MATERIALS ENGINEERING (R18A0305)

2nd Year B. Tech I- sem, Mechanical Engineering

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COURSE OBJECTIVES

UNIT - 1	**CO1:** To understand various mechanical properties of materials.
UNIT - 2	CO2: To understand how and why the properties of materials are controlled by its structure at the microscopic and macroscopic levels.
UNIT - 3	CO3: To understand how and why the structure and composition of a material may be controlled by processing.
UNIT - 4	CO4: To create different types of composite materials and its applications.
UNIT - 5	CO5: To remember polymer material classifications and applications.

UNIT 1

STRUCTURE OF MATERIALS

CO1: **To understand various mechanical properties of materials.**

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UNIT – I (SYLLABUS)

Introduction – Structure of Materials:

- Structure of atom – Atomic models.
- Bonding in solids & its Types, Forces and Energies.

Crystal Systems:

- Crystal structure - Unit Cell – Bravais lattices.
- BCC – FCC – HCP.
- Interstitial sites – NaCl & CsCl crystals.
- Perovskite structure. Diamond structure – Graphite
- Crystal Directions & Planes.

COURSE OUTLINE

UNIT – 1

No. of Lecture Hours: 13

LECTURE	LECTURE TOPIC	KEY ELEMENTS	Learning objectives (2 to 3 objectives)
1	Introduction: Structure of atom Atomic models	Description of matter.	Remember & Understanding of basics on Matter & Analyze the atom structure (B1, B2 & B4)
2	Bonding in solids Ionic, Covalent, metallic and van der Waals Bond	Definition of Solid and bonding types	Understanding of Solids (B2) Analysis of bonding forces (B4)
3	Bonding forces & energies	How bonding forces vary by each bond	Understanding of Solid bonding forces(B2)
4	Crystal structure - Unit Cell – Bravais lattice	Crystal Structures	Understanding of Crystal System (B2) Application of crystal systems (B3)
5	Bravais lattice – BCC – FCC – HCP	Detail understanding of various crystals	Remember & Understanding of crystals (B1 & B2)
6	Interstitial sites – NaCl & CsCl Crystals	Examples of crystals	Apply crystal systems concept (B3)
7	Perovskite structure, Diamond structure, Graphite	Synthetic crystals	Apply & Analyze crystal systems concept (B3)
8	Crystal directions and planes	Crystal directions and planes	Understanding of Crystal directions and planes (B2)

STRUCTURE OF AN ATOM

HISTORY OF ATOM

Democritus(460 BC) developed the idea of "ATOM" -----

He pounded up materials in his pestle and mortar and reduced them to smaller and smaller parts which he called --- "ATOMA"

WHAT IS AN ATOM?

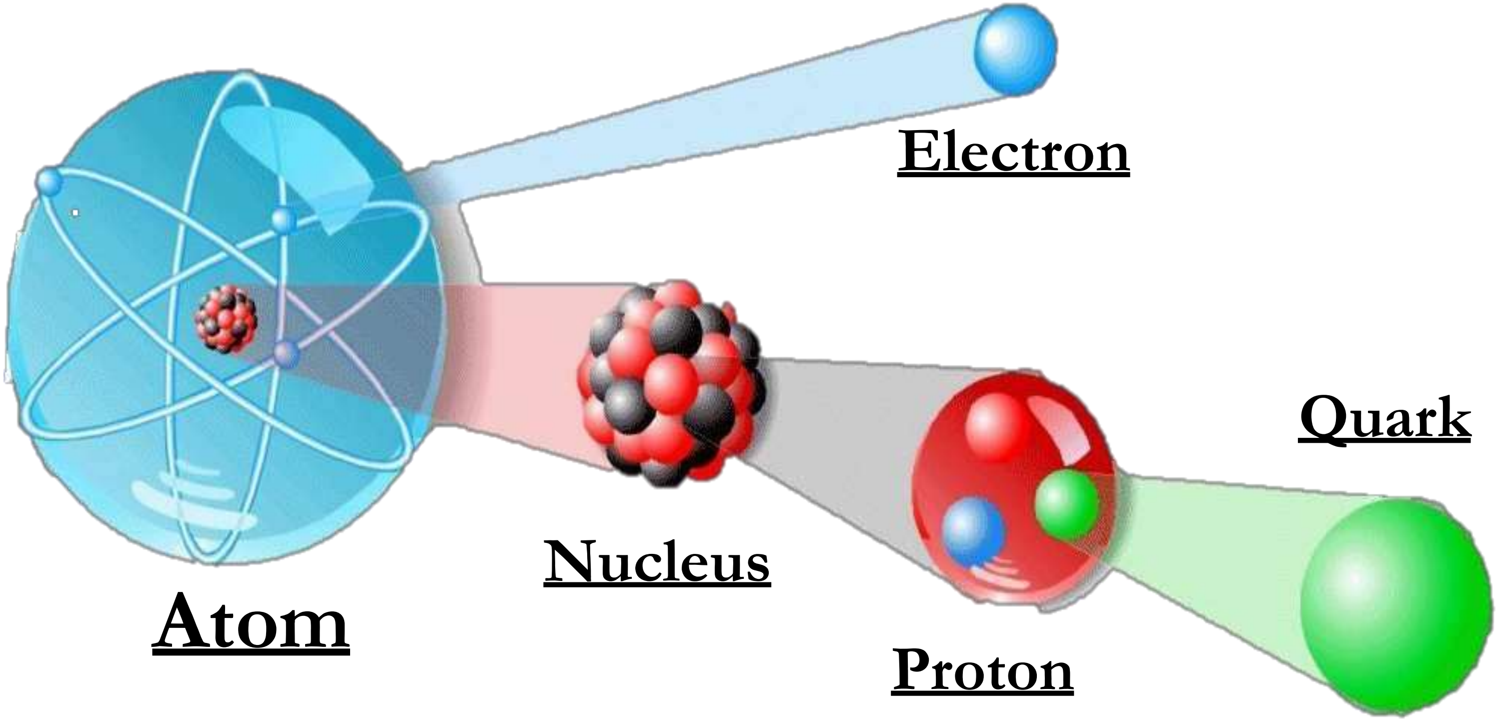
Atom., is a tiny basic building block of matter. All the materials on Earth are composed of various combination of atoms. An atom consist of a cloud of electrons surrounding a small dense nucleus of protons and neutrons.

Atoms are the smallest particle of a chemical element that still exhibit all the chemical properties to that element.

STRUCTURE OF AN ATOM

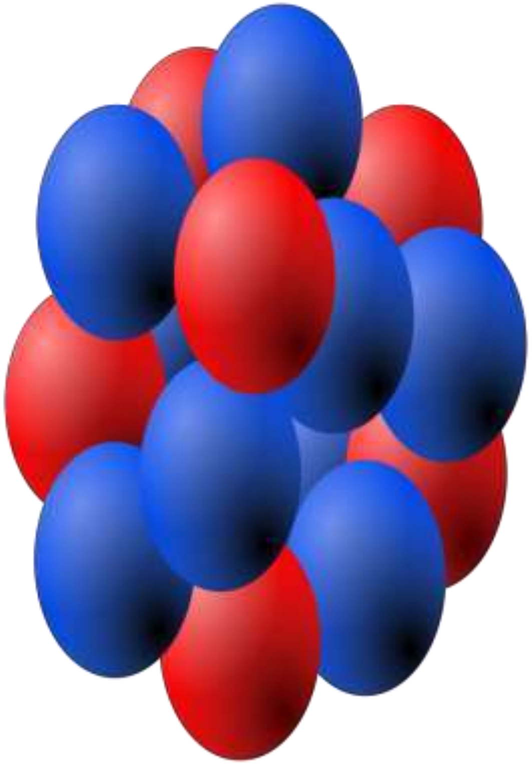
Atoms are made up of smaller particles called electrons, protons and neutrons. Electrons and protons have a property called electric charge which affects the way they interact with each other and with other electrically charged particles.

COND…



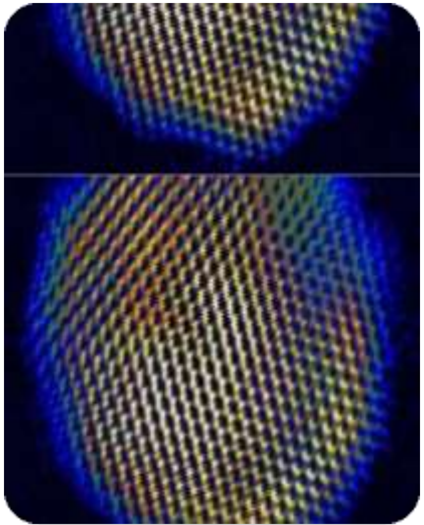
THE NUCLEUS

The nucleus consists of protons and neutrons. The nucleus contains all of the mass of the atom, but, it occupies only a tiny fraction of the space inside the atom. The diameter of a typical nucleus is only about 1 × 10^{-14} m or about 1/100,000 of the entire atom.



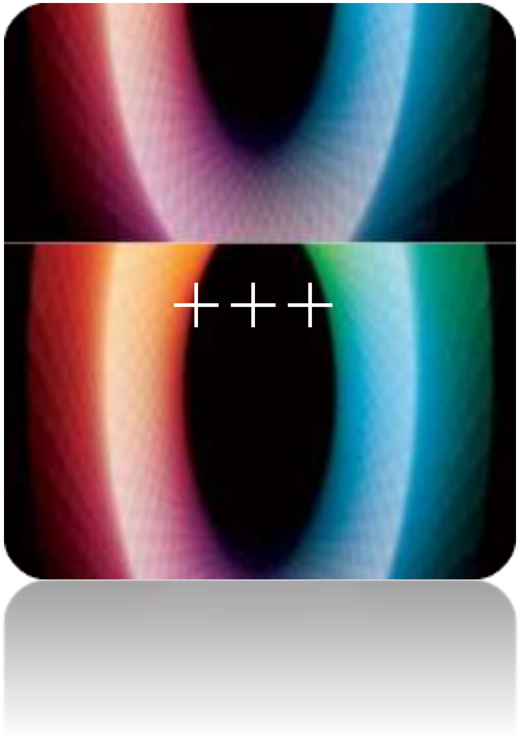
ELECTRON

Electrons were discovered by Sir J. J. Thompson. Electrons are the negatively charged particles of atom. Together, all of the electrons of an atom create a negative charge that balances the positive charge of the protons in the atomic nucleus. Electrons are extremely small compared to all of the other parts of the atom. The mass of an electron is almost 1,000 times smaller than the mass of a proton. They are found near the nucleus. It has a mass of 9.109 ×10^{-31} kg.



PROTONS

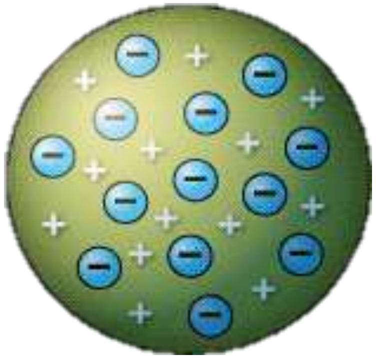
Proton was discovered by E. Goldstein. Protons have a positive electric charge. A protons mass is about 1,840 times that of electron. The number of protons in the nucleus determines the total quantity of protons in the element.



NEUTRONS

Neutron was discovered by Sir James Chadwick. The neutron is slightly heavier than the proton. They are electrically neutral particles that is part of the nucleus of the atom. The neutron is about 10^{-13} cm and weighs about 1.6749×10^{-27} kg.

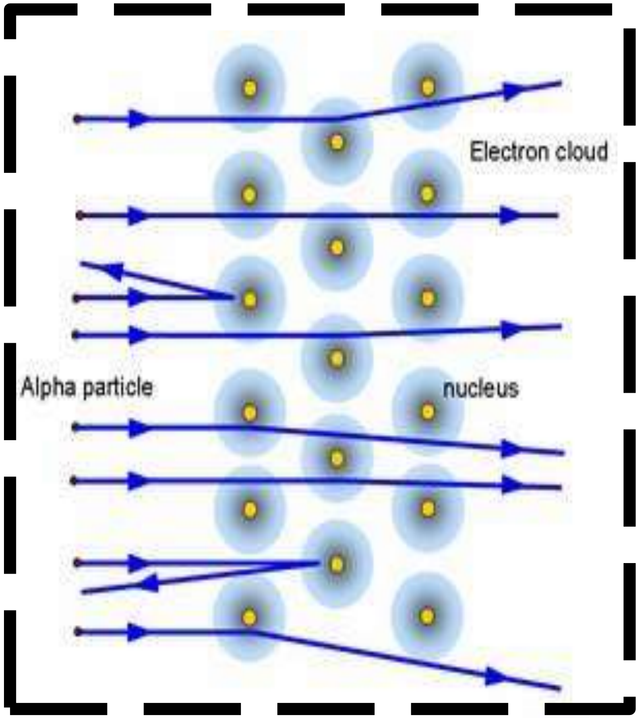
JJ THOMSON'S ATOMIC MODEL



Thomson proposed the model of atom to be similar to a Christmas pudding. The electrons, in a sphere of positive charge, were like currants(dry fruits) in a spherical Christmas pudding.

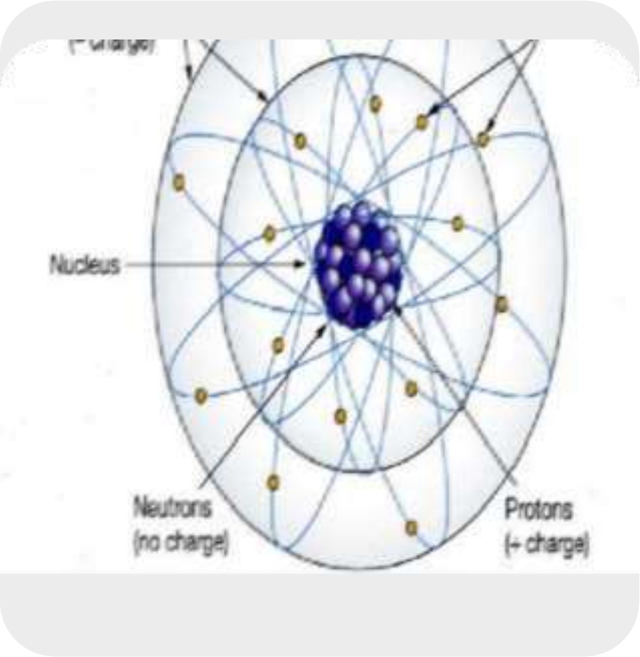
RUTHERFORD'S MODEL OF ATOM

An atom consists of a positively charged center in the atom called nucleus. The mass of the atom is contributed mainly by the nucleus. The size of the nucleus is very small as compared to the atom. The electrons revolve around the nucleus in well defined orbits.



BOHR’S MODEL OF ATOM

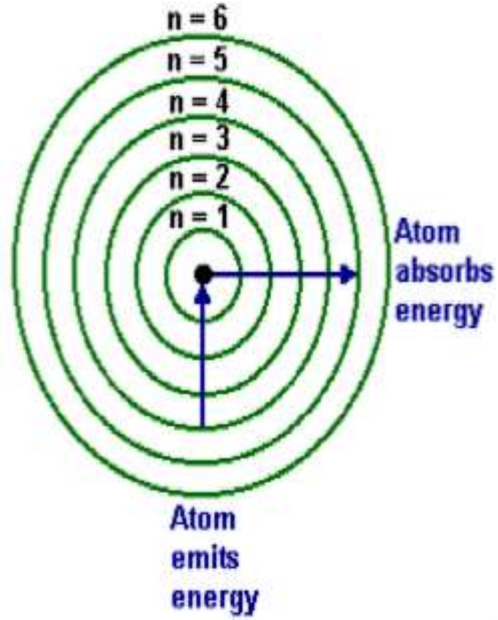
Bohr agreed with most of the points regarding atom as proposed by Rutherford’s model of atom, except the revolution of electrons for which he added that there are only certain orbits where electrons revolve inside the atom. While revolving in their discrete orbits they do not radiate energy.



HOW ARE ELECTRONS DISTRIBUTED IN DIFFERENT ORBITS ?

- The first shell $= 2n^2 = 2(1)^2 = 2$
- The second shell $= 2n^2 = 2(2)^2 = 8$
- The third shell $= 2n^2 = 2(3)^2 = 18$
- The fourth shell $= 2n^2 = 2(4)^2 = 32$

And, the distribution of electron in such a manner is called "Electronic Configuration".



VALENCE

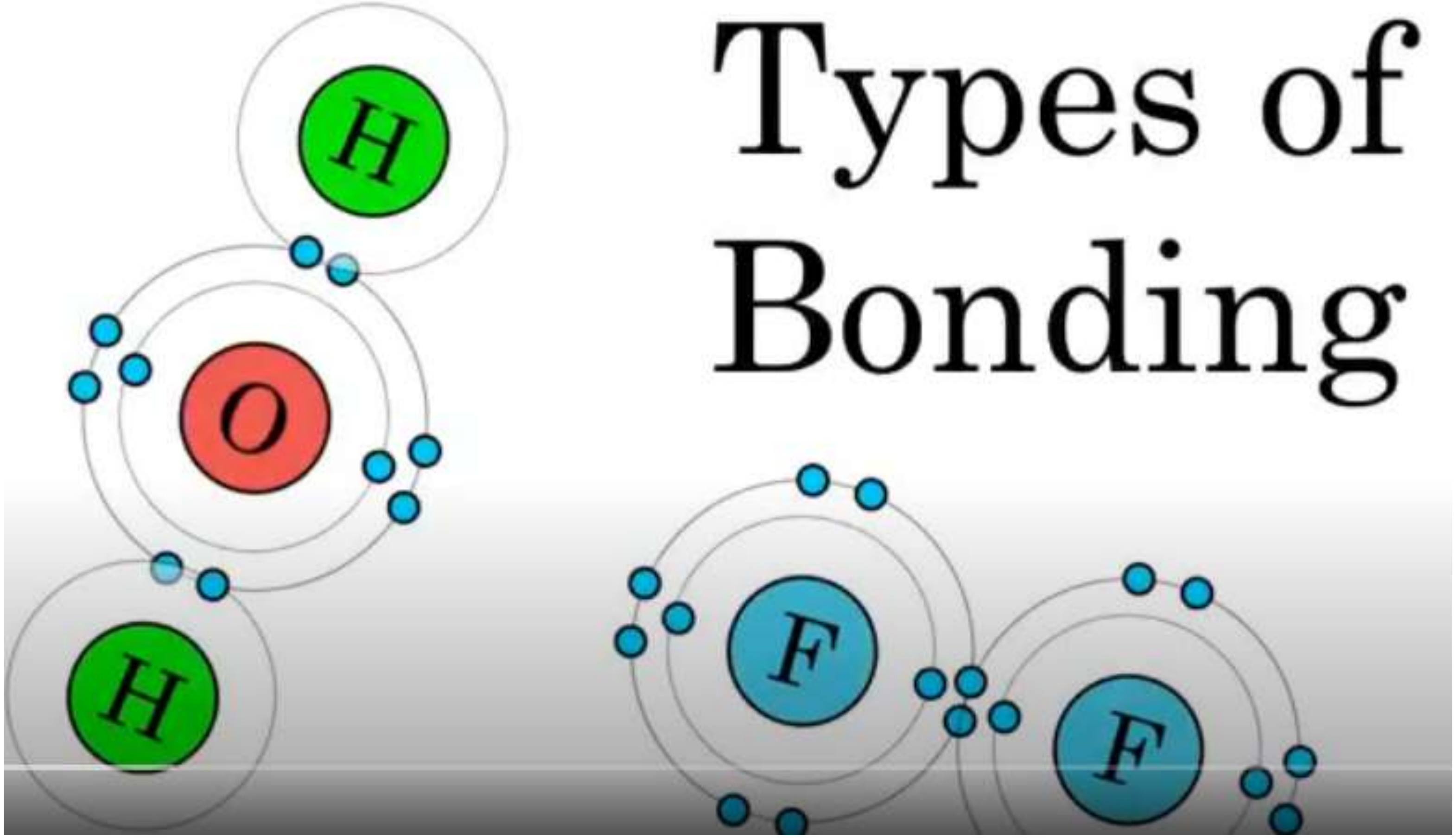
Now we know that electrons in an atom are arranged in different shells. The combining capacity of an element is called its valency. In other words, valency is the number of electrons gained, lost or shared to attain chemical stability, i.e. the nearest noble gas configuration. For e.g., sodium has configuration (2,8,1) and tends to gain the configuration of neon, Ne(2,8) by losing an electron. Hence, its valency is 1.

Note: Charges are not associated with valency, i.e. valency is not + or -.

ATOMIC NUMBER & MASS NUMBER

Atomic Number - The number of protons in an atom is called its atomic number.

Mass Number - The total number of protons and neutrons in an atom is called its mass number.


Types of Bonding
H
O
H
F
F

What is Solid Bonding?

Crystalline solids fall into one of four categories. All four categories involve packing discrete molecules or atoms into a lattice or repeating array, though *network solids* are a special case. The categories are distinguished by the nature of the interactions holding the discrete molecules or atoms together. Based on the nature of the forces that hold the component atoms, molecules, or ions together, solids may be formally classified as ionic, molecular, covalent (network), or metallic. The variation in the relative strengths of these four types of interactions correlates nicely with their wide variation in properties.

Types of bonds

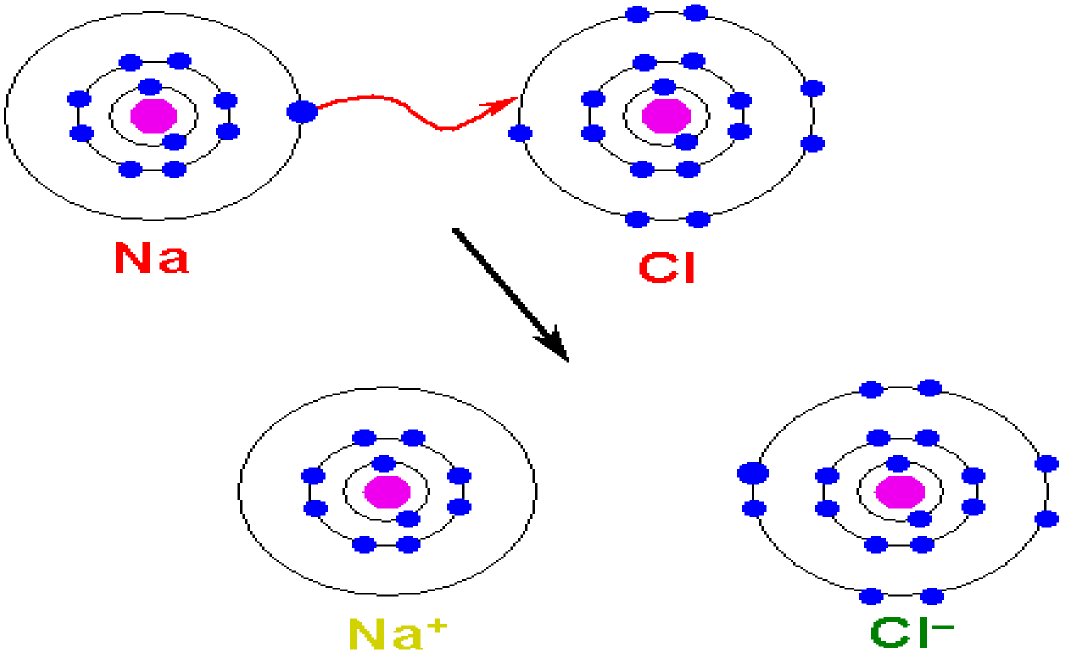
- **Bonding in solids**
    - Ionic bond
    - Covalent bond
    - Metallic bond
    - Intermolecular forces

Type of Solid	Interaction	Properties	Examples
Ionic	Ionic	High Melting Point, Brittle, Hard	NaCl, MgO
Molecular	Hydrogen Bonding, Dipole-Dipole, London Dispersion	Low Melting Point, Nonconducting	H_2, CO_2
Metallic	Metallic Bonding	Variable Hardness and Melting Point (depending upon strength of metallic bonding), Conducting	Fe, Mg
Network	Covalent Bonding	High Melting Point, Hard, Non-conducting	C (diamond), SiO_2 (quartz)

IONIC BOND

An ionic bonding is the Attractive Force existing between positive ion and a negative ion when they are brought into close proximity or surrounding.

They are formed when atoms of different elements lose or gain their electrons in order to achieve stabilized outermost electronic configuration.



Ionic Bonding in NaCl

PROPERTIES OF IONIC SOLIDS

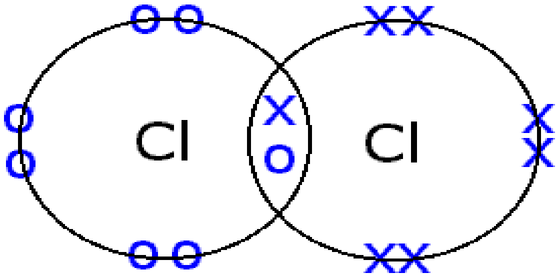
- Ionic solids are rigid, unidirectional and crystalline in nature.
- They have high melting and boiling points.
- Ionic solids are good insulators of electricity in their solid state and good conductor of electricity in their molten state.
- Ionic solids are soluble in water and slightly soluble in organic solvents.

COVALENT BONDING

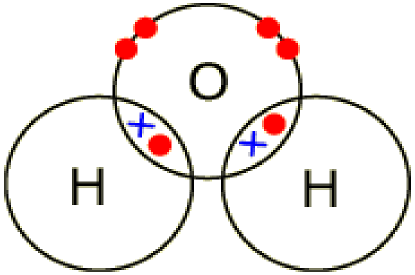
A covalent bond is formed, when two or more electrons of an atom, in its outermost energy level, are shared by other atoms. E.G.-Chlorine molecule. In this bonding a stable arrangement is achieved by sharing of electrons rather than transfer of electrons.

Sometimes a covalent bond is also formed when two atoms of different non-metals share one or more pair of electrons in their outermost energy level.

e.g.- Water molecule



Bonding between two atoms of same element



Bonding between two different non-metals

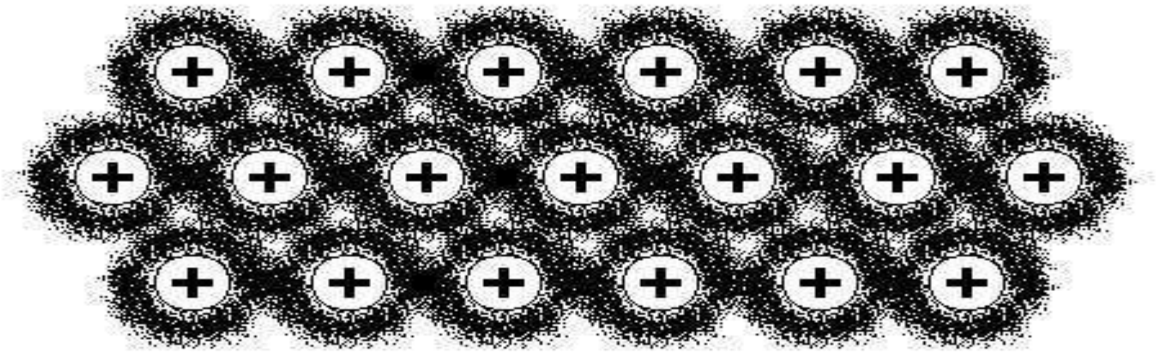
PROPERTIES OF COVALENT SOLIDS

- Covalent compounds are bad conductors of electricity.
- Covalent compounds are having low melting and boiling points.
- Insoluble- in water
- Soluble- in organic solvents like Benzene

METALLIC BONDING

It has been observed that in a metal atoms, the electrons in their outermost energy levels are loosely held by their nucleii.

Thus a metal may be considered as a cluster of positive ions surrounded by a large number of free electrons, forming electron cloud.



Metallic Sea of Electrons

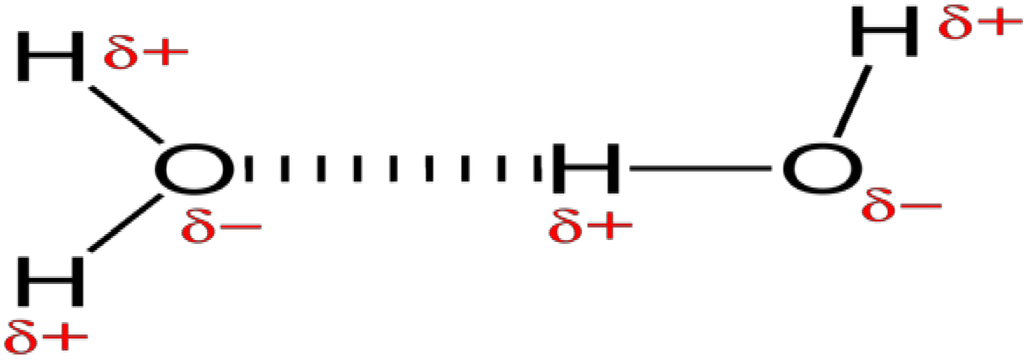
Electrons are not bonded to any particular atom and are free to move about in the solid.

PROPERTIES OF METALLIC SOLIDS

- High thermal and electrical conductivity
- Low melting and boiling point temperature
- Have a bright lustre
- Metallic solids are malleable and ductile

HYDROGEN BONDING

Covalently bonded atoms often produce an electric dipole configuration with hydrogen atom as the positive end of the dipole. If bonds arise as a result of Electrostatic attraction between atoms, it is known as hydrogen bonding.



PROPERTIES OF HYDROGEN BONDED SOLIDS

- The hydrogen bonds are directional
- Relatively strong bonding
- These solids have low melting point
- No valence electrons hence good insulators
- Soluble in both polar and non-polar solvents
- They are transparent to light

e.g. – water molecule, ammonic molecules

VAN DER WALLS BONDING

Weak and temporary bonds between molecules of the same substance are known as Van der Walls bonding.

Types of Van der walls forces:

1. Dipole-dipole
2. Dipole-induced Dipole
3. Dispersion

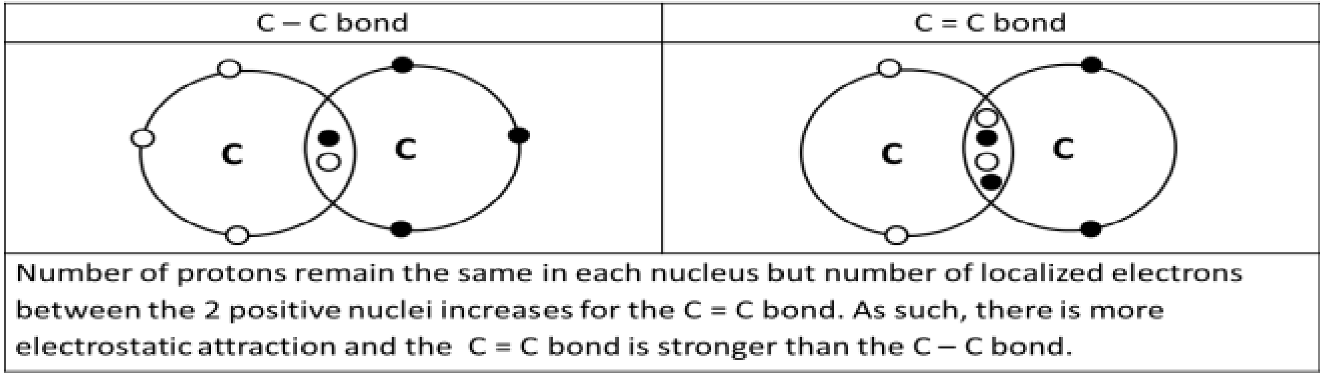
BOND STRENGTH

Bond strength is the degree to which each atom joined to another a chemical bond contributes to the valency of this other atom. As the number of bonds between two atoms increases, the bond grows shorter and stronger.

- Types of Bonds
  1. Single bond
  2. Double bond
  3. Triple Bond

Bond Energy – Amount of energy required to break one mole of bonds. Bond strength depends upon no. of bonds present in molecule.

for e.g.- C=C is stronger than C-C.

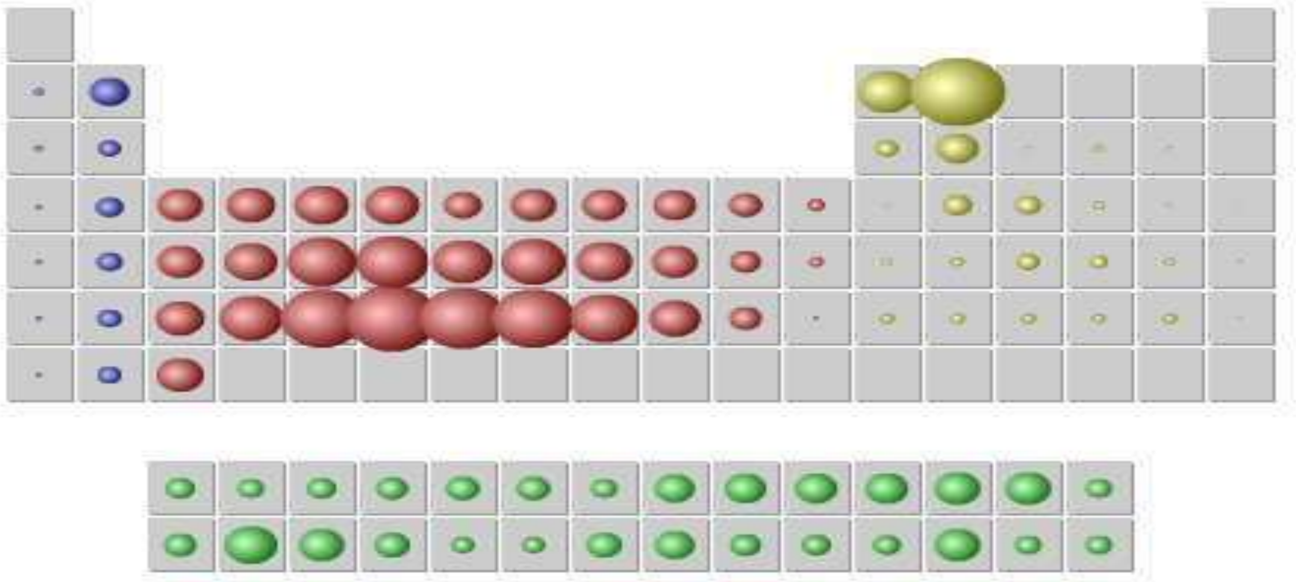


C – C bond | C = C bond

Number of protons remain the same in each nucleus but number of localized electrons between the 2 positive nuclei increases for the C = C bond. As such, there is more electrostatic attraction and the C = C bond is stronger than the C – C bond.

MELTING POINT

Melting Point: The temperature at which a solid becomes liquid. If heat is applied to a solid, its temperature rises until the melting point is reached, when heat energy is then absorbed to form liquid from the solid is then absorbed to form liquid from the solid. Temperature continues to rise once the melting is complete



Variation in melting point in Periodic table

CRYSTAL STRUCTURES

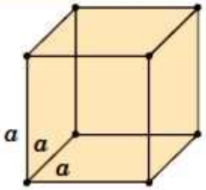
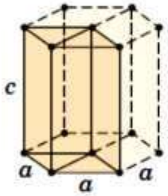
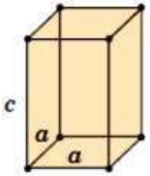
CRYSTAL STRUCTURE

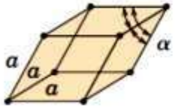
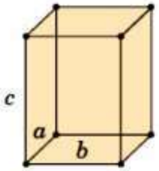
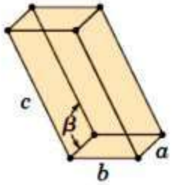
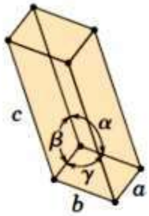
Crystal structure is a unique arrangement of atoms or molecules in a crystalline liquid or solid.

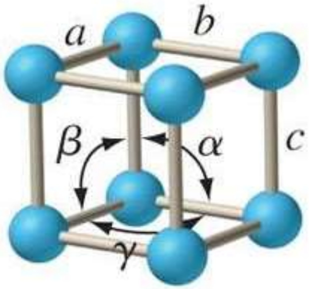
A crystal structure is composed of a pattern, a set of atoms arranged in a particular way, and a lattice exhibiting long-range order and symmetry. Patterns are located upon the points of a lattice, which is an array of points repeating periodically in three dimensions.

The points can be thought of as forming identical tiny boxes, called unit cells, that fill the space of the lattice. The lengths of the edges of a unit cell and the angles between them are called the *lattice parameters.*

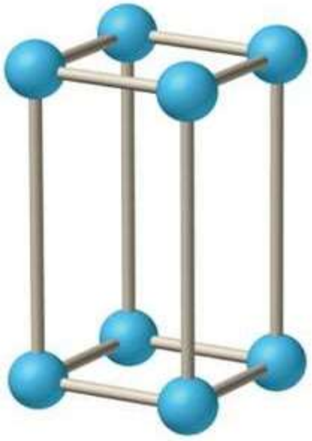
Lattice Parameter Relationships and Figures Showing Unit Cell Geometries for the Seven Crystal Systems

Crystal System	***Axial Relationships***	***Interaxial Angles***	***Unit Cell Geometry***
Cubic	$a = b = c$	$\alpha = \beta = \gamma = 90°$	
Hexagonal	$a = b \neq c$	$\alpha = \beta = 90°, \gamma = 120°$	
Tetragonal	$a = b \neq c$	$\alpha = \beta = \gamma = 90°$	

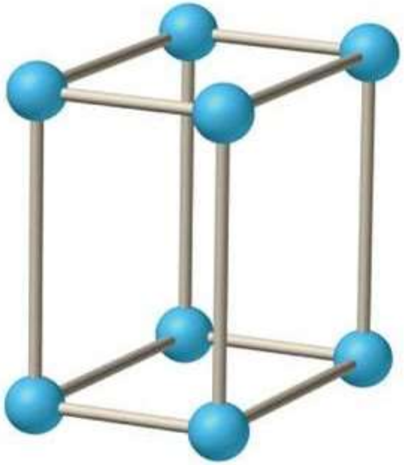
Crystal System	*Axial Relationships*	*Interaxial Angles*	*Unit Cell Geometry*
Rhombohedral (Trigonal)	$a = b = c$	$\alpha = \beta = \gamma \neq 90°$	
Orthorhombic	$a \neq b \neq c$	$\alpha = \beta = \gamma = 90°$	
Monoclinic	$a \neq b \neq c$	$\alpha = \gamma = 90° \neq \beta$	
Triclinic	$a \neq b \neq c$	$\alpha \neq \beta \neq \gamma \neq 90°$	



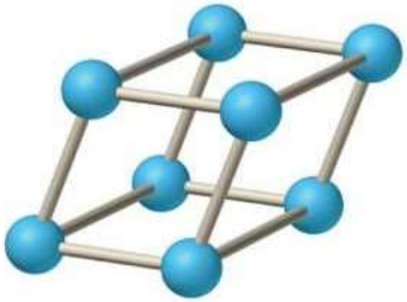
Simple cubic
$a = b = c$
$\alpha = \beta = \gamma = 90^\circ$



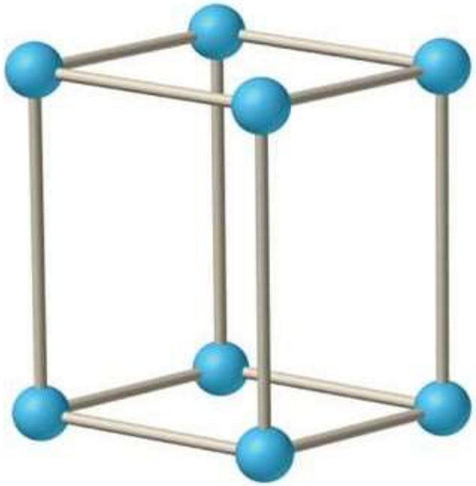
Tetragonal
$a = b \neq c$
$\alpha = \beta = \gamma = 90^\circ$



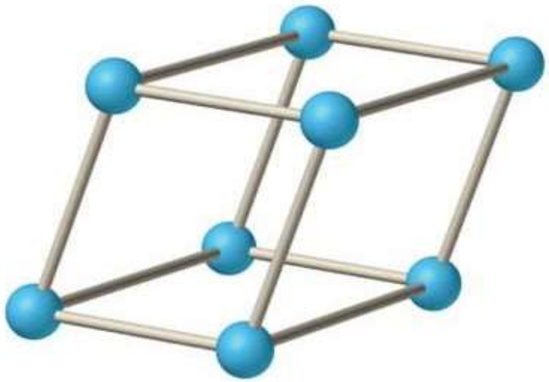
Orthorhombic
$a \neq b \neq c$
$\alpha = \beta = \gamma = 90^\circ$



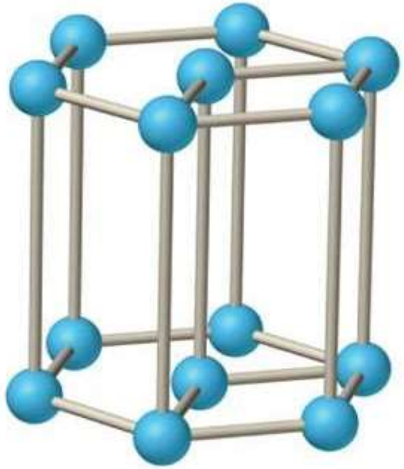
Rhombohedral
$a = b = c$
$\alpha = \beta = \gamma \neq 90^\circ$



Monoclinic
$a \neq b \neq c$
$\gamma \neq \alpha = \beta = 90^\circ$



Triclinic
$a \neq b \neq c$
$\alpha \neq \beta \neq \gamma \neq 90^\circ$



Hexagonal
$a = b \neq c$
$\alpha = \beta = 90^\circ, \gamma = 120^\circ$

THE STRUCTURE OF CRYSTALLINE SOLIDS

Crystal Structure: BCC, FCC and HCP Structures, coordination number and atomic packing factors.

Significant property differences exist between crystalline and non-crystalline materials having the same composition.

Example: Non-crystalline ceramics and polymers normally are optically transparent; the same materials in crystalline (or semi crystalline) form tend to be opaque or, at best, translucent.

CRYSTAL STRUCTURES

Fundamental concepts

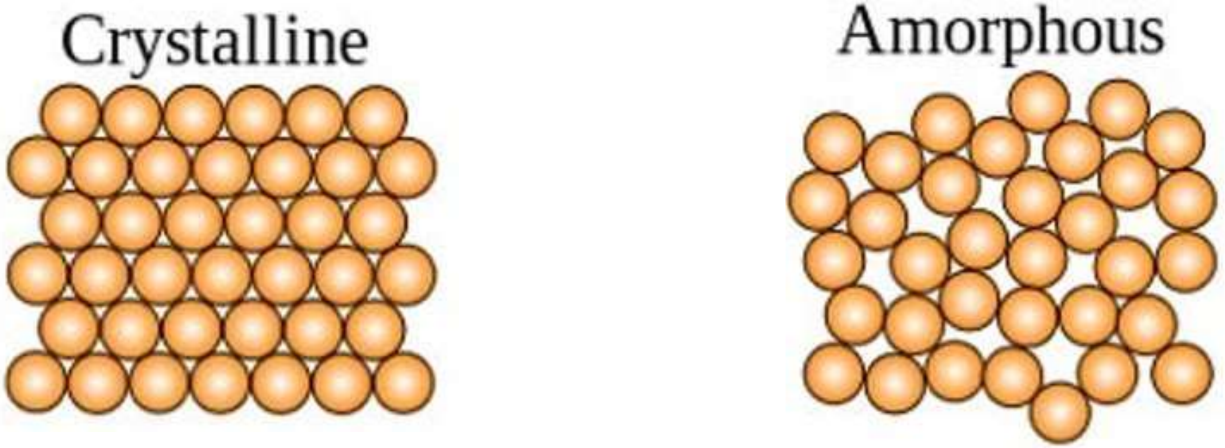
Solid materials may be classified according to the regularity with which atoms or ions are arranged with respect to one another.

- ✓ crystalline solids / material
- ✓ Non Crystalline material / amorphous solids

CRYSTALLINE SOLIDS / MATERIAL

A **crystalline** material is one in which the atoms are situated in a repeating or periodic array over large atomic distances; such that upon solidification, the atoms will position themselves in a repetitive three-dimensional pattern, in which each atom is bonded to its nearest-neighbor atoms.

All metals, many ceramic materials, and certain polymers form crystalline structures


Crystalline
Amorphous

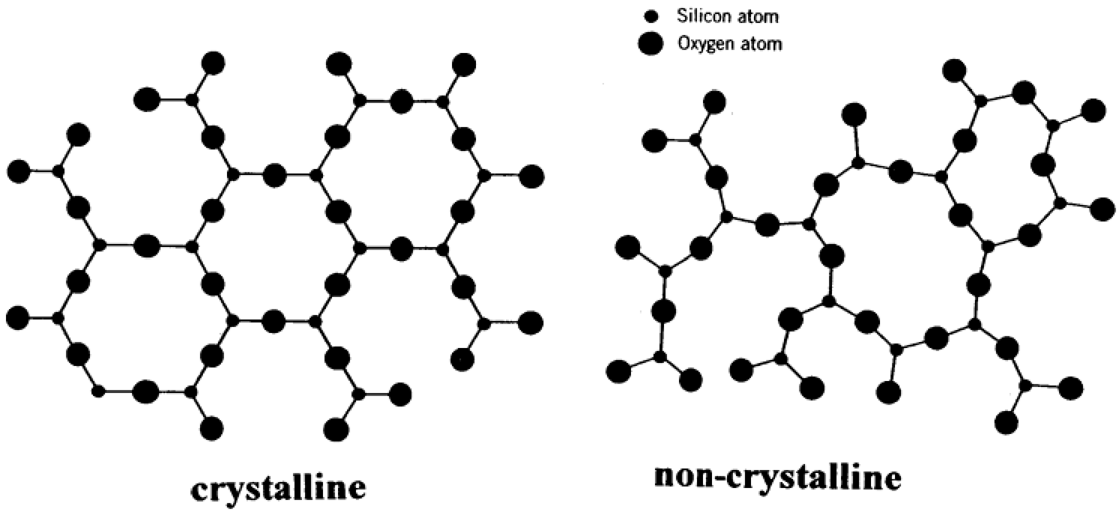
Crystalline Solids	Non-crystalline/Amorphous solids
Basic structural unit is a crystal	Basic structural unit is a molecule.
Each crystal is made up of number of repetitive blocks called unit cells	Chain of molecules are random, irregular and lack symmetry
Have regular arrangement of particles/atom	Have completely random arrangement of particles/atom
Have different physical properties (e.g. thermal/electrical/optical)	Have physical properties same in all directions (Isotropic)
Have sharp melting point	Do not have sharp melting point (e.g. glass)
Higher density	Lower density
Stable and stronger	Unstable and less stronger

AGGREGATES

There are certain material which can occur as both.

E.g. silicate can occur as crystalline solid (quartz) or as non crystalline solid (silicate glass).

E.g. concrete, rocks and minerals



Crystalline silica

Non-Crystalline silica

UNIT CELLS

Unit cell is the basic structural unit or building block of the crystal structure and defines the crystal structure by virtue of its geometry and the atom positions within.

Metallic crystal structures

Three relatively simple crystal structures are found for most of the common metals:

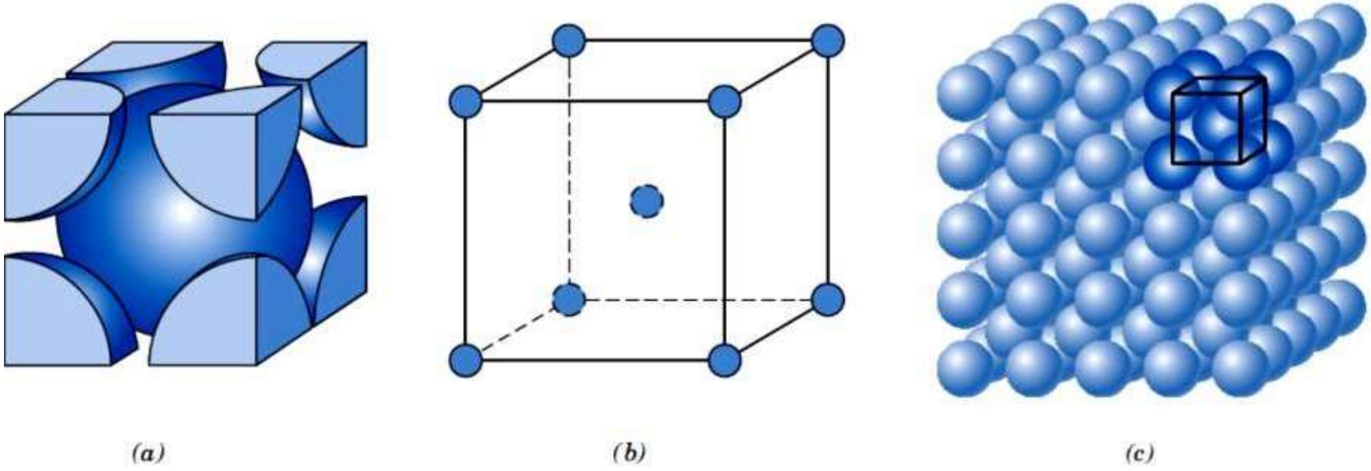
- ✓ face-centered cubic (FCC)
- ✓ body-centered cubic (BCC)
- ✓ hexagonal close-packed (HCP)

METALLIC CRYSTAL STRUCTURES

1.The Body-Centered Cubic Crystal Structure (BCC)

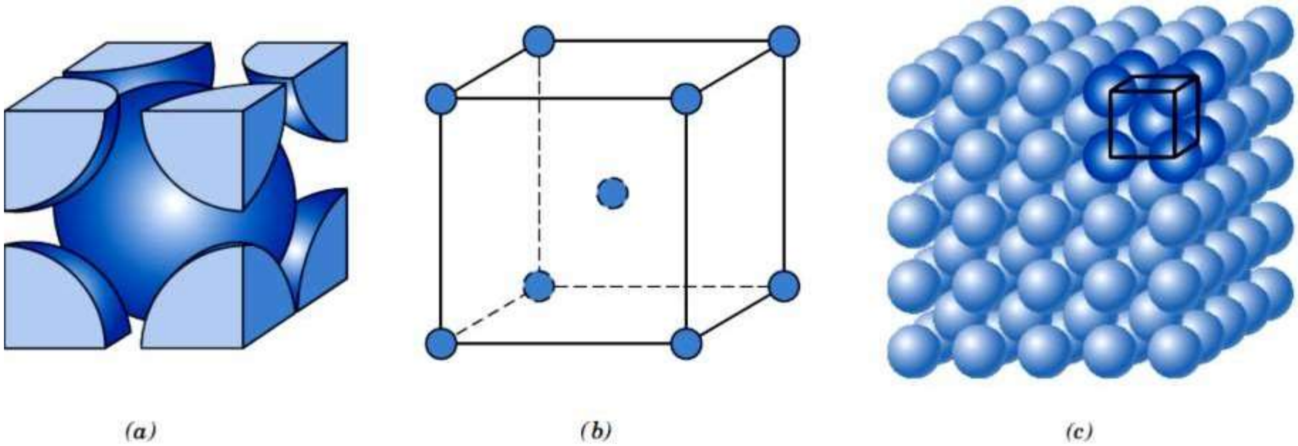
The **body-centered cubic** unit cell is a cube with an atom at each corner of the unit cell and an atom in the **center** of the unit cell.

E.g. Chromium, iron, tungsten



(*a*) a hard sphere unit cell representation, (*b*) a reduced-sphere unit cell, (*c*) an aggregate of many atoms

COUNTING THE ATOMS IN THE BCC STRUCTURE



There is one full atom at the center and one atom at each of the eight corners.

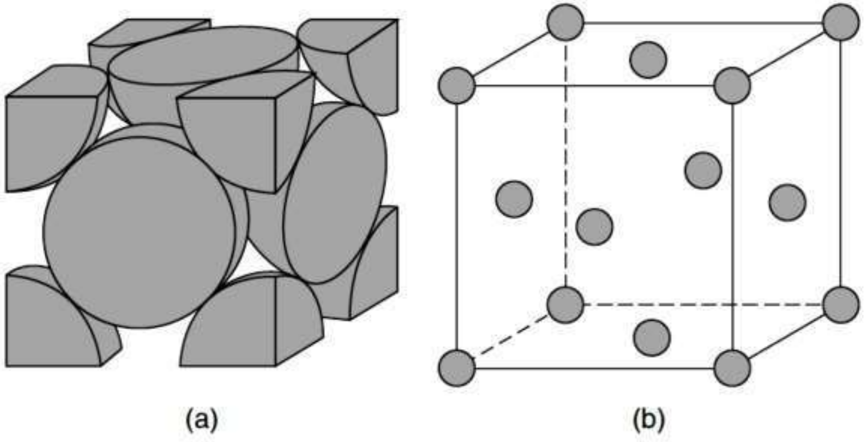
Therefore effective number of atoms inside each unit cell is,

$$1 + 8\,X\,\frac{1}{8} = 2\ atoms$$

FACE-CENTERED CUBIC CRYSTAL STRUCTURE (FCC)

The crystal structure found for many metals has a unit cell of cubic geometry, with atoms located at each of the corners and the centers of all the cube faces.

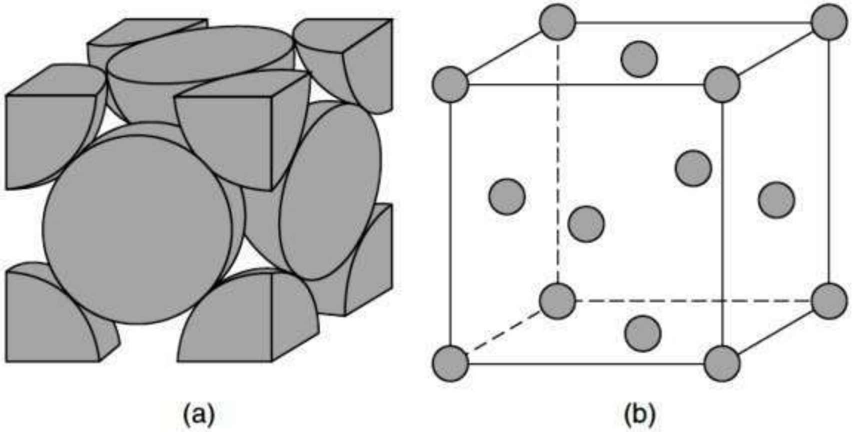
E.g.: copper, aluminum, silver, and gold



(a) atoms bonding (b) atoms as small spheres

COUNTING THE ATOMS IN THE FCC STRUCTURE

pick three atoms along a diagonal. These three atoms form the diagonal on the face of the FCC unit cell.



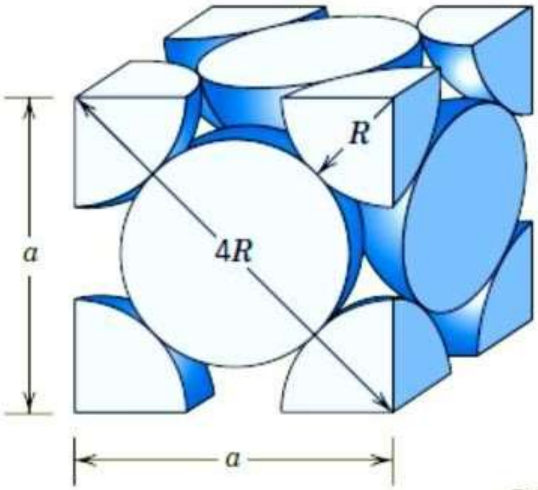
- There are *zero* atoms completely enclosed by the FCC unit cell.
- Six face atoms that are each shared with an adjacent unit cell.
- Eight corner atoms at the intersection of eight unit cells to give

$$
\begin{array}{l}
6 \times (1/2) = 3 \text{ face atoms} \\
8 \times (1/8) = 1 \text{ corner atom} \\
\hline
\qquad\qquad\quad 4 \text{ total atoms}
\end{array}
$$

DETERMINATION OF FCC UNIT CELL VOLUME

Example 1

Calculate the volume of an FCC unit cell in terms of the atomic radius *R*.



- the atoms touch one another across a face-diagonal the length of which is 4*R*.
- Since the unit cell is a cube, its volume is a^3 Where 'a' cell edge length.
- From the right triangle on the face,

$$a^2 + a^2 = (4R)^2$$

or, solving for *a*,

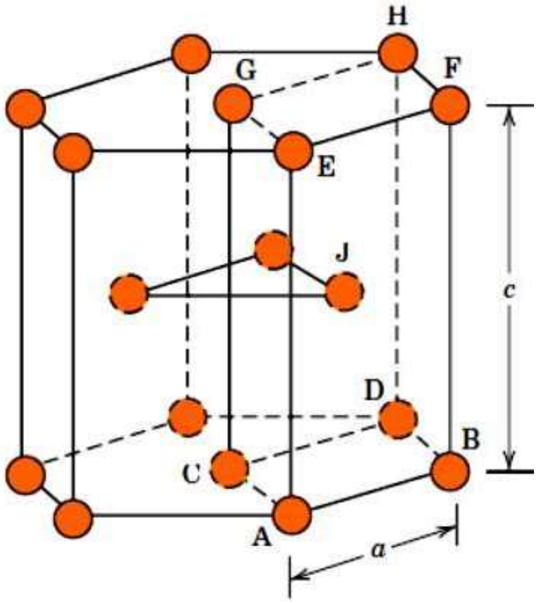
$$a = 2R\sqrt{2}$$

The FCC unit cell volume V_C may be computed from

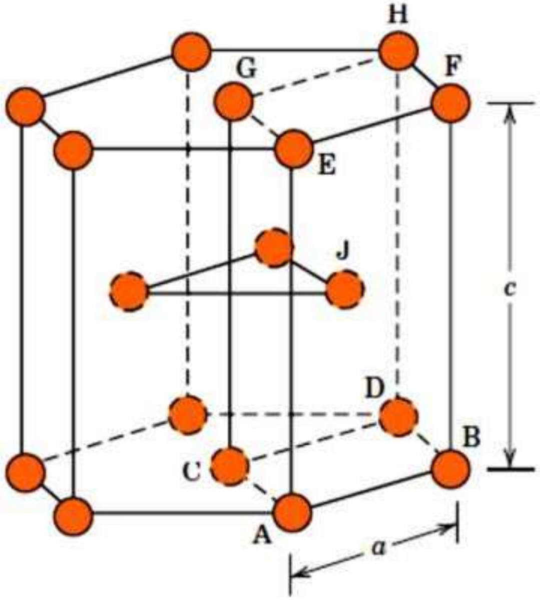
$$V_C = a^3 = (2R\sqrt{2})^3 = 16R^3\sqrt{2}$$

HEXAGONAL CLOSE-PACKED CRYSTAL STRUCTURE (HCP)

- ✓ The top and bottom faces of the unit cell consist of six atoms that form regular hexagons and surround a single atom in the center.
- ✓ Another plane that provides three additional atoms to the unit cell is situated between the top and bottom planes.
- ✓ The atoms in this mid plane have as nearest neighbors atoms in both of the adjacent two planes.

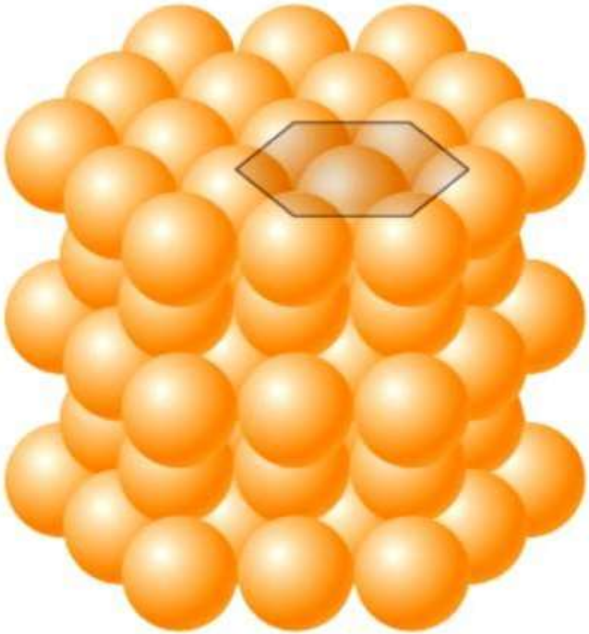


HEXAGONAL CLOSE-PACKED CRYSTAL STRUCTURE (HCP)



(a)

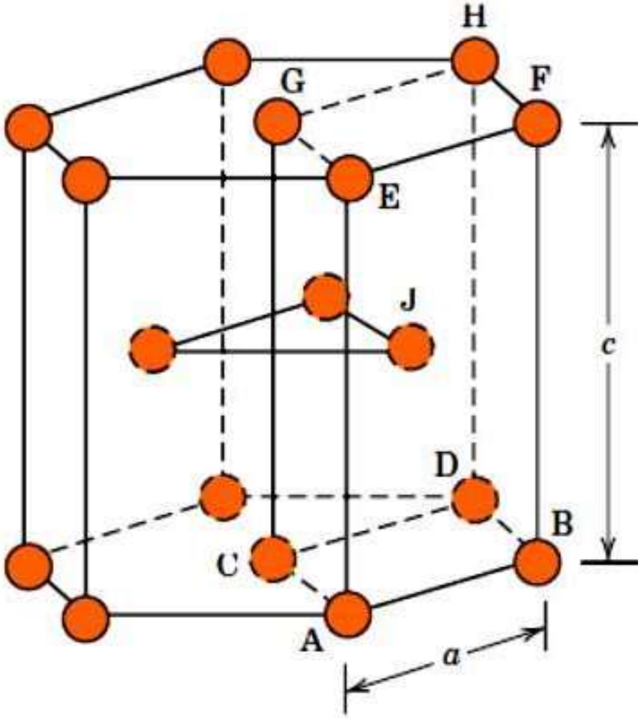
(*a*) a reduced-sphere unit cell (*a* and *c* represent the short and long edge lengths).



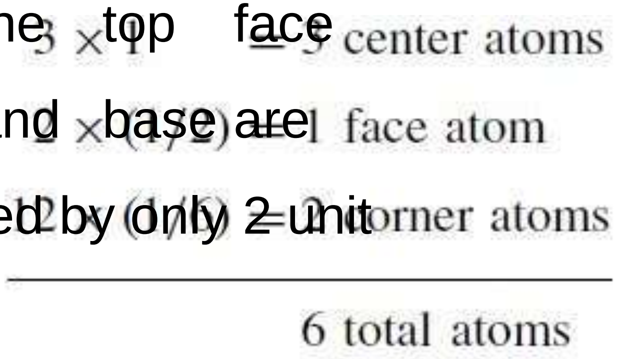
(b)

(*b*) an aggregate of many atoms

COUNTING THE ATOMS IN THE HCP STRUCTURE



- Three full atoms within the volume of each unit cell
- The atoms at the center of the top face and base are shared by only 2 unit cells.



$3 \times 1 = 3$ center atoms

$2 \times (1/2) = 1$ face atom

$12 \times (1/6) = 2$ corner atoms

6 total atoms

- Each of the 12 atoms at the corner of the top

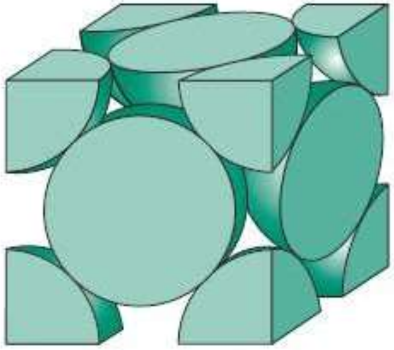
Characteristics of a crystal structure

- coordination number
- APF (Atomic Packing Factor)

Each atom has the same number of nearest-neighbor atoms, which is the coordination number

✓ For face-centered cubics, the coordination number is 12

- Front face atom has four corner nearest-neighbor atoms surrounding it.
- Four face atoms that are in contact from behind.
- Four other equivalent face atoms residing in the next unit cell to the front, which is not shown.



ATOMIC PACKING FACTOR (APF)

The APF is the sum of the sphere volumes of all atoms within a unit cell divided by the unit cell volume. —that is,

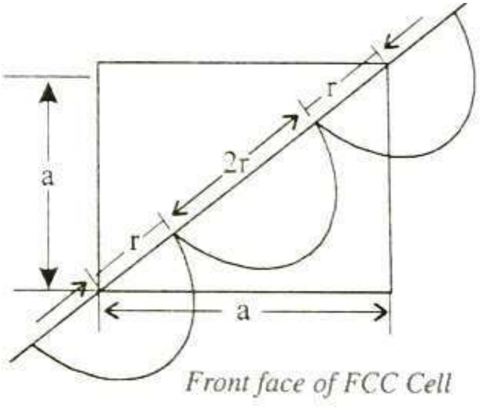
$$\frac{\text{Volume of atoms}}{\text{Volume of unit cell}} = \frac{\text{No. of atoms} \times \text{vol. of each atom}}{\text{Vol. of unit cell}}$$

FCC structure, the atomic packing factor is 0.74

COMPUTATION OF THE ATOMIC PACKING FACTOR FOR FCC

Example 2

Show that the atomic packing factor for the FCC crystal structure is 0.74



Front face of FCC Cell

Solution

$$\text{APF} = \frac{\text{volume of atoms in a unit cell}}{\text{total unit cell volume}} = \frac{V_S}{V_C}$$

The total atom and unit cell volumes may be calculated in terms of the atomic radius *R*.

The volume for a sphere is - $\frac{4}{3}\pi R^3$

since there are 4 atoms per FCC unit cell, the total FCC atom (or sphere) volume is,

$$V_S = (4)\tfrac{4}{3}\pi R^3 = \tfrac{16}{3}\pi R^3$$

FROM EXAMPLE1, THE TOTAL UNIT CELL VOLUME IS

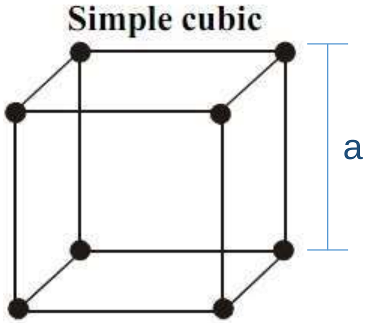
$$V_C = 16R^3\sqrt{2}$$

Therefore, the atomic packing factor is

$$\text{APF} = \frac{V_S}{V_C} = \frac{\left(\frac{16}{3}\right)\pi R^3}{16R^3\sqrt{2}} = 0.74$$

COMPUTATION OF THE ATOMIC PACKING FACTOR (APF) FOR SOME UNIT CELLS

Example 3 Computation of the Atomic Packing Factor for SC (Simple cubic)



Let a = lattice constant

r = atomic radius

The center of each atom coincides with the different corners of the cube and the atoms touch each other at their periphery.

Let us take a =2r

Each one of the atoms at the corners of the cube has effectively only 1/8th of its volume present inside the cubic cell,

$$8\,X\,\frac{1}{8} = 1\ atoms$$

$$\frac{\text{Volume of atoms}}{\text{Volume of unit cell}} = \frac{\text{No. of atoms} \times \text{vol. of each atom}}{\text{Vol. of unit cell}}$$

$$\text{APF} = \frac{1 \times \frac{4\pi r^3}{3}}{a^3} = \frac{4\pi r^3}{3(2r)^3}$$

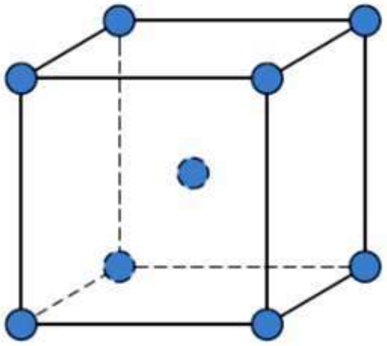
$$\left[\begin{array}{l}\text{Since Vol. of sphere} = \dfrac{4\pi r^3}{3} \\ \text{and } a = 2r\end{array}\right]$$

APF = 0.52

COMPUTATION OF THE ATOMIC PACKING FACTOR (APF) FOR SOME UNIT CELLS

Example 4 **Computation of the Atomic Packing Factor for BCC**

Solution

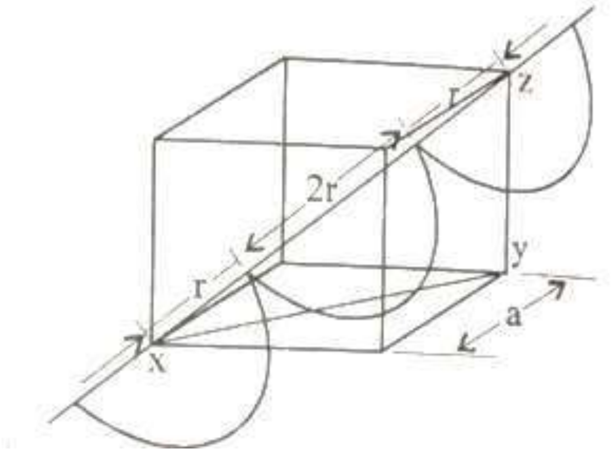


There is one full atom at the center and one atom at each of the eight corners.

Therefore effective number of atoms inside each unit cell is,

$$1 + 8\,X\,\frac{1}{8} = 2\ atoms$$

To find ‘a’ in terms of ‘r’

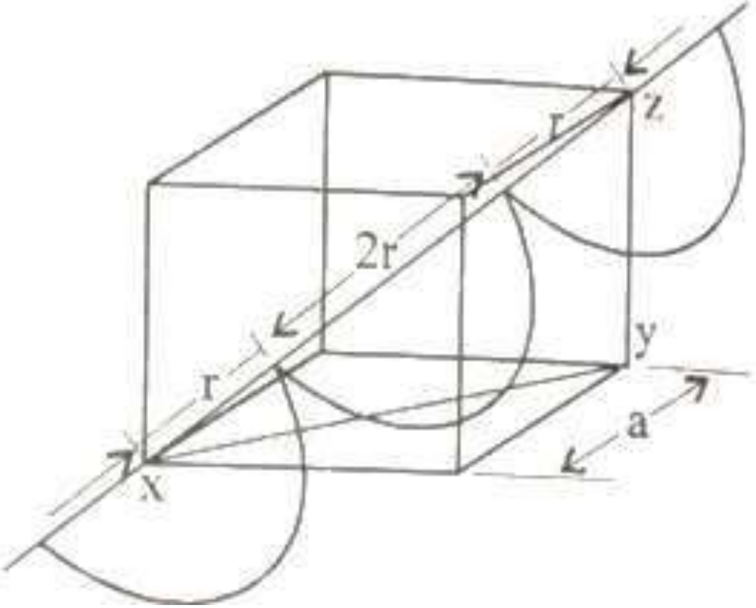


$$xy = \sqrt{a^2 + a^2} = \sqrt{2}a\ (Solid\ diagonal)$$

$$(xz)^2 = (4r)^2 = \left(\sqrt{2}a\right)^2 + a^2$$

$$4r = \sqrt{3a^2}$$

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



$$\text{APF} = \frac{\text{No. of atoms} \times \text{vol. of each atom}}{\text{vol. of unit cell}}$$

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

APF = 0.68

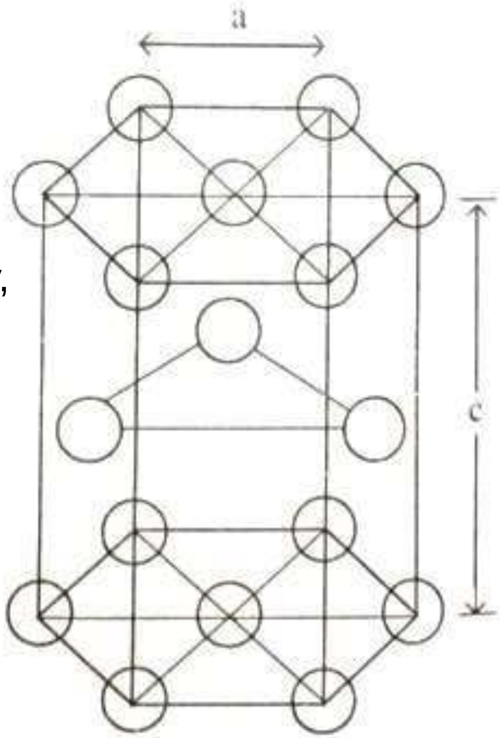
COMPUTATION OF THE ATOMIC PACKING FACTOR (APF) FOR SOME UNIT CELLS

Example 5 Computation of the atomic packing factor for HCP **(given c=1.633a)**

Solution

No. of atoms in one HCP unit cell is,

$$= 12 \times \frac{1}{6} + 2 \times \frac{1}{2} + 3 = 6 \text{ atoms}$$



- Since the corner atoms touch their neighboring atoms at their periphery, We have a =2r.
- And, the ratio of the height of the hexagonal prism to the side of the hexagonal faces is give as C = 1.633a

To find volume of hexagonal unit cell

Volume of HCP unit cell = area of hexagonal face x height of hexagonal prism

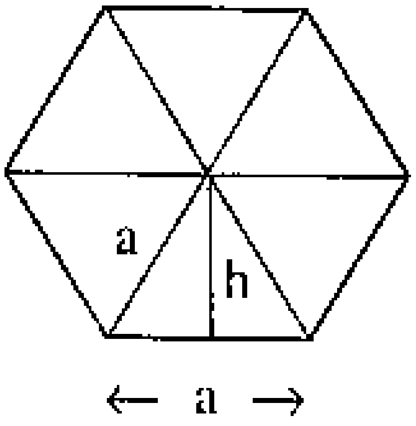
area of hexagonal face = area of each triangle x 6

$$\text{Area of the triangle} = \frac{1}{2} \times \text{base} \times \text{height}$$

$$= \frac{1}{2} \times a \times h$$

$$= \frac{1}{2} \times a \times \frac{a\sqrt{3}}{2}$$

$$\therefore \text{Area of the hexagon} = \frac{a^2\sqrt{3}}{4} \times 6$$



$$\text{Volume of the HCP unit cell} = \frac{a^2\sqrt{3}}{4} \times 6 \times c = \frac{a^2\sqrt{3}}{4} \times 6 \times 1.633\ a$$

$$\text{APF} = \frac{\text{No. of atoms} \times \text{Volume of each atom}}{\text{Volume of unit cell}}$$

$$\text{APF} = \frac{6 \times \frac{4\pi r^3}{3}}{\frac{\sqrt{3}}{4} \times 6 \times 1.633 \times a^3} = \frac{6 \times 4\pi r^3 \times 4}{3 \times \sqrt{3} \times 6 \times 1.633 \times (2r)^3} \quad [\because\ a = 2r]$$

$$\mathbf{APF = 0.74}$$

LIST OF FORMULAE

$$\text{Density of any metal } (\rho) = \frac{nA}{V_C N_A}$$

where n = number of atoms in each unit cell

A = Atomic weight of the metal (g/mol)

V_C = Volume of one unit cell

N_A = Avogadros number = 6.023×10^{23} atoms/mol

Effective number of atoms present in one

(i) Simple cubic unit cell = 1

(ii) Body centered cubic unit cell = 2

(iii) Face centered cubic unit cell = 4

(iv) Hexagonal close packed unit cell = 6

(i) In BCC, $a = \frac{4r}{\sqrt{3}}$

(ii) APF (BCC) = 0.68

(i) Volume of HCP unit cell = $\frac{3\sqrt{3}}{2} a^2 C$

where a = lattice constant

c = height of unit cell

(ii) If C = 1.633 a, volume of HCP cell = $4.24\ a^3$

(iii) APF (HCP) = 0.74

(i) In FCC, $a = \frac{4r}{\sqrt{2}}$

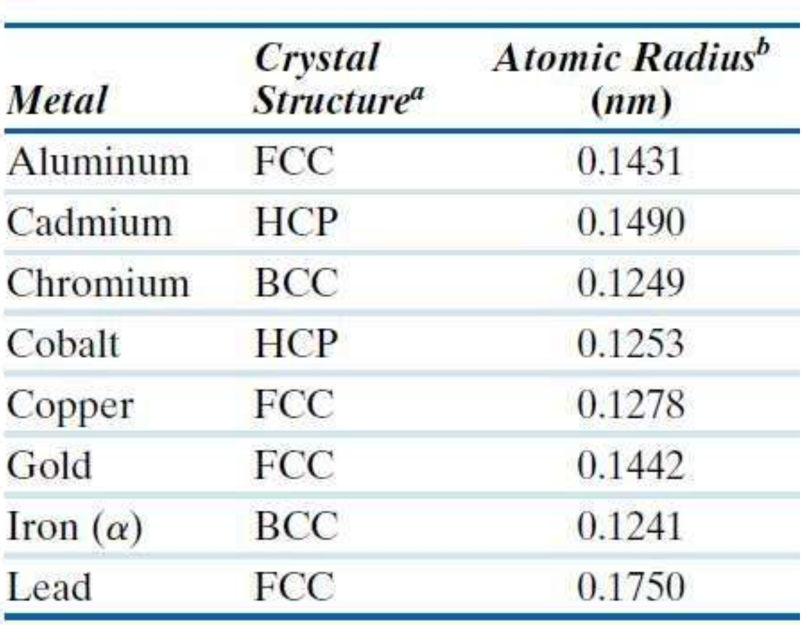
Where r = radius of atom

a = lattice constant or lattice parameter or side of unit cell

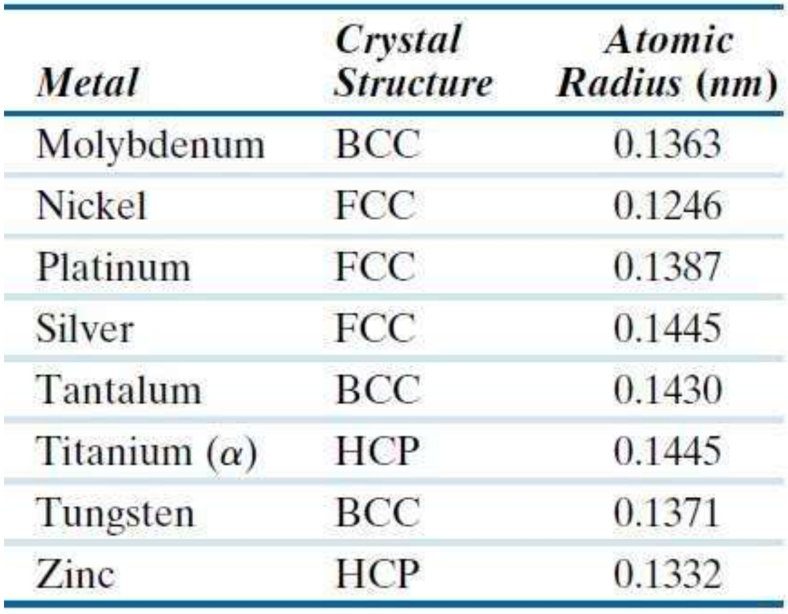
(ii) APF (FCC) = 0.74

Volume of an atom of radius r = $\frac{4}{3} \pi r^3$

ATOMIC RADII AND CRYSTAL STRUCTURES FOR 16 METALS



Metal	*Crystal Structure*[a]	*Atomic Radius*[b] *(nm)*
Aluminum	FCC	0.1431
Cadmium	HCP	0.1490
Chromium	BCC	0.1249
Cobalt	HCP	0.1253
Copper	FCC	0.1278
Gold	FCC	0.1442
Iron (α)	BCC	0.1241
Lead	FCC	0.1750



Metal	*Crystal Structure*	*Atomic Radius (nm)*
Molybdenum	BCC	0.1363
Nickel	FCC	0.1246
Platinum	FCC	0.1387
Silver	FCC	0.1445
Tantalum	BCC	0.1430
Titanium (α)	HCP	0.1445
Tungsten	BCC	0.1371
Zinc	HCP	0.1332

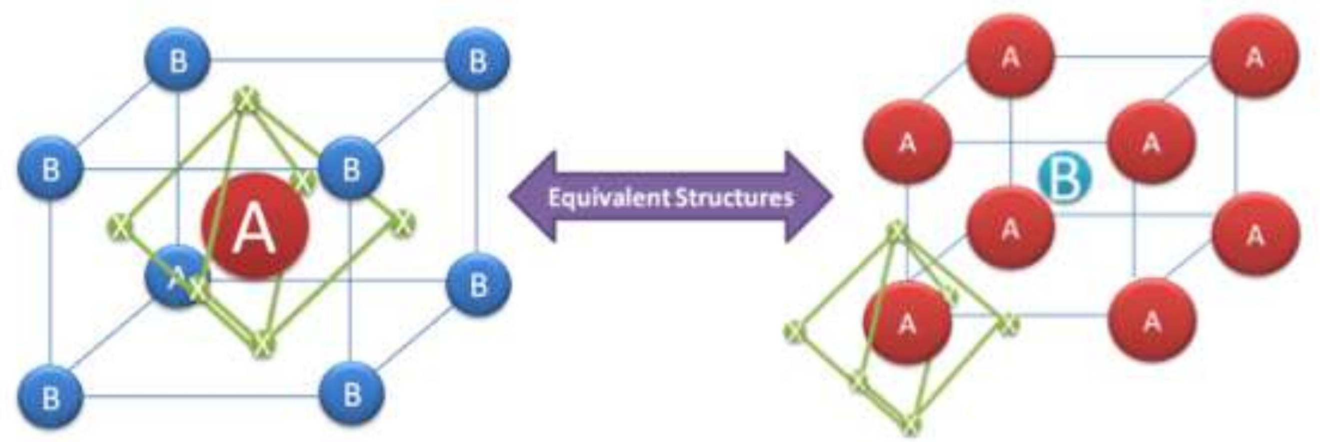
PEROVSKITES

The terms "perovskite" and "perovskite structure" are often used interchangeably. Technically, a perovskite is a type of mineral that was first found in the Ural Mountains and named after Lev Perovski who was the founder of the Russian Geographical Society. A perovskite structure is any compound that has the same structure as the perovskite mineral.

True perovskite (the mineral) is composed of calcium, titanium and oxygen in the form $CaTiO_3$. Meanwhile, a perovskite structure is anything that has the generic form ABX_3 and the same crystallographic structure as perovskite (the mineral). However, since most people in the solar cell world aren’t involved with minerals and geology, perovskite and perovskite structure are used interchangeably.

The perovskite lattice arrangement is demonstrated below. As with many structures in crystallography, it can be represented in multiple ways. The simplest way to think about a perovskite is as a large atomic or molecular cation (positively-charged) of type A in the centre of a cube. The corners of the cube are then occupied by atoms B (also positively-charged cations) and the faces of the cube are occupied by a smaller atom X with negative charge (anion).

CONT....



A generic perovskite crystal structure of the form ABX_3. Note however that the two structures are equivalent – the left hand structure is drawn so that atom B is at the <0,0,0> position while the right hand structure is drawn so that atom (or molecule) A is at the <0,0,0> position. Also note that the lines are a guide to represent crystal orientation rather than bonding patterns.

CONT...

Depending on which atoms/molecules are used in the structure, perovskites can have an impressive array of interesting properties including superconductivity, giant magnetoresistance, spin-dependent transport (spintronics) and catalytic properties. Perovskites therefore represent an exciting playground for physicists, chemists and material scientists.

In the case of perovskite solar cells, the most efficient devices so far have been produced with the following combination of materials in the usual perovskite form ABX_3:

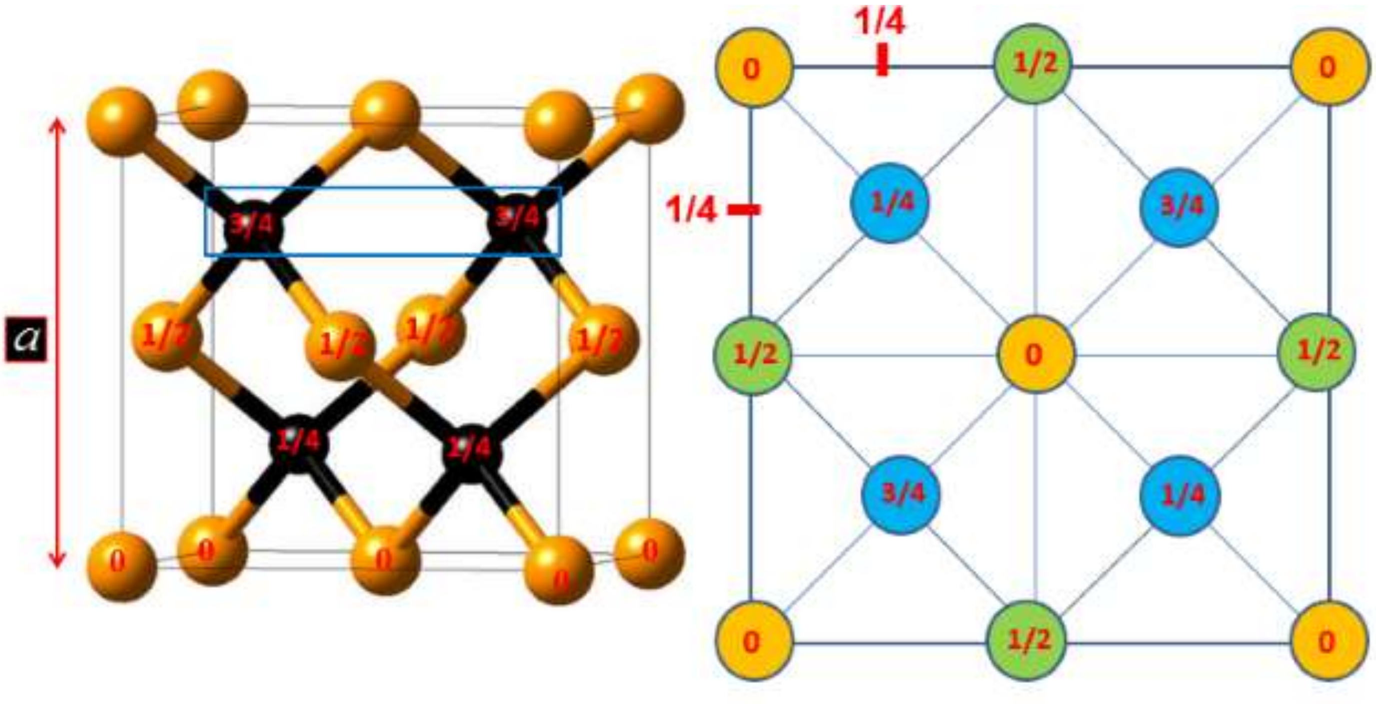
- A = An organic cation - methylammonium $(CH_3NH_3)+$
- B = A big inorganic cation - usually lead(II) (Pb_2+)
- X_3= A slightly smaller halogen anion – usually chloride (Cl-) or iodide (I-)

Since this is a relatively general structure, these perovskite-based devices can also be given a number of different names, which can either refer to a more general class of materials or a specific combination. As an example of this, we've created the below table to highlight how many names can be formed from one basic structure.

DIAMOND STRUCTURE

Diamond Crystal Structure is a metastable allotrope of carbon where the each carbon atom is bonded covalently with other surrounding four carbon atoms and are arranged in a variation of the face centered cubic crystal structure called a diamond lattice. Diamond is a transparent crystal of tetrahedrally bonded carbon atoms (sp^3) that crystallizes into the diamond lattice which is a variation of the face centered cubic structure. Each carbon atom joins four other carbon atoms in regular tetrahedrons (triangular prisms). Based on the cubic form and its highly symmetrical arrangement of atoms, diamond crystals can develop into several different shapes, known as 'crystal habits'.

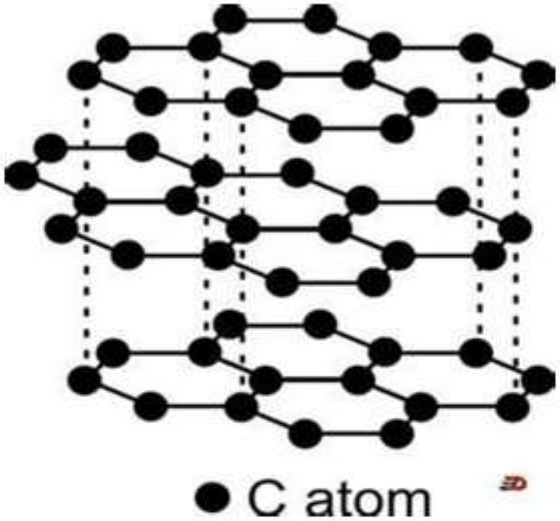
CONT…



The number '0' and fractions '½' , '¼' and '¾' denote the height above the base.

GRAPHITE STRUCTURE

Graphite is a greyish black opaque substance. It is lighter than diamond and is soft and slippery to touch. It conduct electricity. It is made up of carbon atoms only. The structure of graphite is very different from that of diamond. It consists of layers of carbon atoms or sheet of carbon atoms. Each carbon atoms in a graphite layer is joined to three other carbon atoms by strong covalent bonds to form flat hexagonal rings. The various layers of carbon atoms in graphite are held together by weak van der waals forces.



CONT…

The structure of graphite is very different from that of diamond. It consists of layers of carbon atoms or sheet of carbon atoms. Each carbon atoms in a graphite layer is joined to three other carbon atoms by strong covalent bonds to form flat hexagonal rings. The various layers of carbon atoms in graphite are held together by weak van der waals forces. Due to the sheet like structure, graphite is comparatively soft substance. Graphite is good conductor of electricity because due to the presence of free electrons.

Uses of Graphite:

- Graphite can be used for lubricating those machine parts which operate at very high temperature.
- Graphite is used for making graphite electrodes in dry cells and electric arcs.
- Graphite is used for making the cores of our pencils called pencil leads.

SELF LEARNING QUESTIONS

A. Define metallurgy. Explain importance of metallurgy.
B. What are the engineering requirements of materials?
C. Which are the types of metallurgy? Explain any one.
D. Explain selection criteria for material for engineering materials
E. Differentiate micro and macro examination.
F. Explain classification of engineering material.
G. Justify B.C.C. is less dense than F.C.C
H. Define atomic radius and atomic packing factor for B.C.C., F.C.C. and H.C.P.
I. What is solid solution? Explain the types of solid solution
J. Discuss the factors affecting on solid solution.
K. What is crystallization? Explain mechanism of crystallization.

ASSIGNMENT EXERCISES

1. Write in detail about an atom and atomic models?
2. What is a bond and types of bonding's with proper examples?
3. Explain the detail about Ionic and Covalent bonding. Also explain about the strongest bonding with proper justification.
4. Find the atomic packing factors of BCC, FCC & HCP
5. Write a short notes on Bravis lattices?
6. Write in detail about the Pervoskite crystal structure and diamond structure?

THANK YOU

LIVE TO LEARN & LEARN TO SHARE

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MATERIALS ENGINEERING (R18A0305)

2nd Year B. Tech I- sem, Mechanical Engineering

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COURSE OBJECTIVES

UNIT - 1	**CO1:** To understand various mechanical properties of materials.
UNIT - 2	CO2: To understand how and why the properties of materials are controlled by its structure at the microscopic and macroscopic levels.
UNIT - 3	CO3: To understand how and why the structure and composition of a material may be controlled by processing.
UNIT - 4	CO4: To create different types of composite materials and its applications.
UNIT - 5	CO5: To remember polymer material classifications and applications.

UNIT 2

STRUCTURE OF METALS & ALLOYS

CO2: To understand how and why the properties of materials are controlled by its structure at the microscopic and macroscopic levels.

UNIT – II (SYLLABUS)

Structure of Metals & Alloys:

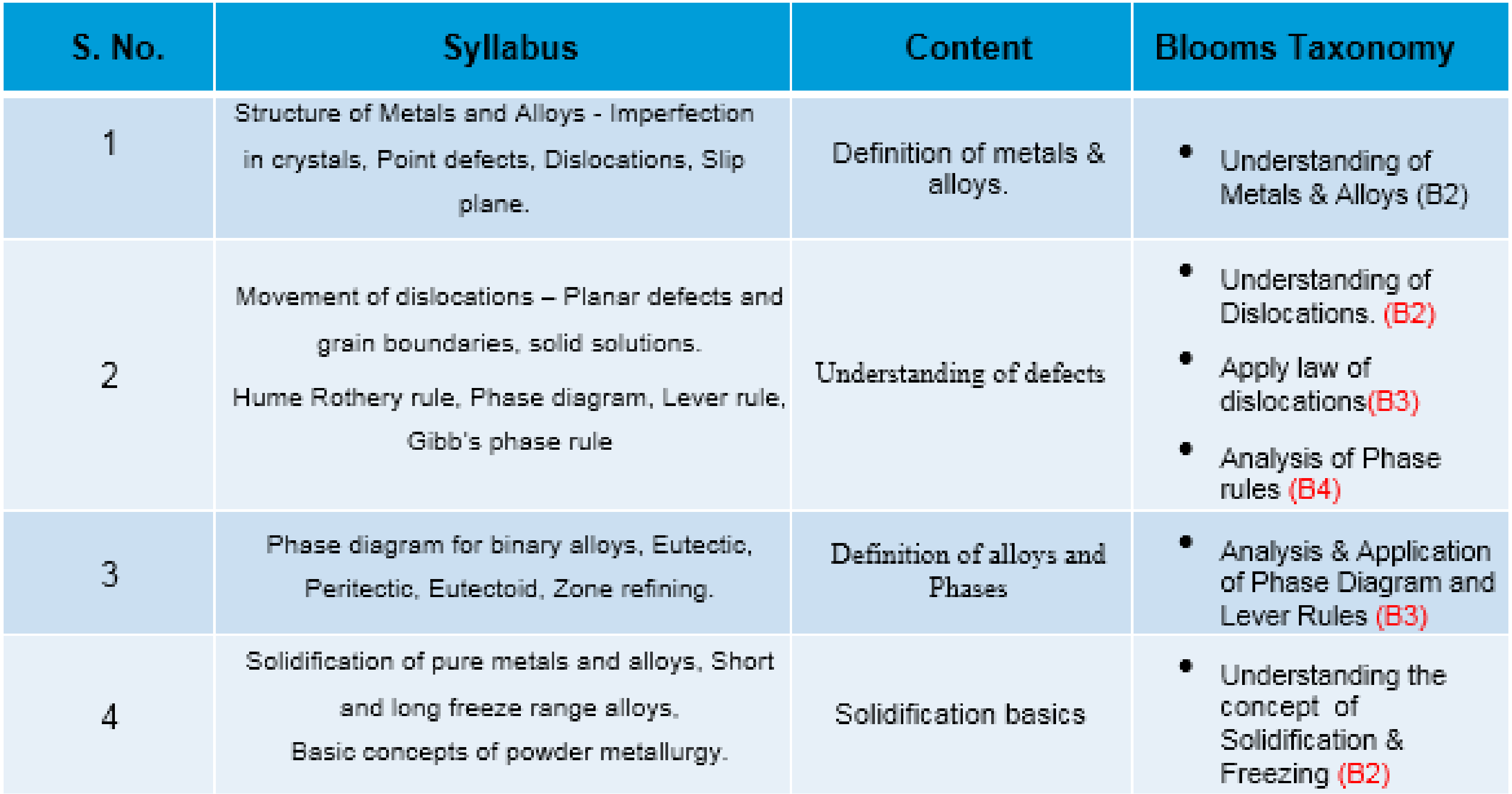
- Imperfection in crystals – Point defects – Dislocations – Slip plane – Movement of dislocations.
- Planar defects and grain boundaries – solid solutions.

Solid Solutions: Phase Diagram & Lever Rule

- Hume Rothery rule – Phase diagram – Lever rule.
- Gibb's phase rule – Phase diagram for Eutectic – Peritectic – Eutectoid – Zone refining.
- Solidification of pure metals and alloys – Short and long freeze range alloys – basic concepts of powder metallurgy.

COURSE OUTLINE

UNIT - 2



S. No.	Syllabus	Content	Blooms Taxonomy
1	Structure of Metals and Alloys - Imperfection in crystals, Point defects, Dislocations, Slip plane.	Definition of metals & alloys.	• Understanding of Metals & Alloys (B2)
2	Movement of dislocations – Planar defects and grain boundaries, solid solutions. Hume Rothery rule, Phase diagram, Lever rule, Gibb's phase rule	Understanding of defects	• Understanding of Dislocations. (B2) • Apply law of dislocations(B3) • Analysis of Phase rules (B4)
3	Phase diagram for binary alloys, Eutectic, Peritectic, Eutectoid, Zone refining.	Definition of alloys and Phases	• Analysis & Application of Phase Diagram and Lever Rules (B3)
4	Solidification of pure metals and alloys, Short and long freeze range alloys. Basic concepts of powder metallurgy.	Solidification basics	• Understanding the concept of Solidification & Freezing (B2)

IMPERFECTIONS IN CRYSTALS

ISSUES TO ADDRESS...

- How do defects affect material properties?
- What types of defects arise in solids?
- Are defects undesirable?

Crystalline Imperfections

There is no such thing as a perfect crystal!

- Thermodynamically “impossible”
- *“defects” lower the energy of a crystal & make it more stable*
- always have vacancies and impurities, to some extent

Defect does not necessarily imply a bad thing

- addition of C to Fe to make steel
- addition of Cu to Ni to make thermocouple wires
- addition of Ge to Si to make thermoelectric materials
- addition of Cr to Fe for corrosion resistance
- introduction of grain boundaries to strengthen materials

…… and so on

“Defect” (in this context) can be either desirable or undesirable.

In general, a defect simply refers to a disruption in the crystalline order of an otherwise periodic material.

Crystal imperfections are broadly classified into four major classes as below:

1. *Point defects (Zero dimensional)*
2. *Line defects (One dimensional)*
3. *Planar or surface defects (Two dimensional)*
4. *Volume defects*

Point Defects

- Atoms in solid possess vibrational energy, some atoms have sufficient energy to break the bonds which hold them in eqbm position. Hence once the atoms are free they give rise to **Point Defects**.

Classes of point defects:

1. Vacancy/Schottky
2. Interstitial/Frenkel

- **Impurities**

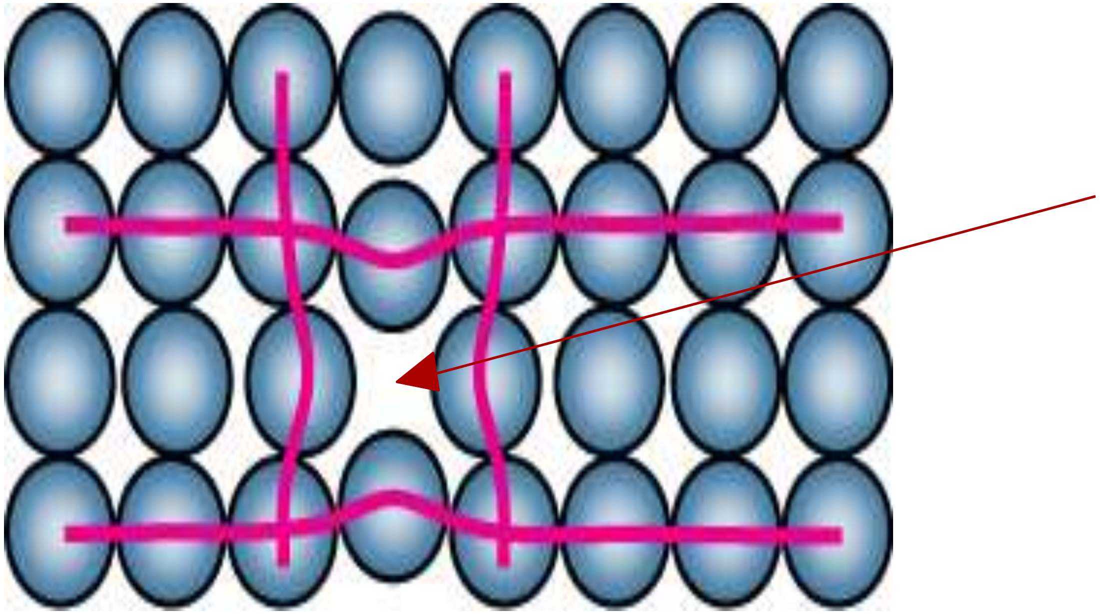
1. Substitution
2. Interstitial

Vacancies

- A lattice position that is vacant because the atom is missing
- There are naturally occurring vacancies in all crystals
- The concentrations of vacancies increase with:
- Increasing temperature
- Decreasing activation energy

Vacancies

- -vacant atomic sites in a structure.



Vacancy

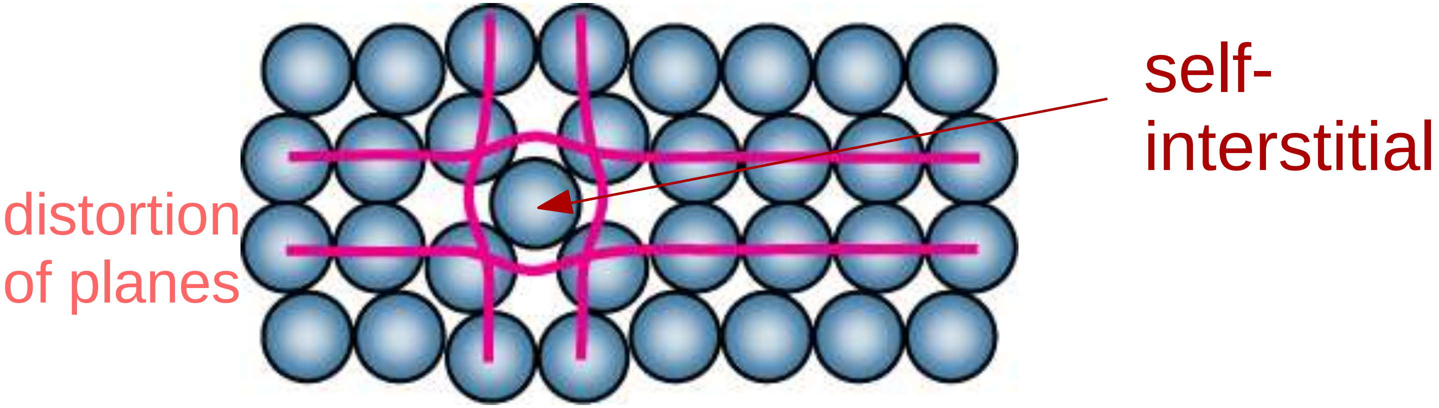
distortion

of planes

Self-Interstitial

- If the matrix atom occupies its own interstitial site, the defect is called Self Interstitial.

- Self-interstitials in metals introduce large distortions in the surrounding lattice.



For Ionic Solids, Frenkel and Schottky defects are likely to form.

- ***Schottky Defects***

  When cation vacancy is associated with anion vacancy, the defect is called Schottky Defect.

- ***Frenkel Defects***

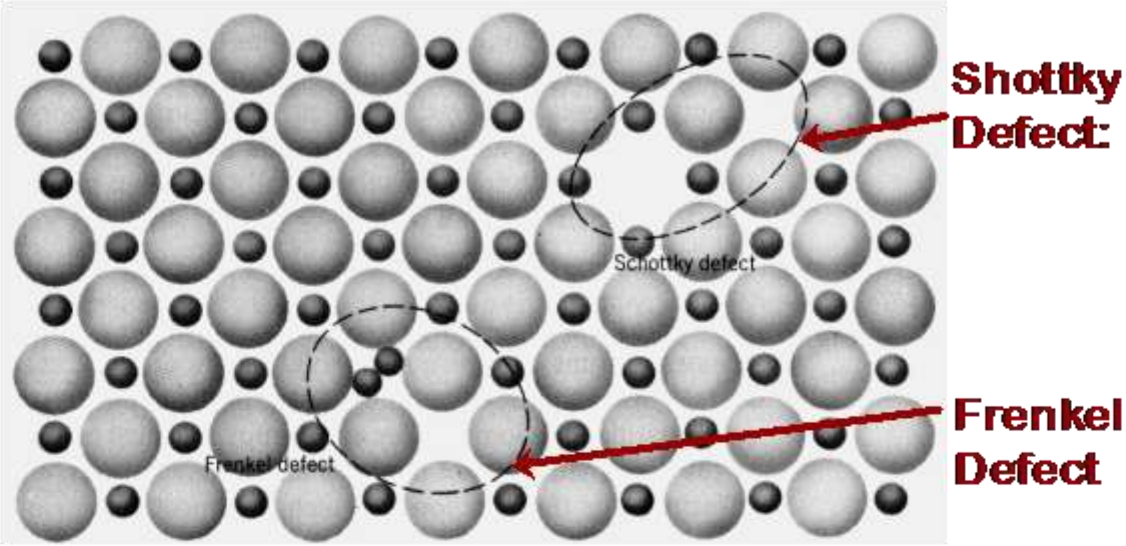
  When an atom leaves its regular site and occupy nearby interstitial site it gives rise to two defects i.e. one vacancy and other self interstitial these two defects are called as Frenkel Defects.

DEFECTS IN CERAMIC STRUCTURES

- Frenkel Defect

  --a cation is out of place.
- Shottky Defect

  --a paired set of cation and anion vacancies.



Adapted from Fig. 13.20, *Callister 5e.* (Fig. 13.20 is from W.G. Moffatt, G.W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. 1, *Structure*, John Wiley and Sons, Inc., p. 78.) See Fig. 12.21, *Callister 6e*.

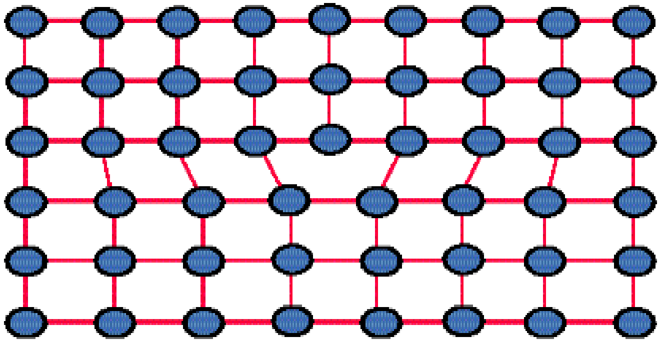
LINE DEFECTS ***(ONE DIMENSIONAL)***

- A *dislocation* is a line discontinuity in the regular crystal structure. A part of the line will be missing from its regular site and this missing row is dislocation. The dislocation is centered along a line and hence the line defect is called dislocation.
- The dislocation is a boundary between the slipped and unslipped region and lies in the slip plane. The structure and behaviour of dislocations affect many of the properties of engineering materials.

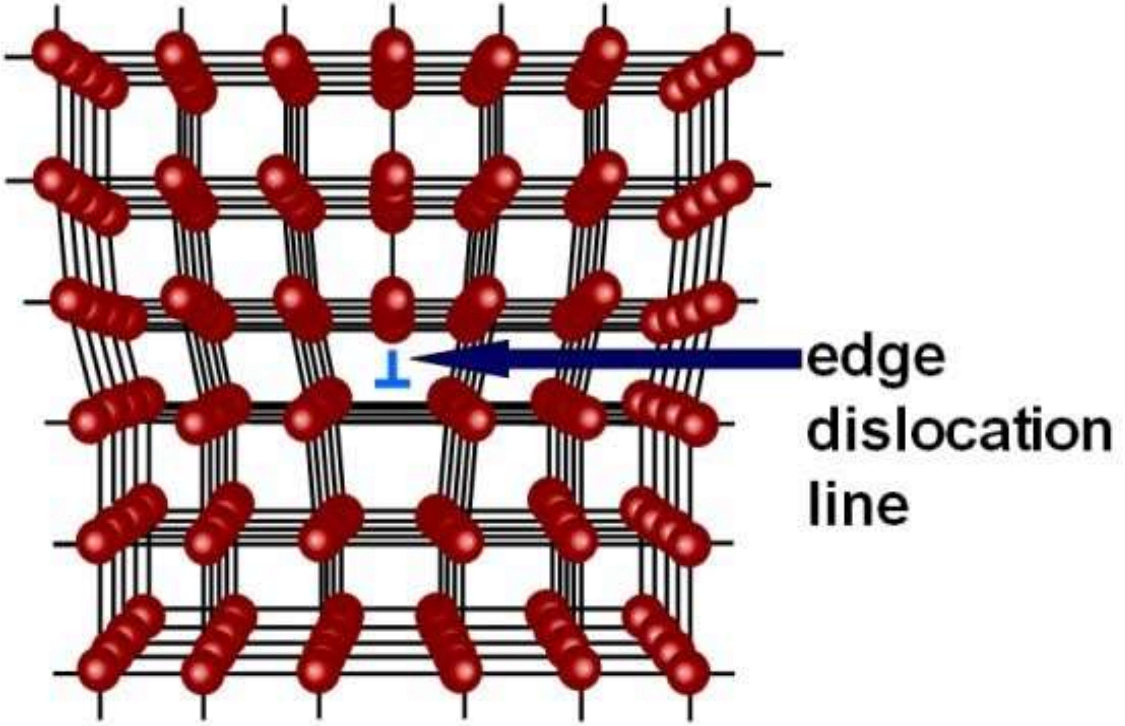
- There are two basic types:
  1. *Edge dislocations*
  2. *Screw dislocations.*

EDGE DISLOCATION

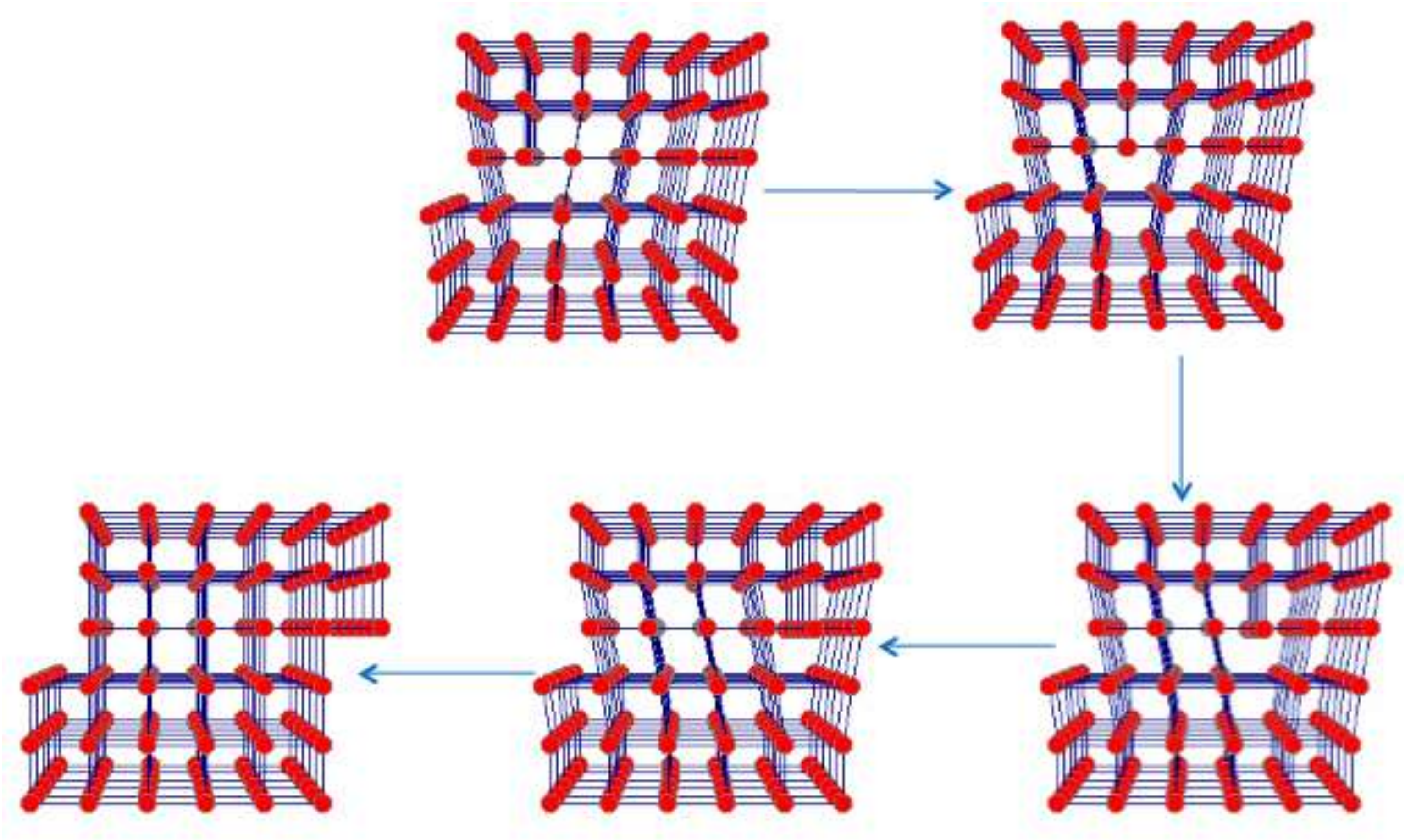
- An *Edge dislocation* in a metal may be regarded as the insertion (or removal) of an extra half plane of atoms in the crystal structure.
- In Ionic and Covalent solids edge dislocations involve extra half planes of *unit cells*.
- If we consider a perfect crystal to be made up of vertical planes parallel to one another and to the side faces. If one of these vertical planes does not extend from the top to the bottom of crystals but ends part way within crystal, it is called as edge dislocation.



- *Berger vector* is perpendicular to dislocation line.



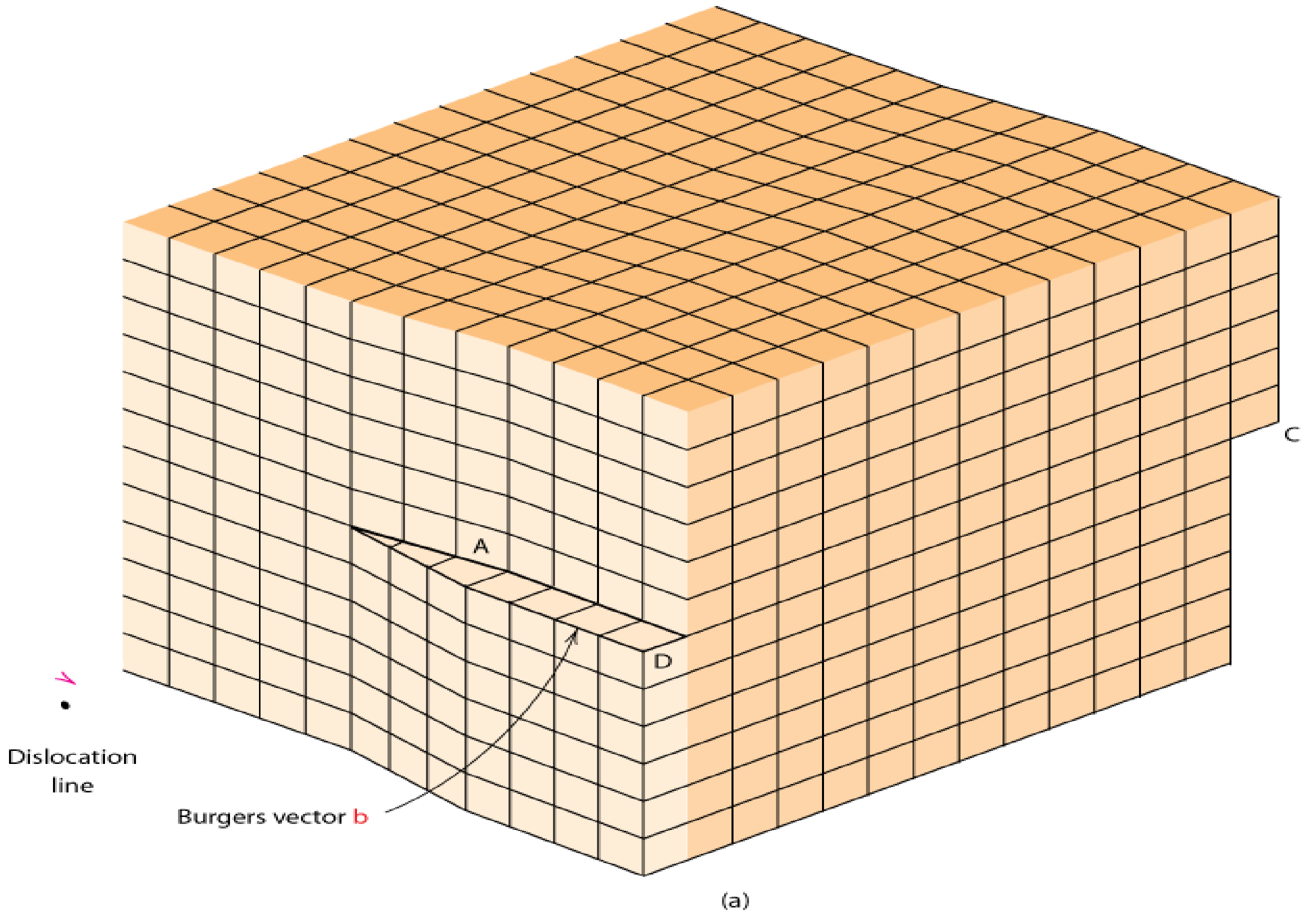
MOVEMENT OF AN EDGE DISLOCATION



2) SCREW DISLOCATION

- In screw dislocation ,there is transformation of successive atomic planes into the surface of helix around dislocation line due to shear stress i.e. it follows *helical* or *screw* path.
- A screw dislocation can be imagined as being produced by cutting the crystal partway through with a knife and then shearing one part of the crystal with respect to the other parallel to the cut.

BERGER VECTOR IS PARALLEL TO DISLOCATION LINE



LINEAR/LINE DEFECTS – (DISLOCATIONS)

- Line imperfection or dislocation are defects that cause lattice distortions.
- Dislocation are created during:
  - Solidification
  - Permanent deformation of crystalline solid
  - Vacancy condensation
  - Atomic mismatch in solid solution
- Different types of line defects are:
  - Edge dislocation
  - Screw dislocation
  - Mixed dislocation

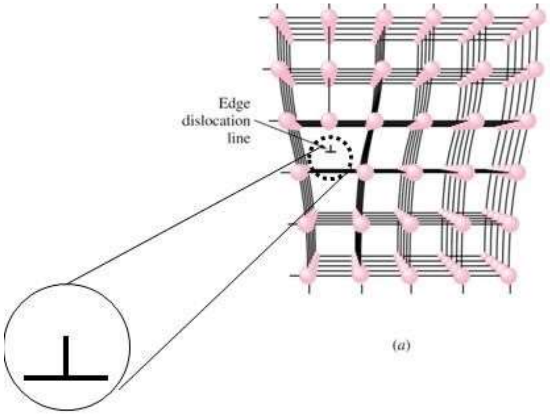
Edge Dislocation

- An edge dislocation is created in a crystal by **insertion** of extra half planes of atoms.

⊥ → Positive edge dislocation

T → Negative edge dislocation

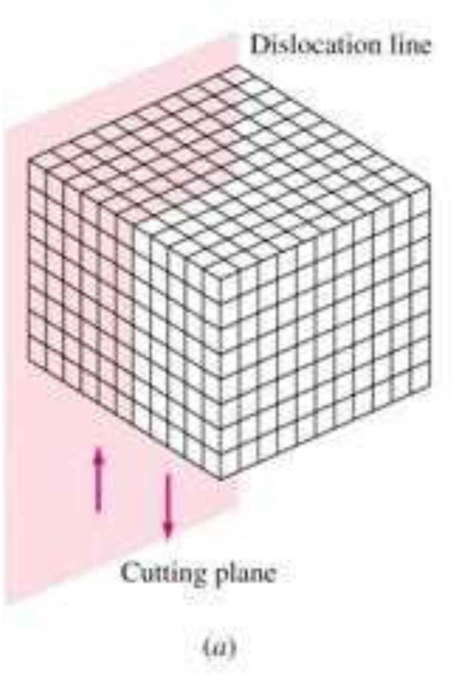
- In figure below, a linear defect occurs in the region just above the inverted T, where an extra half plane of atoms has been wedged in.



Positive edge dislocation in a crystalline lattice.

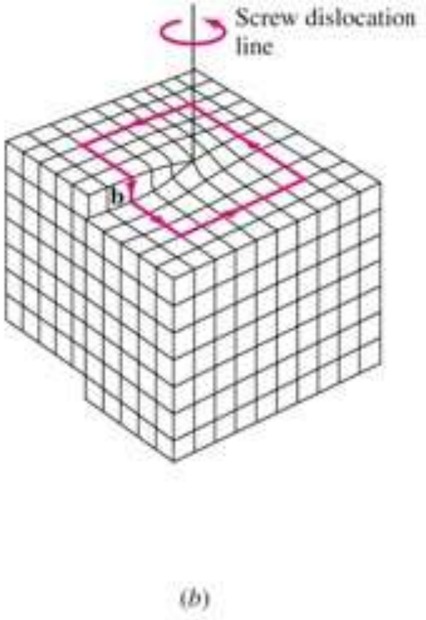
Screw Dislocation

The screw dislocation can be formed in a perfect crystal by applying upward and downward **shear stresses** to regions of a perfect crystal that have been separated by a cutting plane as shown in Figure below.



Formation of a screw dislocation:
A perfect crystal is sliced by a cutting plane, and up and down shear stresses are applied parallel to the cutting plane to form the screw dislocation as in (b).

These shear stresses introduce a region of distorted crystal lattice in the form of a spiral ramp of distorted atoms or screw dislocation as figure below.



Formation of a screw dislocation:
A screw dislocation is shown with its slip or Burgers vector **b** parallel to the dislocation.

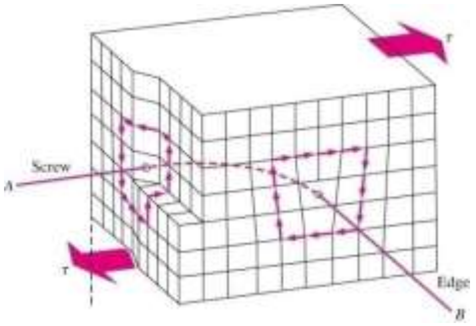
- The region of distorted crystal is not well defined and is at least several atoms in diameter.

- A region of shear strain is created around the screw dislocation in which energy stored.

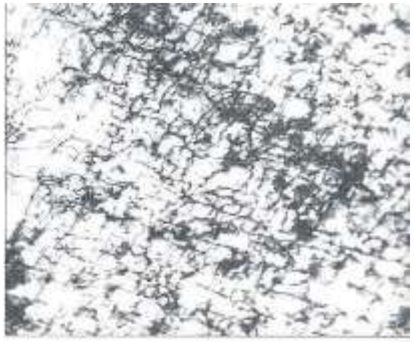
- The slip or Burgers vector of the screw dislocation is *parallel* to the dislocation line as shown in Figure above.

Mixed Dislocation

- Most crystal have components of both edge and screw dislocation.



- Dislocation, since have irregular atomic arrangement will appear as dark lines when observed in electron microscope.



Dislocation structure of iron deformed 14% at –195^{0}C

PLANAR/SURFACE DEFECTS (TWO DIMENSIONAL)

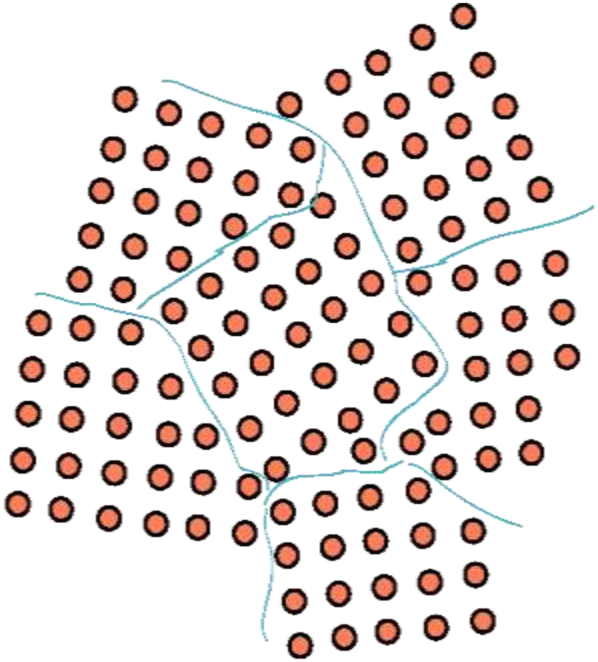
Planar defects arise due to change in the stacking of atomic planes during mechanical and thermal treatments. The change may be of the orientation or of the stacking sequence of the planes.

Planar defects are of following types:

- *Grain boundaries*
- *Tilt boundaries*
- *Twin boundaries*

GRAIN BOUNDARIES

- A Grain Boundary is a general planar defect that separates regions of different crystalline orientation (i.e. *grains*) within a polycrystalline solid . Grain boundaries are usually the result of uneven growth when the solid is crystallizing.



TILT BOUNDARIES

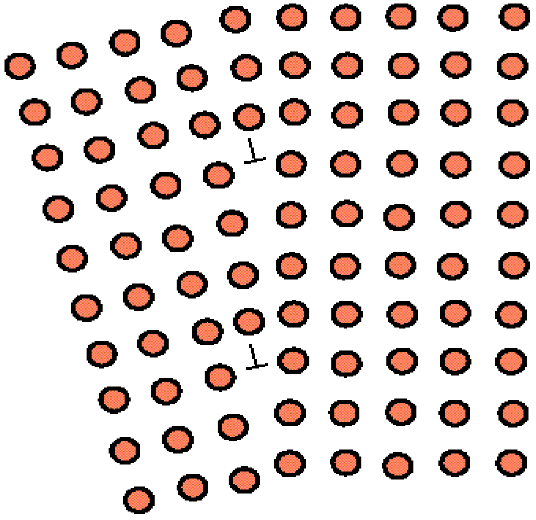
- When the angle between two crystals is less than 10 ,the distortion is not so drastic as to be compared with a non crystalline material .They are also called low angle boundaries.
- It can be described as set of parallel, equally spaced edge dislocation of same sign located

  one above other.
- A Tilt Boundary, between two slightly

  mis-aligned grains appears

  as an *array of edge*

  dislocations.

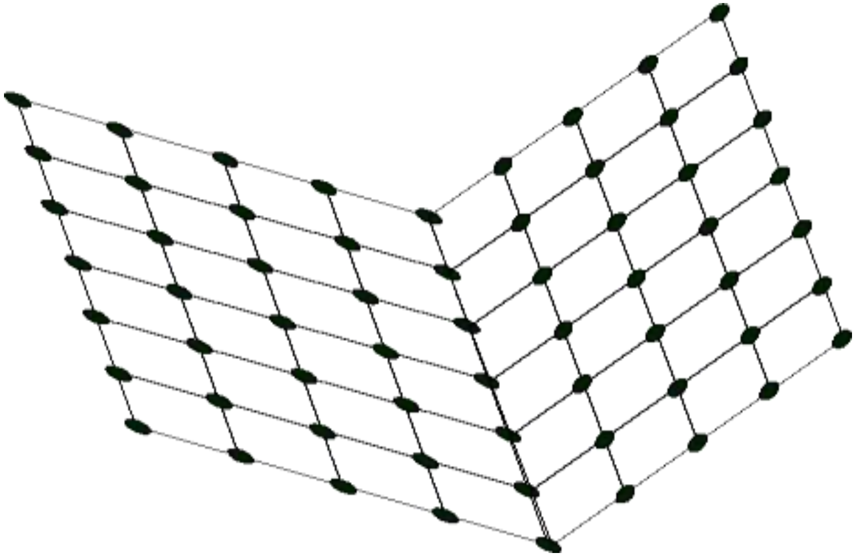


TWIN BOUNDARIES

- These are the boundaries in the grains at which the atomic arrangement on one side of the boundary is the mirror image of the atoms on the other side .The volume of material which has an orientation similar to the mirror image of the matrix orientation is called a twin.

- The plane is called

  twinning plane.



VOLUME DEFECTS

- Volume defects such as stacking faults may arise when there is only small dissimilarity between the stacking sequence of close packed planes in FCC and HCP metals.
- Stacking faults are of two types called as intrinsic and extrinsic .Intrinsic fault results in one break whereas extrinsic fault results in two breaks in the sequence
- The volume defects may affect their mechanical, electrical and optical properties.

SOLID SOLUTIONS

- Solid Solutions
- Substitutional Solid Solution
- Hume-Rothery Rules
- Interstitial Solid solution
- Intermediate Phases

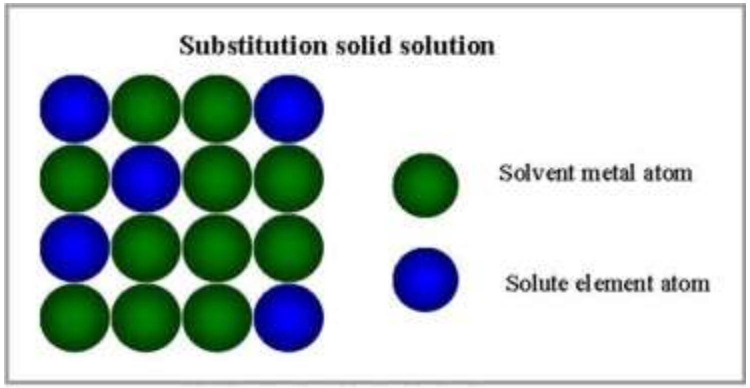
- **Solid Solution or an Alloy is a phase, where two or more elements are completely soluble in each other.**
- **Solid solutions** have important commercial and industrial applications, as such mixtures often have superior properties to pure materials.
- Many metal alloys are solid solutions.
- *Ex: Cu-Ni, Au-Ag etc.*
- **In a solid solution, the metal in the major proportion is called the solvent (host or parent or matrix) and the metal in the minor proportion is called the solute**

CONT…

- There are **two** types of Solid Solutions:
  - Substitutional Solid Solution
  - Interstitial Solid Solution

SUBSTITUTIONAL SOLID SOLUTION

- **In this type of solid solution, the solute atoms substitute the atoms of solvent in the crystal structure of the solvent.** The substitutional solid solution are generally ordered at lower temperatures and at higher disordered temperatures. **Temperature is the deciding factor.**

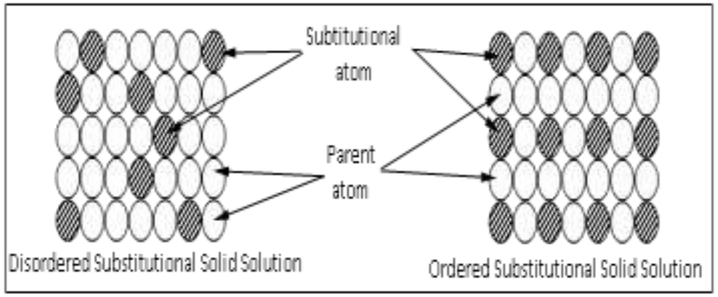


- There are **two** types of substitutional solid solutions:

i. Ordered Substitutional Solid Solution (OSSS)

ii. Disordered Substitutional Solid Solution (DSSS)

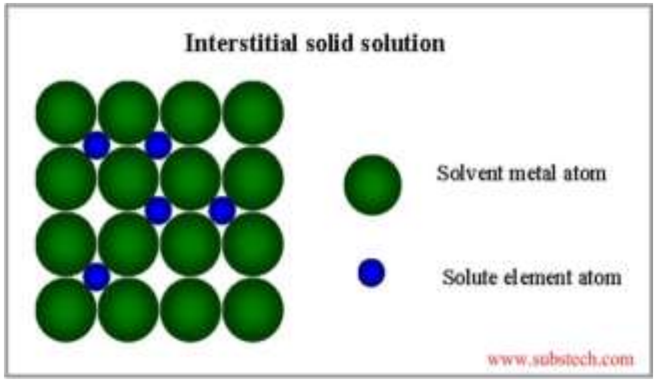
- **OSSS:** In this type, the solute atoms substitute the solvent atoms in an orderly manner, taking up fixed positions of symmetry in lattice. This solid solution has uniform distribution of solute and solvent atoms.
- **DSSS:** In this type, the solute atoms do not occupy any fixed positions but are distributed at random in the lattice structure of solvent. The concentration of solute atoms vary considerably through out lattice structure.



Ordered & Disordered substitutional solid solution

INTERSTITIAL SOLID SOLUTION

- These are formed when atoms of small atomic radii fit into the
- interstitial spaces of larger solvent atoms.
- Atoms of elements such as carbon, nitrogen, boron, hydrogen, etc. which have radii less than 1 A° are likely to form interstitial solute atoms and may dissolve more readily in transition metals such as Fe, Ni, Mn, Cr, etc. than in other metals.



RULES FOR FORMATION OF SOLID SOLUTION

HUME-ROTHARY RULES:

- These are the rules which govern the formation of Solid Solutions.
- In other words, only when these rules are satisfied,a substitutional solid solution is formed.

1.Crystal Structure Factor:

- For complete solubility of two elements, they should have the same type of crystal lattice.
- For example,Au-Ag solution, both should have FCC structure.

2. Relative Size Factor:

- The atoms of the solute and solvent should have the same atomic size approximately.
- This factor is satisfied if the difference of atomic radii of two elements is less than 15%.

CONT…

3. Electro-negativity:

- Higher the electro-negativity, greater is the chance of forming an intermediate phase rather than a solid solution.
- Electro-negativity is the tendency to acquire electrons.

4. Relative Valence Factor:

- Among two metals, which have satisfied all the above rules, the metal with lower valency tends to dissolve more of a metal of higher valency and vice-versa.

INTERMEDIATE PHASES

- Intermediate phases are those phases whose chemical compositions are intermediate between the two pure metals and generally have crystal structure different from those of the base (parent) metals.
- An alloy can be made up of a solid solution phase entirely or can exist along with an intermediate phase.
- **An intermediate phase here is nothing but a compound and is made up of two or more elements of which at least one of them is a metal.**

CONT…

- A compound is a chemical combination of positive and negative valence elements. i.e., atoms of different elements are combined in different proportions and are expressed by chemical formulae like H_2O, NaCl, etc.
- When a compound or intermediate phase is formed, the elements lose their individual identity and properties to a good extent and the compound will have its own characteristic physical, mechanical and chemical properties.

INTERMEDIATE ALLOY PHASES

- There are **three** most common intermediate alloy phases:

1. Intermetallic or Valency Compounds
2. Interstitial Compounds
3. Electron Compounds

INTERMETALLIC OR VALENCE COMPOUNDS

- **When alloy phase are exclusively metal-metal systems, they are called intermetallic compounds.**
- These are formed between chemically dissimilar metals and are combined by following the rules of chemical valence.
- The combination is usually non-metallic and show poor ductility and poor electrical conductivity and have complex crystal structure.

- Examples for intermetallic compounds: Mg_2Pb, Mg_2Sn, $CaSe$, Cu_2Se

INTERSTITIAL COMPOUNDS

- These are similar to interstitial solid solutions except that they have more or less a fixed composition. Example: Fe_3C.
- The interstitial compounds are metallic in nature, have high melting points and are extremely hard.

ELECTRON COMPOUNDS

- These are of variable compositions and do not obey the valence law, but have a definite electron to atom ratio. **Example: Cu_9Al_4**
- Each Cu atom has 1 valence electron and each Al atom has 3 valence electrons.
- So 13 atoms which make up the compound have 21 valence electrons with electron to atom ratio being 21:13
- Electron compounds have properties same as those of solid solutions – wide range of compositions, high ductility and low hardness.

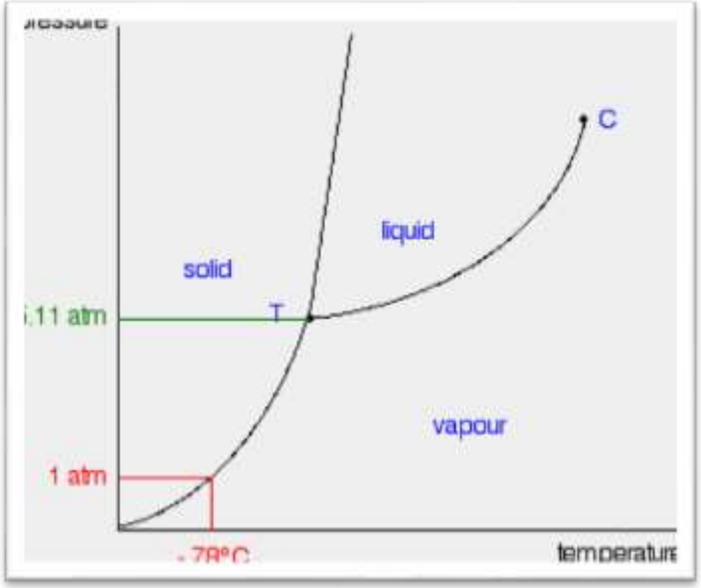
DEFINITION OF PHASE

Phase is Homogenous, physically distinct and mechanically separable part of the system.

Phase diagram for pure substance

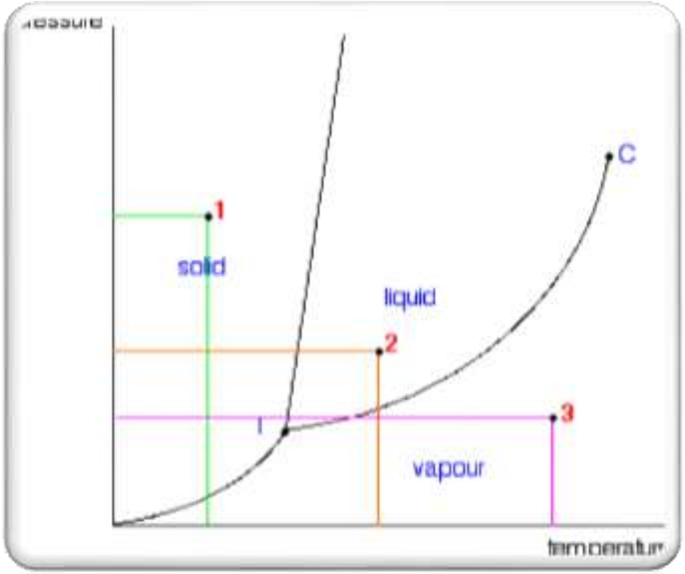
Pure substance- It is a substance constant chemical composition throught its mass. It may exist in one phase or more than one phase

If you look at the diagram, you will see that there are three lines, three areas marked "solid", "liquid" and “Vapour", and two special points marked "C" and "T".



THREE AREAS

At point 1 in the diagram, the substance would be a solid because it falls into that area of the phase diagram. At 2, it would be a liquid; and at 3, it would be a Vapour (a gas)

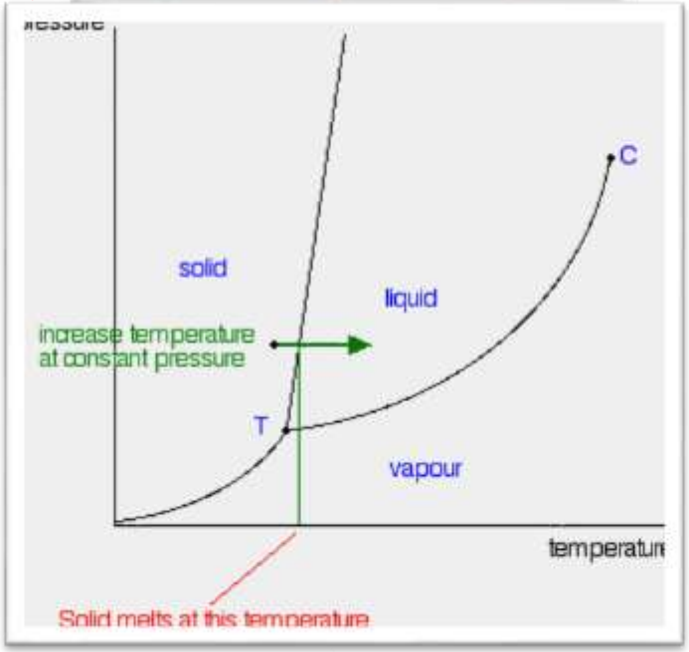


Moving from solid to liquid by changing the temperature:

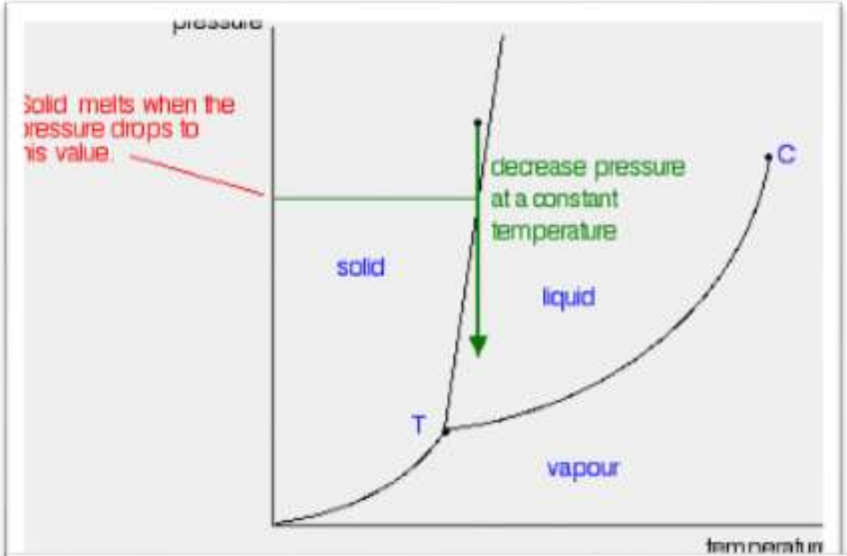
(fusion line)

If increases the temperature while keeping the pressure constant - as shown in the figure. As the temperature increases to the point where it crosses the line, the solid will turn to liquid

(solid melts at higher temperature)



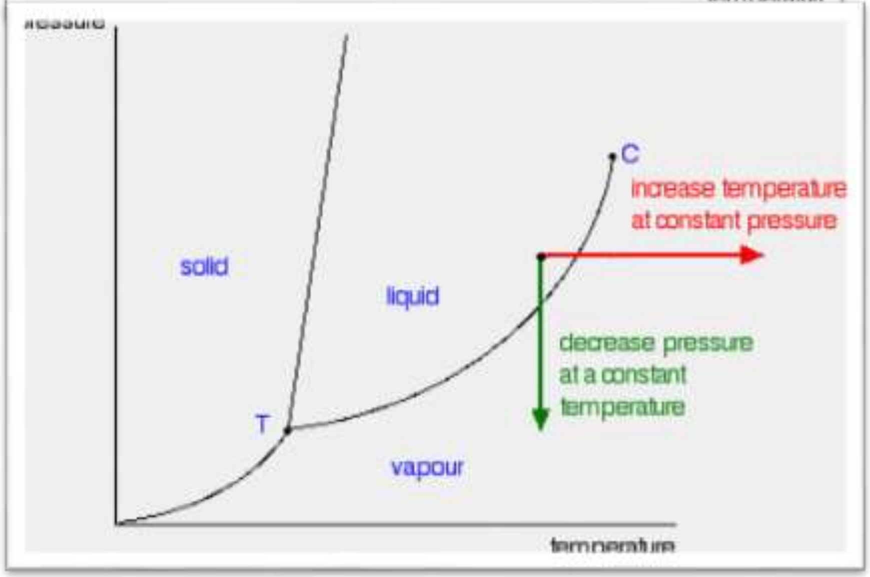
Moving from solid to liquid by changing the pressure:



Moving from liquid to Vapour:

(Vapourisation line)

The liquid will change to a Vapour - it boils - when it crosses the boundary line between the two areas



As the pressure increases, so the boiling point increases.

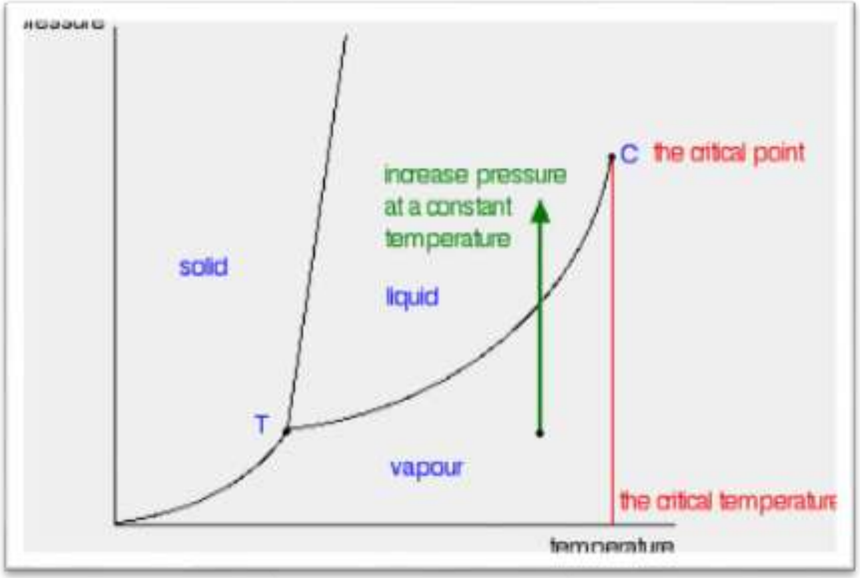
CRITICAL POINT

In liquid-vapour equilibrium curve has a top limit at that point C in the phase diagram. It is called critical point. The temperature and pressure corresponding to this are known as the critical temperature and critical pressure.

If you increase the pressure on a gas (Vapour) at a temperature lower than the critical temperature, you will eventually cross the liquid-Vapour equilibrium line and the Vapour will condense to give a liquid

Shortcut Definition:

The intersection of saturated liquid line and saturated Vapour line.



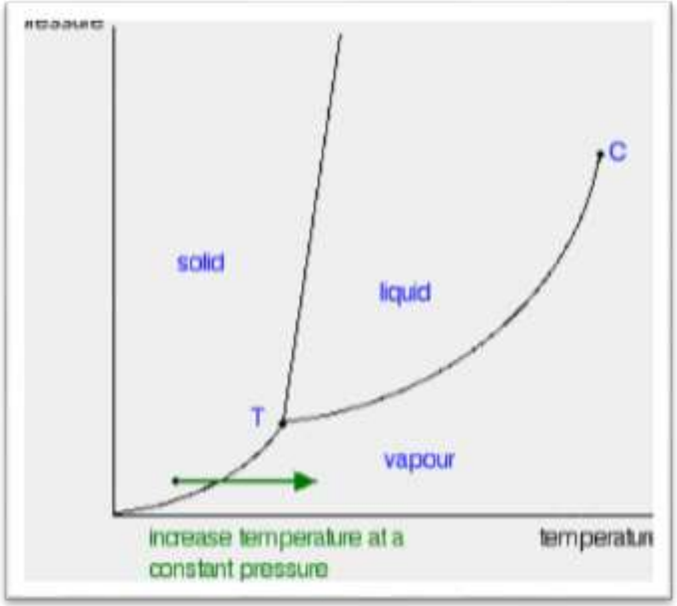
Moving from solid to Vapour (sublimation line)

If the temperature and pressure fell exactly on same line, there would be solid and Vapour in equilibrium with each other - the solid would be subliming. (Sublimation is the change directly from solid to Vapour or vice versa without going through the liquid phase).

The triple point

At point T on the diagram is called the triple point.

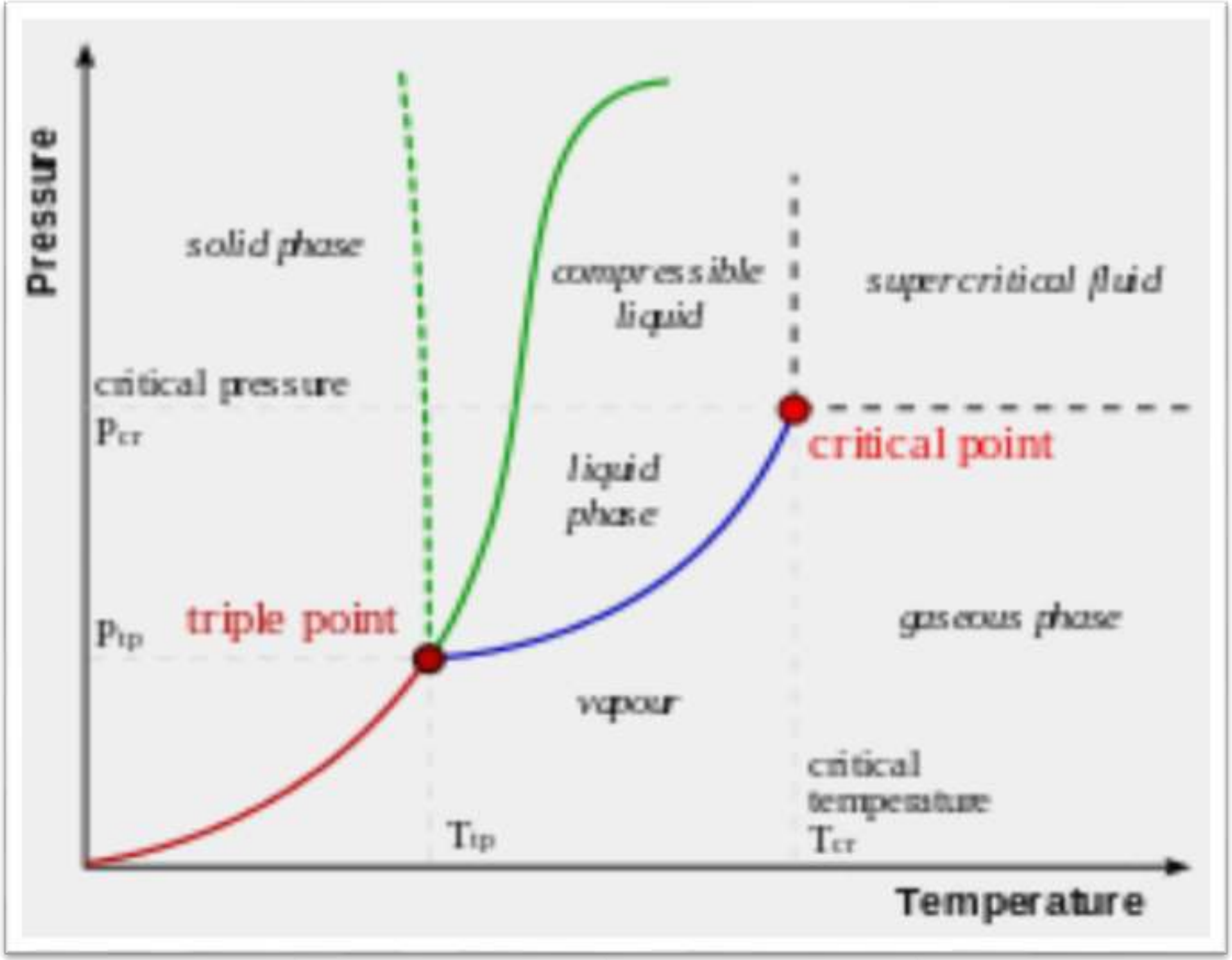
The combination of temperature and pressure where all three phases are in equilibrium together. That's why it is called a triple point.



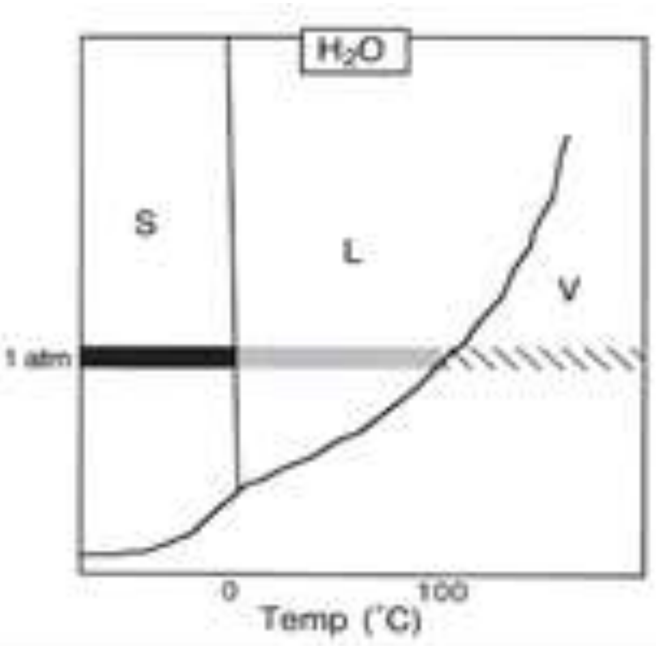
Defination:

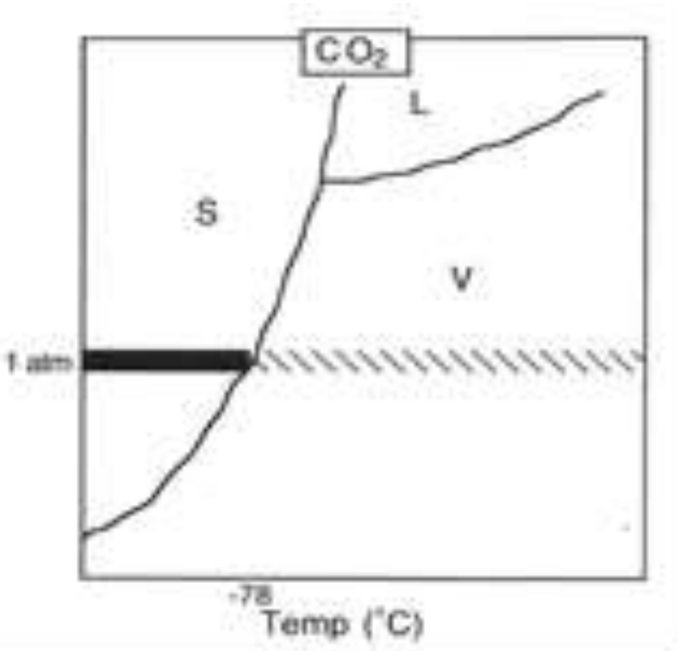
The intersection of fusion line, Vapourisation line and sublimation line Is called triple point

2-D Representation of phase diagram



PHASE DIAGRAMS OF WATER AND CARBON DIOXIDE





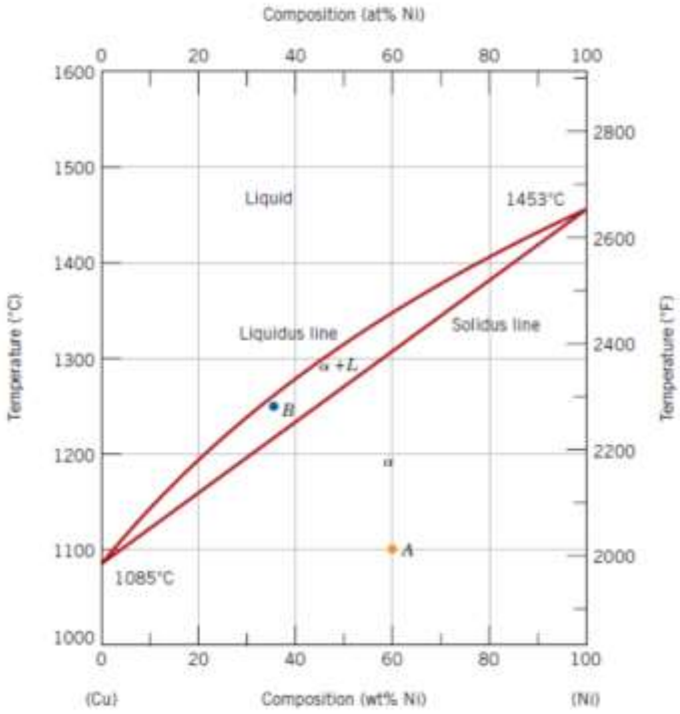
CONT…

Types of phase diagrams

1. ISOMORPHOUS SYSTEMS
2. EUTECTIC SYSTEMS

ISOMORPHOUS SYSTEMS: These diagrams are loop type and are obtained for two metals having complete solubility in the liquid state as well as solid state E.g. – Cu/Ni, Au/Ag

Examples

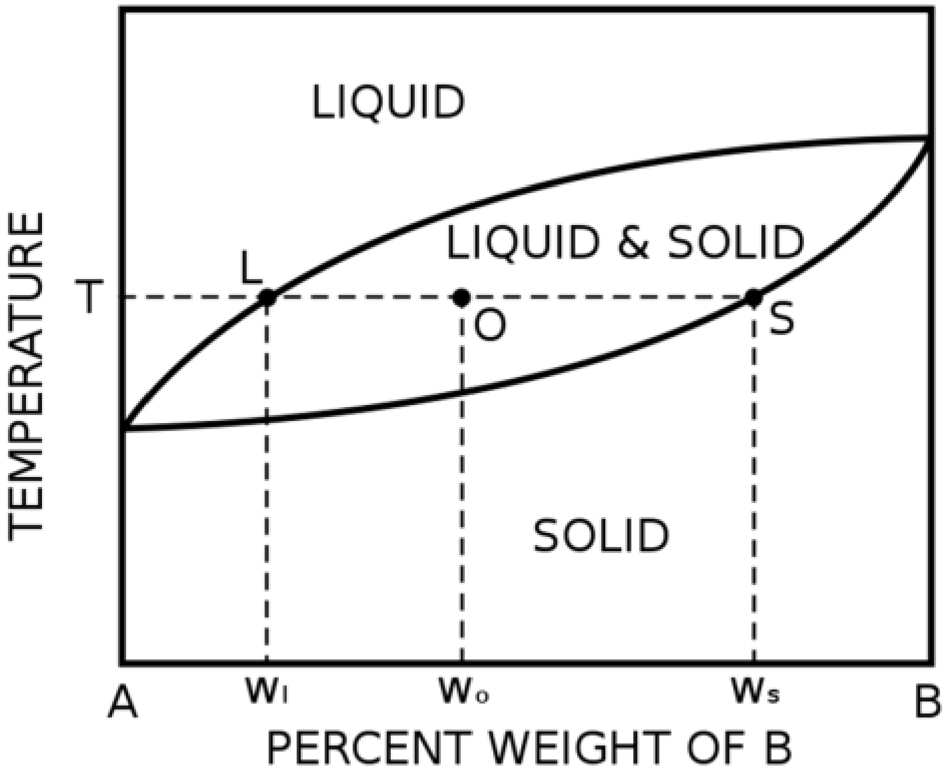


Cu-Ni phase diagram Temperature- Composition Binary isomorphous diagram

LEVER RULE

- Used to find the composition of phases.

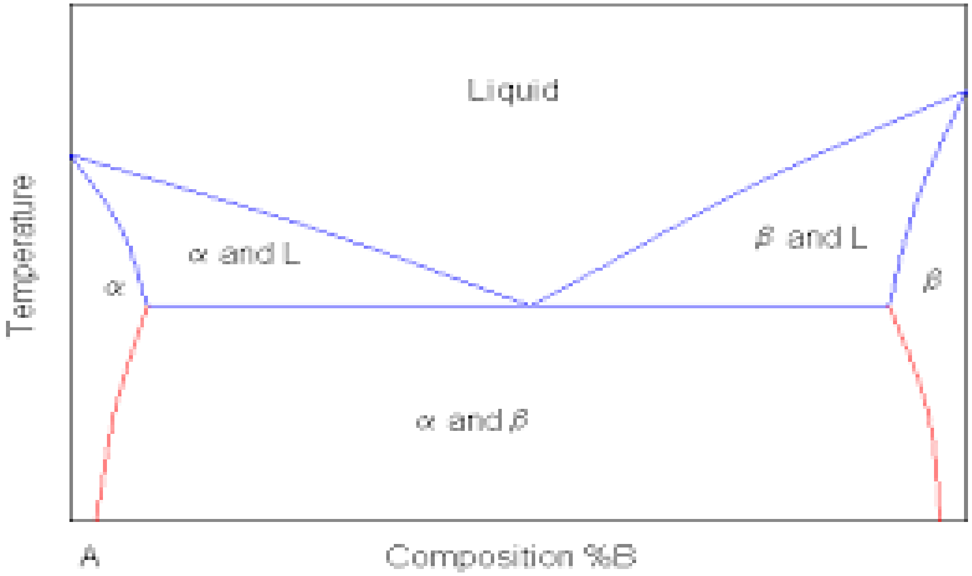
- $W_s = \dfrac{W_o - W_l}{W_s - W_l}$
- $W_l = \dfrac{W_s - W_o}{W_s - W_l}$



BINARY PHASE DIAGRAM

On a two component or binary diagram three variables can be represented. These are generally pressure (P), temperature (T) and compositional changes (X)

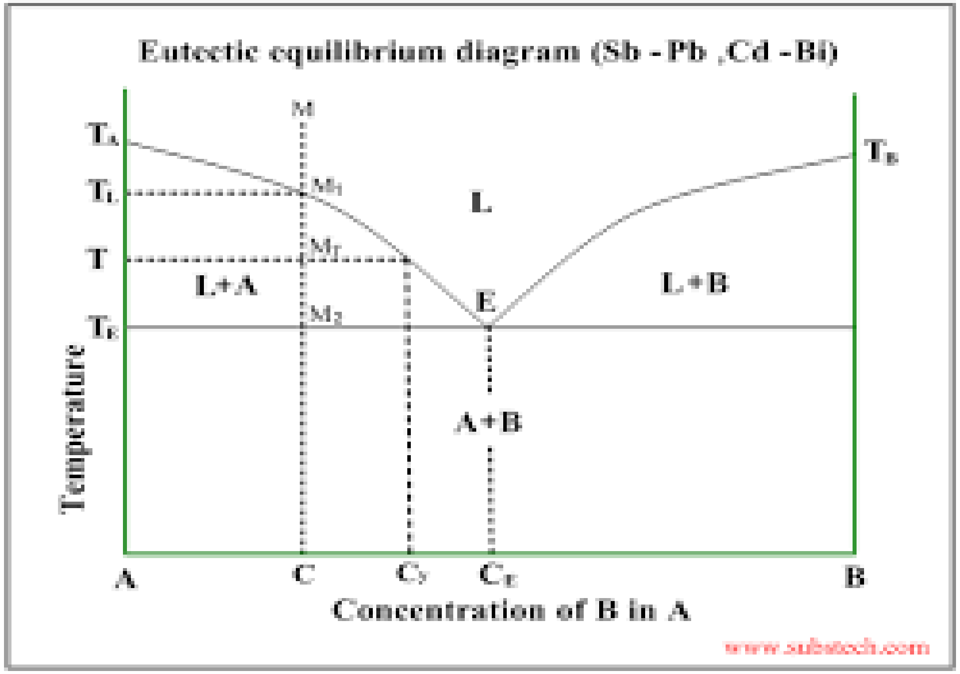
To graphically represent a Binary diagram one variable must be kept constant, which is usually P, and the phase diagram is plotted as a T-X diagram for a specific Pressure. Ex- isomorphous systems



Eutectic systems –

These diagrams are obtained for having complete solubility in the liquid state and complete insolubility in the solid state

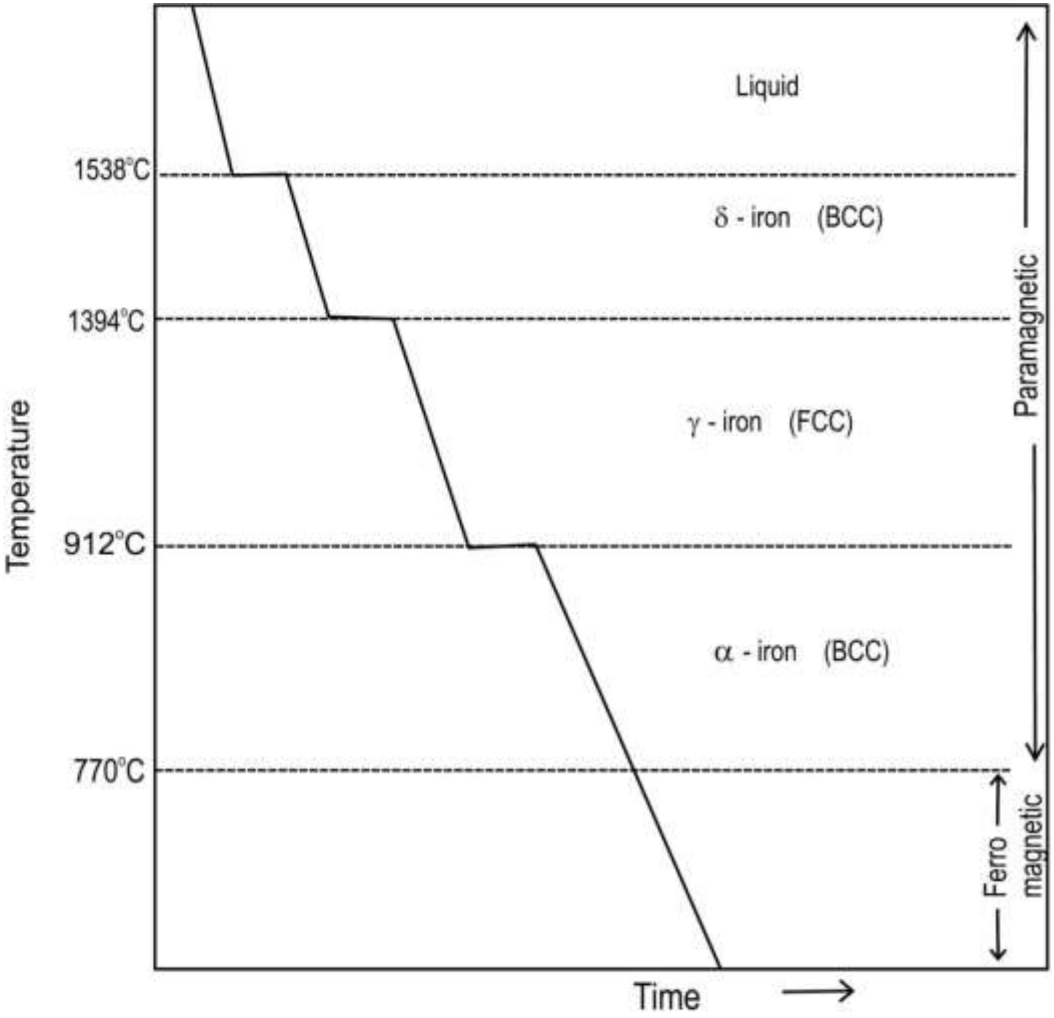
Ex- Pb/As ,bi-cd, th -ti



THE IRON-IRON CARBIDE DIAGRAM

- A map of the temperature at which different phase changes occur on very slow heating and cooling in relation to Carbon, is called Iron- Carbon Diagram.
- Iron- Carbon diagram shows
    - The type of alloys formed under very slow cooling,
    - Proper heat-treatment temperature and
    - How the properties of steels and cast irons can be radically changed by heat-treatment.

COOLING CURVE FOR PURE IRON



IRON-CARBON (FE-C) PHASE DIAGRAM

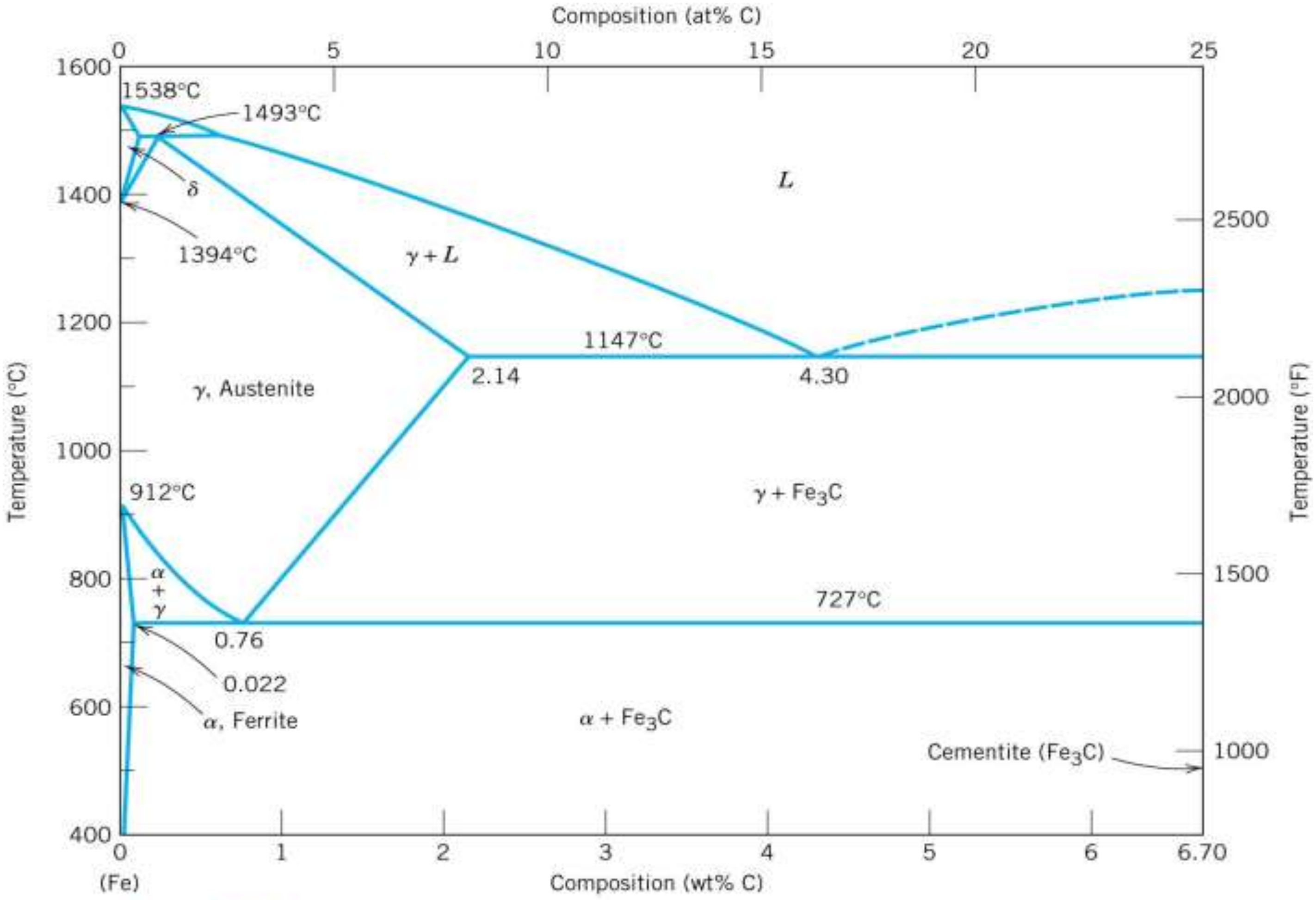
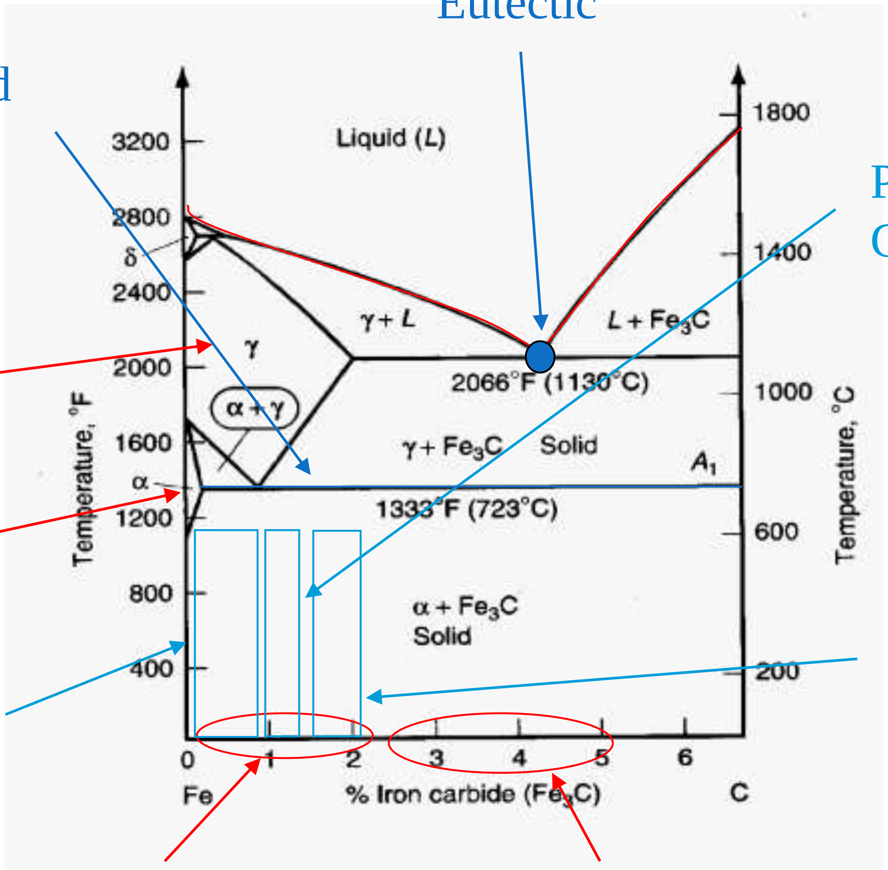


FIGURE 9.21 The iron–iron carbide phase diagram. [Adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

How to read the Fe-C phase diagram



Eutectic

eutectoid

Pearlite and Cementine

Austenite

Ferrite

Pearlite and Carbide

Pearlite

Steel

Cast iron

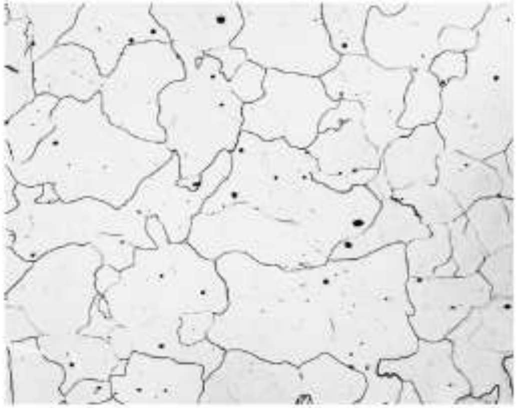
DEFINITION OF STRUCTURES

Various phases that appear on the Iron-Carbon equilibrium phase diagram are as under:

- **Ferrite**
- **Pearlite**
- **Austenite**
- **Cementite**
- **Ledeburite**
- **Martensite**

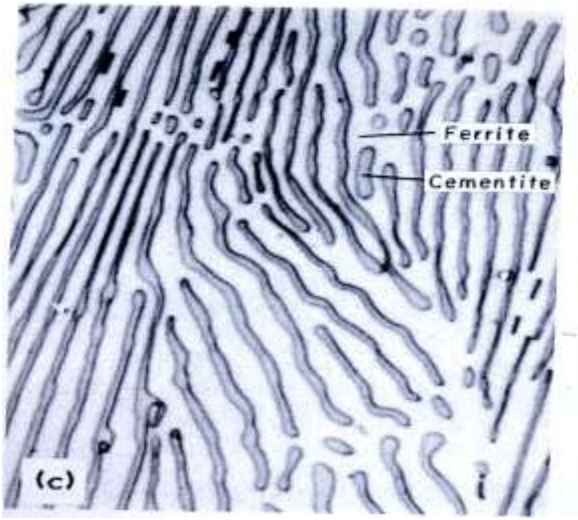
DEFINITION OF STRUCTURES

- **Ferrite** is known as *α* solid solution.
- It is an interstitial solid solution of a small amount of carbon dissolved in *α* (BCC) iron.
- stable form of iron below 912 deg.C
- The maximum solubility is 0.025 % C at 723°C and it dissolves only 0.008 % C at room temperature.
- It is the softest structure that appears on the diagram.



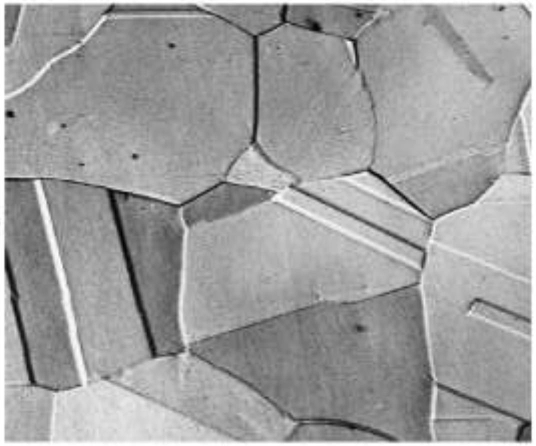
DEFINITION OF STRUCTURES

- **Pearlite** is the eutectoid mixture containing 0.80 % C and is formed at 723°C on very slow cooling.
- It is a very fine platelike or lamellar mixture of ferrite and cementite.
- The white ferritic background or matrix contains thin plates of cementite (dark).



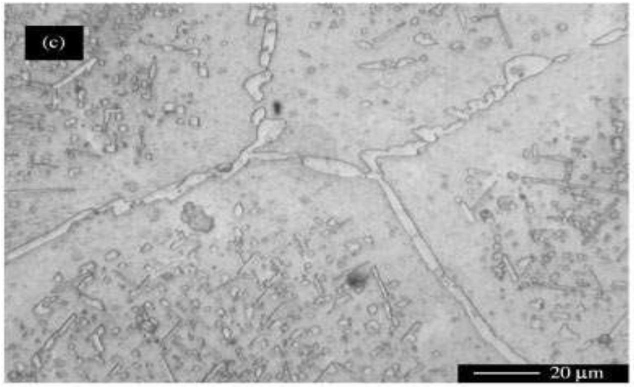
DEFINITION OF STRUCTURES

- **Austenite** is an interstitial solid solution of Carbon dissolved in γ (F.C.C.) iron.
- Maximum solubility is 2.0 % C at 1130°C.
- High formability, most of heat treatments begin with this single phase.
- It is normally not stable at room temperature. But, under certain conditions it is possible to obtain austenite at room temperature.



DEFINITION OF STRUCTURES

- **Cementite** or iron carbide, is very hard, brittle intermetallic compound of iron & carbon, as Fe_3C, contains 6.67 % C.
- It is the hardest structure that appears on the diagram, exact melting point unknown.
- Its crystal structure is orthorhombic.
- It is has
  - low tensile strength (approx. 5,000 psi), but
  - high compressive strength.



DEFINITION OF STRUCTURES

- **Ledeburite** is the eutectic mixture of austenite and cementite.
- It contains 4.3 percent C and is formed at 1130°C.

DEFINITION OF STRUCTURES

- **Martensite** - a super-saturated solid solution of carbon in ferrite.
- It is formed when steel is cooled so rapidly that the change from austenite to pearlite is suppressed.
- The interstitial carbon atoms distort the BCC ferrite into a BC-tetragonal structure (BCT).; responsible for the hardness of quenched steel

MICROSTRUCTURE OF DIFFERENT PHASES OF STEEL

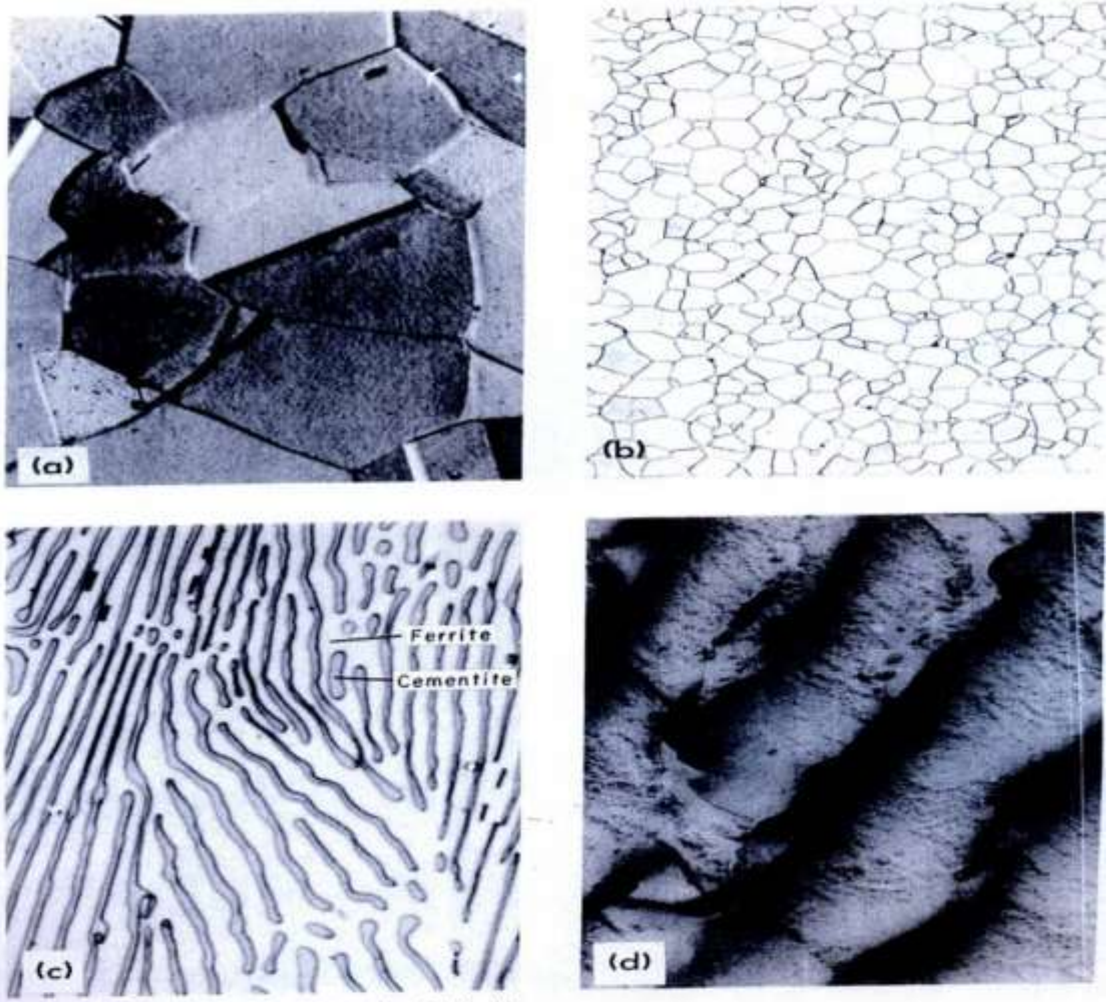


Fig. 7·8 The microstructure of (*a*) austenite, 500X; (*b*) ferrite, 100X; (*c*) pearlite, 2,500X; (*d*) pearlite, electron micrograph, 17,000X; enlarged 3X in printing. (*a*, *b*, and *c*, Research Laboratory, U.S. Steel Corporation.)

VARIOUS FEATURES OF FE-C DIAGRAM

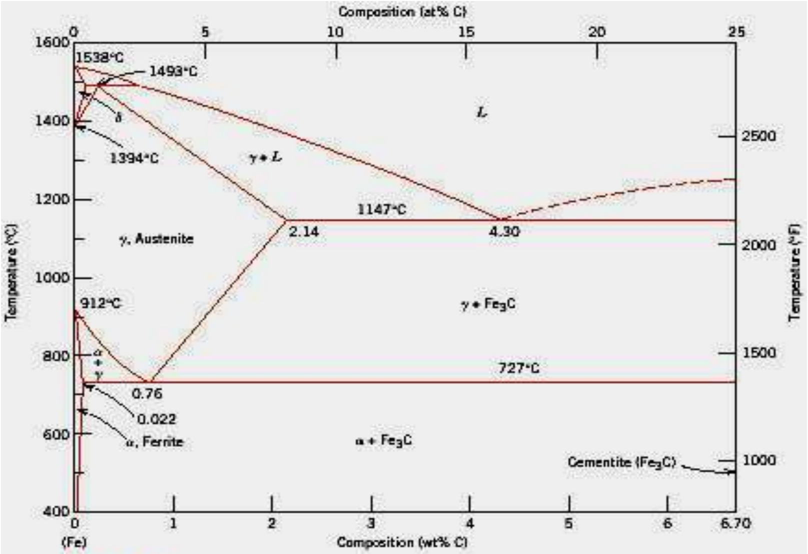


FIGURE 9.22 The iron–iron carbide phase diagram. (Adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 1, T. B. Massalski, Editor-in-Chief, 1990. Reprinted by permission of ASM International, Materials Park, OH.)

Phases present

- Liquid(l)
- δ:BCC structure,Paramagnetic
- α ferrite:BCC structure, Ferromagnetic,Fairly ductile
- γ austenite:FCC structure, Non-magnetic,Ductile
- Fe_3C cementite:Orthorhombic,Hard, brittle

Reactions

Peritectic $L + \delta = \gamma$

Eutectic $L = \gamma + Fe_3C$

Eutectoid $\gamma = \alpha + Fe_3C$

Max. solubility of C in ferrite=0.022%

Max. solubility of C in austenite=2.11%

THREE PHASE REACTIONS

A horizontal line always indicates an invariant reaction in binary phase diagrams

- Peritectic reaction at 1495˚C and 0.18%C,
  - δ-ferrite + $L \leftrightarrow \gamma$-iron (austenite)
  - (almost no engineering importance).
- Eutectic reaction at 1147˚C and 4.3 %C,
  - $L \leftrightarrow \gamma$-iron + Fe_3C (cementite) [ledeburite]
  - alloys called cast irons
- Eutectoid reaction at 727˚C and 0.77%C,
  - γ-iron $\leftrightarrow$ α–ferrite+Fe_3C (cementite) [pearlite]
  - They are steels

THE IRON-IRON CARBIDE DIAGRAM

The diagram shows three horizontal lines which indicate isothermal reactions (on cooling / heating):

- First horizontal line is at 1490°C, where peritectic reaction takes place:

  Liquid + δ ↔ austenite

- Second horizontal line is at 1130°C, where eutectic reaction takes place:

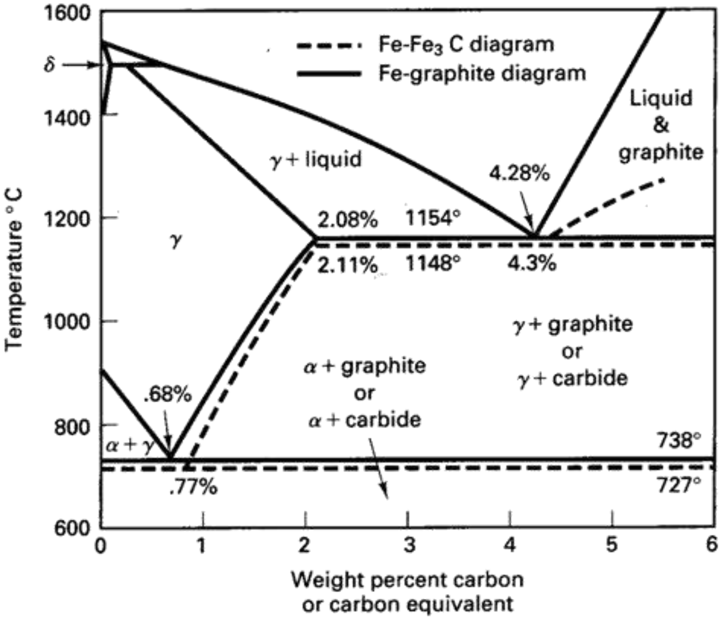
  liquid ↔ austenite + cementite

- Third horizontal line is at 723°C, where eutectoid reaction takes place:

  austenite ↔ pearlite (mixture of ferrite & cementite)

CAST IRONS

- Iron-Carbon alloys of 2.11%C or more are cast irons.
- Typical composition: 2.0-4.0%C,0.5-3.0% Si, less than 1.0% Mn and less than 0.2% S.
- Si-substitutes partially for C and promotes formation of graphite as the carbon rich component instead Fe_3C.



THE AUSTENITE TO FERRITE / CEMENTITE TRANSFORMATION IN RELATION TO FE-C DIAGRAM

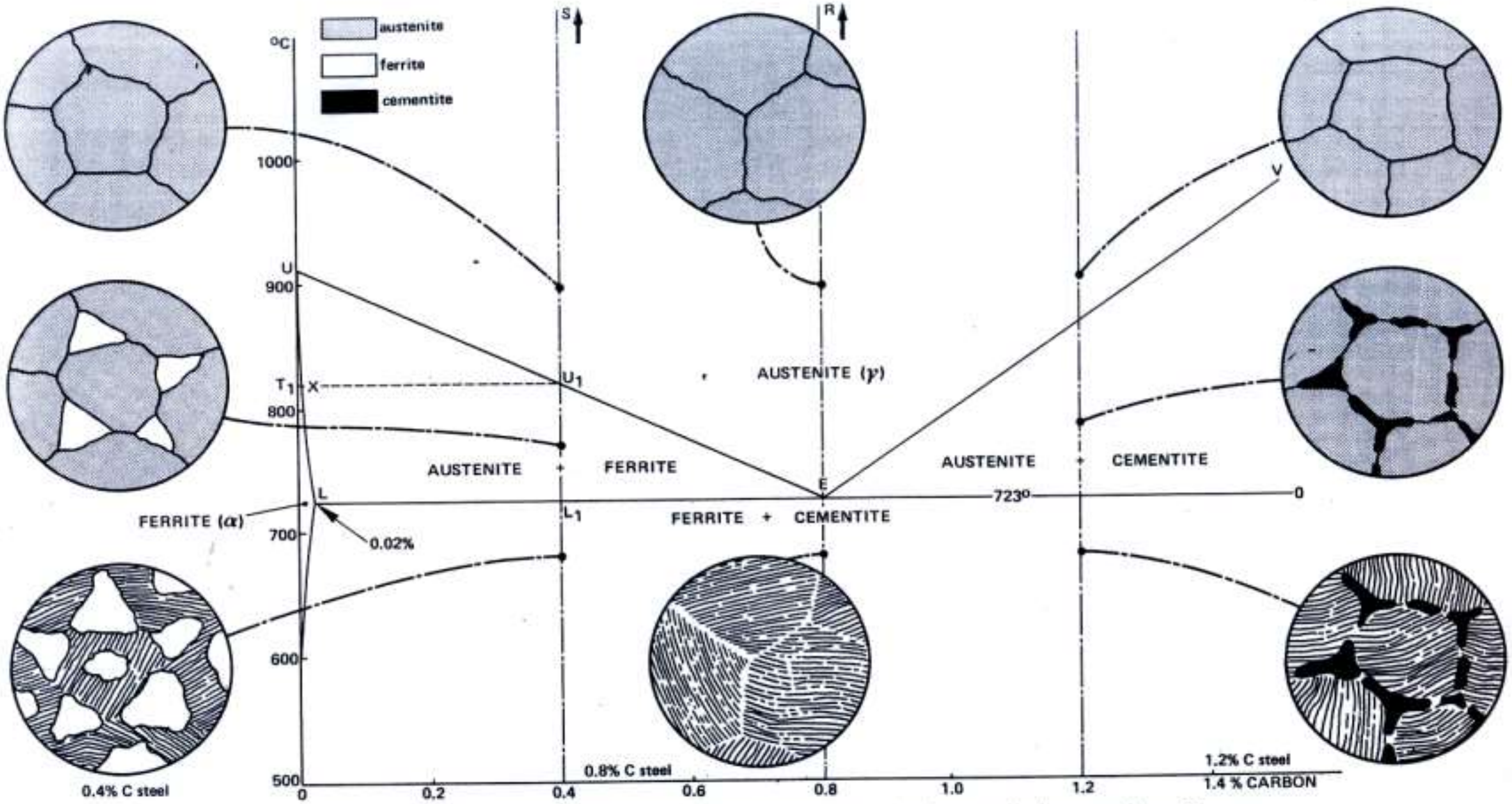
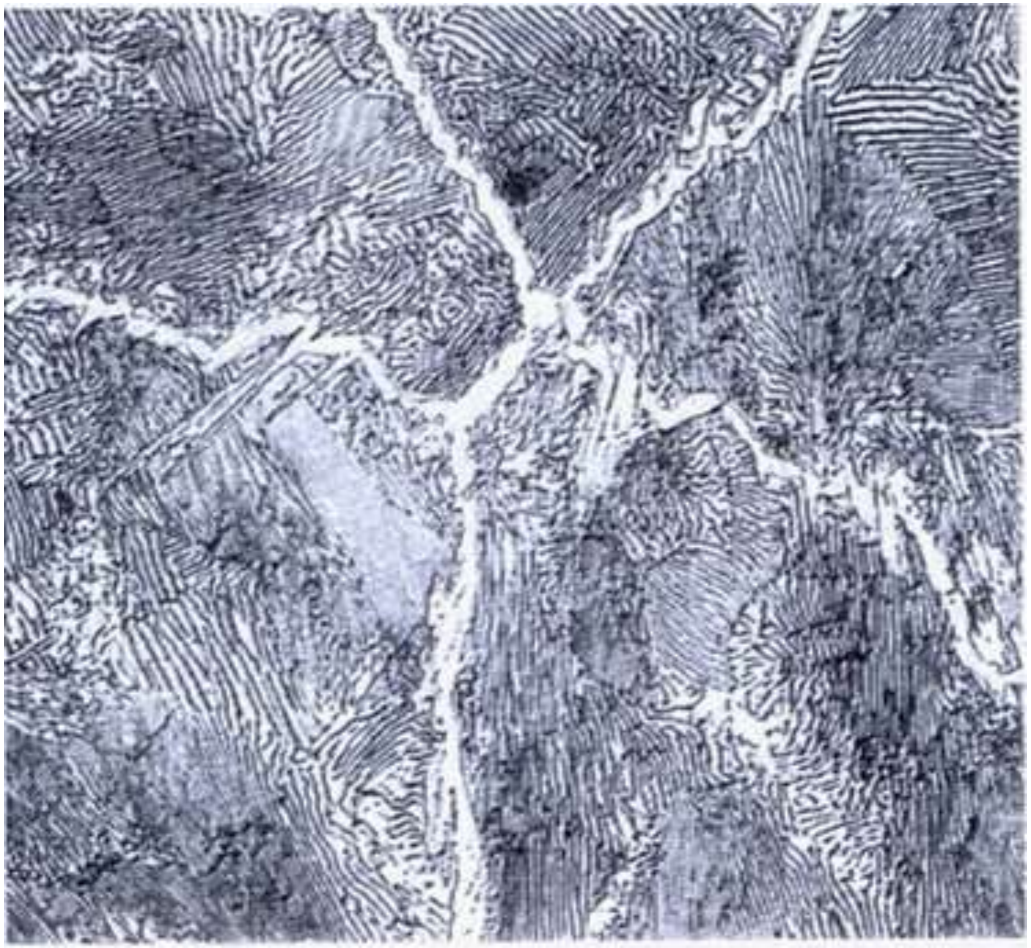


Fig. 9.3—The austenite → ferrite/cementite transformation in relation to the iron–carbon diagram.

THE AUSTENITE TO FERRITE / CEMENTITE TRANSFORMATION IN RELATION TO FE-C DIAGRAM

- The iron wants to change crystal structure from the FCC austenite to the BCC ferrite, but the ferrite can only contain 0.02% carbon in solid solution.
- The excess carbon is rejected and forms the carbon-rich intermetallic known as cementite.

THE AUSTENITE TO FERRITE / CEMENTITE TRANSFORMATION IN RELATION TO FE-C DIAGRAM



Hypo-eutectoid steel showing primary cementite along grain boundaries pearlite

THE AUSTENITE TO FERRITE / CEMENTITE TRANSFORMATION IN RELATION TO FE-C DIAGRAM

- **Hypo-eutectoid steels:** Steels having less than 0.8% carbon are called *hypo-eutectoid steels (hypo* means "less than").
- Consider the cooling of a typical hypo-eutectoid alloy along line *y-y'.*
- At high temperatures the material is entirely austenite.
- Upon cooling it enters a region where the stable phases are ferrite and austenite.
- The low-carbon ferrite nucleates and grows, leaving the remaining austenite richer in carbon.

THE AUSTENITE TO FERRITE / CEMENTITE TRANSFORMATION IN RELATION TO FE-C DIAGRAM

- **Hyper-eutectoid steels** (*hyper* means "greater than") are those that contain more than the eutectoid amount of Carbon.
- When such a steel cools, as along line *z-z'* , the process is similar to the hypo-eutectoid steel, except that the primary or pro-eutectoid phase is now cementite instead of ferrite.

PRINCIPAL PHASES OF STEEL AND THEIR CHARACTERISTICS

Phase	Crystal structure	Characteristics
Ferrite	BCC	Soft, ductile, magnetic
Austenite	FCC	Soft, moderate strength, non-magnetic
Cementite	Compound of Iron & Carbon Fe_3C	Hard &brittle

INDUSTRIAL APPLICATIONS

- It is used tailor properties of steel and to heat treat them.
- It is also used for comparison of crystal structures for metallurgists in case of rupture or fatigue

SELF LEARNING QUESTIONS

1. What is Plastic deformation? Explain deformation by slip.
2. Explain the slip in different lattice structures.
3. What is strain hardening? Explain the effects of strain hardening on properties.
4. What is Recrystallization? Explain the effects on properties of ductile material.
5. Explain methods to control the grain structure resulting from solidification.

ASSIGNMENT EXERCISES

1. What is imperfection in crystal? Explain their effect on properties.
2. Explain solidification defects.
3. Explain unary and binary equilibrium phase diagram.
4. Explain Gibb’s phase rule.
5. Explain lever rule and different reaction like eutectic, eutectoid & peritectic.
6. Explain allotropy of iron.
7. Explain iron carbon diagram with critical reactions.
8. Explain iron – iron carbon diagram for hypo eutectoid steel and hyper eutectoid steel.
9. Explain TTT diagram.

THANK YOU

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LECTURE 2

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TOPICS TO BE COVERED

- Definition of force
- Units - conversions
- Force system
- Resultant of force
- Applications
- Problems
- Assignments

LECTURE 2

Introduction - Resultants of Force System

LECTURE TEMPLATE

- **Introduction**
    - **Definition**
    - **Units**
    - **Classification etc…**
- **Demonstration**
    - Text
    - Graphic/ Pictorial
    - Video etc…
- **Industrial Applications**
- Solved Problems (1-2)
    - Procedure
- Self Learning Questions
- Assignment Exercises
- Summary

INDUSTRIAL APPLICATIONS

SOLVED PROBLEMS

SELF LEARNING QUESTIONS

ASSIGNMENT EXERCISES

THANK YOU

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MATERIALS ENGINEERING (R18A0305)

2nd Year B. Tech I- sem, Mechanical Engineering

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COURSE OBJECTIVES

UNIT - 1	**CO1:** To understand various mechanical properties of materials.
UNIT - 2	CO2: To understand how and why the properties of materials are controlled by its structure at the microscopic and macroscopic levels.
UNIT - 3	CO3: To understand how and why the structure and composition of a material may be controlled by processing.
UNIT - 4	CO4: To create different types of composite materials and its applications.
UNIT - 5	CO5: To remember polymer material classifications and applications.

UNIT 3

FERROUS & NON-FERROUS ALLOYS

CO3: **To understand how and why the structure and composition of a material may be controlled by processing.**

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UNIT – III (SYLLABUS)

Ferrous and Non Ferrous Alloys:

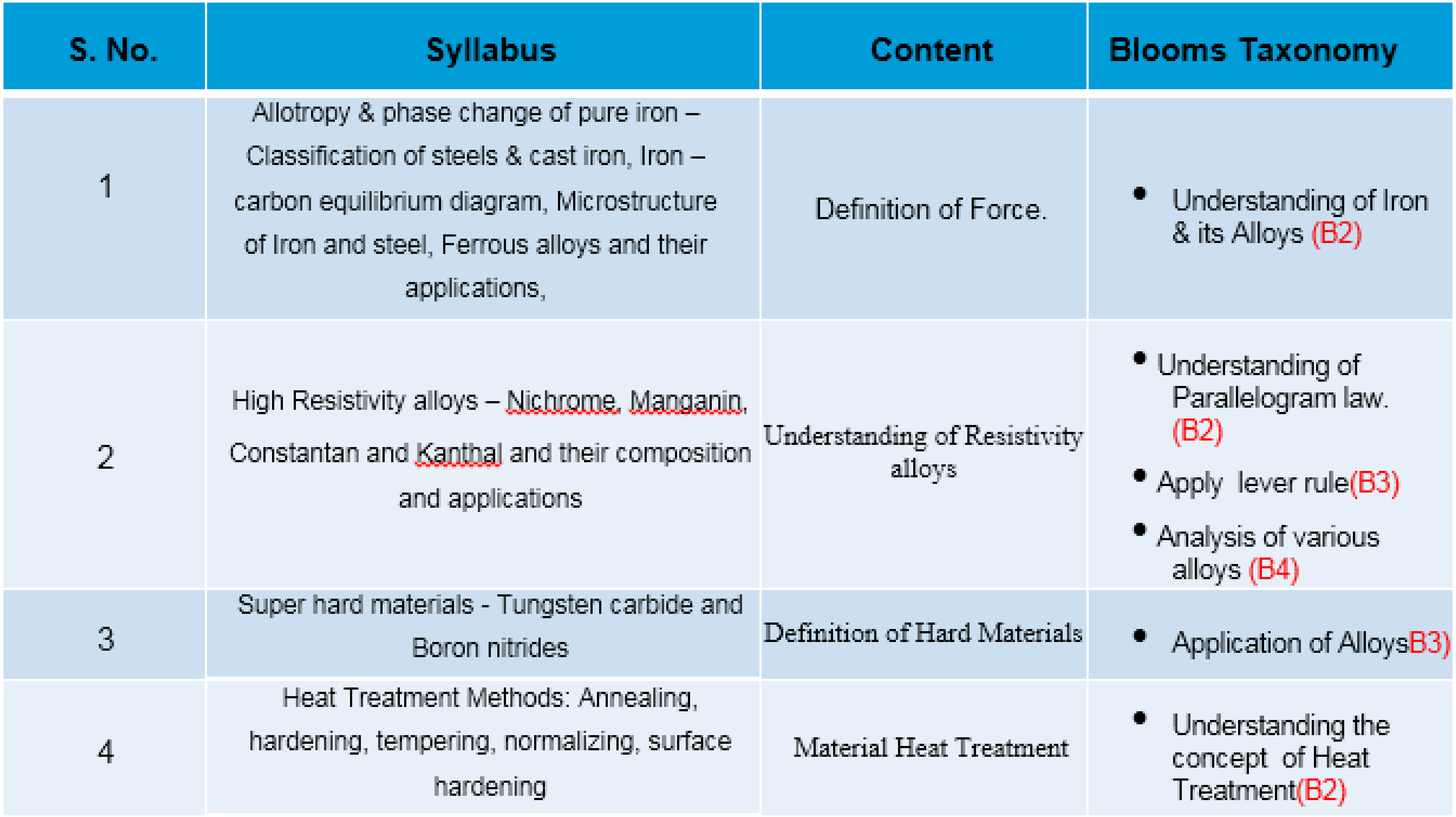
- Allotropy and phase change of pure iron.
- Classification of steels and cast iron – iron – carbon equilibrium diagram – Microstructure of iron and steel.
- Ferrous alloys and their applications
- High Resistivity alloys and their composition and applications.
- Super hard materials – Tungsten carbide and Boron nitrides.

Heat Treatment Methods:

- Annealing – hardening – tempering – normalizing – surface hardening.

COURSE OUTLINE

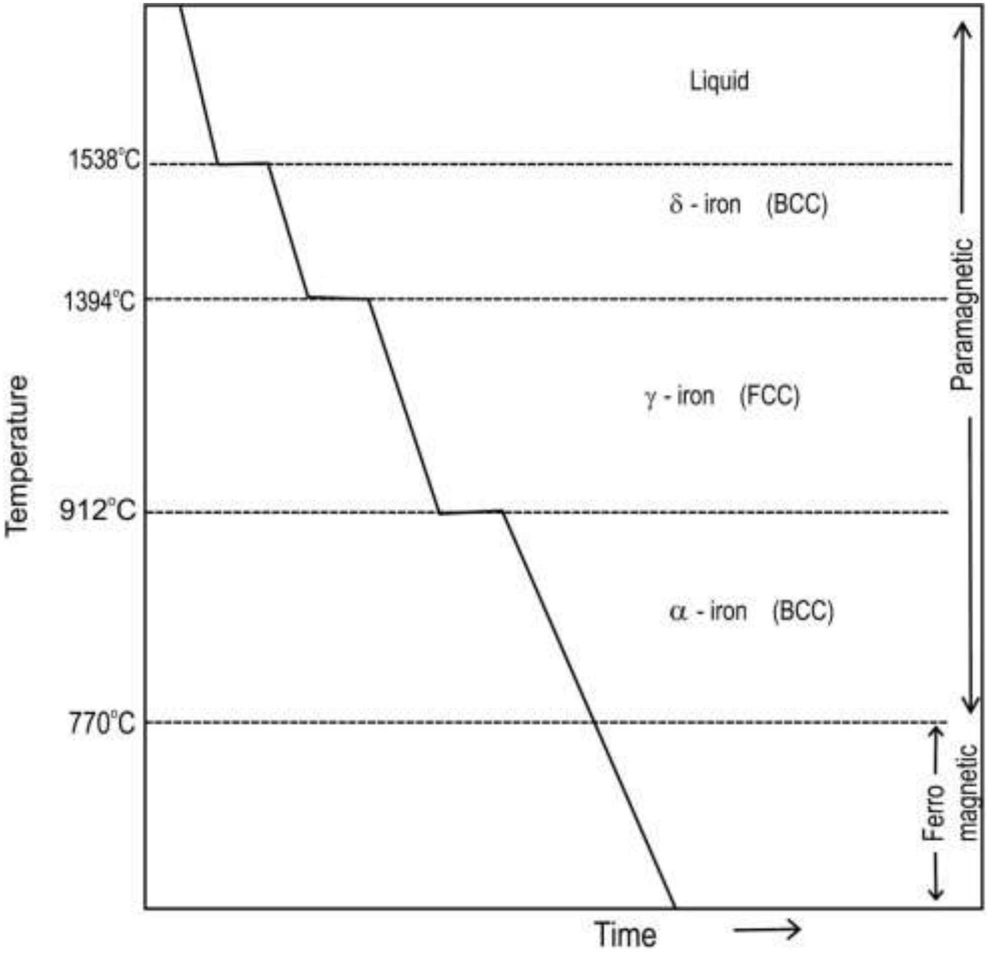
UNIT – 3



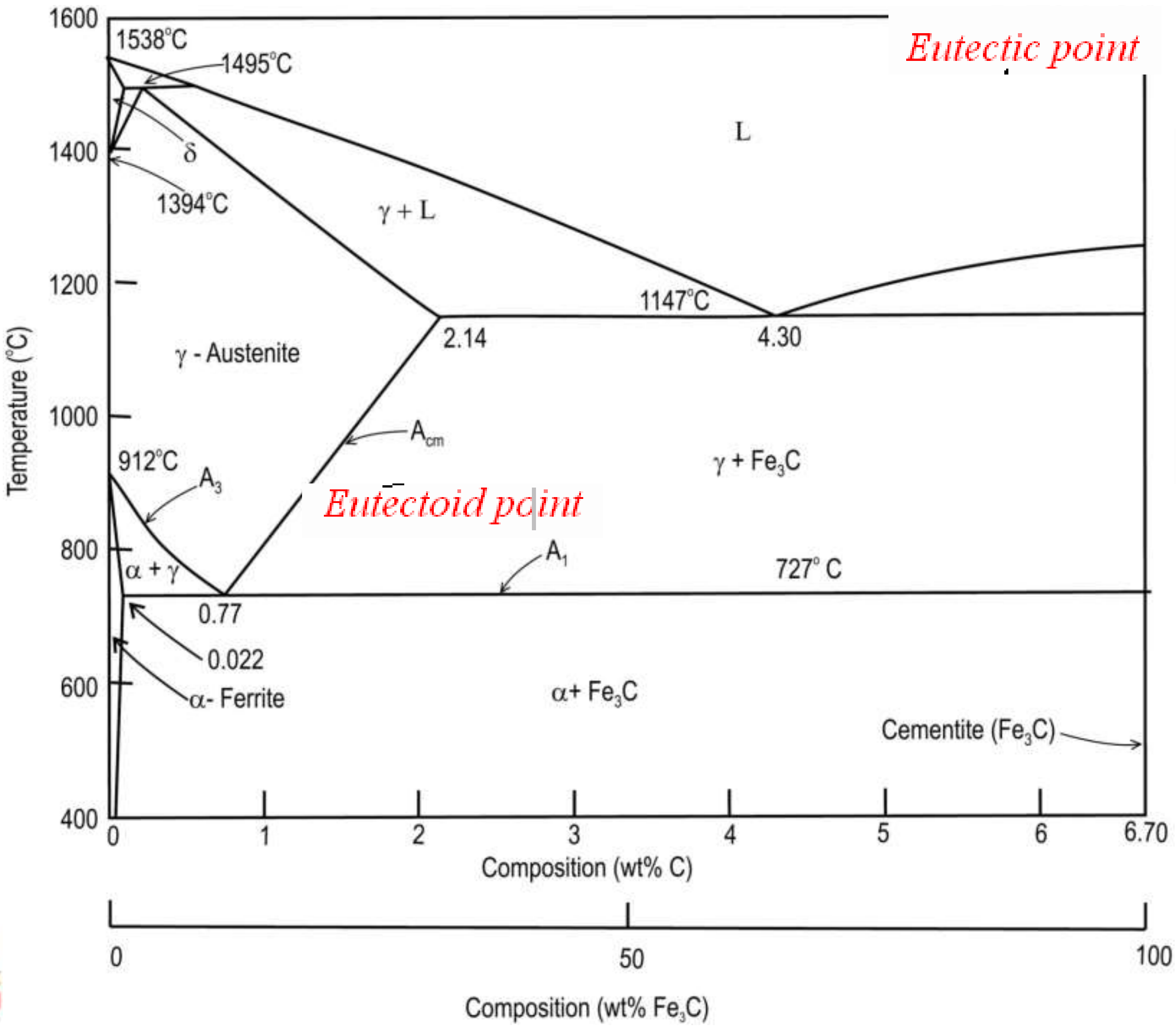
S. No.	Syllabus	Content	Blooms Taxonomy
1	Allotropy & phase change of pure iron – Classification of steels & cast iron, Iron – carbon equilibrium diagram, Microstructure of Iron and steel, Ferrous alloys and their applications,	Definition of Force.	• Understanding of Iron & its Alloys (B2)
2	High Resistivity alloys – Nichrome, Manganin, Constantan and Kanthal and their composition and applications	Understanding of Resistivity alloys	• Understanding of Parallelogram law. (B2) • Apply lever rule(B3) • Analysis of various alloys (B4)
3	Super hard materials - Tungsten carbide and Boron nitrides	Definition of Hard Materials	• Application of AlloysB3)
4	Heat Treatment Methods: Annealing, hardening, tempering, normalizing, surface hardening	Material Heat Treatment	• Understanding the concept of Heat Treatment(B2)

- Iron Carbon Phase diagram
- Theory of Alloys
- Heat Treatment
- Recovery, Recrystallization & Grain Growth
- Factors Effecting: Conductivity and Thermal
- High Resistivity Alloys
- Super Hard Materials

Allotropes of Iron



Fe – Fe_3C Phase Diagram



Eutectic point

Eutectoid point

δ	*Ferrite*
γ	*Austenite*
α	*Ferrite*
Fe_3C	*Cementite*
$\gamma + Fe_3C$	*Ledeburite*
$\alpha + Fe_3C$	*Pearlite*

FIVE INDIVIDUAL PHASES

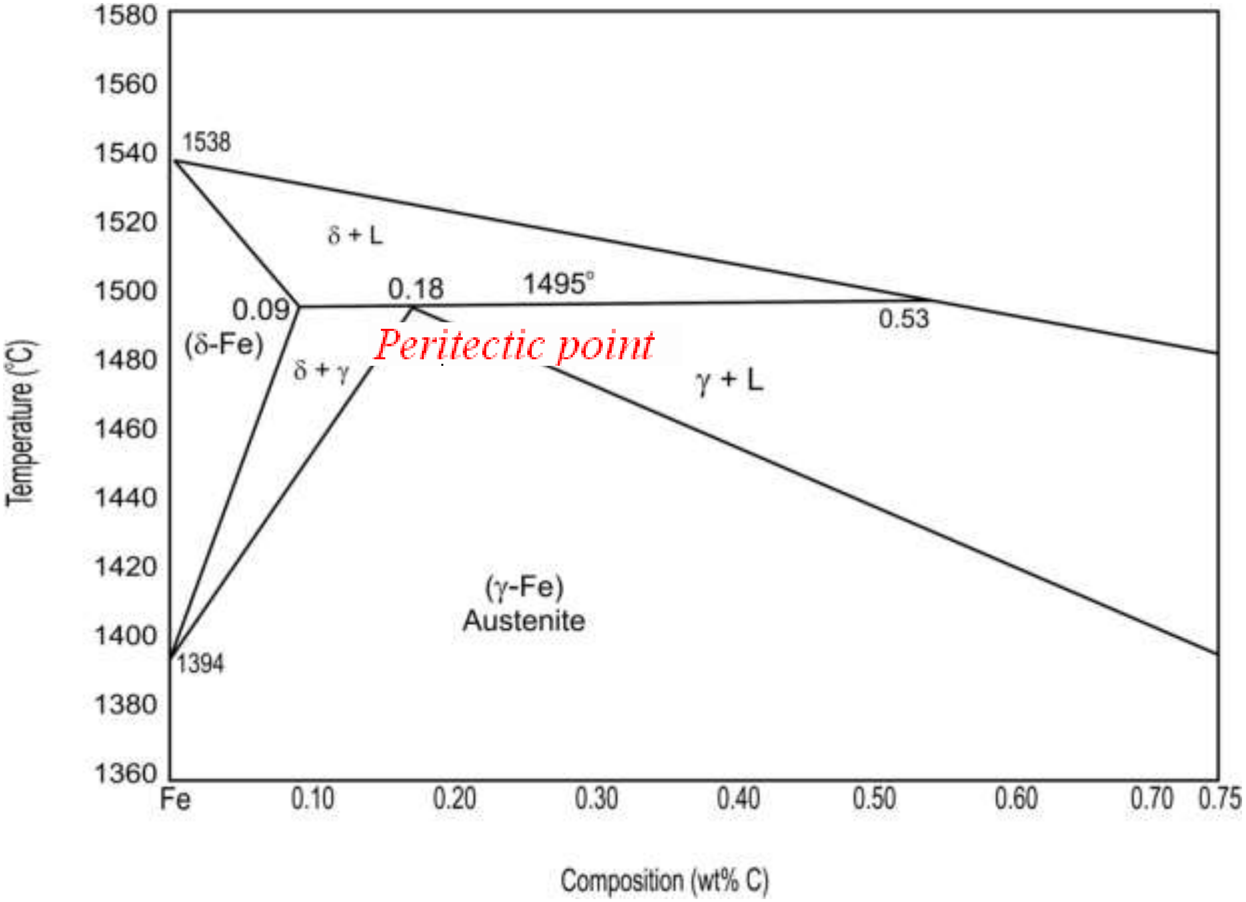
- α–ferrite (BCC) Fe-C solid solution
- γ-austenite (FCC) Fe-C solid solution
- δ-ferrite (BCC) Fe-C solid solution
- Fe_3C (Iron Carbide) *or* cementite –
  an inter-metallic compound
- Liquid Fe-C solution

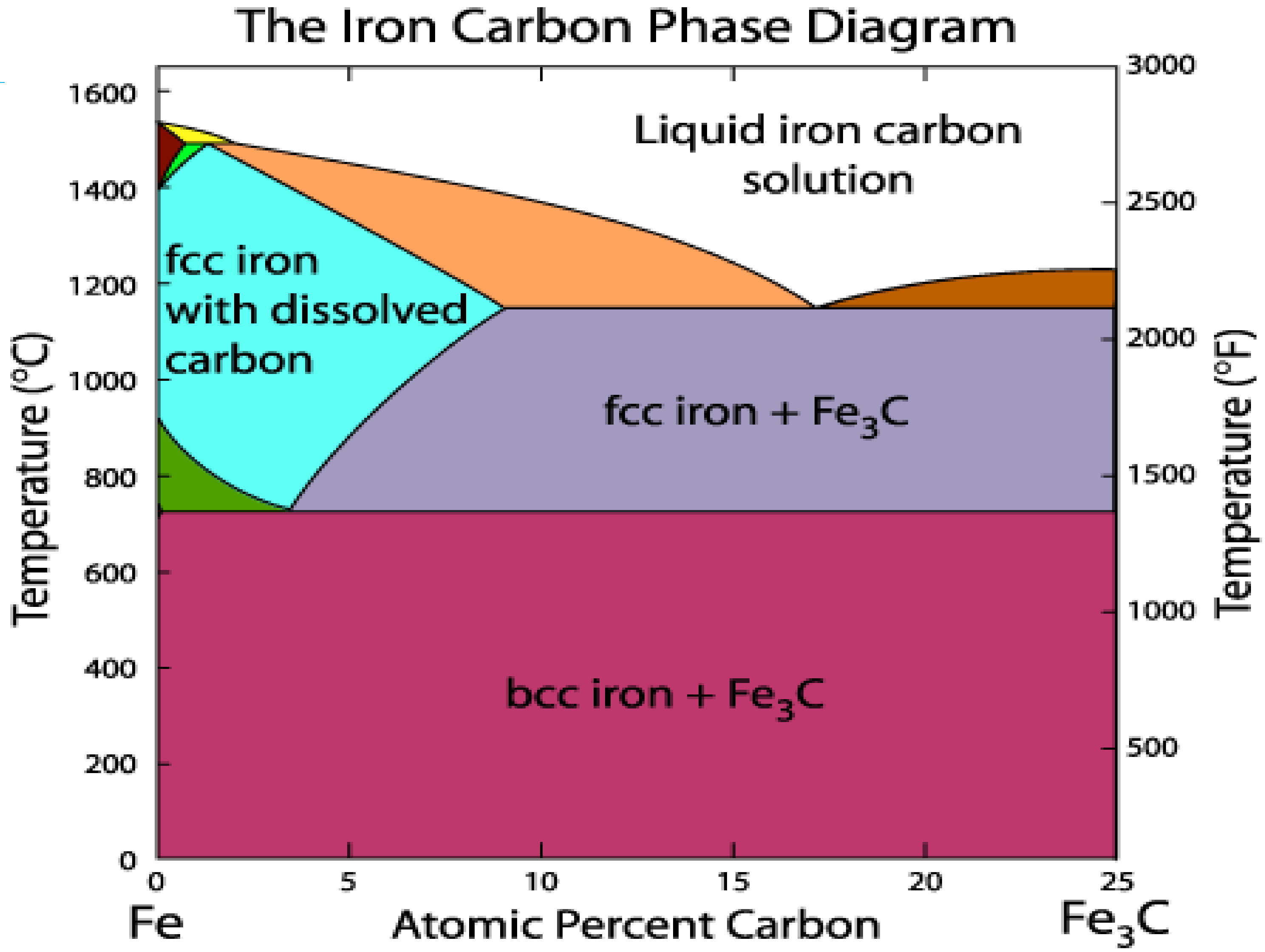
THREE INVARIANT REACTIONS

A horizontal line always indicates an invariant reaction in binary phase diagrams

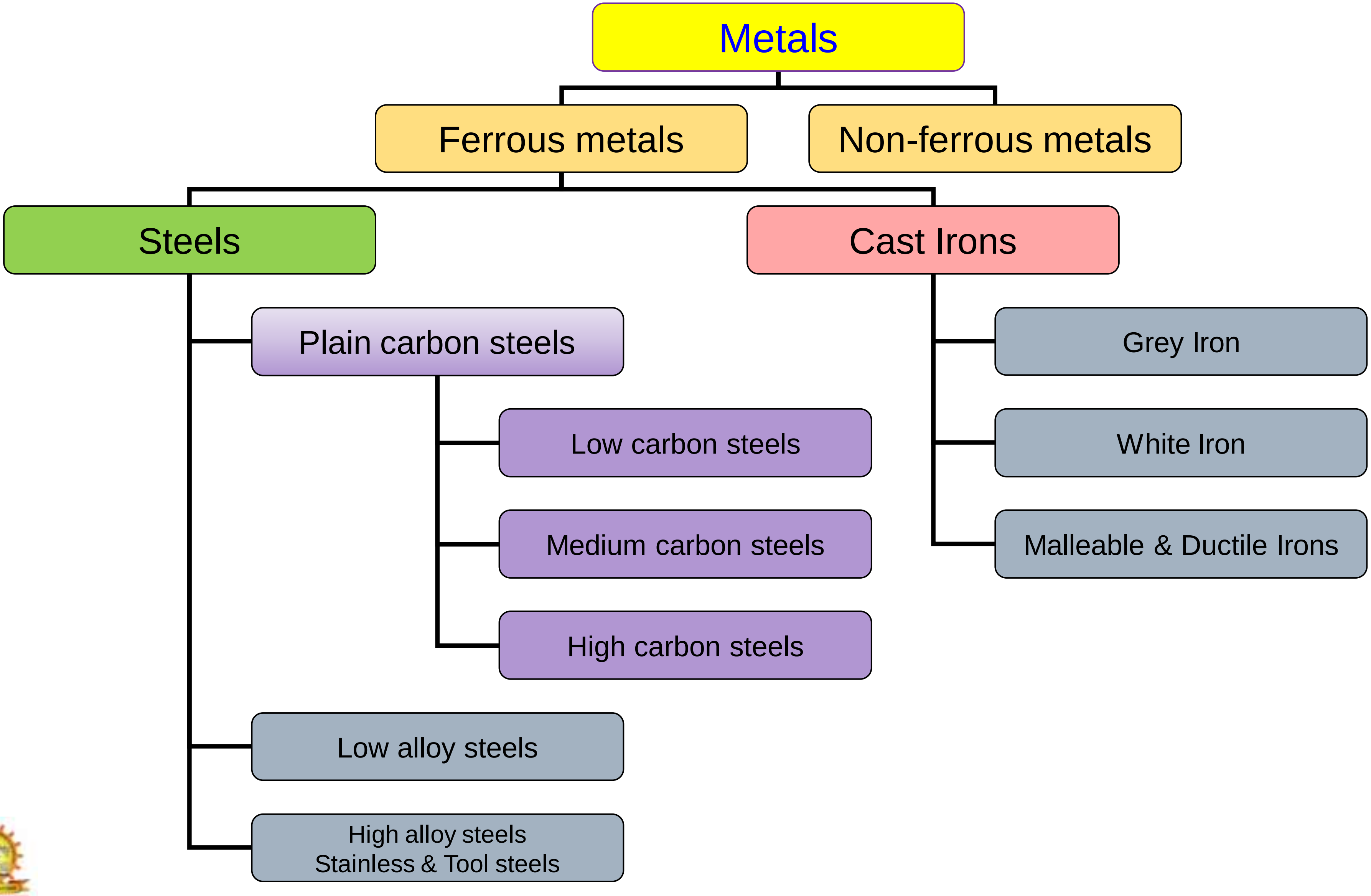
- Peritectic reaction at 1495˚C and 0.18%C,
  - δ-ferrite + $L \leftrightarrow \gamma$-iron (austenite)
- Eutectic reaction at 1147˚C and 4.3 %C,
  - $L \leftrightarrow \gamma$-iron + Fe_3C (cementite) [ledeburite]
- Eutectoid reaction at 727˚C and 0.77%C,
  - γ-iron $\leftrightarrow \alpha$–ferrite+Fe_3C (cementite) [pearlite]

PERITECTIC REACTION




The Iron Carbon Phase Diagram
Liquid iron carbon solution
fcc iron with dissolved carbon
fcc iron + Fe_3C
bcc iron + Fe_3C
Temperature (°C)
1600
1400
1200
1000
800
600
400
200
0
Temperature (°F)
3000
2500
2000
1500
1000
500
0
5
10
15
20
25
Fe
Atomic Percent Carbon
Fe_3C

Fe-C alloy classification



Metals

Ferrous metals

Non-ferrous metals

Steels

Cast Irons

Plain carbon steels

Low carbon steels

Medium carbon steels

High carbon steels

Low alloy steels

High alloy steels
Stainless & Tool steels

Grey Iron

White Iron

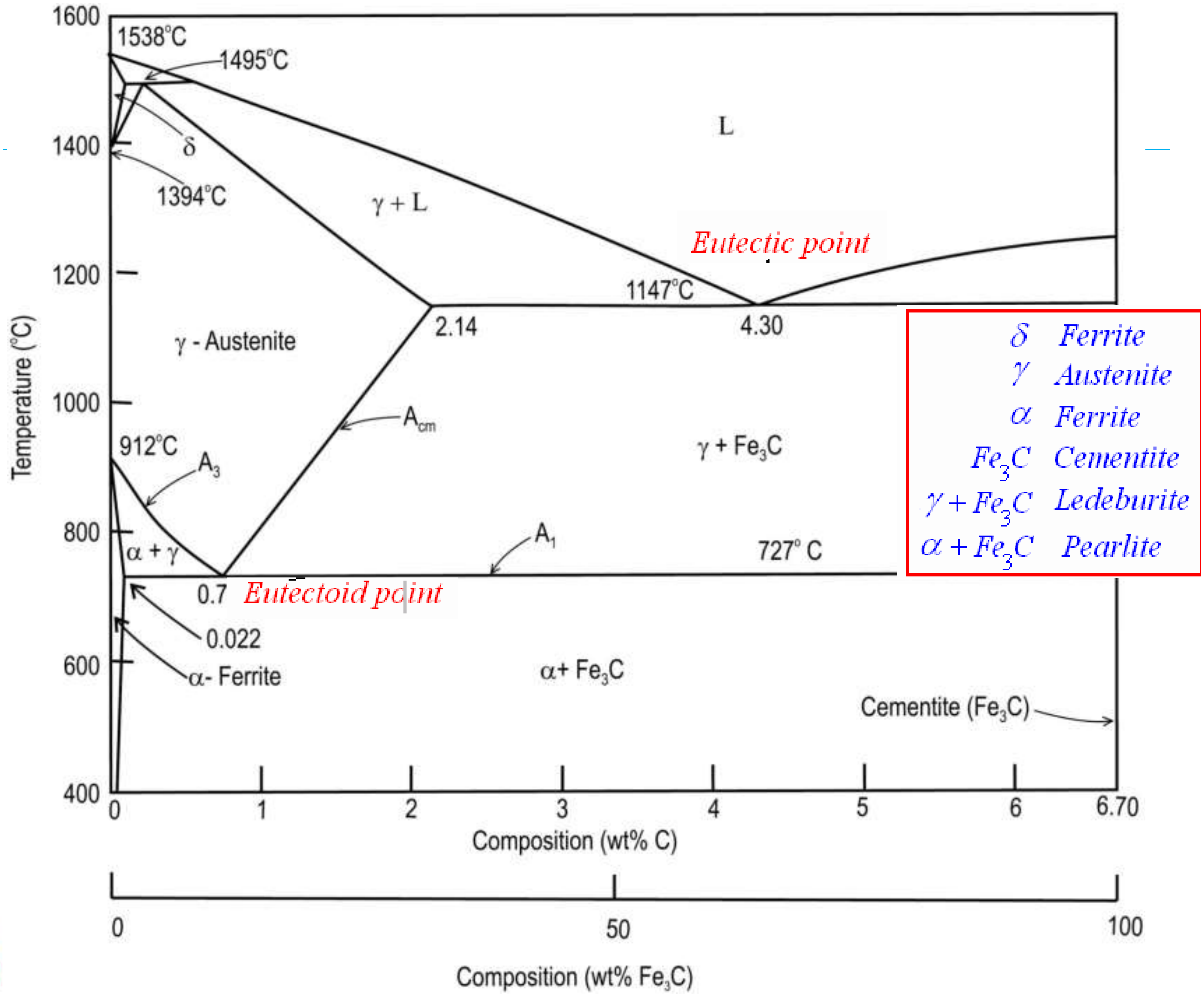
Malleable & Ductile Irons

FE-C ALLOY CLASSIFICATION

- Fe-C alloys are classified according to wt.% C present in the alloys
  - Commercial pure irons % C < 0.008
  - Low-carbon steels 0.008 - %C - 0.3
  - Medium carbon steels 0.3 - %C - 0.8
  - High-carbon steels 0.8- %C - 2.14
  - Cast irons 2.14 < %C

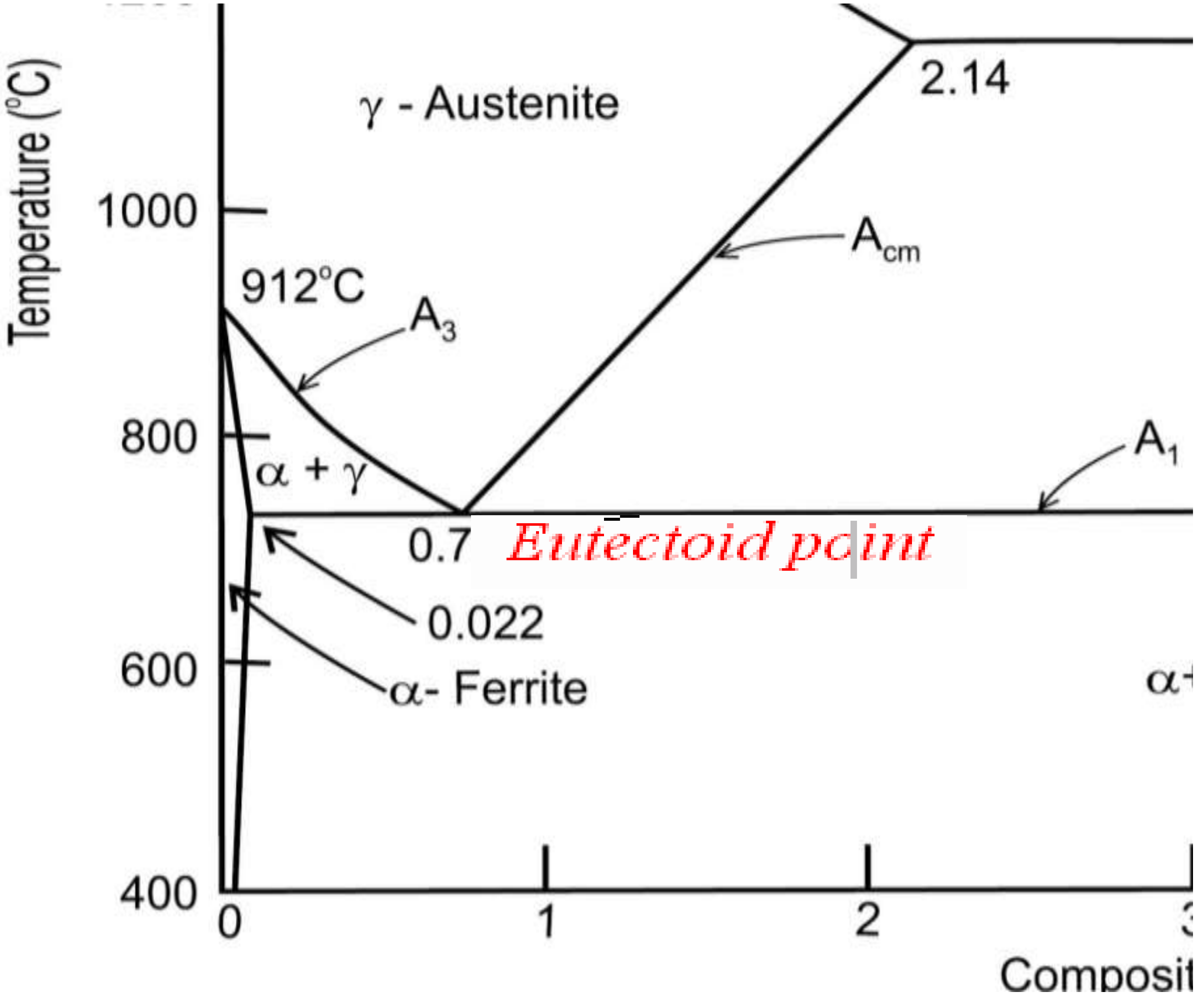
CAST IRONS

- Cast irons that were slowly cooled to room temperature consists of cementite, look whitish – *white cast iron.*
- If it contains graphite, look grayish – *gray cast iron*.
- It is heat treated to have graphite in form of nodules – *malleable cast iron*.
- If inoculants are used in liquid state to have graphite nodules – *spheroidal graphite (SG) cast iron*.

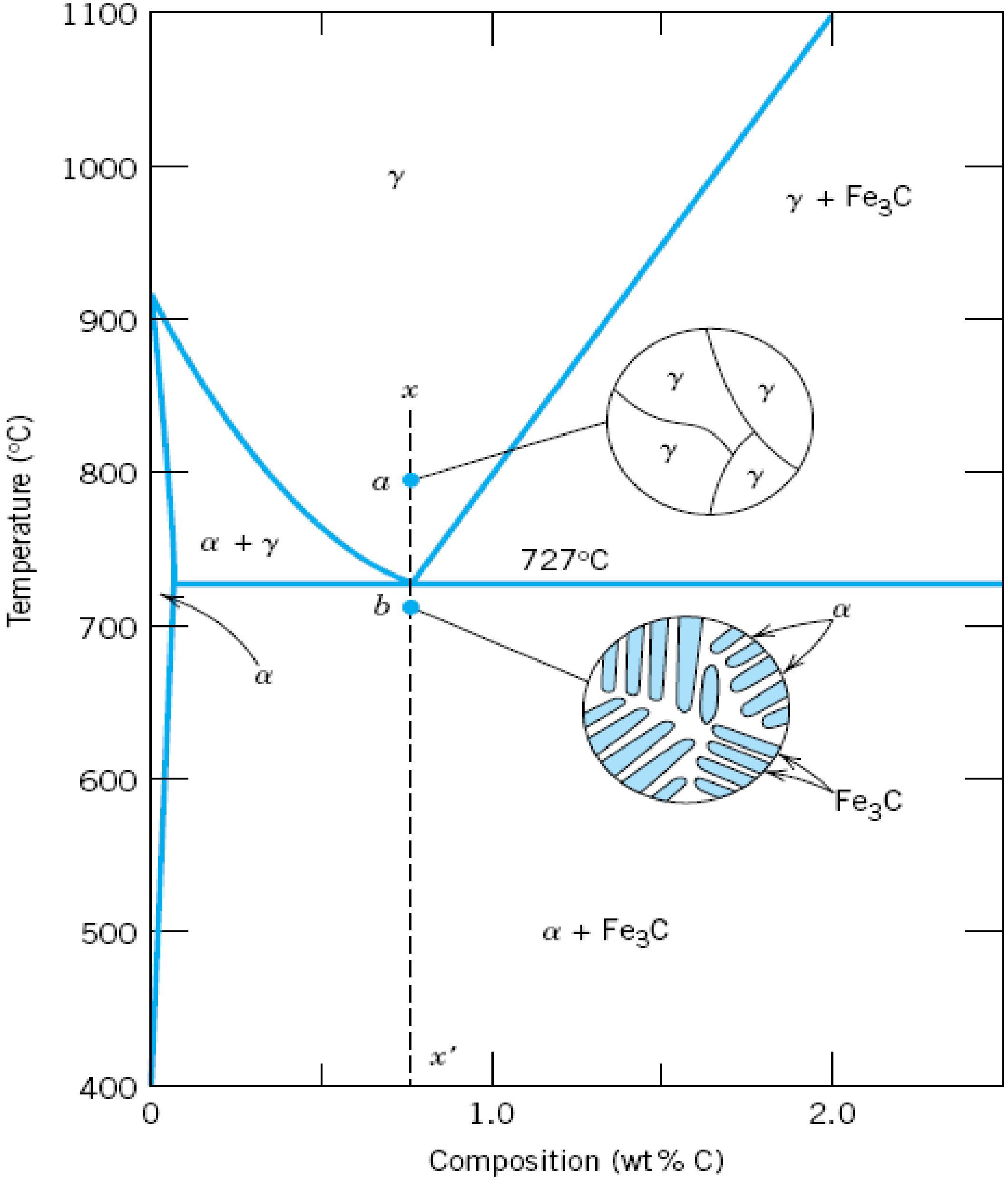


δ Ferrite
γ Austenite
α Ferrite
Fe_3C Cementite
$\gamma + Fe_3C$ Ledeburite
$\alpha + Fe_3C$ Pearlite

Eutectoid Point

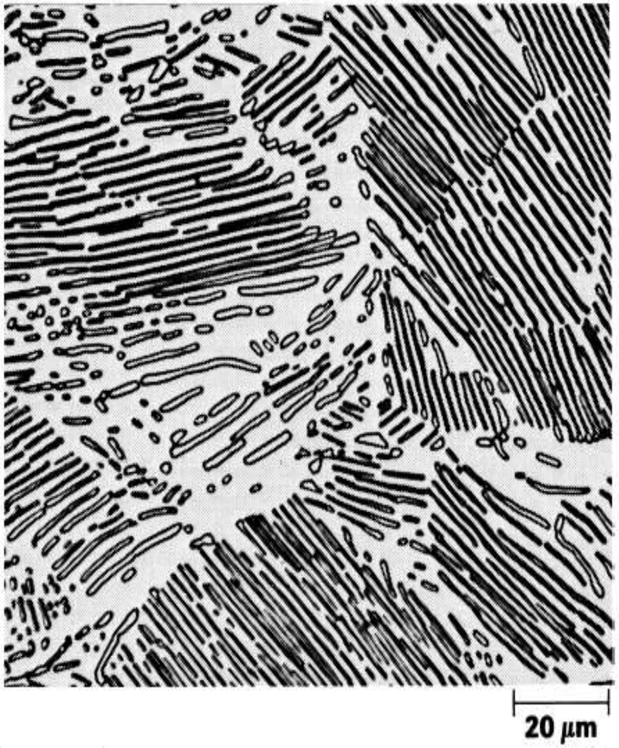


Eutectoid steel

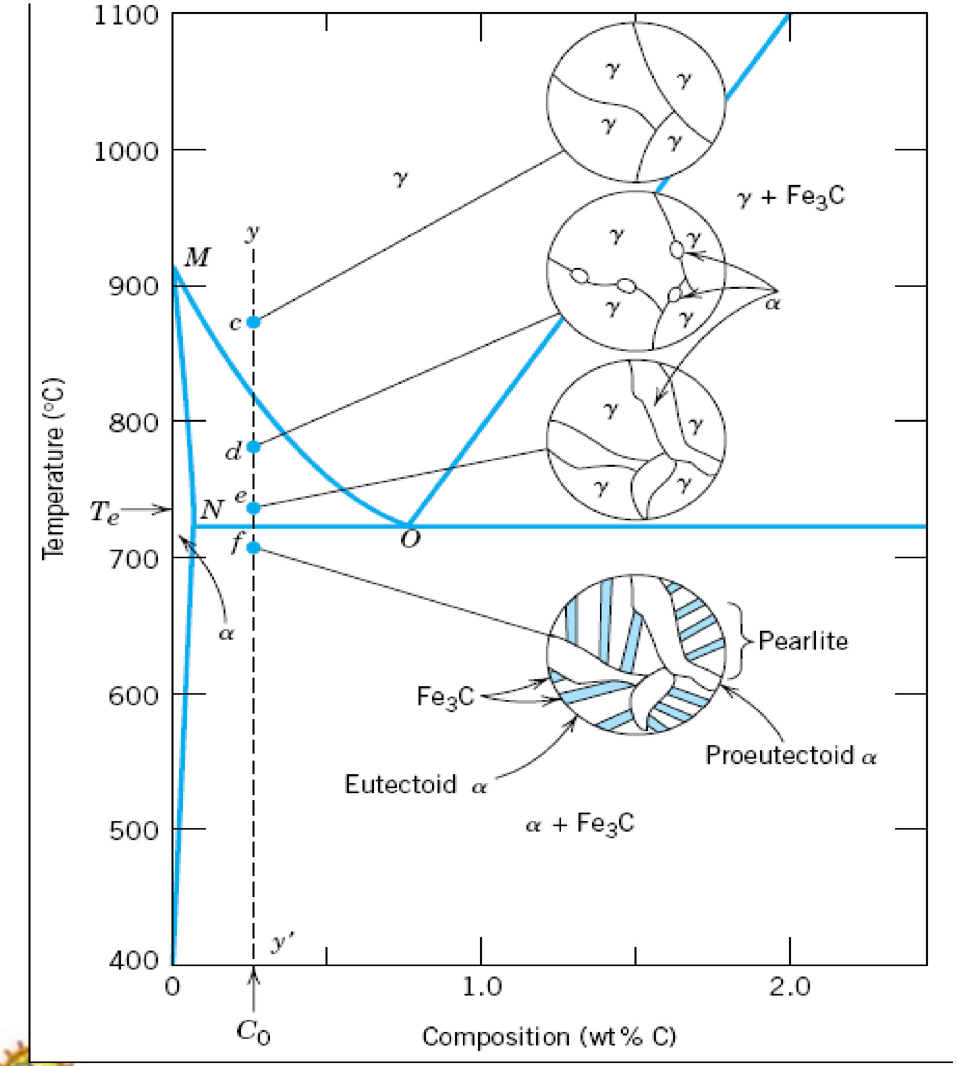


Eutectoid Reaction

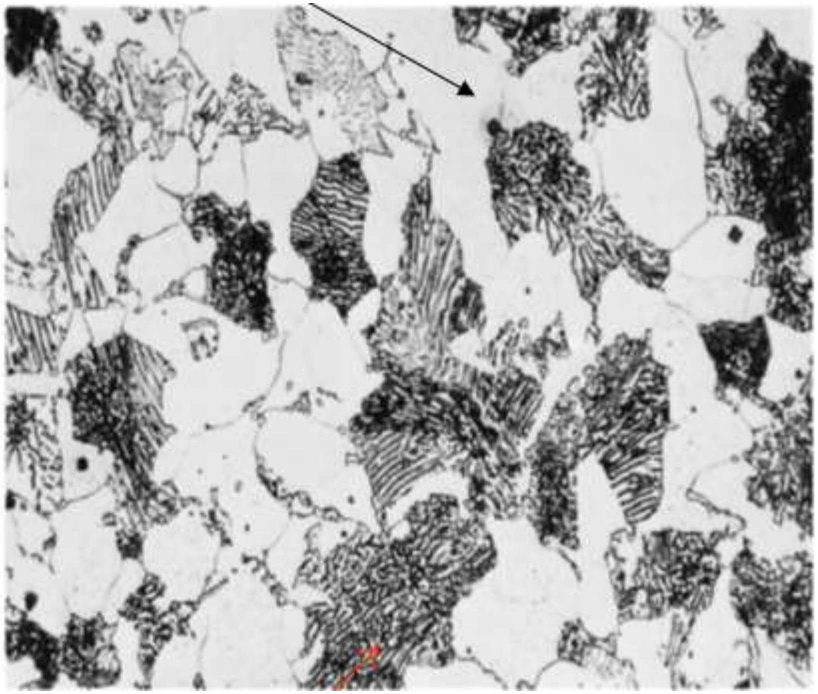
Pearlite



Hypoeutectoid steel



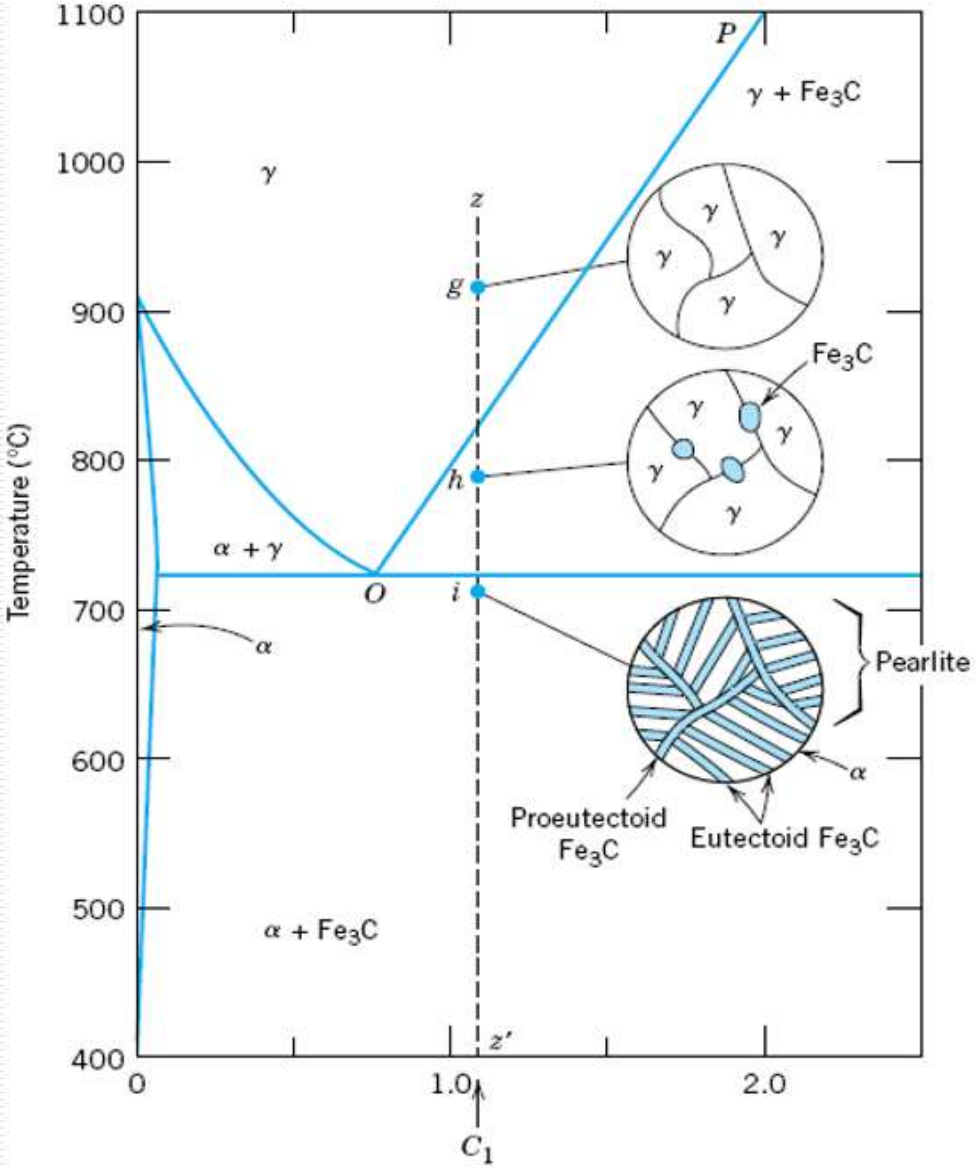
Proeutectoid Ferrite



Pearlite

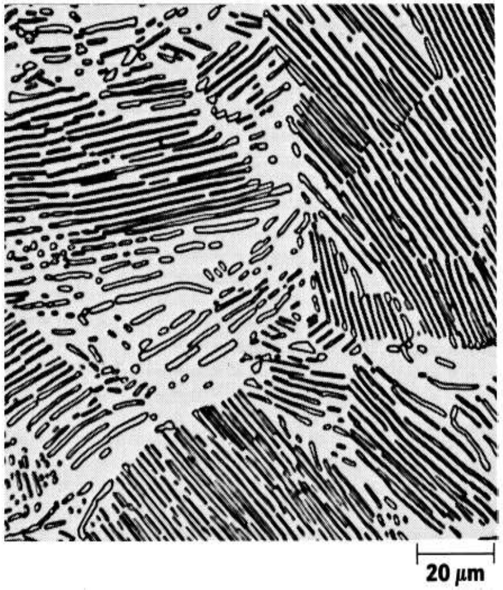
Microstructure of 0.38 wt% C hypoeutectoid steel

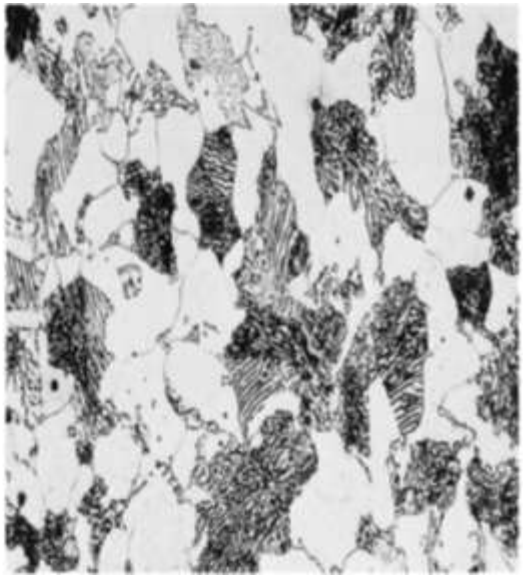
Hypereutectoid steel



Microstructure of 1.4 wt% C hypereutectoid steel

Cont….





Eutectoid steel

$\alpha + Fe_3C$

Pearlite

Hypoeutectoid steel

$\alpha + Fe_3C$

Pearlite + proeutectoid ferrite

Hypereutectoid steel

$\alpha + Fe_3C$

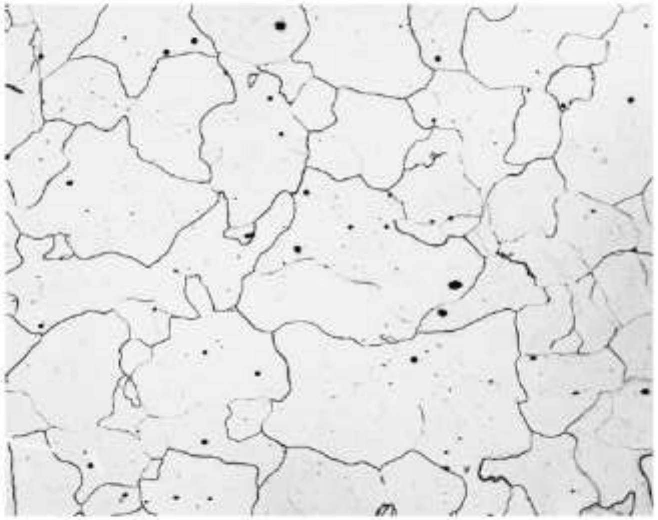
Pearlite + proeutectoid cementite

Phase vs. Microconstituents

- A phase or a mixture of phases which has a distinct identity in a microstructure is called a micro constituent.
- Pearlite is not a phase.
- It is a micro constituent and is a mixture of two phases α- Ferrite and Fe_3C.

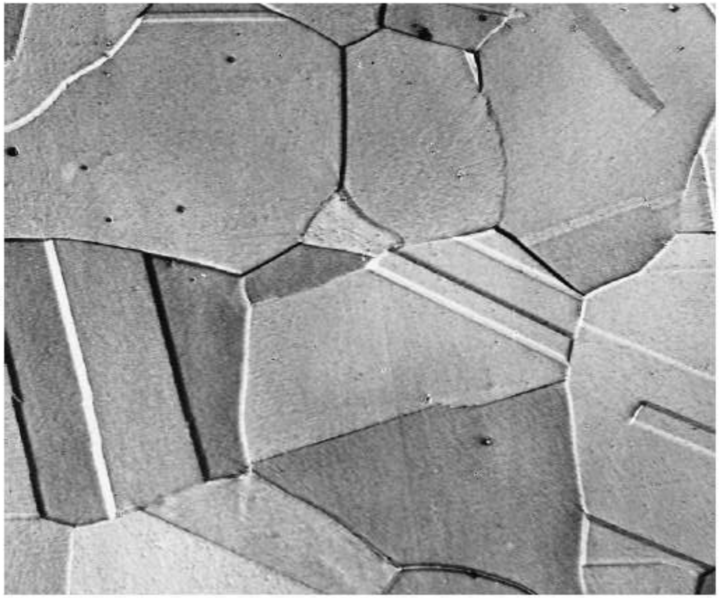
Α–FERRITE

- Known as α -iron
- Pure iron at room temperature
- Body-centered cubic structure
- Soft & ductile and imparts these properties to the steel.
- Less than 0.01% carbon will dissolve in ferrite at room temperature
- High temperature form is δ ferrite, but the two forms are identical.
- Pure ferritic steels are rare



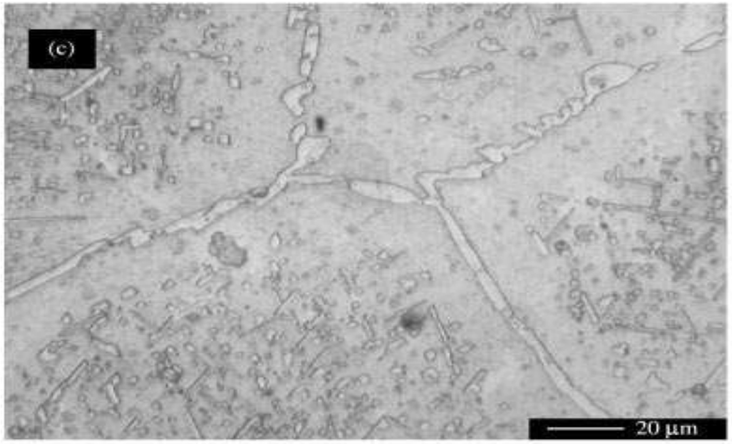
AUSTENITE

- Known as γ -iron
- Face-centered cubic
- Much softer than ferrite
- Not present at room temperatures.
- More easily hot worked



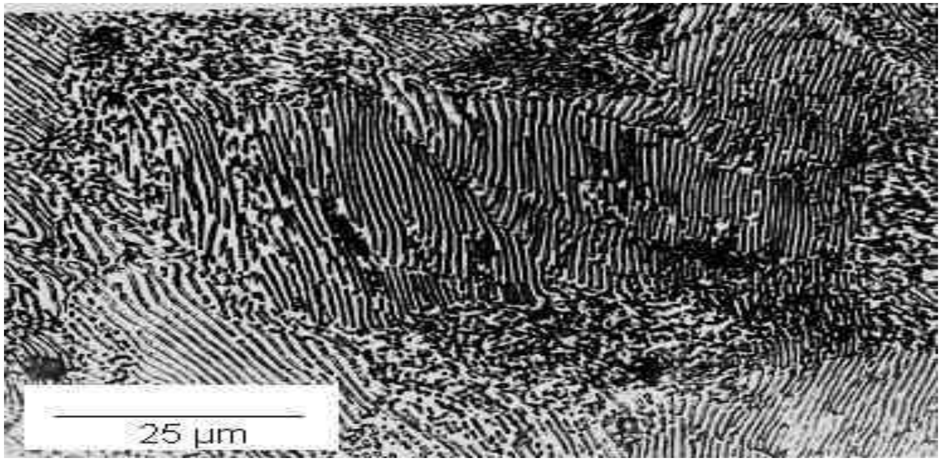
CEMENTITE

- Iron Carbide - an intermetallic compound
- Hard, brittle, white
- melts at 1837°C , density of 7.4 g/cc
- On the phase diagram, cementite corresponds to a vertical line at 6.7% C
- Engineers care only about compounds with less carbon
- Its presence in steels causes an increase in hardness and a reduction in ductility and toughness



PEARLITE

- A laminated structure formed of alternate layers of ferrite and cementite with average composition 0.83% carbon
- Pearly lustre in the microscope
  - Interference of light in its regular layers
- Most common constituent of steel
- It combines the hardness and strength of cementite with the ductility of ferrite and is the key to the wide range of the properties of steels.
- The laminar structure also acts as a barrier to crack movement as in composites. This gives it toughness



PHASE TRANSFORMATIONS

- Involve some alteration of microstructure
  1. No change in number or composition of the phases present, diffusion-dependent. Solidification of pure metals, allotropic transformation.
  2. Some alteration in composition and no of phases, diffusion – dependent. Eutectoid reaction
  3. A metastable phase is produced, diffusionless. Martensitic transformation.

PHASE TRANSFORMATIONS

- At least one new phase is formed
- Do not occur instantaneously
  - Begin by the formation of small particles of new phase – nucleation
    - Homogenous – occurs uniformly throughout the parent phase.
    - Hetrogenous – preferentially at grain boundaries, impurities, dislocations
  - Size of these particles increase in size until completion - growth

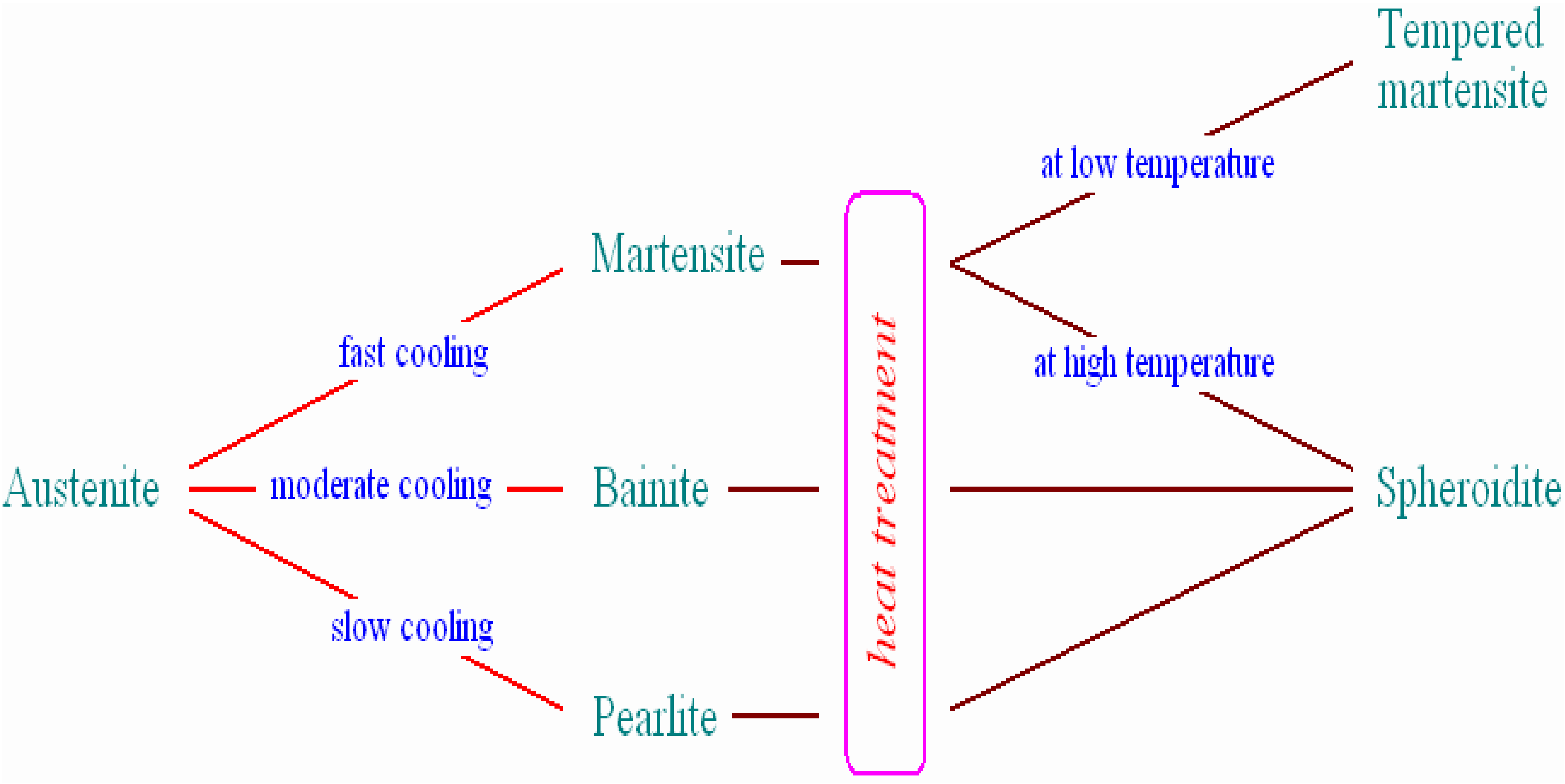
PHASE TRANSFORMATIONS

- Dependent on
  - Temperature
  - Time
  - Composition
- Require some finite time for completion
- Equilibrium is rarely achieved in solids
- Metastable – intermediate between initial and equilibrium states.

TRANSFORMATION OF AUSTENITE IN EUTECTOID STEEL

- Pearlite 727 - 540°C
- Bainite 540 - 210°C
- Martensite below 210°C

TRANSFORMATIONS INVOLVING AUSTENITE


Austenite
fast cooling
moderate cooling
slow cooling
Martensite
Bainite
Pearlite
heat treatment
at low temperature
at high temperature
Tempered martensite
Spheroidite

DEFINE

- Heat treatment may be defined as:

An operation or combination of operations

involving

Heating and cooling of a metal/alloy in solid state

to obtain desirable

Conditions, e.g., that of relieved stresses

Properties, e.g.,
- Better machinability
- Improved ductility
- Homogeneous structure, etc.

PURPOSE

- Cause relief of internal stresses developed during cold working, welding, casting, forging etc.
- Harden and strengthen metals.
- Improve machinability.
- Change grain size
- Soften metals for further (cold) working as in wire drawing or cold rolling.

PURPOSE

- Improve ductility and toughness
- Increase , heat, wear and corrosion resistance of materials.
- Improve electrical and magnetic properties.
- Homogenise the structure to remove coring .
- Spheroidize tiny particales, such as those of Fe_3C in steel, by diffusion.

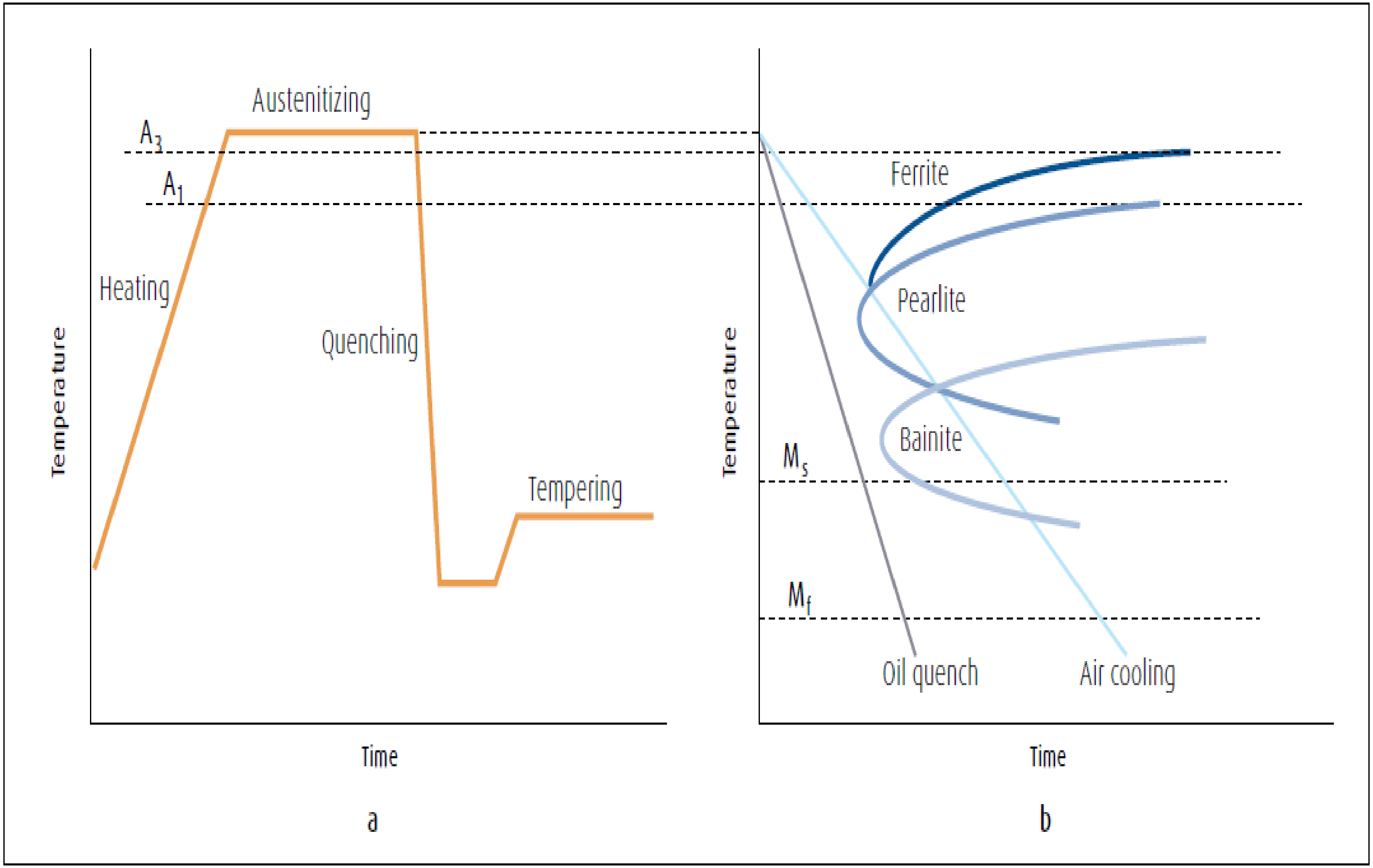
HEAT TREATMENT THEORY

- The various types of heat-treating processes are similar because they all involve the heating and cooling of metals; they differ in the heating temperatures and the cooling rates used and the final results.
- Ferrous metals (metals with iron) are annealing, normalizing, hardening, and tempering.
- Nonferrous metals can be annealed, but never tempered, normalized, or case-hardened.

STAGES OF HEAT TREATMENT

- **Stage I**—Heating the metal slowly to ensure a uniform temperature.
- **Stage 2**—Soaking (holding) the metal at a given temperature for a given period of time.
- **Stage 3**—Cooling the metal to room temperature.

STAGES OF HEAT TREATMENT



a) Temperature-time cycle and b) its relation to the TTT diagram

STAGES OF HEAT TREATMENT

- **Soaking**

- Internal structural changes take place.
- soaking period depends on the chemical analysis of the metal and the mass of the part.

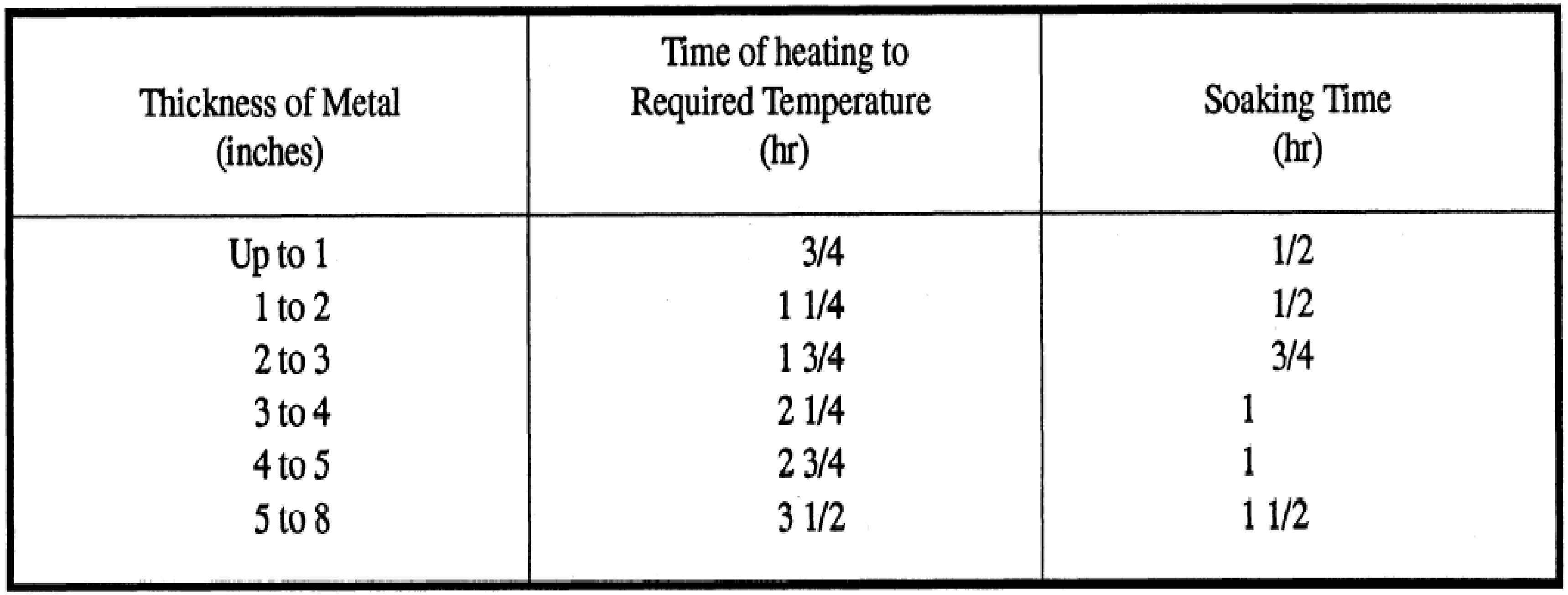
- **Cooling Stage**

- To cool the metal, you can place it in direct contact with a COOLING MEDIUM composed of a gas, liquid, solid, or combination of these.

STAGES OF HEAT TREATMENT

- **Soaking Period**

Table 1: Soaking period for Hardening, Annealing and Normalizing Steel.



Thickness of Metal (inches)	Time of heating to Required Temperature (hr)	Soaking Time (hr)
Up to 1	3/4	1/2
1 to 2	1 1/4	1/2
2 to 3	1 3/4	3/4
3 to 4	2 1/4	1
4 to 5	2 3/4	1
5 to 8	3 1/2	1 1/2

TYPES OF HEAT TREATMENTS

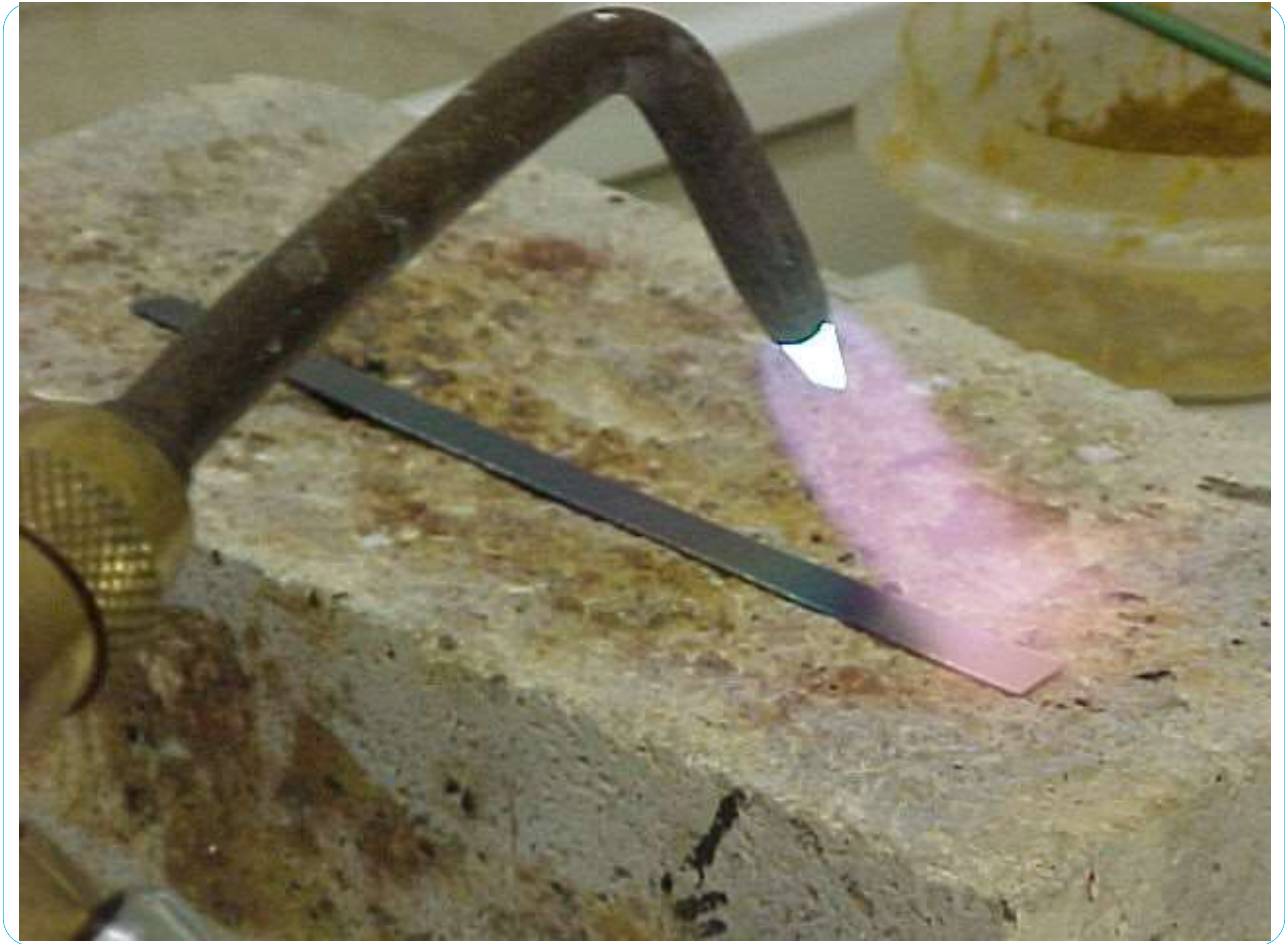
- **Annealing**
- **Normalizing**
- **Hardening**
- **Carburizing**
- **Tempering**

ANNEALING

Steel is annealed to reduce the hardness, improve machine ability, facilitate cold-working, produce a desired microstructure.

Full annealing is the process of softening steel by a heating and cooling cycle, so that it may be bent or cut easily.

In annealing, steel is heated above the transformation temperature to form austenite, and cooled very slowly, usually in the furnace.



ANNEALING

There are several types of annealing like

- Black Annealing,
- Blue Annealing,
- Box Annealing,
- Bright Annealing,
- Flame Annealing,
- Intermediate Annealing,
- Isothermal Annealing,
- Process Annealing,
- Recrystallization Annealing,
- Soft Annealing,
- Finish Annealing
- Spheroidzing Annealing

These are practiced according to their different final product properties in the industry.

CLASSIFICATION

Annealing treatment can be classified into groups based on the following:

1. Heat treatment temperature

- Full annealing
- Partial annealing
- Sub-critical annealing

2. Phase transformation

- First-order annealing
- Second-order annealing

3. Specific purpose

- Full annealing
- Isothermal annealing
- Diffusion annealing
- Partial annealing
- Recrystallization annealing
- Spheroidisation annealing

1. In full annealing the steel is heated above the critical temperature(A_3) and then cooled very slowly.

2. Partial annealing, also known as incomplete annealing or intercritical annealing, involves heating of steel to a temp. lying between lower critical temperature(A_1) and upper critical temperature (A_3 or A_{cm}).

3. Subcritical annealing is a process in which the maximum temp. to which is heated is always less than the lower critical temperature(A_1).

CLASSIFICATION BASED ON PHASE TRANSFORMATION FEATURES.

2.1 **First-order annealing** is performed on steel with the sole aim of achieving some properties. Any change in the characteristics of steel achieved by this type of annealing is not correlated to phase transformation.it can be performed at a wide range of temperatures above or below the critical temperatures.

2.2 The **second-order annealing** differs from the former in the sense that the end results in the former are essentially due to phase transformation which takes place during the treatment.

TYPES OF ANNEALING BASED ON SPECIFIC PURPOSE

3.1 Full annealing

- In this, steel is heated to its 50°C above the austenitic temperature and held for sufficient time to allow the material to fully form austenite or austenite-cementite grain structure. The material is then allowed to cool slowly so that the equilibrium microstructure is obtained.
- The austenitising temp is a function of carbon content of the steel and can be generalized as:
  - For hypoeutectoid steels and eutectoid steel
    - Ac3+(20-40oC) [to obtain single phase austenite]
  - For hypereutectoid steels
    - Ac1+(20-40oC) [to obtain austenite+ cementite]

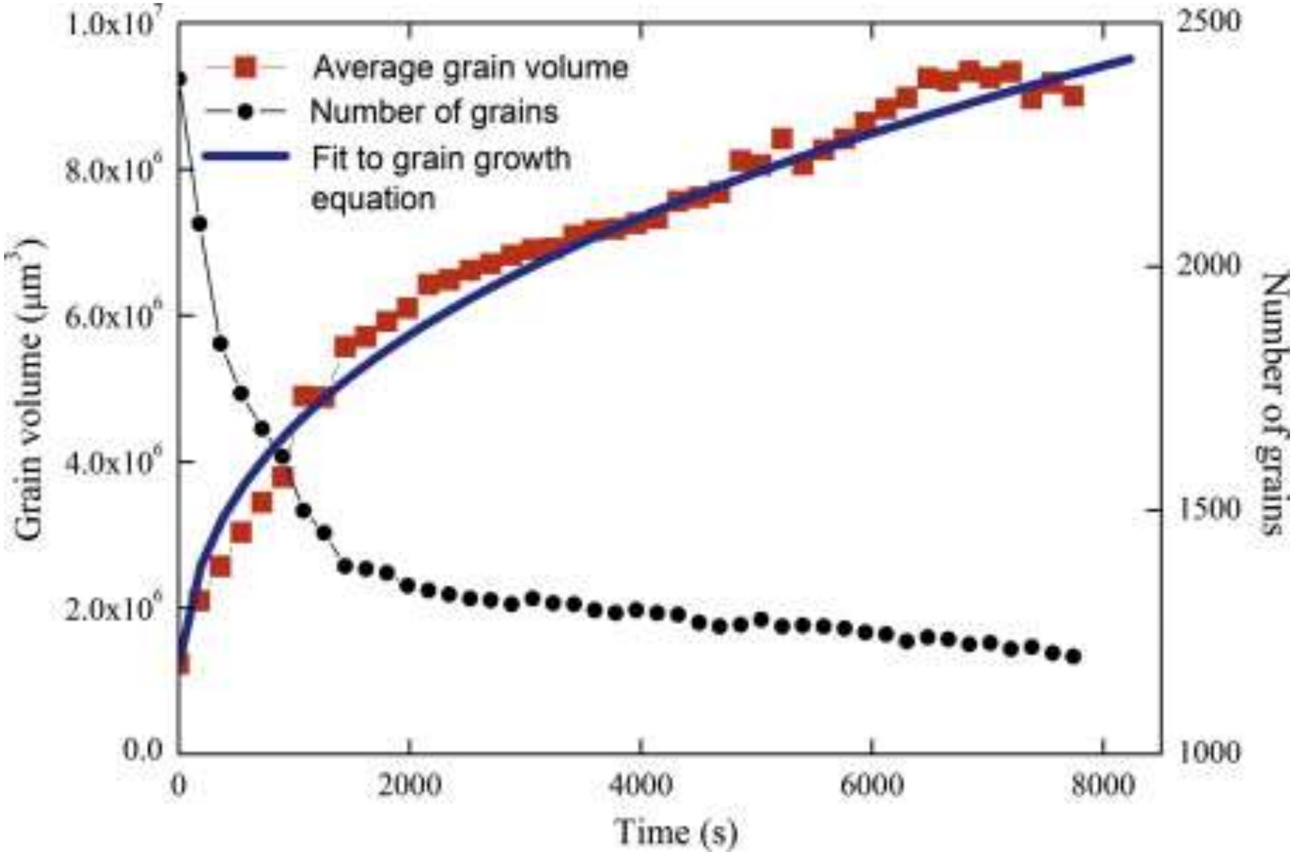
PURPOSE OF FULL ANNEALING

- To relieve internal stresses
- To reduce hardness and increase ductility
- For refining of grain size
- For making the material having homogeneous chemical composition
- For making the material suitable for high machining processes
- To make steel suitable for undergoing other heat treatment processes like hardening, normalizing etc.

3.2 ISOTHERMAL ANNEALING

- It is a process in which hypoeutectoid steel is heated above the upper critical temperature and this temperature is maintained for a time and then the temperature is brought down below lower critical temperature and is again maintained. Then finally it is cooled at room temperature.
- The prefix “isothermal” associated with annealing implies that transformation of austenite takes place at constant temperature.

The closer the temp of isothermal holding is to A1, coarser is the pearlite, softer is the steel, but longer is the time of isothermal transformation.



ADVANTAGES:

- Improved machinability.
- Homogeneous structure and better surface finish.
- Time required for complete cycle is comparably less.
- The process is of great use for alloy steels as the steels have to be cooled slowly.

Limitation:

It is suitable only for small-sized components. Heavy components cannot be subjected to this treatment because it is not possible to cool them rapidly and uniformly to the holding temperature at which transformation occurs. Thus structure wont be homogeneous. so mechanical properties will vary across the cross-section.

3.3 DIFFUSION ANNEALING

- This process, also known as homogenizing annealing, is employed to remove any structural non-uniformity like dendrites, columnar grains and chemical inhomogeneity which promote brittleness and reduce ductility and toughness of steel.

Process:

- Steel is heated sufficiently above the upper critical temperature (say, 1000-2000^{o}C), and held at this temperature for 10-20 hours, followed by slow cooling.
- Segregated zones are eliminated, and a chemically homogeneous steel is obtained by this treatment as a result of diffusion.
- Heating to such a high temp. results in considerable coarsening of austenitic grains & heavy scale formation. The coarse austenite thus obtained further transforms to coarse pearlite on cooling, which is not a desirable structure as mechanical properties are impaired.

- The main aim of homogenising annealing is to make the composition uniform, i.e to remove chemical heterogeneity.
- The impact energy and ductility of the steel increase as the homogenizing temperature increases and the hardness, yield strength and tensile strength decrease with an increase in the homogenizing temperature.
- Homogenizing annealing has a few shortcomings as well. It results in:
  - ☐ Grain coarsening of austenite, thereby impairing the properties
  - ☐ Thick scales on the surface of steels
  - ☐ It is an expensive process

3.4 PARTIAL ANNEALING

- Partial annealing, also known as inter-critical annealing or incomplete annealing, is a process in which steel is heated between A_1 and A_{cm} and is followed by slow cooling.

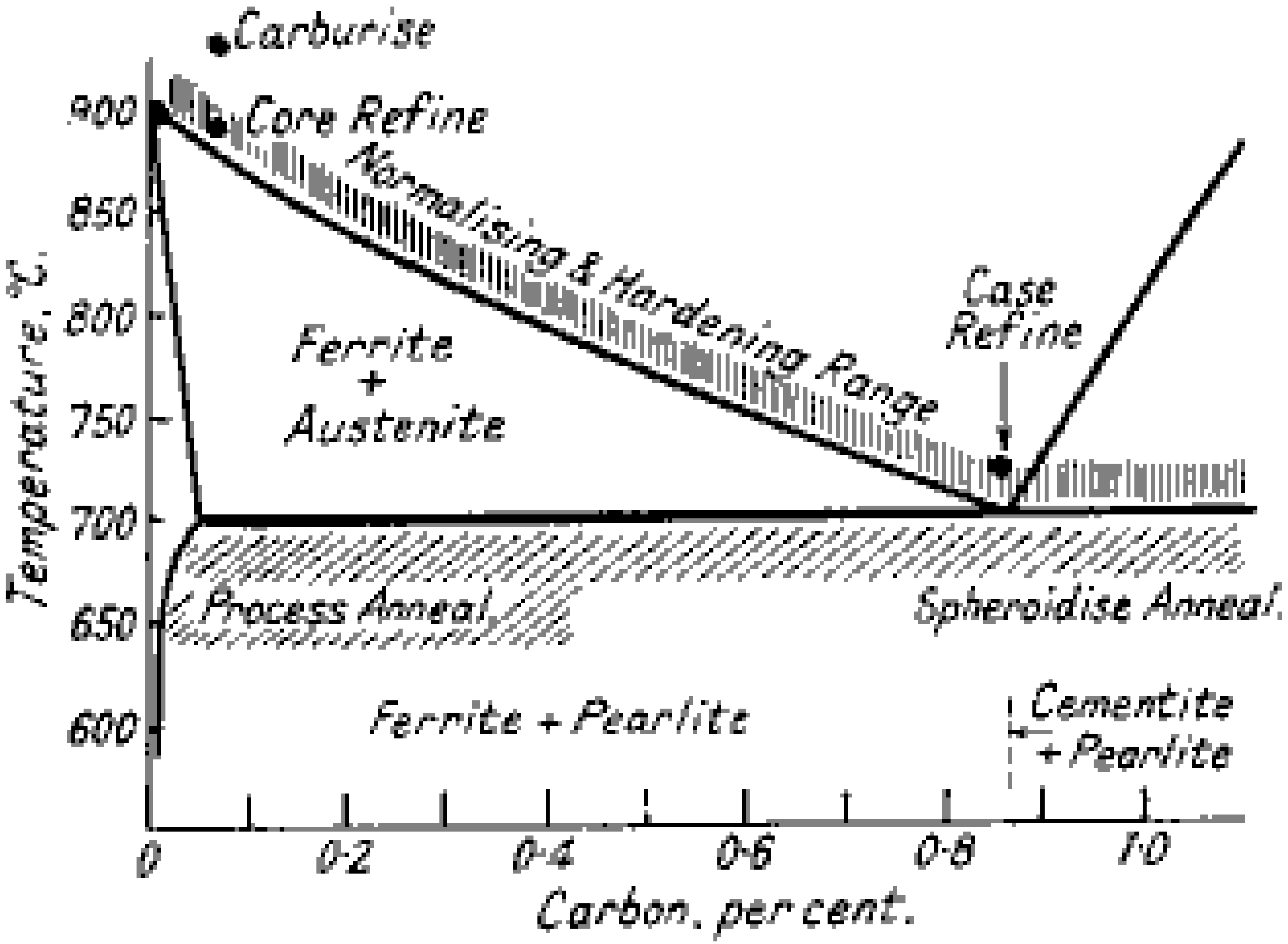
- Generally, hypereutectoid steels are subjected to this treatment. The resultant microstructure consists of fine pearlite and cementite instead of coarse pearlite and a network of cementite at grain boundaries.

- As low temperatures are involved in this process, it is less expensive than full annealing.

- Hypoeutectoid steels are subjected to this treatment to improve machinability.
- However, steels with coarse structure of ferrite and pearlite are not suitable for this treatment. This is because only a considerable amount of ferrite remains untransformed, and only a part of it along with pearlite transforms to austenite.
- This coarse or accicular untransformed ferrite results in poor mechanical properties.

3.5 RECRYSTALLIZATION ANNEALING

- The process consists of heating steel above the recrystallization temperature, holding at this temperature and cooling thereafter.
- It is used to treat work-hardened parts made out of low-Carbon steels (< 0.25% Carbon). This allows the parts to be soft enough to undergo further cold working without fracturing.


Carburise
Core Refine
Normalising & Hardening Range
Case Refine
Ferrite + Austenite
Process Anneal
Spheroidise Anneal.
Ferrite + Pearlite
Cementite + Pearlite
Temperature, °C.
900
850
800
750
700
650
600
0
0·2
0·4
0·6
0·8
1·0
Carbon, per cent.

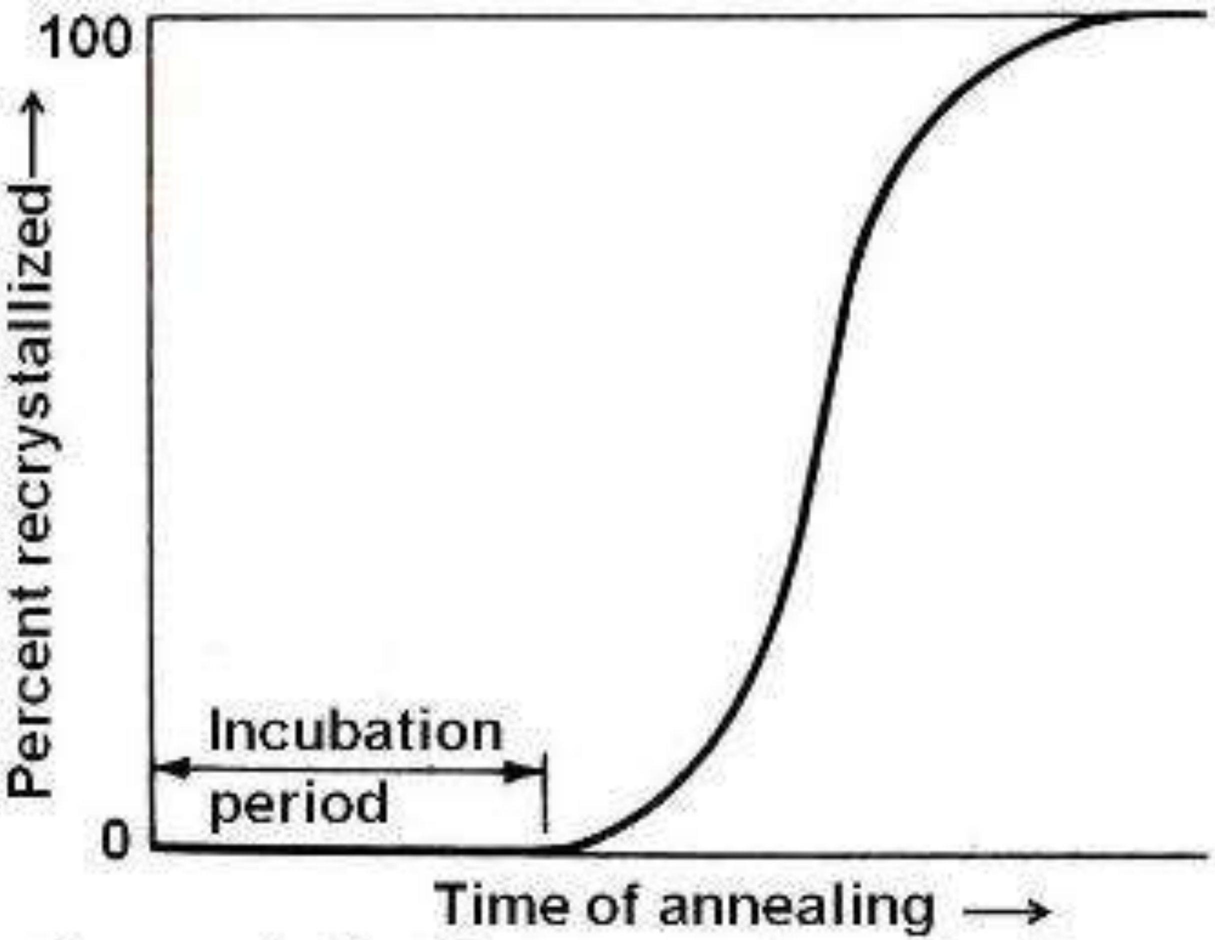
- Recrystallization temp(T_r) is given by:

$$T_r = (0.3\text{-}0.5)T_{mp}$$

- As little scaling and decarburization occurs in recrystallization annealing, it is preferred over full annealing.
- No phase change takes place and the final structure consists of strain-free, equiaxed grains of fine ferrite produced at the expense of deformed elongated ferrite grains.
- However It would produce very coarse grains if the steel has undergone critical amount of deformation. In such cases, full annealing is preferred.

AIMS OF RECRYSTALLIZATION ANNEALING

- To restore ductility
- To refine coarse grains
- To improve electrical and magnetic properties in grain-oriented Si steels.

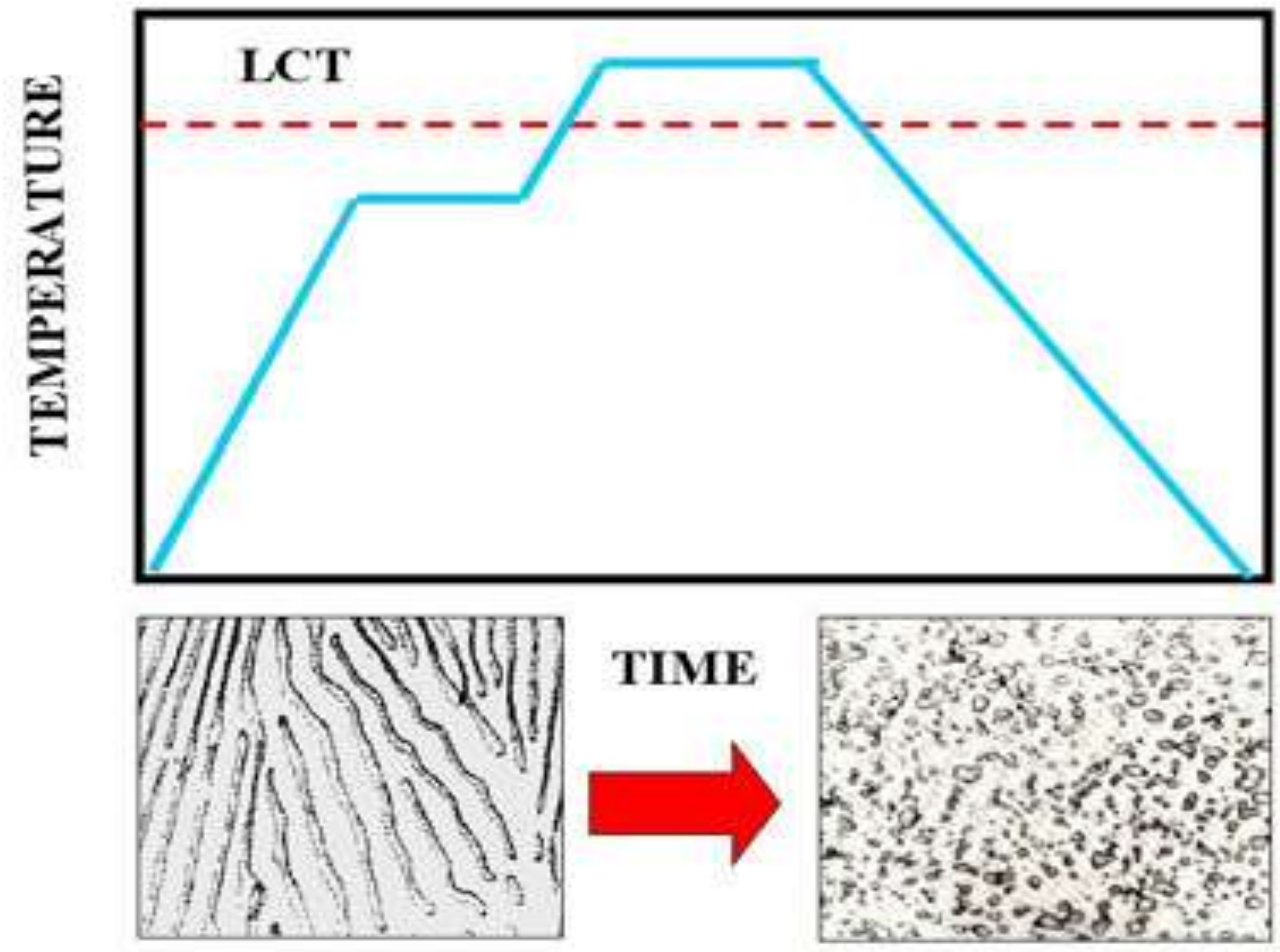


A typical recrystallization curve at constant temperature

3.5 SPHEROIDIZATION ANNEALING

- Spheroidization annealing consists of heating, soaking and cooling, invariably very slowly to produce spheroidal pearlite or globular form of carbides in steels.
- To improve the machinability of the annealed hypereutectoid steel spheroidize annealing is applied.
- Hypereutectoid steels consist of pearlite and cementite. The cementite forms a brittle network around the pearlite. This presents difficulty in machining the hypereutectoid steels.
- This process will produce a spheroidal or globular form of a carbide in a ferritic matrix which makes the machining easy.
- Prolonged time at the elevated temperature will completely break up the pearlitic structure and cementite network. The structure is called spheroidite.

SPHEROIDIZING



Spheroidizing process applied at a temperature below and above the LCT.

Spheroidising Process:

- Heat the part to a temperature just below the Ferrite-Austenite line, line A1 or below the Austenite-Cementite line, essentially below the 727 ºC (1340 ºF) line. Hold the temperature for a prolonged time and follow by fairly slow cooling.

or

- Cycle multiple times between temperatures slightly above and slightly below the 727 ºC (1340 ºF) line, say for example between 700 and 750 ºC (1292 - 1382 ºF), and slow cool.

or

- For tool and alloy steels heat to 750 to 800 ºC (1382-1472 ºF) and hold for several hours followed by slow cooling.

SPHEROIDITE

- All these methods result in a structure in which all the Cementite is in the form of small globules (spheroids) dispersed throughout the ferrite matrix. This structure allows for improved machining in continuous cutting operations such as lathes and screw machines. Spheroidization also improves resistance to abrasion.

AIMS OF SPHEROIDIZATION ANNEALING:

- **minimum hardness**
- **maximum ductility**
- **maximum machinability**
- **maximum softness**

NORMALIZING

- The normalizing of steel is carried out by heating above the UCT (Upper Critical Temperature) to single phase austenitic region to get homogeneous austenite, soaking there for some time and then cooling it in air to room temperature.

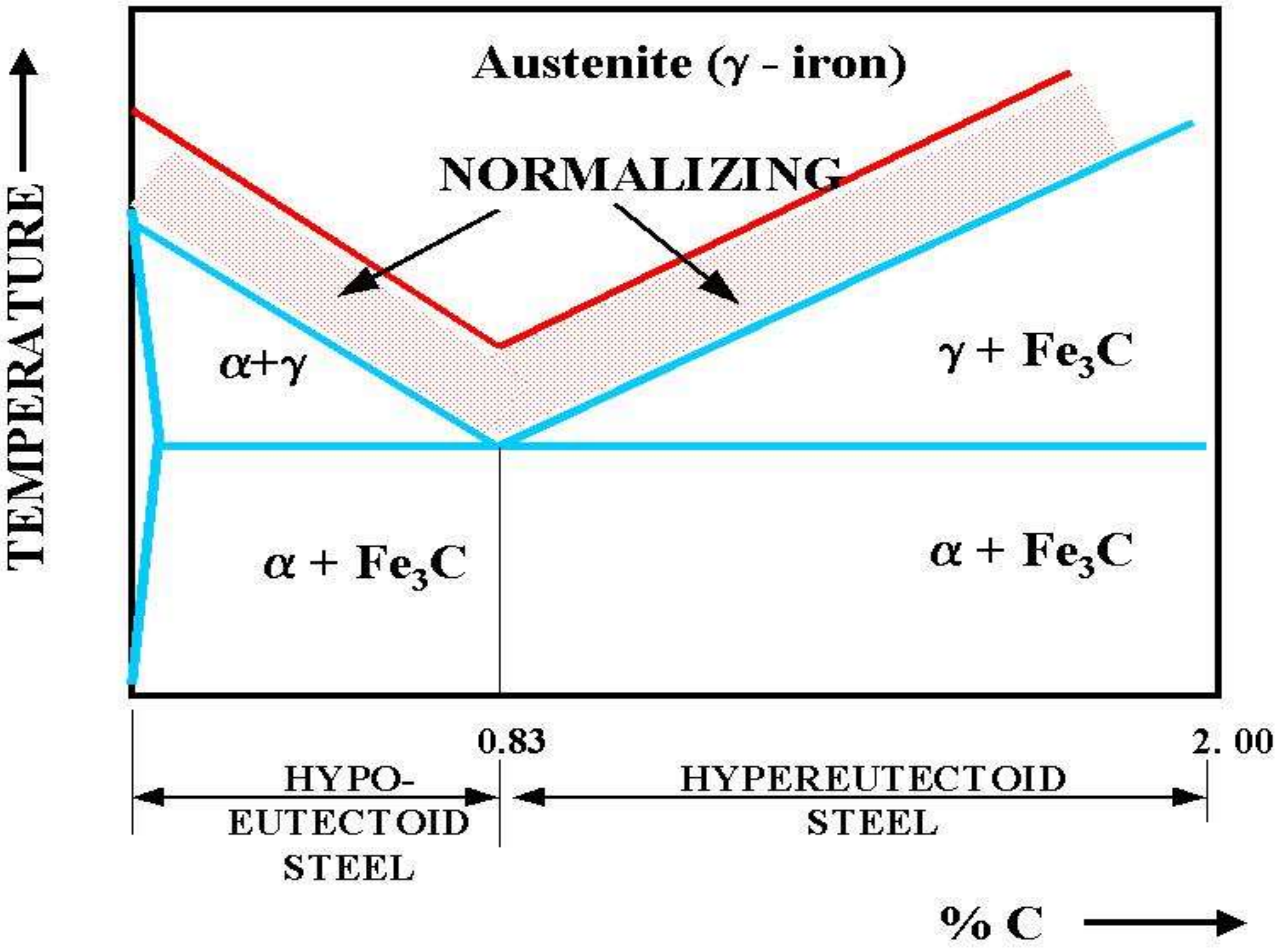
- The austenitising temperature range are:
  - For hypoeutectoid steels and eutectoid steel

    $A_{c3} + (40\text{-}60^{o}C)$
  - For hypereutectoid steels

    $A_{cm} + (30\text{-}50^{o}C)$

- During normalising we use grain refinement which is associated with allotropic transformation upon heating $\gamma \rightarrow \alpha$
- Parts that require maximum toughness and those subjected to impact are often normalized.
- When large cross sections are normalized, they are also tempered to further reduce stress and more closely control mechanical properties.
- The microstructure obtained by normalizing depends on the composition of the castings (which dictates its hardenability) and the cooling rate.

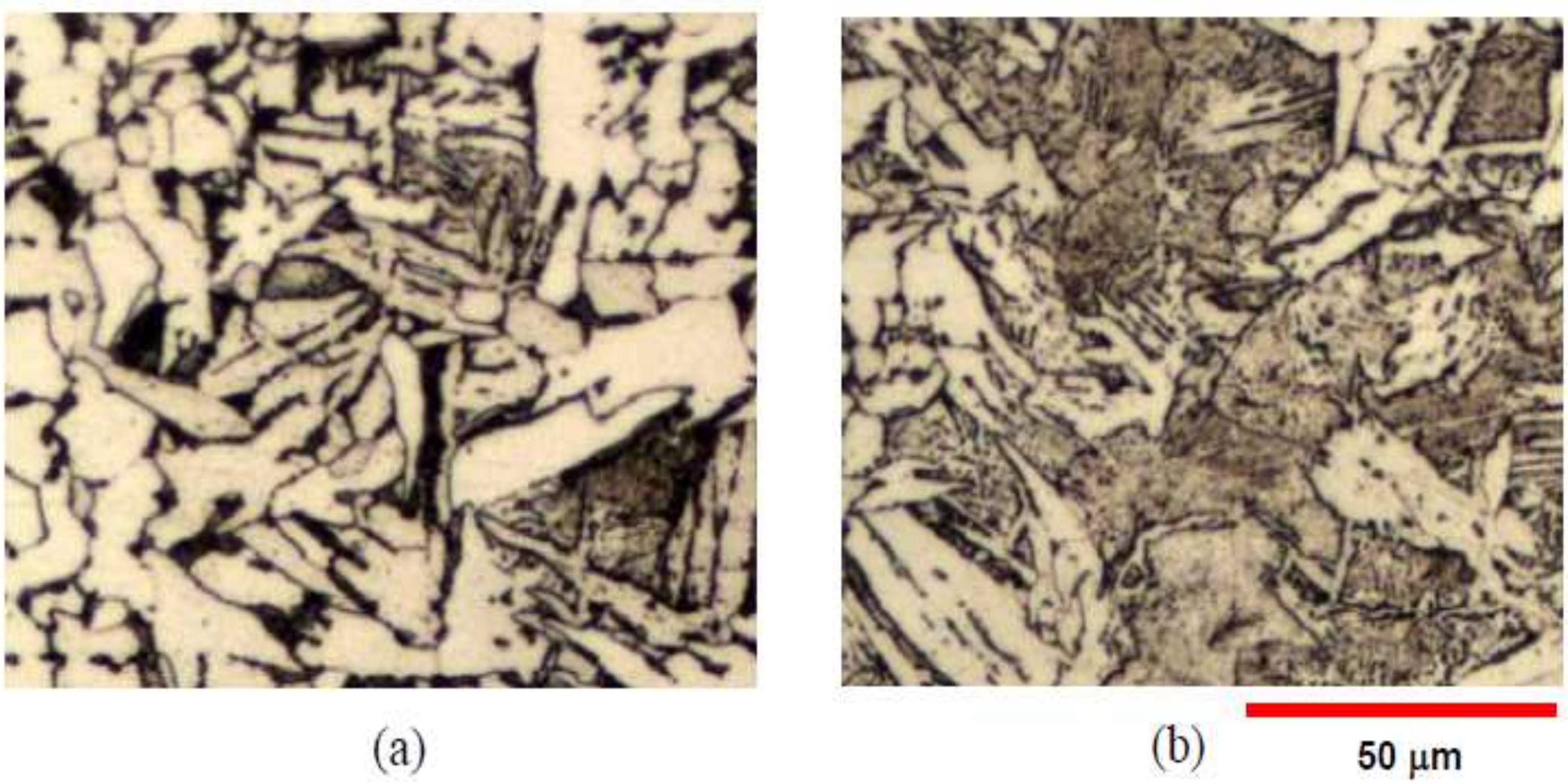
Figure below shows the normalizing temperatures for hypoeutectoid and hypereutectoid steels



AIMS OF NORMALIZING

- To produce a harder and stronger steel than full annealing
- To improve machinability
- To modify and/or refine the grain structure
- To obtain a relatively good ductility without reducing the hardness and strength
- Improve dimensional stability
- Produce a homogeneous microstructure
- Reduce banding
- Provide a more consistent response when hardening or case hardening

EFFECT OF SOAKING TIME ON THE MICROSTRUCTURE:



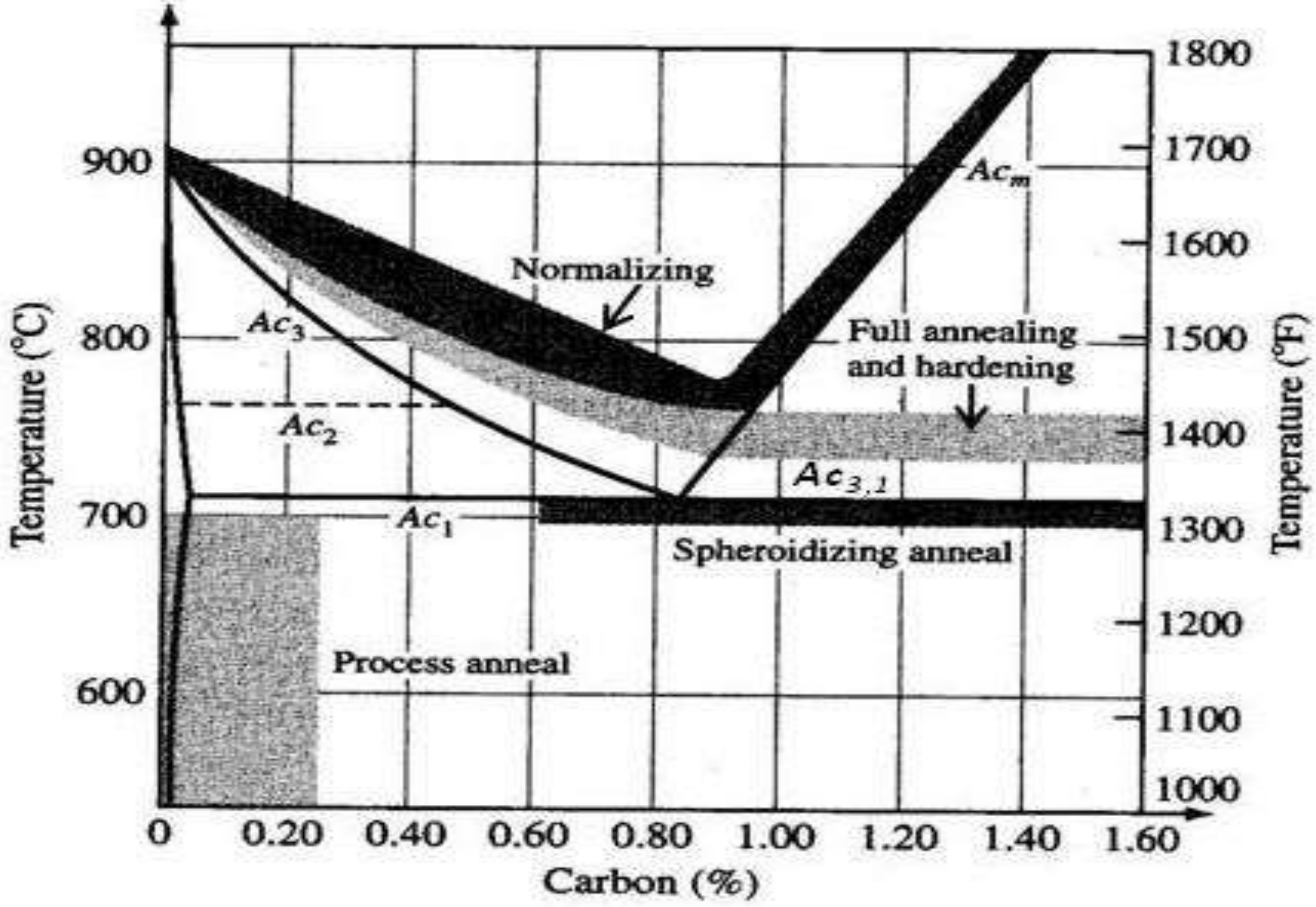
Acicular ferrite in mixture with polygonal ferrite and pearlite, normalized at (a) 960°C, 10 minutes soaking time (b) 960°C, 40 minutes soaking time.

NORMALIZING
VS
ANNEALING

COMPARISON OF ANNEALING AND NORMALIZING

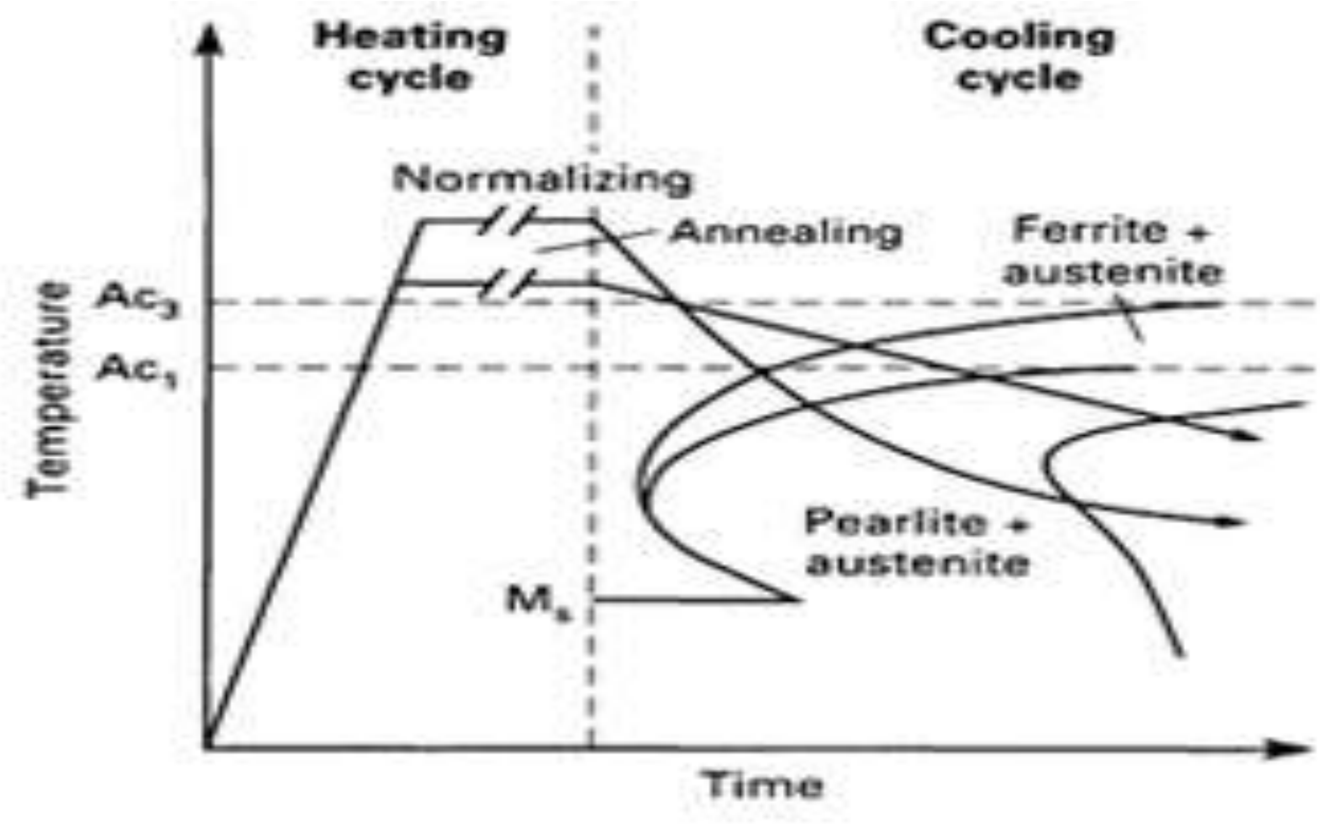
- The metal is heated to a higher temperature and then removed from the furnace for air cooling in normalizing rather than furnace cooling.
- In normalizing, the cooling rate is slower than that of a quench-and-temper operation but faster than that used in annealing.
- As a result of this intermediate cooling rate, the parts will possess a hardness and strength somewhat greater than if annealed.
- Fully annealed parts are uniform in softness (and machinability) throughout the entire part; since the entire part is exposed to the controlled furnace cooling. In the case of the normalized part, depending on the part geometry, the cooling is non-uniform resulting in non-uniform material properties across the part.
- Internal stresses are more in normalizing as compared to annealing.
- Grain size obtained in normalizing is finer than in annealing.
- Normalizing is a cheaper and less time-consuming process.

COMPARISON OF TEMPERATURE RANGES IN ANNEALING AND NORMALIZING



Temperature Range for Heat Treatment of Carbon Steels

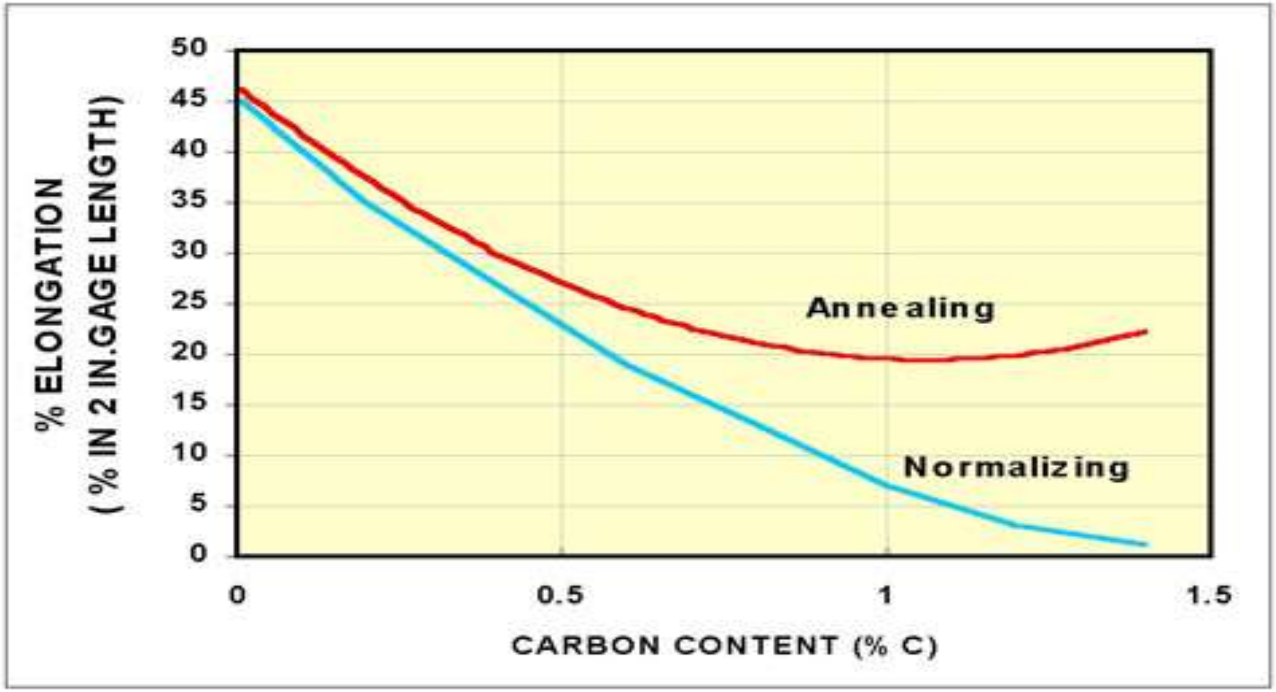
COMPARISON OF TIME-TEMPERATURE CYCLES FOR NORMALIZING AND FULL ANNEALING



The slower cooling of annealing results in higher temperature transformation to ferrite and pearlite and coarser microstructures than does normalizing.

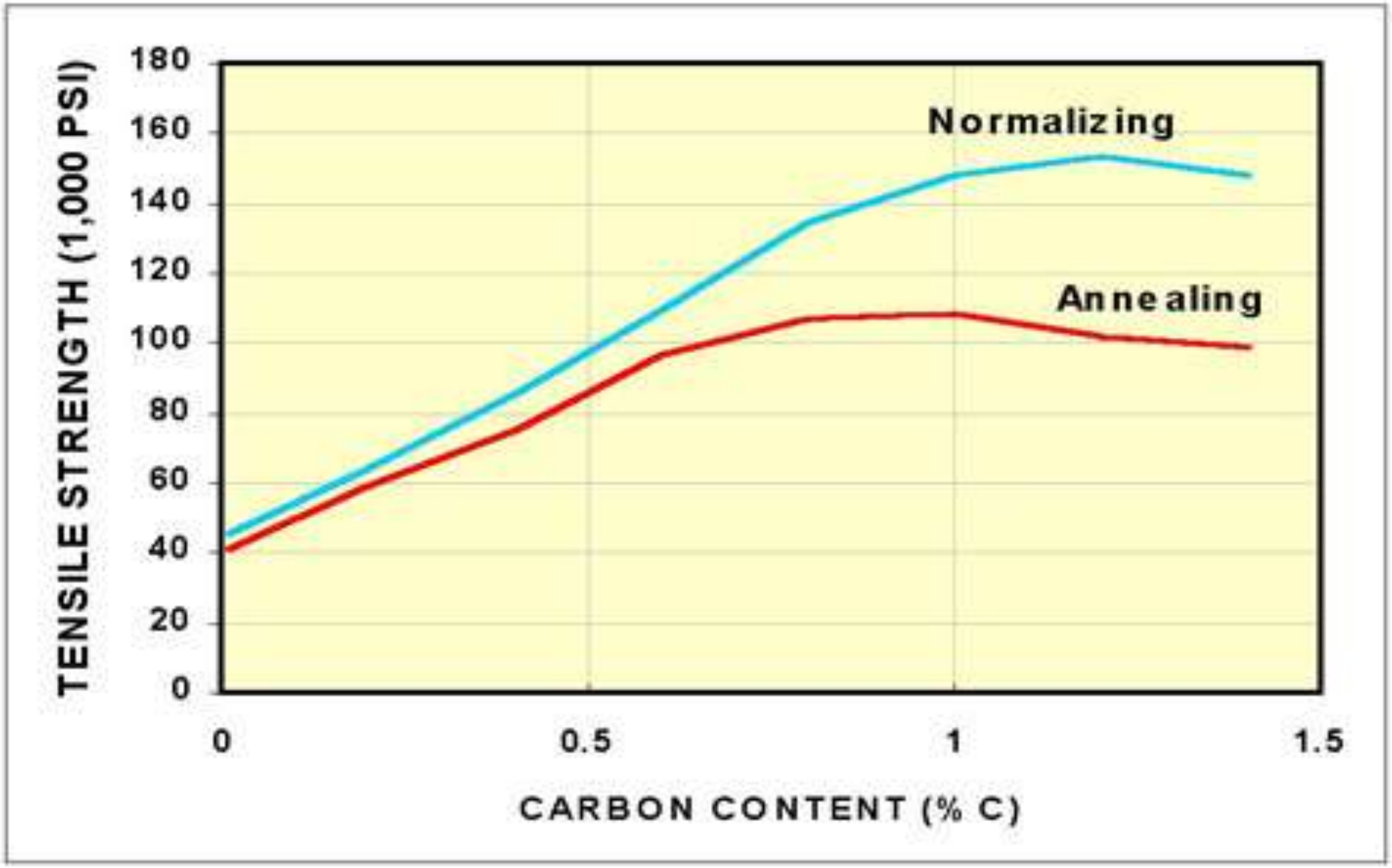
EFFECT OF ANNEALING AND NORMALIZING ON DUCTILITY OF STEELS

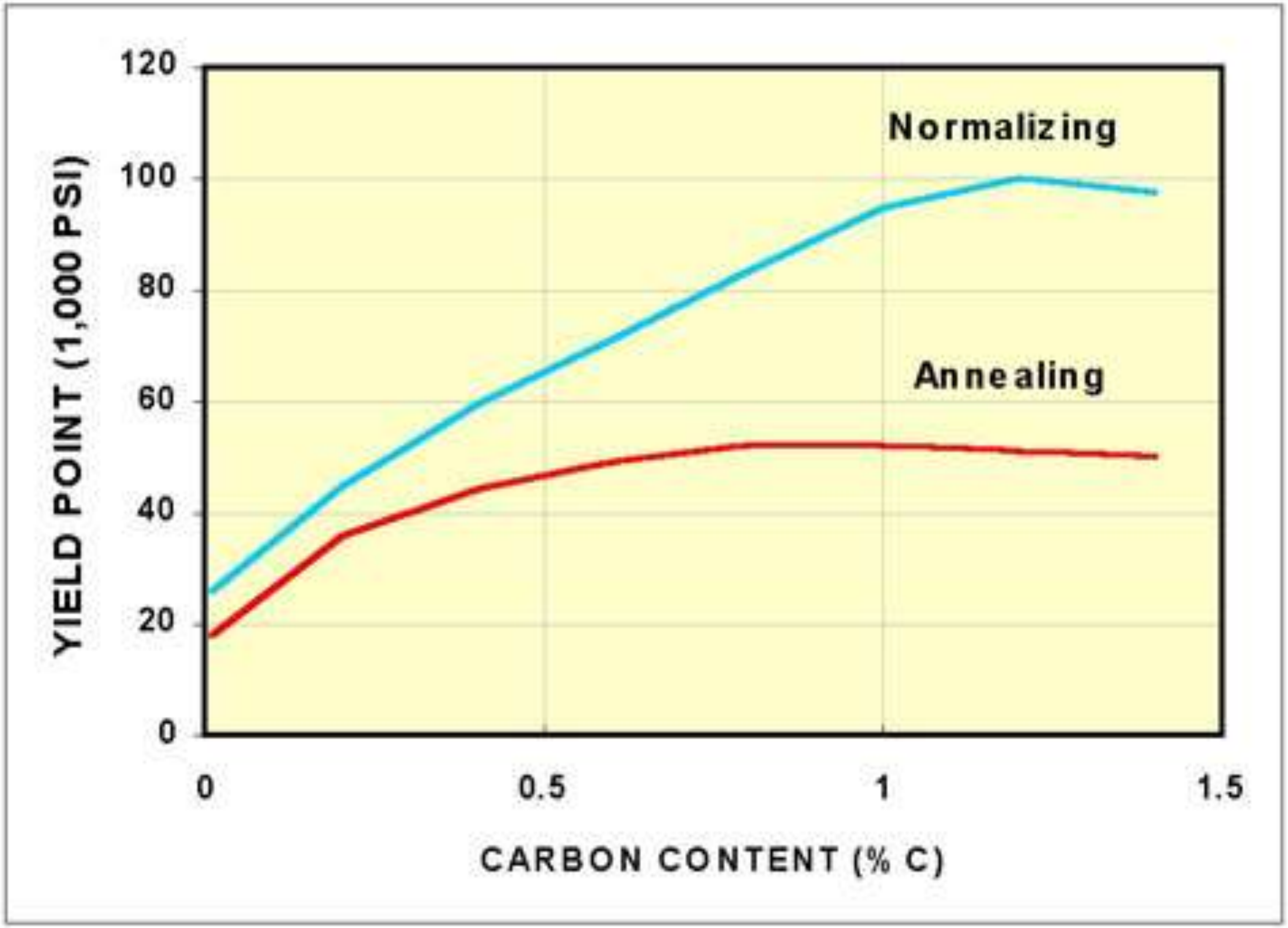
Annealing and normalizing do not present a significant difference on the ductility of low carbon steels. As the carbon content increases, annealing maintains the % elongation around 20%. On the other hand, the ductility of the normalized high carbon steels drop to 1 to 2 % level.



EFFECT OF ANNEALING AND NORMALIZING ON THE TENSILE STRENGTH AND YIELD POINT OF STEELS

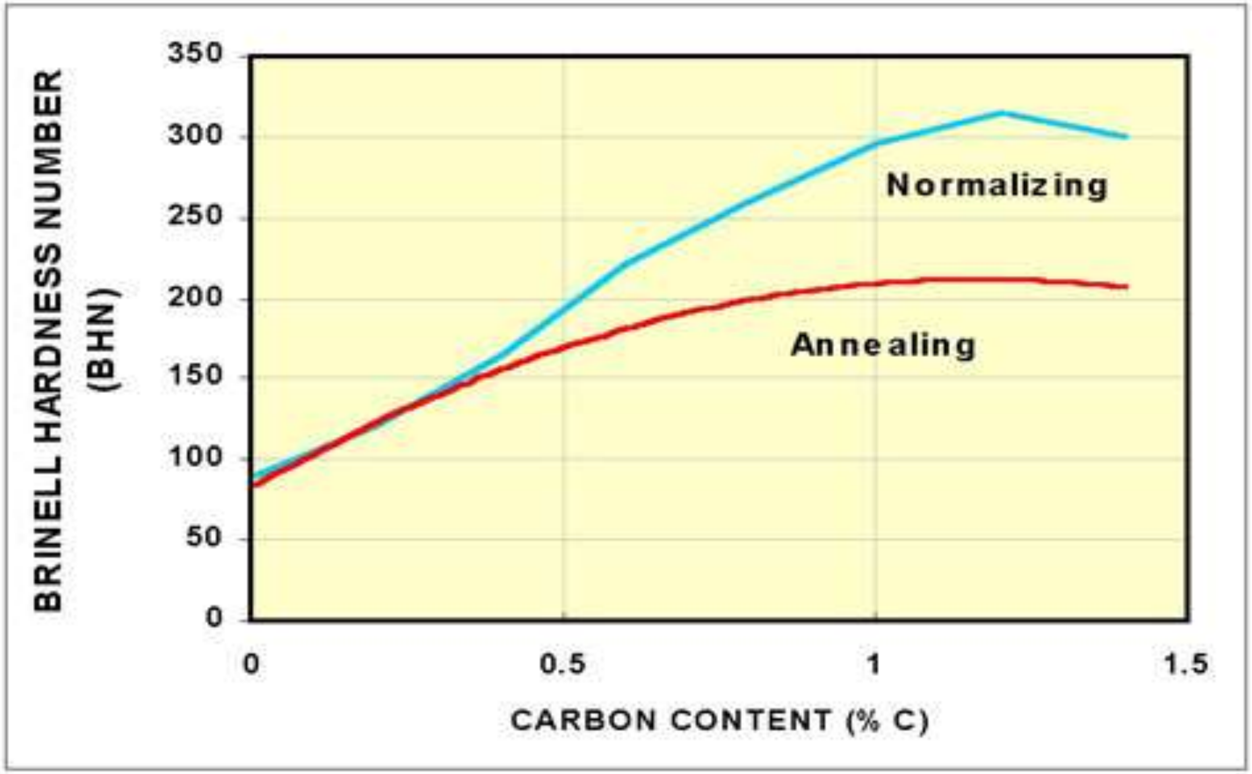
- **The tensile strength and the yield point of the normalized steels are higher than the annealed steels.**
- **Normalizing and annealing do not show a significant difference on the tensile strength and yield point of the low carbon steels.**
- **However, normalized high carbon steels present much higher tensile strength and yield point than those that are annealed. This can be illustrated from the figures.**


TENSILE STRENGTH (1,000 PSI)
180
160
140
120
100
80
60
40
20
0
0
0.5
1
1.5
CARBON CONTENT (% C)
Normalizing
Annealing


120
100
80
60
40
20
0
0
0.5
1
1.5
YIELD POINT (1,000 PSI)
CARBON CONTENT (% C)
Normalizing
Annealing

EFFECT OF ANNEALING AND NORMALIZING ON THE HARDNESS OF STEELS

Low and medium carbon steels can maintain similar hardness levels when normalized or annealed. However, when high carbon steels are normalized they maintain higher levels of hardness than those that are annealed.



ADVANTAGES OF NORMALIZING OVER ANNEALING

- Better mechanical properties
- Lesser time-consuming
- Lower cost of fuel and operation

ADVANTAGES OF ANNEALING OVER NORMALIZING

- Greater softness
- Complete absence of internal stresses which is a necessity in complex and intricate parts

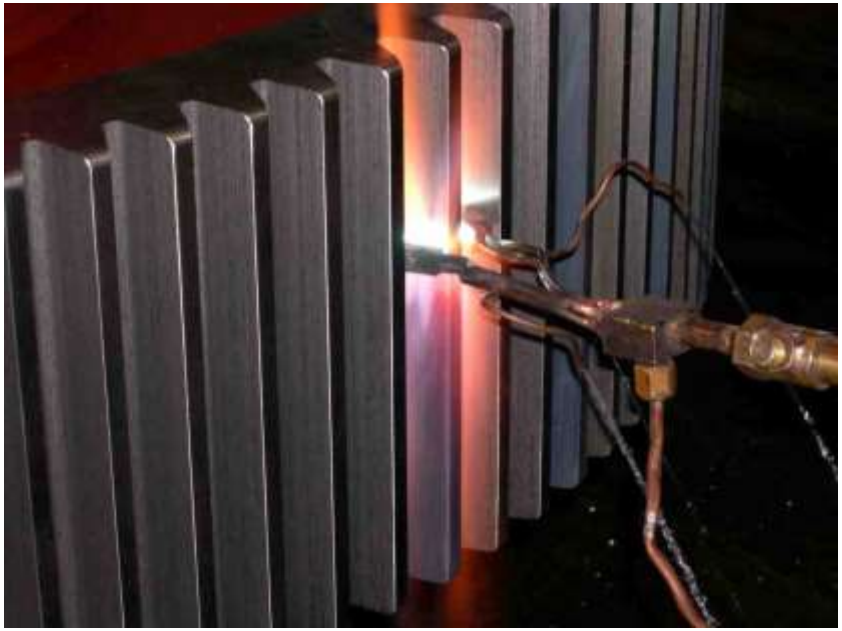
HARDENING

- It is the process of heating the steel to proper austenitizing temperature , soaking at this temperature to get a fine grained and homogeneous austenite , and then cooling the steel at a rate faster than its critical cooling rate.

OBJECTIVES OF HARDENING

The aims of hardening are:

1. Main aim of hardening is to induce high hardness. The cutting ability of a tool is proportional to its hardness.
2. Many machine parts and all tools are hardened to induce high wear resistance higher is the hardness , higher is the wear and the abrasion resistance .For example ,gears, shaft.
3. The main objective of hardening machine components made of structural steel sis to develop high yield strength with good toughness and ductility to bear high working stresses.



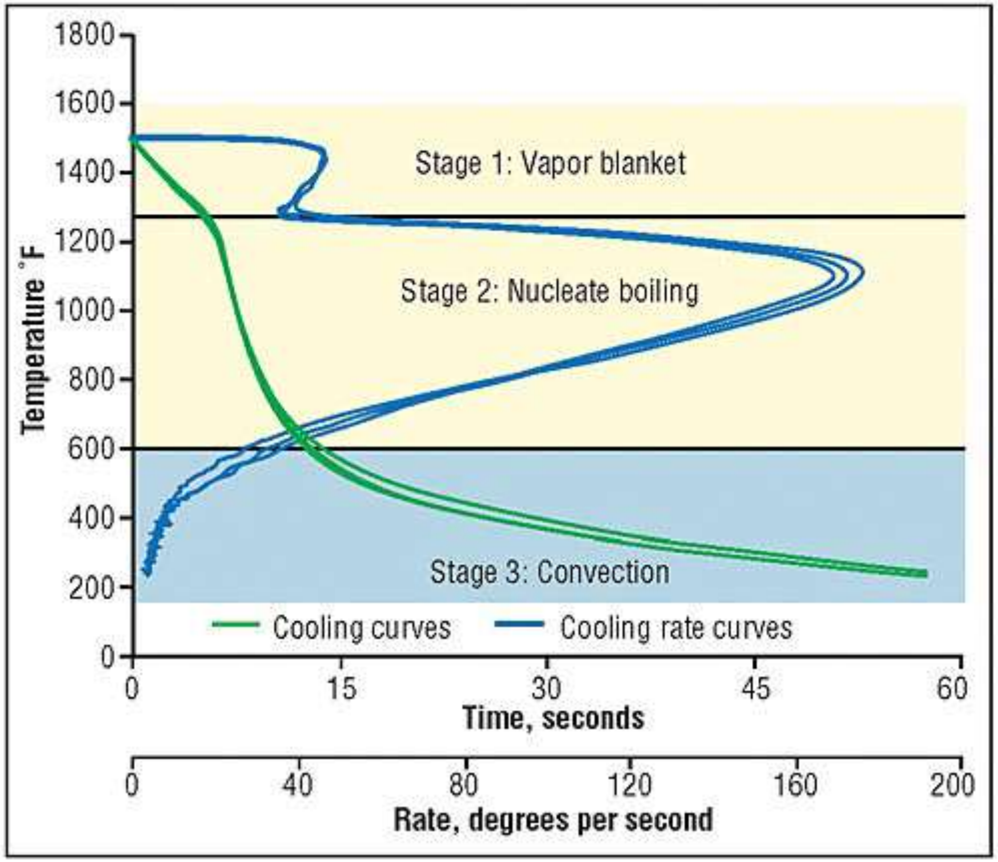
PROCESS OF QUENCHING

- When a heated steel object (say at 840°C) is plunged into a stationary bath of cold it has three stages as:

Stage A -vapour-blanket stage:

- Immediately on quenching, coolant gets vapourized as the steel part is at high temperature, and thus, a continuous vapour- blanket envelopes the steel part.
- Heat escapes from the hot surface very slowly by radiation and conduction through the blanket of water vapour.
- Since the vapour-film is a poor heat conductor, the cooling rate is relatively low (stage A in fig). This long stage is undesirable in most quenching operations.

PROCESS OF QUENCHING



PROCESS OF QUENCHING

Stage B-Intermittent contact stage (Liquid-boiling stage):

- Heat is removed in the form of heat of vaporization in this stage as is indicated by the steep slope of the cooling curve.
- During this stage, the vapour-blanket is broken intermittently allowing the coolant to come in contact with the hot surface at one instant, but soon being pushed away by violent boiling action of vapour bubble.
- The rapid cooling in this stage soon brings the metal surface below the boiling point of the coolant.

PROCESS OF QUENCHING

- The vaporization then stops. Second stage corresponds to temperature range of 500° to 100°c , and this refers to nose of the CCT curve of the steel , when the steel transforms very rapidly (to non martensite product).
- Thus, the rate of cooling in this stage is of great importance in hardening of steels.

Stage C-Direct-Contact stage (Liquid-cooling stage):

- This stage begins when the temperature of steel surface Is below the boiling point of coolant.
- Vapours do not form. The cooling is due to convection and conduction through the liquid. Cooling is slowest here.

WATER

- The oldest and still the most popular quenching medium, water meets the requirements of low cost ,general easy availability, easy handling and safety.
- The cooling characteristics change more than oil with the rise of temperature, specially there is a rapid fall in cooling capacity as the temperature rises above 60°C, because of easy formation of vapour-blanket.
- The optimum cooling pover is when water is 2O-4O°C.
- Thc cooling power of water is between brine and oils.
- Water provides high cooling power to avoid the transformation of austenite to pearlite/bainite, but the major draw back is that it also provides high cooling rate in the the temperature range of martensite formation.
- At this stage, the steel is simultaneously under the influence of structural stresses (non-uniform change in structure) and thermal stresses which increase the risk of crack formation.

BRINE

- Sodium chloride aqueous solutions of about 10% by weight are widely used and are called brines.
- The cooling power is between 10% NaOH aqueous solution and water.
- These are corrosive to appliances.
- The greater cooling efficiency of brines, or other aqueous solutions is based as :
- In brine heating of the solution at the steel surface causes the deposition of crystal of the salt on hot steel surface .
- This layer of solid crystals disrupts with mild explosive violence, und throws off a cloud of crystals. This action destroys the vapour-film from the surface, and thus permits direct contact of the coolant with the steel surface with an accompanying rapid removal of heat.
- Brines are used where cooling rates faster than water arc requited.

OILS

- Oils have cooling power between water at 40°C to water at 90°C.
- In oil-quench, considerable variation can be obtained by the use of animal, vegetable, or mineral oil, or their blends.
- Oils should be used at 50- 80°C when these are more fluid, i.e less VISCOUS, which increases the cooling power.
- As the oils used generally have high boiling points, moderate increase of temperature of oil does not very much increase the vapour blanket stage. However, oils in contrast to water, or brine, have much lower quenching power .
- Its this relatively slow cooling rate in the range of martensitic formation is atlvantageous as it helps in minimsing the danger to crack formation.
- Oils with high viscosity are less volatile, and thus have decreased vapour-blanket stage (increase thecooling rate). As lesser volatile matter is lost, their cooling power is not affected much with use.

POLYMER QUENCHANTS

- polymer quenchants cool rapidly the heated steel to Ms temperature, and then rather slowly when martensite is forming .
- Polymer quenchants are water-soluble organic chemicals of high ,molecular weights, and are generally polyalkylene glycol-based, or polyvinyl pyrolidene-based.
- Widely different cooling rates can be obtained by varying the concentration of Organic additives in water; higher the additions, slower is the cooling rate of solution.
- There are little dangers of distortions and cracks.

SALT BATHS

- It is an ideal quenching medium for a steel of not very large section but with good hardenabilty.
- Addition of O.3-O.5’% water almost doubles the cooling capacity. Normally holding time is 2-4 minutes/cm of section thickness.
- Salt baths used for austenitising keep the steel clean.

TEMPERING

- Tempering (formerly called drawing), consists of reheating a quenched steel to a suitable temperature below the transformation temperature for an appropriate time and cooling back to room temperature. Freshly quenched marten site is hard but not ductile. Tempering is needed to impart ductility to marten site usually at a small sacrifice in strength.
- The effect of tempering may be illustrated as follows. If the head of a hammer were quenched to a fully martensitic structure, it probably would crack after the first few blows. Tempering during manufacture of the hammer imparts shock resistance with only a slight decrease in hardness. Tempering is accomplished by heating a quenched part to some point below the transformation temperature, and holding it at this temperature for an hour or more, depending on its size.
- The micro structural changes accompanying tempering include loss of acicular marten site pattern and the precipitation of tiny carbide particles. This micro structural is referred to as tempered marten site.

SELF LEARNING QUESTIONS

1. What is Carbonitriding? Explain in detail
2. What is cyaniding? Explain in detail
3. What is austempering and martempering? Explain in detail

ASSIGNMENT EXERCISES

1. Explain full annealing and stress relieve annealing.
2. Explain difference between annealing and normalizing.
3. What is heat treatment? List the purpose of heat treatment.
4. What is hardening? Why tempering is done after hardening?
5. What is surface hardening process? Explain
6. What is Gas carburizing? Explain in detail
7. What is Flame hardening? Explain in detail
8. What is Induction hardening? Explain in detail
9. What is Nitriding? Explain in detail

THANK YOU

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MATERIALS ENGINEERING (R18A0305)

2nd Year B. Tech I- sem, Mechanical Engineering

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COURSE OBJECTIVES

UNIT - 1	**CO1:** To understand various mechanical properties of materials.
UNIT - 2	CO2: To understand how and why the properties of materials are controlled by its structure at the microscopic and macroscopic levels.
UNIT - 3	CO3: To understand how and why the structure and composition of a material may be controlled by processing.
UNIT - 4	CO4: To create different types of composite materials and its applications.
UNIT - 5	CO5: To remember polymer material classifications and applications.

UNIT IV

CERAMIC MATERIALS
&
COMPOSITES MATERIALS:

CO4: To create different types of composite materials and its applications.

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UNIT – IV (SYLLABUS)

Ceramic Materials:

Introduction to Ceramics, Advanced Ceramic Materials - Crystal Structures –Silicate ceramics, glass and its manufacturing process, Functional properties and applications of ceramic materials.

Composite Materials:

Introduction,Classification of composites - Fiber reinforced materials – Law of mixtures – Continuous fibers – discontinuous fibers – Particle-reinforced materials – Cermets – Dispersion strengthened materials – Laminates - Application of composites in electrical and mechanical components

WHAT CERAMIC MATERIAL

- Inorganic, nonmetallic materials that consist of metallic and nonmetallic elements bonded together primarily by ionic and/ or covalent bonds
- Its chemical compositions vary considerably, from simple compounds to mixtures of many complex phases bonded together.
- Ceramics used for engineering applications, can be divided
- into two groups: 1) Traditional ceramic materials
  - 2) Advanced ceramic materials
- Typically hard and brittle with low toughness and ductility
- Usually good electrical and thermal insulators
- Normally have relatively high melting temperatures and high chemical stability in many hostile environment

HISTROY OF CERAMIC

26,000 B.C.

Early man discovers that clay, consisting of mammoth fat and bone mixed with bone ash and local loess, can be molded and dried in the sun to form a brittle, heat-resistant material. Thus begins **ceramic** art.

6,000 B.C.

Ceramic **firing** is first used in Ancient Greece. The Greek pottery *Pithoi* is developed and used for storage, burial, and art.

4,000 B.C.

Glass is discovered in ancient Egypt. This primitive glass consisted of a silicate glaze over a sintered quartz body and was primarily used for jewelry. The use of ceramic coating continues today in many things from bathtubs to tailpipes of jet aircraft.

50 B.C. - 50 A.D.

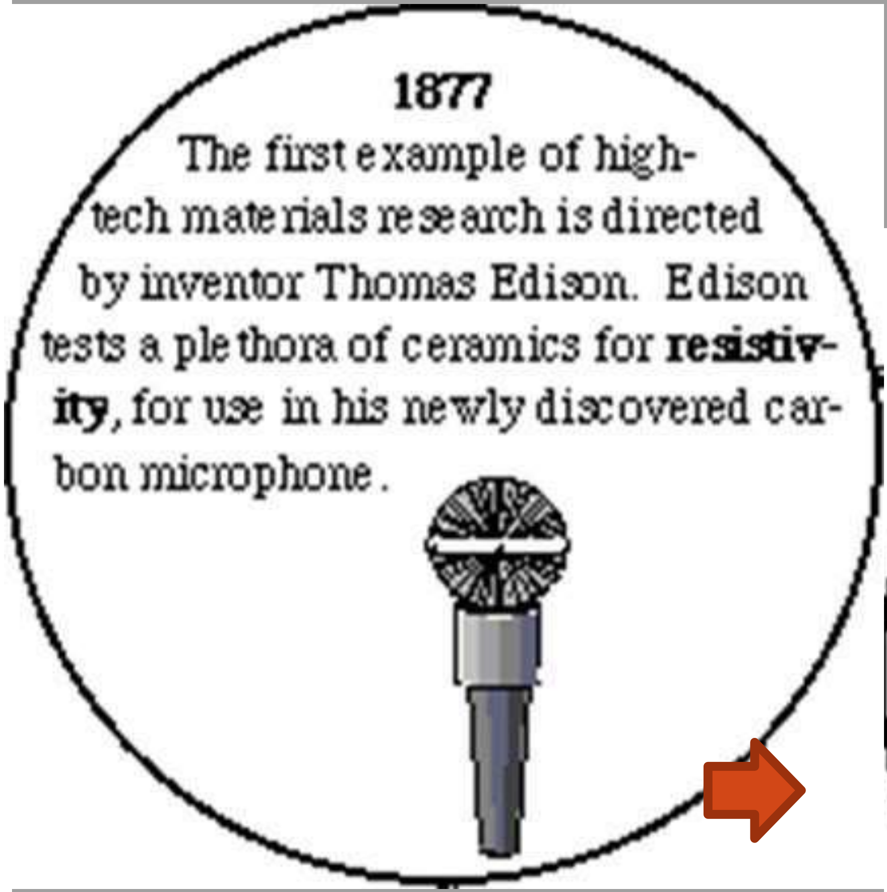
Optical **glass** (lenses and mirrors), window **glass** and **glass** blowing production begins in Rome and spreads around the world with the Roman empire.

600 A.D.

Porcelain, the first ceramic composite, is created by the Chinese. This durable material is made by firing clay along with feldspar and quartz. Porcelain is used in everything from electrical insulators, to dinnerware.

1870's

Refractory materials (able to withstand extremely high temperatures) are introduced during the Industrial revolution. Materials made from lime and MgO are used for everything from bricks for buildings to lining the inside of steel making furnaces.



1877

The first example of high-tech materials research is directed by inventor Thomas Edison. Edison tests a plethora of ceramics for **resistivity**, for use in his newly discovered carbon microphone.

1889

The American Ceramic Society was founded by Elmer E. Gorton, Samuel Geijsbeek and Colonel Edward Orton Jr.. The primary goal of this society continues to be unlocking the mysteries of high-tech ceramics.

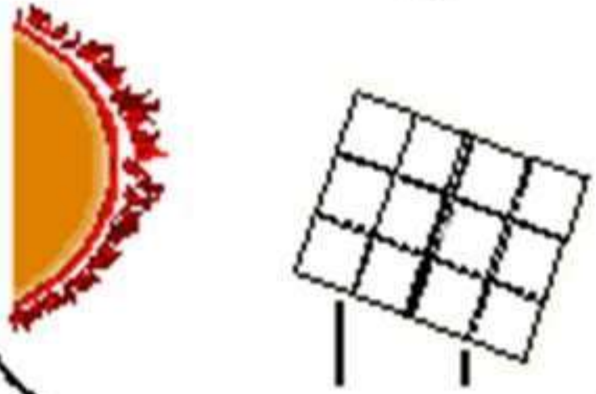
American Ceramic Society
735 Ceramic Place
Westerville, Ohio 43081-8720
614-890-4700

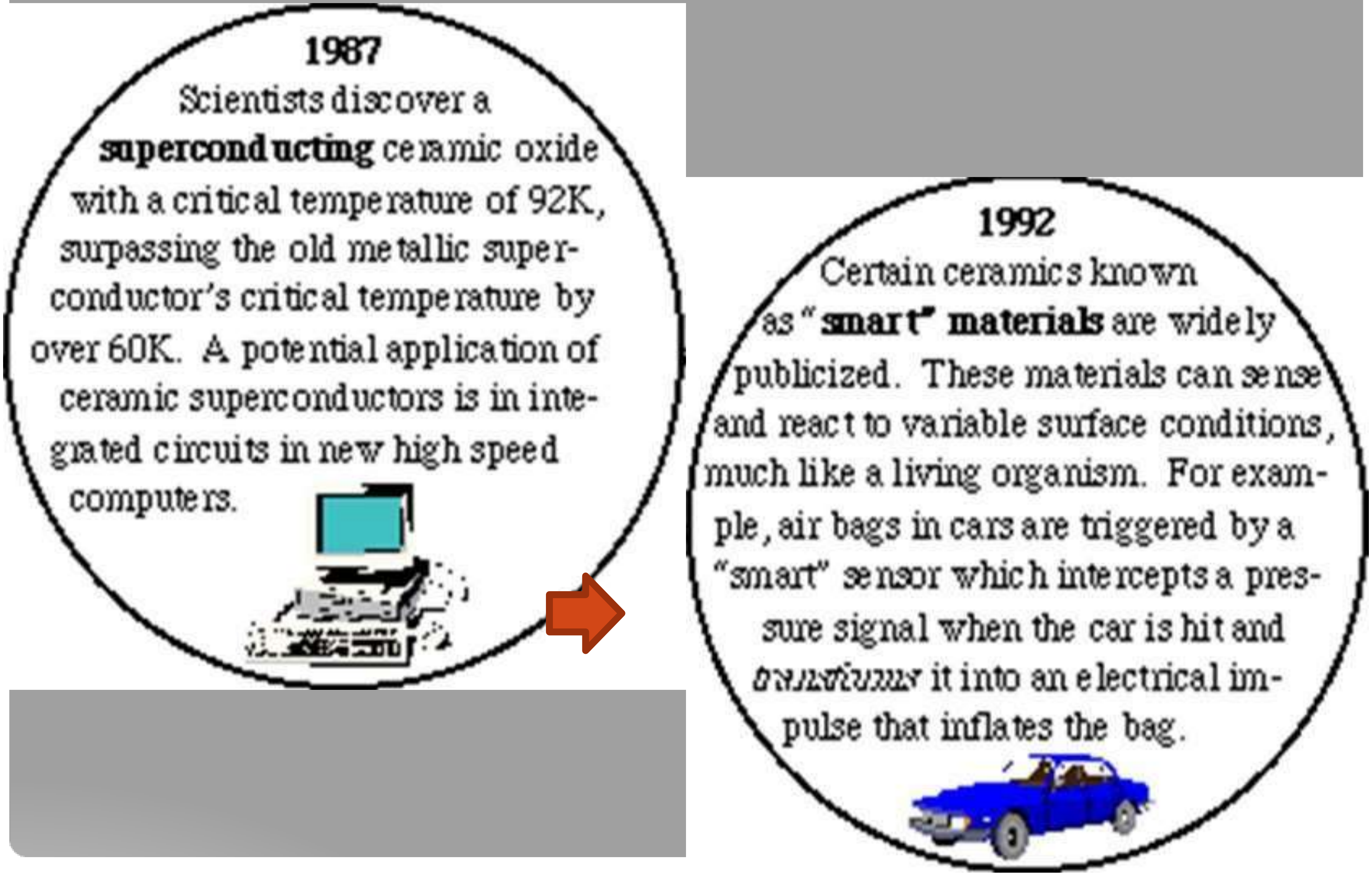
1960

With the discovery of the laser and the observation that its light will travel through glass, a new field called **fiber optics** opens. Fiber optic cable allows light pulses to carry large amounts of information with extremely low energy loss.

1965

The development of **photo-voltaic cells** which convert light into electricity opens a new way to access solar energy.





1987

Scientists discover a **superconducting** ceramic oxide with a critical temperature of 92K, surpassing the old metallic superconductor's critical temperature by over 60K. A potential application of ceramic superconductors is in integrated circuits in new high speed computers.

1992

Certain ceramics known as "**smart" materials** are widely publicized. These materials can sense and react to variable surface conditions, much like a living organism. For example, air bags in cars are triggered by a "smart" sensor which intercepts a pressure signal when the car is hit and transforms it into an electrical impulse that inflates the bag.

CERAMIC CRYSTAL STRUCTURE

- Broader range on chemical composition than metals with more complicated structures
- contains at least 2 and often 3 or more atoms
- usually compounds between metallic ions (e.g. Fe, NI, Al) -called cations - and non-metallic ions (e.g. O, N, Cl) -called anions
- Bonding will usually have some covalent character but is usually mostly ionic

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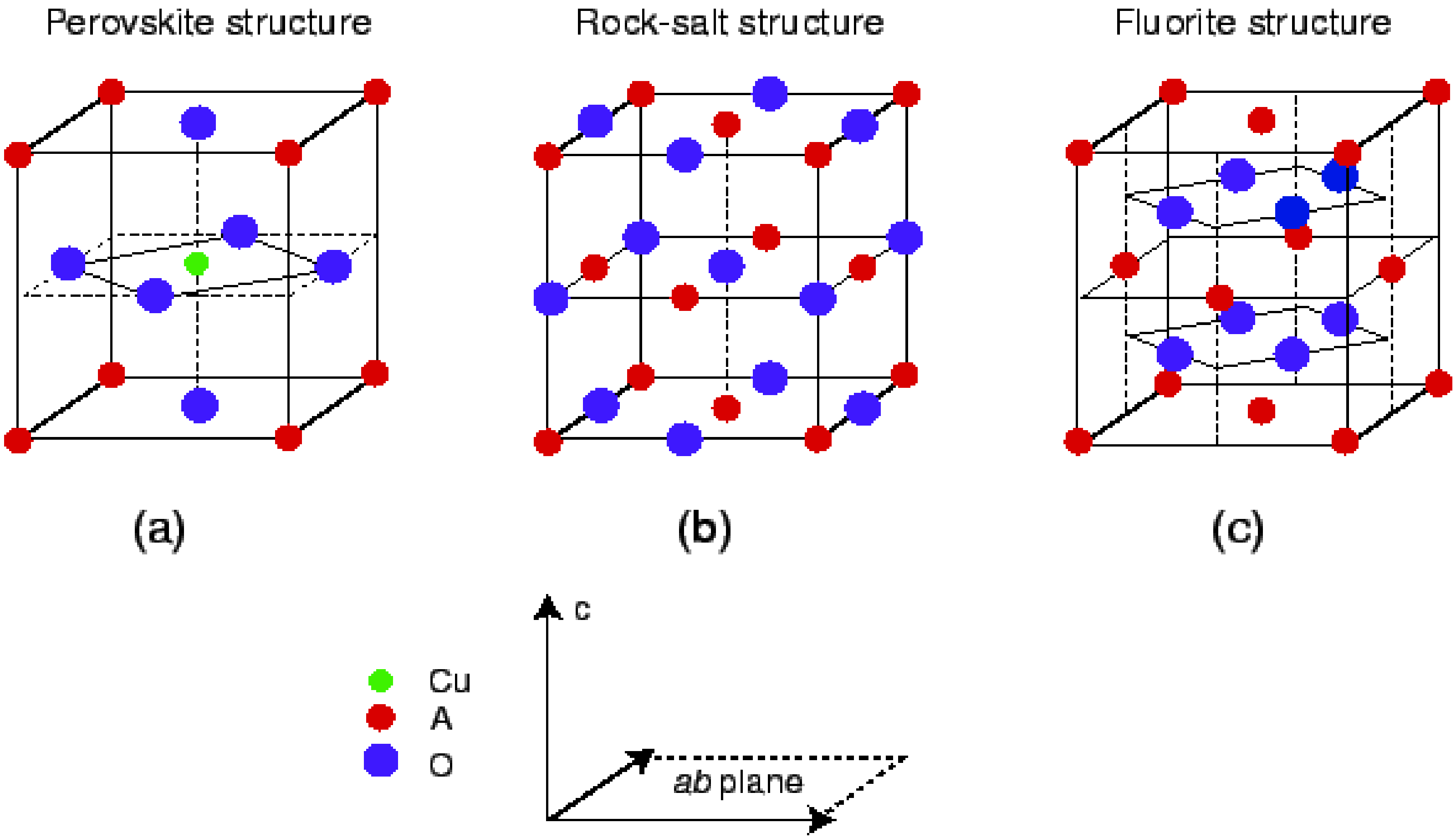
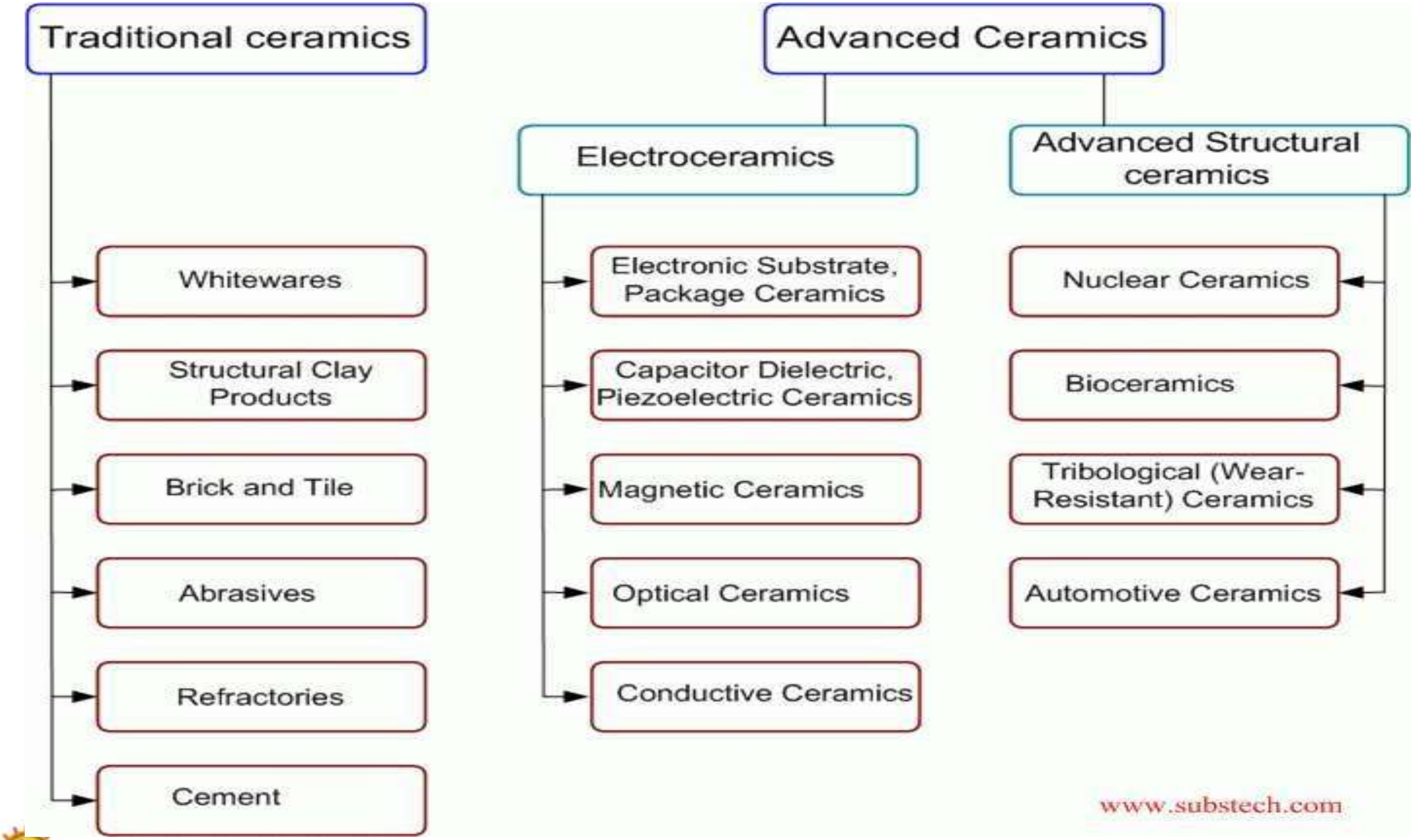
Example Ceramic Crystal Structure



*Classification of Ceramics based on APPLICATION



Traditional ceramics

- Whitewares
- Structural Clay Products
- Brick and Tile
- Abrasives
- Refractories
- Cement

Advanced Ceramics

- Electroceramics
  - Electronic Substrate, Package Ceramics
  - Capacitor Dielectric, Piezoelectric Ceramics
  - Magnetic Ceramics
  - Optical Ceramics
  - Conductive Ceramics
- Advanced Structural ceramics
  - Nuclear Ceramics
  - Bioceramics
  - Tribological (Wear-Resistant) Ceramics
  - Automotive Ceramics

www.substech.com

Traditional Ceramics

- Made from three basic components: clay, silica (flint), and feldspar.
  - The ***clay*** in traditional ceramics provides workability of the material before firing hardens it and constitutes the major body material.
  - The ***silica*** has a high melting temperature and is the refractory component of traditional ceramics.
  - ***Potash feldspar***, has a low melting temperature and makes a glass when the ceramic mix is fired. It bonds the refractory components together.
- A type of ceramic used in traditional applications such as construction, earthenware, and glassware.

WHITEWARES

- Made from components of clay, silica, and feldspar for which the composition is controlled.

Example:

  - Electrical porcelain
  - Dinner china
  - Sanitary ware

Whitewares

Electrical porcelain

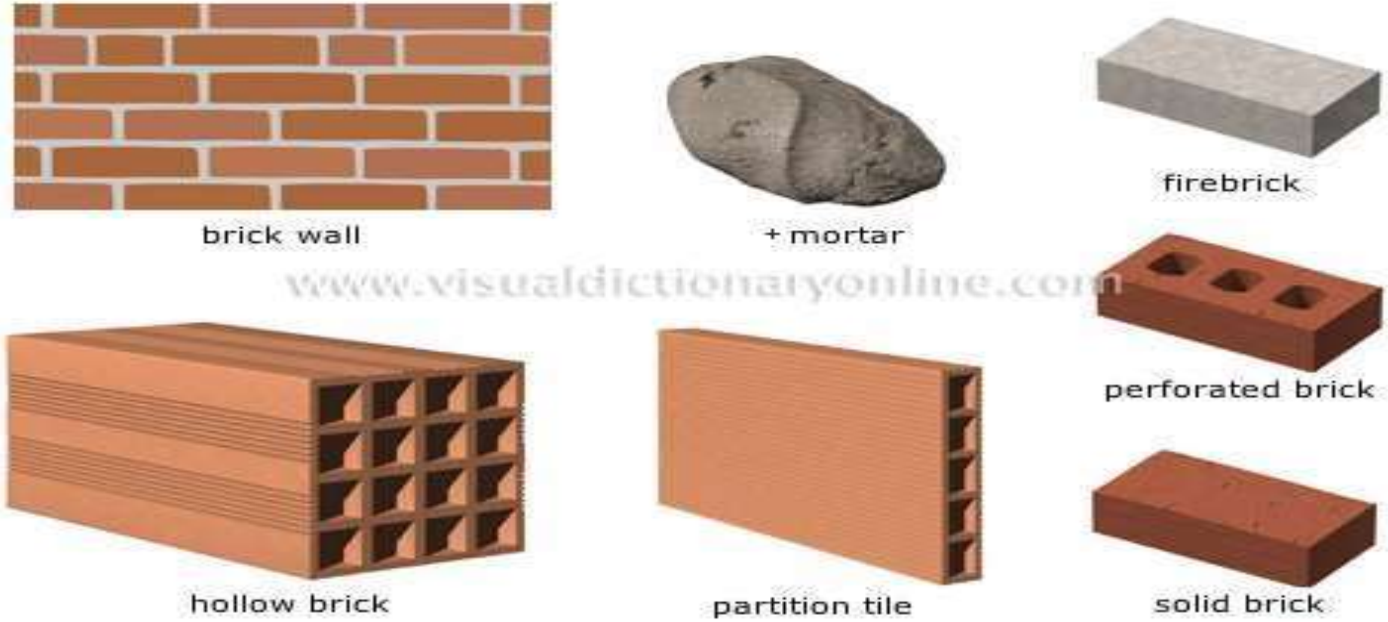
Structural Clay Products

- Made of natural clay, which contains all three basic components.

Example:

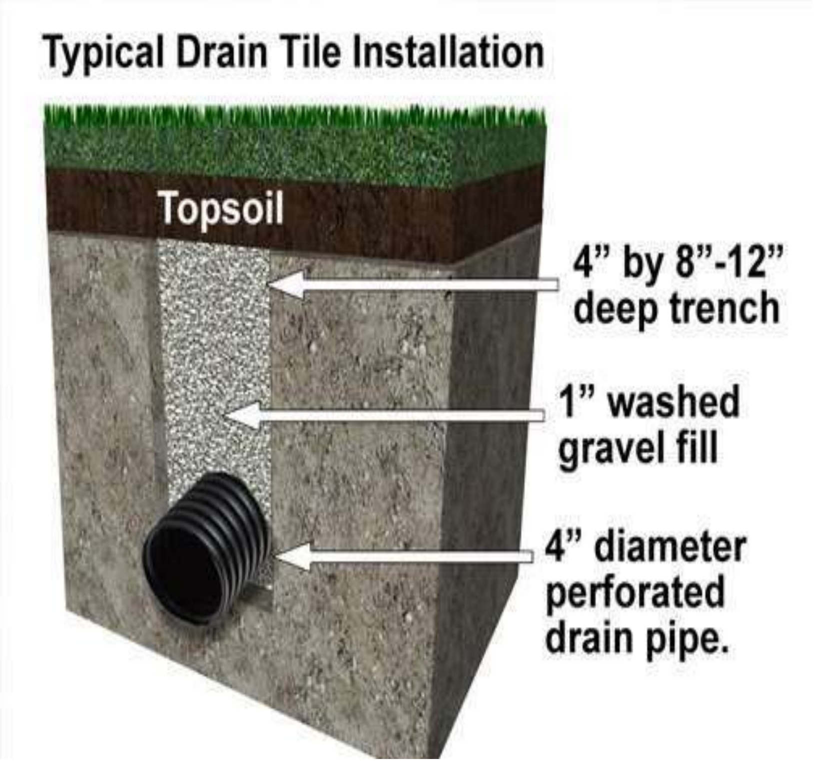
  - Building brick
  - Sewer pipe
  - Drain tile
  - Roofing tile
  - Floor tile

Structural Clay Products



Structural Clay Products

Structural Clay Products



Structural Clay Products

Structural Clay Products

Brick and Tile

- structural clay products, manufactured as standard units, used in building construction
- is a small building unit in the form of a rectangular block, formed from clay or shale or mixtures and burned (fired) in a kiln, or oven, to produce strength, hardness, and heat resistance

Brick and Tile

Abrasives

- is a material, often a mineral, that is used to shape or finish a workpiece through rubbing which leads to part of the workpiece being worn away
- a material often means polishing it to gain a smooth, reflective surface which can also involve roughening as in satin, matte or beaded finishes

Abrasives

Refractories

- is one that retains its strength at high temperature

Example:

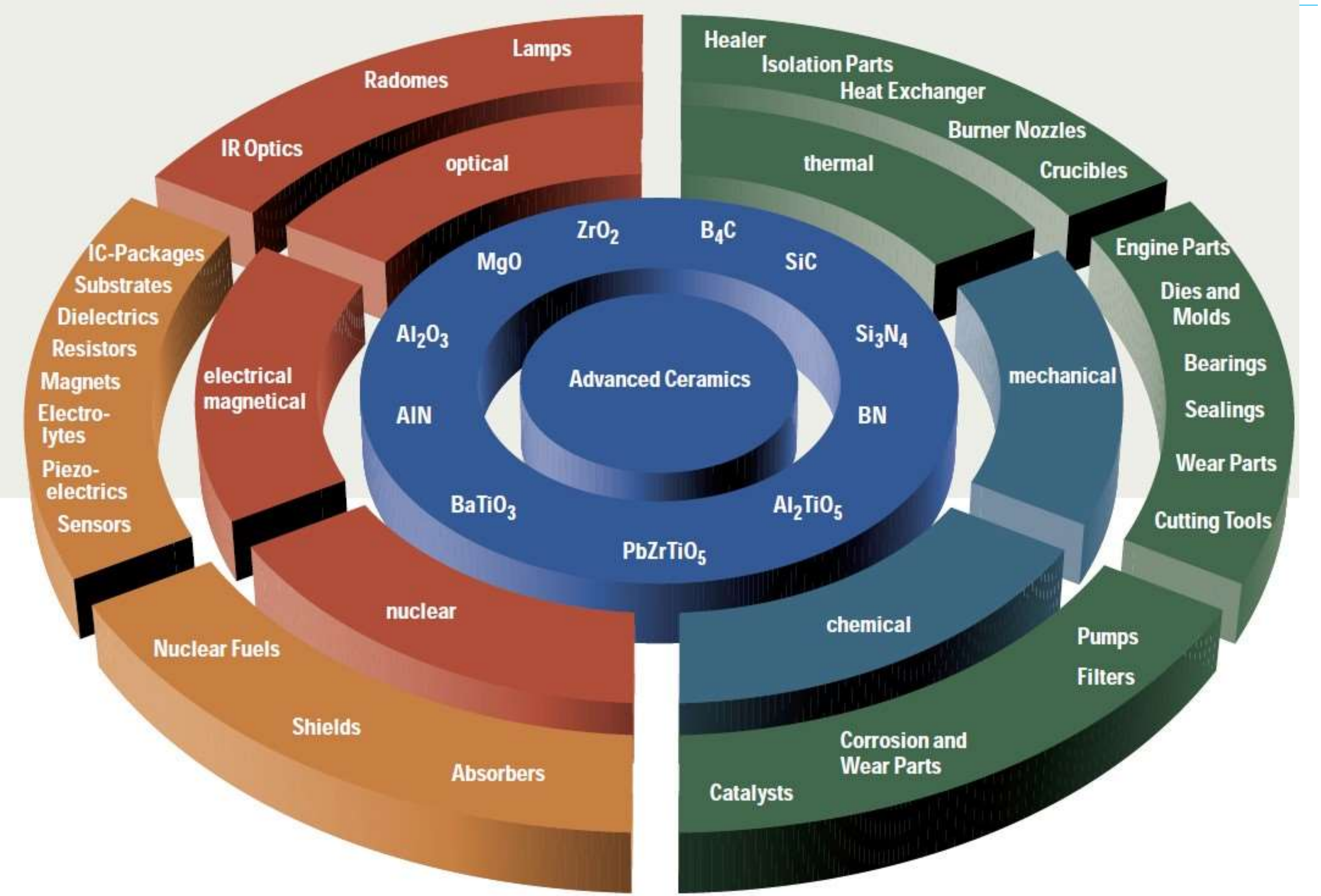
- kiln linings
- gas fire radiants
- steel
- glass making crucibles

Refractories

Advanced Ceramics

- Advanced ceramics are ideally suited for industrial applications that provide a physical interface between different components due to their ability to withstand high temperatures, vibration and mechanical shock.
- A type of ceramic exhibiting a high degree of industrial efficiency.
- A type of ceramic used in specialized, recently developed applications.
- Advanced ceramics often have simple chemical compositions, but they are difficult to manufacture.

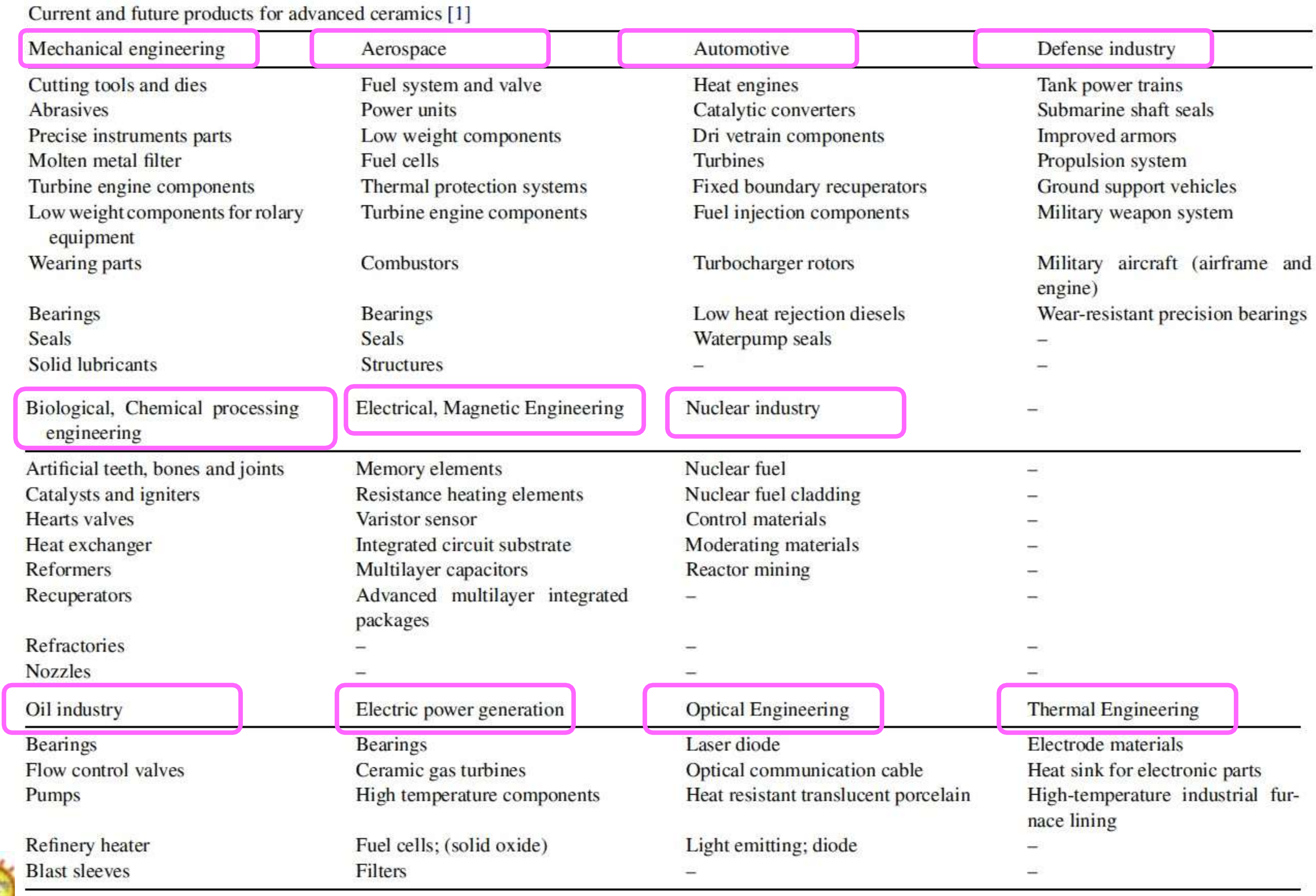
ADVANCED CERAMICS: APPLICATIONS



ADVANCED CERAMICS: APPLICATIONS

Application	Property	Material
Cutting tools	Hardness, toughness	Alumina, SiAlON
Bearing, liners, seals	Wear resistance	Alumina, zirconia
Agricultural machinery	Heat	Alumina, zirconia
Engine and turbine parts	Hardness,	SiC, Alumina, Si_3N_4
Shielding, armour	toughness	Alumina, B_4C
High performance windows	Translucence	Alumina, Magnesia
Artificial bones, teeth	strength	Zirconia, Alumina

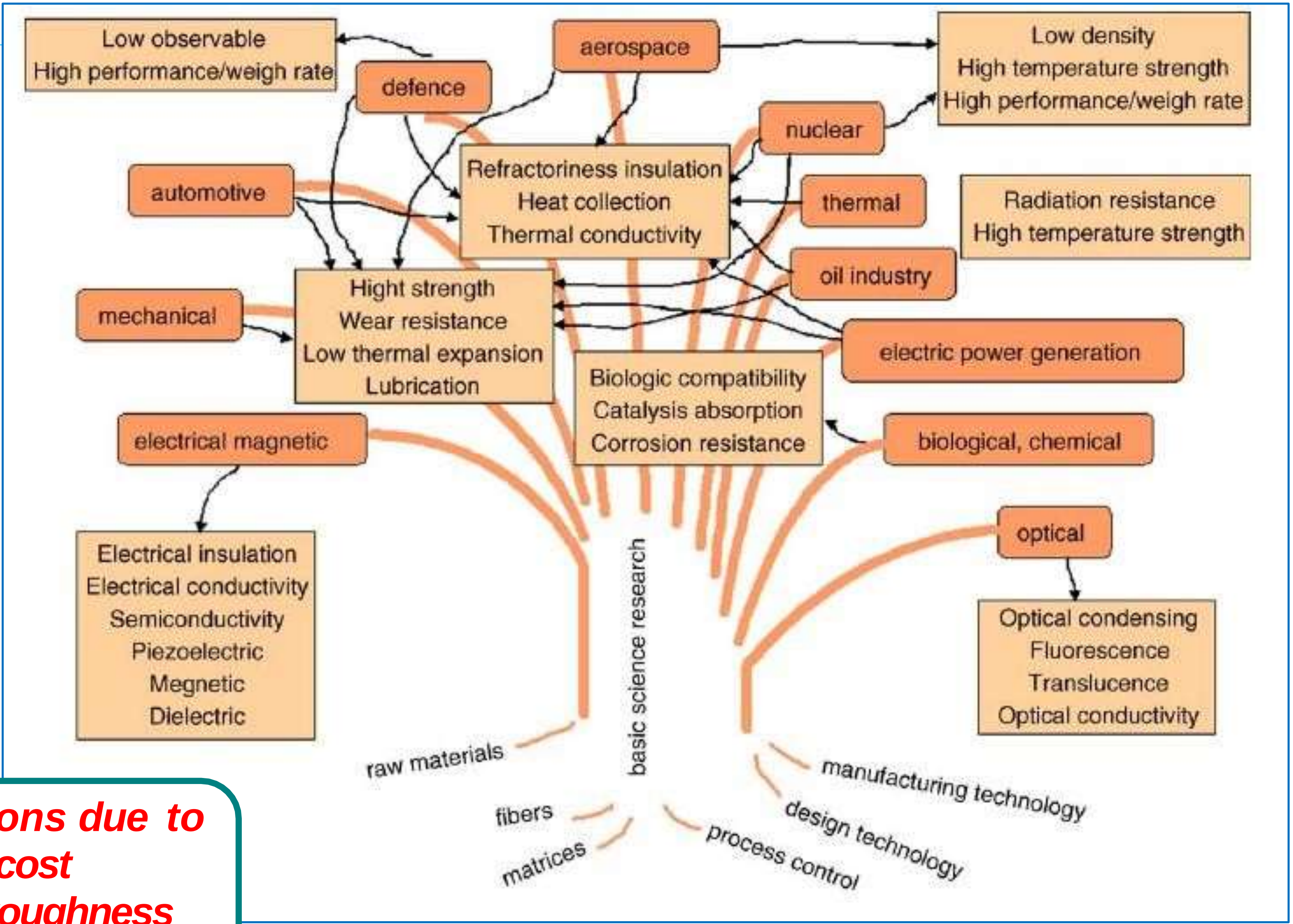
ADVANCED CERAMICS: APPLICATIONS



Current and future products for advanced ceramics [1]

Mechanical engineering	Aerospace	Automotive	Defense industry
Cutting tools and dies	Fuel system and valve	Heat engines	Tank power trains
Abrasives	Power units	Catalytic converters	Submarine shaft seals
Precise instruments parts	Low weight components	Drivetrain components	Improved armors
Molten metal filter	Fuel cells	Turbines	Propulsion system
Turbine engine components	Thermal protection systems	Fixed boundary recuperators	Ground support vehicles
Low weight components for rolary equipment	Turbine engine components	Fuel injection components	Military weapon system
Wearing parts	Combustors	Turbocharger rotors	Military aircraft (airframe and engine)
Bearings	Bearings	Low heat rejection diesels	Wear-resistant precision bearings
Seals	Seals	Waterpump seals	–
Solid lubricants	Structures	–	–
Biological, Chemical processing engineering	**Electrical, Magnetic Engineering**	**Nuclear industry**	–
Artificial teeth, bones and joints	Memory elements	Nuclear fuel	–
Catalysts and igniters	Resistance heating elements	Nuclear fuel cladding	–
Hearts valves	Varistor sensor	Control materials	–
Heat exchanger	Integrated circuit substrate	Moderating materials	–
Reformers	Multilayer capacitors	Reactor mining	–
Recuperators	Advanced multilayer integrated packages	–	–
Refractories	–	–	–
Nozzles	–	–	–
Oil industry	**Electric power generation**	**Optical Engineering**	**Thermal Engineering**
Bearings	Bearings	Laser diode	Electrode materials
Flow control valves	Ceramic gas turbines	Optical communication cable	Heat sink for electronic parts
Pumps	High temperature components	Heat resistant translucent porcelain	High-temperature industrial furnace lining
Refinery heater	Fuel cells; (solid oxide)	Light emitting; diode	–
Blast sleeves	Filters	–	–

ADVANCED CERAMICS: APPLICATIONS



Limitations due to
- **High cost**
- **Low toughness**
- **Low reliability**

M. Rosso, Ceramic and metal matrix composites: Routes and properties, Journal of Materials Processing Technology 175 (2006) 364–375

➢ Optical Ceramics

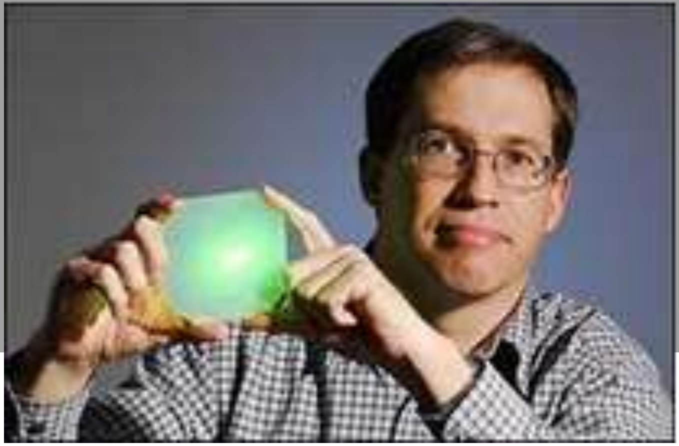
- are polycrystalline materials produced through controlled crystallization of base glass.
- Glass-ceramic materials share many properties with both glasses and ceramics.
- Glass-ceramics have an amorphous phase and one or more crystalline phases and are produced by a so-called "controlled crystallization" in contrast to a spontaneous crystallization, which is usually not wanted in glass manufacturing.
- Glass-ceramics have the fabrication advantage of glass as well as special properties of ceramics.
- Glass ceramics has a variety of properties such as, high strength, toughness, translucency or opacity, opalescence, low or even negative thermal expansion, high temperature stability.

➢ Optical Ceramics

Watch Glasses

Optical Glass Lenses

High-pressure sodium-vapour lamp bulb



Advance Structural Ceramics

- ceramic materials that demonstrate enhanced mechanical properties under demanding conditions. Because they serve as structural members, often being subjected to mechanical loading, they are given the name structural ceramics. Ordinarily, for structural applications ceramics tend to be expensive replacements for other materials, such as metals, polymers, and composites.

Amorphous Ceramics: Glasses

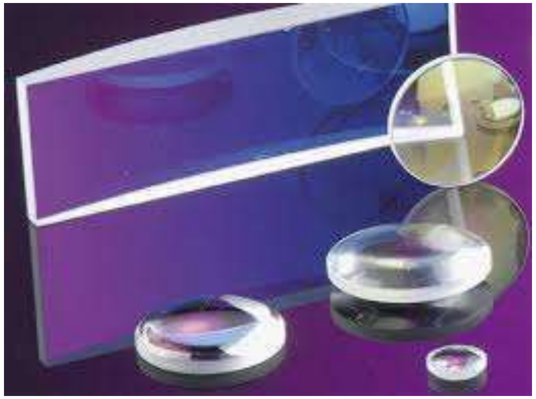
- a ceramic material which is an inorganic product of fusion that has cooled to a rigid condition without crystallization
- has a noncrystalline or amorphous structure
- The molecules in a glass change their orientation in a random manner throughout the solid material.

*Types of Glasses based on Composition

- **Fused silica glass, vitreous silica glass**
  - silica (SiO_2). Has very low thermal expansion, is very hard and resists high temperatures (1000–1500 °C). It is also the most resistant against weathering (alkali ions leaching out of the glass, while staining it). It is used for high temperature applications such as furnace tubes, melting crucibles, etc.
  - the most important singe-component glass, has a high spectral transmission and is not subject to radiation damage, which cause browning of other glasses
  - ideal glass for space vehicle windows, wind tunnel windows, and optical system in spectrophometric devices
  - difficult to process and expensive

Fused silica glass, vitreous silica glass

Optical Lenses



Mirror Substrates

Space Vehicle Glass Windows

Crucibles, trays and boats

*Types of Glasses based on Composition

- **Soda-lime-silica glass, window glass**:
  - silica 72% + sodium oxide (Na_2O) 14.2% + magnesia (MgO) 2.5% + lime (CaO) 10.0% + alumina (Al_2O_3) 0.6%. Is transparent, easily formed and most suitable for window glass. It has a high thermal expansion and poor resistance to heat (500–600 °C).
  - Used for flat glass, containers, pressed and blown ware, and lighting products where high chemical durability and heat resistant are not needed.

*Types of Glasses based on Composition

- **Aluminosilicate glass**
    - A small, but important type of glass, aluminosilicate, contains 20% aluminium oxide (alumina-Al_2O_3) often including calcium oxide, magnesium oxide and boric oxide in relatively small amounts, but with only very small amounts of soda or potash.
    - It is able to withstand high temperatures and thermal shock and is typically used in combustion tubes, gauge glasses for high-pressure steam boilers, and in halogen-tungsten lamps capable of operating at temperature as high as 750°C.

*Types of Glasses based on Composition

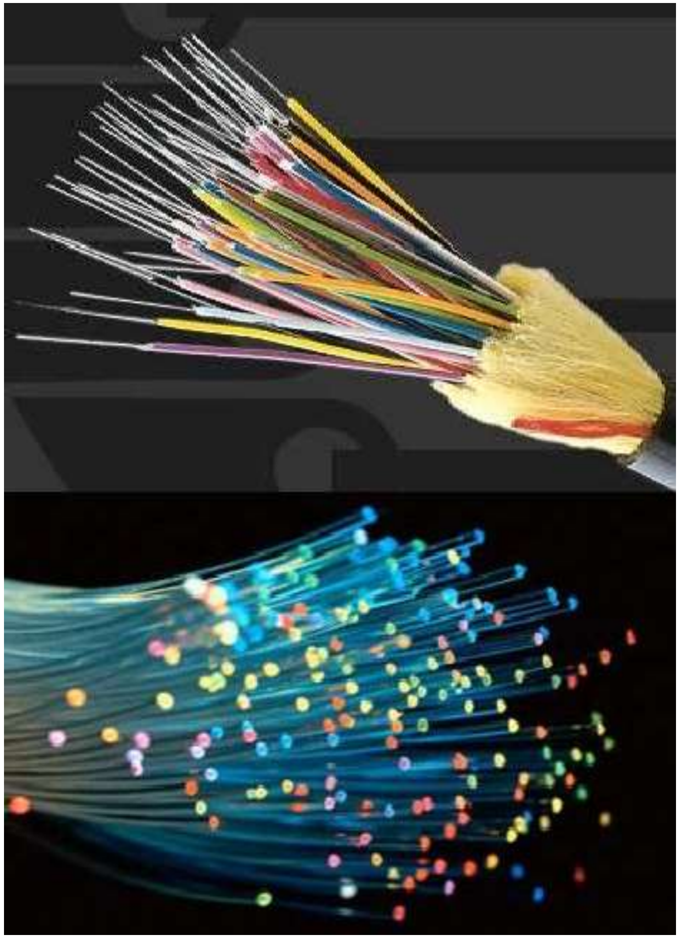
Halogen-Tungsten Lamps

Boiler Gauge Glass

Iphone's Aluminosilicate Sheet Glass

*Types of Glasses based on Composition

- **Oxide glass**
  - alumina 90% + germanium oxide (GeO_2) 10%. Extremely clear glass, used for fiber-optic wave guides in communication networks. Light loses only 5% of its intensity through 1 km of glass fiber.



Fiber-Optic Waveguides

PROCESSING OF CERAMICS

Most traditional and engineering ceramic products are manufacture by compacting powders or particles into shapes that are subsequently heated to a high enough temperature to bond the particles together.

- The 3 basic steps in the processing of ceramics by the agglomeration of particles are:
  1. Material Preparation
  2. Forming and Casting
  3. Thermal treatment by **drying** and **firing**

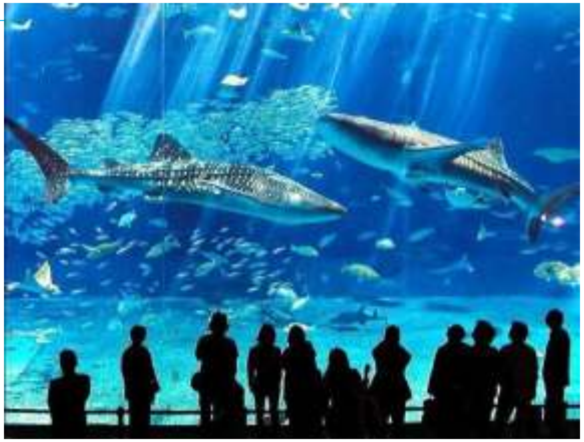
SPECIAL GLASS PRODUCTS

Laminated Glass

Laminated glass is widely used for

- bullet proof
- burglar-proof
- showcase
- counter
- aquarium
- skylight
- long corridor
- sidelite, etc.

http://www.livingetc.com
Glass staircase



www.aarticommercial.com
Laminated Windscreen Glass

If the laminated glass is made from "ordinary" float glass, it is still workable (cutting and drilling is possible) and the PVB helps the fractured glass to stay put inside the construction.

SPECIAL GLASS PRODUCTS

Laminated Glass

BULLETPROOF GLASS

Bulletproof glass is made of laminated glasses and films which have special shielding capability towards bullets.

The different levels of bullet proof glasses are able to shield the bullets from penetration and prevent the broken parts from injuring people. They are widely applied in bank, counters of jewelry and gold shops, cash trucks and other regions requiring special safety prevention.

www.bmw-security-vehicles.com

22-millimetre glass/plastic laminate with a polycarbonate coating on the inside to prevent flying splinters. The 22-millimetre glass protects against:

➢

- Blunt instruments

➢.44 Magnum with full-jacket flat-nose bullets

➢ .357 Magnum with coned bullets

➢ 9-millimetre Luger with round-nose bullets

COMPOSITE MATERIALS

- A composite material is made by combining two or more materials

  -often ones that have very different properties.

- The two materials work together to give the composite unique properties.

- However, within the composite you can easily tell the different materials apart as they do not dissolve or blend into each other.

ADVANTAGES OF COMPOSITES

i. Light in weight

- ii. Ratios of Strength-to-weight and Stiffness-to-weight are greater than steel or aluminum.

- Fatigue properties are better than common engineering metals.

iii.

iv. Composites cannot corrode like steel.

v. Possible to achieve combinations of properties not attainable with metals, ceramics, or polymers alone.

vi. Toughness is improved.

vii. Fabrication or production is cheaper.

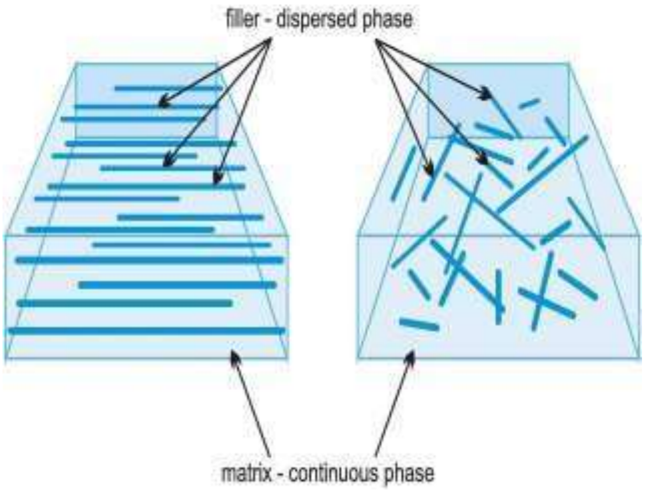
COMPOSITION OF COMPOSITES

- They generally have two phases:-

Matrix Phase :-

It is the continuous material constituent which encloses the composite and give it its bulk form.

Matrix phase may be metal , ceramic or polymer.

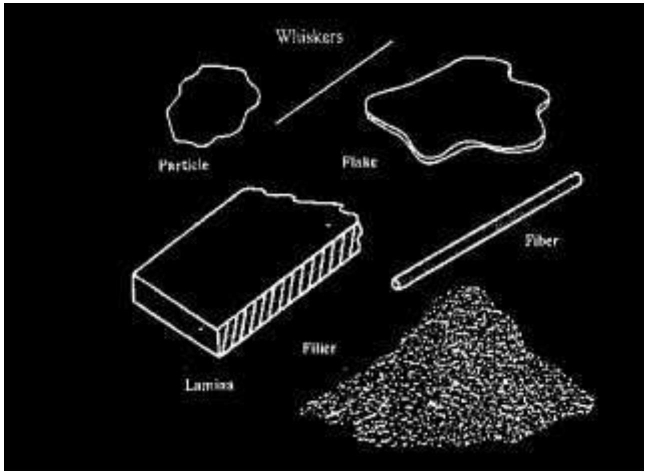


Dispersion Phase:-

It is the structure constituent , which determines the internal structure of composite.

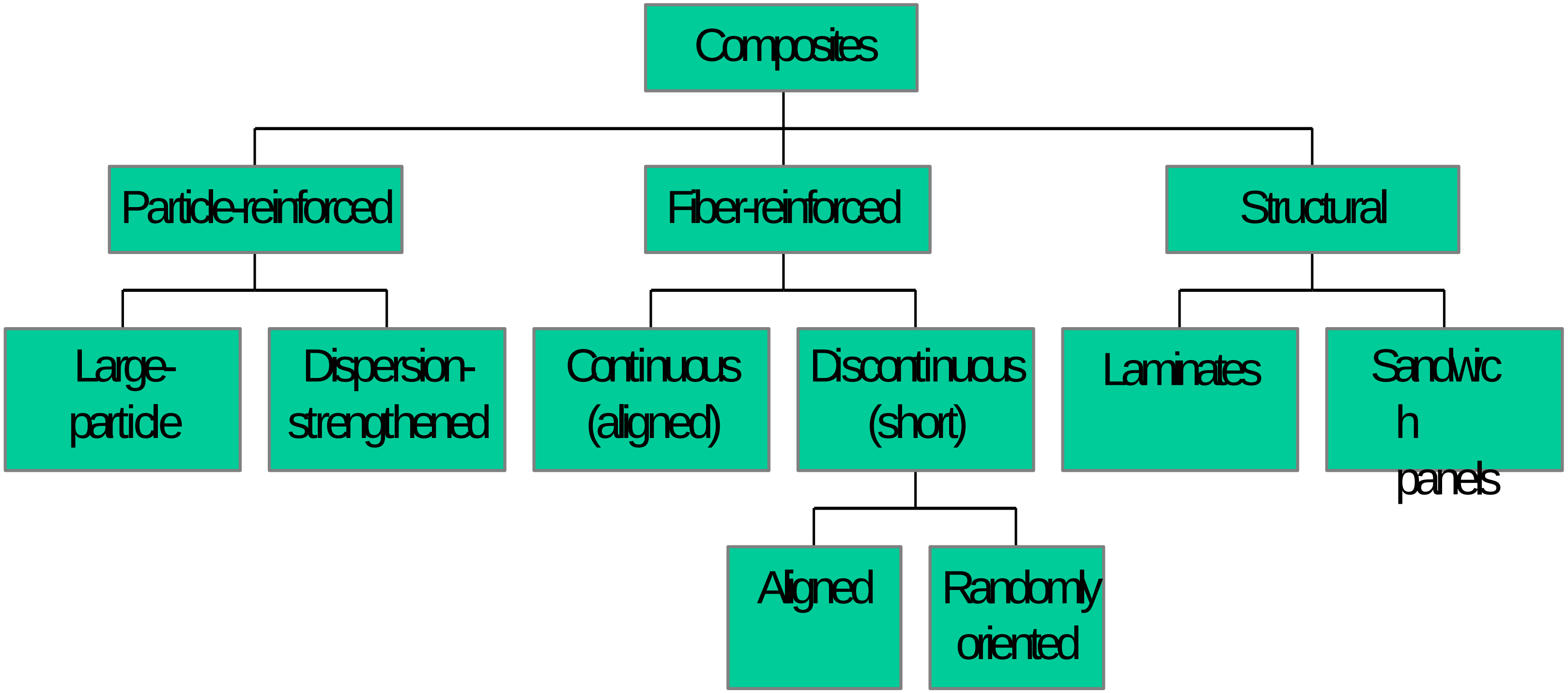
Also called ‘Reinforcement’.

- Fibers, particles, flakes, whiskers etc.



CLASSIFICATION OF COMPOSITES

Based on type of Reinforcement



- Composites
  - Particle-reinforced
    - Large-particle
    - Dispersion-strengthened
  - Fiber-reinforced
    - Continuous (aligned)
    - Discontinuous (short)
      - Aligned
      - Randomly oriented
  - Structural
    - Laminates
    - Sandwich panels

PARTICLE REINFORCED COMPOSITES

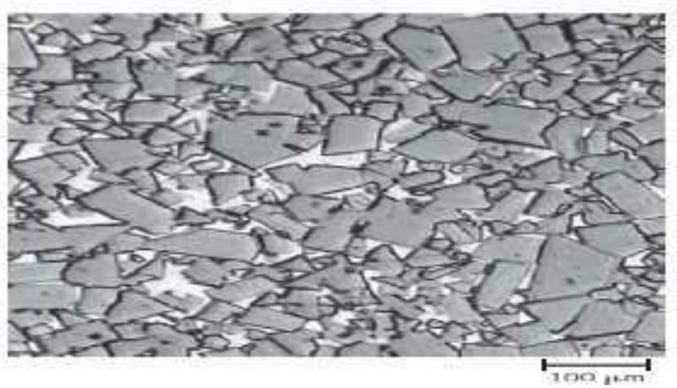
Particle composites consist of particles of one material dispersed in a matrix of a second material.

1) Large-particle composite

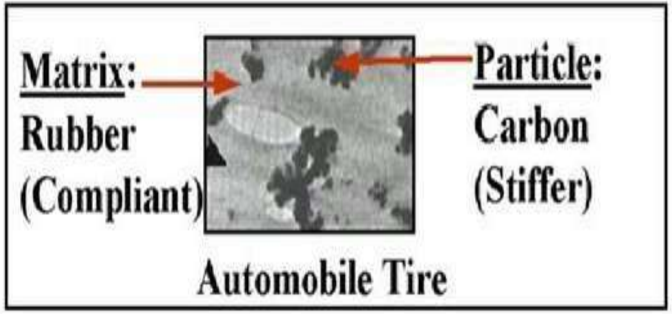
- Particle size is 1-50µm.
- **Concrete** and **Cermets** etc.

2) Dispersion strengthened composite

- Uniformly dispersed fine, hard and inert particles of size less than 0.1µm are used as reinforcement
- **SAP** , **TD-Nickel** etc.



WC–Co cemented carbide

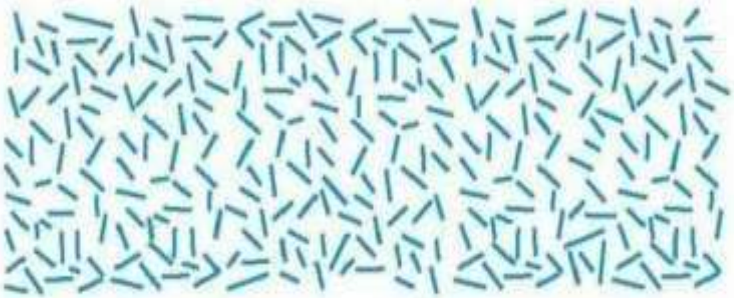


FIBER-REINFORCED COMPOSITES

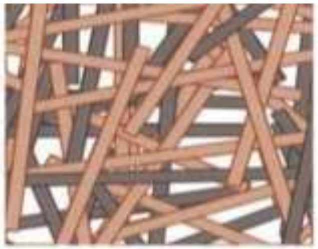
- Mechanical properties of FRC depend on
  - Fiber properties
  - Degree to which an applied load is transmitted to the fibers by the matrix phase: good interfacial bond between fiber and matrix is necessary
- Depending on the matrix material
  - Polymer matrix composites (PMC)
  - Metal matrix composites (MMC)
  - Ceramic matrix composites (CMC)

FIBER ALIGNMENT

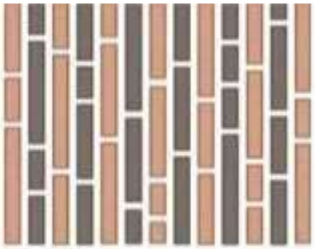
Aligned Fibers



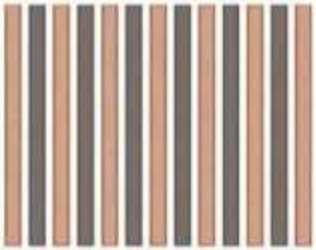
Random Fibers



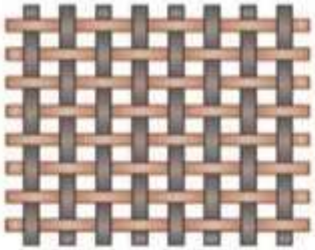
Discontinuous and randomly oriented



Discontinuous and aligned



Continuous and aligned



Fabric

Classification of Composites

Based on type of Matrix

1. *Metal Matrix Composites* (MMCs) - mixtures of ceramics and metals, such as cemented carbides and other cermets

2. *Ceramic Matrix Composites* (CMCs) - Al_2O_3 and SiC imbedded with fibers to improve properties, especially in high temperature applications

3. *Polymer Matrix Composites* (PMCs) - thermosetting resins are widely used in PMCs

POLYMER MATRIX COMPOSITES (PMCS)

- Consists of a polymer resin as the matrix
- Being used in the greatest diversity and largest quantities
- Glass fiber-reinforced polymer composites (GFRPs)
  - ❑ Produced in the largest quantities

Carbon fiber-reinforced polymer composites (CFRPs)

  - ❑ High performance composites

Aramid fiber-reinforced polymer composites (AFRPs)

  - ❑ High strength, high modulus & high impact resistance composites

METAL MATRIX COMPOSITES (MMCS)

- The matrix is more ductile than the reinforcements
- The reinforcement may improve specific strength/stiffness, abrasion resistance, creep resistance, thermal conductivity and dimensional stability of the overall composites
- Advantages over PMC
  - ❑ Higher operating temperatures
  - ❑ Non-flammability
  - ❑ Greater resistance to degradation by organic fluids
- Disadvantages
  - ❑ Expensive & higher density

APPLICATION

Fig: Partial short fibers reinforced light metal diesel pistons.

Fig: Cast brake disk particle of reinforced aluminum.

CERAMICS METAL COMPOSITES (CMCS)

- For use in high temperature and severe stress applications, e.g. automobile and aircraft gas turbine engines
- **Advantages**
  - ☐ High strength and modulus
  - ☐ Very high service temperature
  - ☐ Reduced weight (lower fuel consumption)
- **Disadvantages**
  - ☐ Very brittle

Turbine Blade

Cutting Tool Inserts

STRUCTURAL COMPOSITES

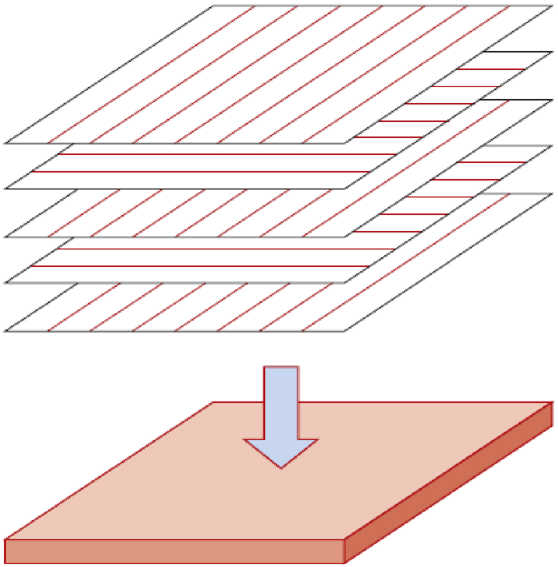
- A structural composite consists of both homogeneous and composite material. There properties depend on, the characteristic properties of the **constituent materials** as well as the **geometric design**.

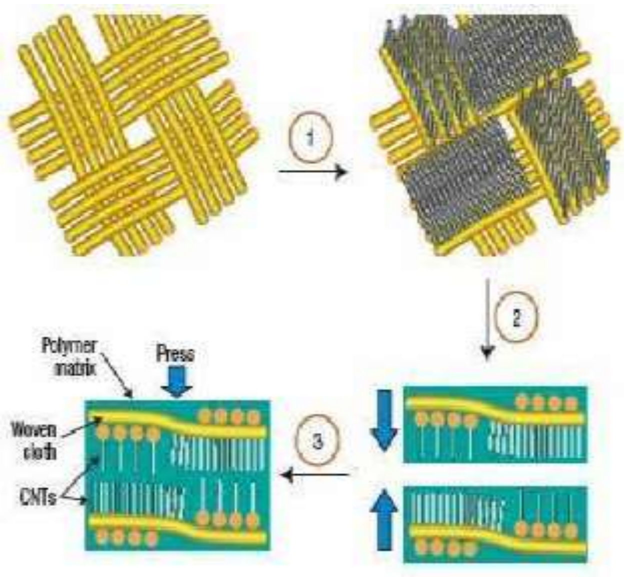
Structural composite are of two types:-

1) **Laminar composite**
2) **Sandwich Panel**

LAMINAR COMPOSITES

- It consists of panels or sheets which are two dimensional. These panels possess preferred directions to achieve high strength.
- Such successively oriented layers are stacked one above with preferred directions and then are cemented





SANDWICH PANELS

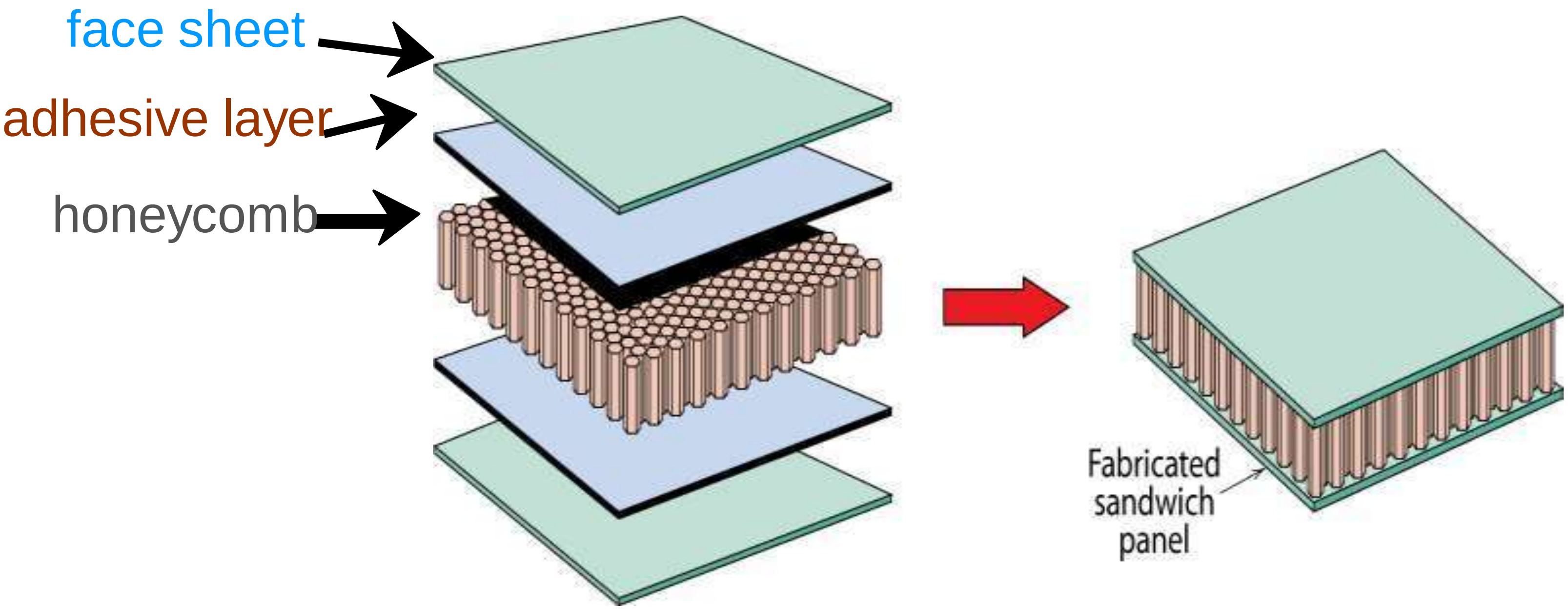
- Sandwich panels

  -- low density, honeycomb core

  -- benefit: light weight, large bending stiffness

- Core materials

  -- rigid polymeric, foams (epoxy, polyurethanes), wood (i.e., balsa wood) and honeycombs



APPLICATIONS OF COMPOSITE MATERIALS

1. In automobile industries (e.g. Steel &Aluminum body)
2. Marine applications like shafts, hulls, spars (for racing boats)
3. Aeronautical application like components of rockets, aircrafts (business and military),missiles
4. Communication antennae, electronic circuit boards (e.g. PCB, breadboard)

Safety equipment like ballistic protection and Air

MATERIALS ENGINEERING (R18A0305)

2nd Year B. Tech I- sem, Mechanical Engineering

LIVE TO LEARN & LEARN TO SHARE

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UGC Autonomous

www.mrcet.ac.in

COURSE OBJECTIVES

UNIT - 1	**CO1:** To understand various mechanical properties of materials.
UNIT - 2	CO2: To understand how and why the properties of materials are controlled by its structure at the microscopic and macroscopic levels.
UNIT - 3	CO3: To understand how and why the structure and composition of a material may be controlled by processing.
UNIT - 4	CO4: To create different types of composite materials and its applications.
UNIT - 5	CO5: To remember polymer material classifications and applications.

UNIT V

POLYMER MATERIALS

CO5: **To remember polymer material classifications and applications.**

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www.mrcet.ac.in

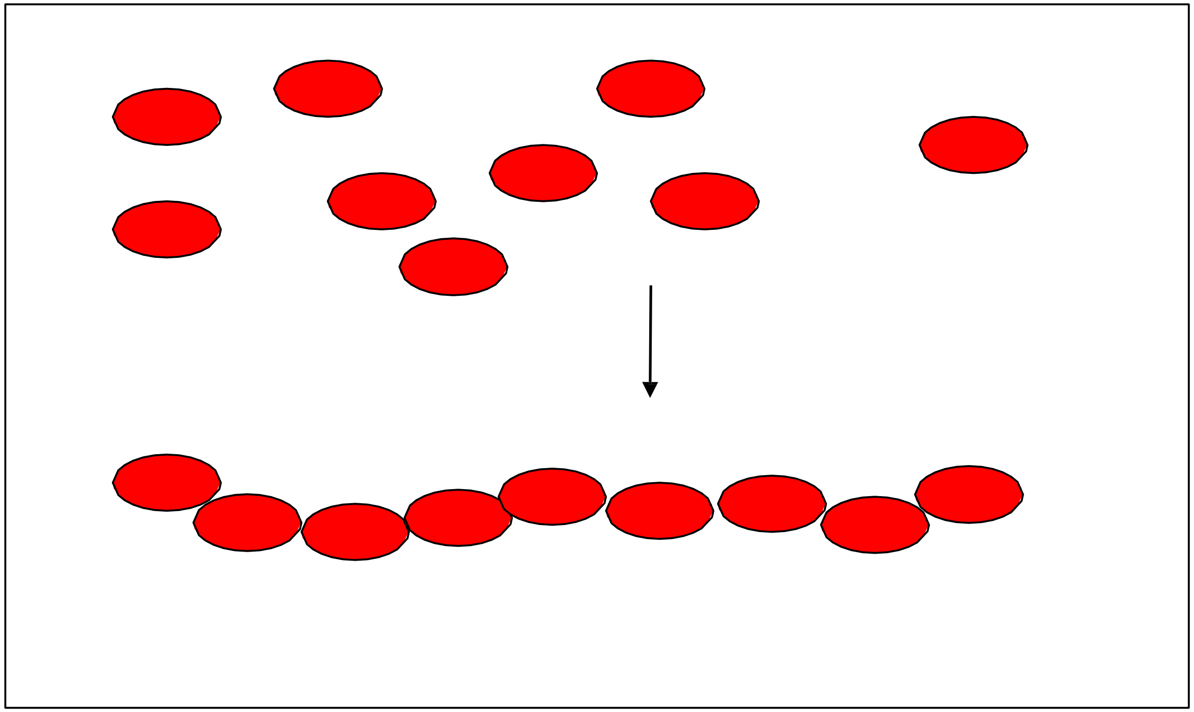
UNIT – V (SYLLABUS)

Polymer Materials:

Polymers,Classification of polymer – Mechanisms of polymerization - Some commercially important individual polymer – Thermoplastics - Elastomers – Thermosets – Engineering plastics - Liquid crystal polymers - Conductive polymers – High Performance fibers - Biomedical applications – Photonic polymers.

WHAT IS A POLYMER?

- A long molecule made up from lots of small molecules called *monomers.*

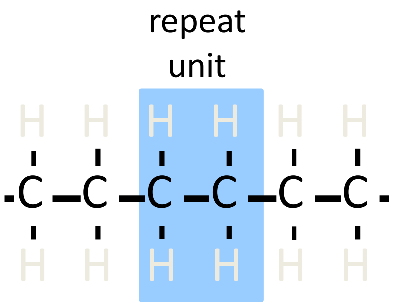


POLYMERS

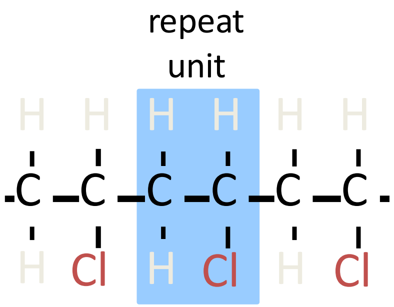
Very Large molecules structures chain-like in nature.

Poly **mer**

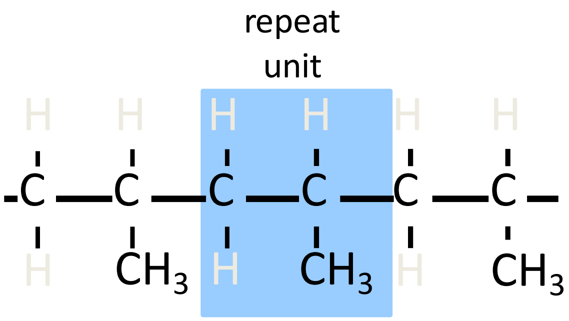
many **repeat unit**



Polyethylene (PE)



Polyvinyl chloride (PVC)



Polypropylene (PP)

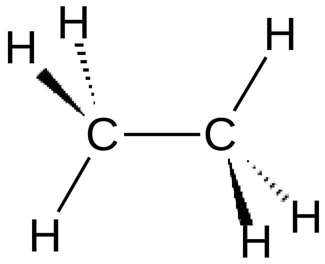
Adapted from Fig. 14.2, *Callister 7e.*

POLYMER COMPOSITION

Most polymers are hydrocarbons

- **i.e. made up of H and C**

- **Saturated hydrocarbons**
  - **Each carbon bonded to four other atoms**



C_nH_{2n+2}

DEFINITION OF POLYMER

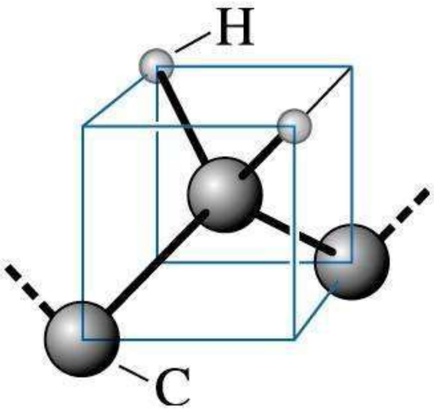
- A **polymer** (Greek poly-, "many" + -mer, "part") is a large molecule, or macromolecule, composed of many repeated subunits.
- Due to their broad range of properties,both synthetic and natural polymers play essential and ubiquitous roles in everyday life.
- Polymers range from familiar synthetic plastics such as polystyrene to natural biopolymers such as DNA and proteins that are fundamental to biological structure and function.
- Polymers, both natural and synthetic, are created via polymerization of many small molecules, known as monomers.
- Their consequently large molecular mass, relative to small molecule compounds, produces unique physical properties including toughness, viscoelasticity, and a tendency to form glasses and semicrystalline structures rather than crystals.

COMMON EXAMPLES OF POLYMERS

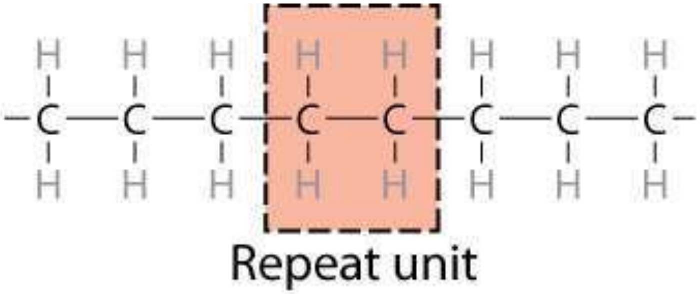
- Polymers are of two types: naturally occurring and synthetic or *man made*.
- Natural polymeric materials such as hemp, shellac, amber, wool, silk, and natural rubber have been used for centuries. A variety of other natural polymers exist, such as cellulose, which is the main constituent of wood and paper.
- The list of synthetic polymers, roughly in order of worldwide demand, includes polyethylene, polypropylene, polystyrene, polyvinyl chloride, synthetic rubber, phenol formaldehyde resin (or Bakelite), neoprene, nylon, polyacrylonitrile, PVB, silicone, and many more. More than 330 million tons of these polymers are made every year (2015).

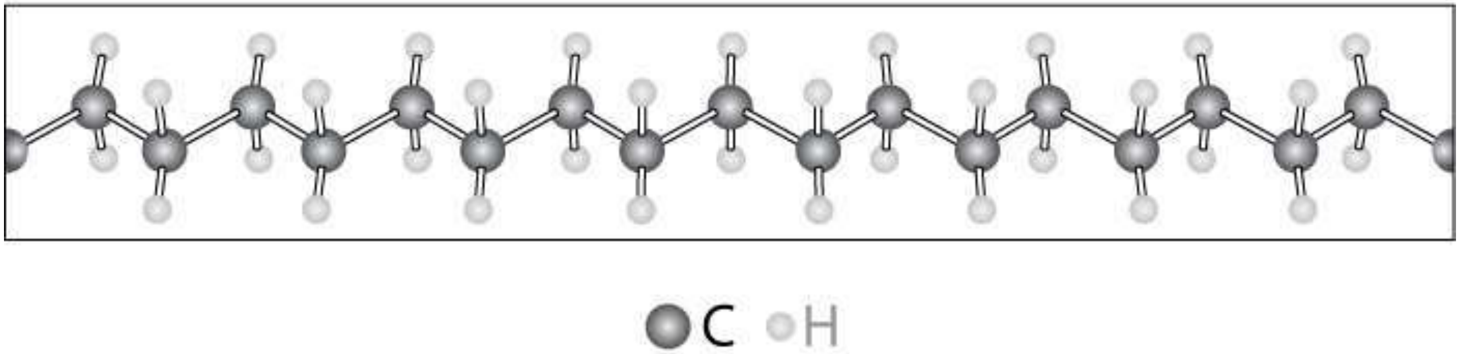
- Most commonly, the continuously linked backbone of a polymer used for the preparation of plastics consists mainly of carbon atoms.
- A simple example is polyethylene ('polythene' in British English), whose repeating unit is based on ethylene monomer.
- Many other structures do exist; for example, elements such as silicon form familiar materials such as silicones, examples being Silly Putty and waterproof plumbing sealant.
- Oxygen is also commonly present in polymer backbones, such as those of polyethylene glycol, polysaccharides (in glycosidic bonds), and DNA (in phosphodiester bonds)

CHEMISTRY AND STRUCTURE OF POLYETHYLENE



Tetrahedral arrangement of C-H



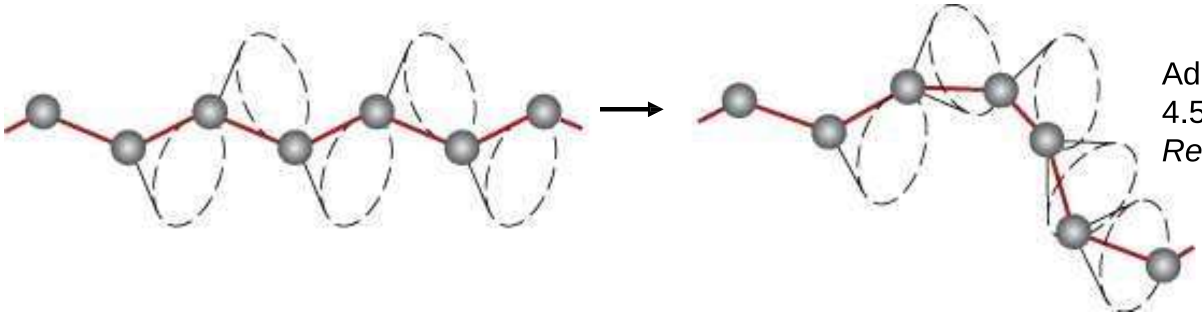


- Polyethylene is a long-chain hydrocarbon.
- Top figure shows repeat unit and chain structures.
- Other figure shows zigzag backbone structure.

POLYMERS – MOLECULAR SHAPE

Molecular Shape (or Conformation) – chain bending and twisting are possible by rotation of carbon atoms around their chain bonds

- note: not necessary to break chain bonds to alter molecular shape



Adapted from Fig. 4.5, *Callister & Rethwisch 3e.*

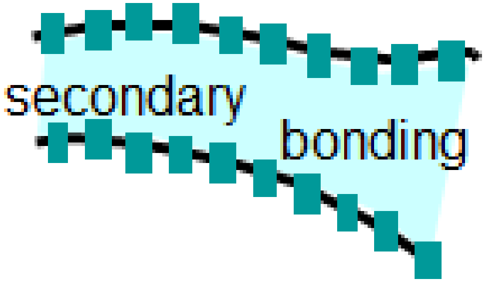
– **C-C bonds are typically 109° (tetrahedral, *sp*^{3} carbon)**

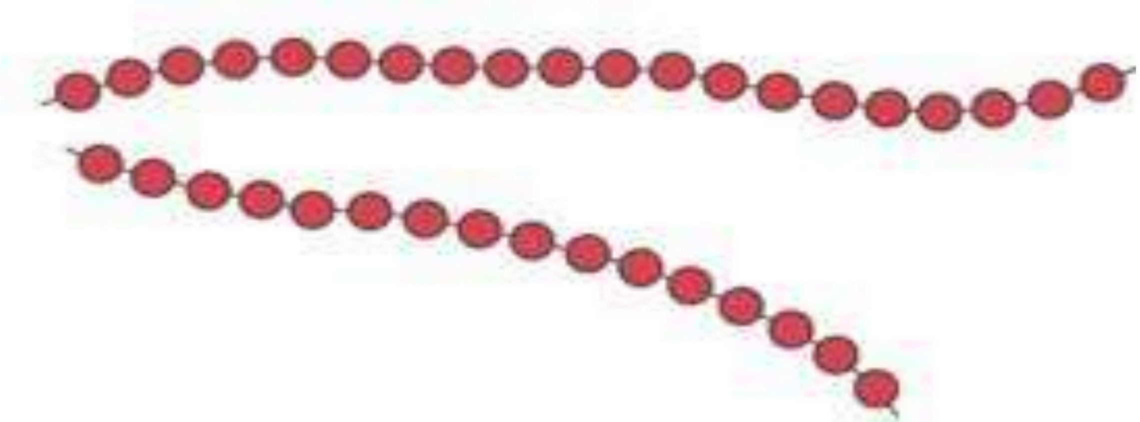
- **Molecular structure of Polymers-**
  - Physical properties of polymers depend not only on their molecular weight/shape, but also on the difference in the chain structure.

  - **Four main structures**
    - Linear polymers
    - Branched polymers
    - Crosslinked polymers
    - Network polymers

1.LINEAR POLYMERS

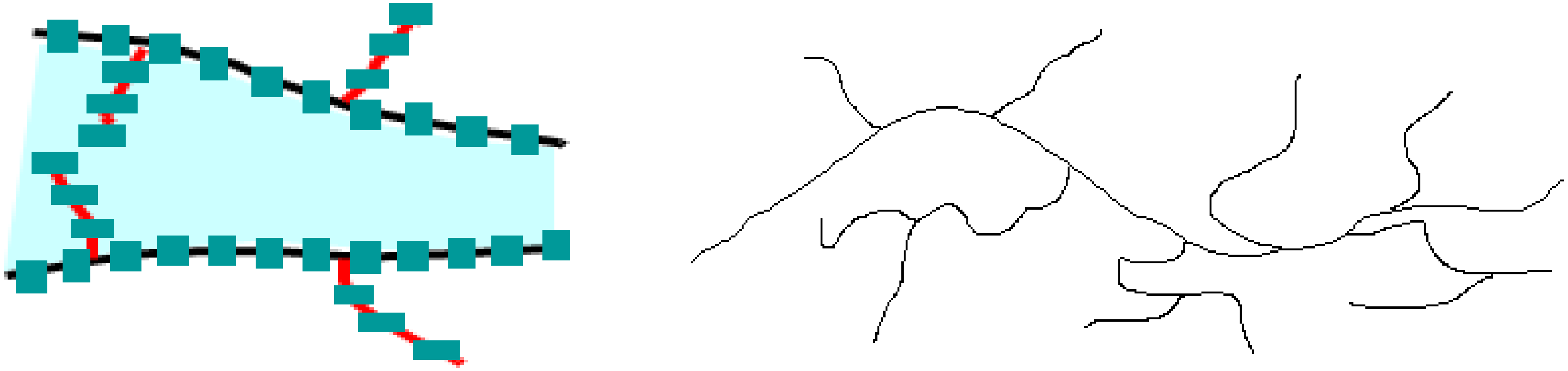
- polymers in which the mer units are connected end-to-end along the whole length of the chain
- These types of polymers are often quite flexible
  - Van der waal’s forces and H-bonding are the two main types of interactions between chains
  - Some examples – polyethylene, teflon, PVC, polypropylene





2.BRANCHED POLYMERS

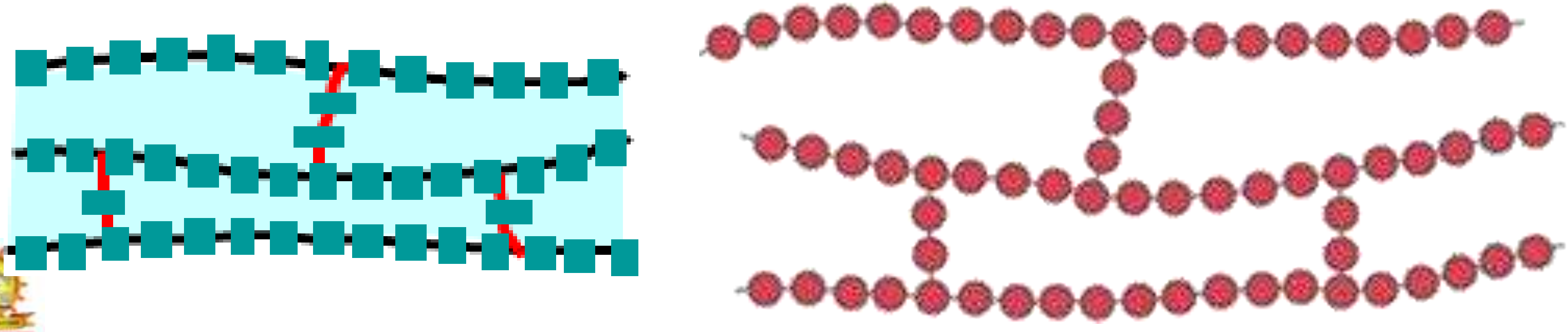
- Polymer chains can be like branches:



- Or the fibers may aligned parallel, as in fibers and some plastic sheets.
- This leads to inability of chains to pack very closely together
- These branches are usually a result of side-reactions during the polymerization of the main chain

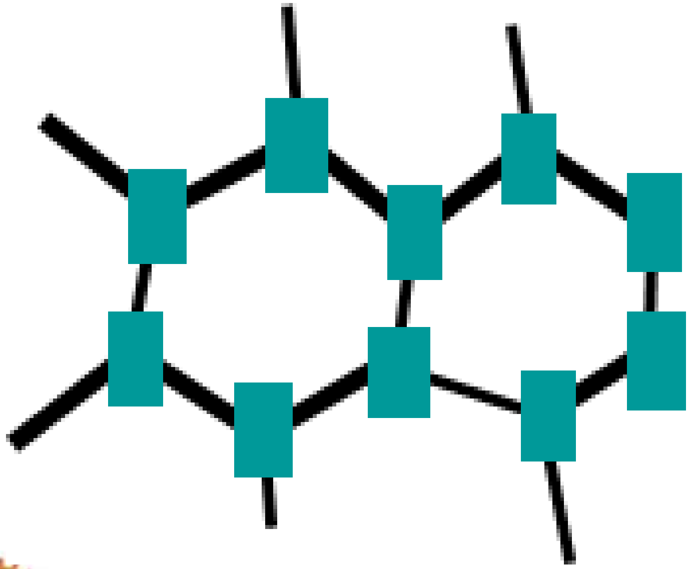
3.CROSSLINKED POLYMERS

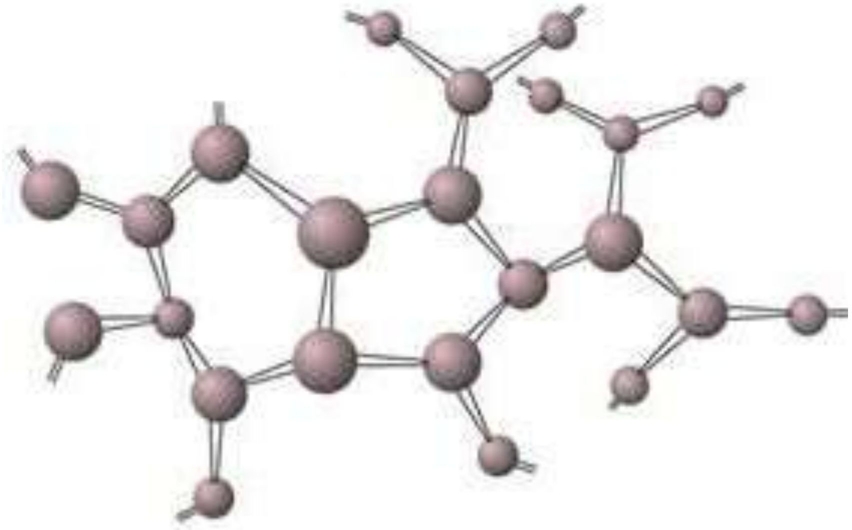
- Molecular structure
  - adjacent chains attached via covalent bonds
    - Carried out during polymerization or by a non-reversible reaction after synthesis (referred to as crosslinking)
    - Materials often behave very differently from linear polymers
    - Many “rubbery” polymers are crosslinked to modify their mechanical properties; in that case it is often called vulcanization
    - Generally, amorphous polymers are weak and cross-linking adds strength: vulcanized rubber is polyisoprene with sulphur cross-links:



4.NETWORK POLYMERS

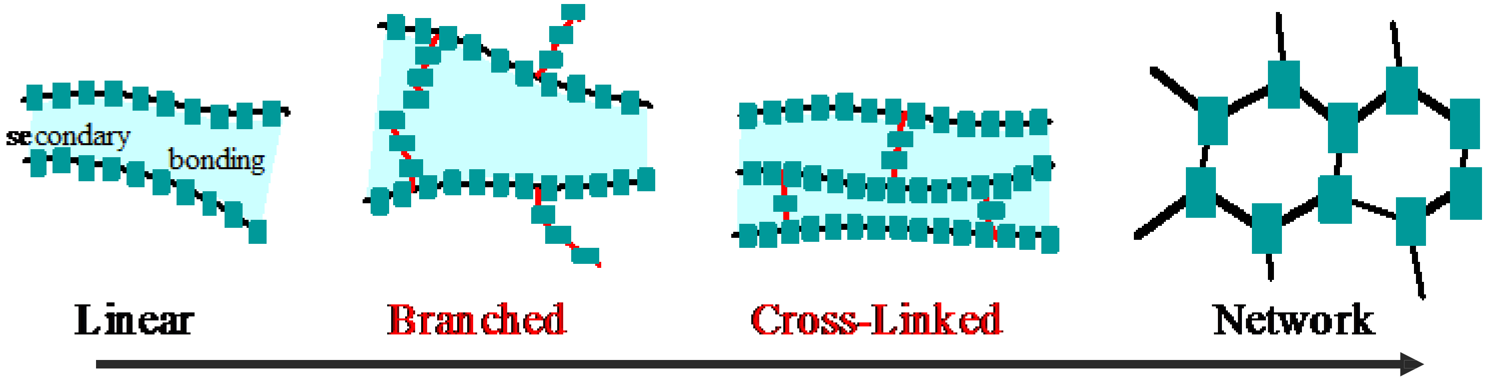
- – polymers that are “trifunctional” instead of bifunctional
- – There are three points on the mer that can react
- – This leads to three-dimensional connectivity of the polymer backbone
  - Highly crosslinked polymers can also be classified as network polymers
  - Examples: epoxies, phenol-formaldehyde polymers





POLYMER MICROSTRUCTURE

- Covalent chain configurations and strength:



Direction of increasing strength

Adapted from Fig. 14.7, *Callister 6e.*

POLYMERIZATION:- PROCESS OF FORMING POLYMER.

Linear Polymer:- Polymer which is obtained by simply adding monomers together to form long chain.

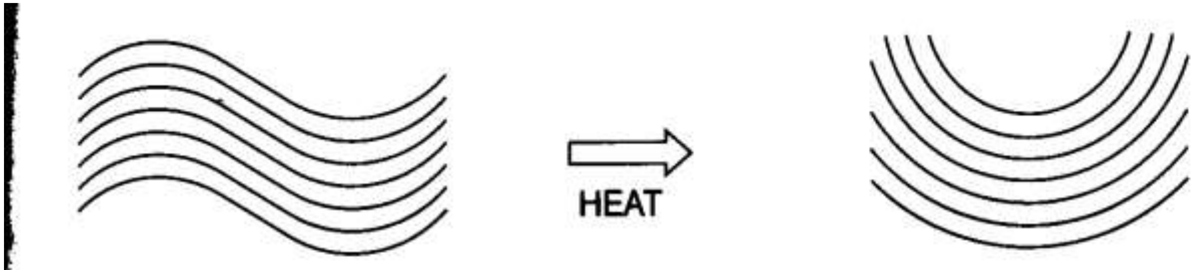
Copolymer:- Polymer which is obtained by different types of monomers.

Degree of Polymerization, *DP :-*

It is ratio of molecular weight of polymer to molecular weight of single monomer.

TYPES OF POLYMERS:-

1.Thermoplastics

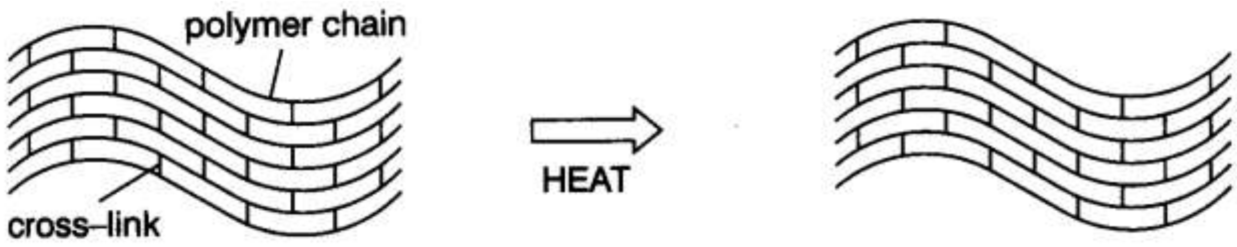


(a) Thermoplastic: no cross–linking

Weak forces between polymer chains easily broken by heating; polymer can be moulded into new shape.

- No cross links between chains.
- Weak attractive forces between chains broken by *warming*.
- Change shape - can be remoulded.
- Weak forces reform in new shape when cold.
- E.g. Polyethylene ,PVC, Polystyrene

2.THERMOSETS



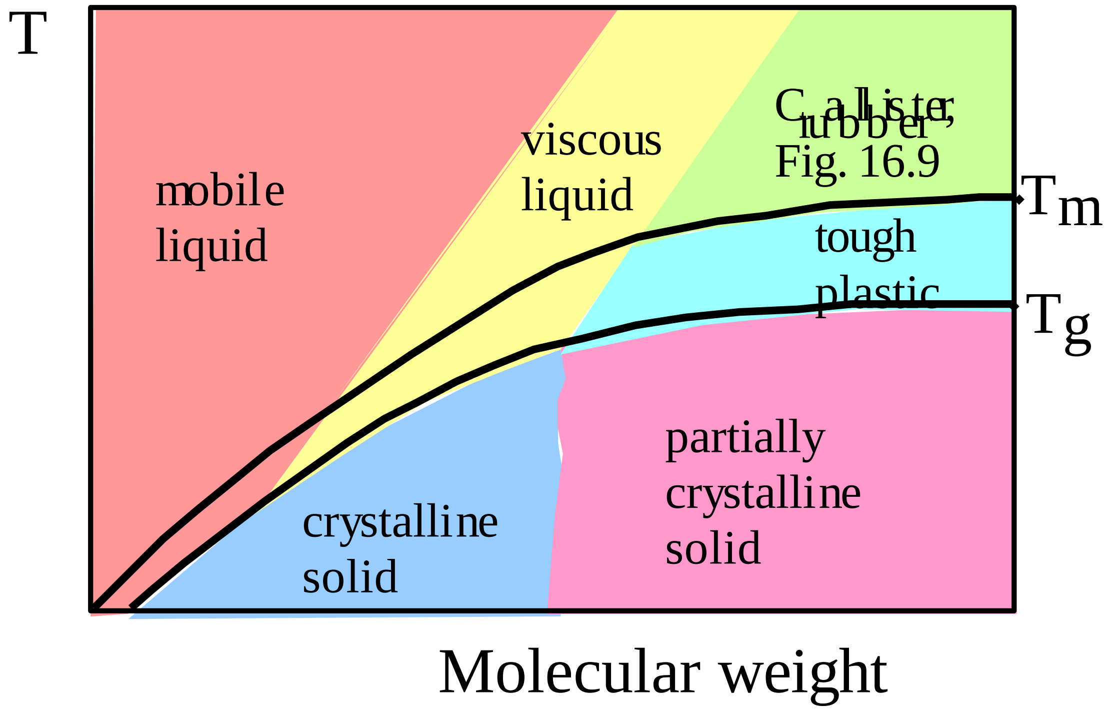
(b) **Thermoset:** extensive cross–linking

Strong covalent bonds between polymer chains cannot be easily broken; polymer keeps shape on heating.

- Extensive cross-linking formed by covalent bonds.
- Bonds prevent chains moving relative to each other.
- E.g. Epoxies ,Phenolics

THERMOPLASTIC VS THERMOSET

- Thermoplastics:
  - --little cross linking
  - --ductile
  - --soften with heating
  - --polyethylene
polypropylene
polycarbonate
polystyrene



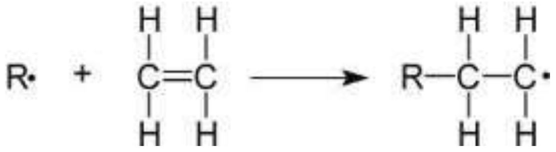
Callister, Fig. 16.9

- Thermosets:
  - --large cross linking (10 to 50% of mers)
  - --hard and brittle
  - --do NOT soften with heating
  - --vulcanized rubber, epoxies, polyester resin, phenolic resin

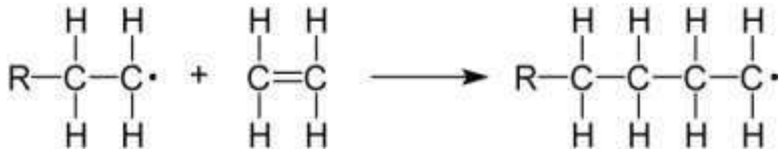
TYPES OF POLYMERIZATION

1.ADDITION (CHAIN) POLYMERIZATION

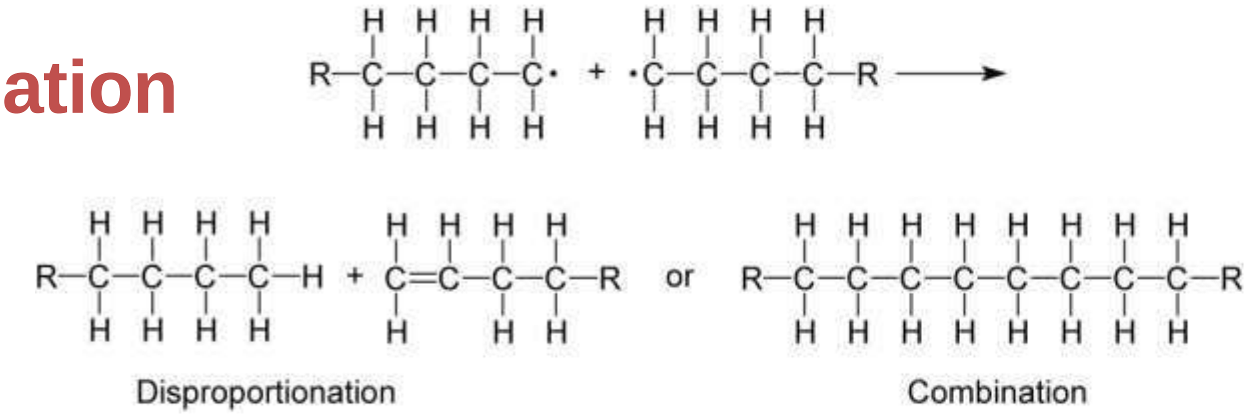
- **Initiation**



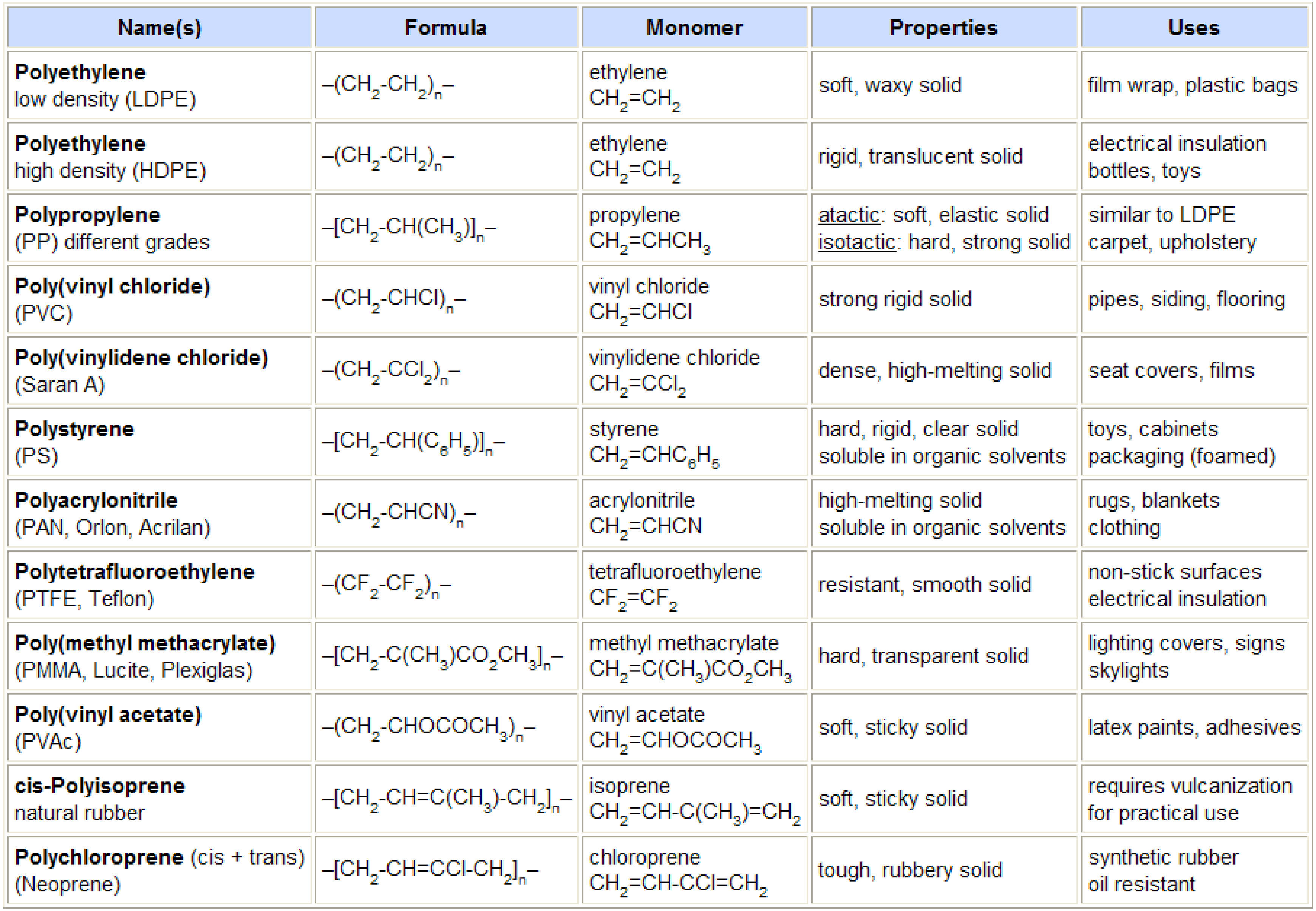
- **Propagation**



- **Termination**

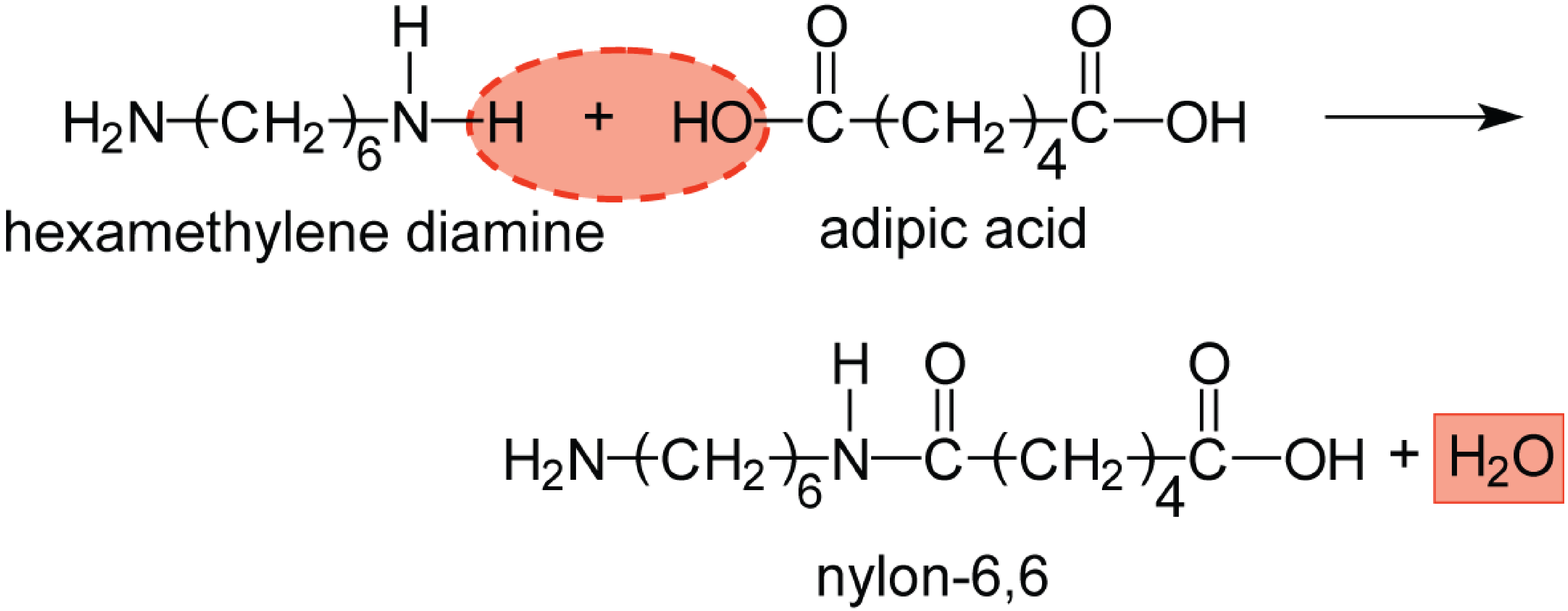


SOME COMMON ADDITION



Name(s)	Formula	Monomer	Properties	Uses
Polyethylene low density (LDPE)	$–(CH_2\text{-}CH_2)_n–$	ethylene $CH_2{=}CH_2$	soft, waxy solid	film wrap, plastic bags
Polyethylene high density (HDPE)	$–(CH_2\text{-}CH_2)_n–$	ethylene $CH_2{=}CH_2$	rigid, translucent solid	electrical insulation bottles, toys
Polypropylene (PP) different grades	$–[CH_2\text{-}CH(CH_3)]_n–$	propylene $CH_2{=}CHCH_3$	atactic: soft, elastic solid isotactic: hard, strong solid	similar to LDPE carpet, upholstery
Poly(vinyl chloride) (PVC)	$–(CH_2\text{-}CHCl)_n–$	vinyl chloride $CH_2{=}CHCl$	strong rigid solid	pipes, siding, flooring
Poly(vinylidene chloride) (Saran A)	$–(CH_2\text{-}CCl_2)_n–$	vinylidene chloride $CH_2{=}CCl_2$	dense, high-melting solid	seat covers, films
Polystyrene (PS)	$–[CH_2\text{-}CH(C_6H_5)]_n–$	styrene $CH_2{=}CHC_6H_5$	hard, rigid, clear solid soluble in organic solvents	toys, cabinets packaging (foamed)
Polyacrylonitrile (PAN, Orlon, Acrilan)	$–(CH_2\text{-}CHCN)_n–$	acrylonitrile $CH_2{=}CHCN$	high-melting solid soluble in organic solvents	rugs, blankets clothing
Polytetrafluoroethylene (PTFE, Teflon)	$–(CF_2\text{-}CF_2)_n–$	tetrafluoroethylene $CF_2{=}CF_2$	resistant, smooth solid	non-stick surfaces electrical insulation
Poly(methyl methacrylate) (PMMA, Lucite, Plexiglas)	$–[CH_2\text{-}C(CH_3)CO_2CH_3]_n–$	methyl methacrylate $CH_2{=}C(CH_3)CO_2CH_3$	hard, transparent solid	lighting covers, signs skylights
Poly(vinyl acetate) (PVAc)	$–(CH_2\text{-}CHOCOCH_3)_n–$	vinyl acetate $CH_2{=}CHOCOCH_3$	soft, sticky solid	latex paints, adhesives
cis-Polyisoprene natural rubber	$–[CH_2\text{-}CH{=}C(CH_3)\text{-}CH_2]_n–$	isoprene $CH_2{=}CH\text{-}C(CH_3){=}CH_2$	soft, sticky solid	requires vulcanization for practical use
Polychloroprene (cis + trans) (Neoprene)	$–[CH_2\text{-}CH{=}CCl\text{-}CH_2]_n–$	chloroprene $CH_2{=}CH\text{-}CCl{=}CH_2$	tough, rubbery solid	synthetic rubber oil resistant

2.CONDENSATION (STEP) POLYMERIZATION



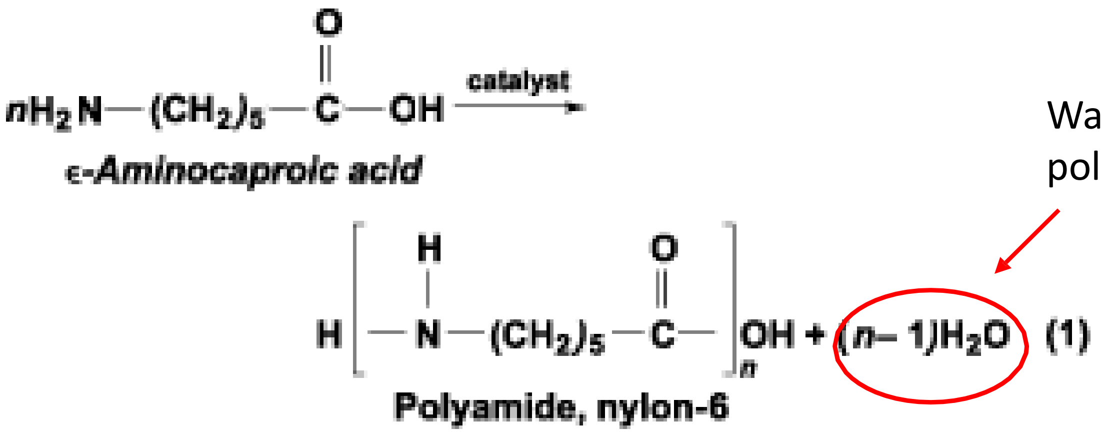
$$H_2N{-}(CH_2)_6{-}\overset{H}{\overset{|}{N}}{-}H + HO{-}\overset{O}{\overset{\|}{C}}{-}(CH_2)_4{-}\overset{O}{\overset{\|}{C}}{-}OH \longrightarrow H_2N{-}(CH_2)_6{-}\overset{H}{\overset{|}{N}}{-}\overset{O}{\overset{\|}{C}}{-}(CH_2)_4{-}\overset{O}{\overset{\|}{C}}{-}OH + \boxed{H_2O}$$

hexamethylene diamine

adipic acid

nylon-6,6

CONDENSATION POLYMERIZATION

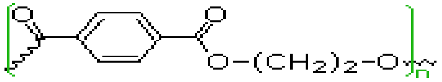
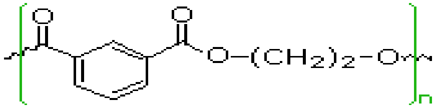
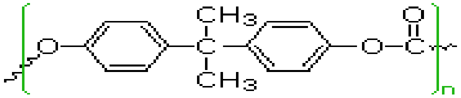
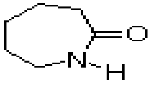
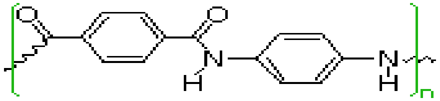
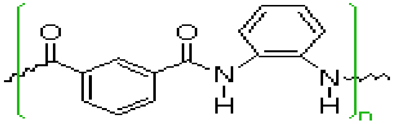
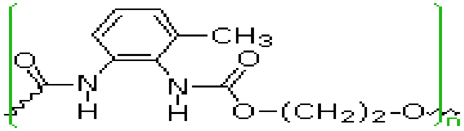
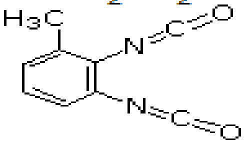


$$nH_2N-(CH_2)_5-\overset{O}{\overset{\|}{C}}-OH \xrightarrow{\text{catalyst}} H\left[-\overset{H}{\overset{|}{N}}-(CH_2)_5-\overset{O}{\overset{\|}{C}}-\right]_n OH + (n-1)H_2O \quad (1)$$

Water is "Condensed out" during polymerization of Nylon

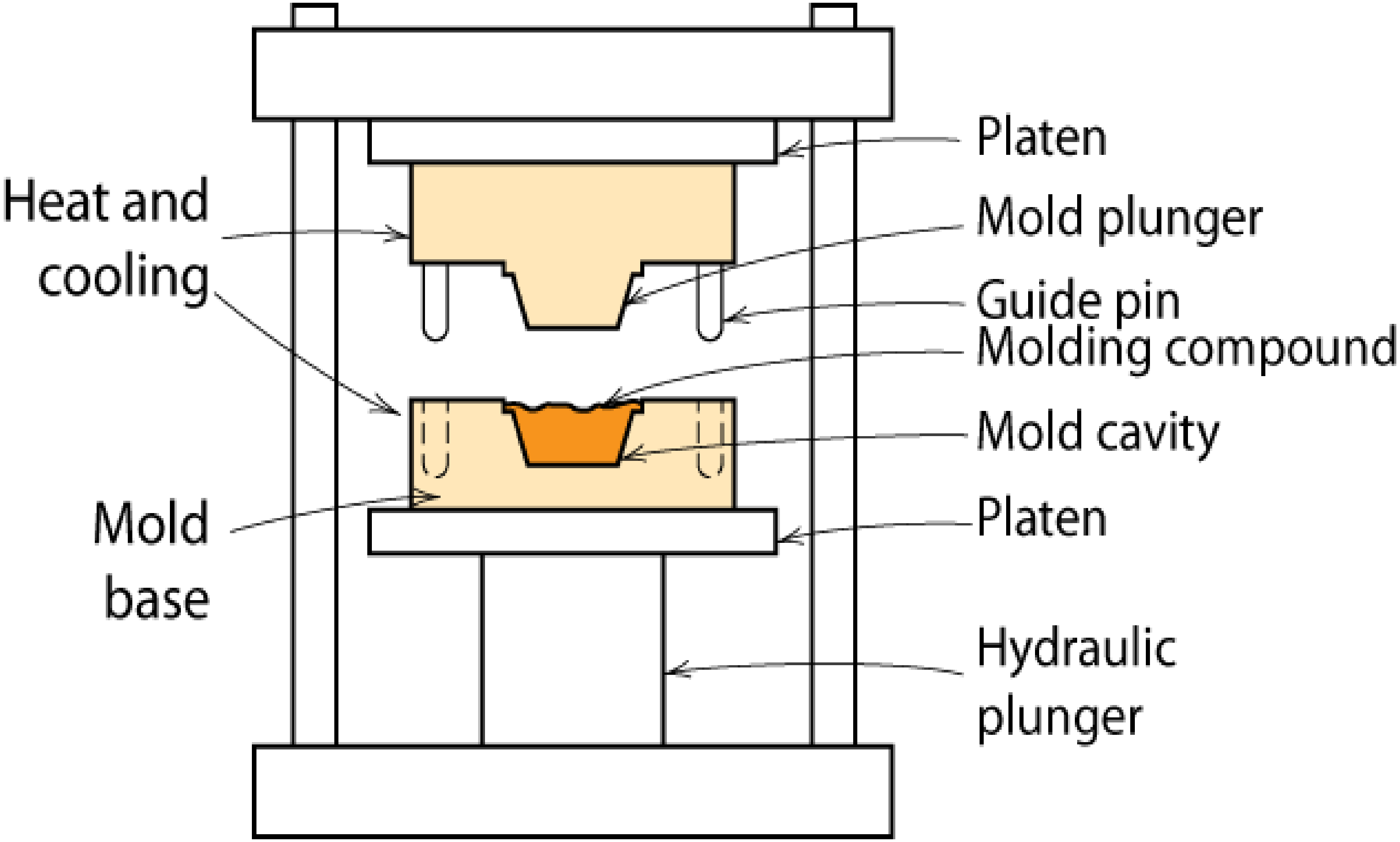
- Some of the original monomer's materials are shed (condensed out) during polymerization process
- Process is conducted in the presence of a catalyst
- Water, CO_2 are commonly condensed out but other compounds can be emitted including HCN or other acids

SOME CONDENSATION

Formula	Type	Components	T_g °C	T_m °C
$\sim[CO(CH_2)_4CO\text{-}OCH_2CH_2O]_n\sim$	**polyester**	$HO_2C\text{-}(CH_2)_4\text{-}CO_2H$ $HO\text{-}CH_2CH_2\text{-}OH$	< 0	50
	**polyester** Dacron Mylar	para $HO_2C\text{-}C_6H_4\text{-}CO_2H$ $HO\text{-}CH_2CH_2\text{-}OH$	70	265
	**polyester**	meta $HO_2C\text{-}C_6H_4\text{-}CO_2H$ $HO\text{-}CH_2CH_2\text{-}OH$	50	240
	**polycarbonate** Lexan	$(HO\text{-}C_6H_4\text{-})_2C(CH_3)_2$ (Bisphenol A) $X_2C{=}O$ (X = OCH_3 or Cl)	150	267
$\sim[CO(CH_2)_4CO\text{-}NH(CH_2)_6NH]_n\sim$	**polyamide** Nylon 66	$HO_2C\text{-}(CH_2)_4\text{-}CO_2H$ $H_2N\text{-}(CH_2)_6\text{-}NH_2$	45	265
$\sim[CO(CH_2)_5NH]_n\sim$	**polyamide** Nylon 6 Perlon		53	223
	**polyamide** Kevlar	para $HO_2C\text{-}C_6H_4\text{-}CO_2H$ para $H_2N\text{-}C_6H_4\text{-}NH_2$	---	500
	**polyamide** Nomex	meta $HO_2C\text{-}C_6H_4\text{-}CO_2H$ meta $H_2N\text{-}C_6H_4\text{-}NH_2$	273	390
	**polyurethane** Spandex	$HOCH_2CH_2OH$ 	52	---

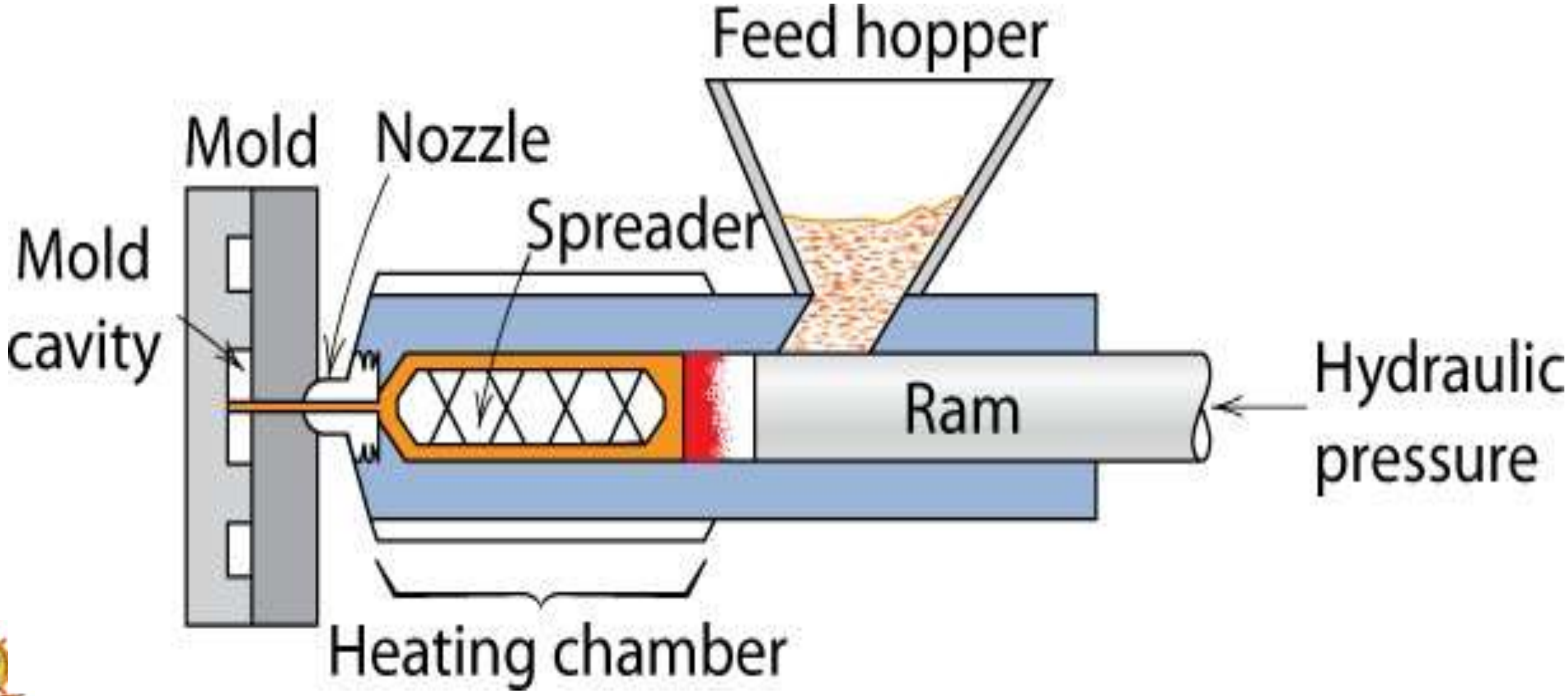
1. Molding:

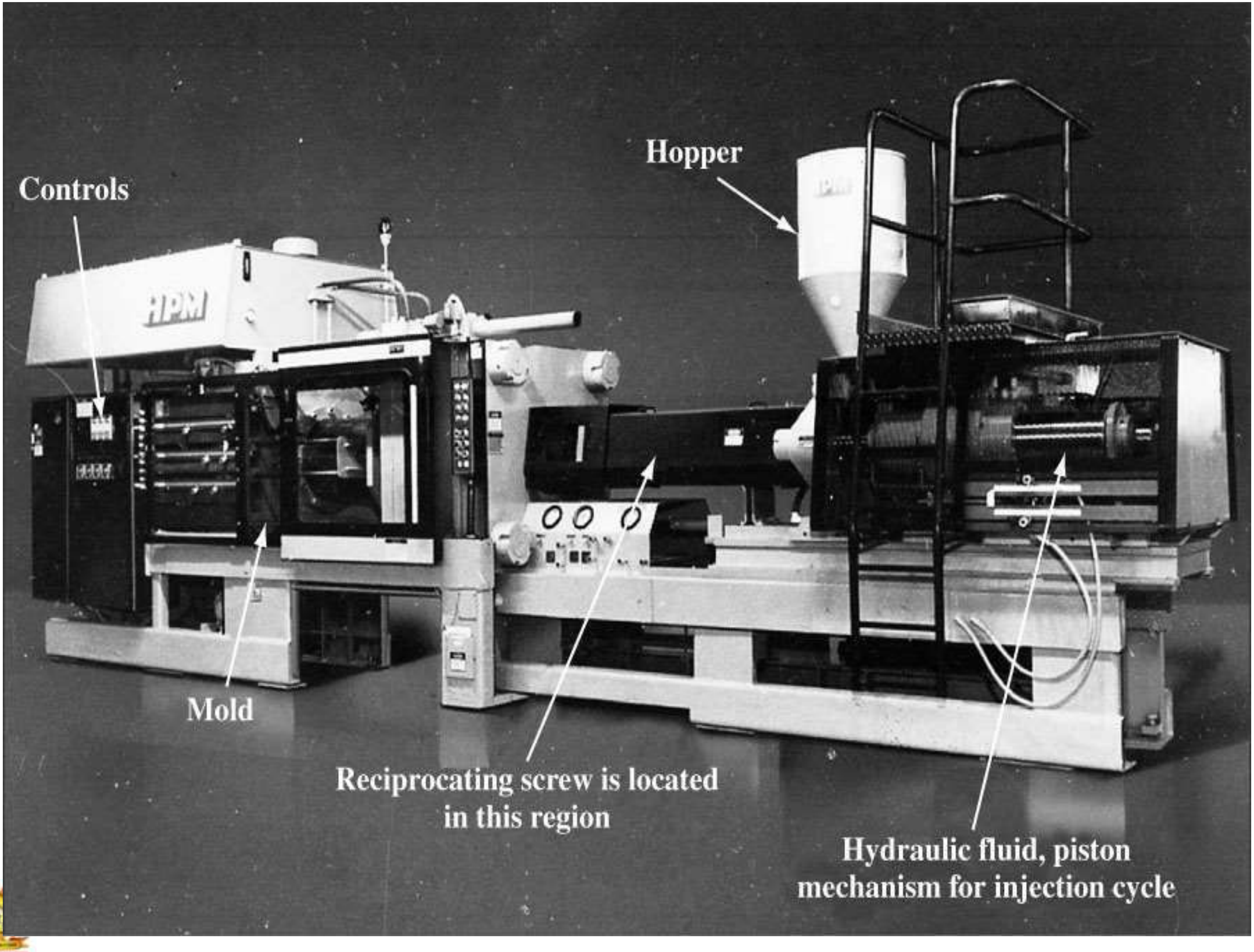
- Compression and transfer molding
  - Applicable for thermoplastics or thermosets



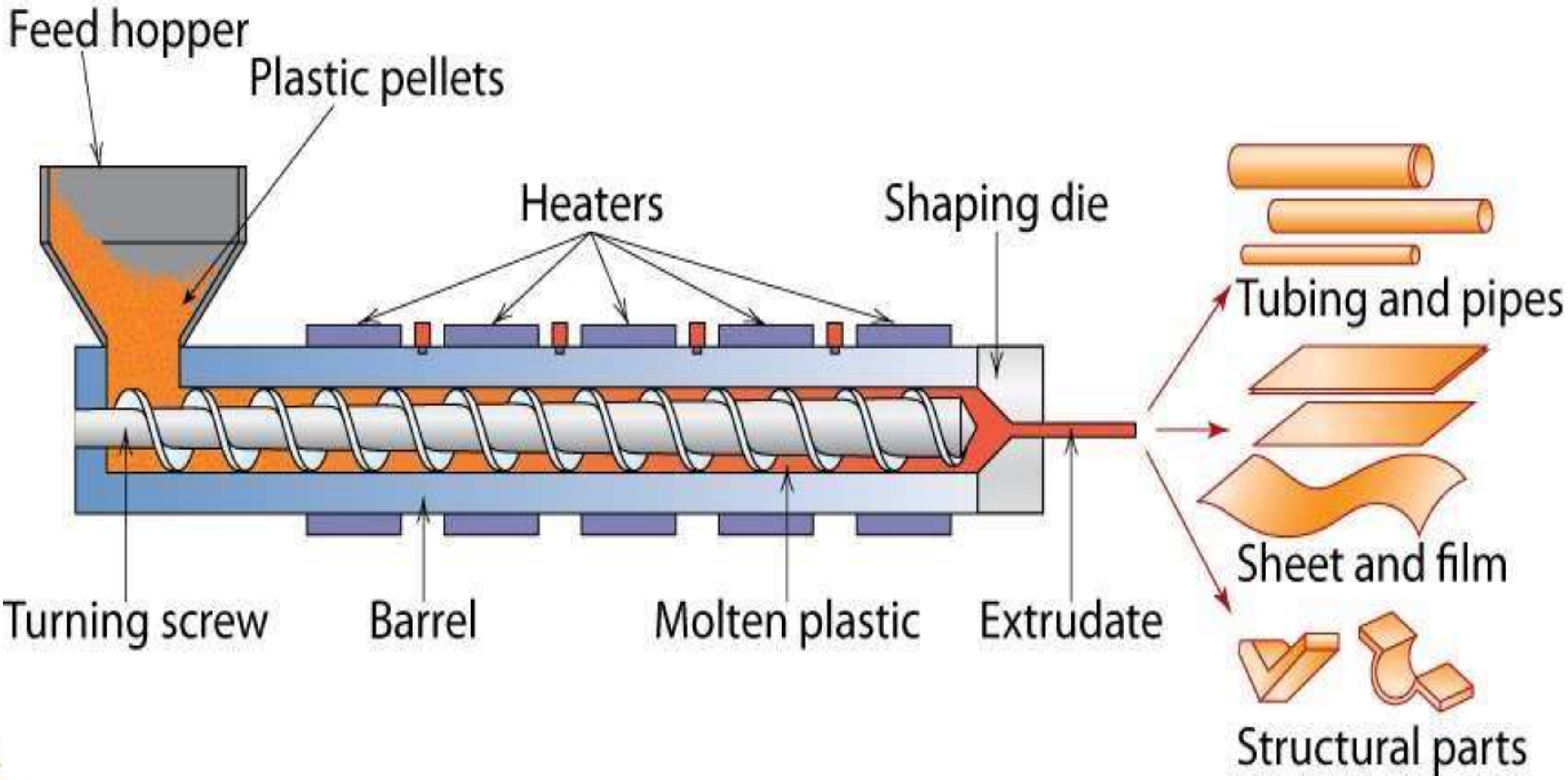
2. Injection molding: Polymer is melted in chamber & then the molten polymer is forced under pressure into the die

- thermoplastic & some thermosets
- High speed production



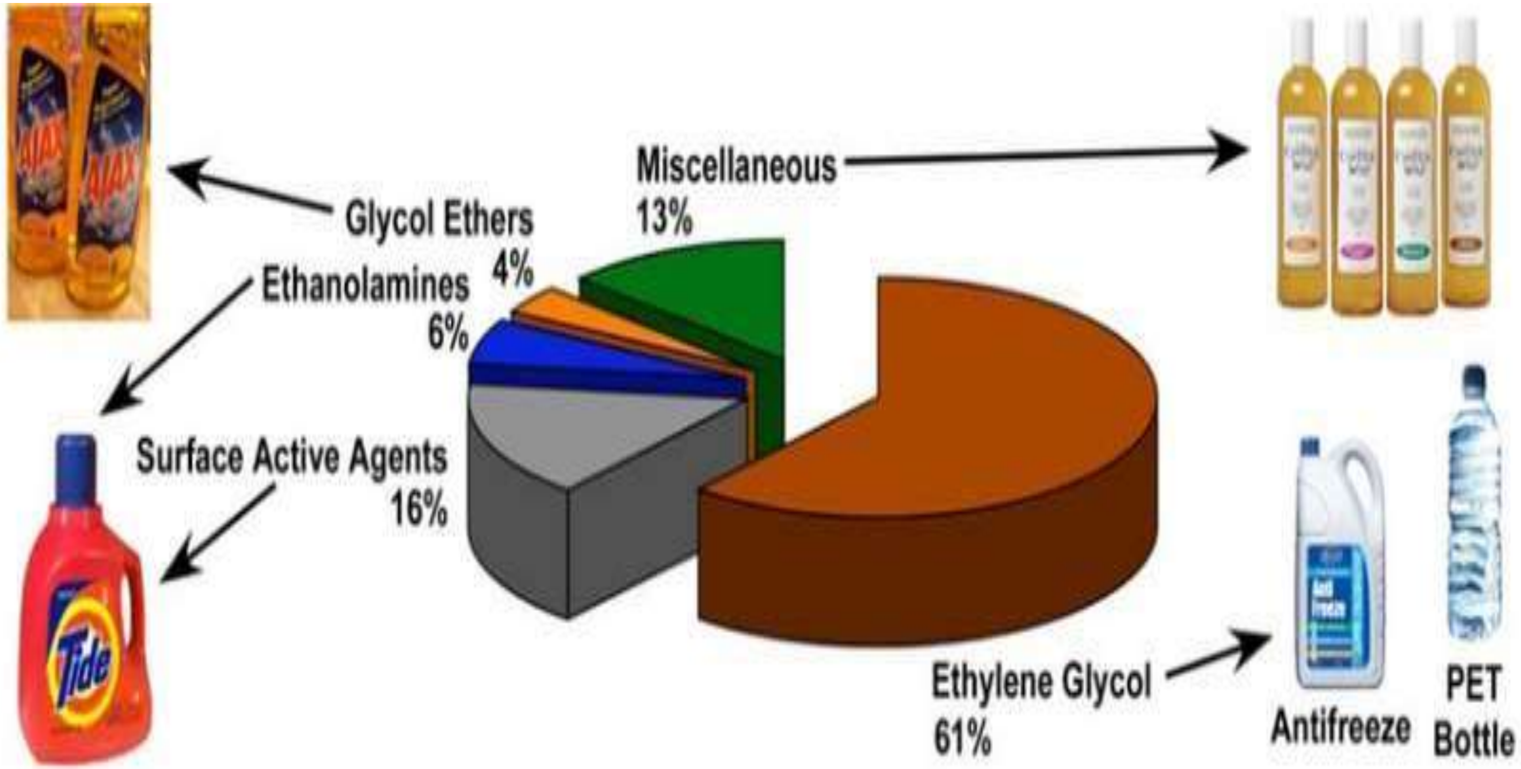

Hopper
Controls
HPM
Mold
Reciprocating screw is located in this region
Hydraulic fluid, piston mechanism for injection cycle

3. EXTRUSION: AN EXTRUDER IS A DEVICE THAT USES A LARGE SCREW AND HEATING COILS TO MELT A POLYMER, COMPRESS IT, & FORCE IT INTO A MOLD.



Applications of Polymers

Applications of Ethylene:



- Applications of Ethylene: