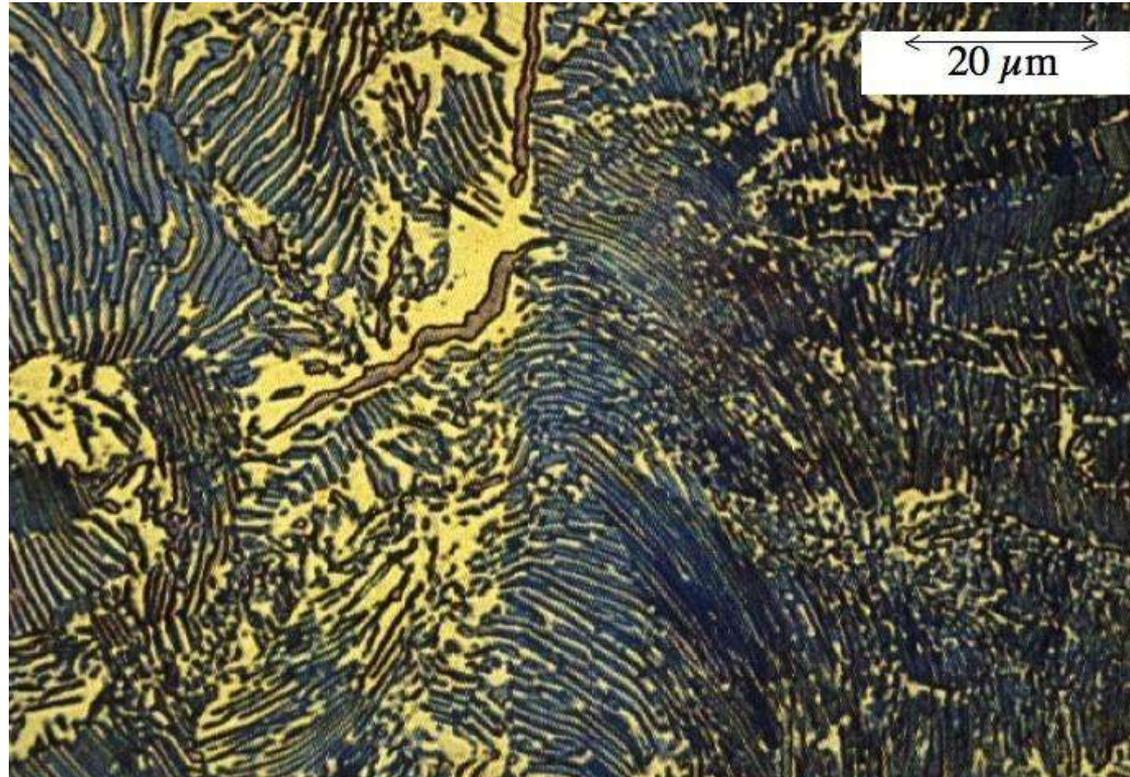
$$\text{Fe}_3\text{C} = 7.7 \text{ gcm}^{-3}$$

volume ratio of α - ferrite:Fe₃C=7.9:1

Initiation of pearlite
(Howell)



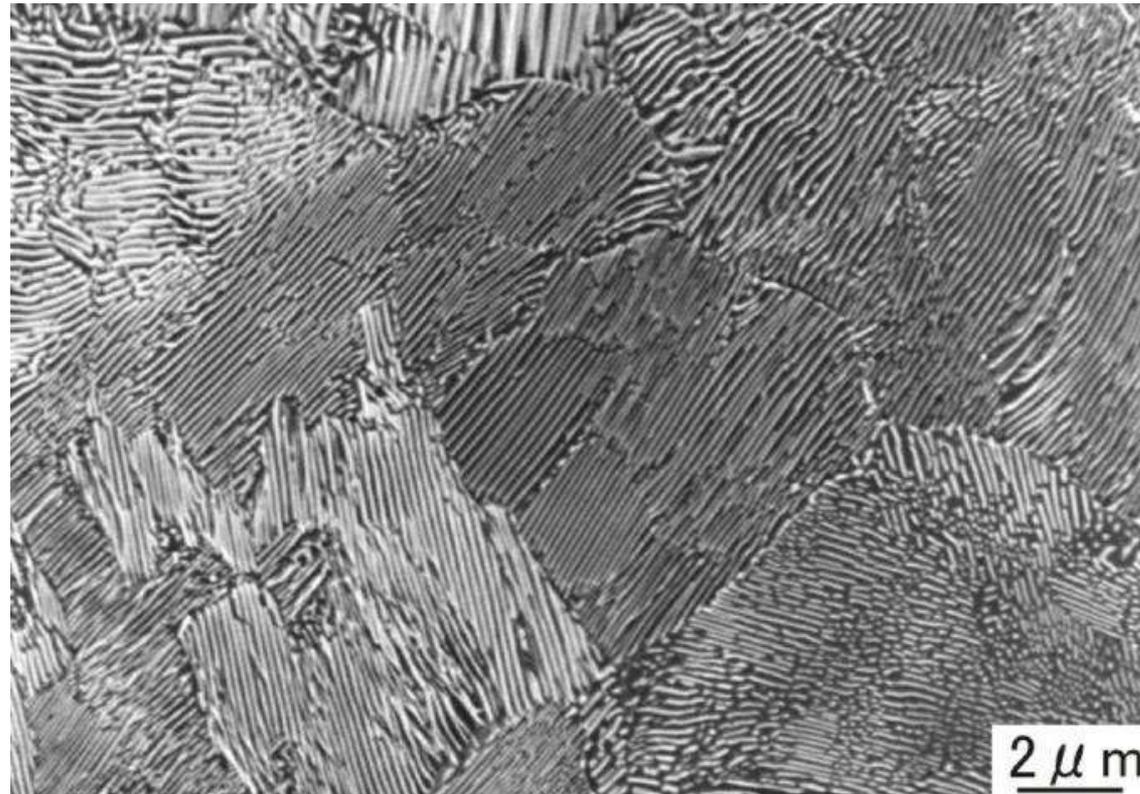
The process by which a colony of pearlite evolves in a hypoeutectoid steel.



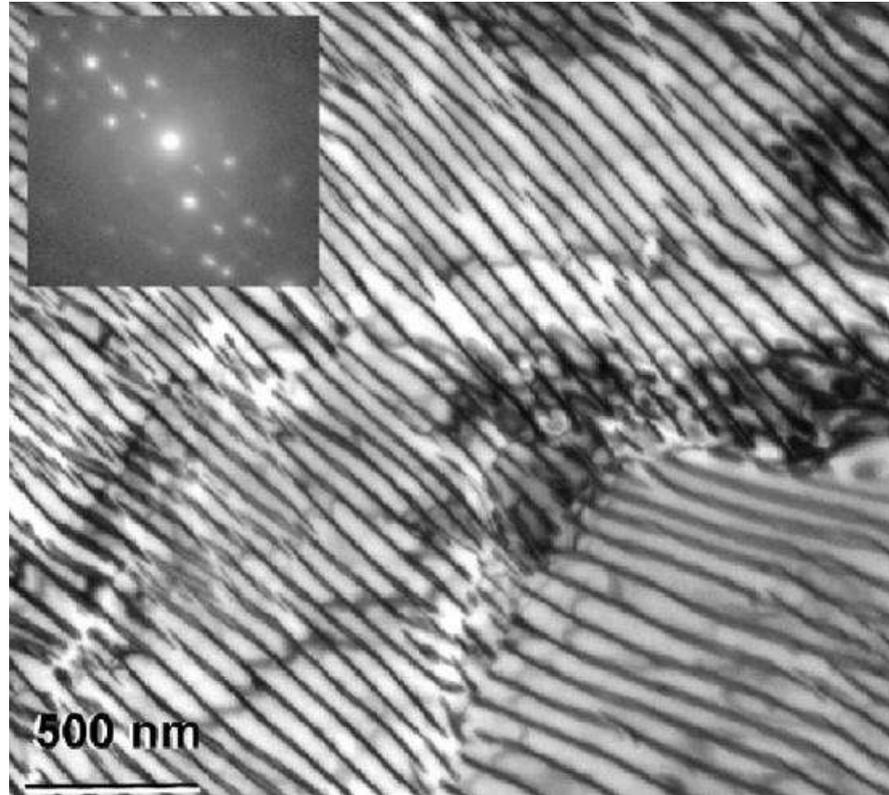
The appearance of a pearlitic microstructure under optical microscope.



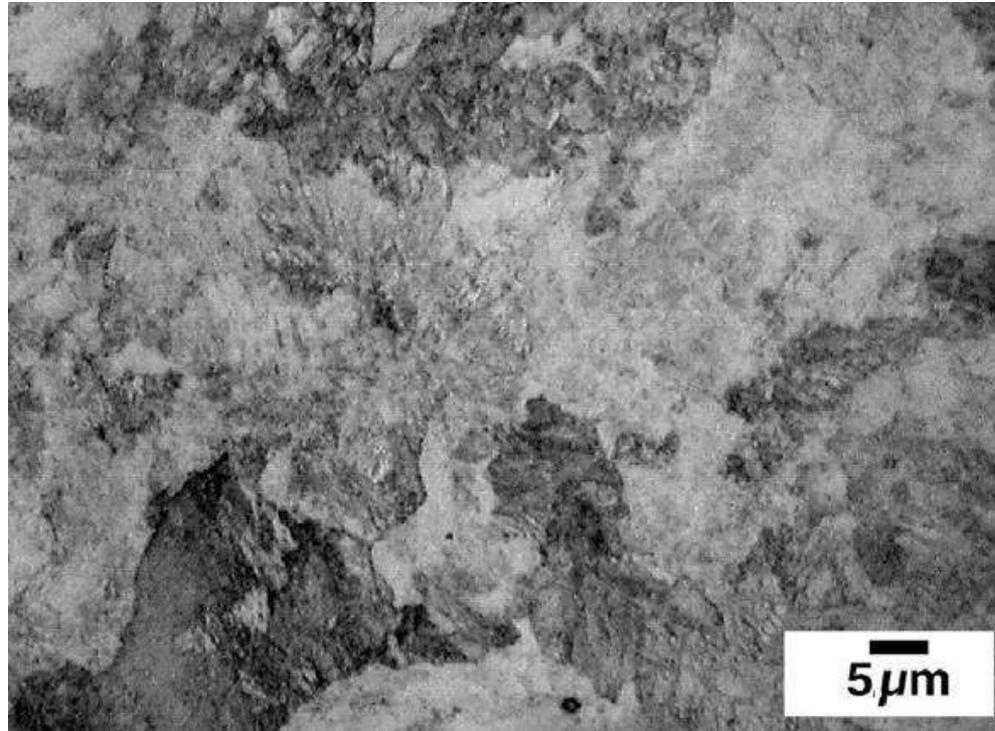
A cabbage filled with water analogy of the three-dimensional structure of a single colony of pearlite, an interpenetrating bi-crystal of ferrite and cementite.



Optical micrograph showing colonies of pearlite



Transmission electron micrograph of extremely fine pearlite.



Optical micrograph of extremely fine pearlite from the same sample as used to create Fig. 18. The individual lamellae cannot now be resolved.

Evolution of microstructure (equilibrium cooling)

Sequence of evolution of microstructure can be described by the projected cooling on compositions A, B, C, D, E, F.

At composition A



At composition B



At composition C

$$L \longrightarrow L+\gamma_I \longrightarrow \gamma \longrightarrow \gamma_{II}+Cm_{II} \longrightarrow P(\alpha_{ed}+Cm_{ed})+Cm_{II}$$

$$\longrightarrow P(\alpha_{ed}(\alpha'_{ed}+Cm_{III})+Cm_{ed})+Cm_{II}$$

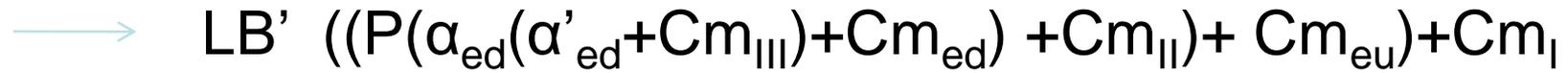
At composition D

$$L \longrightarrow L+\gamma_I \longrightarrow \gamma_I+LB \longrightarrow \gamma_I'(\gamma_{II}+Cm_{II})+LB' (\gamma'_{eu}(\gamma_{II}+Cm_{II})+Cm_{eu})$$

$$\longrightarrow (P(\alpha_{ed}+Cm_{ed})+Cm_{II})+ LB' (P(\alpha_{ed}+Cm_{ed})+Cm_{II}+Cm_{eu})$$

$$\longrightarrow (P(\alpha_{ed}(\alpha'_{ed}+Cm_{III})+Cm_{ed}) +Cm_{II})+ LB' ((P(\alpha_{ed}(\alpha'_{ed}+Cm_{III})+Cm_{ed})+Cm_{II})+Cm_{eu})$$

At composition E



At composition F



Limitations of equilibrium phase diagram

Fe-Fe₃C equilibrium/metastable phase diagram

Stability of the phases under equilibrium condition only.

It does not give any information about other metastable phases. i.e. bainite, martensite

It does not indicate the possibilities of suppression of proeutectoid phase separation.

No information about kinetics

No information about size

No information on properties.

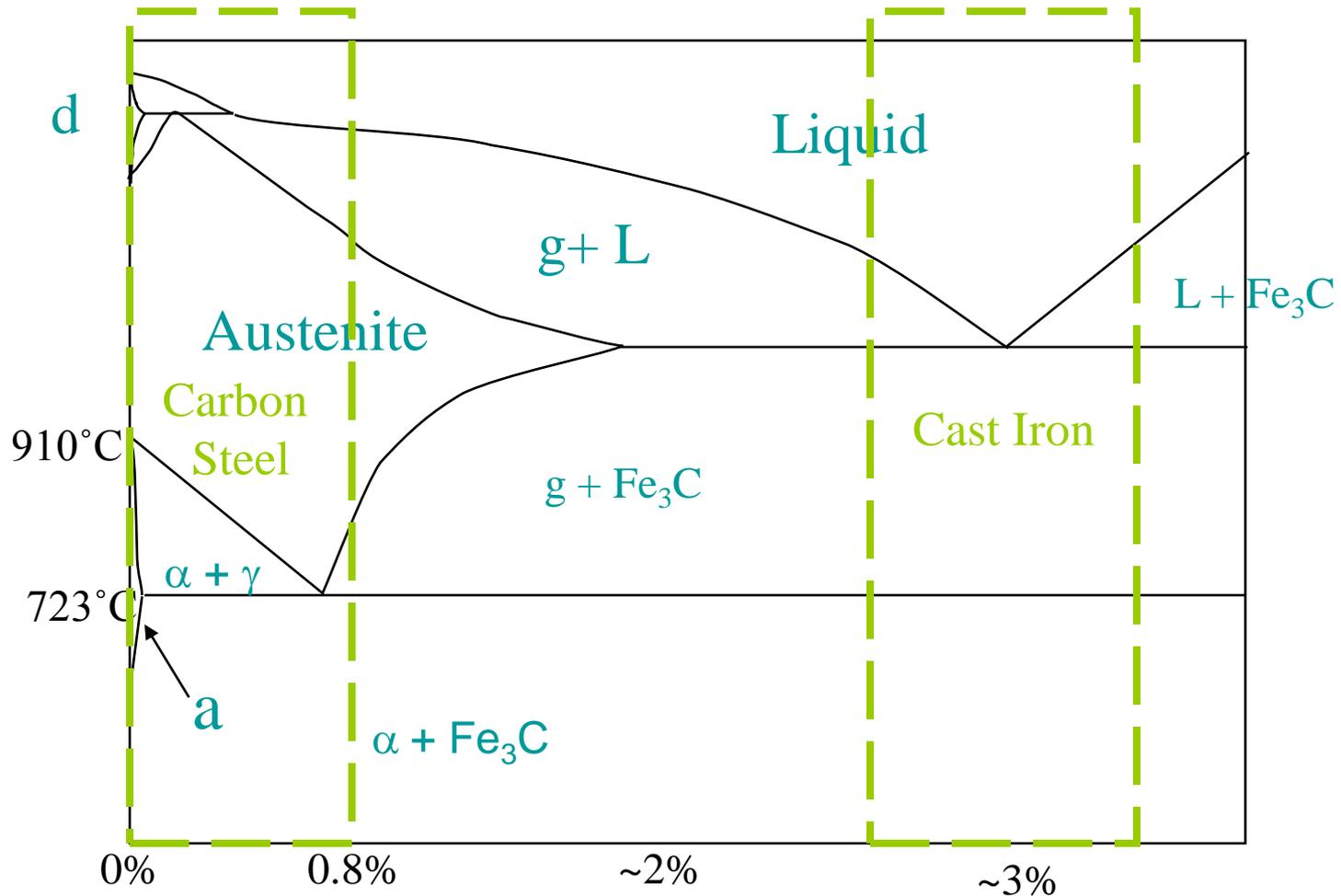
UNIT IV

- **Engineering Materials –II: Cast Irons:** Structure and properties of White cast iron, malleable cast iron, Grey cast iron.
- **Engineering materials –III: Non-ferrous metals and alloys:** Structure and properties of aluminum copper and its alloys, Al-Cu phase diagram, Titanium and its alloys.

Overview of cast iron

- Iron with 1.7 to 4.5% carbon and 0.5 to 3% silicon
- Lower melting point and more fluid than steel (better castability)
- Low cost material usually produced by sand casting
- A wide range of properties, depending on composition & cooling rate
 - Strength
 - Hardness
 - Ductility
 - Thermal conductivity
 - Damping capacity

Iron carbon diagram



Production of cast iron

- Pig iron, scrap steel, limestone and carbon (coke)
- Cupola
- Electric arc furnace
- Electric induction furnace
- Usually sand cast, but can be gravity die cast in reusable graphite moulds
- Not formed, finished by machining

Types of cast iron

- Grey cast iron - carbon as graphite
- White cast iron - carbides, often alloyed
- Ductile cast iron
 - nodular, spheroidal graphite
- Malleable cast iron
- Compacted graphite cast iron
 - CG or Vermicular Iron

Effect of cooling rate

- Slow cooling favours the formation of graphite & low hardness
- Rapid cooling promotes carbides with high hardness
- Thick sections cool slowly, while thin sections cool quickly
- Sand moulds cool slowly, but metal chills can be used to increase cooling rate & promote white iron

Effect of composition

Carbon equivalent $CE = C + \frac{S + P}{3}$

- A CE over 4.3 (hypereutectic) leads to carbide or graphite solidifying first & promotes grey cast iron
- A CE less than 4.3 (hypoeutectic) leads to austenite solidifying first & promotes white iron

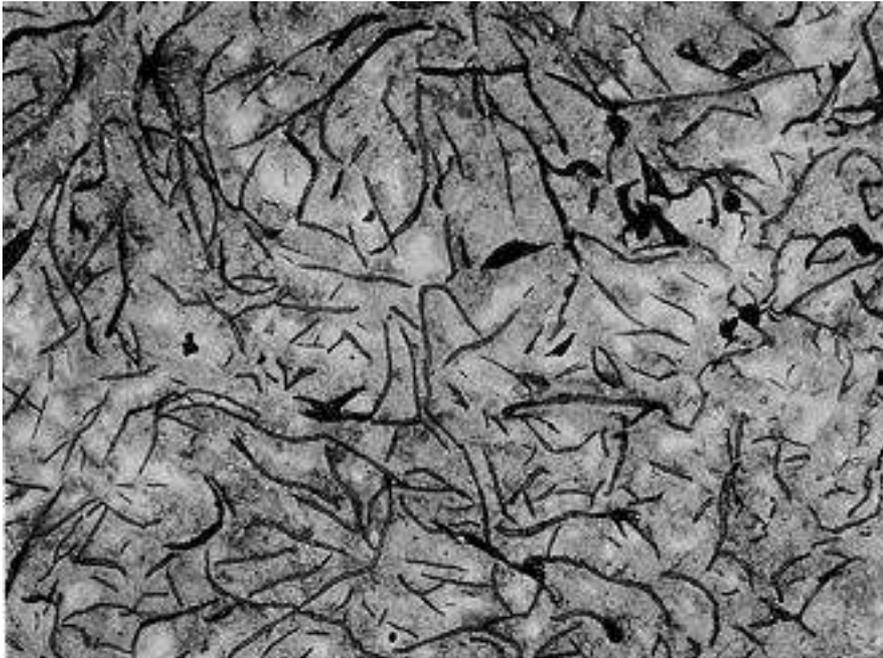
Grey cast iron

- Flake graphite in a matrix of pearlite, ferrite or martensite
- Wide range of applications
- Low ductility - elongation 0.6%
- Grey cast iron forms when
 - Cooling is slow, as in heavy sections
 - High silicon or carbon

Typical properties

- Depend strongly on casting shape & thickness
- AS1830 & ASTM A48 specifies properties
- Low strength, A48 Class 20, R_m 120 MPa
 - High carbon, 3.6 to 3.8%
 - Kish graphite (hypereutectic)
 - High conductivity, high damping
- High strength, A48 Class 60, R_m 410 MPa
 - Low carbon, (eutectic composition)

Graphite form



- Uniform
- Rosette
- Superimposed (Kish and normal)
- Interdendritic random
- Interdendritic preferred orientation
- See AS5094 “designation of microstructure of graphite”

Matrix structure

- Pearlite or ferrite
- Transformation is to ferrite when
 - Cooling rate is slow
 - High silicon content
 - High carbon equivalence
 - Presence of fine undercooled graphite

Properties of grey cast iron

- Machineability is excellent
- Ductility is low (0.6%), impact resistance low
- Damping capacity high
- Thermal conductivity high
- Dry and normal wear properties excellent

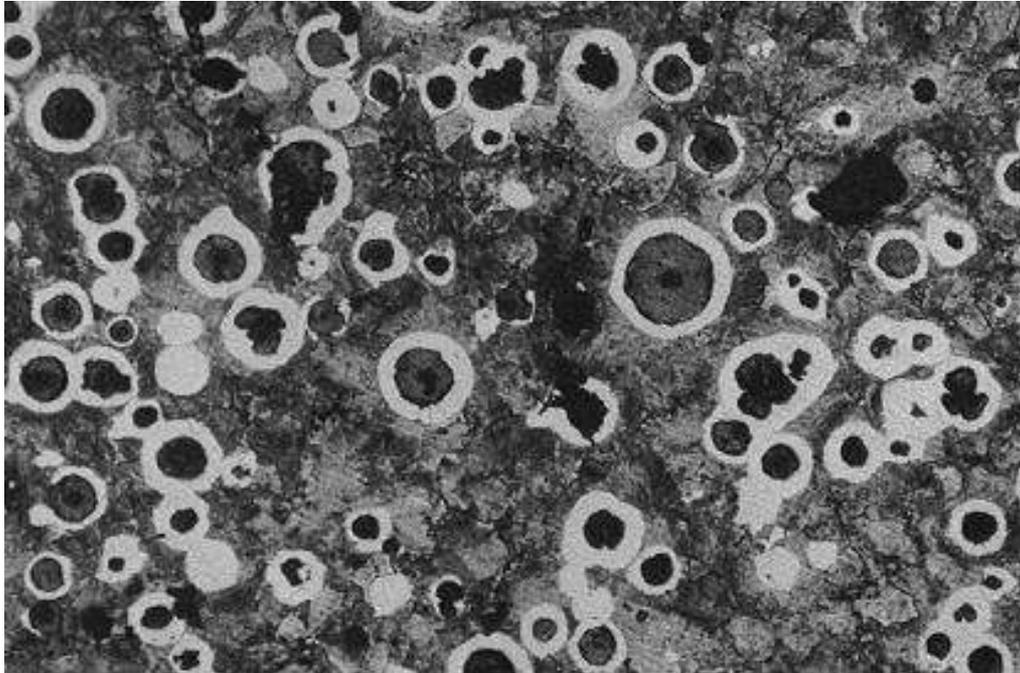
Applications

- Engines
 - Cylinder blocks, liners,
- Brake drums, clutch plates
- Pressure pipe fittings (AS2544)
- Machinery beds
- Furnace parts, ingot and glass moulds

Ductile iron

- Inoculation with Ce or Mg or both causes graphite to form as spherulites, rather than flakes
- Also known as spheroidal graphite (SG), and nodular graphite iron
- Far better ductility than grey cast iron
- See AS1831

Microstructure



- Graphite spheres surrounded by ferrite
- Usually some pearlite
- May be some cementite
- Can be hardened to martensite by heat treatment

Production

- Composition similar to grey cast iron except for higher purity.
- Melt is added to inoculant in ladle.
- Magnesium as wire, ingots or pellets is added to ladle before adding hot iron.
- Mg vapour rises through melt, removing sulphur.

Verification

- Testing is required to ensure nodularisation is complete.
- Microstructural examination
- Mechanical testing on standard test bars (ductility)
- Ultrasonic testing

Properties

- Strength higher than grey cast iron
- Ductility up to 6% as cast or 20% annealed
- Low cost
 - Simple manufacturing process makes complex shapes
- Machineability better than steel

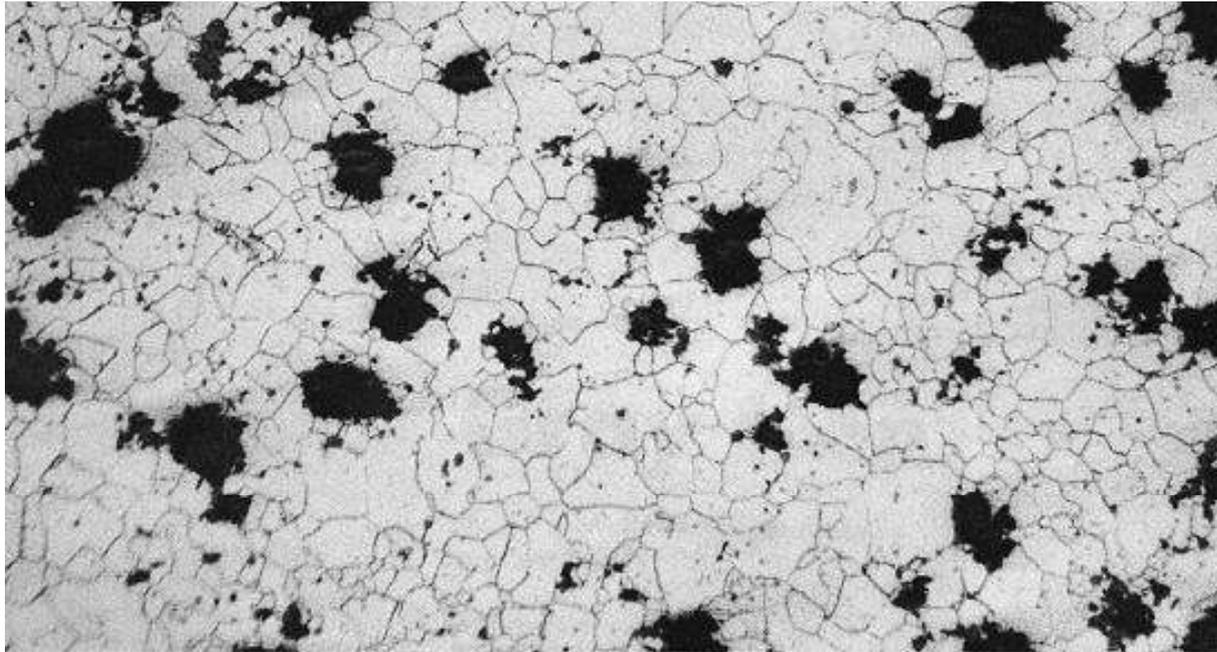
Applications

- Automotive industry 55% of ductile iron in USA
 - Crankshafts, front wheel spindle supports, steering knuckles, disc brake callipers
- Pipe and pipe fittings (joined by welding) see AS2280

Malleable iron

- Graphite in nodular form
- Produced by heat treatment of white cast iron
- Graphite nodules are irregular clusters
- Similar properties to ductile iron
- See AS1832

Microstructure



- Uniformly dispersed graphite
- Ferrite, pearlite or tempered martensite matrix
- Ferritic castings require 2 stage anneal.
- Pearlitic castings - 1st stage only

Annealing treatments

- Ferritic malleable iron
 - Depends on C and Si
 - 1st stage 2 to 36 hours at 940°C in a controlled atmosphere
 - Cool rapidly to 750°C & hold for 1 to 6 hours
- For pearlitic malleable iron
 - Similar 1st stage above (2 - 36 h at 940°C)
 - Cool to 870°C slowly, then air cool & temper to specification
- Harden and temper pearlitic iron for martensitic castings

Properties

- Similar to ductile iron
- Good shock resistance
- Good ductility
- Good machineability

Applications

- Similar applications to ductile iron
- Malleable iron is better for thinner castings
- Ductile iron better for thicker castings >40mm
- Vehicle components
 - Power trains, frames, suspensions and wheels
 - Steering components, transmission and differential parts, connecting rods
- Railway components
- Pipe fittings AS3673

Joining cast iron

- Welding
- Braze-welding
- Brazing
- Soldering
- Mechanical connections

Welding

- Weldability of cast iron is low and depends on the material type, thickness, complexity of the casting, and on whether machinability is important

Braze welding

- Repair of cracked or broken cast iron
- Oxy-fuel gas process using filler which melts between 450°C and the melting temperature of the casting
- Joint is similar to that for welding
- Low dilution
- Preheat 320 to 400°C
- Copper-zinc filler with suitable flux

Brazing

- Used for capillary joints
- Any brazing process
 - Those with automatic temperature control are best
- Lower melting silver brazing alloys are best
 - Must not contain phosphorus

Weldability

- White cast iron - not weldable
 - Small attachments only
- Grey cast iron - low weldability
 - Welding largely restricted to salvage and repair
- Ductile and malleable irons - good weldability (inferior to structural steel)
 - Welding increasingly used during manufacture

Welding problems

- High carbon content
 - Tendency to form martensite and cementite in HAZ
 - Loss of ductility, cracking and impairment of machinability
- Difficulty wetting
 - Pre-cleaning important, fluxing
- Low ductility of casting
 - Residual stress causes cracking

Oxyfuel gas welding

- Low power process with wide HAZ
- 600°C preheat of whole casting, 90° to 120° included angle
- Filler is cast iron of matching composition
 - Inoculating fluxes available for ductile irons
- Weld closely matches base material (machinability and corrosion resistance)
- Particularly suited to repair of casting defects at foundry in grey cast iron

MMAW cold method

- Suits small repairs in grey cast iron
- Drill crack ends, 70° included angle
- Use nickel or Ni-55Fe alloy electrodes
 - Low strength ductile weld metal
- Keep casting cold
 - Small diameter, 2.5mm, short weld runs
 - Backstep weld runs, max interpass temperature 100°C
 - HAZ contains martensite and is unmachinable
- Peen each weld run

Ductile and malleable irons

- MMAW, SAW, GTAW, GMAW and FCAW
- Preheat may not be required
 - Preheat is not recommended for ferritic ductile and malleable irons
 - Preheat of up to 320°C for pearlitic irons
- Ni, 55Ni-45Fe, 53Ni-43Fe-4.5Mn fillers used

White cast iron

- White fracture surface
- No graphite, because carbon forms Fe_3C or more complex carbides
- Abrasion resistant
- Often alloyed
- Australian Standard DR20394 “Wear resistant white cast irons”

Effects of alloy elements

- Promote graphite (Si, Ni)
- Promote carbides (Cr)
- Affect matrix microstructure
 - Ferrite, pearlite, martensite or austenite
- Corrosion resistance (Cr)
- Specific effects

Increasing carbon

- Increases depth of chill in chilled iron
- Increases hardness
- Increases brittleness
- Promotes graphite during solidification

Increasing silicon

- Lowers carbon content of eutectic
- Promotes graphite on solidification
 - Reduces depth of chill
- Negative effect on hardenability
 - Promotes pearlite over martensite
- Raises M_s if martensite forms
- Can improve resistance to scaling at high temperature

Manganese and sulphur

- Each alone increases depth of chill
- Together reduces effect of other (MnS)
- Mn in excess scavenges S and stabilises austenite
- Solid solution strengthener of ferrite / pearlite
- Sulphur lowers abrasion resistance

Phosphorus

- Mild graphitiser
 - Reduces chill depth
 - Considered detrimental in alloy cast irons

Chromium

- Main uses:
 - Forms carbides
 - Gives corrosion resistance
 - High temperature stability
- Up to 3% - no effect on hardenability
- More than 10% - M_7C_3 carbides stronger and tougher than M_3C

High chromium irons

- 12 to 28% chromium
- Less effect on hardenability than in steels
- Mo, Ni, Mn, and Cu also added for hardenability to give martensite

Nickel

- Promotes graphite
- Increases strength of pearlite
- Increases hardenability
 - 2.5 to 4.5% Ni-Hard irons
- Stabilises austenite
 - Over 6.5%

Ni-hard irons

- Grinding balls
- 1-2.2 Si, 5-7 Ni, 7-11 Cr
- M_7C_3 eutectic carbides in martensite

Copper

- Suppresses pearlite formation in martensitic irons
 - Synergistic effect with Mo
- 3 to 10% in some high Ni grey irons

Molybdenum

- Increases depth of chill mildly
- Hardens and toughens pearlite
- Suppresses pearlite
- Increases hardenability

Vanadium

- Potent carbide stabiliser
- Increases depth of chill
- 0.1 to 0.5%

Inoculants

- Ferrosilicon as graphitiser
- Mg and Ce as spheroidisers
- Tellurium, bismuth and vanadium promote carbides in white irons

Abrasion resistant irons

- Pearlitic white irons
 - Cheap but wear more quickly
- Martensitic white irons
 - More expensive but better wearing
- ASTM A532-75A

Can be heat treated

- Stress relief up to 700°C
- Tempering of martensite
- Subzero treatment to remove retained austenite
- Annealing for machining followed by QT

Microstructures

- Pearlite and ferrite in Fe_3C matrix
- Austenite / martensite in Fe_3C matrix
- M_7C_3 in a martensite matrix

Abrasion resistance

- Depends on cast iron
- Depends also on abrasive and environment
 - Eg Silicon carbide wears martensitic and pearlite equally
 - Silica wears martensitic irons much less than pearlitic ones

NON-FERROUS METALS AND ALLOYS

Al, Cu, Zn, Mg, Ti, Ni, Co, W, V ...
and their alloys – all except of Fe and
ferrous alloys (*steels and cast irons*)

Classification of non-ferrous materials (1)

a) Density based:

- light metals and alloys $\rho < 5000 \text{ kg/m}^3$ (Mg, Al, Ti)
- medium metals and alloys $\rho = 5000 \dots 10000 \text{ kg/m}^3$ (Sn, Zn, Sb, Cr, Ni, Mn, Fe, Cu)
- heavy metals and alloys $\rho > 10000 \text{ kg/m}^3$ (Pb, Ag, Au, Ta, W, Mo)

b) Melting temperature based:

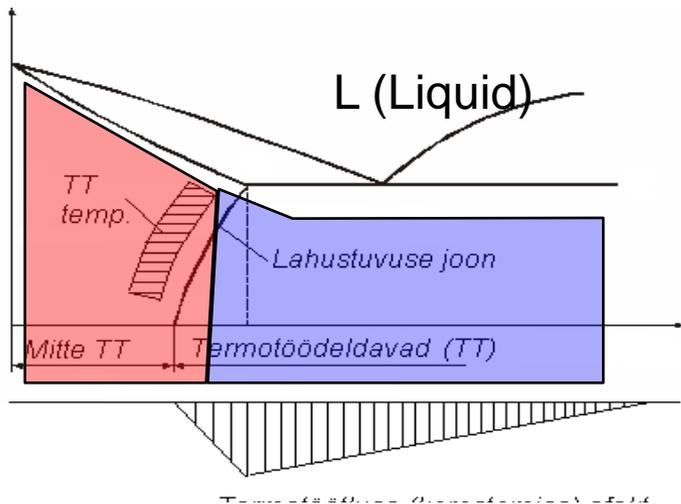
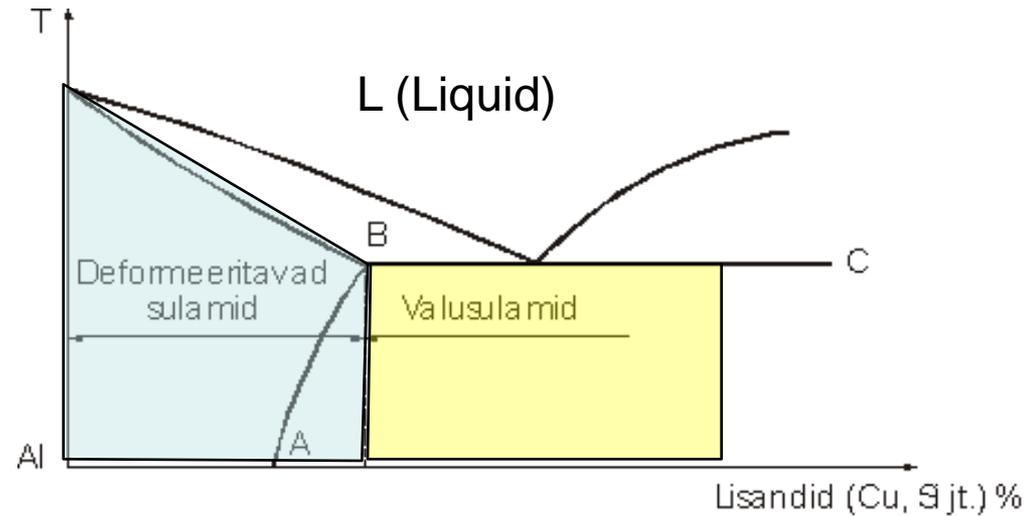
- low melting point $T_m < T_m^{\text{Pb}} = 327 \text{ }^\circ\text{C}$ (Sn, Pb, Bi)
- medium melting point = $327 \dots 1539 \text{ }^\circ\text{C}$ (Al, Mg, Mn, Cu, Ni, Co, Ag, Au)
- refractory $T_m > T_m^{\text{Fe}} = 1539 \text{ }^\circ\text{C}$

Element	Ti	Cr	V	Nb	Mo	Ta	W
$T_m, \text{ }^\circ\text{C}$	1660	1875	1900	2415	2610	2996	3410

Classification of non-ferrous materials(2)

c) Manufacturing based (schematic classification by phase diagram):

- deformable alloys 
- cast alloys 



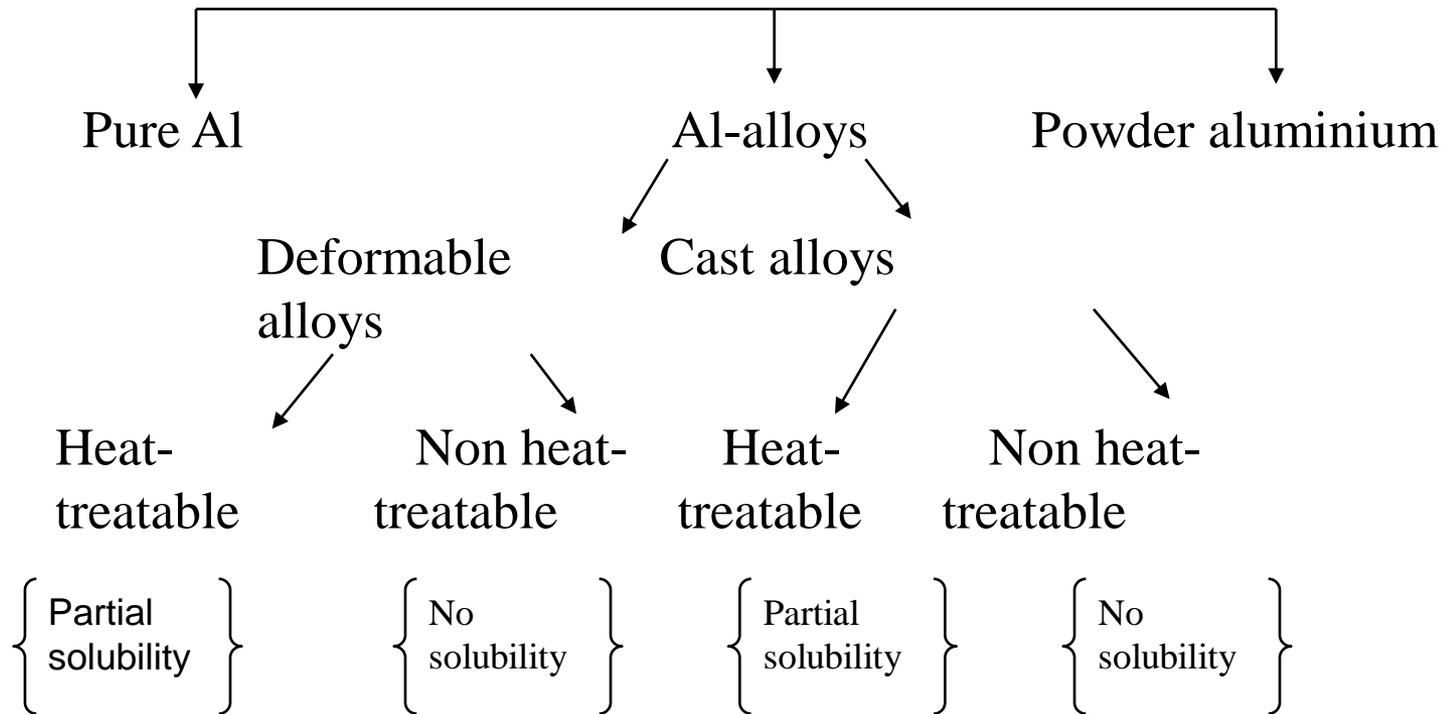
The heat treatment effect

d) Heat treatment based:

HT: annealing, hardening, ageing

- non heat treatable  (no solubility)
- heat treatable (HT) 

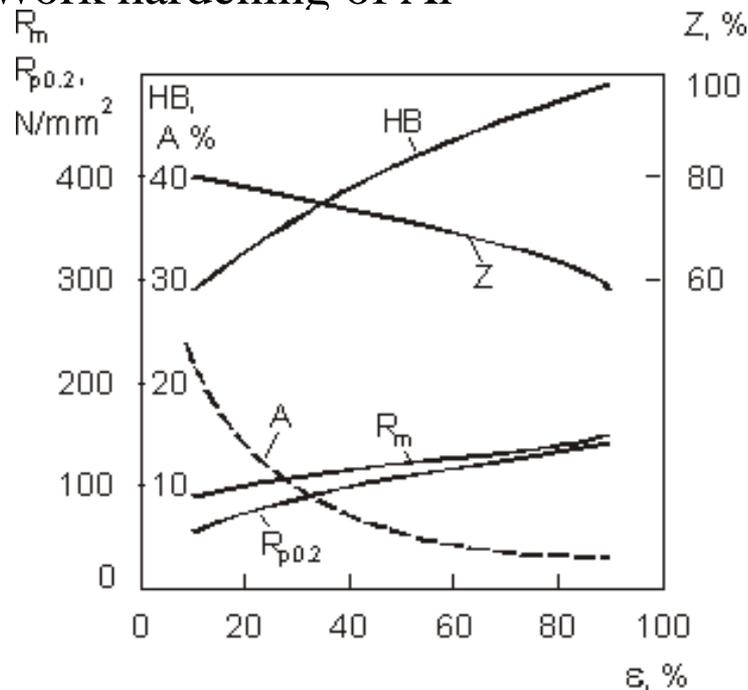
Aluminium and aluminium alloys



Pure Al

- Metallurgical (99,5...99,8% Al)
 - Refined (up to 99,9% Al)
- Al 99,9% $R_m = 70...135 \text{ N/mm}^2$

Work hardening of Al



Conditions designations

O – annealed

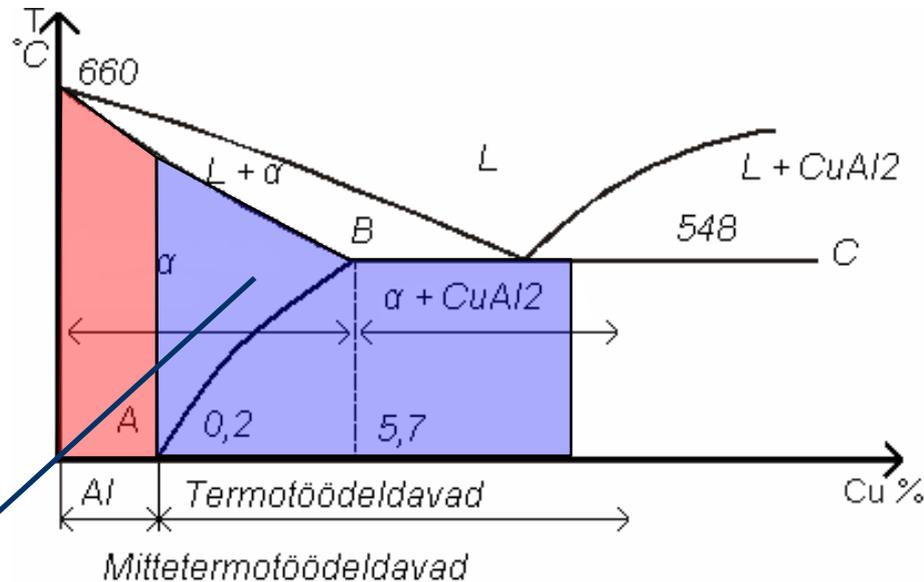
H – work hardened

(degree of hardening H1-H9)

W – quenched

T – quenched and aged (T1-T9)

Heat treatment of Al-alloys (1)



Quenching \rightarrow water \rightarrow α -structure $R_m, R_{p0,2} \downarrow; A, Z \uparrow$

Ageing: \leftarrow naturally aged (20°C) \rightarrow structure $\alpha + \text{Guinier`-Preston zones}$

artificially aged $R_m, R_{p0,2} \uparrow, A, Z \downarrow$

Result –
precipitation
hardening

low ($100 \dots 150^{\circ}\text{C}$)

high ($200 \dots 250^{\circ}\text{C}$)

($R_{p0,2}/R_m = 0,6 \dots 0,7$)

($R_{p0,2}/R_m = 0,9 \dots 0,95$)

Designation system of Al and Al-alloys

(EVS-EN573 and 1780)

Designation

(chemical composition based)

- deformable alloys – EN-AW...(EN-AW-AlCu4Mg1)
- cast alloys – EN-AC...(EN-AC-AlSi11)

Designation of heat treatment (EN515)

- O – annealed (for ex. 01, 02, 03)
- H – work hardened (for ex. H1, H2...H9)
- W – quenched
- T – heat treated (for ex. T1, T2...T10, T31, T3510)

Mainly used: T4 – quenching + natural ageing

T6 – quenching + artificial ageing

Designation system of Al and Al-alloys(2)

Materials numbers

Deformable alloys

Series	1000 – pure Al
	2000 – Al-Cu-alloys (for ex EN-AW-2014)
	3000 – Al-Mn-alloys
	4000 – Al-Si-alloys
	5000 – Al-Mg-alloys
	6000 – Al-Mg-Si-alloys
	7000 – Al-Zn-alloys
	8000 – Al-Fe-alloys

Cast alloys

Series	10000 – pure Al
	20000 – Al-Cu-alloys
	40000-48000 – Al-Si-alloys (for ex EN-AC-44000)
	50000 – Al-Mg-alloys
	70000 – Al-Zn-alloys

Aluminium alloys (1)

Deformable alloys

- Deformable and heat treatable

	Solubility
1) Al-Cu-Mg-alloys (duraluminium)	Cu → 5,7%
2) Al-Cu-Mg-Si-alloys (forgable)	Mg → 14,9%
3) Al-Mg-Si-alloys (corrosion resistance)	
4) Al-Zn-Mg-Cu-alloys (high strength)	
5) Al-Cu-Mg-Ni-Fe-alloys (heat resistance)	

$R_m \rightarrow 500 \text{ N/mm}^2$; $R_{p0,2} \rightarrow 390 \text{ N/mm}^2$; $A \rightarrow 25\%$

Aluminium alloys (2)

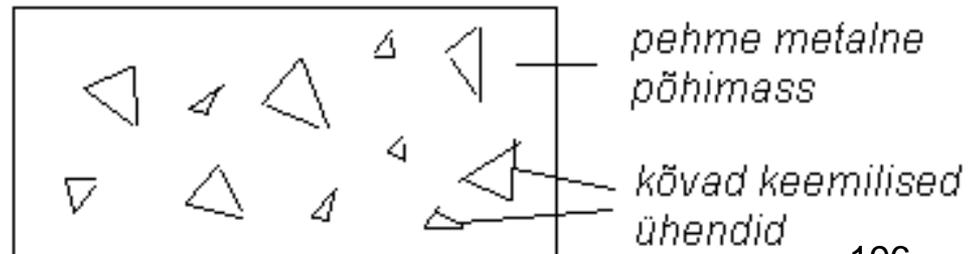
- Deformable and non heat treatable

- 1) Al-Mn-alloys 1...2% Mn
- 2) Al-Mg-alloys (magnalium) 2...5% Mg

$R_m \rightarrow 300 \text{ N/mm}^2$; $R_{p0,2} \rightarrow 150 \text{ N/mm}^2$; $A \rightarrow 25\%$

- plane bearing alloys (for mono- and bimetallic bearing shells)

Al-Sn; Al-Ni; Al-Cu-Sb Typical structure of bearing material

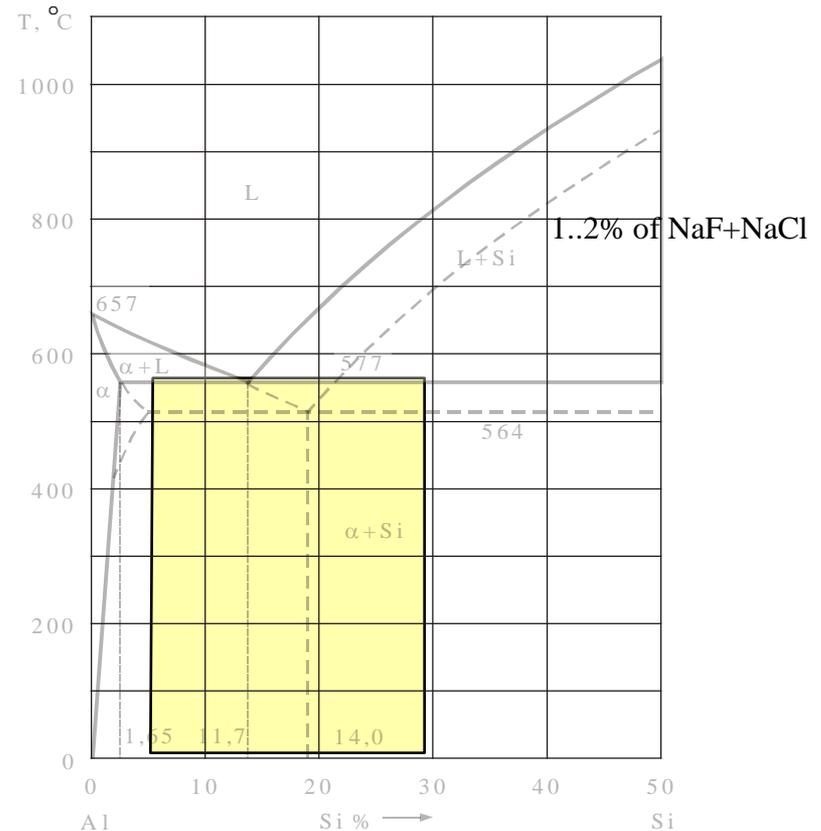


Aluminium alloys (3)

Cast alloys (1)

Requirements:

- low T_m (Al-Si eutectic alloys - 577 °C at 11,7 % Si, by modification 564 °C at 14 % Si)
- high fluidity (short interval of liquidus and solidus lines)



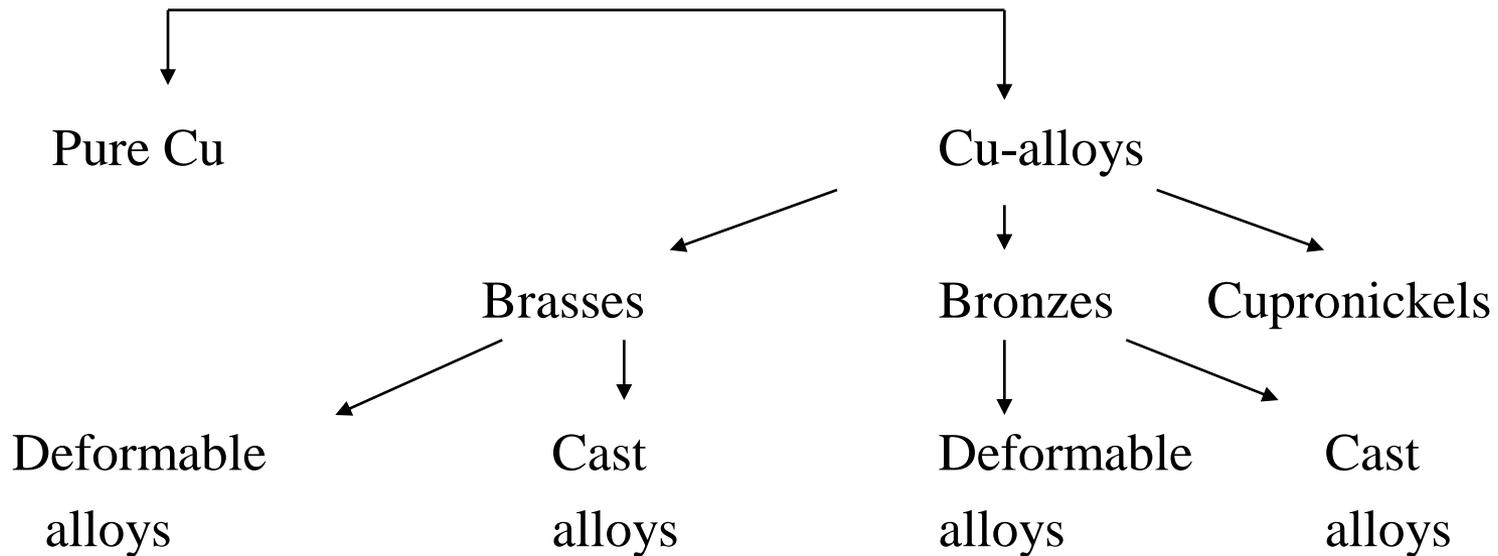
Aluminium alloys (4)

Cast alloys (2)

1) Al-Si-alloys	↓ R_m (250), $A = 1,7 \%$	Pumps and engine bodies, cylinder heads
2) Al-Cu-alloys	$R_m \uparrow$ than I group ↓ high temp. strength	Cylinder heads, apparatuses bodies
3) Al-Si-Cu-alloys	$R_m \uparrow$ than I group ↓ high temp. strength	→ 350 °C
4) Al-Mg-alloys (magnalium)	R_m, A ; good corr. resist.; ↓ castability	→ 100 °C
5) Al- other inclusions	high temperature strength	→ 350 °C parts of aircraft engines

$R_m \rightarrow 340 \text{ N/mm}^2$; $A \rightarrow 8\%$ (depending on casting mode)

Copper and copper alloys

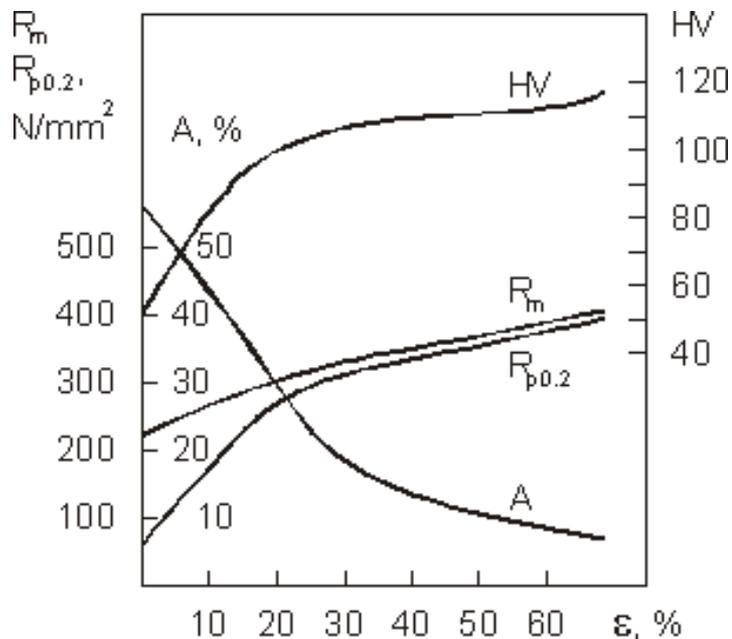


Pure Cu

Annealed Cu (99,85% Cu); $R_m \rightarrow 250 \text{ N/mm}^2$

El. conductivity $1/\rho = 58 \text{ } \Omega \cdot \text{mm}^2/\text{m} = 100\% \text{ IACS}$

Strengthening of Cu at work hardening



Conditions designations

A – elongation (ex A007)

B – bending strength (ex B410)

G – grain size (ex G020)

H – HB or HV (ex H150)

R – tensile strength (ex R500)

Y – yield strength (ex Y460)

Designation system of Cu and Cu-alloys (1)

Designation

- pure Cu – Cu-ETP etc.
- Cu deformable alloys – CuZn36Pb3
- Cu cast alloys – G-CuSn10 (types of casting : GS – sand casting, GM – die casting, GZ – centrifugal casting, GS – cont. casting , GP – pressure die casting)

Conditions (properties) based designation after main designation (EN1173)

Letters

A – elongation (ex Cu-OF-A007)

B – bending strength (ex CuSn8-B410)

D – drawn, without mech. properties

G – grain size (ex CuZn37-G020)

H – hardness (Brinell or Vickers) (ex CuZn37-H150)

M – as manufactured cond. , without mech. properties

R – tensile strength (ex CuZn39Pb3-R500)

Y – yield strength (ex CuZn30-Y460)

Designation system of Cu and Cu-alloys (2)

Materials numbers

Includes 2-digit marking, followed by three digit designating the material group

(000...999)

C – copper based alloy

CB – ingot

CC – casting

CM – master alloy

CR – refined Cu

CS – brazing and welding material

CW – wrought

CX – non standardized material

For example

Deformable copper

Deformable alloys

Cast copper

Cast alloys

Designation

Cu-0F

CuZn37

Cu-C

CuSn10-C

Material No.

CW009A

CW508L

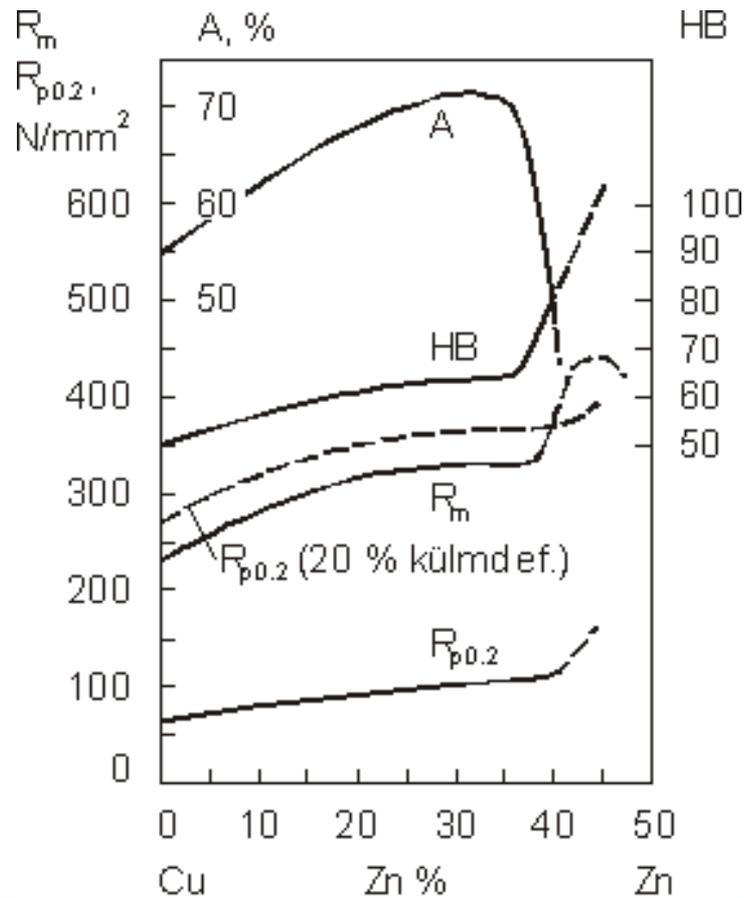
CC040A

CC480K

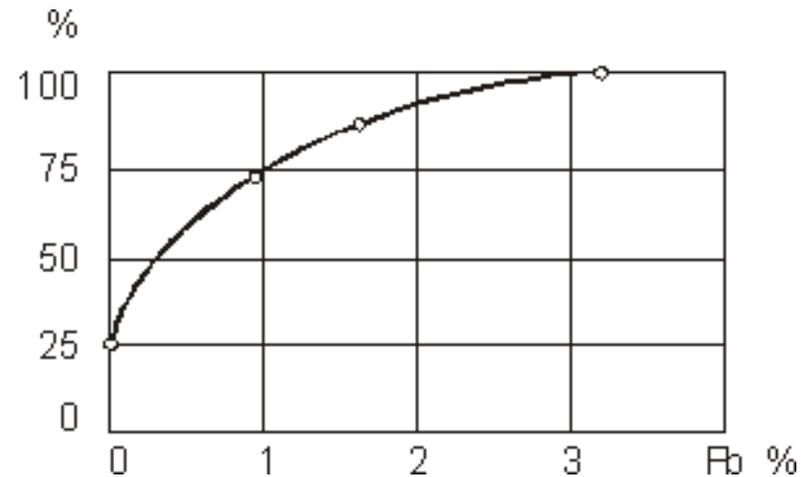
Copper alloys (1)

Cu-Zn alloys – brasses (ex CuZn20)

Influence of Zn to properties



Influence of Pb to machining



Free cutting brass – 100%
(comp.: 40% Zn, 2% Pb) →
CuZn40Pb2

Copper alloys (2)

Cu-Ni alloys (\rightarrow 50% Ni)

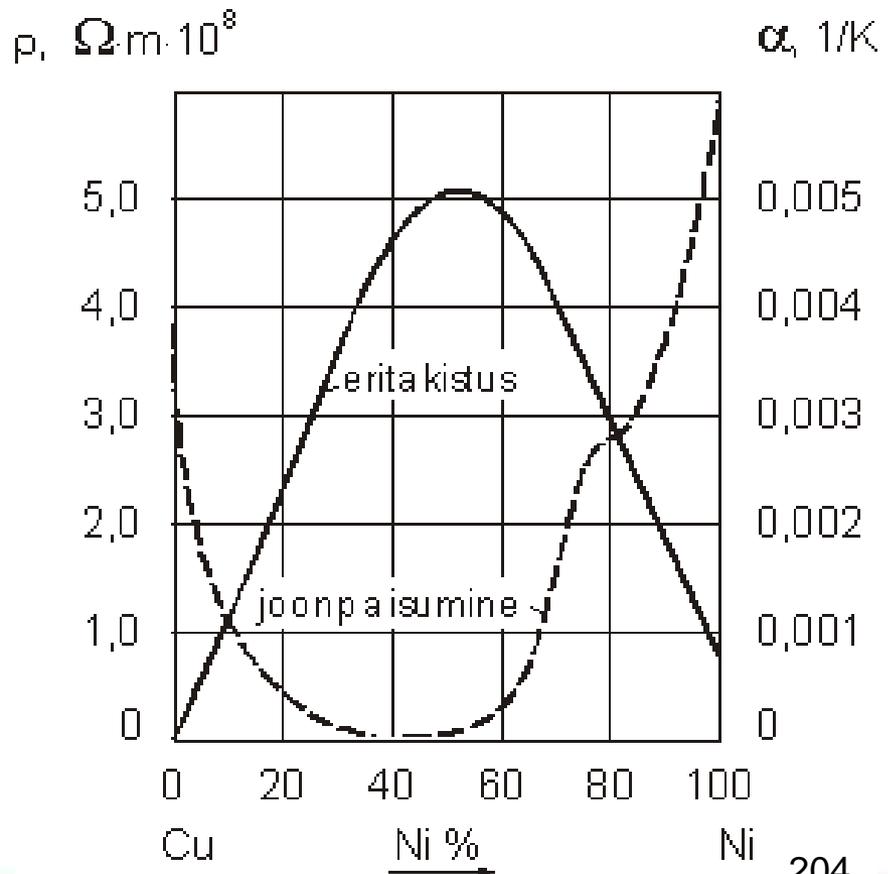
- permanent CTE
(constantan) – 45% Ni
- corrosion resistant
(Ni+Fe+Mn) – 30% Ni

Cu - 25% Ni

(coin melhor, cupronickel).

Cu - 10-20% Ni + 20-35% Zn

(new silver, alpaca).

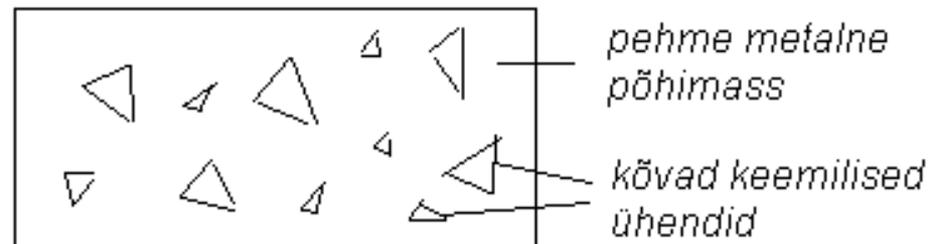


Copper alloys (3)

Cu with other elements - bronzes

- Cu-Sn (tin bronzes) → solubility 15,8% Sn (5...20%)
- Cu-Sn-P (phosphor bronzes) → 0,1%P
- Cu-Pb (lead bronzes) → 20% Pb
- Cu-Al (aluminium bronzes) → 9,8% Al (~10% Al)
 $R_m \rightarrow 700 \text{ N/mm}^2$
- Cu-Si (silicon bronzes) → 5,3% Si (~3% Si)
- Cu-Be (beryllium bronzes) – spring bronze
 $R_m \rightarrow 1400 \text{ N/mm}^2$ (H + AA) Typical structure of bearing material

Application as plane bearing materials (as cast)



Cu-alloys: Estonian* vs Euro coins**

Alloy: Cu93Al5Ni2
 Diameter (mm): 17,20
 Weight (g): 1,87



Alloy: Nordic gold (Cu89Al5Zn5Sn1)
 Diameter (mm): 19,75
 Weight (g): 4,10



Alloy: Cu93Al5Ni2
 Diameter (mm): 18,95
 Weight (g): 2,27



Alloy: Nordic gold (Cu89Al5Zn5Sn1)
 Diameter (mm): 22,25
 Weight (g): 5,74



Alloy: Cu93Al5Ni2
 Diameter (mm): 19,50
 Weight (g): 2,99



Alloy: Nordic gold (Cu89Al5Zn5Sn1)
 Diameter (mm): 24,25
 Weight (g): 7,8



Alloy: Cu89Al5Zn5Sn1
 Diameter (mm): 23,25
 Weight (g): 5,00



Alloy: rim - nickelbronze (Cu75Zn20Ni5);
 center - three layered: cupronickel
 (Cu75Ni25), nickel, cupronickel
 Diameter (mm): 23,25
 Weight (g): 7,50



Alloy: rim - kupronickel;
 center - three layered: nickelbronze,
 nickel, nickelbronze
 Diameter (mm): 25,75
 Weight (g): 8,50



Zinc and zinc alloys

Pure Zn

$T_m - 419\text{ }^\circ\text{C}$

Density – 7140 kg/m³

Good corrosion resistance

Zn- alloys

Zn – Al

Precision casting material

Zn – Al – Cu

Bearing alloy material

Designation

ex ZnAl8Cu1

Material No.

ZP0810

Z – Zn-alloy

P – casting

first two numbers – Al%, 3.– Cu%, 4.–T- rest

Zinc cast alloys (EN12844)

Designation	R_m N/mm ²	$R_{po,2}$ N/mm ²	A %	HB	Application
ZnAl4 (ZP3)	280	200	10	83	Excellent castability, machinability;
ZnAl4Cu1 (ZP5)	330	250	5	92	
ZnAl8Cu1 (ZP8)	370	220	8	100	Universal applications: deep-draw and blow molds for plastics
ZnAl11Cu1 (ZP12)	400	300	5	100	
ZnAl27Cu2 (ZP27)	425	300	2,5	120	

Magnesium and magnesium alloys

Pure Mg

$T_m - 649 \text{ }^\circ\text{C}$

Density – 1740 kg/m^3 (lightest among the engineering materials)

Mg-alloys

- Mg – Mn (up to 2,5 %)
- Mg – Al – Zn (up to 10 % Al, 5 % Zn)

Heat treatment of Mg-alloys

Similar to Al-alloys

Quenching + age hardening (NA, AA \rightarrow MgZn_2 , Mg_4Al_3 jt) $\rightarrow R_m \uparrow$
20 ... 30 %

Mg-alloys

Designation

- deformable (ex MgMn2)
- cast alloys (ex designation MCMgAl8 / material No. MC21110)

Deformable Mg-alloys

Designation	R_m	$R_{p0,2}$	A	Applications
	N/mm ²		%	
MgMn2	200	145	15	Corrosion resistant, weldable cold formable; containers, car , aircraft and machine manufacturing
MgAl8Zn	310	215	6	

Mg cast alloys (EN173)

MCMgAl8Zn1	240	90	8	Good castability. Dynamically loadable. Car and aircraft manufacturing.
MCMgAl6	190-250	120-150	4-14	
MCMgAl4Si	200-250	120-150	3-12	

Titanium and titanium alloys

Pure Ti

$T_m - 1660\text{ °C}$

Density – 4540 kg/m³

Very active to O, C, N → 2x hardness increase

Ti-alloys, classification

Ti – Al – alloys (4...6 % Al) – α -alloys

Ti – Al – Cr, V, Cu, Mo - alloys – $\alpha + \beta$ -alloys

Ti – Al – Mo, Cr, Zr - alloys – β -alloys

Heat treatment of Ti alloys

Heating up to β -area (850...950 °C) and cooling → martensitic transformation.

Ageing (450...600 °C) – max effect by β -stabilisators

(Cr, Mn, Fe, Ni, Cu, Si)

Additional heat treatment – nitriding (750...900 °C)

Titanium alloys

Designation	HB	R_m N/mm ²	$R_{po,2}$ N/mm ²	A %	Applications
Ti 1...3	120-170	290-590	180-320	30-18	Weldable, machinable and cold formable.
Ti1Pd, Ti2 Pd	120-150	290-540	180-250	30-22	Corrosion resistant light constructions.
TiAl6V4	310	900-920	830-870	8	Machine elements in medicine, food, chemical and aircraft industry.
ZnAL11Cu1 (ZP12)	350	≥ 1050	1050	9	

Advantages:

- highest specific strength
- good formability

Disadvantages:

- need for a protective atmosphere at HT (Ar) & problematically casted (reacting with ladle material, ZrO₂ must be used)

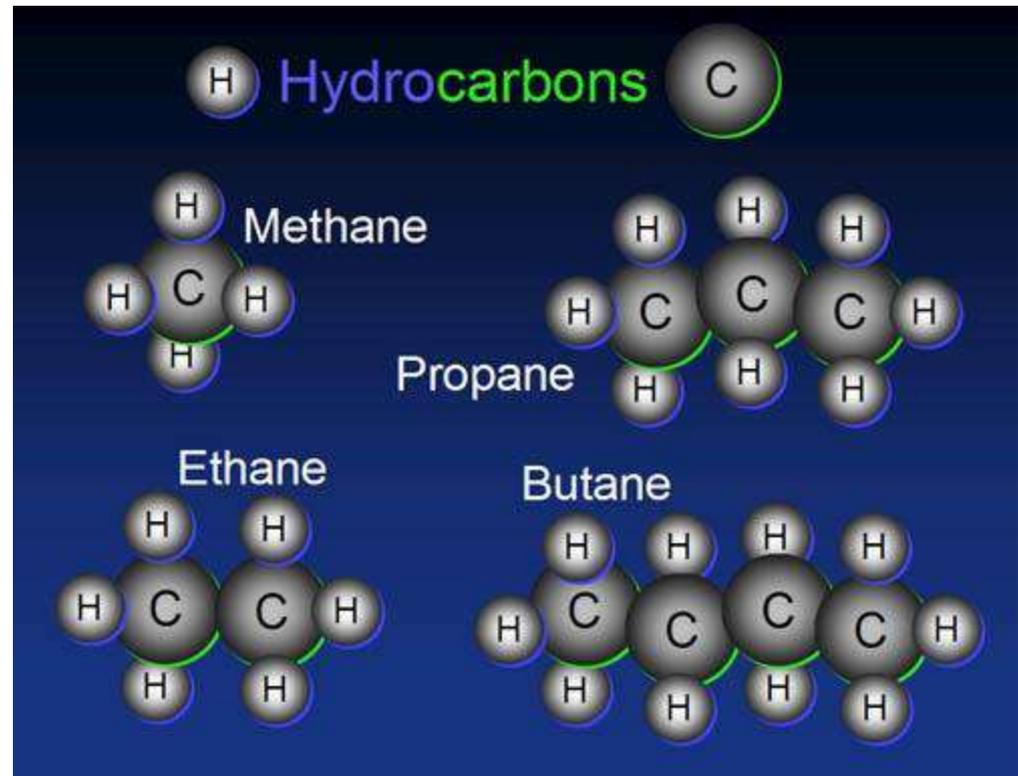
UNIT V

- **Engineering materials –IV:** Ceramics, Polymers and composites: Crystalline ceramics, glasses, cermet's: Structure, properties and applications. Classification, properties and applications of composites, Classification, properties and applications of polymers.

HYDROCARBONS

ex: Alkanes

- 1 – Meth-
- 2 – Eth-
- 3 – Prop-
- 4 – But-
- 5 – Pent-
- 6 – Hex-
- 7 – Hept-
- 8 – Oct-
- 9 – Non-
- 10 – Dec-
- 11 – Undec-
- 12 – Dodec-



Hydrocarbons at Room Temperature

- Gas

- Methane
- Ethane
- Propane
- Butane

- Liquid

5 to 19
Carbons

- Waxy

20 to 40
Carbons

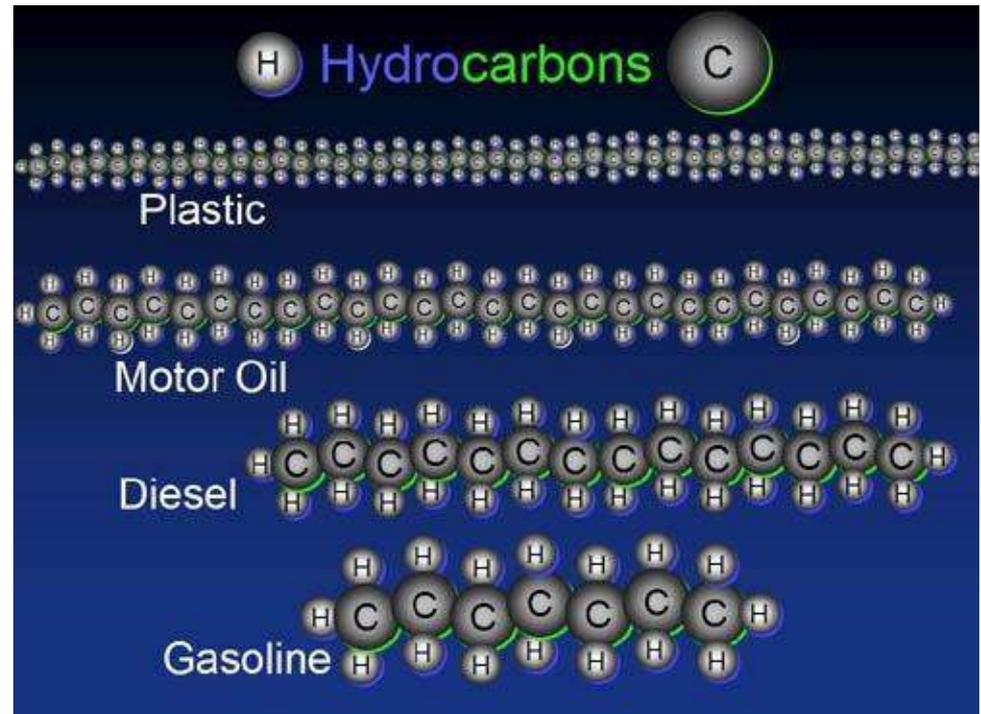
- Plastic

40 or more
Carbons

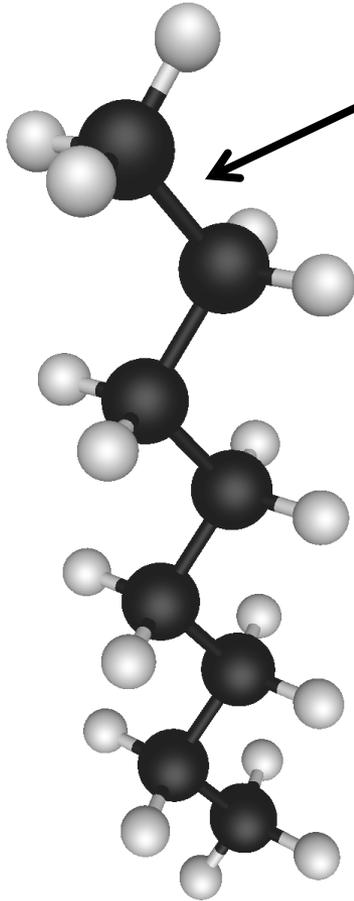


What other material properties change?

- Viscosity
- Hardness
- Toughness
- Flammability



Bonding



- Covalent
- Ionic (NaCl)
- Polar (H₂O)
- Van der Waal

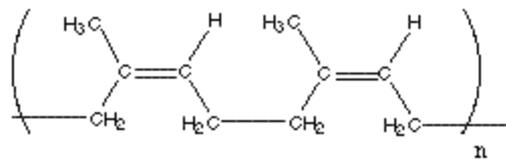


Rubber Tree

- Sap:
 - Sticky
 - Viscous
 - Gooney
- Goodyear
 - Experiment
 - Luck
 - Profit (\$0)

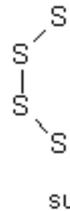


Vulcanization

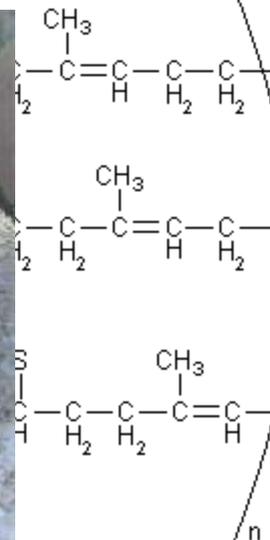


poly(isoprene)

+



cross-linked poly(isoprene)

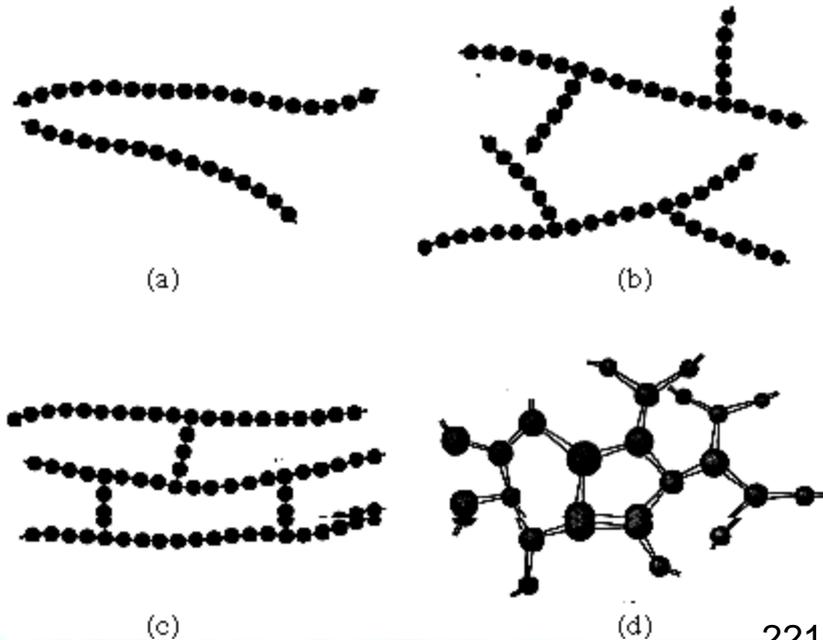


Time for an Activity!

- Please find a partner.
- Follow me into the hall.

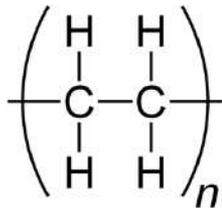
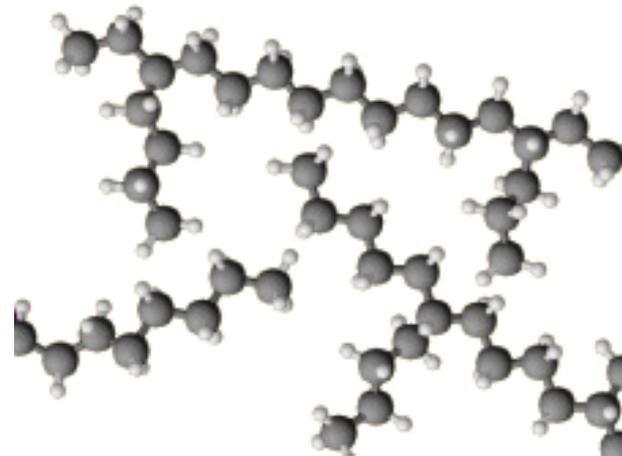
Molecular Structure of Polymers

- **Linear**
 - High Density Polyethylene (HDPE), PVC, Nylon, Cotton
- **Branched**
 - Low Density Polyethylene (LDPE)
- **Cross-linked**
 - Rubber
- **Network**
 - Kevlar, Epoxy



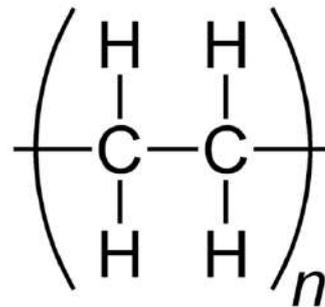
Chain Length: 1000 - 2000

Low-Density Polyethylene (LDPE)

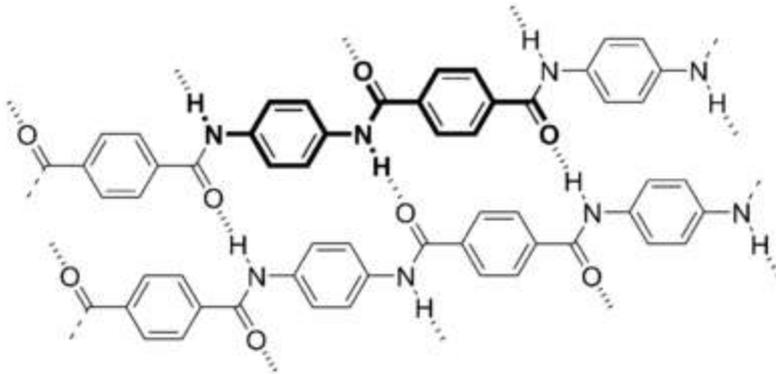


Chain Length: 10,000 – 100,000

High-Density Polyethylene (HDPE)



Kevlar



Strong Network of **Covalent Bonds**
And Polar **Hydrogen Bonds**



Inorganic Polymers

III	IV	V
5 B 10.811	6 C 12.011	7 N 14.0067
13 Al 27.98	14 Si 28.086	15 P 30.974
31 Ga	32 Ge	33 As

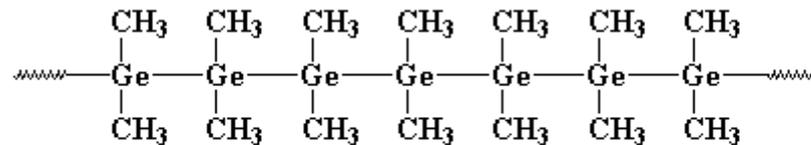
- Silicon (Si)



Inorganic Polymers

III	IV	V
5 B 10.811	6 C 12.011	7 N 14.0067
13 Al 27.98	14 Si 28.086	15 P 30.974
31 Ga	32 Ge	33 As

- Silicon (Si)
- Germanium (Ge)



polydimethylgermane

Inorganic Polymers

III	IV	V
5 B 10.811	6 C 12.011	7 N 14.0067
13 Al 27.98	14 Si 28.086	15 P 30.974
31 Ga	32 Ge	33 As

- Silicon (Si)
- Germanium (Ge)
- Boron-Nitrogen (B – N)

Inorganic Polymers

III	IV	V
5 B 10.811	6 C 12.011	7 N 14.0067
13 Al 27.98	14 Si 28.086	15 P 30.974
31 Ga	32 Ge	33 As

- Silicon (Si)
- Germanium (Ge)
- Boron-Nitrogen (B – N)
- Aluminum – Nitrogen (Al – N)
- On and on

Conclusions:

- Polymers make up all sorts of materials that are all around us!
- They can have a **huge** range of material properties based on their:
 - Functional Groups
 - Structure
 - Backbone
- Keep thinking about how **chemical interactions on the nano-scale** correspond to **material properties on the macro-scale**

ABRASIVES

- Four Areas of Cabinet Manufacturing
 - machining room
 - sanding room
 - assembly room
 - finishing room

ABRASIVES

- Machining Room
 - sawing
 - shaping
 - carving
 - dimensioning
 - turning
 - Abrasive Machinery Used
 - [abrasive sanders](#)
 - wide belt sanders
- 30% of abrasives used are consumed in this area.

ABRASIVES

- Sanding Room - Dimensioned pieces are brought to closer tolerances
- Abrasive Machinery Used:
 - [wide belt sanders](#)
 - [drum sanders](#)
 - [molding sanders](#)
 - [stroke sanders](#)
 - [brush sanders](#)

48% of abrasives used are consumed in this area

ABRASIVES

- Cabinet Room – Parts are assembled and prepared for final finishing.

- Touch-up machined parts
- Remove excess glue
- Repair other defects

Abrasive Machinery Used – portable belt sanders, dual action sanders, disk sanders, straight line and hand sanding.

10% of abrasives used are consumed in this area

ABRASIVES

- Finish Room – transparent and opaque finishes are applied to cabinetry. Sanding occurs between coats.
- Abrasive Machinery Used – orbital, and hand sanding

12% of abrasives used are consumed in this area

ABRASIVES

- Abrasive Grain
 - Aluminum Oxide – most commonly used
 - synthetic abrasive – hard and tough, used on most metals and woods. self-sharpening
 - color – red brown and white aluminum
 - use - all purpose

ABRASIVES

– Silicon Carbide

- synthetic abrasive – harder and sharper than aluminum oxide however not as tough. Self sharpening
- color- black
- use – sanding between coats of finish also for very soft resinous woods like pine.

ABRASIVES

- Alumina-Zirconia – fairly new
 - synthetic abrasive – extremely tough and self sharpening
 - use – used in heavy duty sanding and abrasive planing

ABRASIVES

- Garnet
 - natural mineral – not as hard and tough as synthetic.
Has widely been replaced by aluminum oxide

ABRASIVES

- Abrasive backings -Paper and Cloth
 - Paper – excellent for hand sanding, disk and sheet power sanding. Also good for belt sanding flat parts
 - Finish – paper backing will often give a finer finish than comparable grit abrasives with cloth backing
 - Identification – Paper is identified by a letter indicating the weight of the paper in reams
 - 1 ream is the weight of 480 24”x36” sheets*

ABRASIVES

- Paper Weights
 - A & B - Lightest weight considered “finishing papers”
 - C & D – Intermediate weight “cabinet papers”
 - » Best for power sanders using sheets or disks
 - E & F – Heavy Weight – Laminated papers. Used for belts where strength is necessary

Abrasives

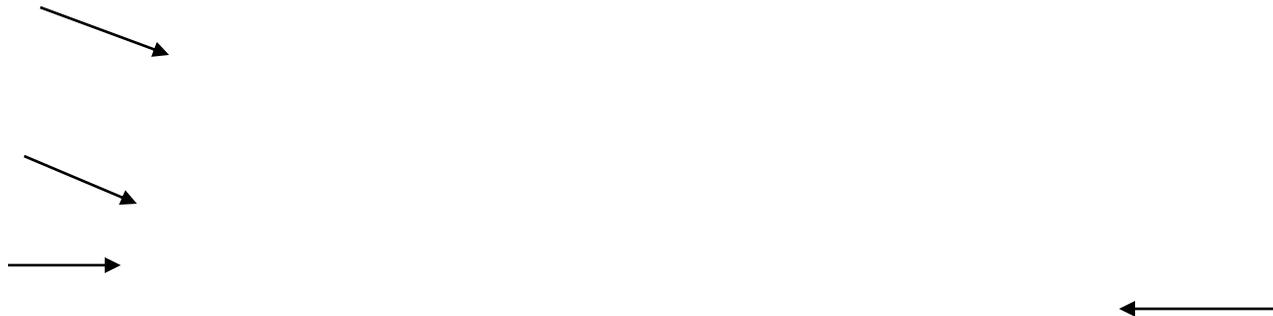
- Cloth Backing – Cotton or Polyester
 - Strong and tear resistant, made with different flexibility
 - Identification – J, X & Y

ABRASIVES

- Cloth Identification
 - J Weight – Where flexibility is necessary such as sanding contours and shapes
 - X Weight – Most common found on virtually all sizes of abrasive belts
 - Y Weight – Very heavy duty sanding

ABRASIVES

- Bonding
 - backing
 - maker coat – holds the grain to the backing
 - size coat - locks the grain together and prevents them from being pulled out of the maker coat
 - abrasive grit
 - most modern abrasives use resins rather than hide glues giving greater flexibility , heat resistance and moisture resistance



ABRASIVES

- Open Coat vs. Closed Coat
 - Closed Coat - most coated abrasives have grit surfaces completely covered by abrasive grain
 - More even scratch pattern gives better finish
 - Open Coat – 50% to 70% coverage good for softwoods, painted surfaces, soft metals, etc.
 - Slightly more flexible than closed coat products
 - Most effective in the coarse to intermediate grit sizes

ABRASIVES

- Sanding Regiment
 - Oak 80 : 100 : 120 : 150
 - Maple 80 : 120 : 150 : 180
 - Cherry 120 : 150 : 180 : 220
 - Soft Woods 120 : 180

ABRASIVES

- Sanding Tips
 - Always sand with the grain
 - Wipe the surface of the work piece frequently with a soft wet cloth or tack cloth
 - Use a strong light to illuminate the work piece from an angle
 - Tap your sanding block frequently to clean the abrasive
 - Stand at the end of the work piece to sand
 - When sanding face frames sand rails then stiles

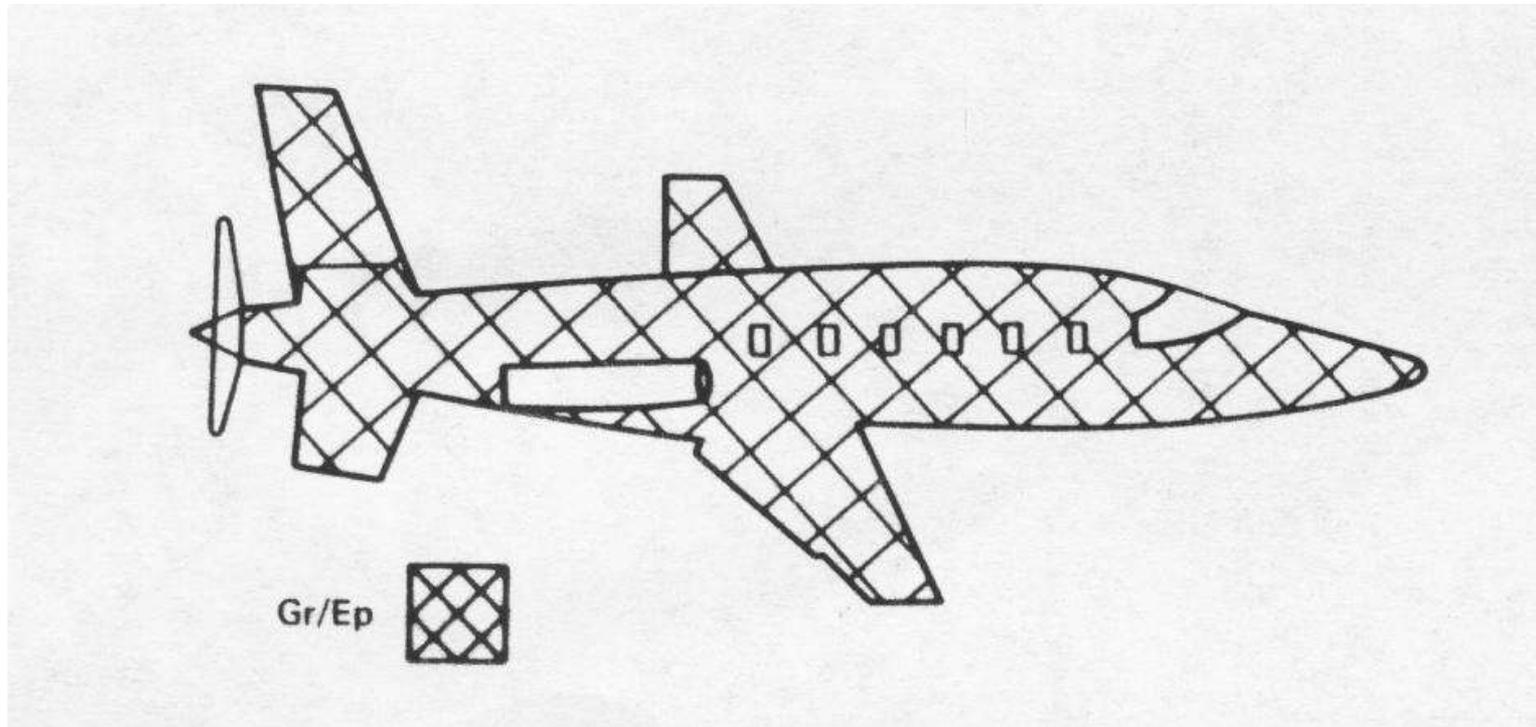
Composite Materials

Introduction

- A Composite material is a material system composed of two or more **macro constituents** that differ in shape and chemical composition and which are insoluble in each other. The history of composite materials dates back to early 20th century. In 1940, fiber glass was first used to reinforce epoxy.
- Applications:
 - Aerospace industry
 - Sporting Goods Industry
 - Automotive Industry
 - Home Appliance Industry

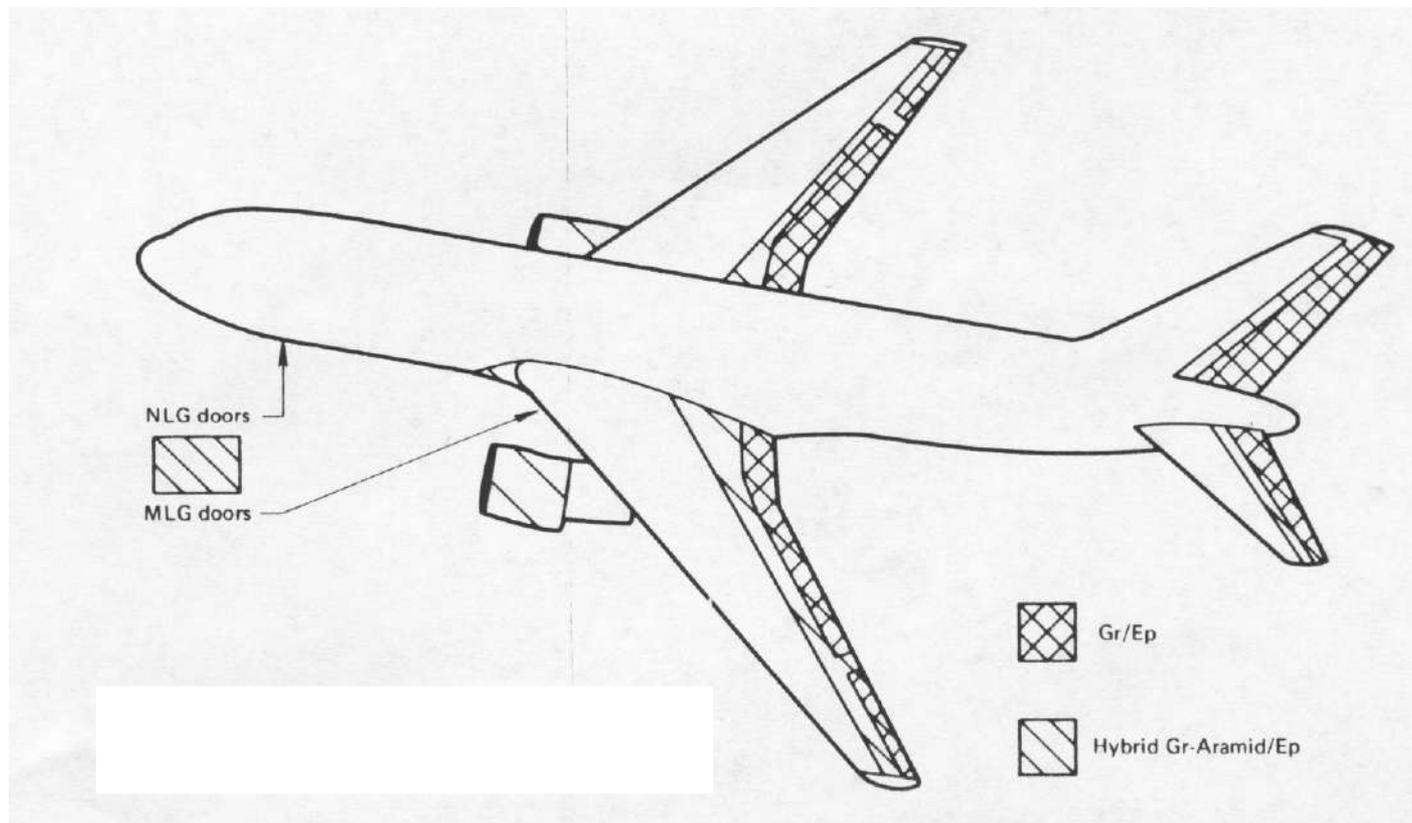
Advanced Aerospace Application:

Lear Fan 2100 “all-composite” aircraft



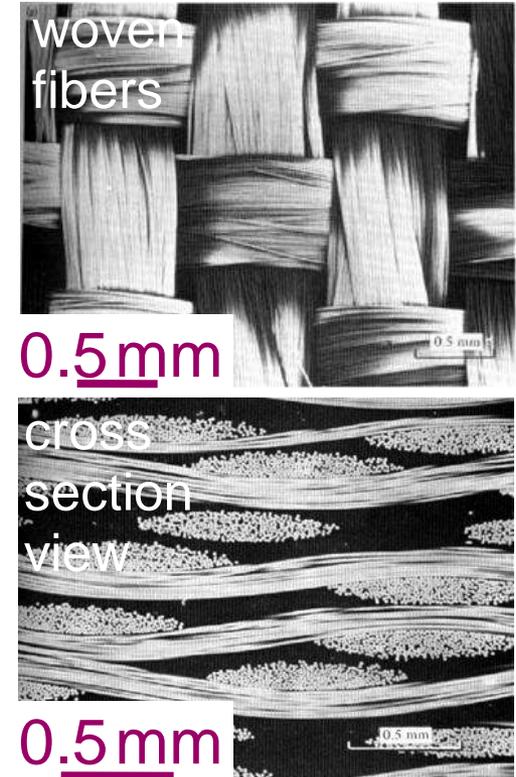
Advanced Aerospace Application:

Boeing 767 (and in 777, 787 airplanes w/ the latest, full wing box is composite):

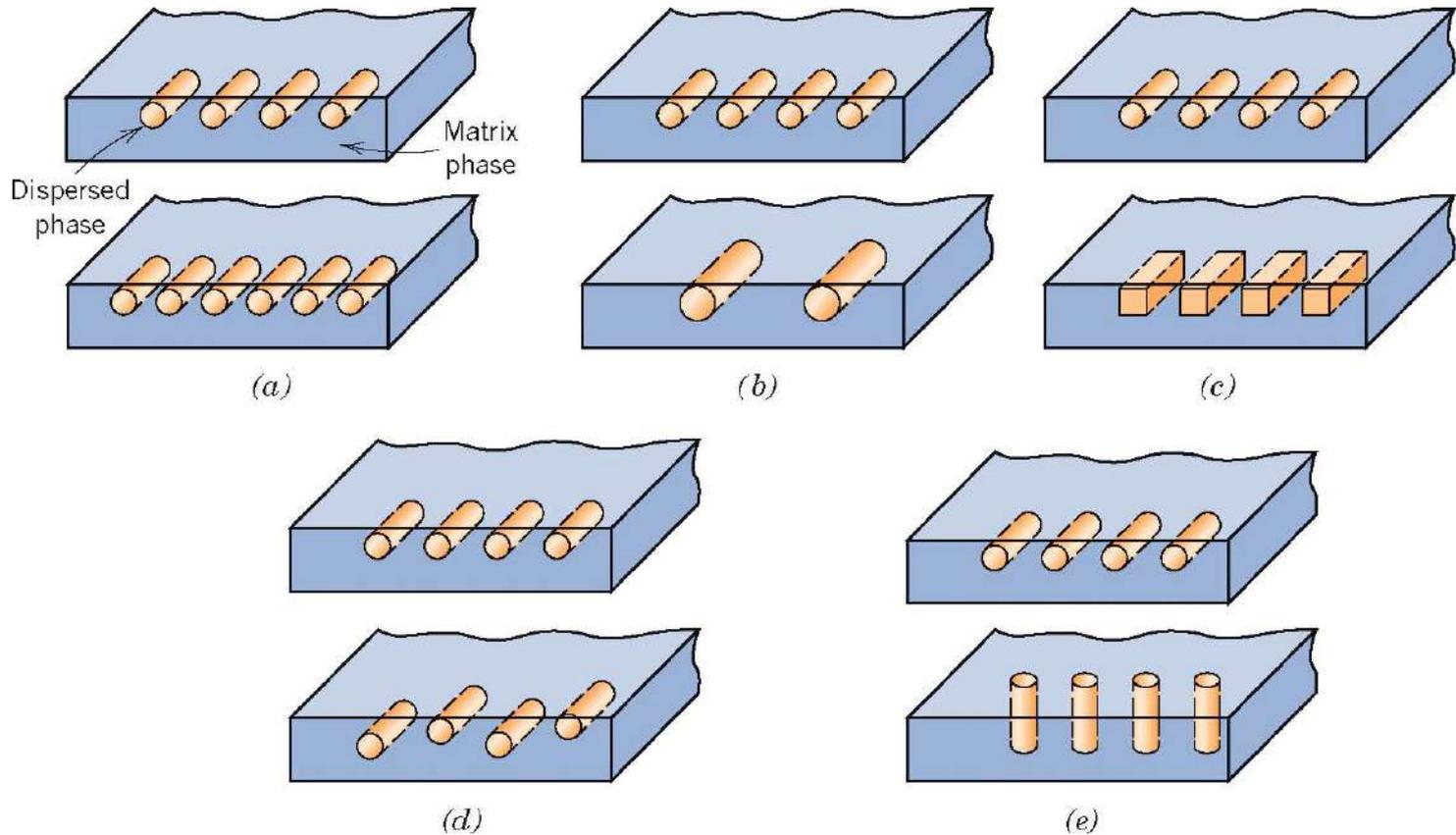


Terminology/Classification

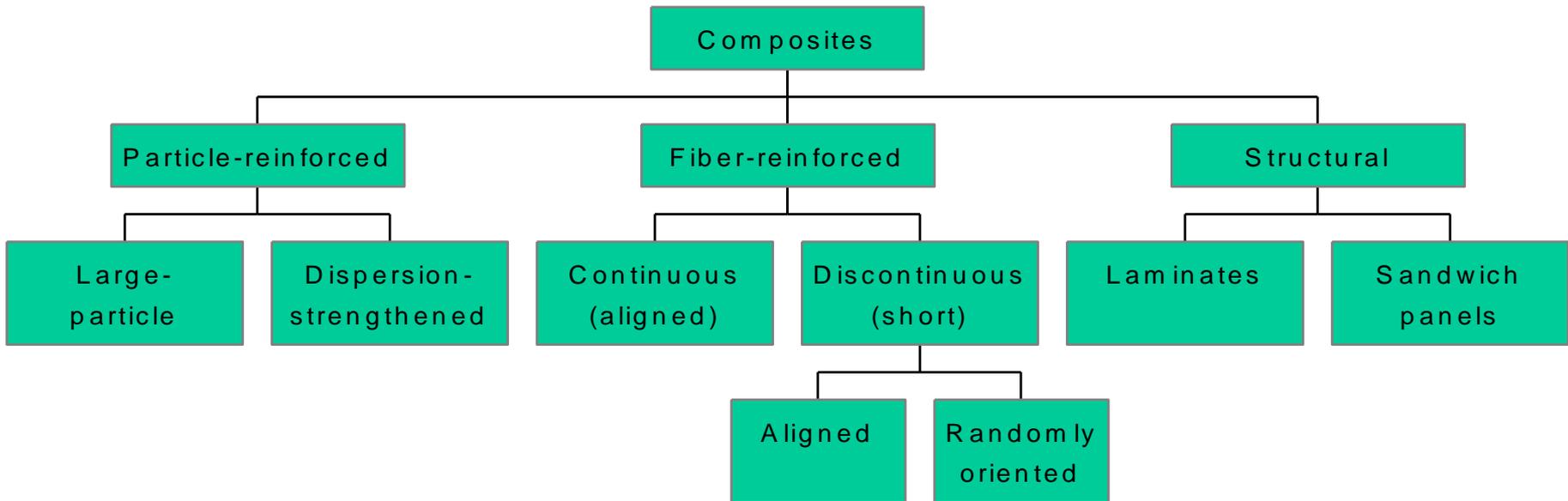
- **Composites:**
 - Multiphase material w/significant proportions of each phase.
- **Matrix:**
 - The continuous phase
 - Purpose is to:
 - transfer stress to other phases
 - protect phases from environment
 - Classification: **MMC**, **CMC**, **PMC**
 - metal → ceramic → polymer
- **Dispersed phase:**
 - Purpose: enhance matrix properties.
 - MMC**: increase s_y , TS , creep resist.
 - CMC**: increase K_c
 - PMC**: increase E , s_y , TS , creep resist.
 - Classification: **Particle, fiber, structural**



Composite Structural Organization: the design variations

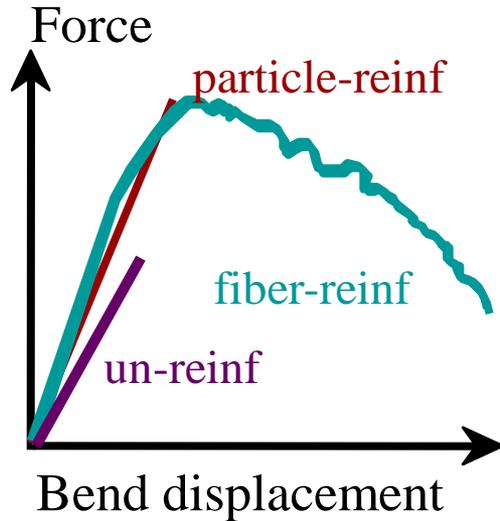


Composite Survey

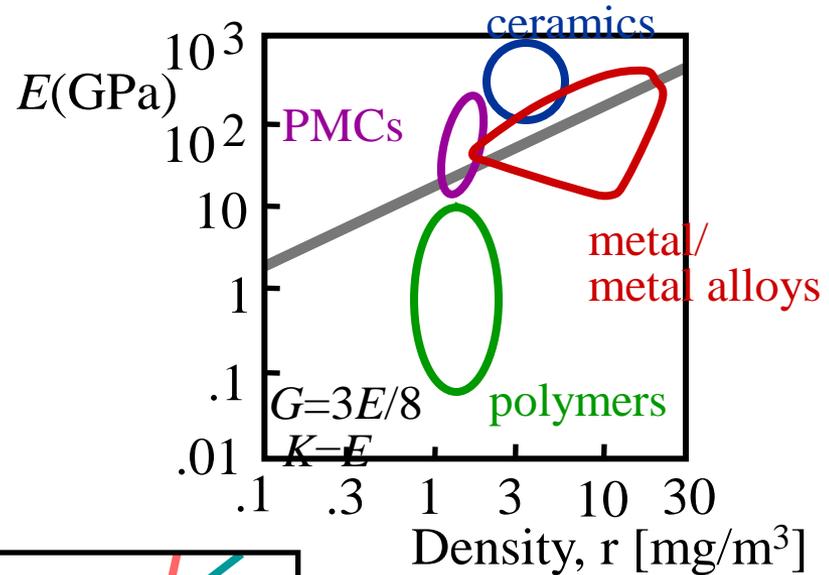


Composite Benefits

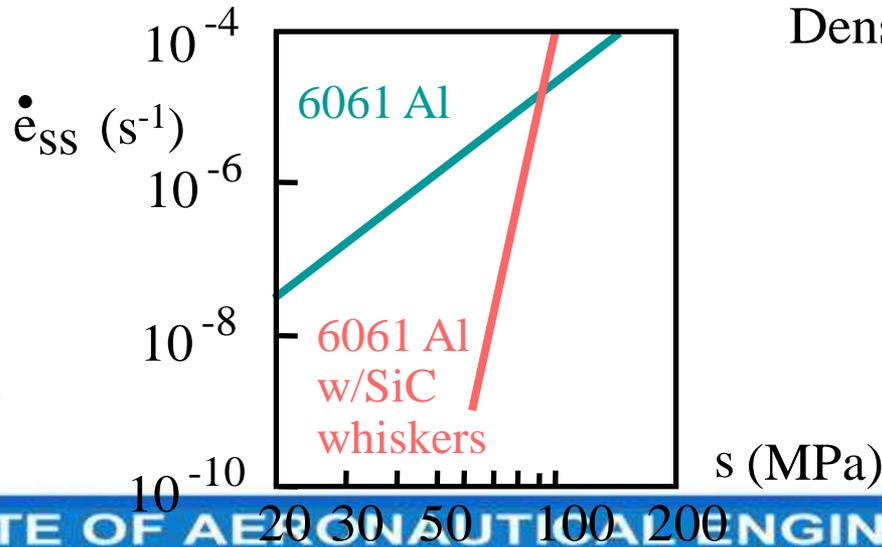
- CMCs: Increased toughness



- PMCs: Increased E/r



- MMCs:
Increased creep resistance



Composite Survey: Particle-I

Particle-reinforced

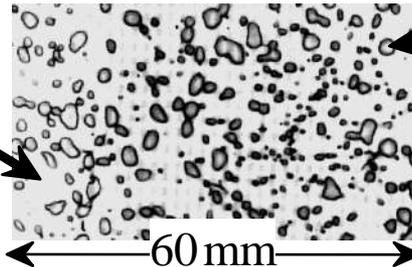
Fiber-reinforced

Structural

- Examples:

- Spheroidite steel

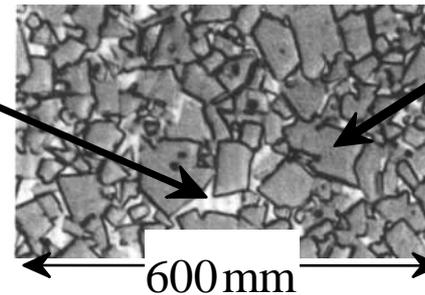
matrix:
ferrite (a)
(ductile)



particles:
cementite
(Fe₃C)
(brittle)

- WC/Co cemented carbide

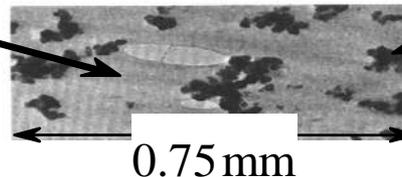
matrix:
cobalt
(ductile)
 V_m :
5-12 vol%!



particles:
WC
(brittle,
hard)

- Automobile tires

matrix:
rubber
(compliant)



particles:
(stiffer)

Composite Survey: Particle-II

Particle-reinforced

Fiber-reinforced

Structural

Concrete – gravel + sand + cement

- Why sand *and* gravel? Sand packs into gravel voids

Reinforced concrete - Reinforce with steel rebar or remesh

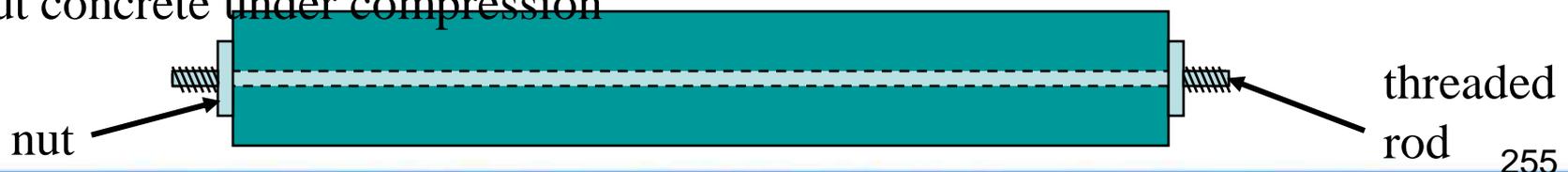
- increases strength - even if cement matrix is cracked

Prestressed concrete - remesh under tension during setting of concrete.

Tension release puts concrete under compressive force

- Concrete much stronger under compression.
- Applied tension must exceed compressive force

Post tensioning – tighten nuts to put under rod under tension but concrete under compression



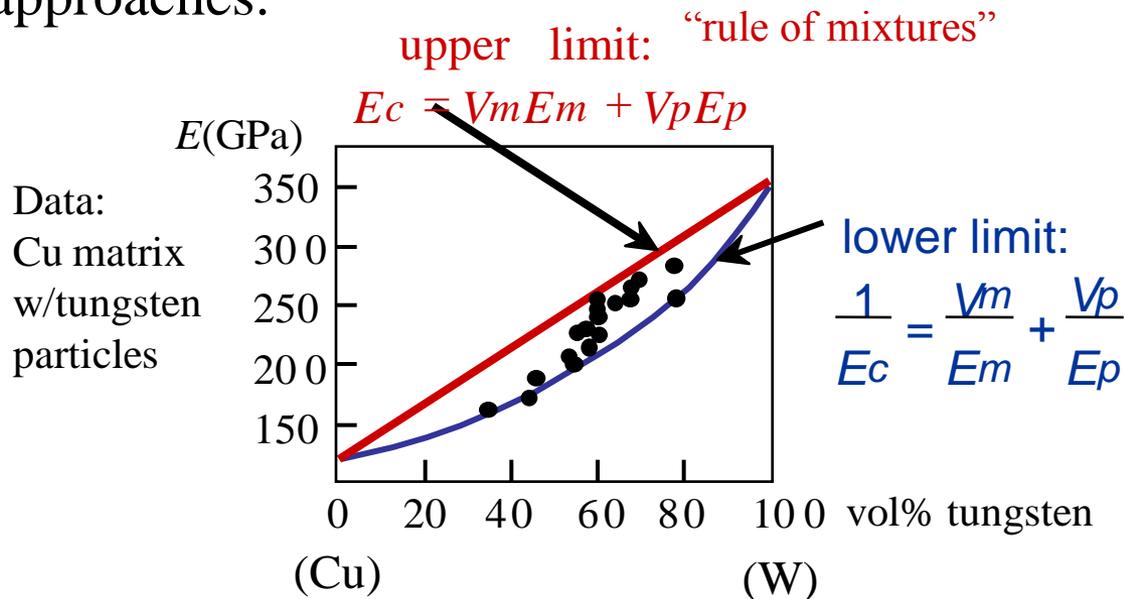
Composite Survey: Particle-III

Particle-reinforced

Fiber-reinforced

Structural

- **Elastic modulus**, E_c , of composites:
-- two approaches.



- Application to other properties:
-- **Electrical conductivity**, s_e : Replace E in the above equations with s_e .
-- **Thermal conductivity**, k : Replace E in above equations with k .

Composite Survey: Fiber

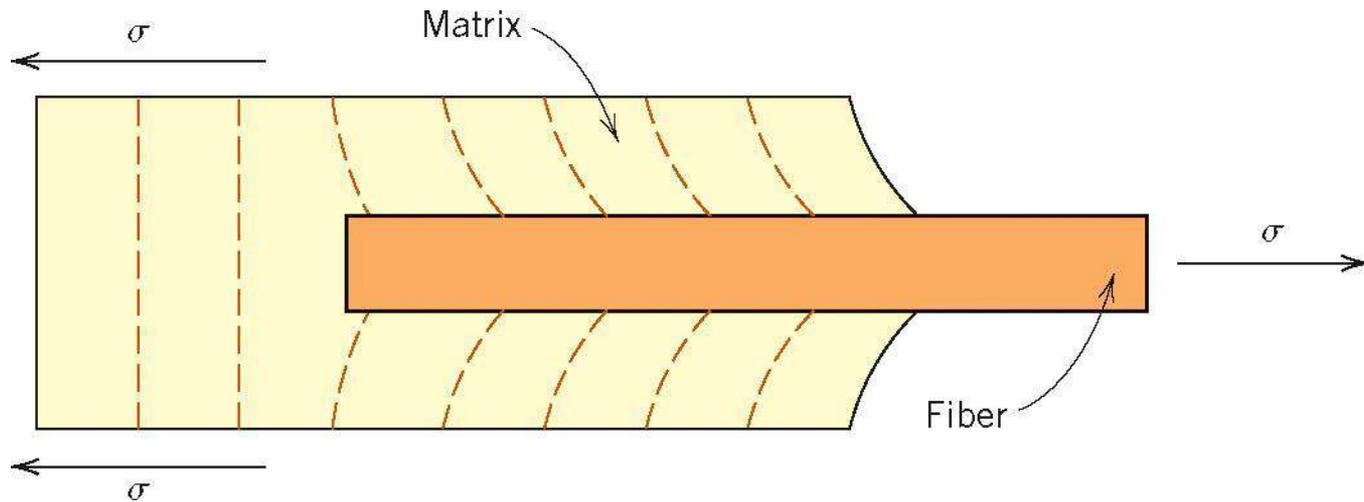
Particle-reinforced

Fiber-reinforced

Structural

- **Fibers themselves are very strong**
 - Provide significant strength improvement to material
 - **Ex: fiber-glass**
 - **Continuous glass filaments in a polymer matrix**
 - **Strength due to fibers**
 - **Polymer simply holds them in place and environmentally protects them**

Fiber Loading Effect under Stress:



Composite Survey: Fiber

Particle-reinforced

Fiber-reinforced

Structural

- Critical fiber length (l_c) for effective stiffening & strengthening:
fiber strength in tension

fiber length $> 15 \frac{\sigma_f d}{\tau_c}$

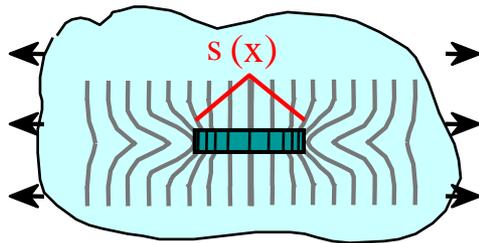
Labels: $\sigma_f d$, fiber diameter, shear strength of fiber-matrix interface, τ_c

- Ex: For fiberglass, a fiber length > 15 mm is needed since this length provides a “Continuous fiber” based on usual glass fiber properties

- Why? Longer fibers carry stress more efficiently!

Shorter, thicker fiber:

fiber length $< 15 \frac{\sigma_f d}{\tau_c}$

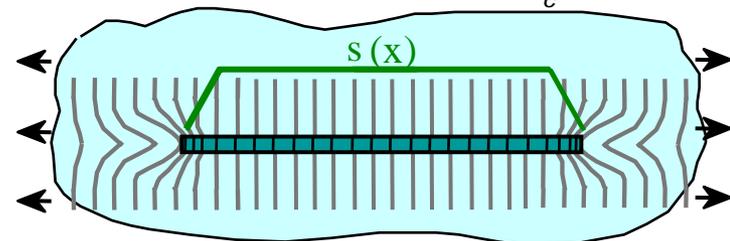


Poorer fiber efficiency

Adapted from Fig. 16.7,
Callister 7e.

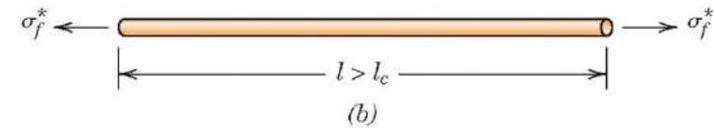
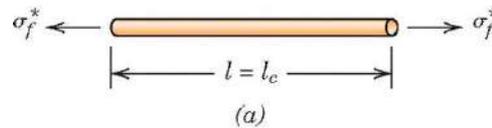
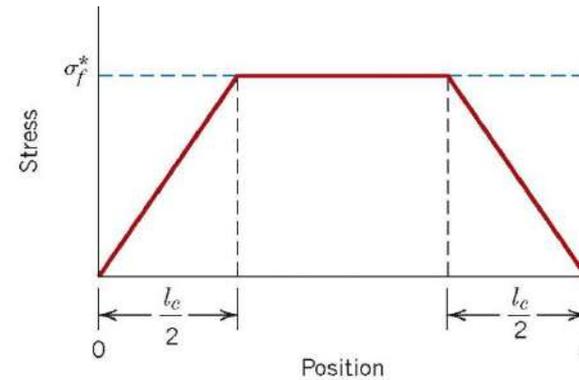
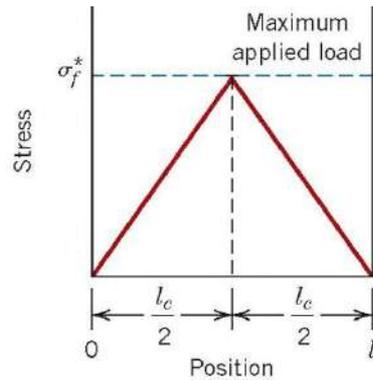
Longer, thinner fiber:

fiber length $> 15 \frac{\sigma_f d}{\tau_c}$

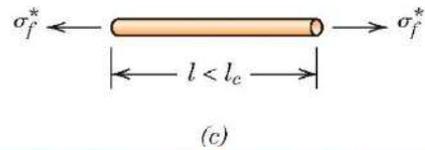
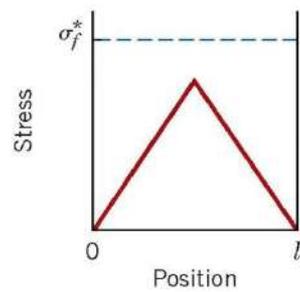


Better fiber efficiency

Fiber Load Behavior under Stress:



$$l_c = \frac{\sigma_f^* d}{2\tau_c}$$



Composite Survey: Fiber

Particle-reinforced

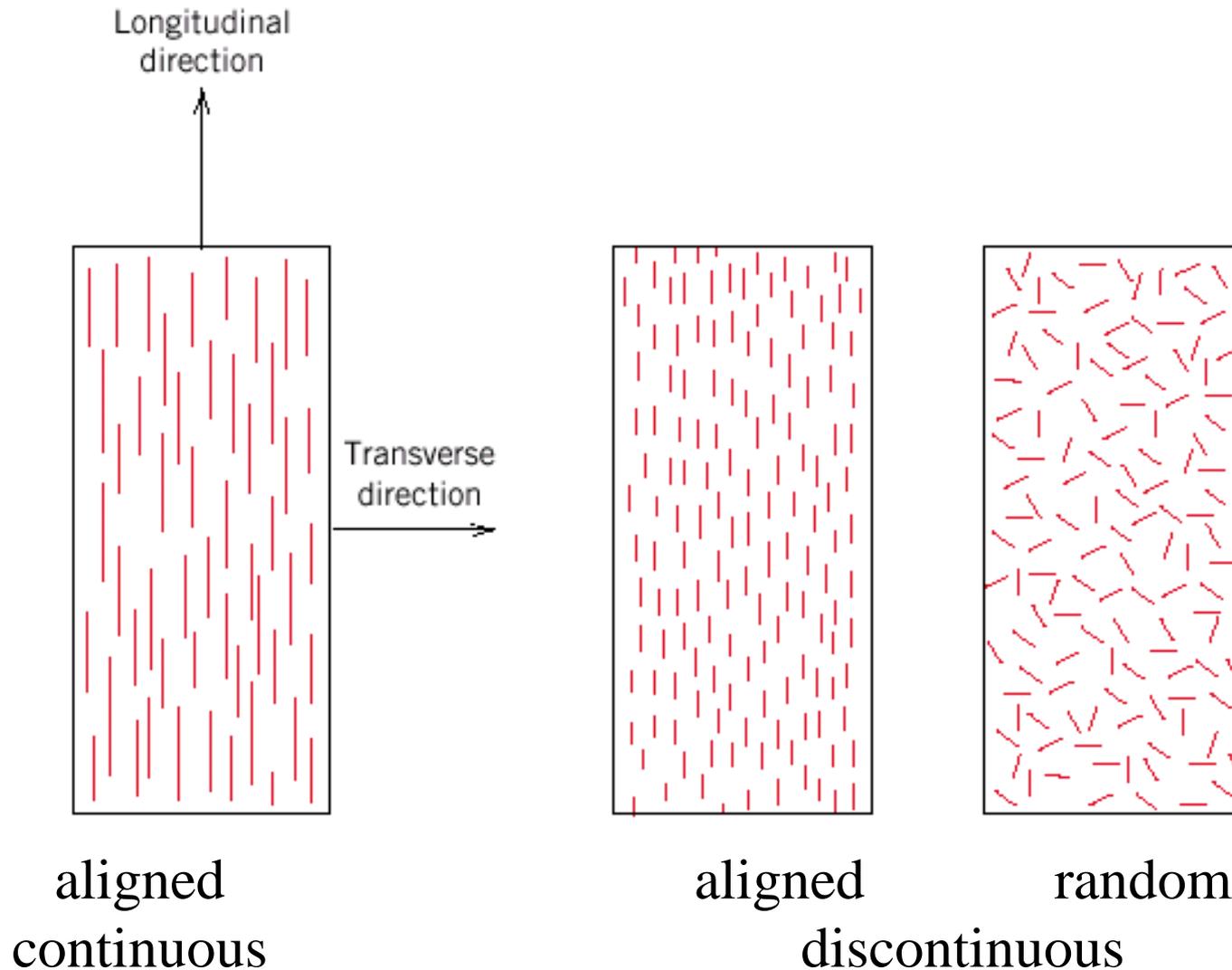
Fiber-reinforced

Structural

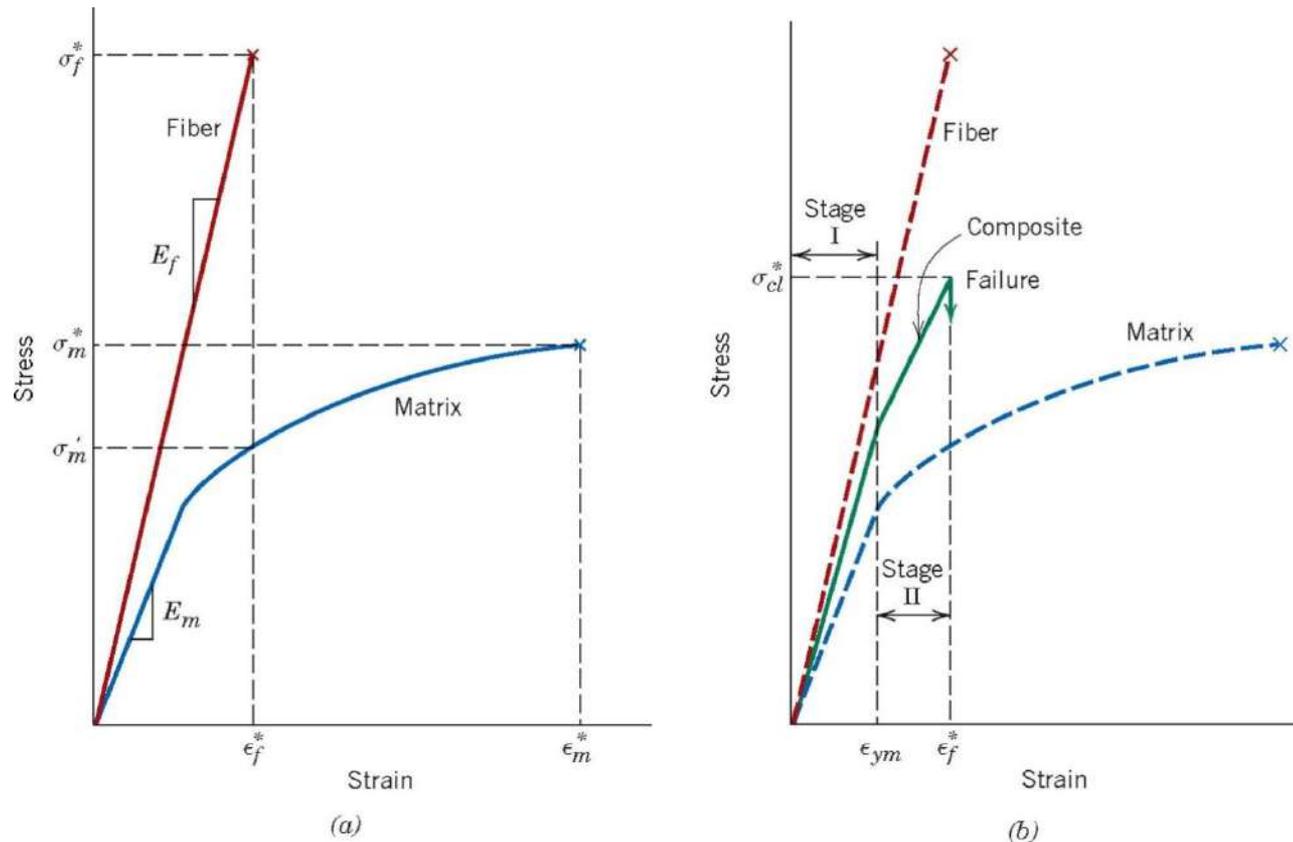
- **Fiber Materials**

- **Whiskers** - Thin single crystals - large length to diameter ratio
 - graphite, SiN, SiC
 - high crystal perfection – extremely strong, strongest known
 - very expensive
- **Fibers**
 - polycrystalline or amorphous
 - generally polymers or ceramics
 - Ex: Al₂O₃ , Aramid, E-glass, Boron, UHMWPE
- **Wires**
 - Metal – steel, Mo, W

Fiber Alignment



Behavior under load for Fibers & Matrix



Composite Strength: Longitudinal Loading

Continuous fibers - Estimate fiber-reinforced composite strength for long continuous fibers in a matrix

- Longitudinal deformation

$$\sigma_c = \sigma_m V_m + \sigma_f V_f \quad \text{but} \quad \epsilon_c = \epsilon_m = \epsilon_f$$

↑ volume fraction ↑ isostrain

$$\therefore E_{ce} = E_m V_m + E_f V_f$$

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

longitudinal (extensional)
modulus

f = fiber
 m = matrix

Remembering: $E = \sigma/\epsilon$
and note, this model corresponds to the “upper bound” for particulate composites

Composite Strength: Transverse Loading

- In transverse loading the fibers carry less of the load and are in a state of ‘isostress’

$$\sigma_c = \sigma_m = \sigma_f = \sigma$$

$$\epsilon_c = \epsilon_m V_m + \epsilon_f V_f$$

$$\therefore \frac{1}{E_{ct}} = \frac{V_m}{E_m} + \frac{V_f}{E_f}$$

transverse modulus

Remembering: $E = \sigma/\epsilon$
and note, this model
corresponds to the “lower
bound” for particulate
composites

An Example:

Example: Given an epoxy/carbon unidirectional continuous fiber composite with $V_f = .60$ and the following fiber and matrix properties:

	Ultimate Strength σ_u psi	Modulus E_L psi
Epoxy	$\sigma_{um} = 8400$	$E_m = 550,000$
Carbon Fibers	$\sigma_{uf} = 305,000$	$E_f = 58,000,000$

UTS, SI	Modulus, SI
57.9 MPa	3.8 GPa
2.4 GPa	399.9 GPa

a) Calculate the longitudinal stiffness (moduli) of the composite (E_{cL}):

$$E_{cL} = E_f V_f + E_m V_m = 58,000,000(.60) + 550,000(.40) = 35,020,000 \text{ psi} \quad (241.5 \text{ GPa})$$

b) Calculate the transverse stiffness (moduli) of the composite (E_{cT}):

$$E_{cT} = \frac{E_f E_m}{V_f (E_m - E_f) + E_f} = \frac{58,000,000 \cdot 550,000}{.60(550,000 - 58,000,000) + 58,000,000} = 1,355,716 \text{ psi} \quad (9.34 \text{ GPa})$$

The transverse moduli ($E_{cT} = 1,355,716 \text{ psi}$) is only 3.9% of the longitudinal moduli ($E_{cL} = 35,020,000 \text{ psi}$).

Note: (for ease of conversion)
6870 N/m² per psi!

Composite Strength

Particle-reinforced

Fiber-reinforced

Structural

- Estimate of E_c and TS for discontinuous fibers:

-- valid when fiber length $> 15 \frac{\sigma_f d}{\tau_c}$

-- Elastic modulus in fiber direction:

$$E_c = E_m V_m + K E_f V_f$$

efficiency factor:

-- aligned 1D: $K = 1$ (aligned \parallel)

-- aligned 1D: $K = 0$ (aligned \perp)

-- random 2D: $K = 3/8$ (2D isotropy)

-- random 3D: $K = 1/5$ (3D isotropy)

-- TS in fiber direction:

$$(TS)_c = (TS)_m V_m + (TS)_f V_f \quad (\text{aligned 1D})$$

Composite Survey: Fiber

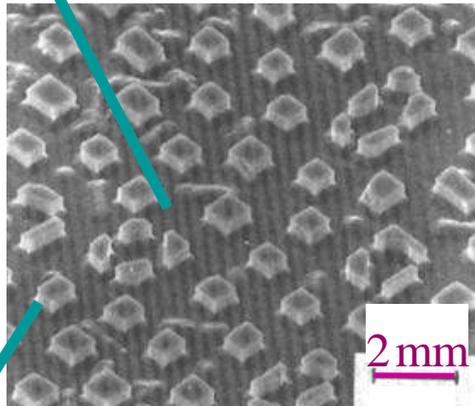
Particle-reinforced

Fiber-reinforced

Structural

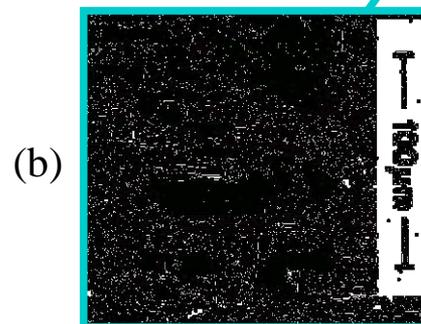
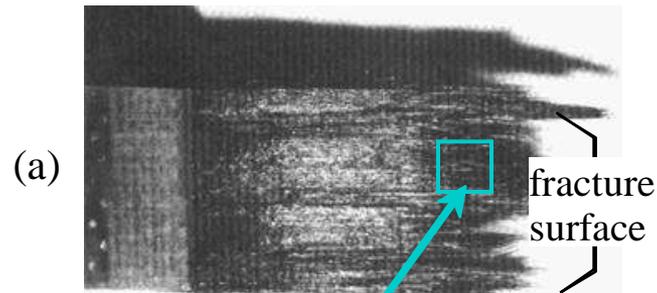
- Aligned Continuous fibers
- Examples:

-- **Metal**: $g'(Ni_3Al)-a(Mo)$
by eutectic solidification.
matrix: $a(Mo)$ (ductile)



fibers: $g'(Ni_3Al)$ (brittle)

-- **Ceramic**: Glass w/SiC fibers
formed by glass slurry
 $E_{glass} = 76 \text{ GPa}$; $E_{SiC} = 400 \text{ GPa}$.



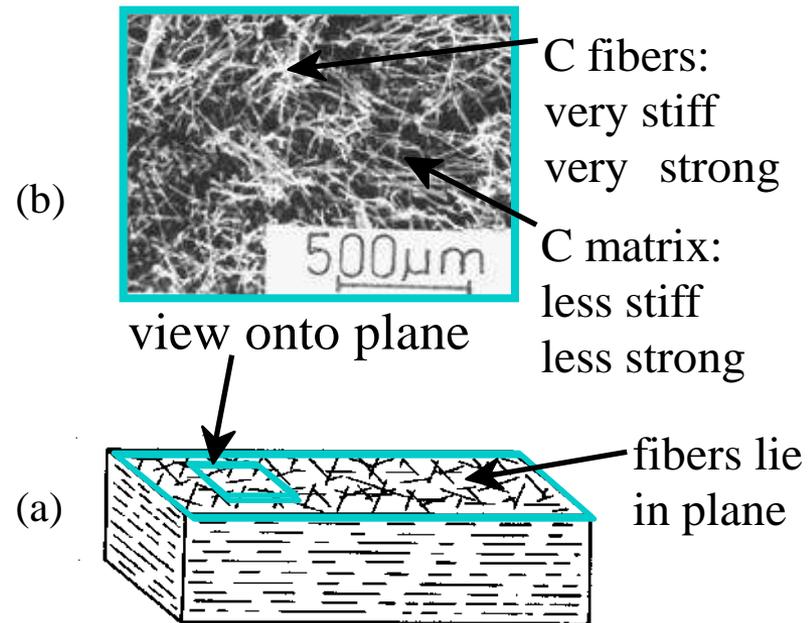
Composite Survey: Fiber

Particle-reinforced

Fiber-reinforced

Structural

- Discontinuous, random 2D fibers
- Example: Carbon-Carbon
 - process: fiber/pitch, then burn out at up to 2500°C.
 - uses: disk brakes, gas turbine exhaust flaps, nose cones.
- Other variations:
 - Discontinuous, random 3D
 - Discontinuous, 1D



$$E_c = E_m V_m + K E_f V_f$$

efficiency factor:

-- random 2D: $K = 3/8$ (2D isotropy)

-- random 3D: $K = 1/5$ (3D isotropy)

Looking at strength:

$$l > l_c$$

$$\sigma_{cd}^* = \sigma_f^* V_f \left(1 - \frac{l_c}{2l} \right) + \sigma_m' (1 - V_f)$$

where σ_f^* is fiber fracture strength

& σ_m' is matrix stress when composite fails

$$l < l_c$$

$$\sigma_{cd}^* = \frac{l\tau_c}{d} V_f + \sigma_m' (1 - V_f)$$

where: d is fiber diameter &

τ_c is smaller of Matrix Fiber shear strength

or matrix shear yield strength

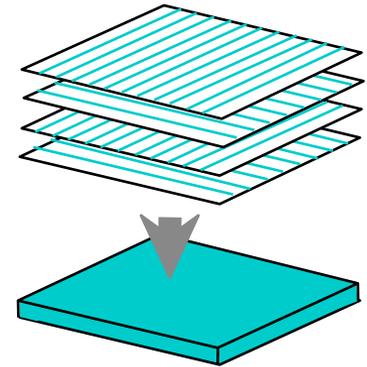
Composite Survey: Structural

Particle-reinforced

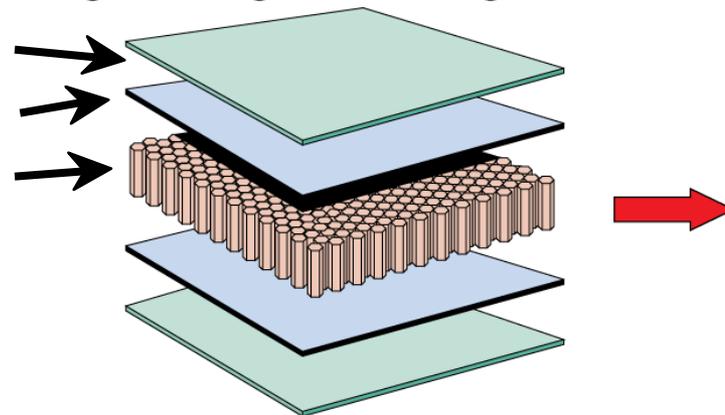
Fiber-reinforced

Structural

- Stacked and bonded fiber-reinforced sheets
 - stacking sequence: e.g., $0^\circ/90^\circ$ or $0^\circ/45^\circ/90^\circ$
 - benefit: balanced, in-plane stiffness
- Sandwich panels
 - low density, honeycomb core
 - benefit: light weight, large bending stiffness



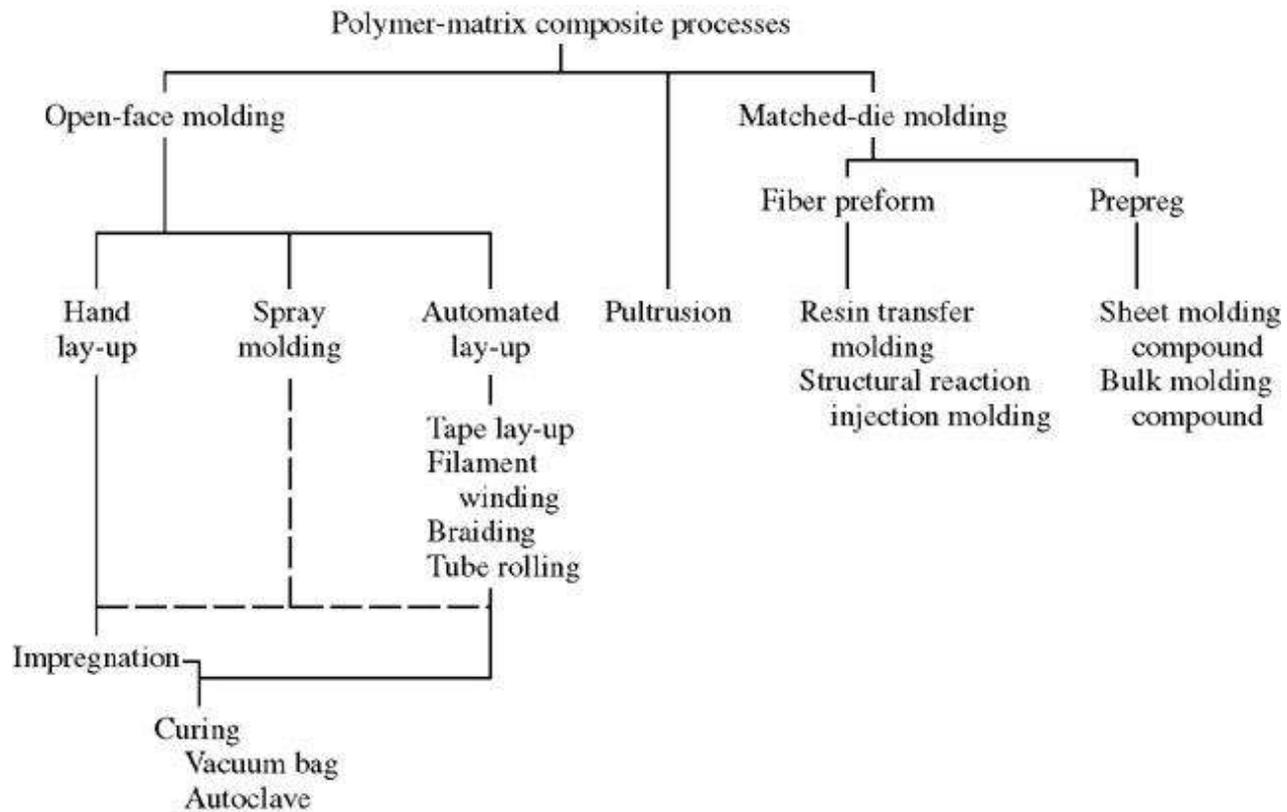
face sheet
adhesive layer
honeycomb



Fabricated sandwich panel

Composite Manufacturing Processes

- Particulate Methods: Sintering
- Fiber reinforced: Several
- Structural: Usually Hand lay-up and atmospheric curing or vacuum curing



Open Mold Processes

Only one mold (male or female) is needed and may be made of any material such as wood, reinforced plastic or , for longer runs, sheet metal or electroformed nickel. The final part is usually very smooth.

Shaping. Steps that may be taken for high quality

1. Mold release agent (silicone, polyvinyl alcohol, fluorocarbon, or sometimes, plastic film) is first applied.
2. Unreinforced surface layer (gel coat) may be deposited for best surface quality.

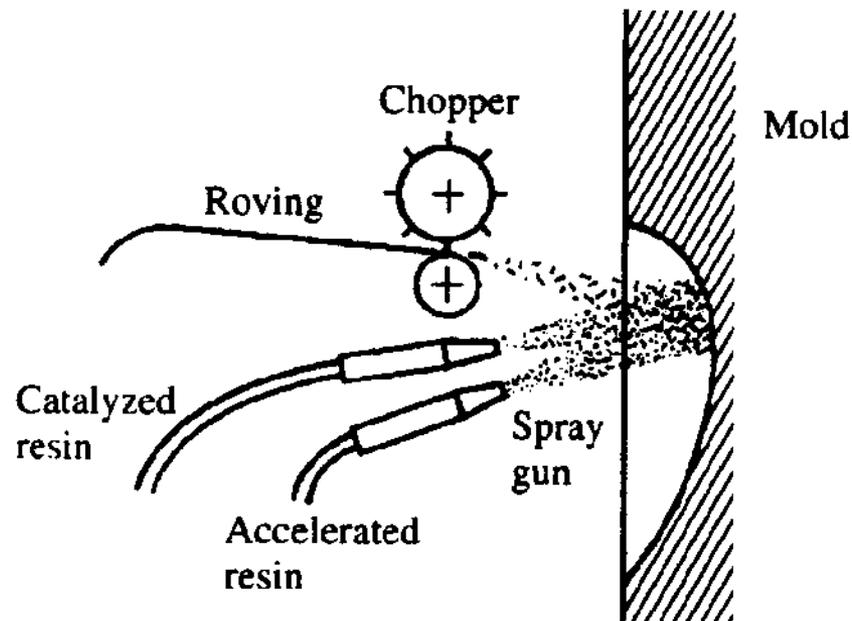
Hand Lay-Up: The resin and fiber (or pieces cut from prepreg) are placed manually, air is expelled with squeegees and if necessary, multiple layers are built up.

- Hardening is at room temperature but may be improved by heating.
- Void volume is typically 1%.
- Foam cores may be incorporated (and left in the part) for greater shape complexity. Thus essentially all shapes can be produced.
- Process is slow (deposition rate around 1 kg/h) and labor-intensive
- Quality is highly dependent on operator skill.
- Extensively used for products such as airframe components, boats, truck bodies, tanks, swimming pools, and ducts.

SPRAY-UP MOLDING

A spray gun supplying resin in two converging streams into which roving is chopped

- Automation with robots results in highly reproducible production
- Labor costs are lower



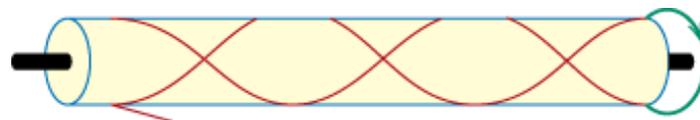
Tape-Laying Machines (Automated Lay-Up)

Cut and lay the ply or prepreg under computer control and without tension; may allow reentrant shapes to be made.

- Cost is about half of hand lay-up
- Extensively used for products such as airframe components, boats, truck bodies, tanks, swimming pools, and ducts.

- Filament Winding

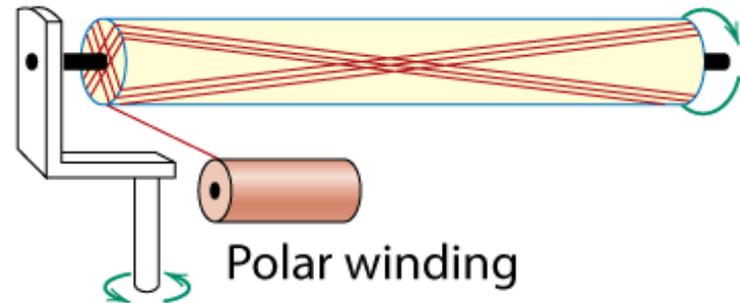
- Ex: pressure tanks
- Continuous filaments wound onto mandrel



Helical winding



Circumferential winding



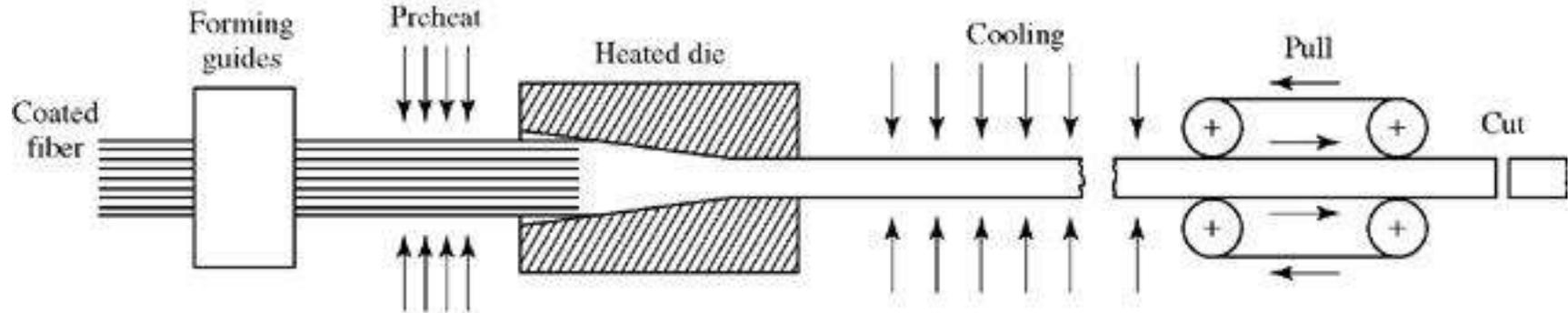
Polar winding

Filament Winding Characteristics

- ◊ Because of the tension, reentrant shapes cannot be produced.
- ◊ CNC winding machines with several degrees of freedom (sometimes 7) are frequently employed.
- ◊ The filament (or tape, tow, or band) is either precoated with the polymer or is drawn through a polymer bath so that it picks up polymer on its way to the winder.
- ◊ Void volume can be higher (3%)
- ◊ The cost is about half that of tape laying
- ◊ Productivity is high (50 kg/h).
- ◊ Applications include: fabrication of composite pipes, tanks, and pressure vessels. Carbon fiber reinforced rocket motor cases used for Space Shuttle and other rockets are made this way.

Pultrusion

- Fibers are impregnated with a prepolymer, exactly positioned with guides, preheated, and pulled through a heated, tapering die where curing takes place.

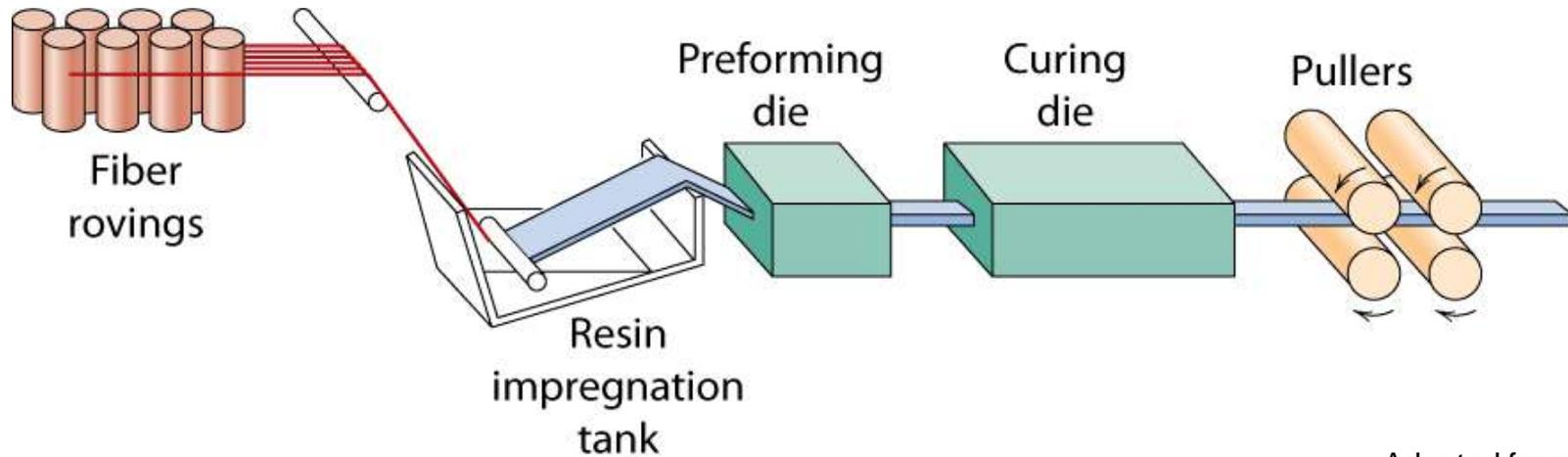


- Emerging product is cooled and pulled by oscillating clamps
- Small diameter products are wound up
- Two dimensional shapes including solid rods, profiles, or hollow tubes, similar to those produced by extrusion, are made, hence its name 'pultrusion'

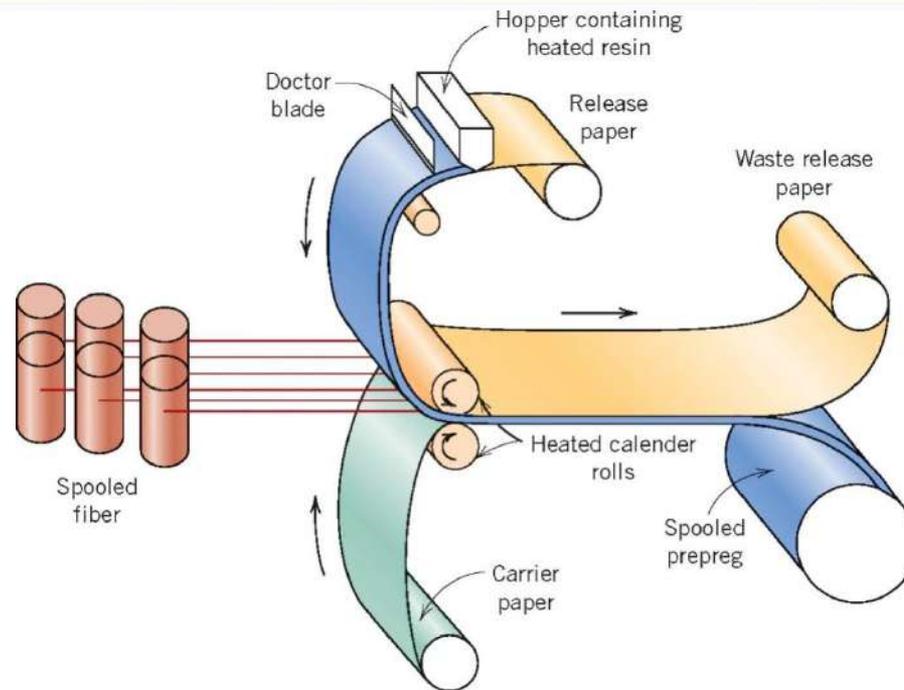
Composite Production Methods

Pultrusion

- Continuous fibers pulled through resin tank, then preforming die & oven to cure



- Production rates around 1 m/min.
- Applications are to sporting goods (golf club shafts), vehicle drive shafts (because of the high damping capacity), nonconductive ladder rails for electrical service, and structural members for vehicle and aerospace applications.



PREPREG PRODUCTION PROCESSES

- Prepreg is the composite industry's term for continuous fiber reinforcement pre-impregnated with a polymer resin that is only partially cured.
- Prepreg is delivered in tape form to the manufacturer who then molds and fully cures the product without having to add any resin.
- This is the composite form most widely used for structural applications

PrePreg Process

- Manufacturing begins by collimating a series of spool-wound continuous fiber tows.
- Tows are then sandwiched and pressed between sheets of release and carrier paper using heated rollers (calendering).
- The release paper sheet has been coated with a thin film of heated resin solution to provide for its thorough impregnation of the fibers.

PrePreg Process

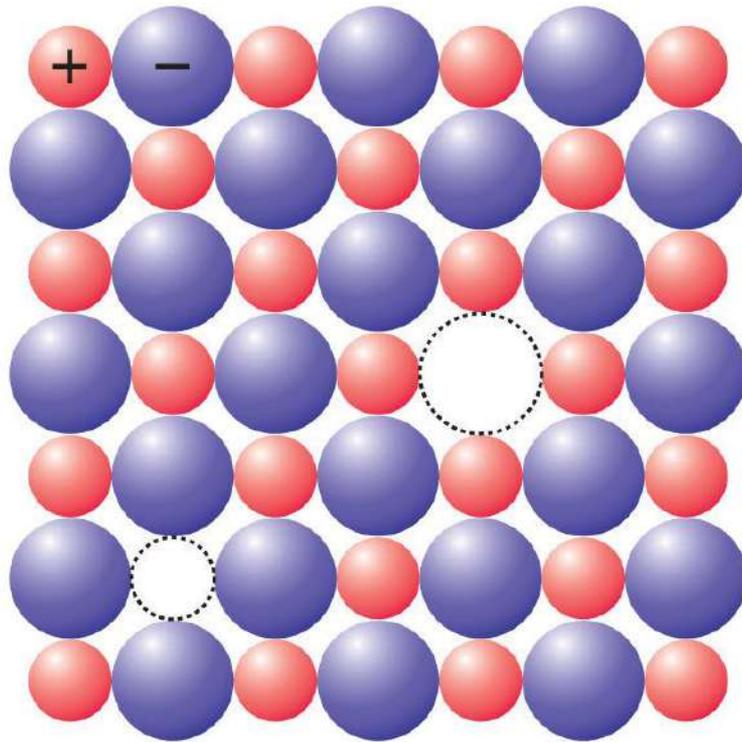
- The final prepreg product is a thin tape consisting of continuous and aligned fibers embedded in a partially cured resin
- Prepared for packaging by winding onto a cardboard core.
- Typical tape thicknesses range between 0.08 and 0.25 mm
- Tape widths range between 25 and 1525 mm.
- Resin content lies between about 35 and 45 vol%

PrePreg Process

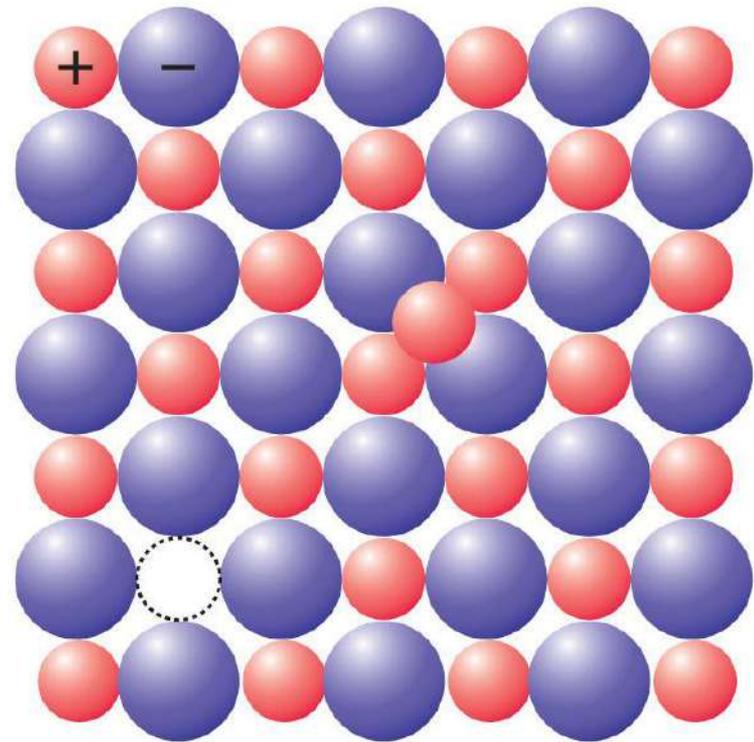
- The prepreg is stored at 0°C (32 °F) or lower because thermoset matrix undergoes curing reactions at room temperature. Also the time in use at room temperature must be minimized. Life time is about 6 months if properly handled.
- Both thermoplastic and thermosetting resins are utilized: carbon, glass, and aramid fibers are the common reinforcements.
- Actual fabrication begins with the lay-up. Normally a number of plies are laid up to provide the desired thickness.
- The lay-up can be by hand or automated.

Summary

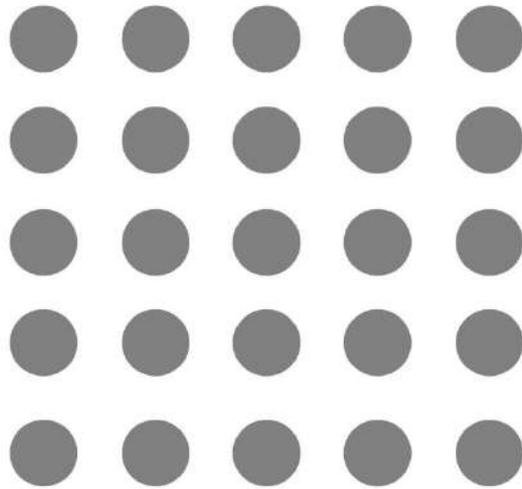
- Composites are classified according to:
 - the matrix material (CMC, MMC, PMC)
 - the reinforcement geometry (particles, fibers, layers).
- Composites enhance matrix properties:
 - MMC: enhance s_y , TS , creep performance
 - CMC: enhance K_c
 - PMC: enhance E , s_y , TS , creep performance
- **Particulate-reinforced:**
 - Elastic modulus can be estimated.
 - Properties are isotropic.
- **Fiber-reinforced:**
 - Elastic modulus and TS can be estimated along fiber dir.
 - Properties can be isotropic or anisotropic.
- **Structural:**
 - Based on build-up of sandwiches in layered form.



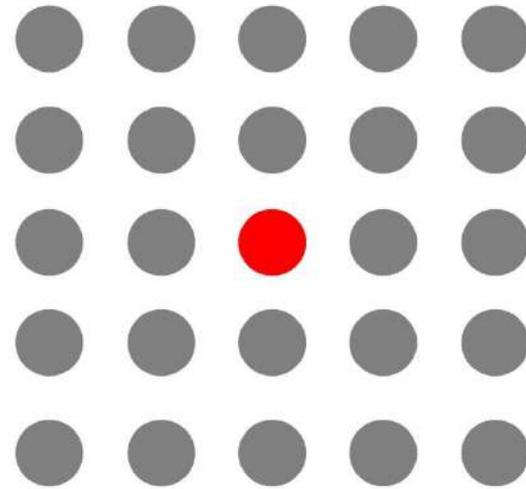
(a) Schottky defect



(b) Frenkel defect



Perfect Crystal



Substitutional Atom - Point Defect

