

SCHOOL OF AERONAUTICS (NEEMRANA)

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CLASS: B.Tech AERONAUTICAL

SUBJECT CODE: 3AN2

SEMESTER: III

SUBJECT NAME: - MATERIAL SCIENCE AND ENGINEERING

CONTENTS :-

UNIT-1 ATOMIC STRUCTURE OF METALS

- Atomic structure of Metals: Crystal structure, crystal lattice of (i) Body centred cubic (ii) Face centred cubic (iii) Closed packed hexagonal, crystallographic
- Notation of atomic planes and Directions (Miller Indices), polymorphism and allotropy, Crystal imperfection.

- The properties of some materials are directly related to their crystal structures. i.e. pure and undeformed magnesium and beryllium, having one crystal structure, are much more brittle (lower degrees of deformation) than are pure and undeformed metals such as gold and silver that have yet another crystal structure.
- A knowledge of the crystal structure for iron helps us understand transformations that occur when steels are heat treated to improve their mechanical properties.
- Furthermore, significant property differences exist between crystalline and noncrystalline materials having the same composition.

Er. Saurabh Malpotra

1.1 WHY TO STUDY ATOMIC STRUCTURE OF CRYSTALLINE SOLIDS?

A crystalline material is one in which the atoms are situated in an orderly, repeating pattern extending in all three dimension .i.e.Nacl ,CsF etc.

- Crystalline solids depend on the crystal structure of the material, the manner in which atoms, ions, or molecules are spatially(three dimension) arranged.
- **Lattice** is used in the context of crystal structures; in this sense lattice means a three-dimensional array of points coinciding with atom positions (or sphere centers).
- **Amorphous solid** is one in which the atom are not situated in an orderly, repeating pattern. i.e. glass , rubber, plastic etc.

over temperature range.

**Crystalline solid
solid**

Amorphous

noncrystalline silicon
dioxide.

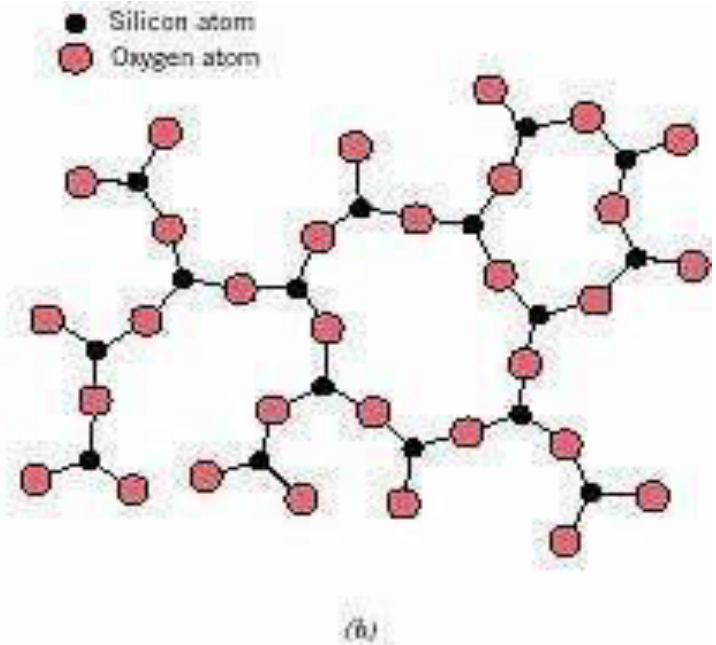
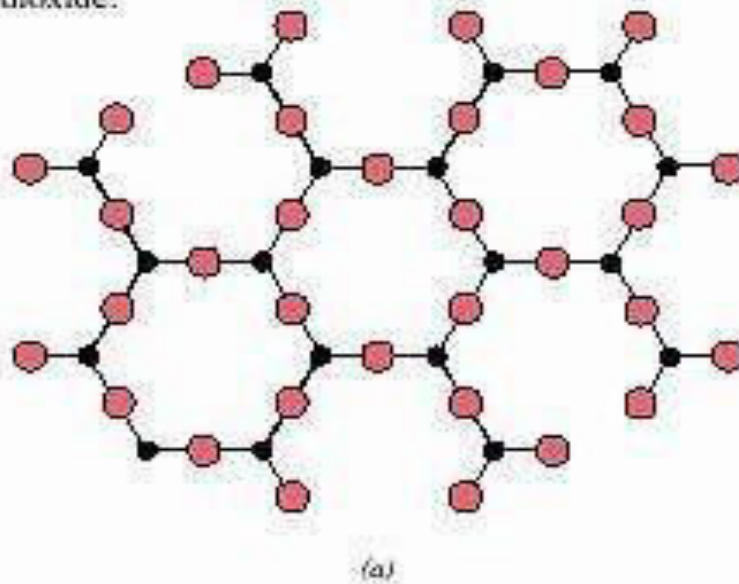


Fig. 1.1 Crystalline and Amorphous solid

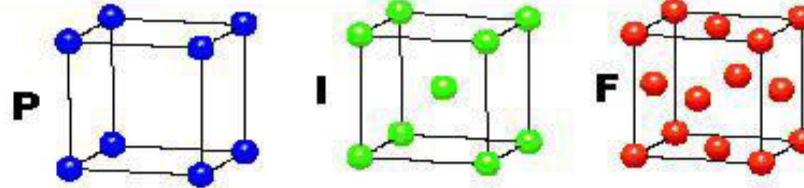
- The smallest repeating unit in a crystal is a **unit cell**.
- Three-dimensional packing of unit cells produces the crystal lattice.
- There are seven different unit cells:-
- **Cubic:** All three axes have same length and intercept at right angles.
- **Tetragonal:** The three axes intercept at right angles, but one axis is longer or shorter than the other two equal axes.
- **Hexagonal:** Three of the four axes are in one plane, intercept at 120° , and are of the same length.
- **Trigonal:** Same axes as hexagonal, but angle lie b/w right angle to 120° .
- **Orthorhombic:** The three axes are of different lengths and are at right angles to each other.
- **Monoclinic:** The three axes are of different lengths and two are at right angles to each other. The third axis is inclined.
- **Triclinic:** All three axes are of different lengths and form oblique angles.

1.2 CRYSTAL SYSTEMS :-

CUBIC

$$a = b = c$$

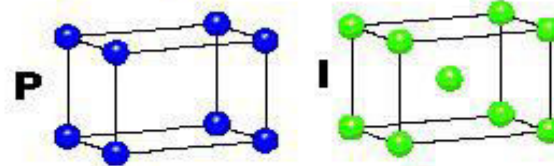
$$\alpha = \beta = \gamma = 90^\circ$$



TETRAGONAL

$$a = b \neq c$$

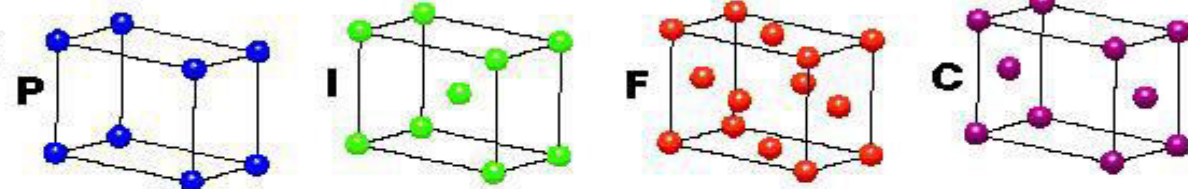
$$\alpha = \beta = \gamma = 90^\circ$$



ORTHORHOMBIC

$$a \neq b \neq c$$

$$\alpha = \beta = \gamma = 90^\circ$$

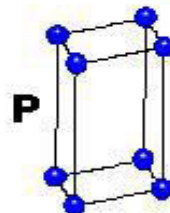


HEXAGONAL

$$a = b \neq c$$

$$\alpha = \beta = 90^\circ$$

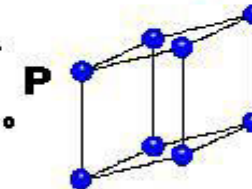
$$\gamma = 120^\circ$$



TRIGONAL

$$a = b = c$$

$$\alpha = \beta = \gamma \neq 90^\circ$$

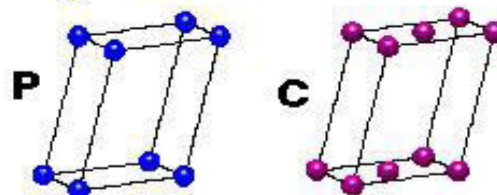


MONOCLINIC

$$a \neq b \neq c$$

$$\alpha = \gamma = 90^\circ$$

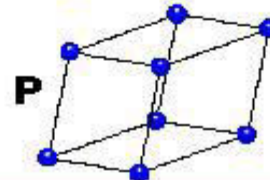
$$\beta \neq 120^\circ$$



TRICLINIC

$$a \neq b \neq c$$

$$\alpha \neq \beta \neq \gamma \neq 90^\circ$$



4 Types of Unit Cell

P = Primitive

I = Body-Centred

F = Face-Centred

C = Side-Centred

+

7 Crystal Classes

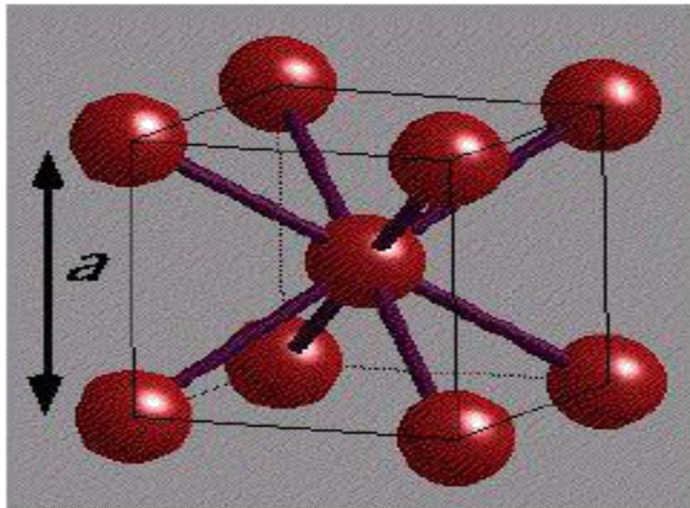
→ 14 Bravais Lattices

1.3 METALLIC CRYSTAL STRUCTURES :-

- The atomic bonding in this group of materials is metallic and thus non-directional in nature.
- For metals, using the hard-sphere model for the crystal structure, each sphere represents an ion core.
- There are three principle crystal structures for metals:-
 1. Body-center-cubic (BCC)
 2. Face-centered cubic (FCC)
 3. Hexagonal closed packed(HCP)

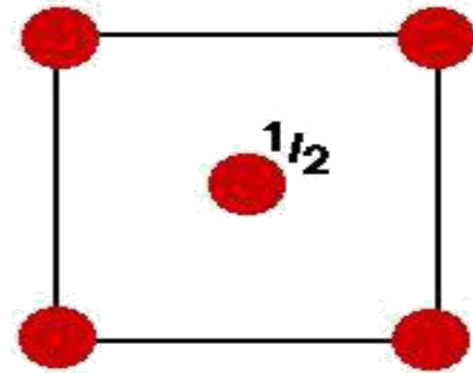
1.3.1 BODY CENTERED CUBIC STRUCTURE :-

- In BCC atoms located at all eight corners and a single atom at the cube center.
- This is called a body-centered cubic (BCC) crystal structure.
- Example: Cr, W, Fe, Tantalum, Molybdenum
 - Coordination # = 8



Body-Centred Cubic

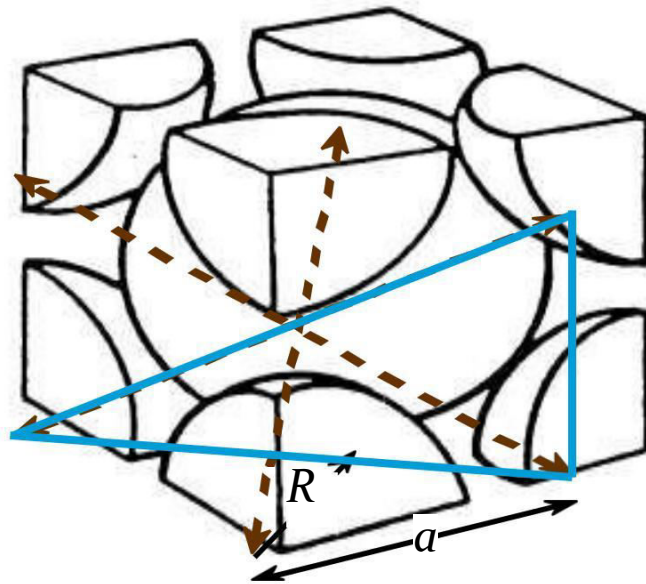
BCC



2 atoms/unit cell: 1 center + 8 corners \times 1/8.

Fig. 1.2 Body centered cubic structure

1. 3. 2 ATOMIC PACKING FACTOR: BCC :-



Close-packed directions:
length = $4R$
 $= \sqrt{3} a$

Unit cell contains:

$$1 + 8 \times 1/8$$

= 2 atoms/unit cell

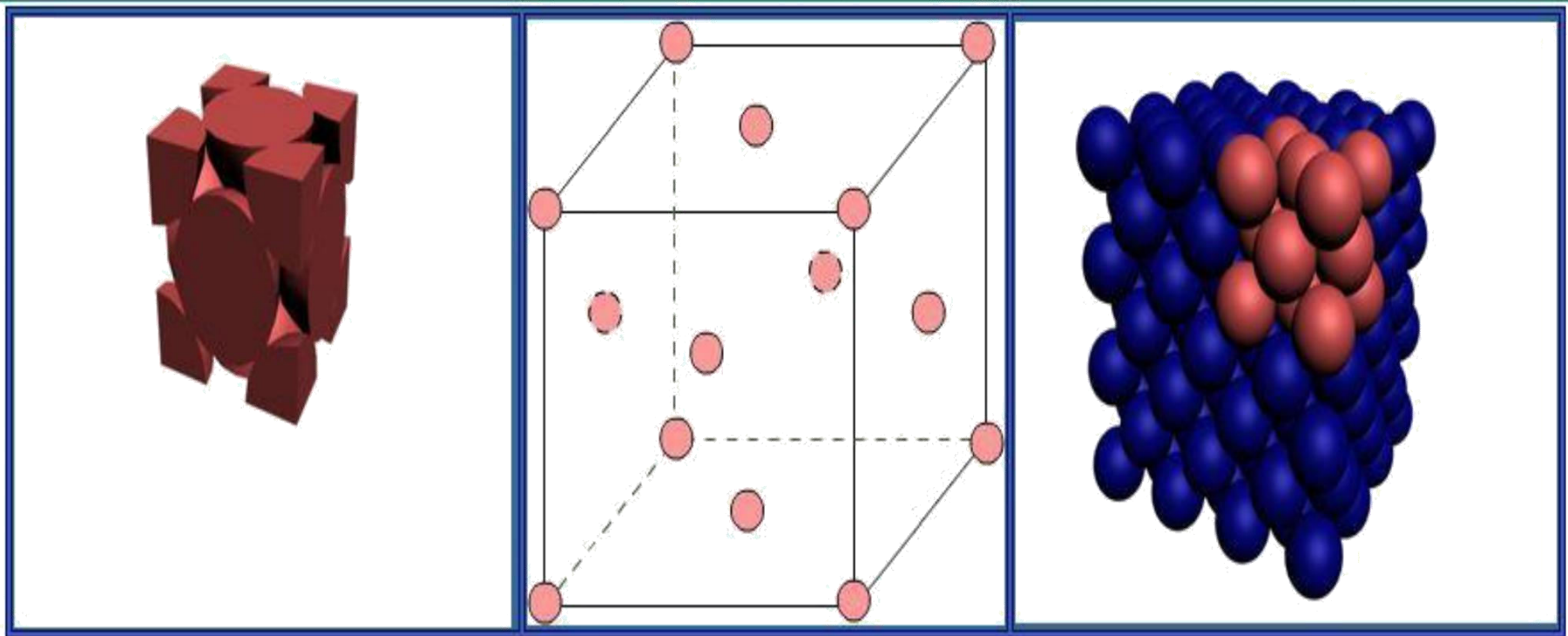
$$\text{APF} = \frac{\text{atoms unit cell} \times \text{volume atom}}{\text{volume unit cell}}$$

The diagram shows the formula for the Atomic Packing Factor (APF) for a BCC unit cell. The numerator is the product of the number of atoms per unit cell (2) and the volume of one atom ($\frac{4}{3} \pi (\sqrt{3}a/4)^3$). The denominator is the volume of the unit cell (a^3). Arrows point from the labels to the corresponding parts of the formula: 'atoms unit cell' points to '2', 'volume atom' points to the atom volume term, and 'volume unit cell' points to a^3 .

• APF for a body-centered cubic structure = $\frac{3}{8} = 0.68$

1.3.3 FACE CENTERED CUBIC STRUCTURE (FCC) :-

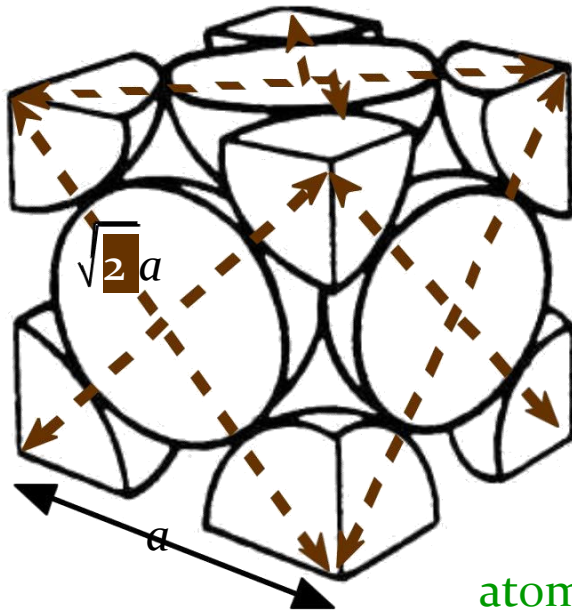
- In FCC atoms located at each of the corners and the centers of all the cube faces. This is called the face-centered cubic (FCC) crystal structure.
- Example: Al, Cu, Au, Pb, Ni, Pt, Ag
- Coordination # = 12



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

Fig. 1.3 Face centered cubic structure (fcc)

1.3. 4ATOMIC PACKING FACTOR: FCC :-



Close-packed directions:

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

Unit cell contains:

$$6 \times \frac{1}{2} + 8 \times \frac{1}{8}$$

$$= 4 \text{ atoms/unitcell}$$

atoms
unitcell

APF =

$$\frac{4}{4} \frac{\pi}{3} \left(\frac{2a}{4} \right)^3$$

volume
atom

$$a^3$$

volume
unitcell

1.3.5 HEXAGONAL CLOSE-PACKED STRUCTURE :-

- In a hexagonal closest packed structure, the third layer has the same arrangement of spheres as the first layer and covers all the tetrahedral holes. Since the structure repeats itself after every two layers, the stacking for HCP may be described as "a-b-a-b-a-b." The atoms in a hexagonal closest packed structure efficiently occupy 74% of space while 26% is empty space.

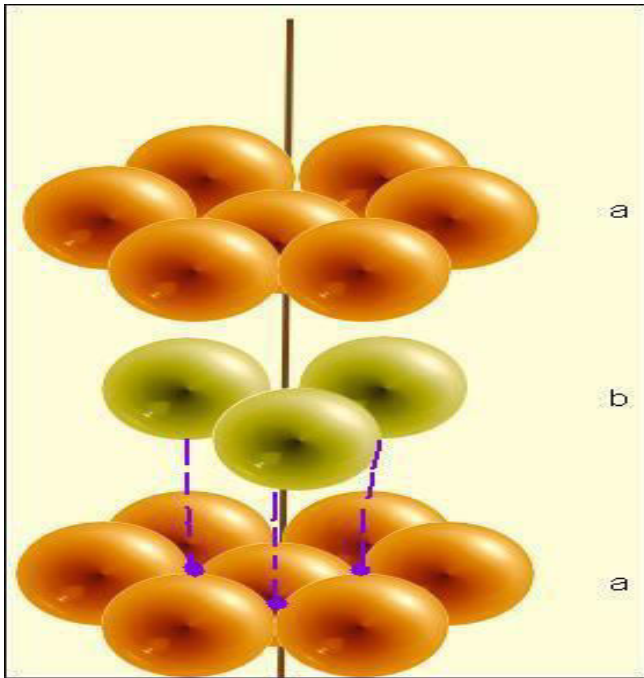


Fig. 1. 4 Hexagonal close-packed structure

1.4 VARIOUS MATERIALS UNDER BCC,FCC,HCP :-

Metal	Crystal Structure	Atomic Radius (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 (Alpha)	BCC	0.1241
Lead	FCC	0.1750
Magnesium	HCP	0.1599
Molybdenum	BCC	0.1363
Nickel	FCC	0.1246
Platinum	FCC	0.1387
Silver	FCC	0.1445
Tantalum	BCC	0.1430
Titanium (Alpha)	HCP	0.1445
Tungsten	BCC	0.1371
Zinc	HCP	0.1332

Table 1.1 Various materials under bcc,fcc,hcp

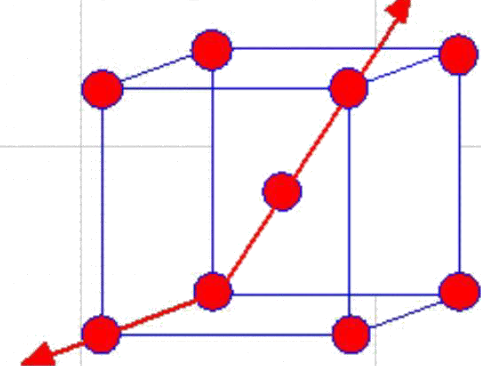
1.5 SINGLE VS POLYCRYSTALS :-

- Single Crystals

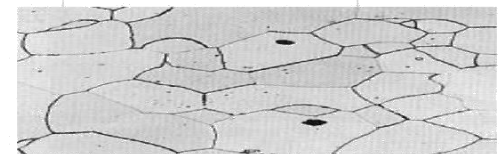
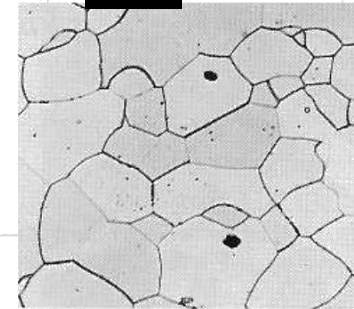
A single crystal is formed by the growth of a crystal nucleus without secondary nucleation or impingement on other crystals.

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

$$E \text{ (diagonal)} = 273 \text{ GPa}$$



$$E \text{ (edge)} = 125 \text{ GPa}$$



- Polycrystals
- an object composed of randomly oriented crystals, formed by rapid solidification
- Properties may/may not vary with direction.
 - If grains are randomly oriented: **isotropic**.
($E_{\text{poly iron}} = 210 \text{ GPa}$)
 - If grains are **textured**, anisotropic.

1.6 ISOTROPIC :-

- Substances in which measured (physical) properties are independent of the direction of measurement are isotropic.
- when the properties of a material are the same in all directions, the material is said to be **isotropic**. For many polycrystalline materials the grain orientations are random before any working (deformation) of the material is done. Therefore, even if the individual grains are anisotropic, the property differences tend to average out and, overall, the material is isotropic. When a material is formed, the grains are usually distorted and elongated in one or more directions which makes the material anisotropic. Material forming will be discussed later but let's continue discussing crystalline structure at the atomic level.

ANISOTROPY:-

The substance in which physical properties are show variation with changing the direction . Such substance are called anisotropic. A different chemical bonding in all directions is also a condition for anisotropy.

1.7 SINGLE VS POLYCRYSTALS :-

- Crystal is a homogeneous portion of a crystalline substance, composed of a regular pattern of structural units (ions, atoms or molecules) by plane surfaces making definite angles with each other giving a regular geometric form.
- A regular array of points (showing atoms/ions) in three dimensions is commonly called as a space lattice, or lattice.
- Each point in a space lattice represents an atom or a group of atoms.
- Each point in a space lattice has identical surroundings throughout.
- A three dimensional group of lattice points which when repeated in space generates the crystal called unit cell.
- The unit cell is described by the lengths of its edges, a , b , c (which are related to the spacing between layers) and the angles between the edges,

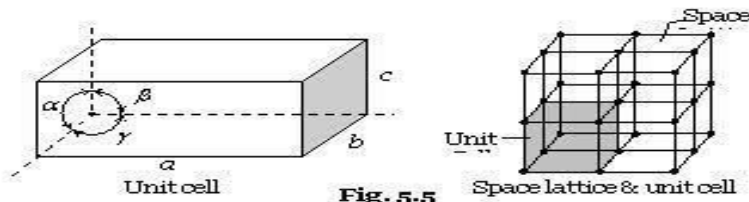


Fig. 1.6 Single vs polycrystals

1.8 CRYSTAL LATTICE :-

A regular three dimensional arrangement of constituent particles represented by point in space, is known as crystal lattice.

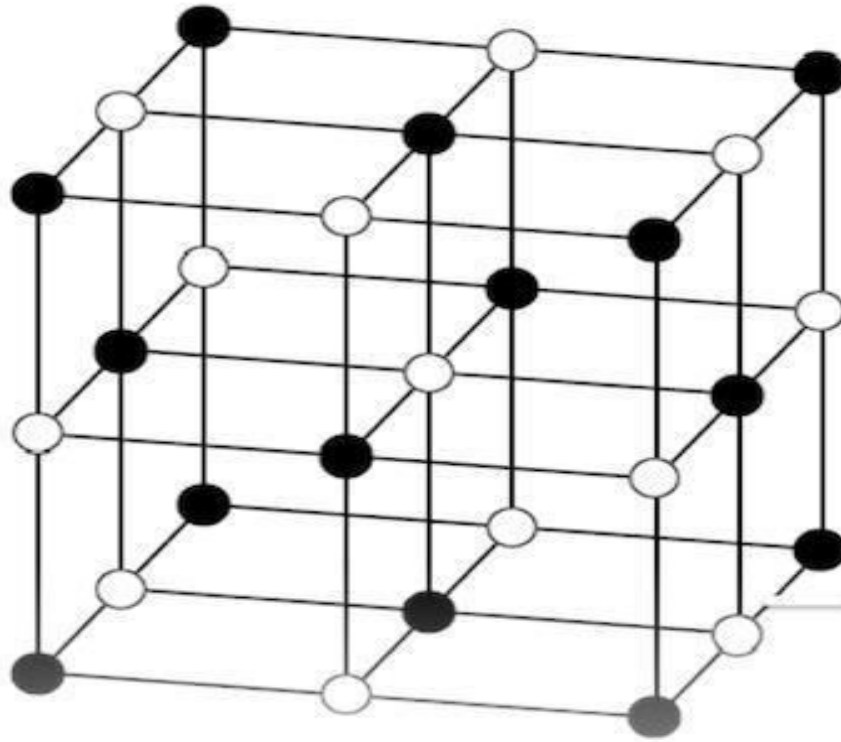


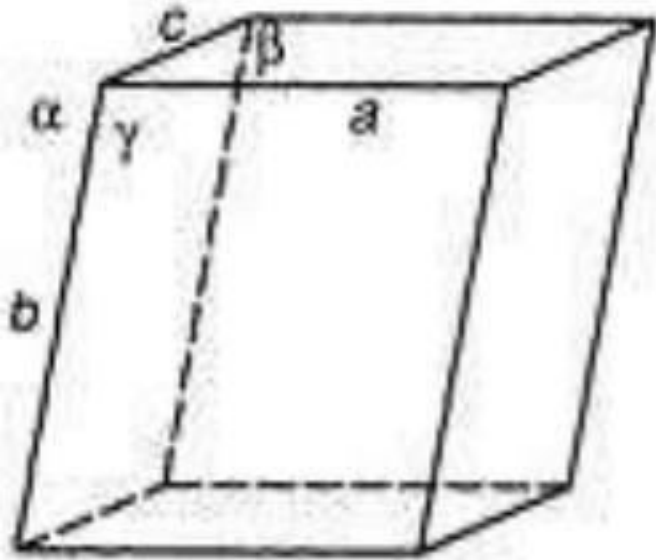
Diagram 1: Example of a Crystal Lattice Structure

Fig. 1.6 Crystal lattice

1.9 UNIT CELL :-

The Smallest portion of a crystal lattice is known as Unit Cell which when repeated in different direction generates the complete lattice.

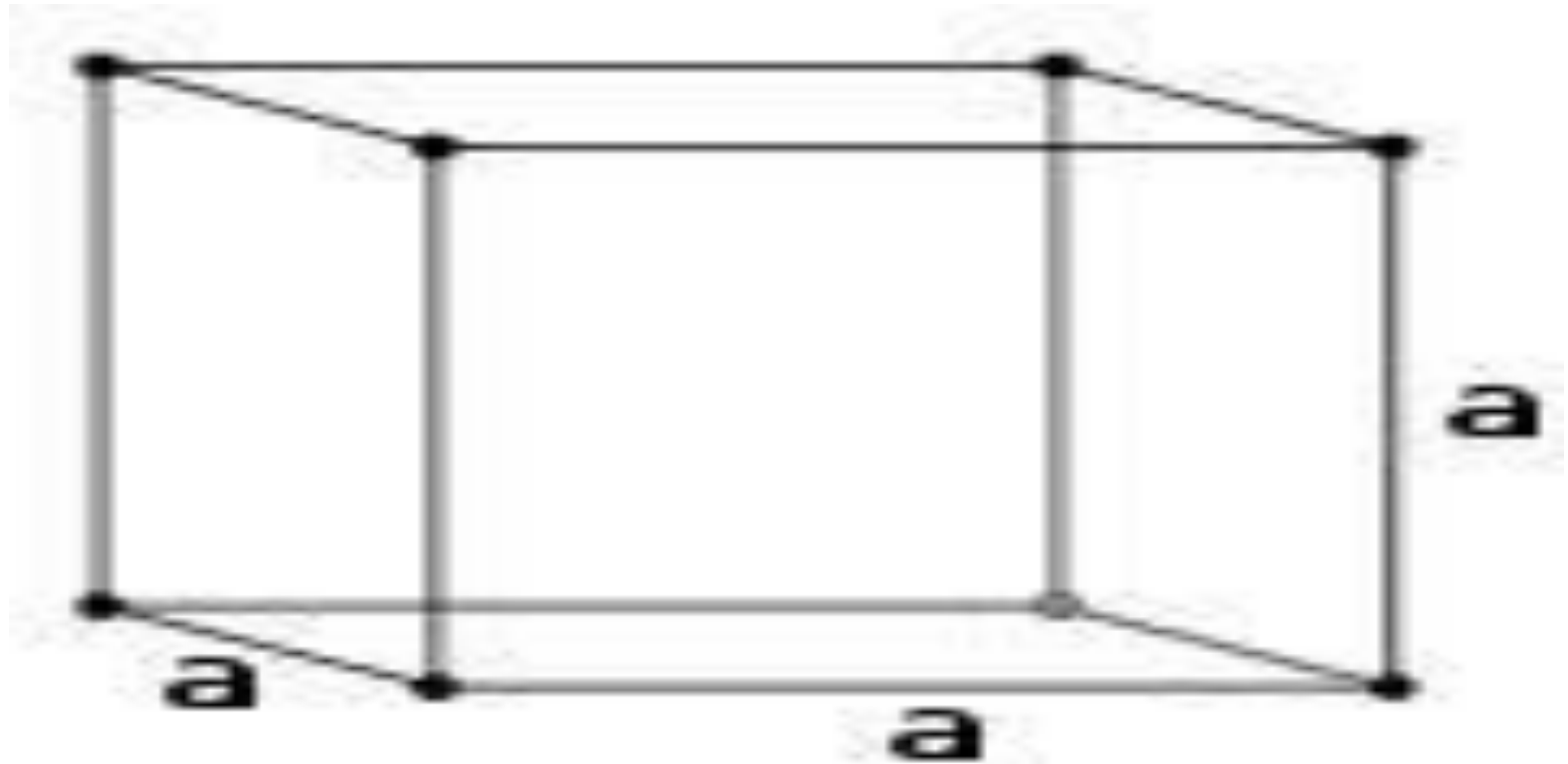
The Unit Cell



γ is the angle between a and b
 β is the angle between a and c
 α is the angle between b and c

Fig. 1.7 Unit Cell

1.10 CUBIC CRYSTAL SYSTEM :-



Axial Relationship $\rightarrow a=b=c$

Inter axial angle $\rightarrow \alpha=\beta=\gamma$

Fig. 1.8 Cubic crystal system

1.11 DEFECTS IN SOLIDS :-

1. Vacancy Defect:- This defect develops in any crystal when some lattice sites are empty. As a result, the density of the substance decreases. This Defects may develops when some substance heated.

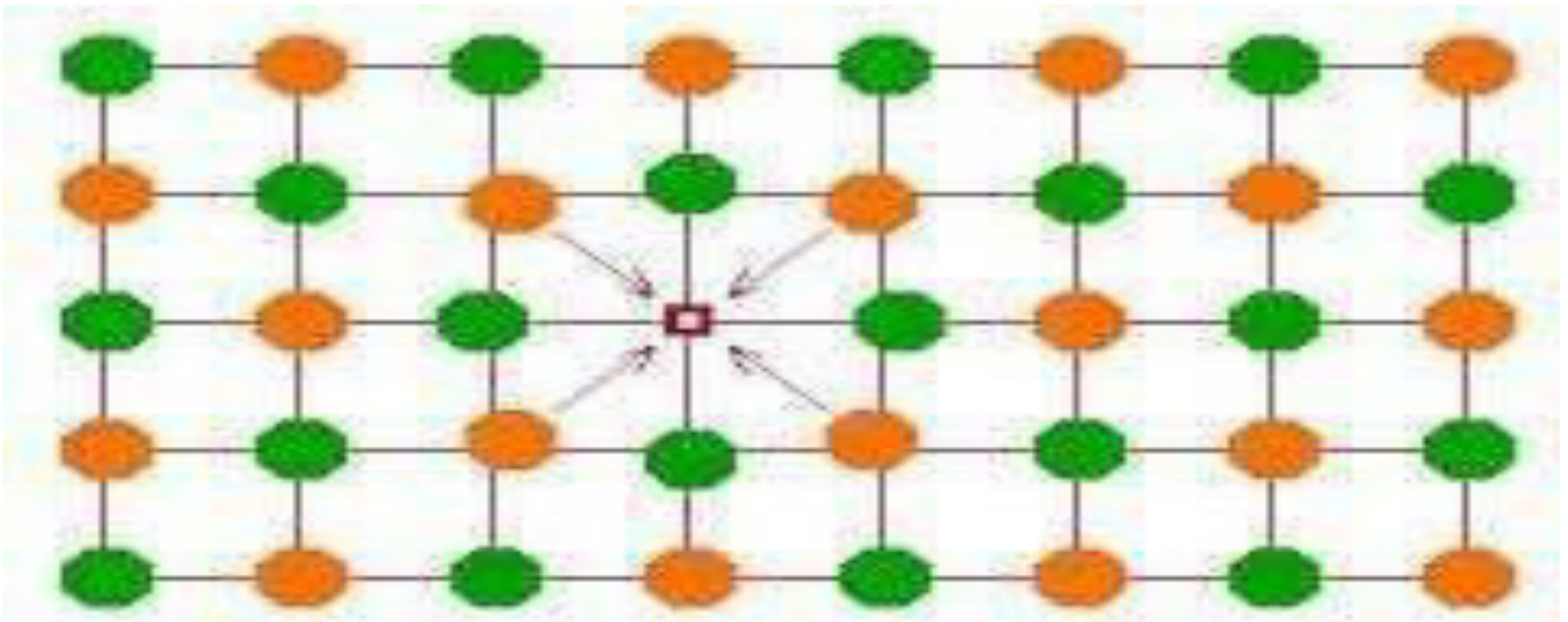


Fig. 1.9 Vacancy Defect

2. Interstitial Defect :- This defect develops when some constituents particles occupy interstitial sites. Due to this defects, the density of the crystal increases.

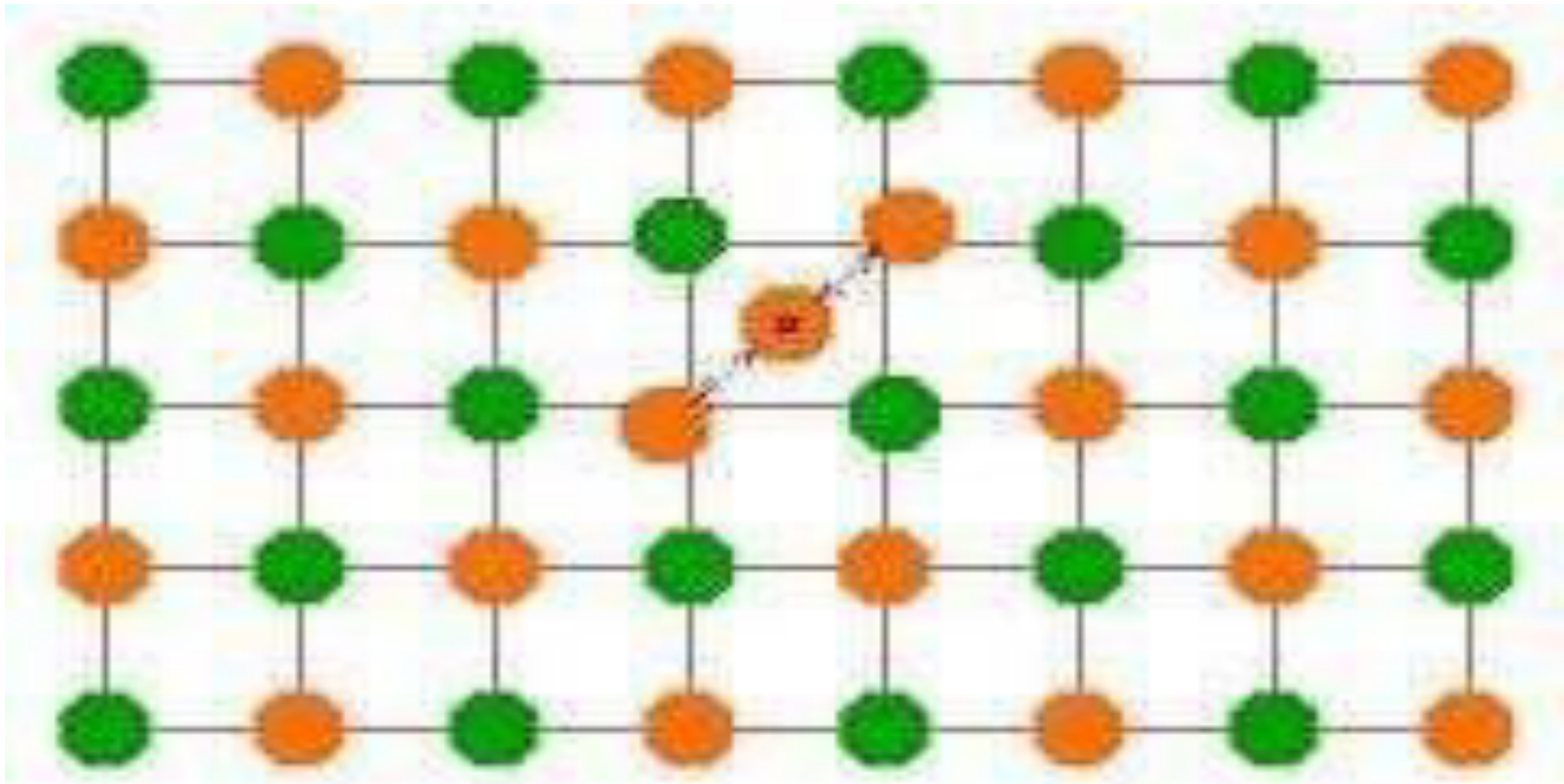


Fig. 1.10 Interstitial Defect

3. Frenkel Defect :- In this Defect smaller ion (cation) is dislocated from its original sites to an interstitial sites due to which vacancy defect is developed at its original location.

It is also called with the name Dislocation Defect.

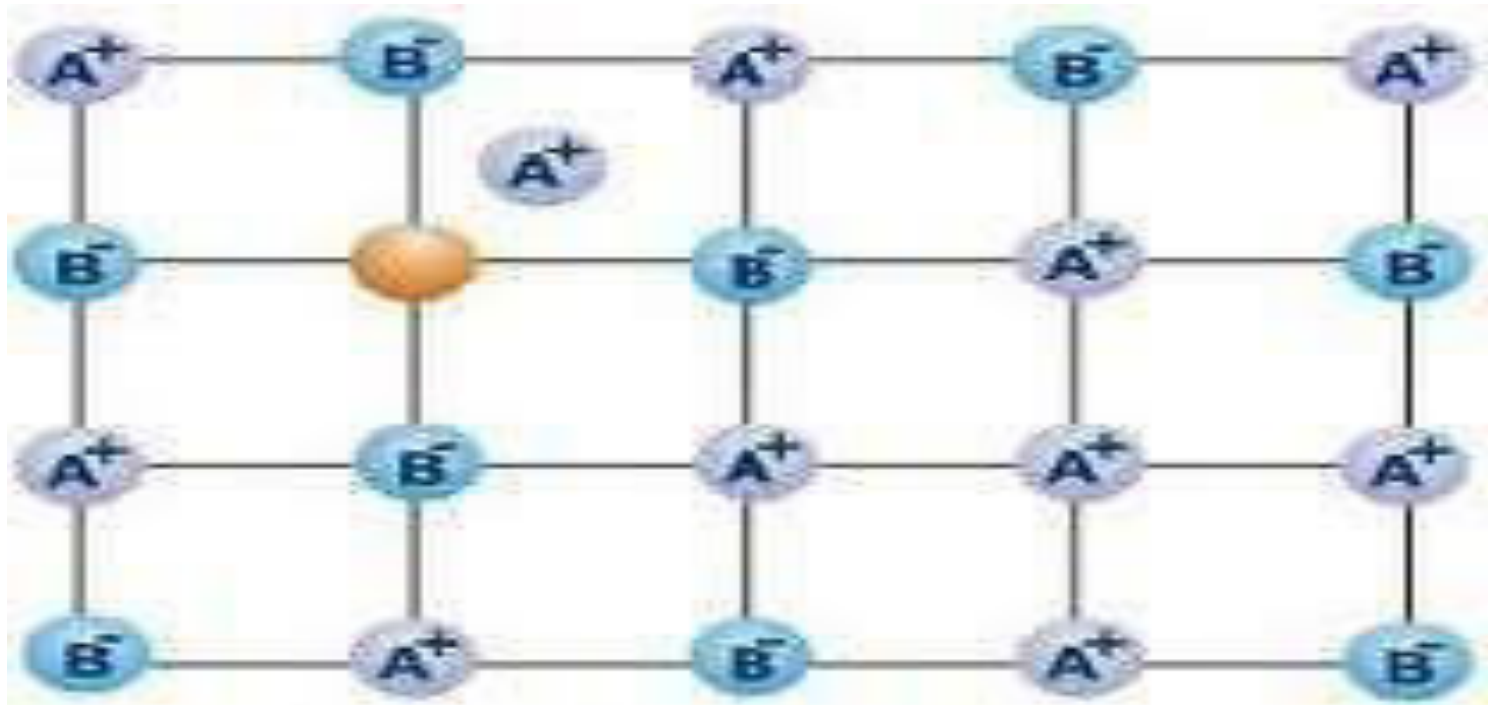


Fig. 1.12 Frenkel Defect

4. Schottky Defect :- This defect develops when some cation & anion are missing from their lattice sites due to which the crystal remain neutral. So, it is a vacancy defect in ionic solid. Due to Schottky Defect, the density of the crystal decreases.

This defect is shown by those ionic crystal solids in which the cations & anions are of almost similar sizes.

AgBr shows both frenkel & Schottky Defect.

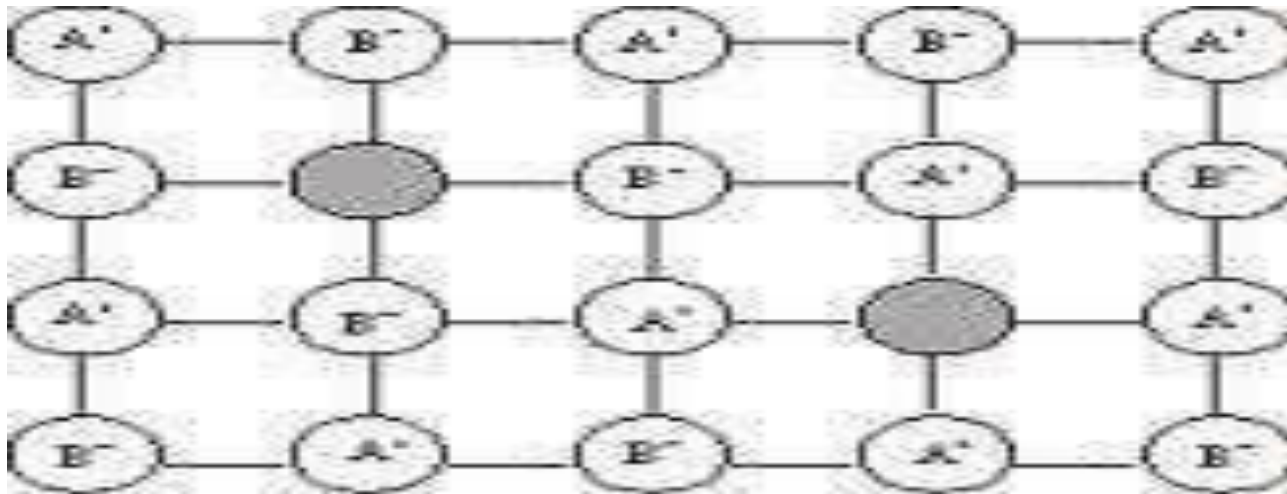


Fig. 1.13 Schottky Defect in AgBr

CONTENTS:-

UNIT-II THEORIES OF PLASTIC DEFORMATION :-

- *Theories of plastic deformation. Phenomenon of slip, twinning and dislocation. Identification of crystallographic possible slip planes and direction in FCC, BCC, HCP.*
- *Recovery and recrystallization, preferred orientation causes and effects on the property of metals.*

2.1 PLASTIC DEFORMATION :-

- If the solid body is loaded beyond the elastic limit, the body will experience a permanent change in shape and size, even if the load is removed .
- Plastic deformation of metals and alloys is generally studied under two categories namely,
 - i. Plastic deformation of single crystals.
 - ii. Plastic deformation of polycrystalline materials

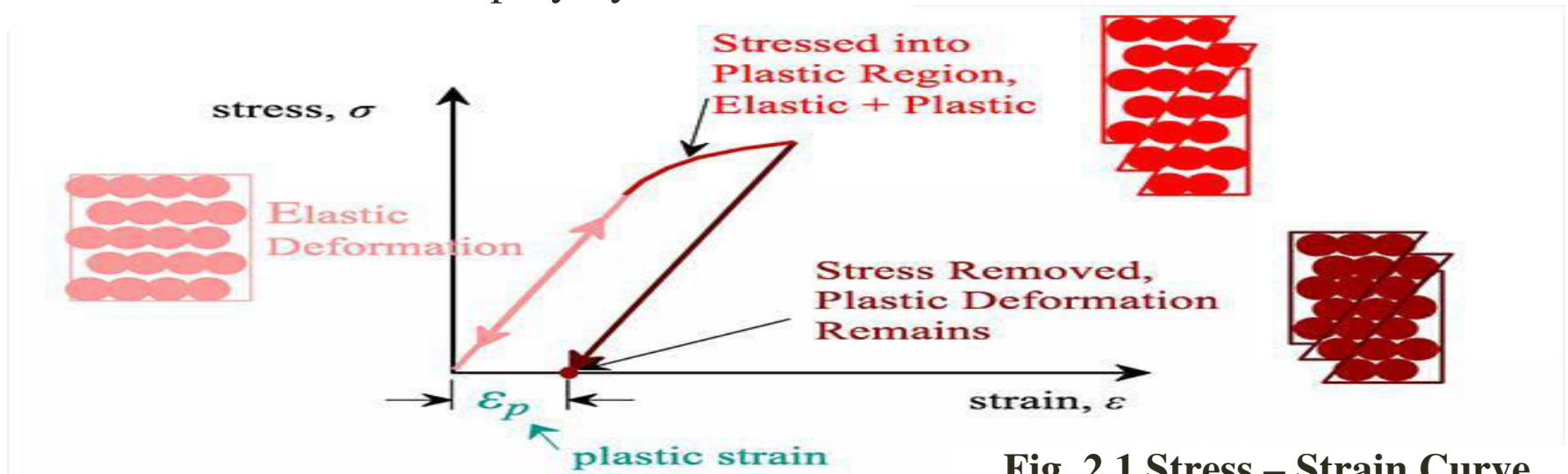


Fig. 2.1 Stress – Strain Curve

- Plastic deformation of single crystals involve the study of one single crystal and observing how it behaves under stress.
- A single crystal is nothing but a single grain and has no grain boundaries.
- Plastic deformation in single crystals may take place by
 - i. Slip
 - ii. Twinning or
 - iii. a combination of both.

2.2 PLASTIC DEFORMATION BYSLIP :-

- Slip is the most common mode of plastic deformation among crystals.
- When a single crystal in tension is stressed beyond its elastic limit, a step appears such that the single crystal divides into two blocks .
- When the tensile load is further increased, the blocks become again divided and relative displacement takes place.
- Slip occurs due to the movement of dislocations through the crystal as shown in below figure.

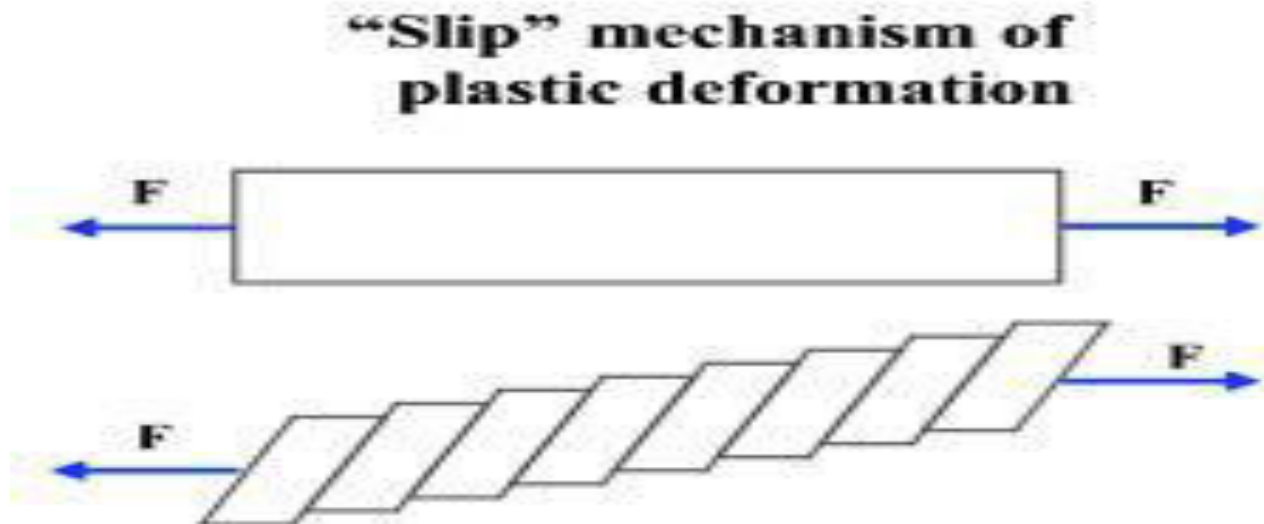


Fig. 2.2 Plastic deformation byslip

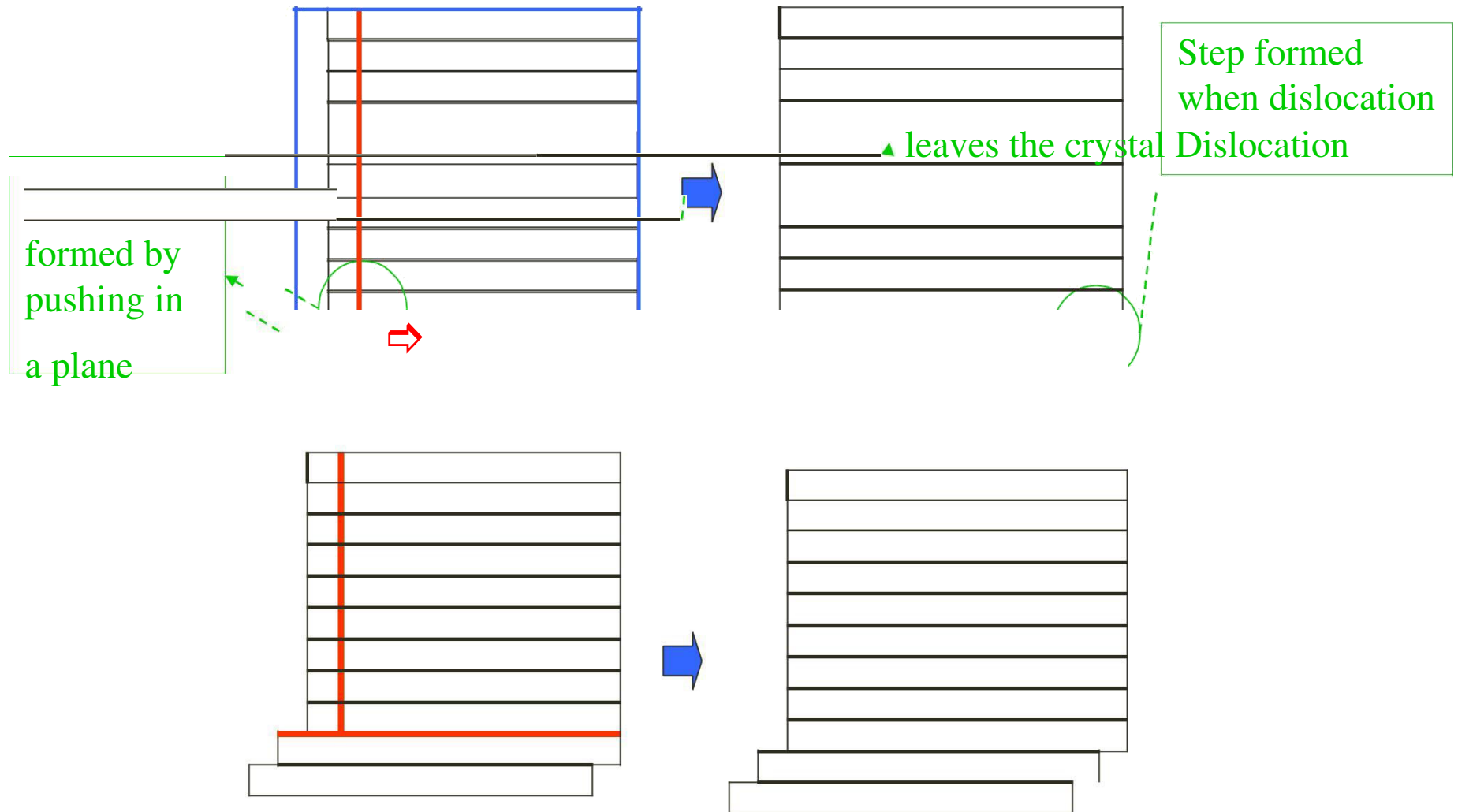


Fig. 2.3 Plastic deformation by slip

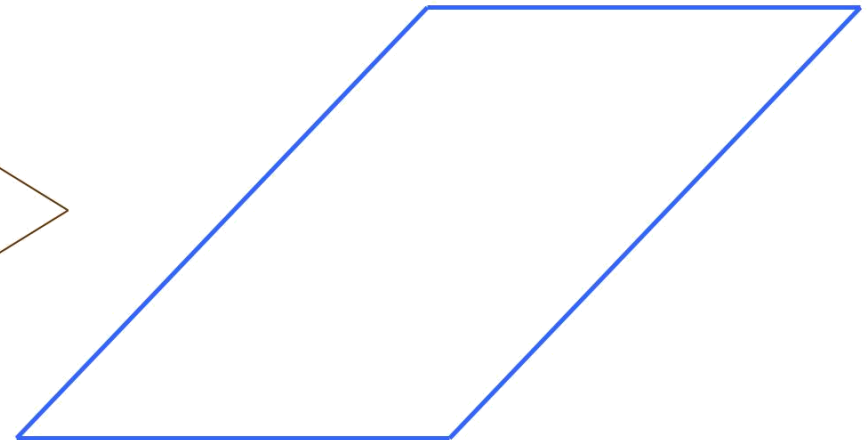
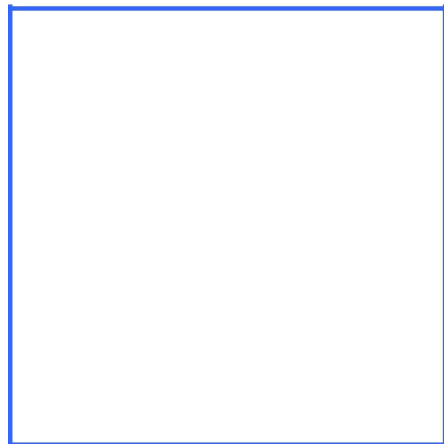
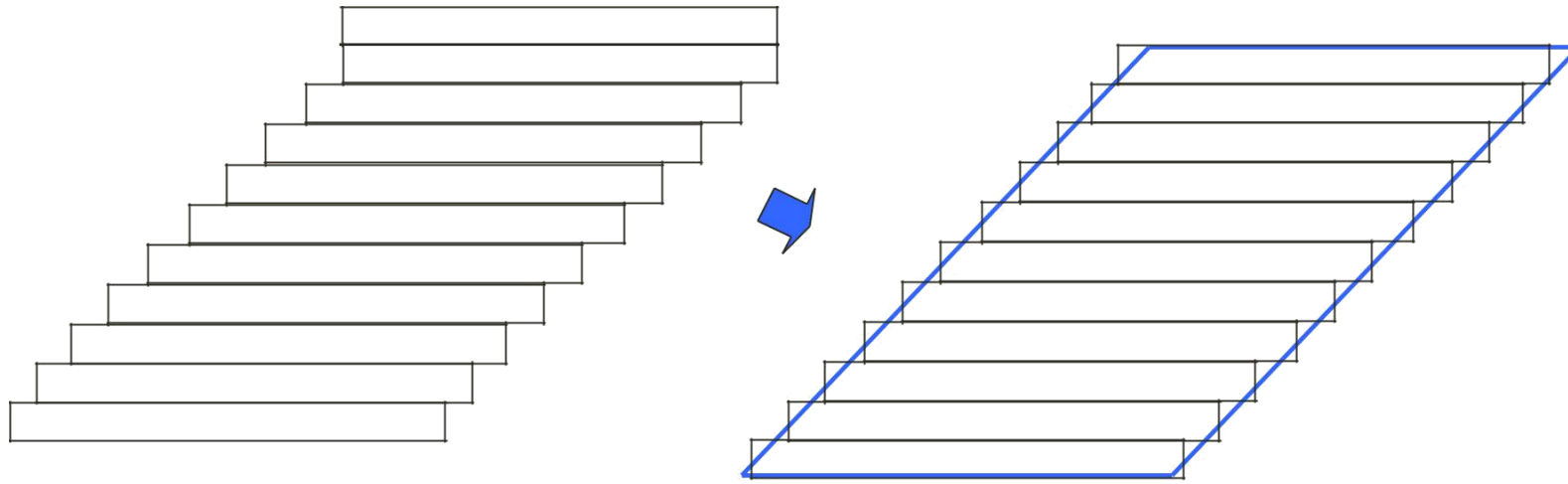
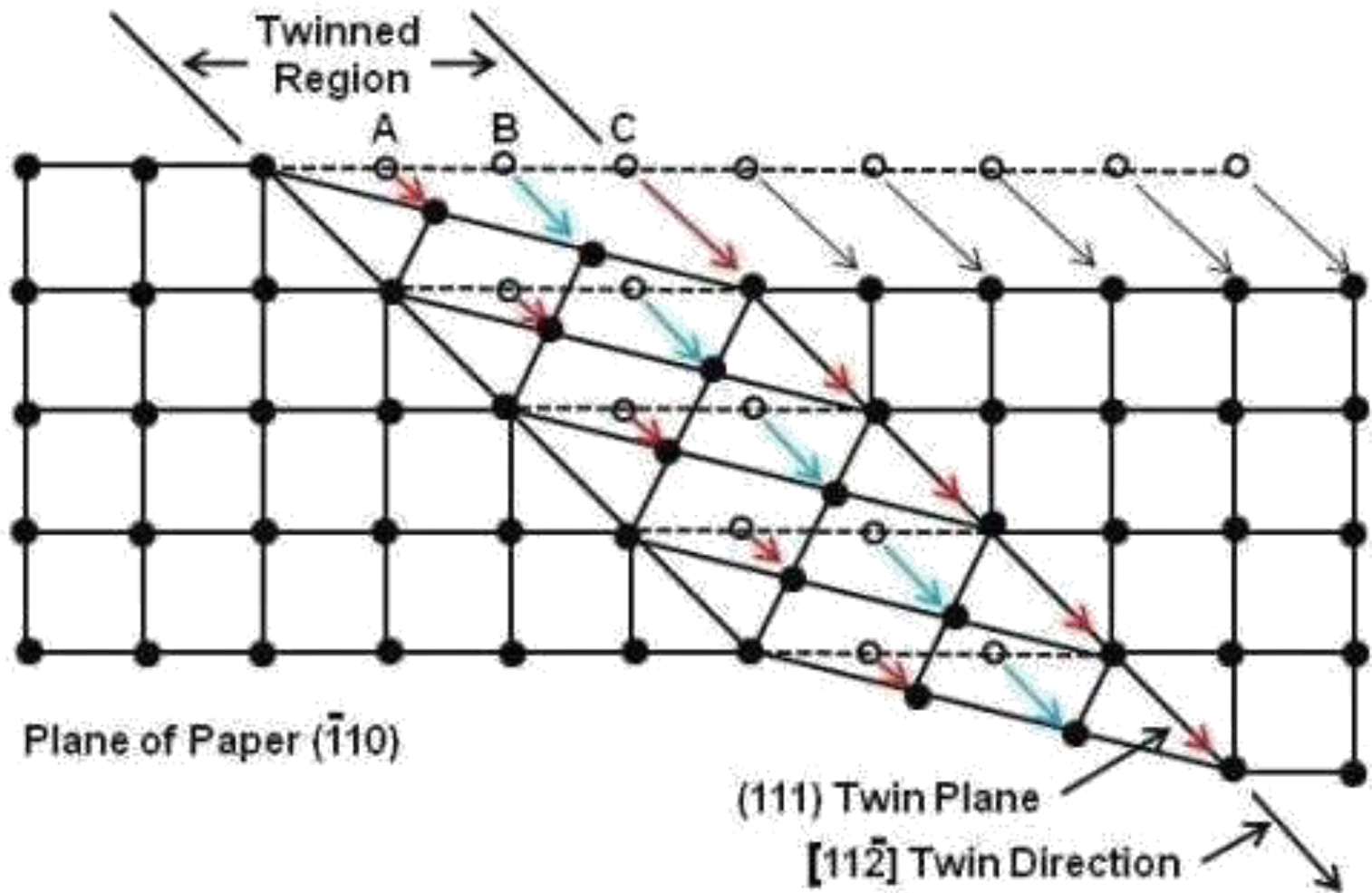


Fig. 2.5 Theory of twisting and shearing

This sequence of events finally leads to deformed shape which can be approximated to a rhombus

2.3 PLASTIC DEFORMATION BY TWINNING

- In twinning each plane of atoms move through a definite distance and in the same direction.
- The extent of movement of each plane is proportional to its distance from the twinning plane.
- When a shear stress is applied, the crystal will twin about the twinning plane in such a way that the region to the left of the twinning plane is not deformed whereas the region to the right is deformed.
- The atomic arrangement on either side of the twinned plane is in such a way that they are mirror reflections of each other.



Schematic Diagram of Twinning in an f.c.c. Lattice

Fig. 2.6 Theory of twisting in F.C.C lattice

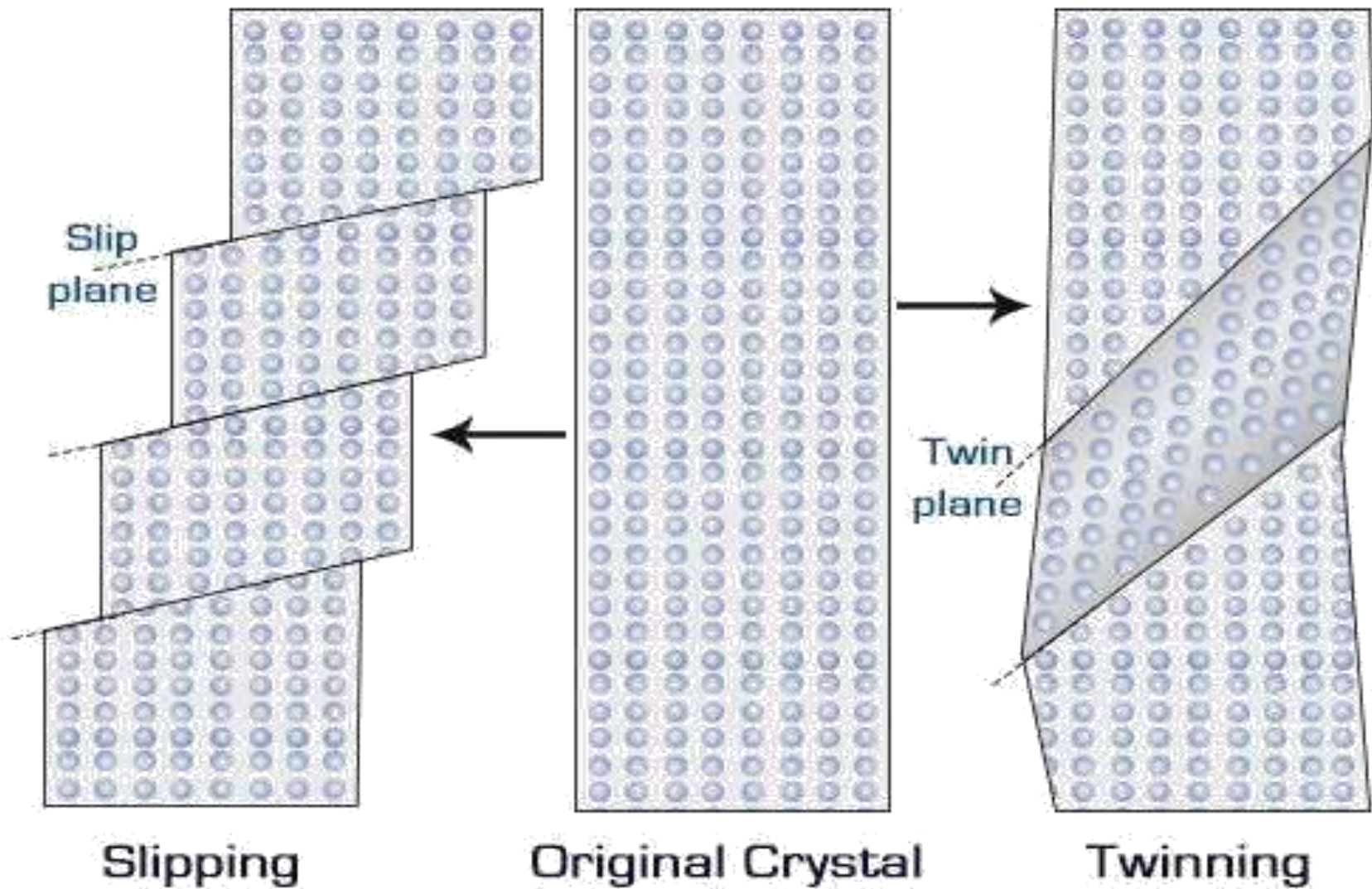


Fig. 2.7 Theory of Twisting and Slipping

CONTENTS:-

UNIT-III SOLIDIFICATION OF METALS AND ALLOYS :-

- *Classification of engineering materials. Solidification of metals and of some typical alloys: Mechanism of crystallisation (i) nuclear formation (ii) crystal growth. General principles of phase transformation in alloys, phase rule and equilibrium diagrams, Equilibrium diagram of binary system having complete mutual solubility in liquid state and limited solubility in solid state, Binary isomorphous alloy system. Hume-Rothery rule, Binary system with limited solid solubility of terminal phase and in which solubility decreases with temperature and also alloy with a peritectic transformation. Equilibrium diagram of a system whose components are subject to allotropic change.*
- *Iron carbon Equilibrium diagram, phase transformation in the iron carbon diagram (i) Formation of Austenite (ii) Transformation of Austenite into pearlite (iii) Martensite transformation in steel, TTT curves.*

GENERAL PRINCIPLE OF PHASE TRANSFORMATION IN ALLOYS

- The phase is a physically and chemically homogeneous portion of the matter.
- They may be solid, liquid and gases phases.
- But solid phase is more important in material science.
- A phase changes requires to change in properties.
- All pure materials are single phases materials, while alloys are both single phases and multi phases materials depending upon the solid solubility of the metals melted together to form a alloys.
- Steel and cast iron are the typical example of multi-phase alloys.
- The phase is defined by any homogeneous physically distinct part of a system which is mechanically separable and bounded by a definite surface.

- To fully understand phase diagrams. We must first define several terms commonly used to interpret and discuss these plots.
- a. **SYSTEM** :- A series of possible metal mixture (called alloys) consisting of the same components, but without regard to alloy composition.

for example:- Fe-C system
- b. **PHASES** :- A phase in a material in terms of its microstructure is a region that differs in structure and/or composition from another region.

As a atoms/molecules in a gases are mixed at atomic/molecular level therefore the gaseous state is a single phases.

C. COMPONENTS: - components refer to the independent chemical species that comprises the system. The components of a system may be elements, ions and components.

for example :- in ice-water system, the component = H_2O .

D. DEGREE OF FREEDOM :- The degree of freedom (F) are those externally controllable conditions of temperature, pressure and composition which independently variable and which must be specific in order to define completely the state of the system at equilibrium.

E. EQUILIBRIUM PHASE :- A phase which minimize a system free energy for a specified combination of temperature, pressure and compositions.

F. METASTABLE (OR NON- EQUILIBRIUM) PHASE :- A phase that can be produced by a very rapid change in system conditions(i.e temperature of Pressure) in some cases, the metastable state may persist indefinitely, as the movement towards equilibrium is virtually imperceptible over long period of time. This is very important for the processing of the materials.

G. SOLID SOLUTION :- A mixture of two (or more) types of atoms in which the solute atoms occupy either substitution or interstitial positions within the solvent lattice and the crystal structure of the solvent is maintained.

H. SOLUBILITY LIMIT :- The maximum concentration of solute atoms that can dissolved in a solvent to form a single phase i.e is the limit or exceeded, another solid solution or component of different composition will form.

I. MICROSTRUCTURE: - The microscopic structure of an alloy (i.e spatial arrangement of phases) as viewed using an optical or electron microscope of note, the term microstructure refers to features on the scale of micrometers.

- Phase diagram are classified on the basis of the number of components in the system.
- Single component system have unary diagram.

- Two component system have a binary diagram.
- Three component system have a ternary diagram.

J. PURE SUBSTANCES :- a pure substance (solid, liquid, gases) made of one chemical species only has one phase.

Example: - oxygen (O_2), ice (H_2O)

K. MIXTURE OF GASES: - a mixture of gases say H_2 , N_2 and O_2 contribute one phase only as all gases mix freely to form a homogeneous mixture.

L. AQUEOUS SOLUTIONS: - A aqueous solution of a solid substance such as NaCl is uniform throughout. So, there is only one liquid phase.

3.2 COOLING CURVE :-

- The best way to monitor the process of solidification is to measure its temperature by a thermocouple. Figure 1 gives a plot of temperature (T) as a function of time (t). It shows that temperature keeps dropping continuously till it reaches a temperature when cooling stops till the liquid gets transformed totally into solid. Thereafter temperature keeps dropping again.
- **Fig 3.1:** Shows cooling curve of pure metal as it cools from liquid state. Gibb's phase rule gives a simple relationship between numbers of phases (P), number of component (C), and degree of freedom (F) for a given system. This is stated as $P + F = C + 2$. Note that $C = 1$ since it is a pure metal & $P = 1$ since there is only one phase above T_m (melting point). Therefore $F = 2$. It means this state can have 2 controllable variables. These are temperature and pressure.

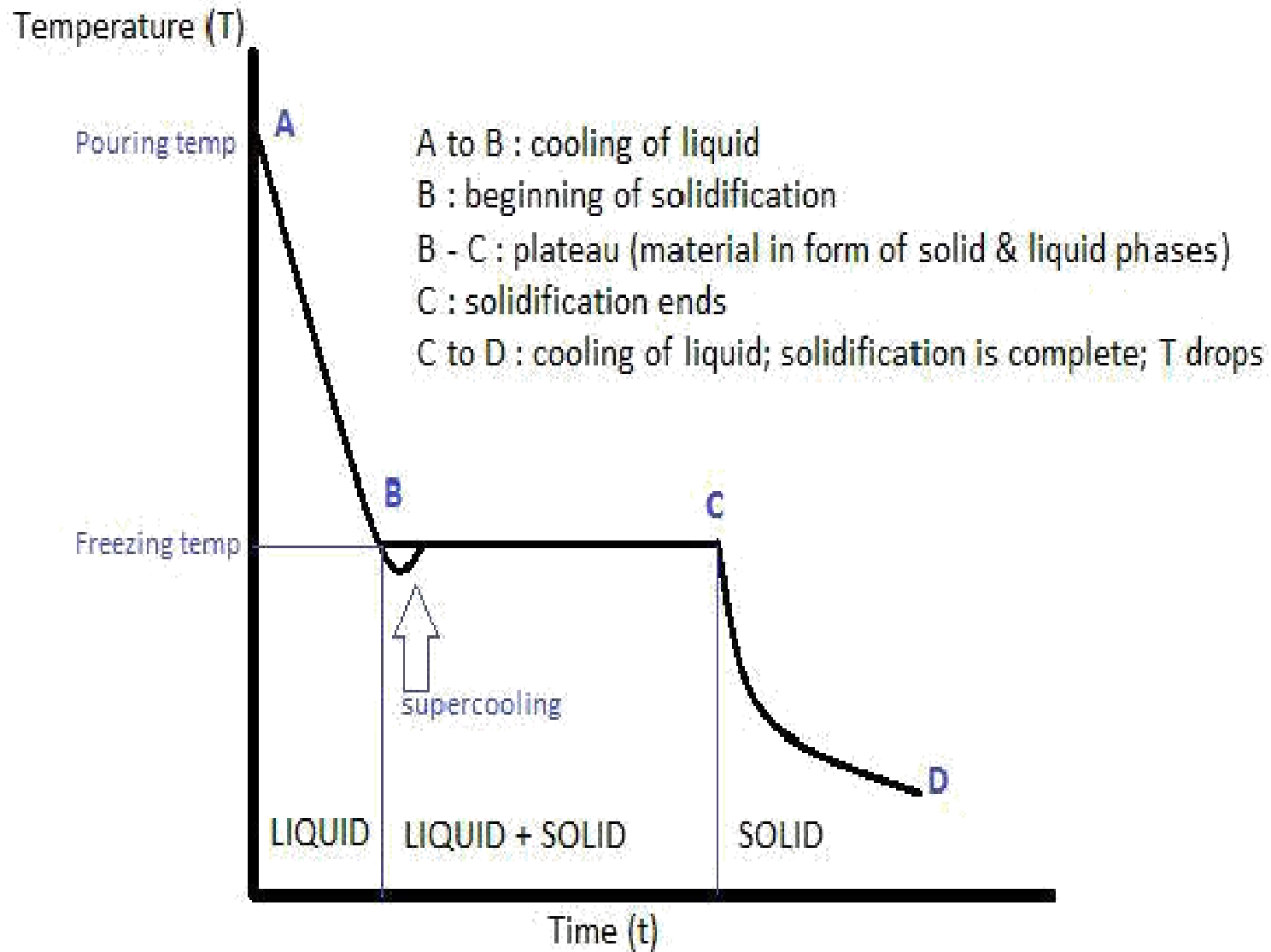


Diagram showing cooling curve of a pure metal

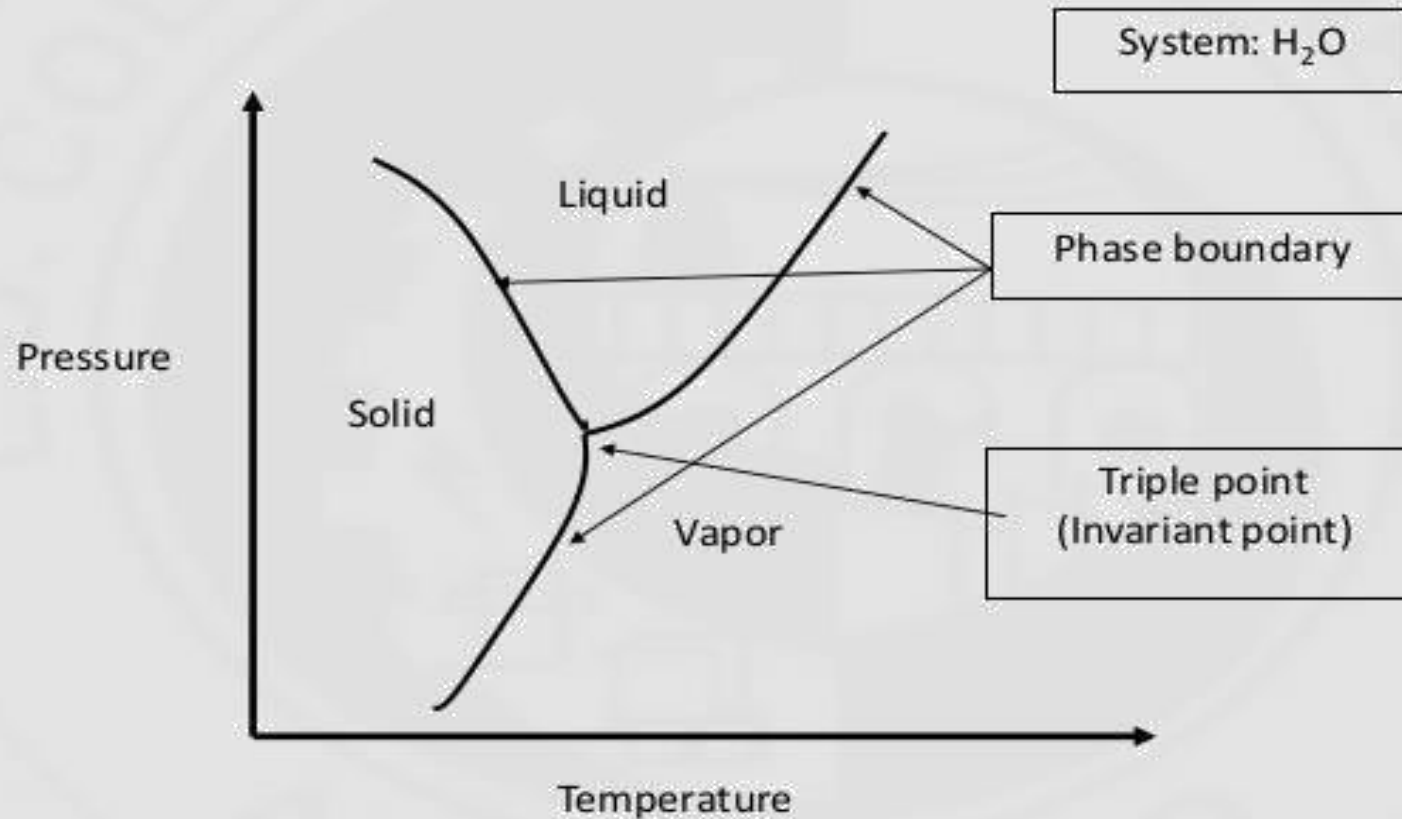
3.3 GIBB'S PHASE RULE ($P+F = C+2$) :-

- The degree of freedom that determines the number of control parameters (like temperature, volume, pressure, composition) for any closed system follows Gibbs phase rule as stated in the caption of fig1. Above the melting point this is equal to 2. Clearly these variables here are the temperature and pressure.
- The cooling curve given above has been obtained at atmospheric pressure which is of course fixed. Therefore what the phase rule tells us is that the liquid state is stable over a range of temperature.
- Let us apply this to the state where both liquid and solid can co-exist. Here $P = 2$ and $C = 1$. From phase rule $F = 1$. This state can have only one variable which in this case is pressure.
- This means in the case of a pure metal liquid & solid can coexist only at a definite temperature which happens to be its melting point.

3.4 PHASE DIAGRAM OF PURE METAL :-

- Phase diagram of a pure metal or a substance is a graphical representation of the domain in which a given state is stable. For example it gives the range of temperature and pressure over which it exists as solid (S), liquid (L) or gas (G). Figure 2 gives a typical phase diagram of a pure metal.
- **Fig 3.2:** A schematic phase diagram of a pure metal indicating the pressure temperature domain where it can exist as solid, liquid or gas. The line indicates boundary between two phases. On any point on the line two phases are equally stable. There is a point where three lines meet. This is a critical point (triple point) where three phases can coexist. Apply phase rule. This gives $F=0$ meaning that it has no degree of freedom. Three phases can coexist only at a fixed temperature & pressure. For water the triple point is at 0.006 atmosphere 0.01°C .

A simple phase diagram



3.5 GIBB’S FREE ENERGY (G) :-

- Gibb’s free energy (G) is a measure of the stability of a phase at a given temperature and pressure.
- The lower the free energy higher is its stability.
- At a given temperature (T) this is defined in terms of molar enthalpy (H) and molar entropy (S) of a particular phase as follows:-

$$G = H - T S1$$

- This can be written in differential form in terms of pressure (P) & temperature (T), the two common variables for most transformation processes, as:-

$$dG = V dP - S dT2$$

- The equation 2 is valid both for solid and liquid. Let us write these explicitly for the two using subscript S (for solid) & L (for liquid).
- Figure 3 gives a schematic plot showing how free energy varies with temperature for the two phases at 1 atmosphere pressure. The point where the two lines intersect denotes the melting point at 1atm.

$$dGL = VL dP - SLdT - \text{ for liquid }3$$

$$dGS = VS dP - SsdT - \text{ for solid }4$$

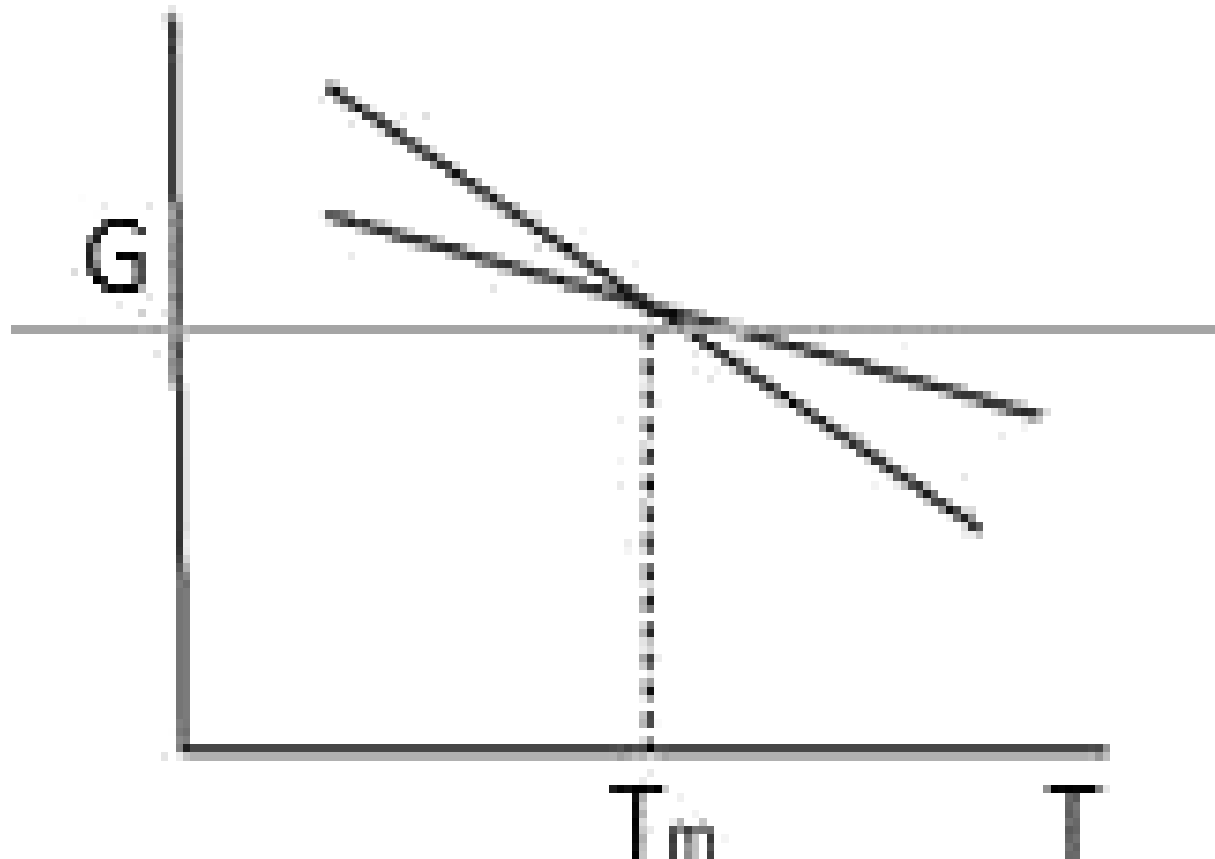


Fig 3.3: A sketch showing how G varies as a function of T for solid (S) and liquid phase (L). The two intersect at melting point T_m . Below this temperature solid is stable whereas above T_m liquid is stable. At any temperature the difference between the two is the driving force for the transformation.

At the melting point the free energy of solid and liquid should be the same.

Equating equation 3 & 4 and subsequent rearrangement of the terms one gets the following expression:-

$$\frac{dP}{dT} = \frac{S_L - S_S}{V_L - V_S} = \frac{T_m}{T_m} \left(\frac{\Delta S_{L-S}}{\Delta V_{L-S}} \right) = \frac{\Delta H_{L-S}}{T_m \Delta V_{L-S}}$$

Apply this to ice making. When water becomes ice there is an increase in volume and it is accompanied by release of heat.

Therefore V_{L-S} is positive; whereas H_{L-S} is negative.

Consequently (dP/dT) or the slope of the line denoting L-S equilibrium should be negative signifying that at higher pressure ice forms at lower temperature.

3.6 MECHANISM OF CRYSTALLIZATION :-

• **CONCEPT OF NUCLEATION AND GROWTH** :-



Solidification takes place by nucleation and growth.



Atoms in a solid or in a liquid are never stationary.



Assume that in a pool of molten metal there is a virtual boundary that separates a potential stable nucleus (embryo) from the surrounding liquid. Such virtual nuclei infinitesimally small in size may be assumed to be present in the liquid that is about to solidify. Atoms keep trying to cross the barrier.



Let ν_0 be the number of attempts per unit time made by an atom to cross the boundary. The number of successful attempt is given by the Boltzmann statistics. This is represented mathematically as follows:

$$\nu = \nu_0 \exp \left(-\frac{E}{kT} \right)$$

- ✓
Note that k is Boltzmann constant and E is the energy needed by atom to overcome the barrier to cross the boundary.
- ✓
In this case this corresponds to $fT \max.$ (where f is the size of the atom)
- ✓
However this represents the total energy needed by all the atoms in a unit volume (n).
- ✓
Therefore the energy needed by a single $E = fT \max / n$.
- ✓
This shows that with increasing E the probability of formation of stable nuclei should decrease.
- ✓
Once stable nuclei form they would continue to grow. Initially the growth occurs at same rate in all direction until the growth is hindered due to impingement.
- ✓
The size of the grains may differ depending on whether it developed from a nucleus formed right in the beginning or towards the end of the process. This is shown pictorially in fig 9.

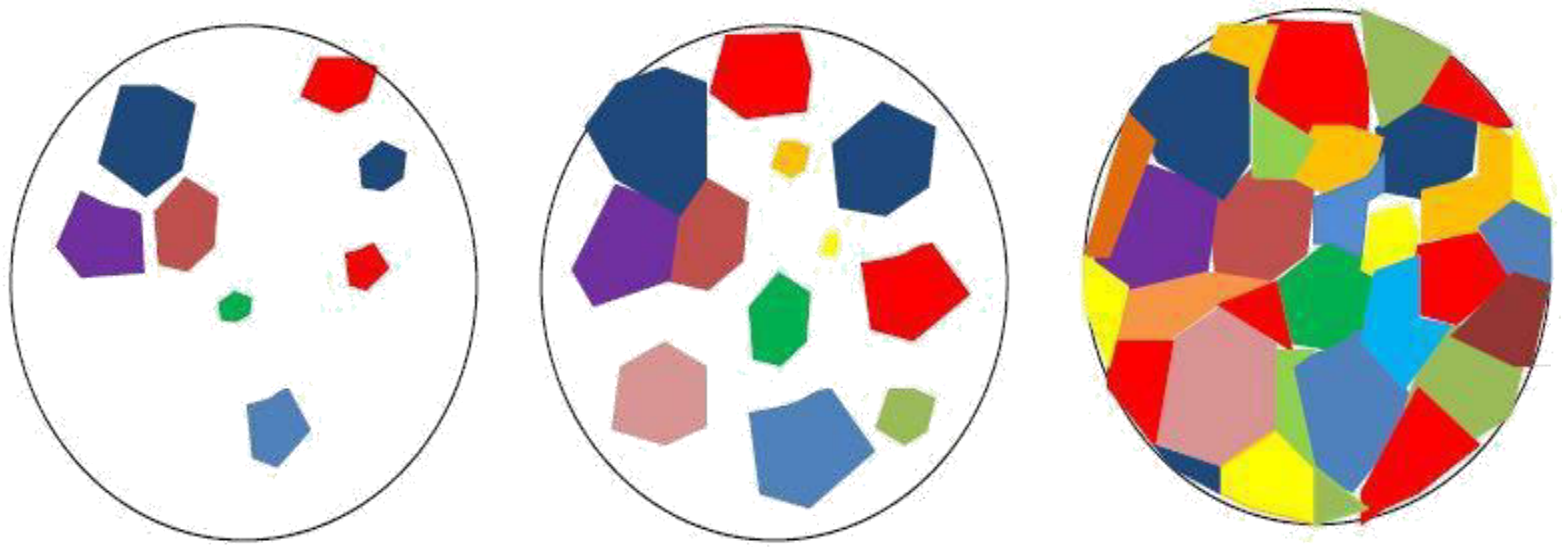


Fig 3.4: A sketch showing a schematic representation of nucleation and growth of solid nuclei during solidification from the molten liquid state. Colours denote different orientations of grains. (a) Initially there are fewer nuclei. Some of them have grown. (b) Shows that growth ceases along certain directions due to impingement. A few more nuclei have formed. All of these continue to grow. (c) Shows a state when most of the space is filled up indicating that the process is nearly complete. Grains appear to be randomly oriented.

3.7 GRAIN ORIENTATION:-

- The process of nucleation described above is totally random. Grains may nucleate anywhere in the melt. It is also known as homogeneous nucleation.

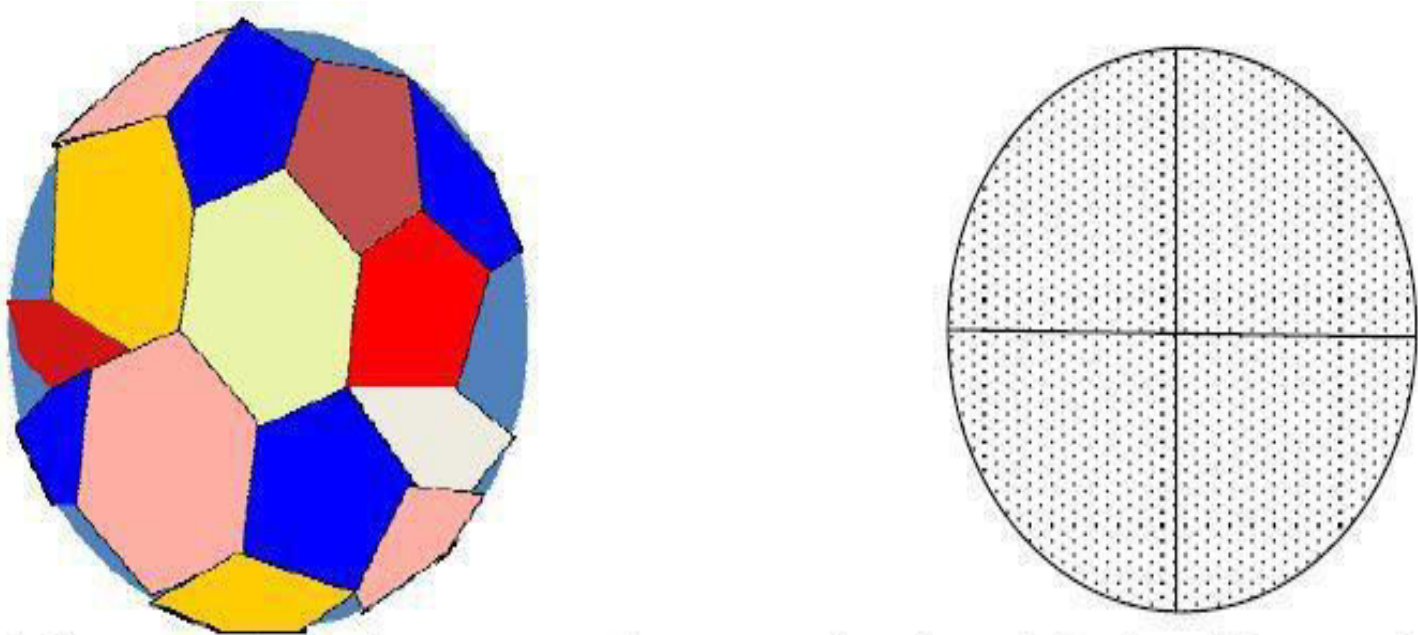


Fig 10: (a) Shows a typical microstructure of pure metal each grain having different orientations. Sometimes grain lustre depends on its orientation. (b) This shows distribution of $\langle 001 \rangle$ poles of all the grains on a standard projection. This type of diagram is known as pole figure.

Homogeneous versus heterogeneous nucleation

3.8 HOMOGENOUS VS HETROGENOUS NEUCLEATION :-

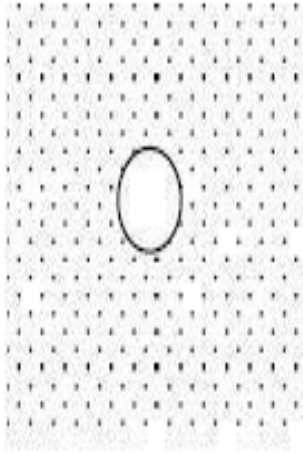


Fig 11 a) A sketch showing homogeneous nucleation of a solid spherical ball in a molten pool of metal in a hypothetical mould without any boundary.

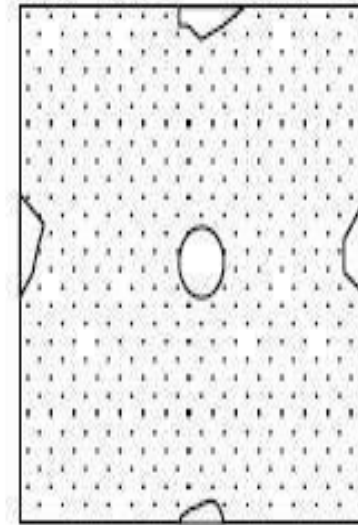


Fig 11 b) Sketch showing a case where apart from an embryo at the centre there are several nuclei each formed on the interface between the mould wall and the liquid metal.

3.9 PHASE DIAGRAM OF PURE IRON :-

- Iron can exist in more than one crystalline form.
- Melting point of pure iron is 1539°C.
- If it is cooled from its molten state it first solidifies in the form a bcc phase. This form of iron is known as **ferrite**.
- As the temperature goes down at 1400°C it transforms from phase to fcc phase. This is commonly known as iron or **austenite**.
- Later at 910°C it again transforms into bcc crystal known as **ferrite**.
- Each of these transformations is associated with a change in volume and

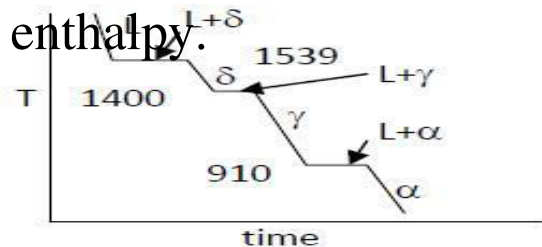


Fig 4: Cooling curve for pure iron showing three steps representing following transformations:

L = δ at 1539°C
 δ = γ at 1400°C
 γ = α at 910°C

Fig. 4.5 Phase transformations Diagram

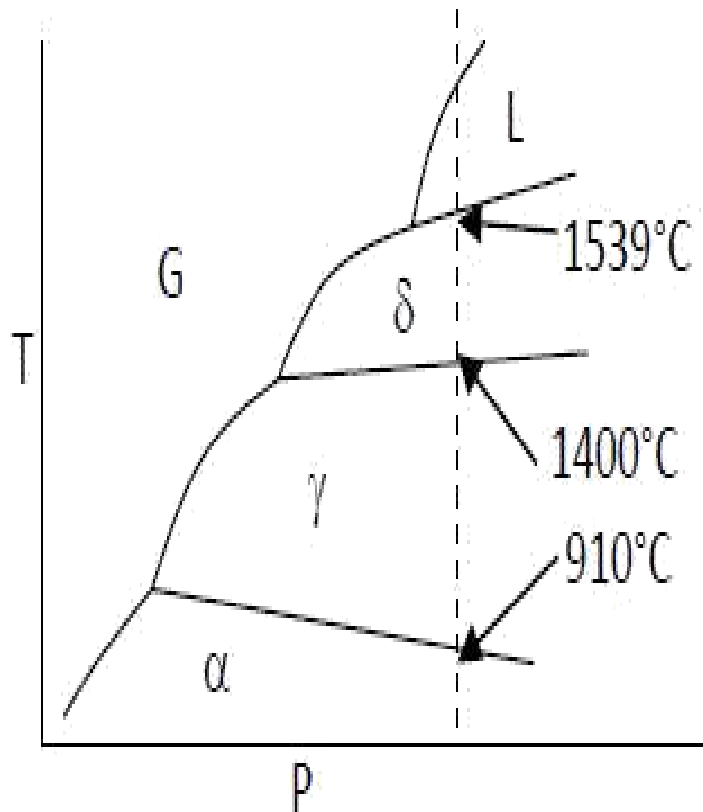


Fig 5: A sketch showing the phase diagram of pure iron. This gives the stability of α , γ , δ , L & G phases in various temperature pressure domains.

- The phase diagram of pure iron is shown in above figure. This shows the effect of pressure on the temperatures at which transformation of iron from one crystalline form to another takes place.

3.10 REAL COOLING CURVE: SUPER (UNDER) COOLING :-

- The cooling curve of a pure metal as shown in fig 1 is indeed an idealization of the solidification process. In reality the transformation from liquid to solid state begins only after it has cooled below its melting point.
- Figure 3.6 shows a sketch of real cooling curve.
- **Fig 3.6: A sketch showing real cooling curve.** Along with this G versus T plot of the solid and liquid phases have been shown. At a temperature lower than its melting point $G_S < G_L$ signifying S is more stable than L.

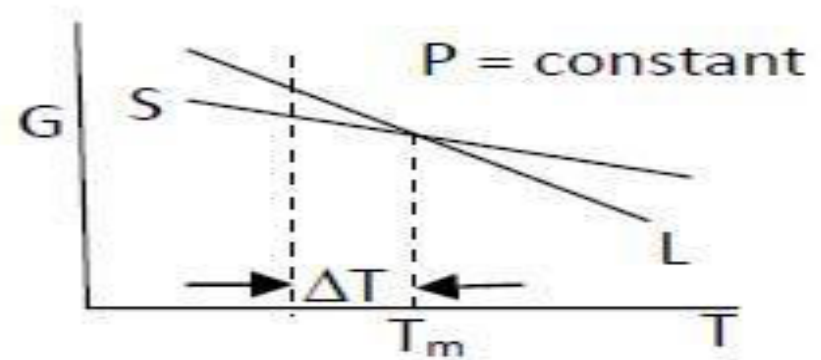
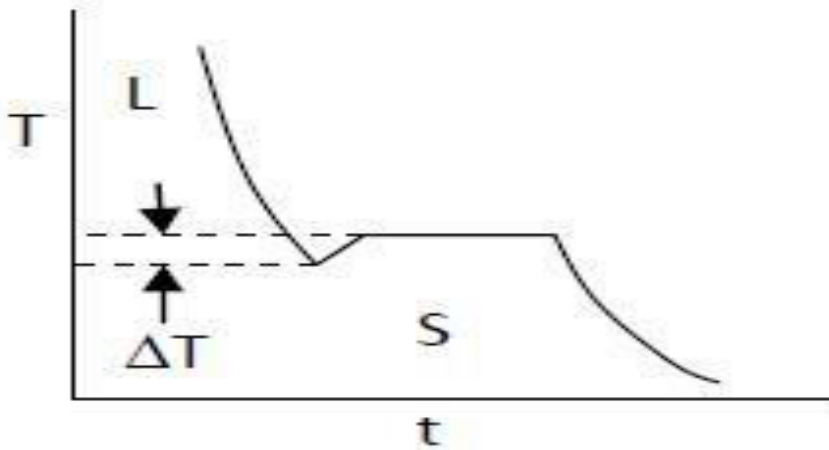


Fig. 3.6 Super (under) Cooling

When a solid forms in a pool of liquid a new surface is created (see fig 7). This has a finite energy. It is seen from fig 6 that $G_S < G_L$ when solidification begins. This difference in free energy acts as the driving force for solidification.

- Once this is large enough for a stable nucleus of solid to form then process of solidification begins. Until then unstable nuclei may appear and disappear again and again. Soon after a stable nucleus forms it keeps growing. Thus the process of solidification can be visualized as one of nucleation and growth.
- Fig 4.7: A sketch showing a spherical nucleus of solid of radius r formed in a pool of liquid. This has a volume $\frac{4\pi}{3}r^3$ and surface area $4\pi r^2$. The creation of a new surface needs energy. Note that $G_S < G_L$, $\Delta G_L - S < 0$. This can help do so. Assuming that surface energy / unit area is σ and free energy change /unit volume is f_v it is possible to derive an expression for the total change in energy for solidification.

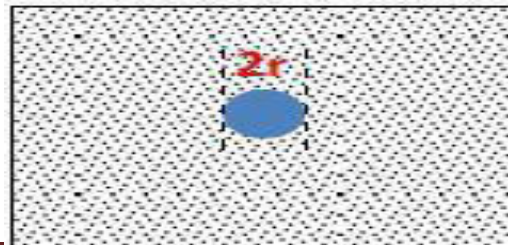


Fig. 3.7 Sketch of pool liquid

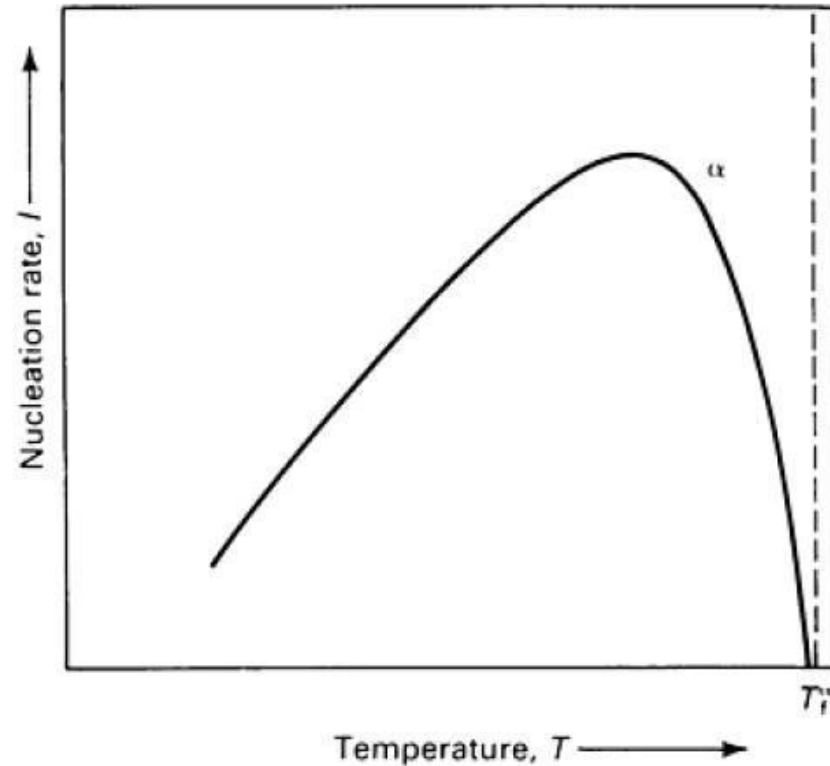
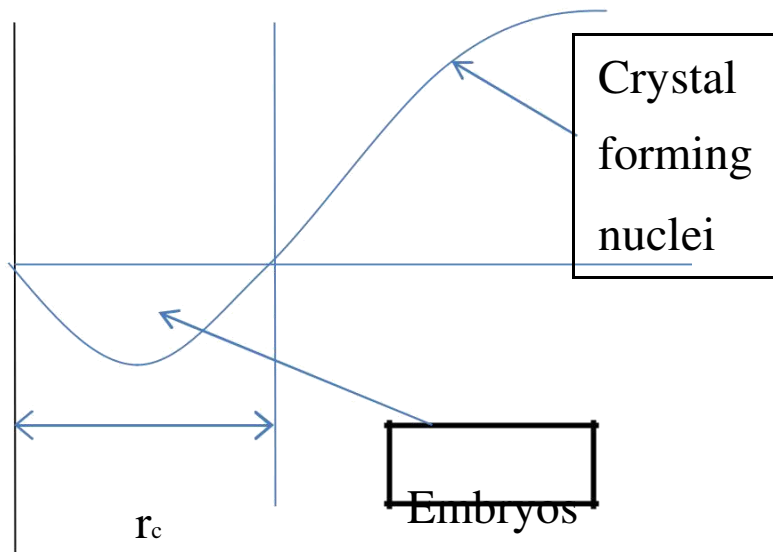
3.11 SOLIDIFICATION :-

- SOLIDIFICATION :
 - Process of a material of transforming from liquid to solid state is called solidification.
- STEPS IN SOLIDIFICATION :
 - Liquid state
 - Nucleation
 - Crystallization and solid liquid interface
 - Grain growth
- WHY STUDY SOLIDIFICATION :
 - It affects properties of material
 - Most metals are made through casting
 - For process and quality control during casting
 - For controlling phases in material

3.12 NUCLEATION :-

- NUCLEATION :- Formation of a centre around which further crystallization takes place is called nuclei and process of its formation is called nucleation.
 - It largely depends on critical radius of nucleation (r_c)
 - Nuclei with smaller than r_c are less likely to form crystal and are called embryos. They may get dissolve in liquid again.
 - Generally nucleation is combination of both types.
- HOMOGENEOUS NUCLEATION :-
 - Nucleation takes place throughout material simultaneously
 - Nucleation sites uniform throughout material
 - Takes place due to under cooling
 - Most of solidification takes place through it.
- HETEROGENEOUS NUCLEATION :-
 - Nucleation takes place randomly
 - Takes place at mould melt interface surface of melt and impurities
 - Smaller role in solidification

F e c
r n h
e e a
e r n
g g
y e



Nucleation

Nuclei with radius $> r_c$ will form crystals

Nuclei with radius $< r_c$ will dissolve as liquid

Max under cooling ($^{\circ}\text{K}$) for metals : Hg 88, Cd 110, Pb 153, Al 160, Sn 187 Ag 227, Au 230, Cu 236, Fe 286, Mn 308 Ni 365, Pt 370, Nb 525

Fig. 3.8 Formation of Nuclei

3.13 CRYSTALLIZATION AND SOLID LIQUID INTERFACE :-

- Crystal Growth from the Liquid Phase:
- The movement of a boundary separating liquid from solid, under the influence of a temperature gradient normal to the boundary, is the result of two different atomic movements.

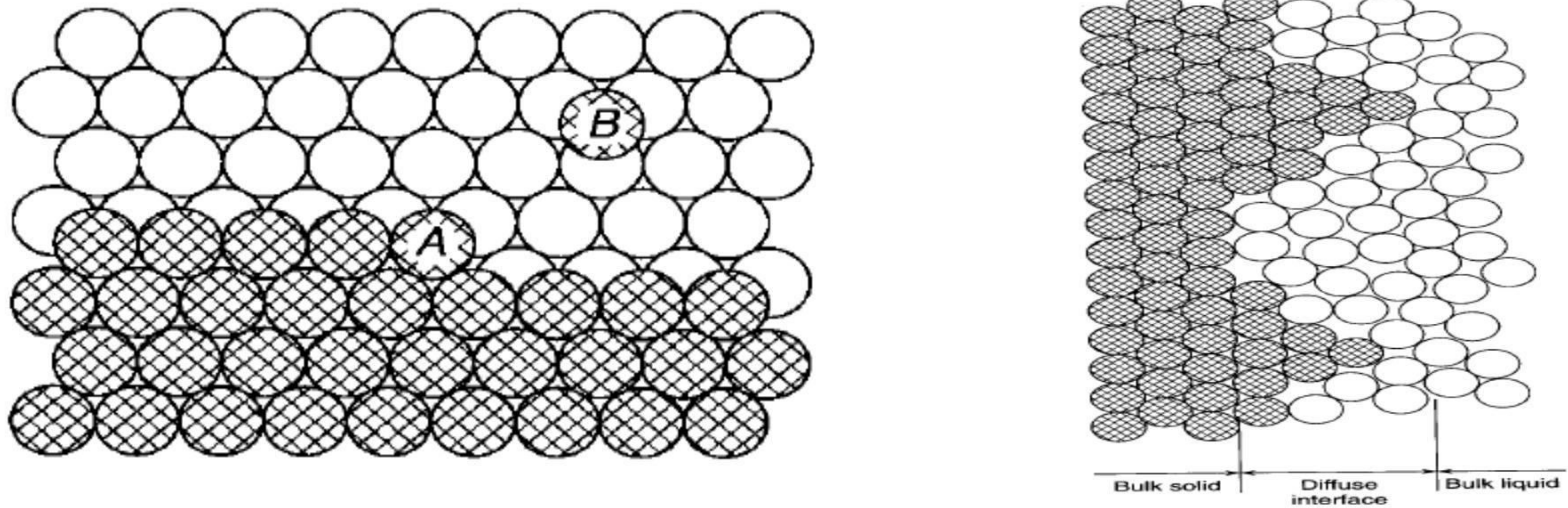


Fig. 3.9 Crystallization and solid liquid interface

Atoms leave the liquid and join the solid = rate of attachment (SOLIDIFICATION)

Atoms leave the solid and join the liquid = rate of detachment (MELTING)

3.14 GRAIN GROWTH :-

- Types of grain growth

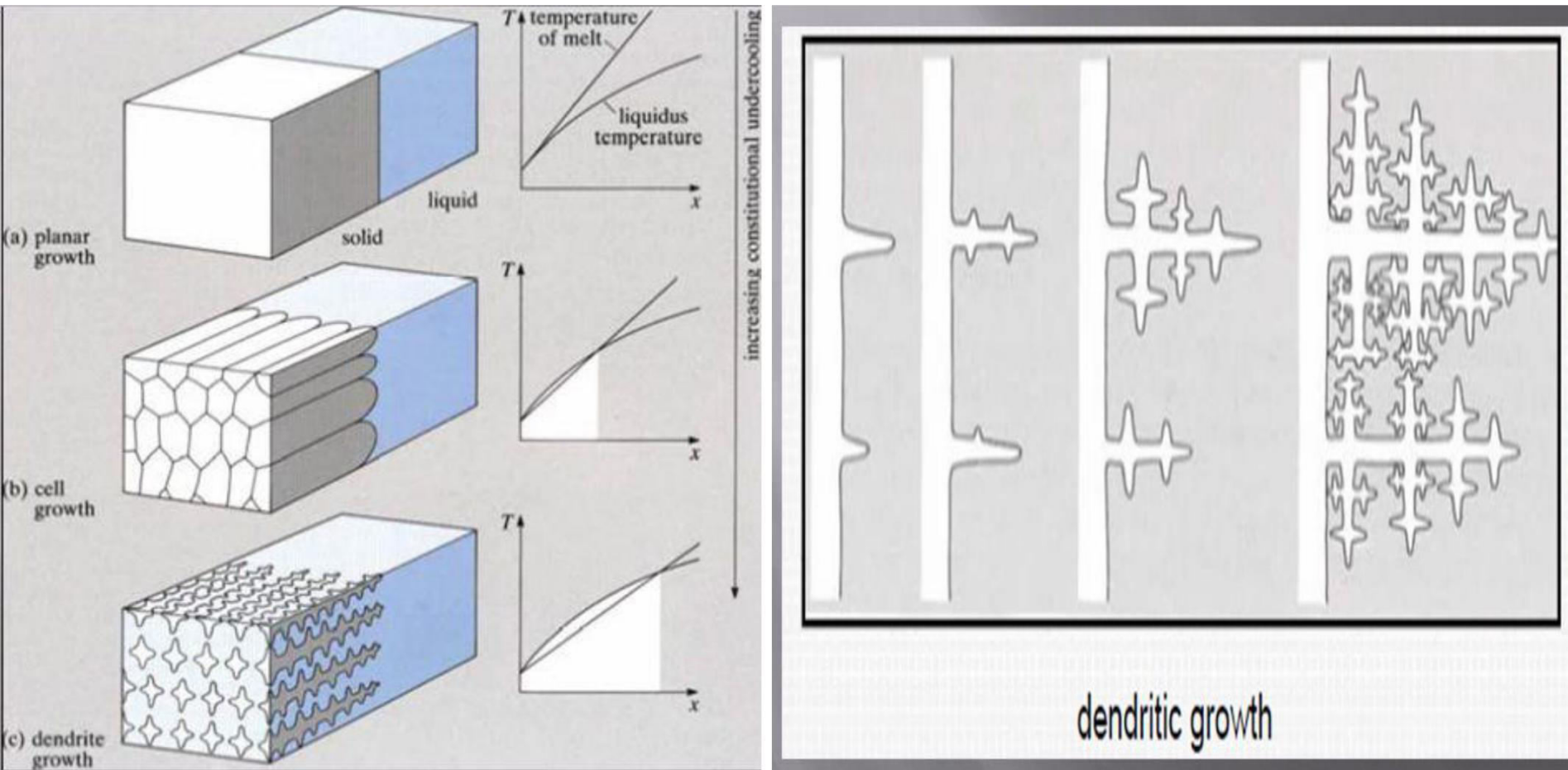


Fig. 3.10 Types of grain growth

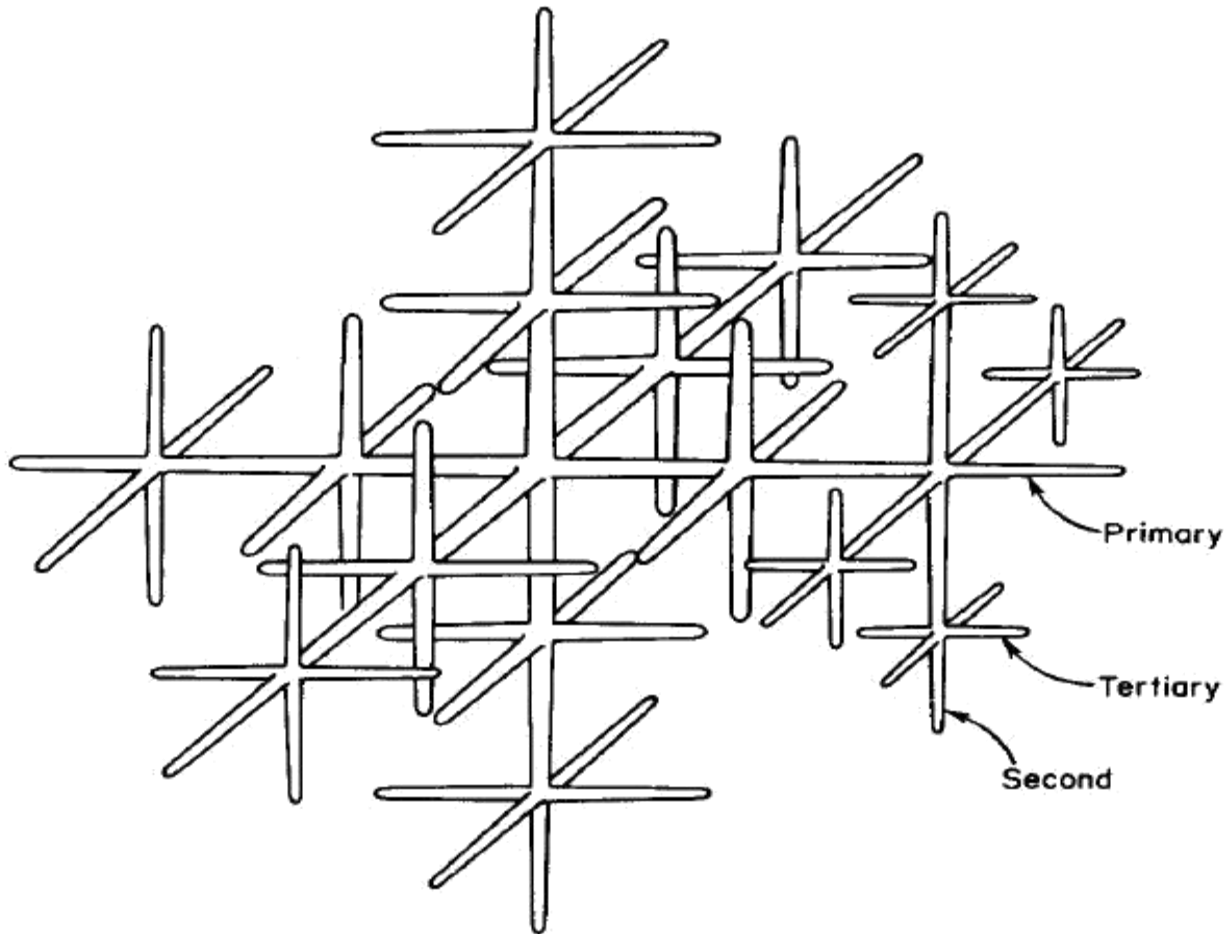


Fig. 3.11 Dendritic grain growth 3 D

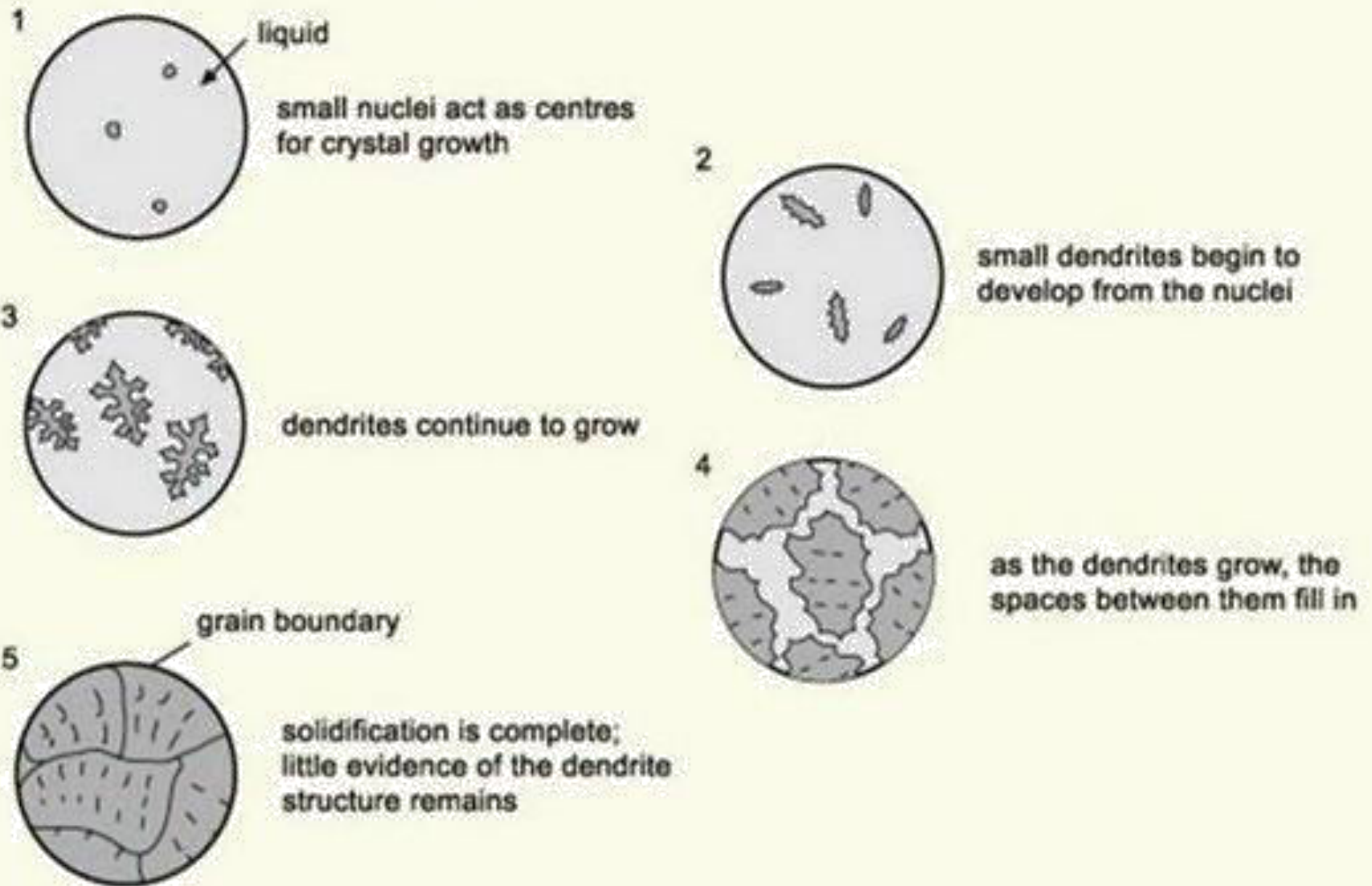


Fig. 3.12 Steps in solidification of alloys

3.15 SOLIDIFICATION OF ALLOYS :-

- Solidification of iso morphous alloys
 - Takes place over a range of temperature
 - Solute solvent distribution is given as chart below

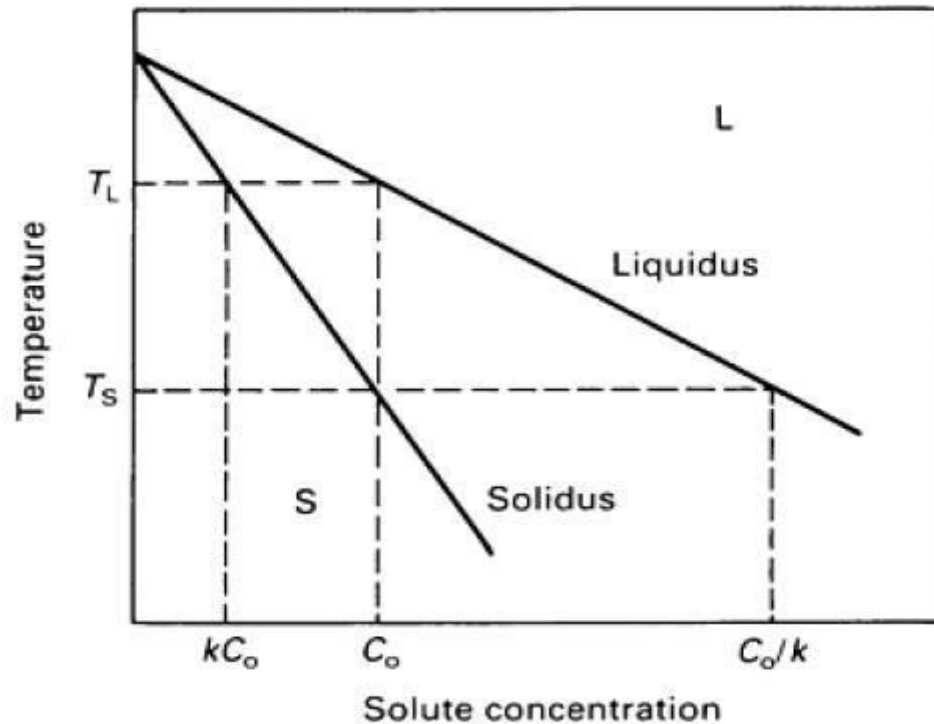


Fig. 3.13 Solidification of alloys

3.16 COOLING CURVE FOR AN ALLOY :-

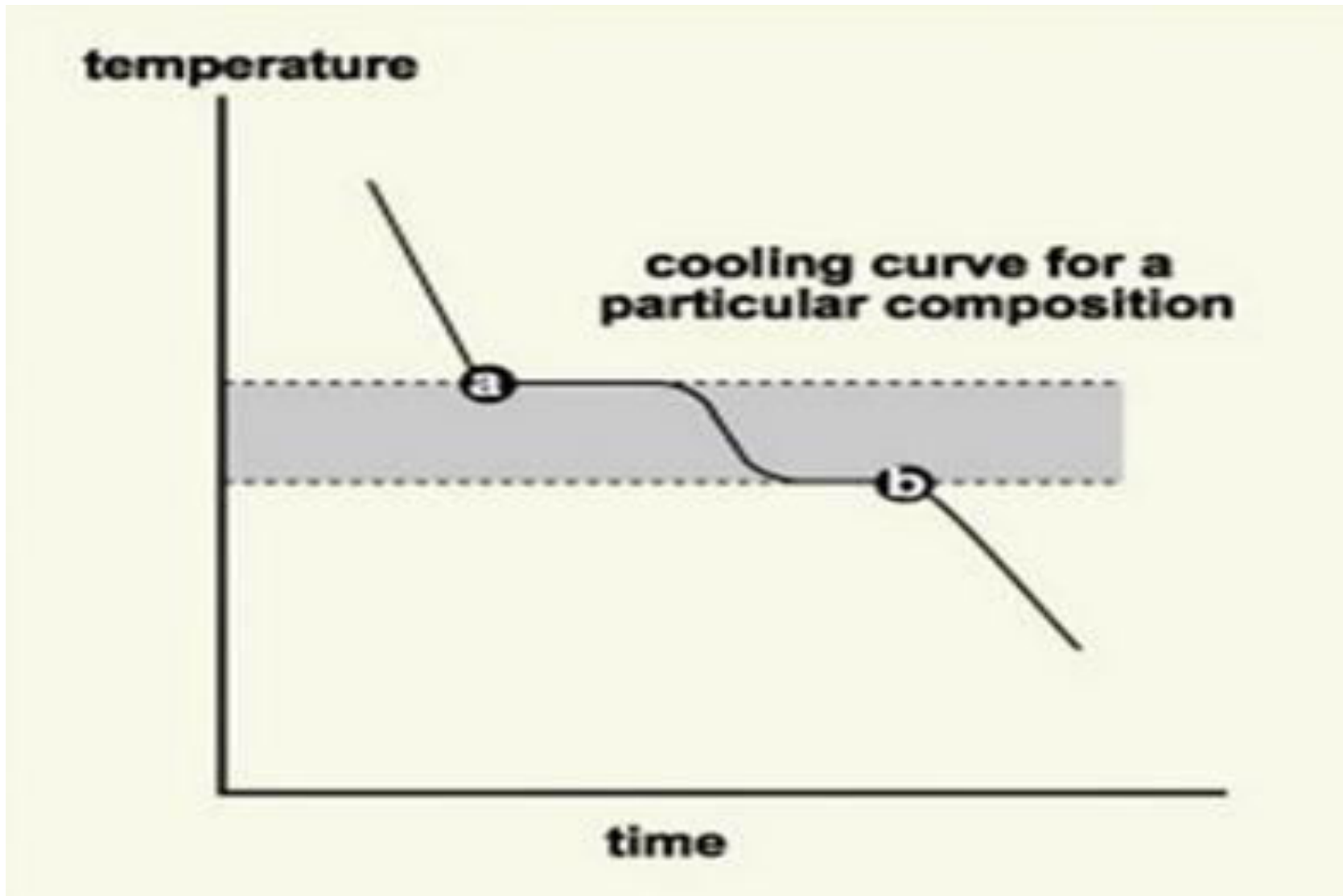


Fig. 3.14 Cooling curve for an alloy

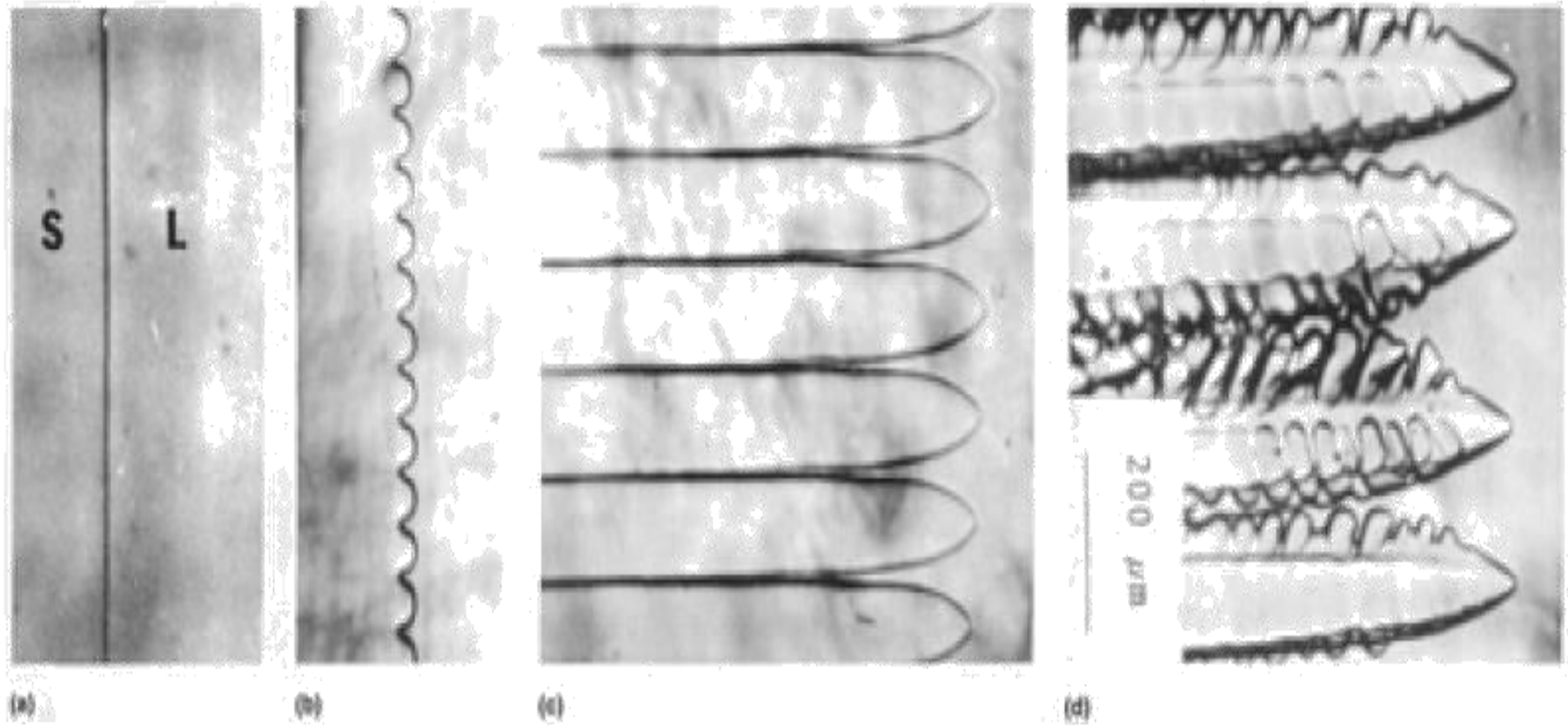
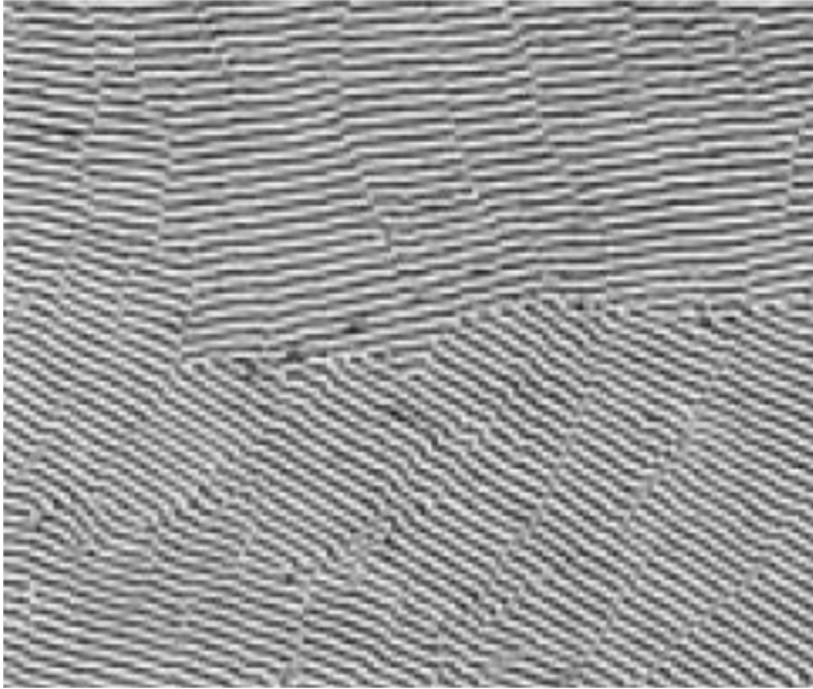
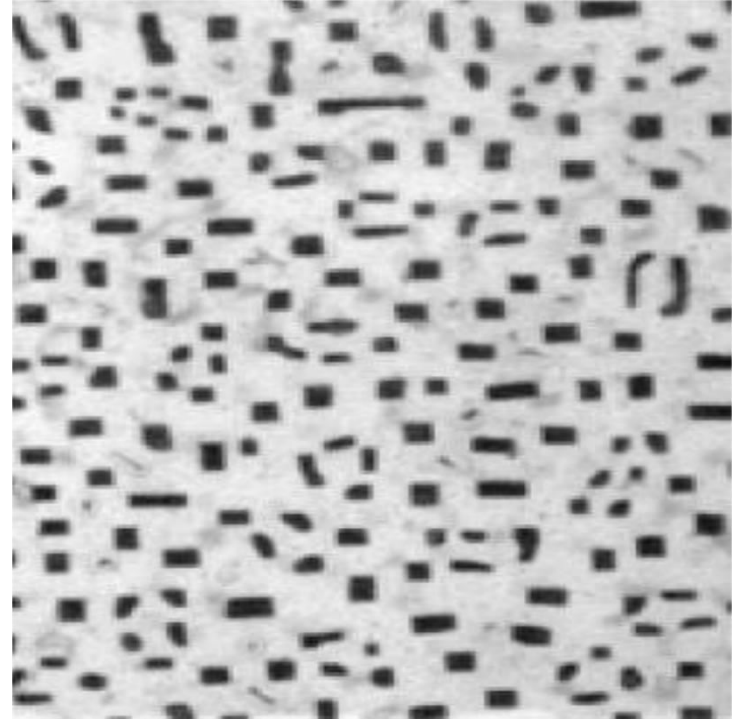


Fig. 3.15 Effect of increasing growth rate on the shape of the solid/liquid interface in a transparent organic system, pivalic acid-0.076 wt% ethanol, solidified directionally at $G = 2.98 \text{ K/mm}$ (75.7 K/in.). (a) $v = 0.2 \text{ } \mu\text{m/s}$ ($8 \text{ } \mu\text{in./s}$). (b) $v = 1.0 \text{ } \mu\text{m/s}$ ($40 \text{ } \mu\text{in./s}$). (c) $v = 3.0 \text{ } \mu\text{m/s}$ ($120 \text{ } \mu\text{in./s}$). (d) $v = 7.0 \text{ } \mu\text{m/s}$ ($280 \text{ } \mu\text{in./s}$)

3.17 SOLIDIFICATION OF EUTECTIC ALLOY



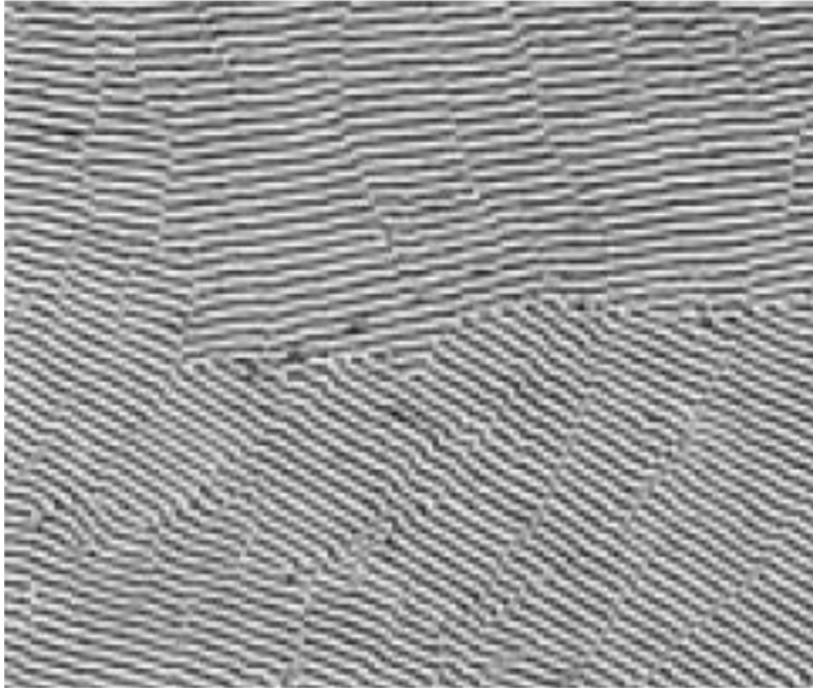
Example of a **lamellar** eutectic microstructure (Al-Al₂Cu) with approximately equal volume fractions of the phases. Transverse section of a directionally solidified sample. As-polished.



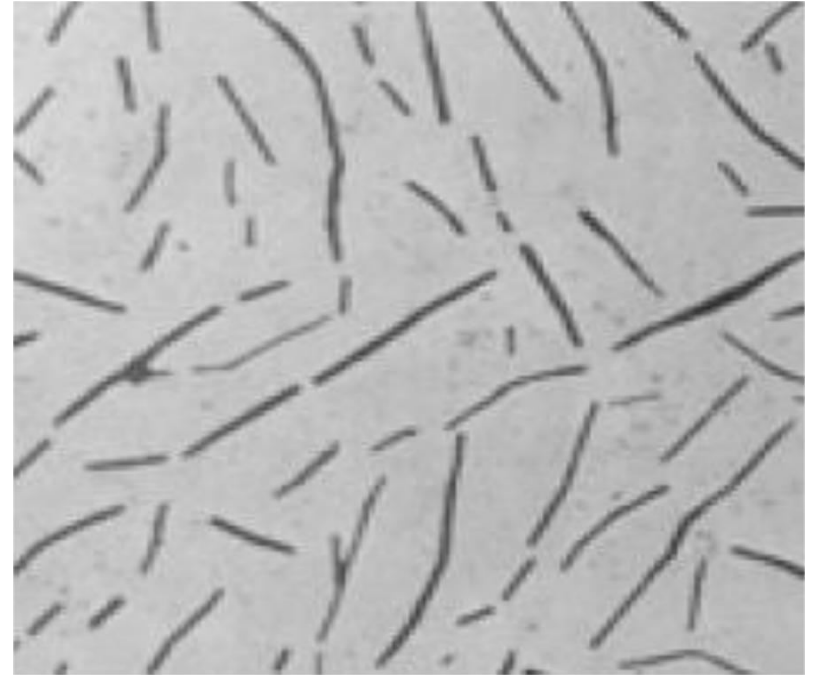
Example of a **fibrous** eutectic microstructure with a small volume fraction of one phase (molybdenum fibers in NiAl matrix). As-polished.

Fig. 3.16 Solidification of eutectic alloy

3.18 REGULAR & IRREGULAR GROWTH :-



Regular growth
Repetitive pattern



Irregular growth
Non repetitive pattern

Fig. 3.16 Regular & irregular growth

3.19 SOLIDIFICATION OF PERITECTIC ALLOY (LESS

SOLID SOLUBILITY) :-

- Diffusion through the β (solid) layer
- Precipitation of β (solid) directly from the liquid
- Precipitation of β directly from the α (liquid) phase

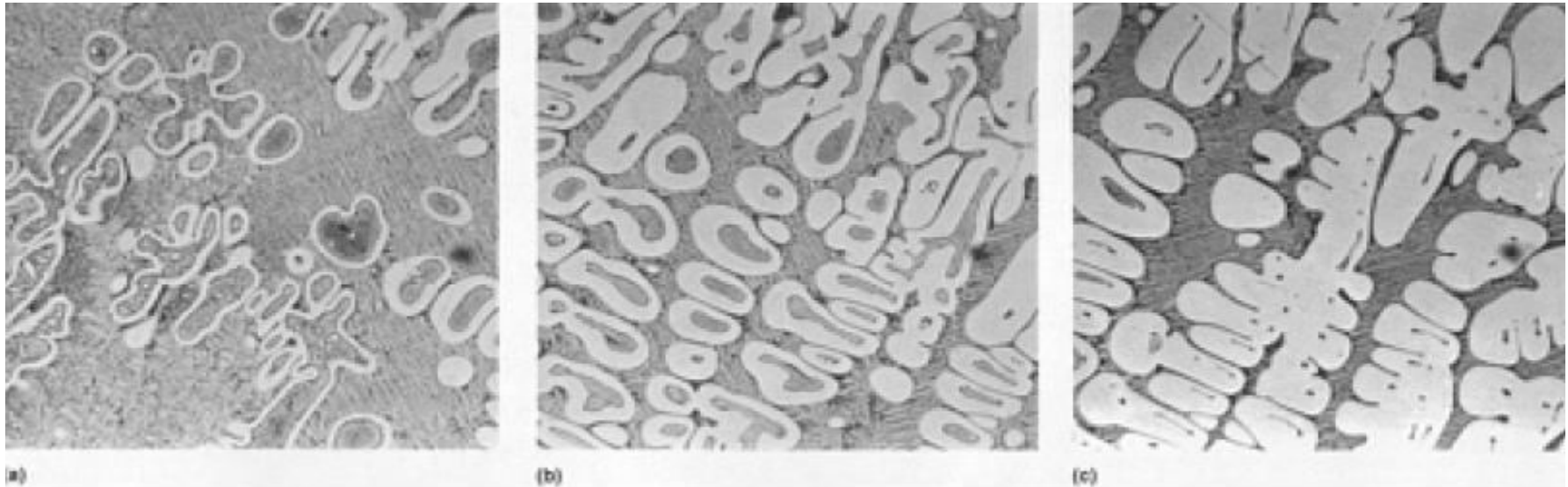


Fig. 3.17 Three stages of a peritectic reaction in a unidirectionally solidified high-speed steel. (a) First stage structure. Dark gray is austenite, white is ferrite. The mottled structure is quenched liquid. (b) Subsequent peritectic transformation of (a). (c) Further peritectic transformation of (a) and (b). Dark gray in the middle of the white ferrite is newly formed solid

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PERITECTIC ALLOYS

- ▶ Peritectic is a phase where there is limited solid solubility.
- ▶ They are not of much use in dentistry except for silver tin system.

Eg: Silver-tin

Silver-platinum

Palladium-ruthenium

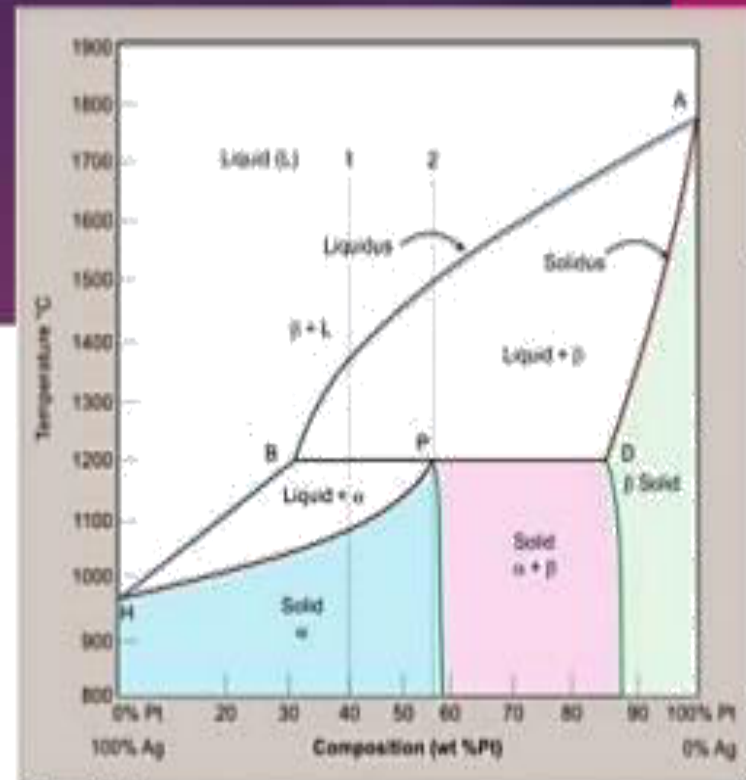


FIGURE 3.13 Equilibrium phase diagram for the platinum-silver system demonstrating peritectic reaction

α - Silver rich phase

β - Platinum rich phase

P - Peritectic transformation point

A - Platinum melting point (1768 °C)

H - Silver melting point (961.8 °C)

A peritectic reaction is a reaction where a solid phase (β) and liquid phase will together form a second solid phase (α) at a particular temperature and composition. In this case, it occurs at a composition of 56% Pt.



3.20 BINARY ISOMORPHOUS SYSTEMS :-

- Isomorphous system - complete solid solubility of the two components (both in the liquid and solid phases).
- Such a phase diagram forms when there is complete solid and liquid solubility.
- The solid mentioned is crystalline.
- The solid + liquid region is not a semi-solid (like partly molten wax or silicate glass). It is a crystal of well defined composition in equilibrium with a liquid of well defined composition.
- Both the solid and the liquid and the solid (except pure A and pure B) have both A and B components in them.

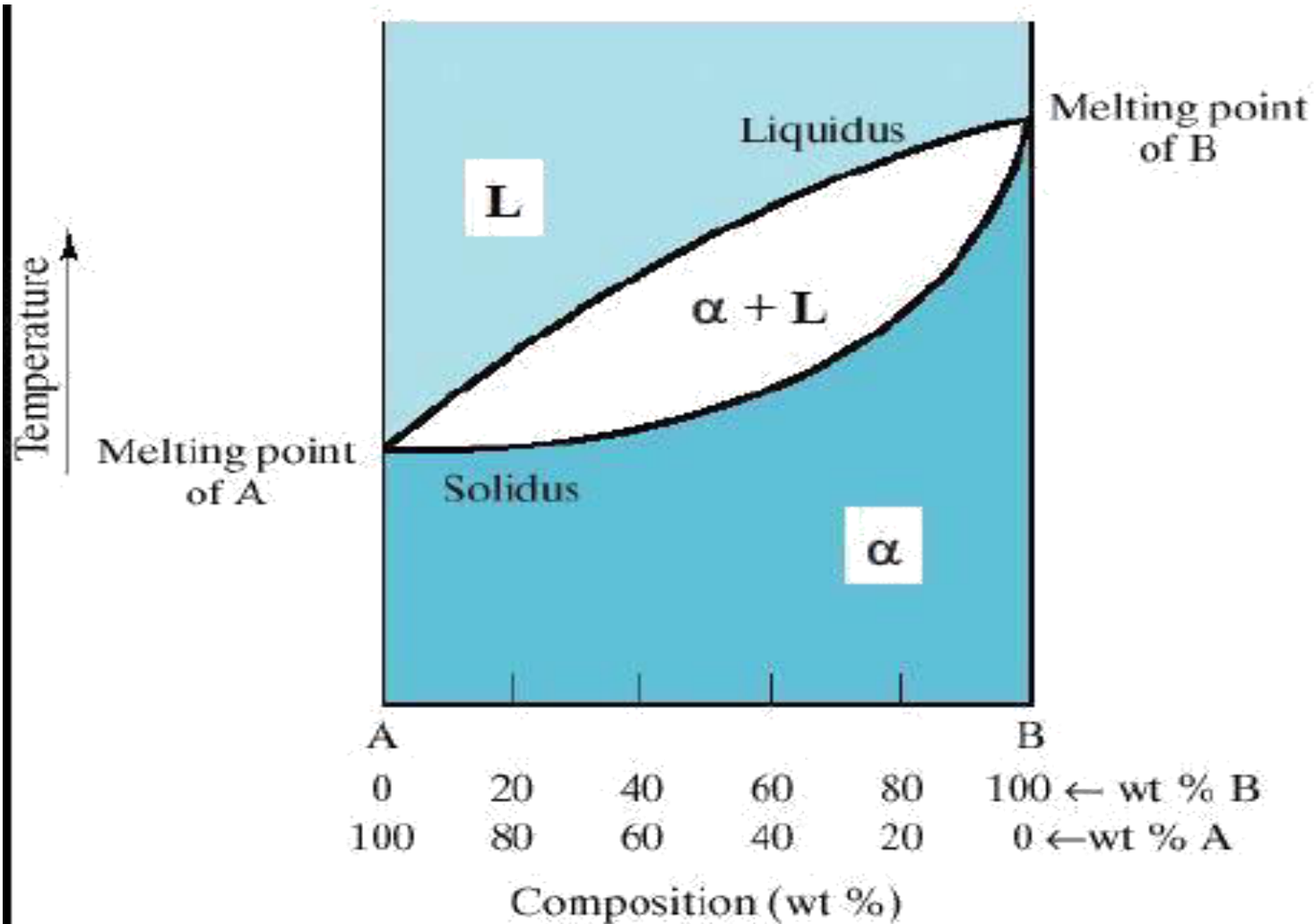


Fig. 3.18 Binary isomorphous systems

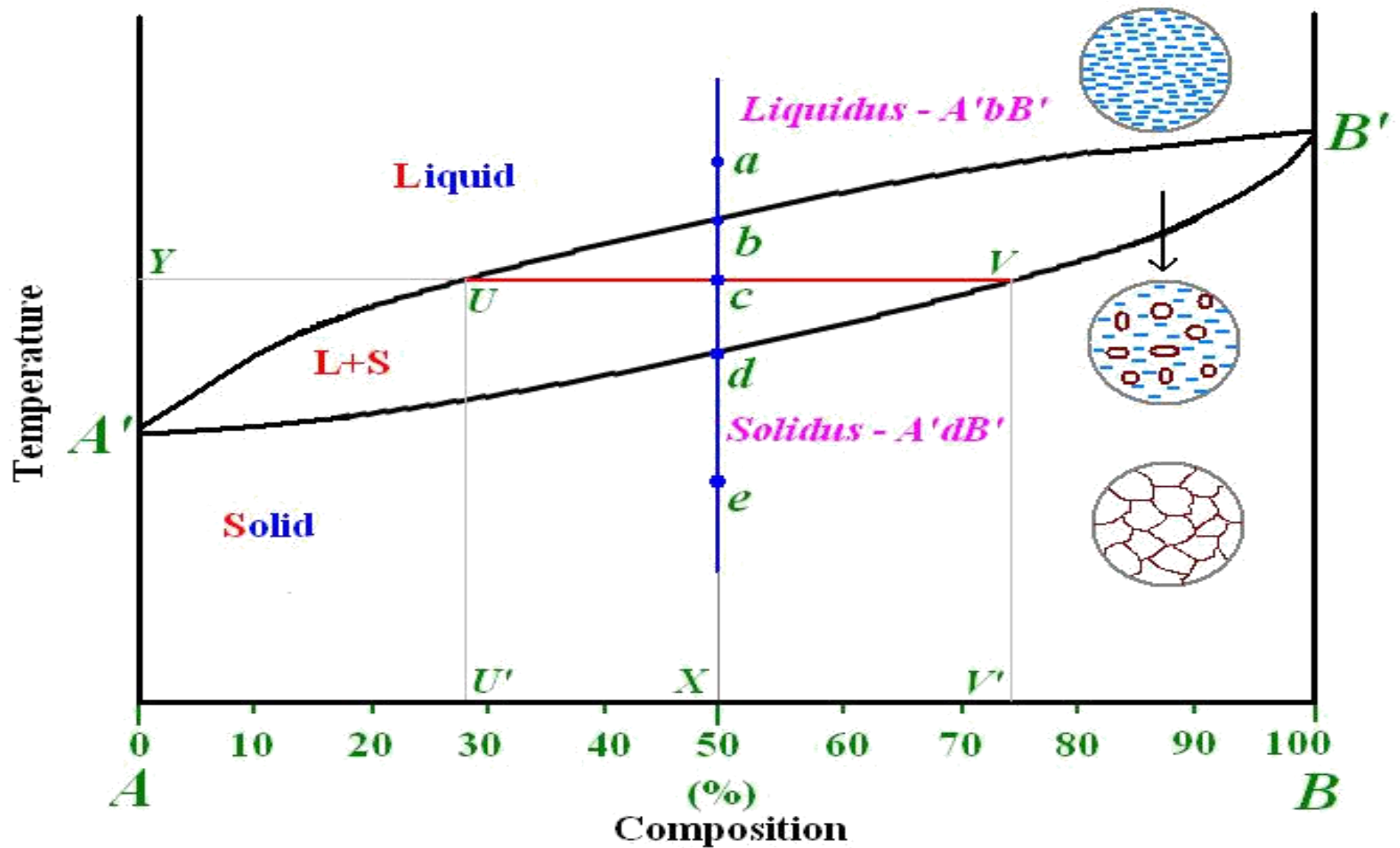


Fig. 3.19 Iron-carbon diagram

- Three phase region can be identified on the phase diagram:-
- Liquid (L), solid + liquid (α +L), solid (α).
- Liquidus line separates liquid from liquid + solid.
- Solidus line separates solid from liquid + solid.

Example of isomorphous system: Cu-Ni (the complete solubility occurs because both Cu and Ni have the same crystal structure, FCC, similar radii, electro negativity and valence).

There are basically three zones in this equilibrium diagram namely:-

1. LIQUID

2. SOLID +LIQUID

3,.SOLID

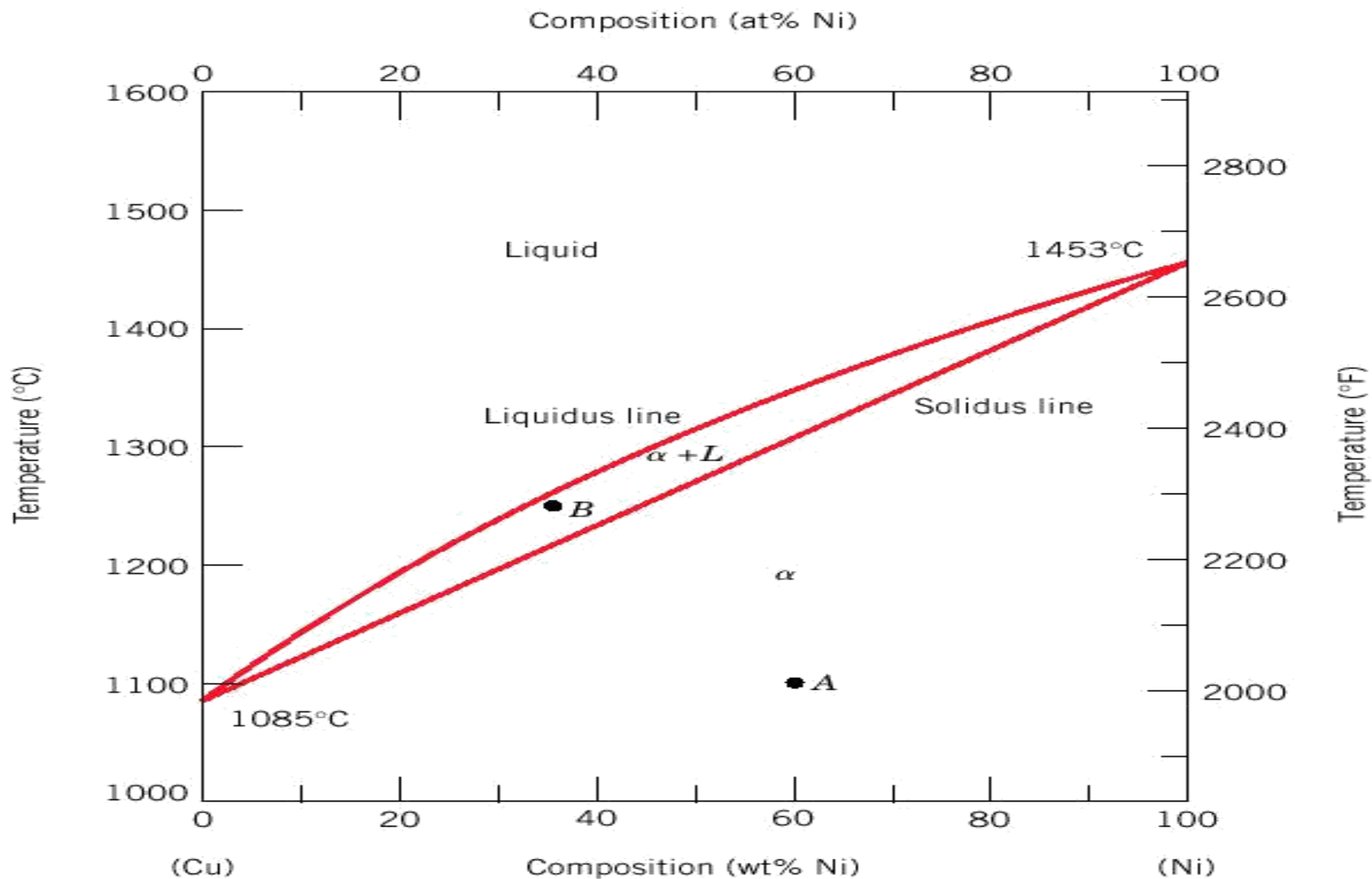


Fig. 3.19 Solidification of alloys transition phases

- In one-component system melting occurs at a well-defined melting temperature.
- In multi-component systems melting occurs over the range of temperatures, between the solidus and liquidus lines.
- Solid and liquid phases are in equilibrium in this temperature range.

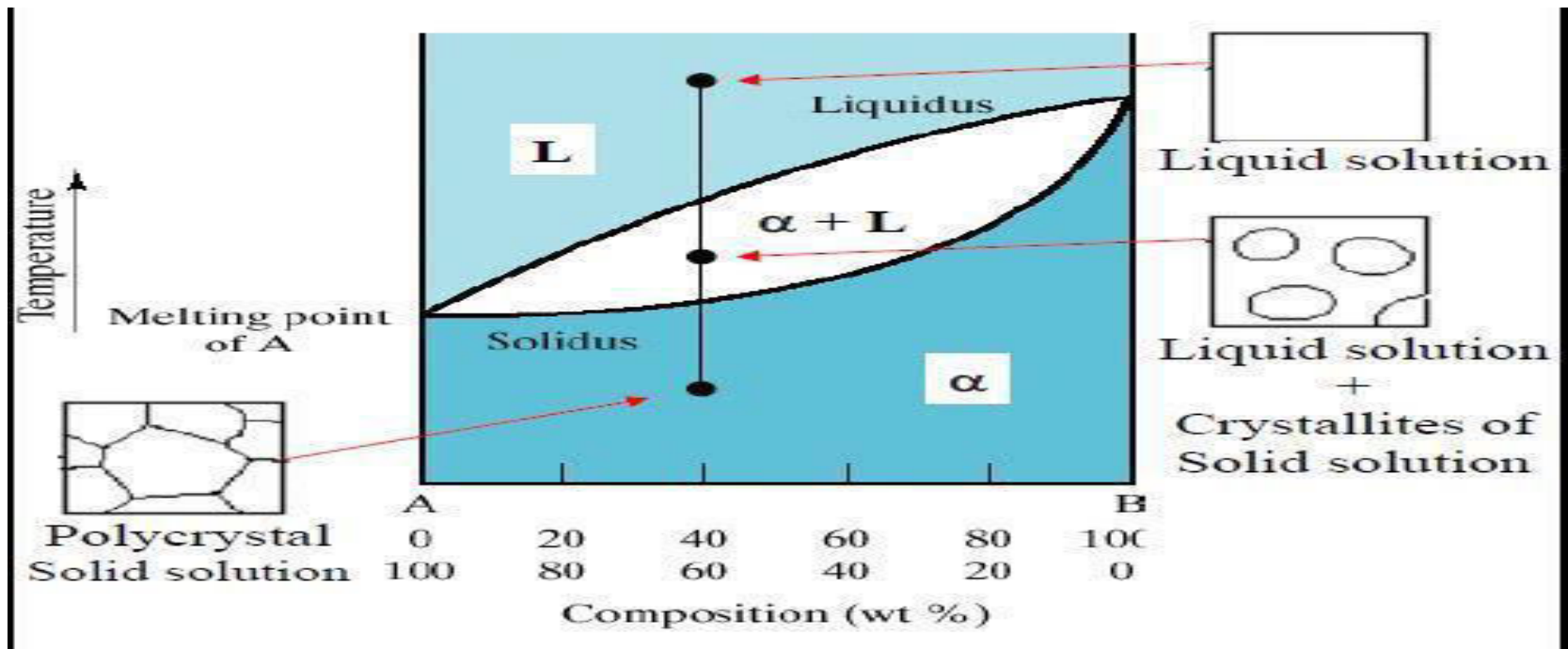


Fig. 3.20 Multi-component systems

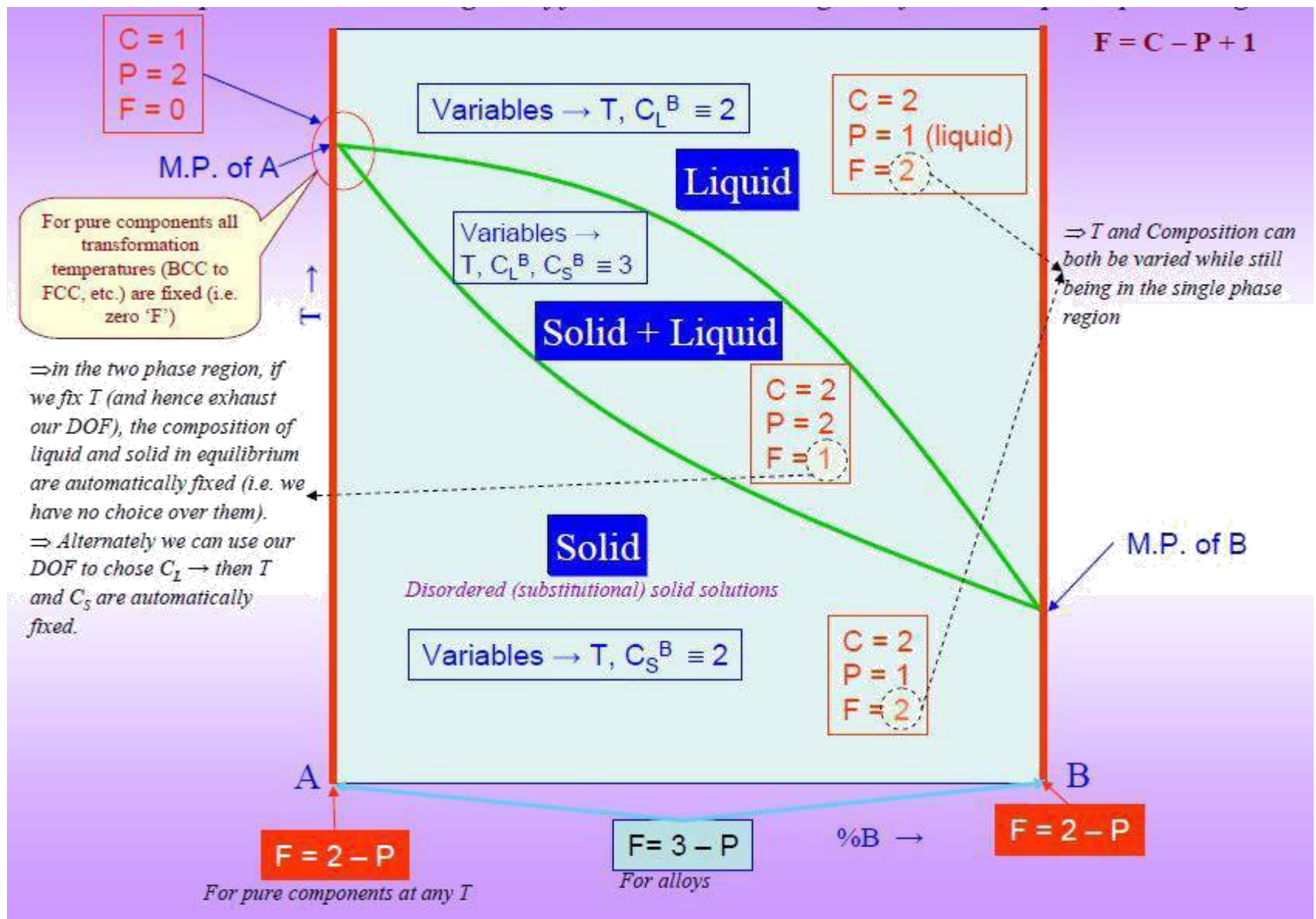


Fig. 3.21 Iron- carbon equilibrium diagram

- Isomorphous phase diagrams form when there is complete solid and liquid solubility.
- Complete solid solubility implies that the crystal structure of the two components have to be same and Hume-Rothery rules have to be followed.
- In some systems (e.g. Au-Ni system) there might be phase separation in the solid state (i.e. the complete solid solubility criterion may not be followed) → these will be considered later in this chapter as a variation of the isomorphous system (with complete solubility in the solid and the liquid state).
- Pure components (A,B) melt at a single temperature. (General) Alloys melt over a range of temperatures.
- Both the liquid and solid contain the components A and B.
- In Binary phase diagrams between two single phase regions there will be a two phase region → In the isomorphous diagram between the liquid and solid state there is the (Liquid + Solid) state.

- The Liquid + Solid state is NOT a ‘semi-solid’ state → it is a solid of fixed composition and structure, in equilibrium with a liquid of fixed composition.
- In the single phase region the composition of the alloy is ‘the composition’. In the two phase region the composition of the two phases is different and is NOT the nominal composition of the alloy (but, is given by the lever rule).

3.21 HUME-ROTHERY RULES :-

- The **Hume-Rothery rules**, named after William Hume-Rothery, are a set of basic rules that describe the conditions under which an element could dissolve in a metal, forming a solid solution. There are two sets of rules; one refers to substitutional solid solutions, and the other refers to interstitial solid solutions.
- Hume-Rothery (1899-1968) was a metallurgist who studied the alloying of metals. His research was conducted at Oxford University where in 1958, he was appointed to the first chair in metallurgy.
- His research led to some simple and useful rules on the extent to which an element might dissolve in a metal [1-4]. The rules that he derived are paraphrased here. The rules are still used widely. For example, the miscibility gap in Au-Ni is correlated with the fact that the lattice parameter of Au is 1.15 times that of Ni, thus acting maximally according to Hume-Rothery [5].
- If a solute differs in its atomic size by more than about 15% from the host, then it is likely to have a low solubility in that metal. The *size factor* is said to be unfavourable.

3.22 IRON-IRON-CARBON DIAGRAM :-

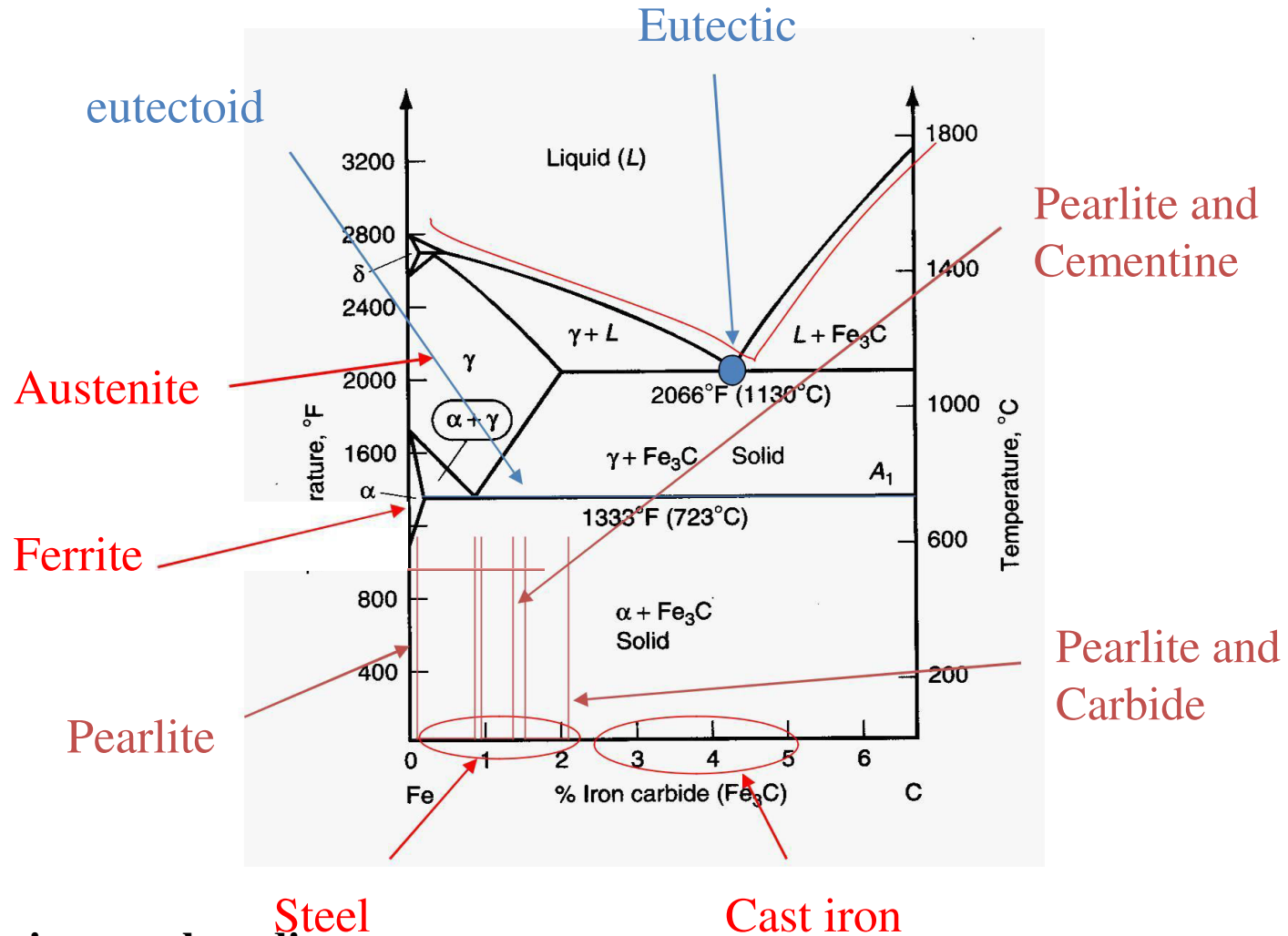


Fig. 3.22 Iron iron-carbon diagram

3.23 COOLING CURVE FOR PURE IRON :-

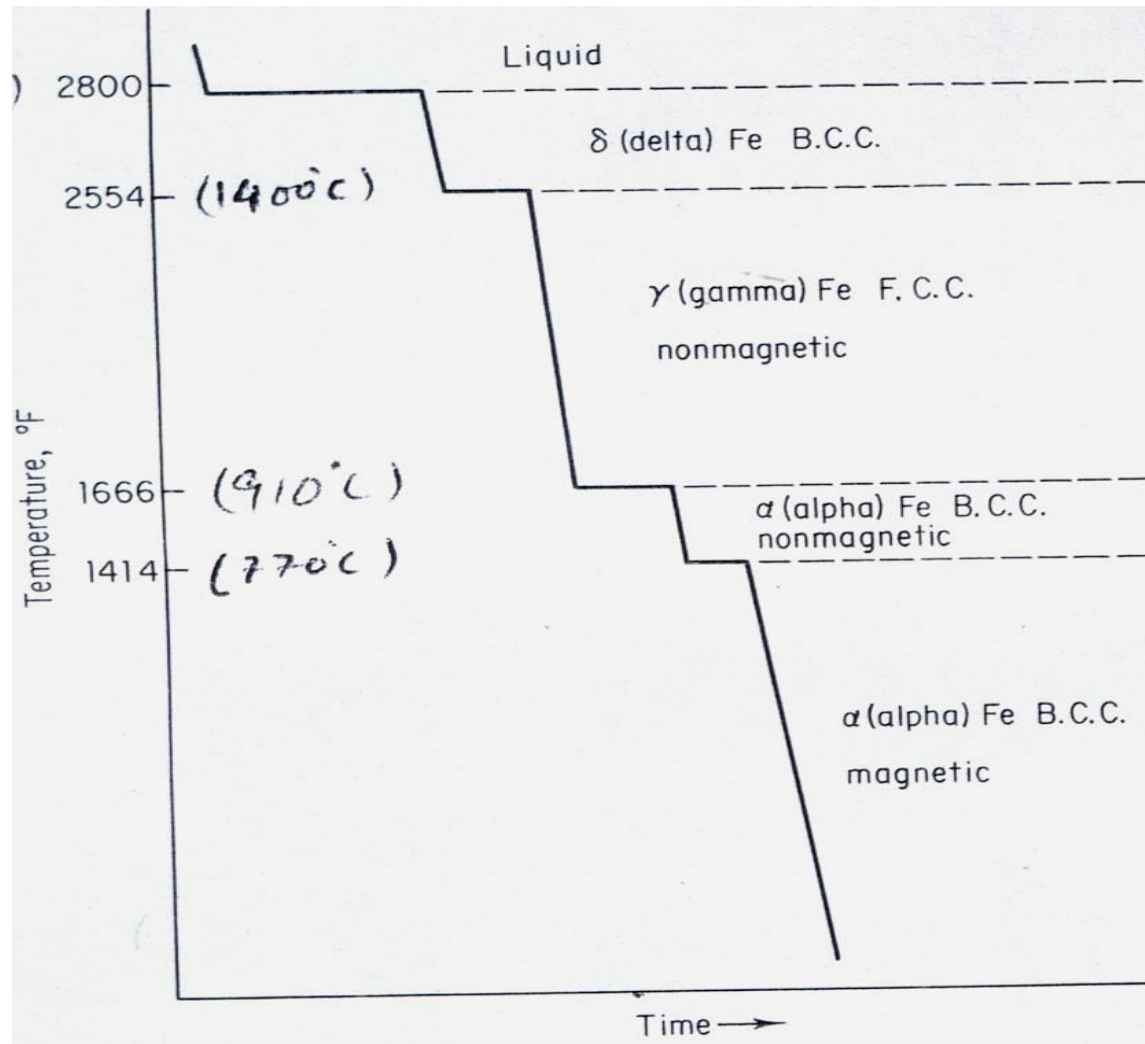


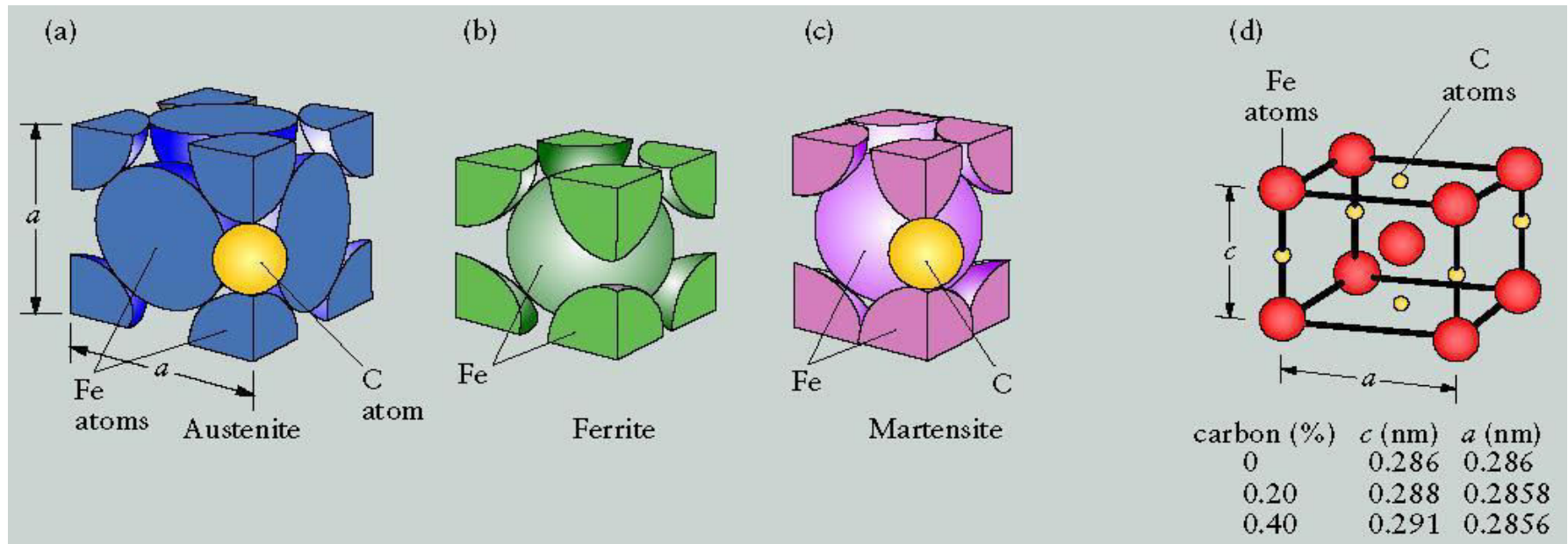
Fig. 3.23 Cooling curve for pure iron

3.24 DEFINITION OF STRUCTURES :-

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

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

3.25 UNIT CELLS OF VARIOUS METALS :-



- Fig. 3.24 The unit cell for (a) austenite, (b) ferrite, and (c) martensite. The effect of the percentage of carbon (by weight) on the lattice dimensions for martensite is shown in (d). Note the interstitial position of the carbon atoms and the increase in dimension c with increasing carbon content. Thus, the unit cell of martensite is in the shape of a rectangular prism.

3.26 MICROSTRUCTURE OF DIFFERENT PHASES OF STEEL :-

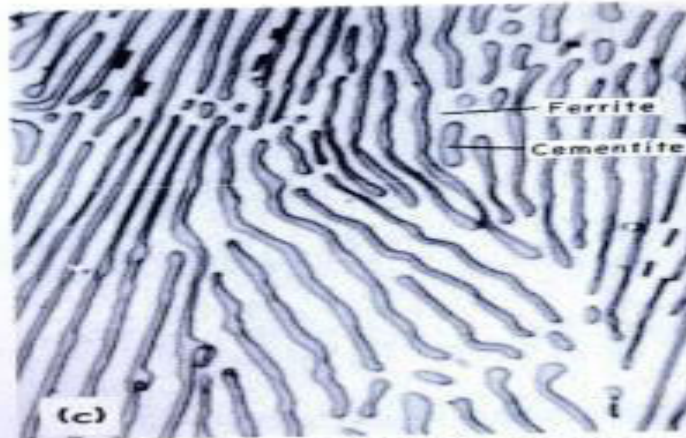
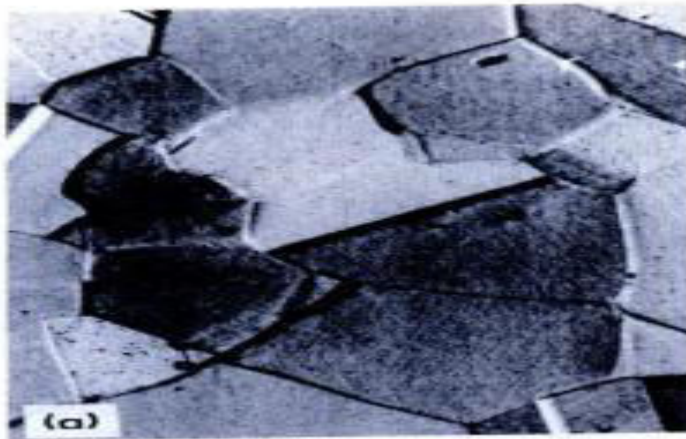


Fig. 7-8 The microstructure of (a) austenite, 500X; (b) ferrite, 100X; (c) pearlite, 2,500X; (d) pearlite, electron micrograph, 17,000X; enlarged 3X in printing. (a, b, and c, Re-

Fig. 3.25 Microstructure of different phases of steel

3.27 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°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.
- Average properties are:
 - Tensile strength = 40,000 psi;
 - Elongation = 40 % in 2 in;
 - Hardness > Rockwell C 0 or Rockwell B 90

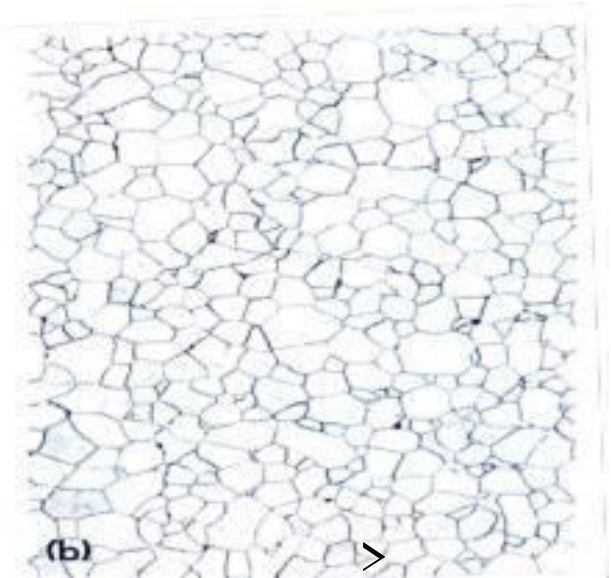


Fig.3.26 Ferrite

- **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).
- Average properties are:
 - Tensile strength = 120,000 psi;
 - Elongation = 20 % in 2 in.;
 - Hardness = Rockwell C 20, Rockwell B 95-100, or BHN 250-300.

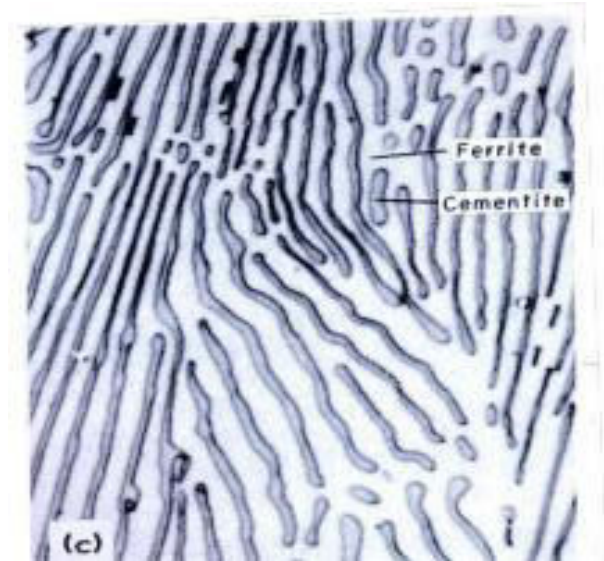


Fig. 3.27 Pearlite structure

- **Austenite** is an interstitial solid solution of Carbon dissolved in (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.
- Average properties are:
 - Tensile strength = 150,000 psi;
 - Elongation = 10 percent in 2 in.;
 - Hardness = Rockwell C 40, approx; and
 - toughness = high

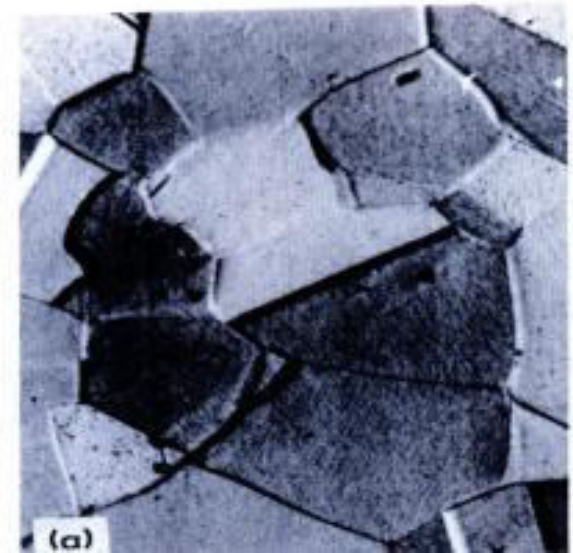


Fig. 3.28 Austenite structure

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.

Ledeburite is the eutectic mixture of austenite and cementite.

- It contains 4.3 percent C and is formed at 1130°C.

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

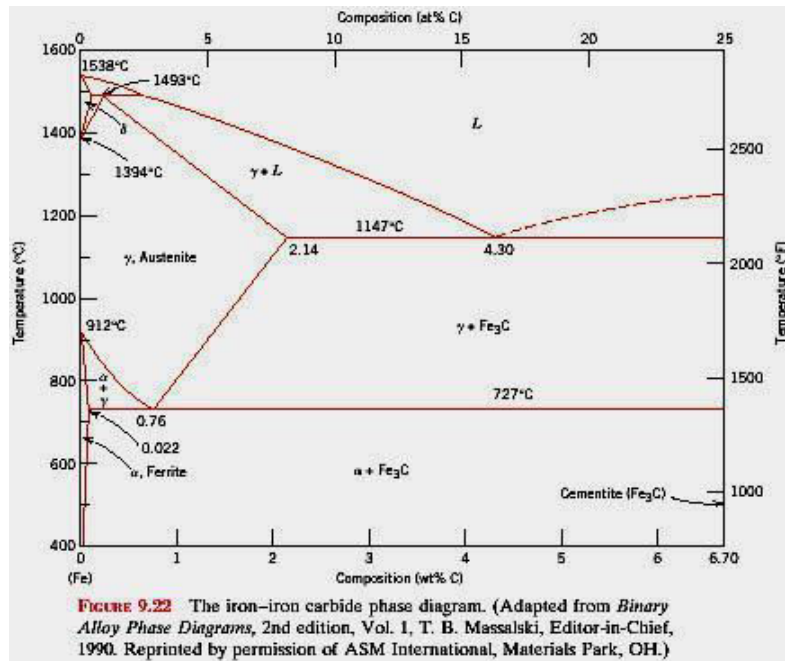
3.28 THE IRON-IRON CARBIDE DIAGRAM :-

- 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.

THREE PHASE REACTIONS :-

- Peritectic, at 1490 deg.C, with low wt% C alloys (almost no engineering importance).
- Eutectic, at 1130 deg.C, with 4.3wt% C, alloys called cast irons.
- Eutectoid, at 723 deg.C with eutectoid composition of 0.8wt% C, two-phase mixture (ferrite & cementite). They are steels.

3.29 VARIOUS FEATURES OF FE-C DIAGRAM :-



Phases present

L

d
BCC structure
Paramagnetic

austenite
FCC structure
Non-magnetic
ductile

a ferrite BCC
structure
Ferromagnetic
Fairly ductile

Fe₃C cementite
Orthorhombic
Hard
brittle

Reactions

Peritectic $L + d =$

Max. solubility of C in ferrite=0.022%

Eutectic $L = + Fe_3C$ Eutectoid

Max. solubility of C in austenite=2.11%

$= a + Fe_3C$

Er. Saurabh Malpotra

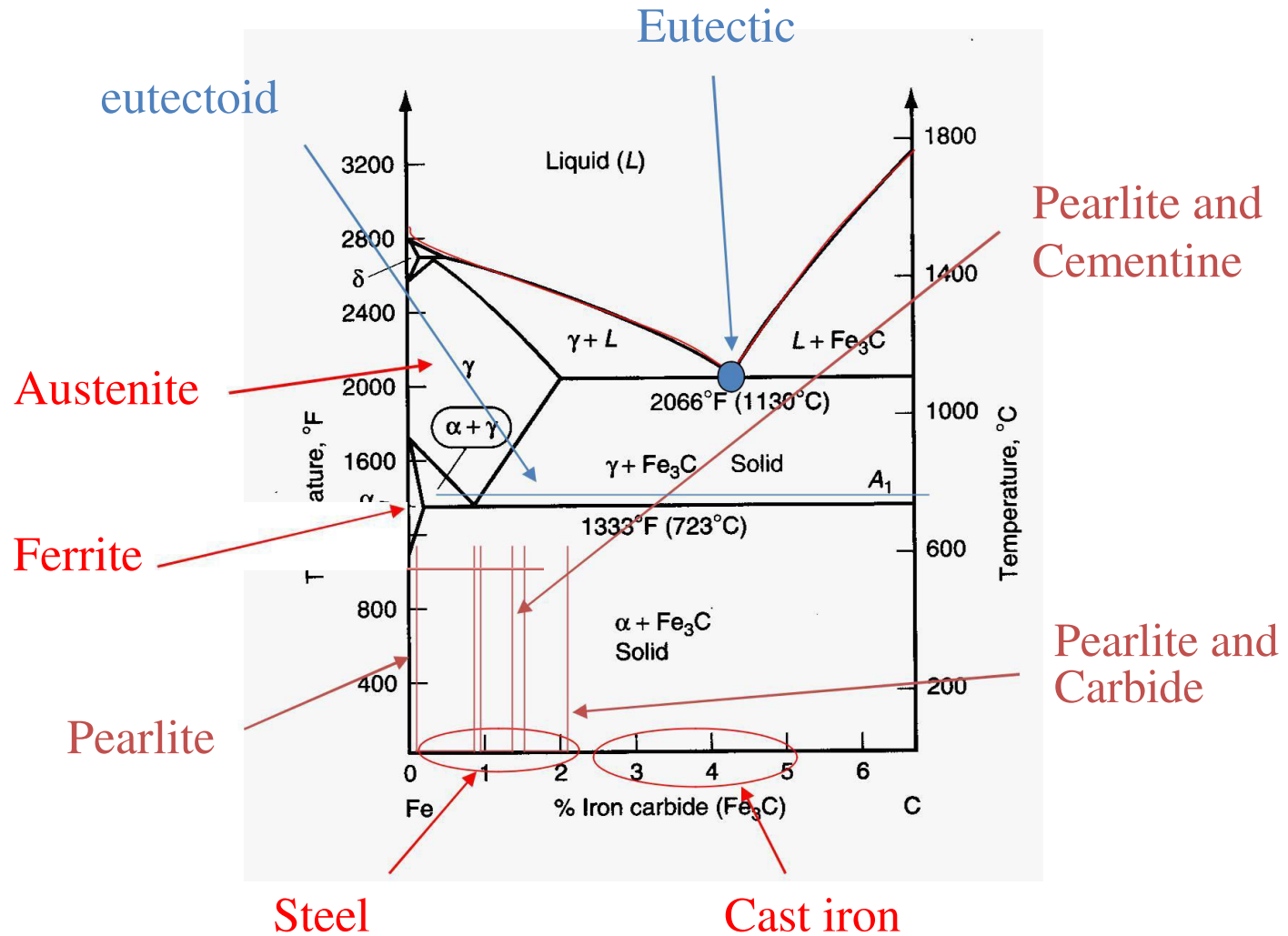


Fig. 3.29 Iron-carbon diagram

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: $\text{Liquid} + \text{d} \leftrightarrow \text{austenite}$
- Second horizontal line is at 1130°C , where eutectic reaction takes place: $\text{liquid} \leftrightarrow \text{austenite} + \text{cementite}$
- Third horizontal line is at 723°C , where eutectoid reaction takes place: $\text{austenite} \leftrightarrow \text{pearlite (mixture of ferrite \& cementite)}$

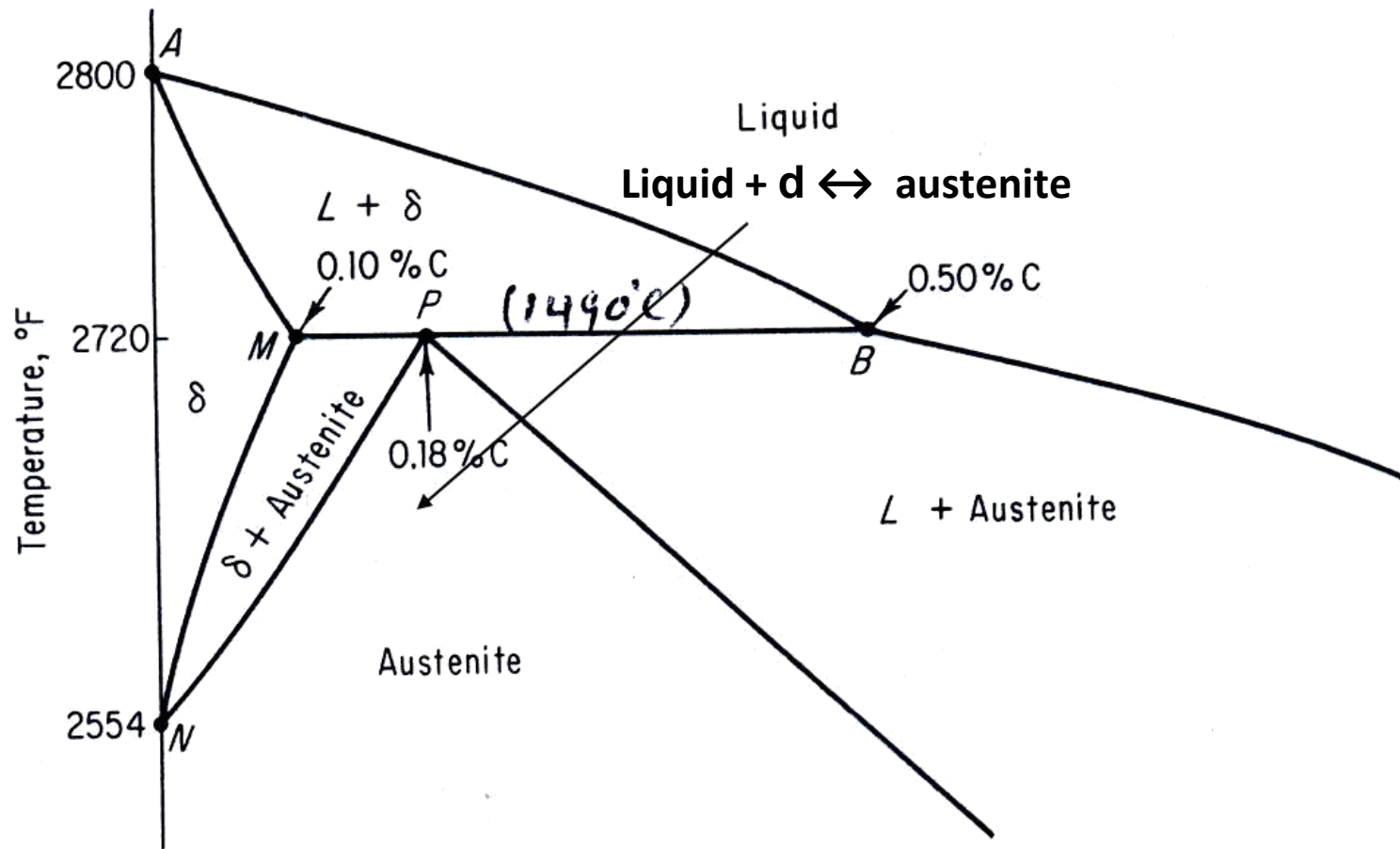
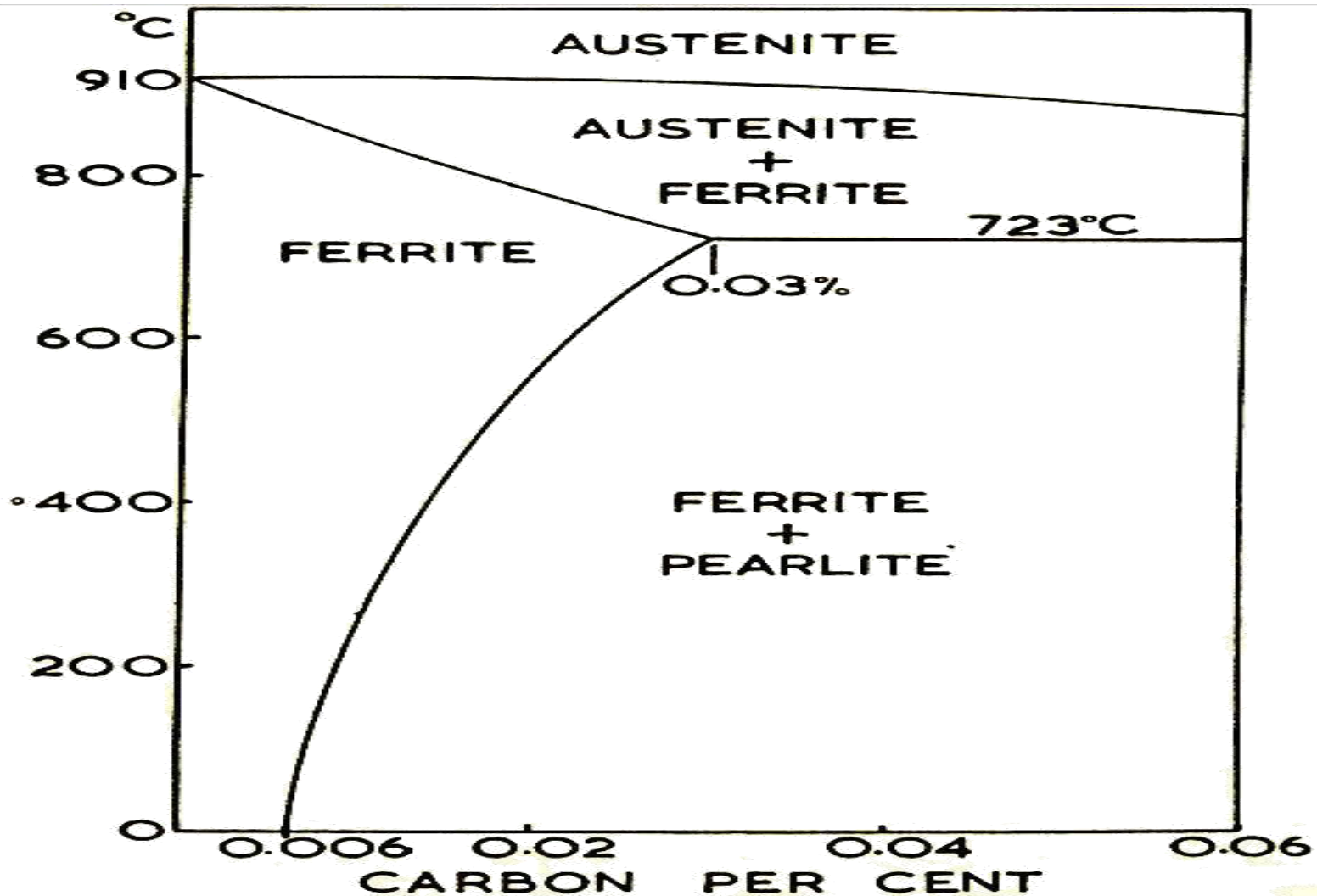


Fig. 3.20 Delta region of Fe-Fe carbide diagram



2.—The “Ferrite Area” of the Iron–Carbon Equilibrium Diagram, Showing the Extent to Which Carbon is Soluble in α Iron.

Fig. 3.31 Ferrite region of Fe-Fe Carbide diagram

Austenite \leftrightarrow Pearlite (mixture of ferrite & cementite)

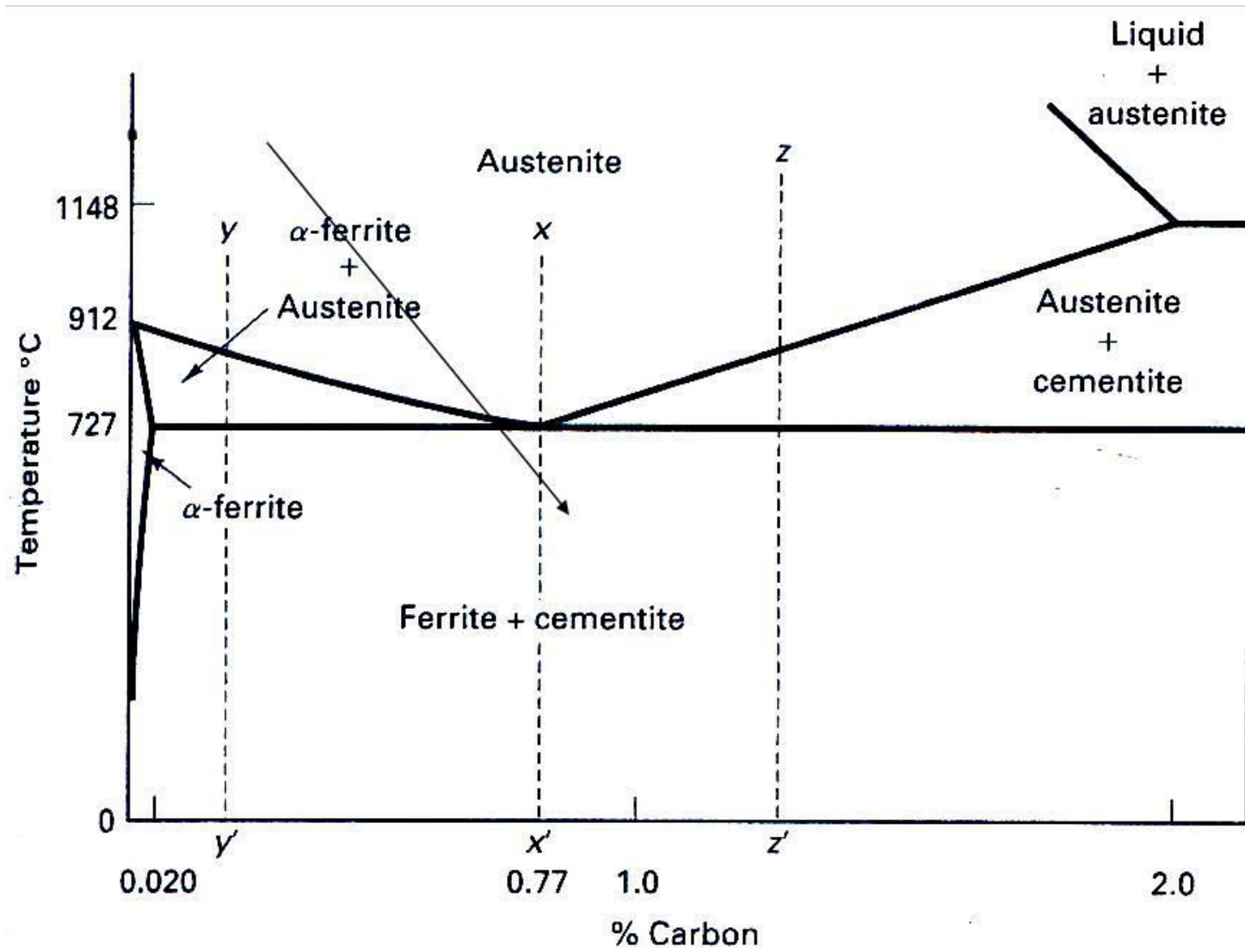


Fig. 3.31 Simplified Iron-Carbon phase diagram

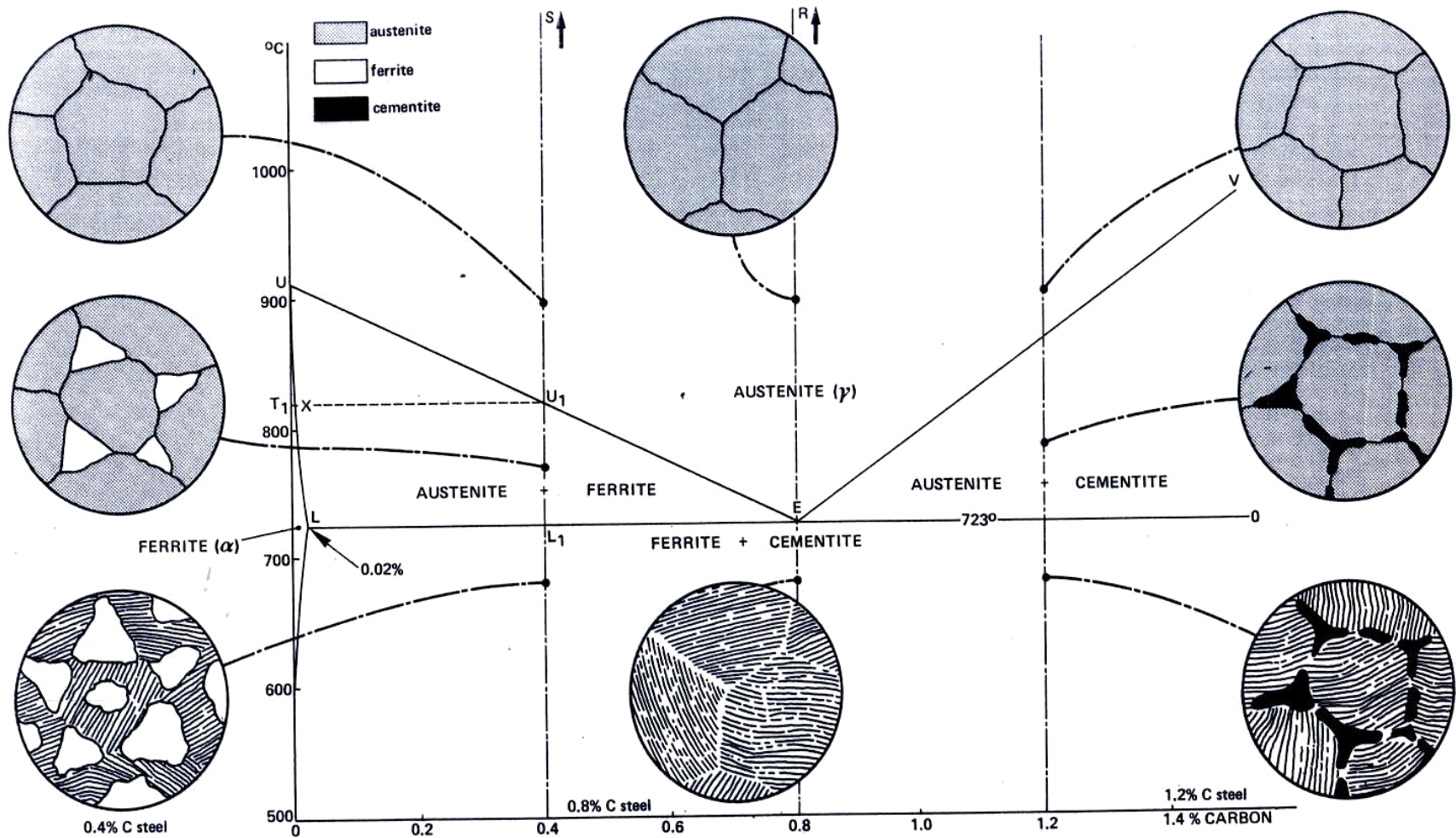


Fig. 9.3—The austenite → ferrite/cementite transformation in relation to the iron–carbon diagram.

Fig. 3.32 The Austenite to ferrite / cementite transformation in relation to Fe-C diagram

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

- In order to understand the transformation processes, consider a steel of the eutectoid composition. 0.8% carbon, being slow cooled along line $x-x'$.
- At the upper temperatures, only austenite is present, with the 0.8% carbon being dissolved in solid solution within the FCC. When the steel cools through 723°C, several changes occur simultaneously.
- 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.

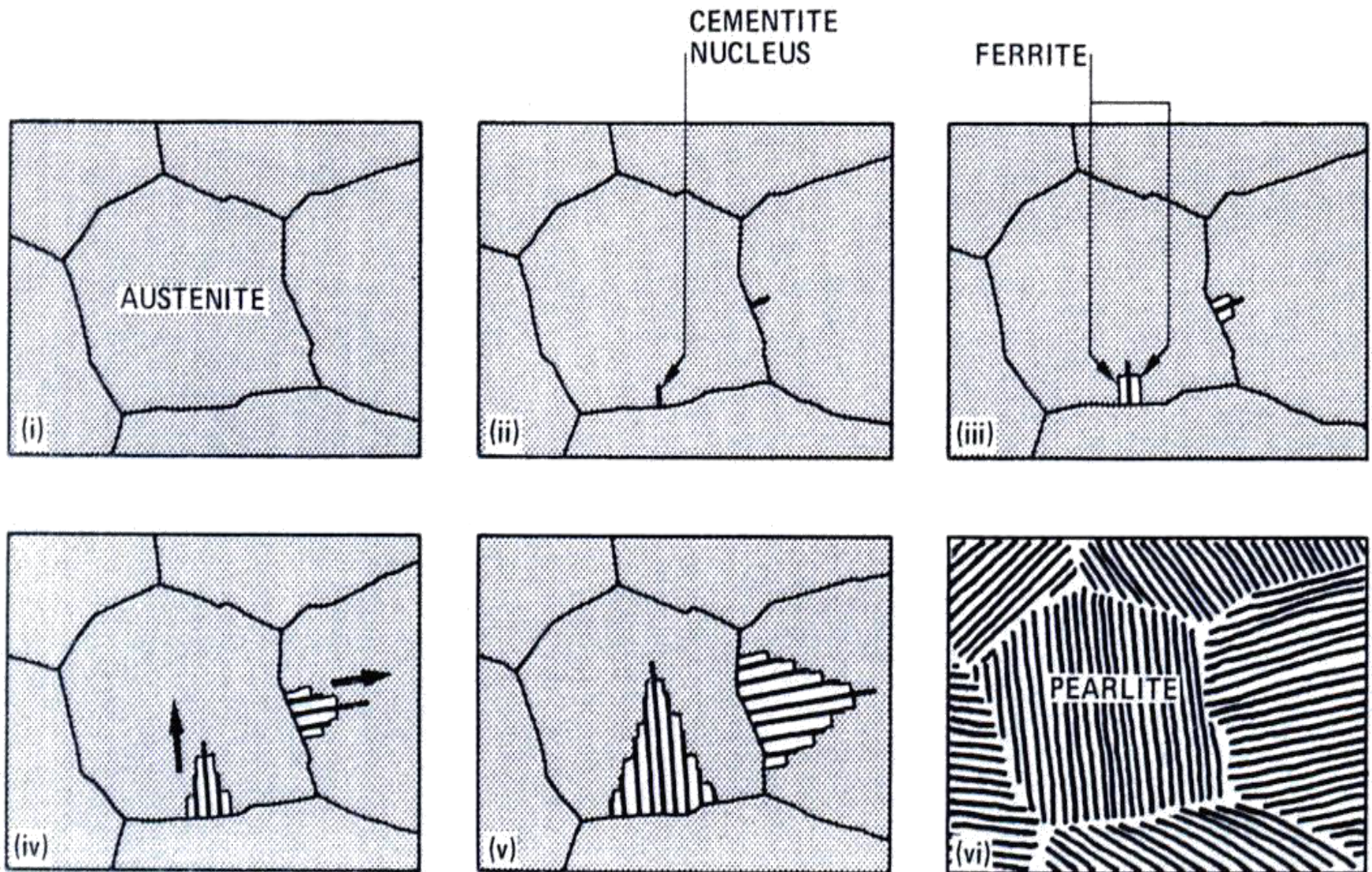


Fig. 3.33 Nucleation & growth of pearlite

3.31 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.
- **Hypo-eutectoid steels:-** At 723°C, the remaining austenite will have assumed the eutectoid composition (0.8% carbon), and further cooling transforms it to pearlite.

- The resulting structure, is a mixture of *primary* or *pro-eutectoid ferrite* (ferrite that forms before the eutectoid reaction) and regions of pearlite.

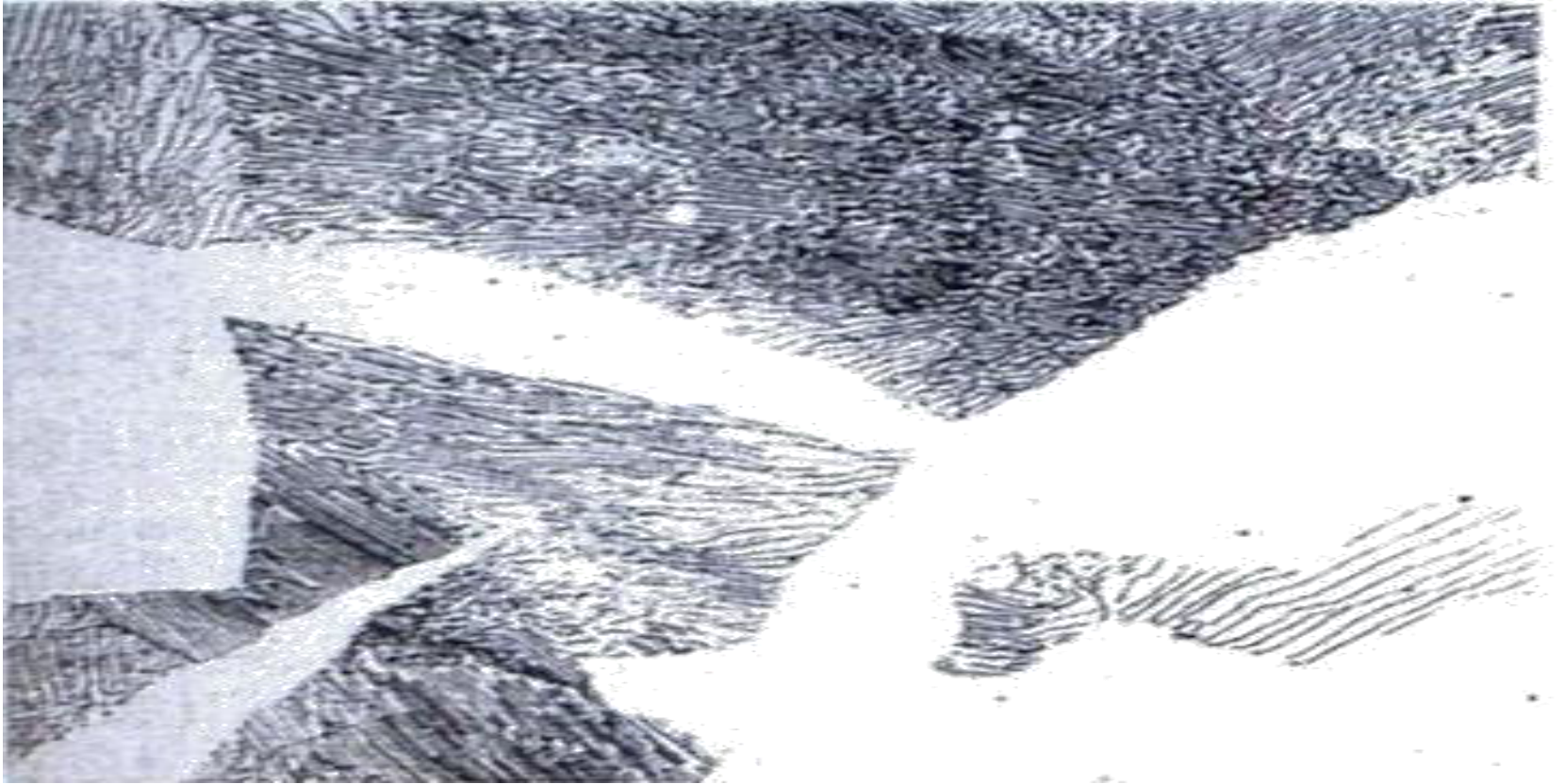


Fig. 3.34 Austenite to ferrite / cementite Transformation

- As the carbon-rich phase nucleates and grows, the remaining austenite decreases in carbon content, again reaching the eutectoid composition at 723°C.

- This austenite transforms to pearlite upon slow cooling through the eutectoid temperature.
- The resulting structure consists of primary cementite and pearlite.
- The continuous network of primary cementite will cause the material to be extremely brittle.

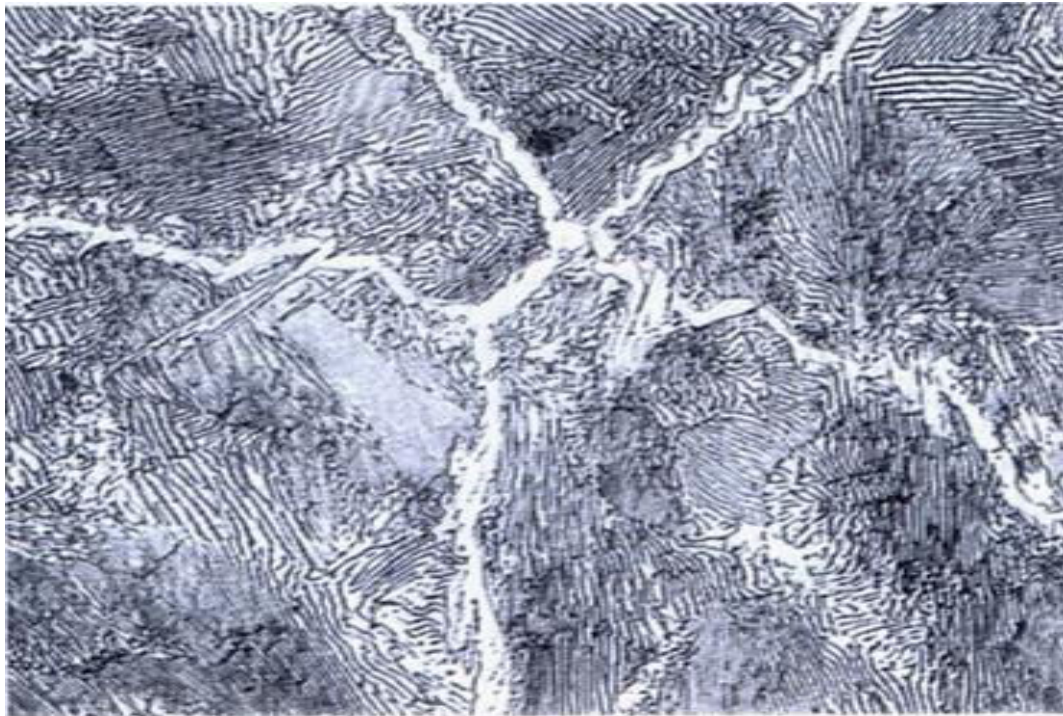


Fig. 3.35 Hypo-eutectoid steel showing

- It should be noted that the transitions as discussed, are for equilibrium conditions, as a result of slow cooling.
- Upon slow heating the transitions will occur in the reverse manner.
- When the alloys are cooled rapidly, entirely different results are obtained, since sufficient time may not be provided for the normal phase reactions to occur.
- In these cases, the equilibrium phase diagram is no longer a valid tool for engineering analysis.
- Rapid-cool processes are important in the heat treatment of steels and other metals (to be discussed later in H/T of steels).

3.32 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

CONTENTS :-

UNIT-4 HEAT TREATMENT OF METALS AND ALLOYS :-

- *Basic principles involved in heat treatment of plain carbon steel, alloy steels, cast iron and Non-ferrous metals and their alloys.*
- *Chemical Heat treatment of steels: Physical principles involved in chemical heat treatment procedure for carburizing, Nitriding, Cyaniding, carbo-nitriding of steel.*

4.1 HEAT TREATMENT IN PLAIN CARBON STEEL :-

- Carbon steel (plain carbon steel) is steel which contain main alloying element is carbon. Here we find maximum up to 1.5% carbon and other alloying elements like copper, manganese, silicon. Most of the steel produced now-a-days is plain carbon steel. It is divided into the following types depending upon the carbon content.
 1. Dead or mild steel (up to 0.15% carbon)
 2. Low carbon steel (0.15%-0.45% carbon)
 3. Medium carbon steel(0.45%-0.8% carbon)
 4. High carbon steel (0.8%-1.5% carbon)
- Steel with low carbon content has properties similar to iron. As the carbon content increases the metal becomes harder and stronger but less ductile and more difficult to weld. Higher carbon content lowers the melting point and its temperature resistance carbon content cannot alter yield strength of material.

- The process of heat treatment is carried out first by heating the material and then cooling it in the brine, water and oil. The purpose of heat treatment is to soften the metal, to change the grain size, to modify the structure of the material and to relieve the stress set up in the material after hot and cold working.
- The various heat treatment processes commonly employed in engineering practice as follows:-

4.1.1 ANNEALING:-

- **Spherodizing:-**
- Spherodite forms when carbon steel is heated to approximately 700 for over 30 hours. The purpose is to soften higher carbon steel and allow more formability. This is the softest and most ductile form of steel. Here cementite is present.

- **Full annealing:-**

Carbon steel is heated to approximately above the upper critical temperature (550-650) for 1 hour. Here all the ferrite transforms into austenite.

- The steel must then cooled in the realm of 38 per hour. This results in a coarse pearlite structure. Full annealed steel is soft and ductile with no internal stress.
- **Process annealing:-**
- The steel is heated to a temperature below or close to the lower critical temperature (550-650), held at this temperature for some time and then cooled slowly. The purpose is to relieve stress in a cold worked carbon steel with less than 0.3%wt c.
- **4.1.2.NORMALISING:-**
- The process of normalizing consist of heating the metal to a temperature of 30 to 50⁰ C above the upper critical temperature for hypo-eutectoid steels and by the same temperature above the lower critical temperature for hyper-eutectoid steel.
- It is held at this temperature for a considerable time and then quenched in suitable cooling medium. The purpose of normalizing is to refine grain structure, improve machinability and improve tensile strength, to remove strain and to remove disloca

- **4.1.3.HARDENING:-**

- The process of hardening consist of heating the metal to a temperature of 30-50 °C above the upper critical point for hypo-eutectoid steels and by the same temperature above the lower critical temperature for hyper-eutectoid steels. It is held this temperature for some time and then quenched. The purposes of hardening are to increase the hardness of the metal and to make suitable cutting tools.

- **4.1.5.MARTEMPERING:-**

This process is also known as steeped quenching or interrupted quenching. It consists of heating steel above the upper critical temperature and quenching it in a **salt bath kept** at a suitable temperature.

- **4.1.6.TEMPERING:-**

This process consists of reheating the hardened steel to some temperature below the lower critical temperature, followed by any desired rate of cooling. The purpose is to relive internal stress, to reduce brittleness and to make steel tough to resist shock and fatigue.

- **4.1.7 SURFACE HARDENING:-**

In many engineering applications, it is desirable that steel being used should have a hardened surface to resist wear and tear. At this time, it should have soft and tough interior or core so that it can absorb any shocks. Case hardening is the process of hardening the surface of metal, often a low carbon steel by infusing elements into the metal surface forming a hard, wear resistance skin but preserving a tough and ductile interior. This type of treatment is applied to gears, ball bearings, and railway wheels.

4.2 HEAT TREATMENT OF CAST-IRON :-

- Cast iron is a generic term used to designate a family of metals with a wide variety of properties. All cast irons contain more than 2% carbon and an appreciable amount of silicon (usually 1-3%). The high carbon and silicon content means that they are easily melted, have good fluidity in the liquid state and have excellent pouring properties. The basic types of cast iron are best differentiated by their microstructure as opposed to their chemical analysis because the various types overlap.
- The metallurgy of cast iron is more complex than its economics and, in fact, is one of the more complex metallurgical systems [Fig 2]. Iron-carbon alloys with less than 2% carbon are metastable; the true stable system being iron-graphite (Fe-C). The general term cast iron includes pig iron, gray iron, malleable iron, chilled iron, white iron, and nodular or ductile iron. If an iron alloy exceeds about 2% carbon, the carbon does not have to nucleate from decomposition of austenite, but instead, it can form directly from the melt by a eutectic reaction. Note that cementite (Fe_3C) can still nucleate at the eutectic more readily than graphite, but on sufficiently slow cooling, graphite itself is able to form and grow.

- Consider the solidification of a 3% carbon cast iron (Fig. 3). At a rapid cooling rate, dendrites of austenite form as the alloy cools below the liquidus and grow until the eutectic temperature is reached. At the eutectic, graphite formation is suppressed, but austenite and cementite precipitate to form ledeburite, **a form of eutectic that consists of spheres of austenite embedded in cementite**. Ledeburite forms at the Fe-Fe₃C eutectic (solid line “nm”). On further cooling, the cementite grows as the austenite decreases in carbon content (along the solid line “no”) At the eutectic (point “o”), the remaining austenite transforms to pearlite. At room temperature, the iron is hard and brittle and is called white iron because the surface of a fractured piece of iron is white and (somewhat) lustrous. Upon slow cooling of a 3% carbon cast iron, austenite forms from the melt, but eutectic freezing is now slow enough so the products of the eutectic reaction are austenite and graphite (the reaction takes place at the dotted line “nm”).

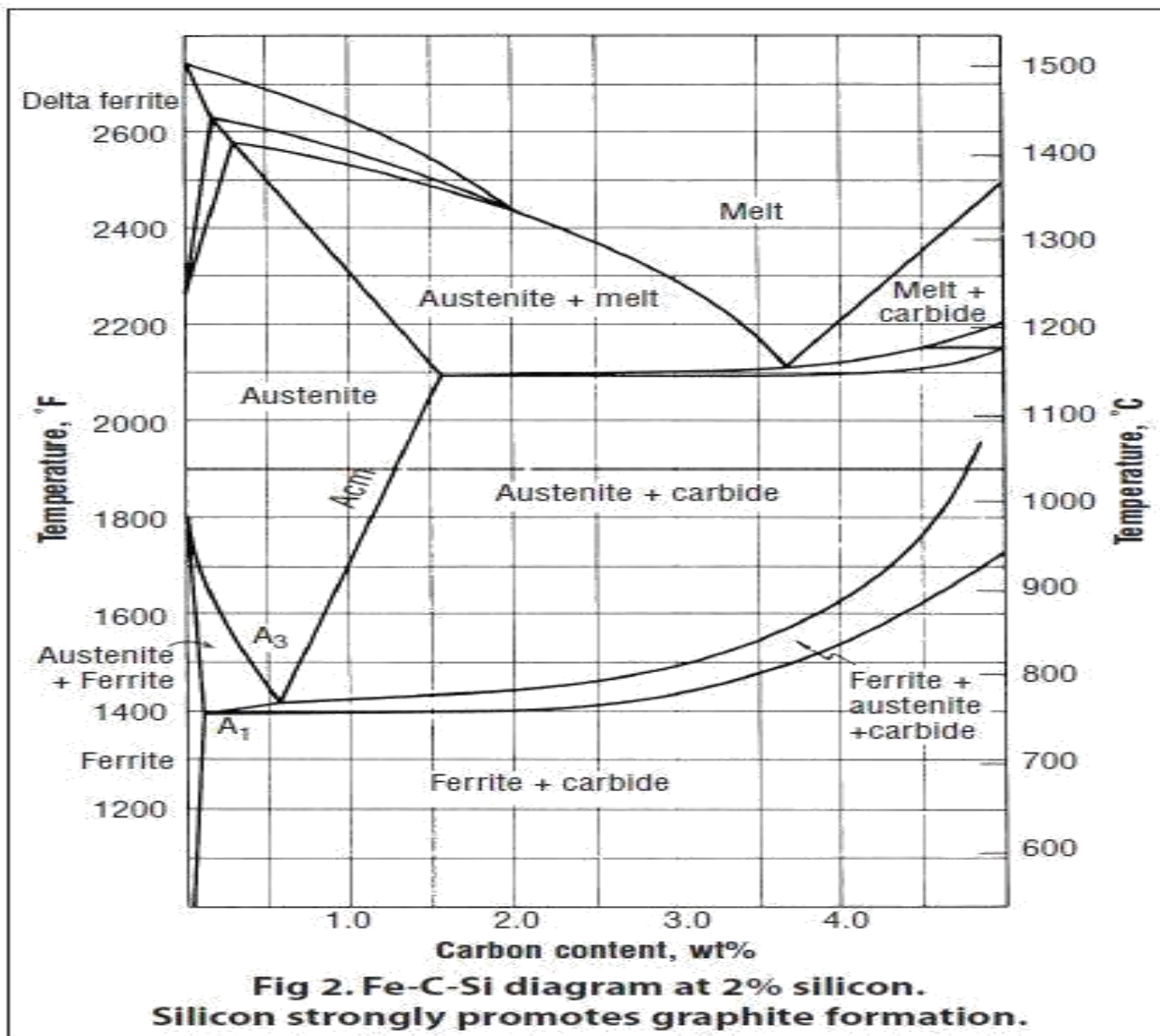


Fig. 4.1 Iron- Carbon diagram

- The eutectic graphite tends to form flakes surrounded by eutectic austenite. As cooling continues, the austenite decreases in carbon content (along the dotted line “no”), while the remaining austenite transforms to pearlite. Because the fracture surface appears dull gray the material is known as gray iron (or pearlitic gray iron).
- Cooling at an extremely slow rate results in phase changes similar to those of a slow cooled component, except the eutectoid cooling is sufficiently slow to permit graphite to precipitate rather than pearlite. No new graphite flakes will form, but the ones present will increase in size. The final microstructure consists of graphite flakes embedded in a ferrite matrix. The resultant material is called ferritic gray iron (cooling of actual castings cooling is seldom slow enough to obtain this structure).

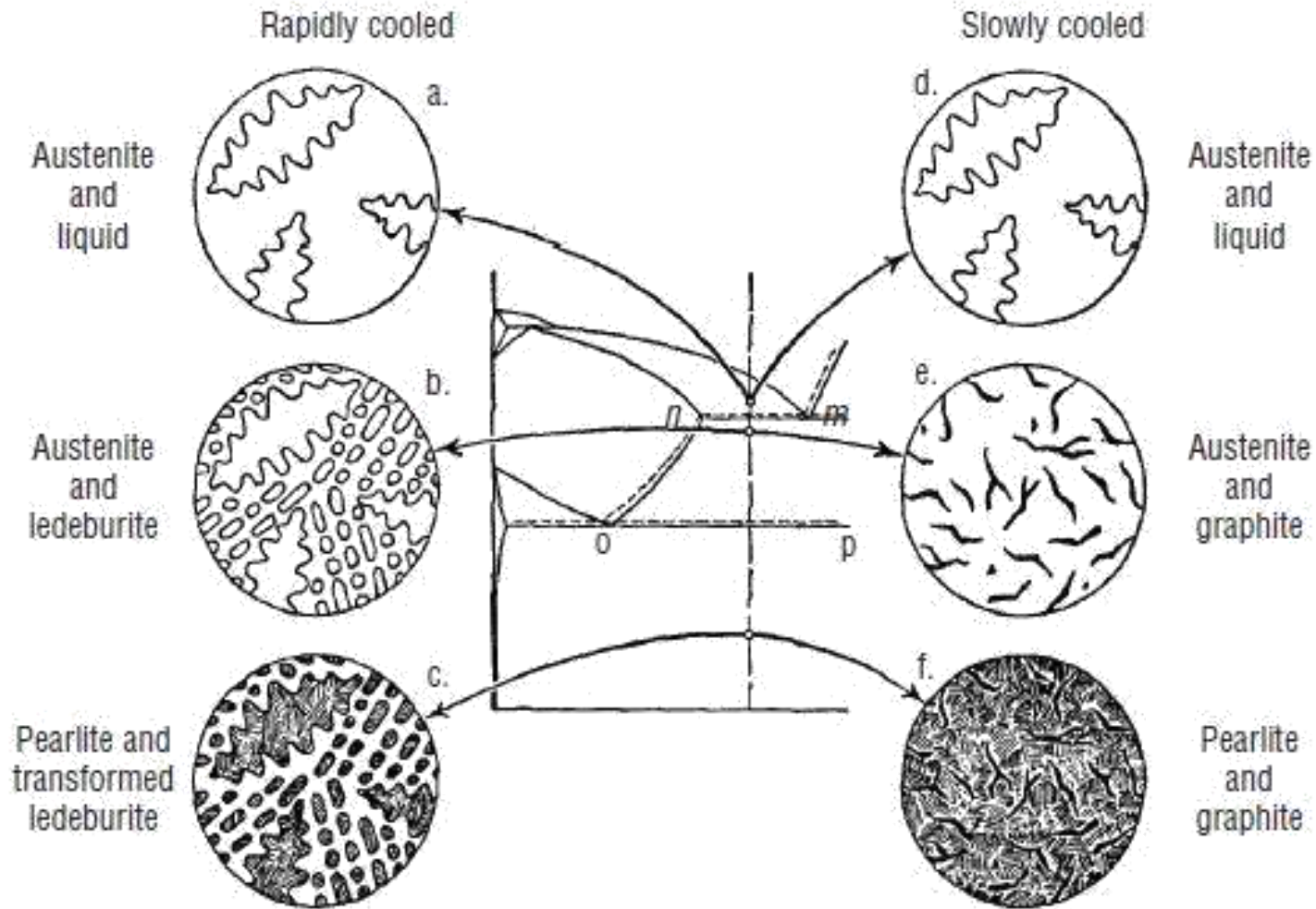


Fig 3. Iron-graphite phase diagram [4]. Microstructures obtained by cooling and solidification of cast iron; white iron (left) and gray iron (right).

Fig. 4.2 Iron-graphite phase diagram (cooling of actual castings cooling is seldom slow enough to obtain this structure)

4.3 HEAT TREATMENT OF NON- FERROUS METALS :-

4.3.1 ALUMINIUM ALLOY :-

- Aluminum is a white, lustrous metal, light in weight and corrosion resistant in its pure state. It is ductile, malleable, and nonmagnetic. Aluminum combined with various percentages of other metals, generally copper, manganese, and magnesium, form the aluminum alloys that are used in aircraft construction. Aluminum alloys are lightweight and strong, but do not possess the corrosion resistance of pure aluminum and are generally treated to prevent deterioration. "**Alclad**" is an aluminum alloy with a protective coating of aluminum to make it almost equal to the pure metal in corrosion resistance.
- Several of the aluminum alloys respond readily to heat treatment. In general, this treatment consists of heating the alloy to a known temperature, holding this temperature for a definite time, then quenching the part to room temperature or below. During the heating process, a greater number of the constituents of the metal are put into solid solution. Rapid quenching retains this condition, which results in a considerable

improvement in the strength characteristics.

The heating of aluminum alloy should be done in an electric furnace or molten salt bath.

The salt bath generally used is a mixture of equal parts of potassium nitrate and sodium nitrate. Parts heated by this method must be thoroughly washed in water after treatment. The salt bath method of heating should never be used for complicated parts and assemblies that cannot be easily washed free of the salt.

- **HEAT TREATING PROCEDURES :-**

- There are two types of heat treatment applicable to aluminum alloys. They are known as solution and precipitation heat treatment. Certain alloys develop their full strength from the solution treatment, while others require both treatments for maximum strength. The NA 01-1A-9 lists the different temper designations assigned to aluminum alloys and gives an example of the alloys using these temper designations.

SOLUTION HEAT TREATMENT :- The solution treatment consists of heating the metal to the temperature required to cause the constituents to go into a solid solution.

- To complete the solution, often the metal is held at a high temperature for a sufficient time, and then quenched rapidly in cold water to retain this condition. It is necessary that solution heat treatment of aluminum alloys be accomplished within close limits in reference to temperature control and quenching. The temperature for heat-treating is usually chosen as high as possible without danger of exceeding the melting point of any element of the alloy. This is necessary to obtain the maximum improvement in mechanical properties. If the maximum specified temperature is exceeded, eutectic melting will occur. The consequence will be inferior physical properties, and usually a severely blistered surface. If the temperature of the heat treatment is low, maximum strength will not be obtained.

4.3.2 COPPER :-

- Copper tends to become hard and brittle, when hammered or cold worked. It can be softened by annealing. All plates, rods, tubes etc of copper are thoroughly annealed before use. Annealing is done by heating to a dull red colour (650°C), keeping the pieces at this temperature for a few minutes, and then quenching in water or allowing it to cool in the air. During the process of drawing into wire, copper must be annealed to avoid fracture.
- Copper should not be heated in a reducing atmosphere, such as coal gas or carbon monoxide produced on the brazing hearth with a slow fire. Prolonged heating at a high temperature will also produce brittleness due to very coarse crystallization.

4.3.3 BRASS :-

- Brass is hardened by cold working. It can be annealed by heating between 535°C to 670°C and cooled either in air or water. Normalizing is done by heating it up to 700°C and cooling either in air or water.

4.3.4 Zinc :-

- Zinc is bluish white metal. It is brittle at normal temperature, but is malleable and ductile between 100°C to 150°C . Small pieces of zinc can be annealed by dipping them in boiling water. The temperature should be such that a hand touch can bear. Large jobs may be annealed by heating with a blowlamp or torch to the same temperature, which the hand can bear.

4.4 CARBURIZING :-

- It is a heat treatment process.
- Increasing Carbon on the surface of iron or steel followed by heat treatment.
- Absorbs Carbon liberated when the metal is heated in the presence of Carbon bearing materials.
- Carbon bearing materials can be Charcoal, Carbon Monoxide or Carbon gases.

- WORKPIECE MATERIAL :-

- Low Carbon alloy steels.
- Carbon contents should be ranging from 0.2 to 0.3%..



Fig. 4. 3 Carburizing

4.4.1 HARDENING AGENTS :-

- Carbon Monoxide Gas
- Sodium Cyanide
- Barium Carbonate
- Hardwood Charcoal

EFFECTING FACTORS:-

- Longer Carburizing time and higher temperatures lead to greater diffusion of carbon into the metal/alloy.
- Rapid Cooling/Quenching results transformation of austenite to martensite.
- While core remains soft and tough as a ferritic or pearlitic microstructure.

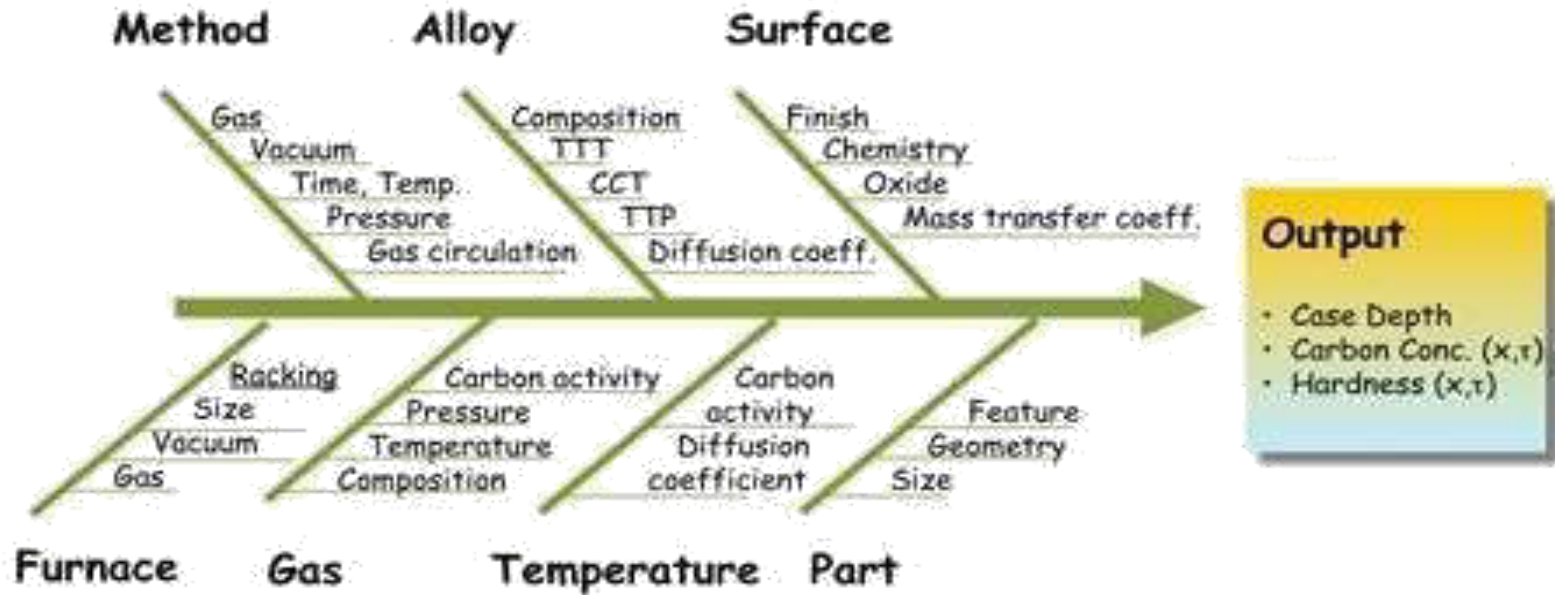


Fig. 4.4 FLOW SHEET DIAGRAM

WHY CARBURIZING IS USED?

It is used to increase

- Ductility
- Toughness
- Hardness

- **4.4.2 TYPES OF CARBURIZING :-**

- Gas Carburizing
- Vacuum Carburizing
- Pack Carburizing
- Liquid Carburizing

1. GAS CARBURIZING :-

Process Description:-

- Surface chemistry process.

- Main carburizing agent can be either Methane, Propane, Natural Gas or any other Carbon carrying gas.
- Work pieces are heated with carbon carrying gas.
- Then held for period of time at specific temperature between 800°C - 950°C .
- After that quench the sample.



Fig.4.5 Heat flow in gas carburizing



Fig.4.6 Gas carburizing method

- **Advantages:**

- Surface Carbon contents & case depth can be controlled accurately.
- It is much cleaner and more efficient method.

- **Disadvantages:**

- Furnace & gas generator are expensive.
- Handling of fire hazards & toxic gases is difficult.

2. VACUUM CARBURIZING :-

- It is done under very low pressure.
- Sample is heated in vacuum above transformation temperature.
- Then exposed to carbon carrying gas or mixture under partial pressure.
- **Temperature Range:** 800°C to 1100°C
- **Pressure Range:** 1 to 20 torrs



Fig. 4. 7 Vacuum carburizing

- **Advantages:**
 - Absence of inter-granular oxidation.
 - The process is clean, safe & simple to operate and easy to operate.
- **Disadvantages:**
 - Higher initial equipment cost.
 - Formation of soot & tar due to pressure and Hydrogen gas introduced.

3. PACK CARBURIZING :-

- Sample is packed in a steel container & sample is completely surrounded by granules of charcoal.
- Then heated in a furnace for 12 to 72 hours at 900°C .
- Due to high temperature, carbon diffuses into the surface of sample.

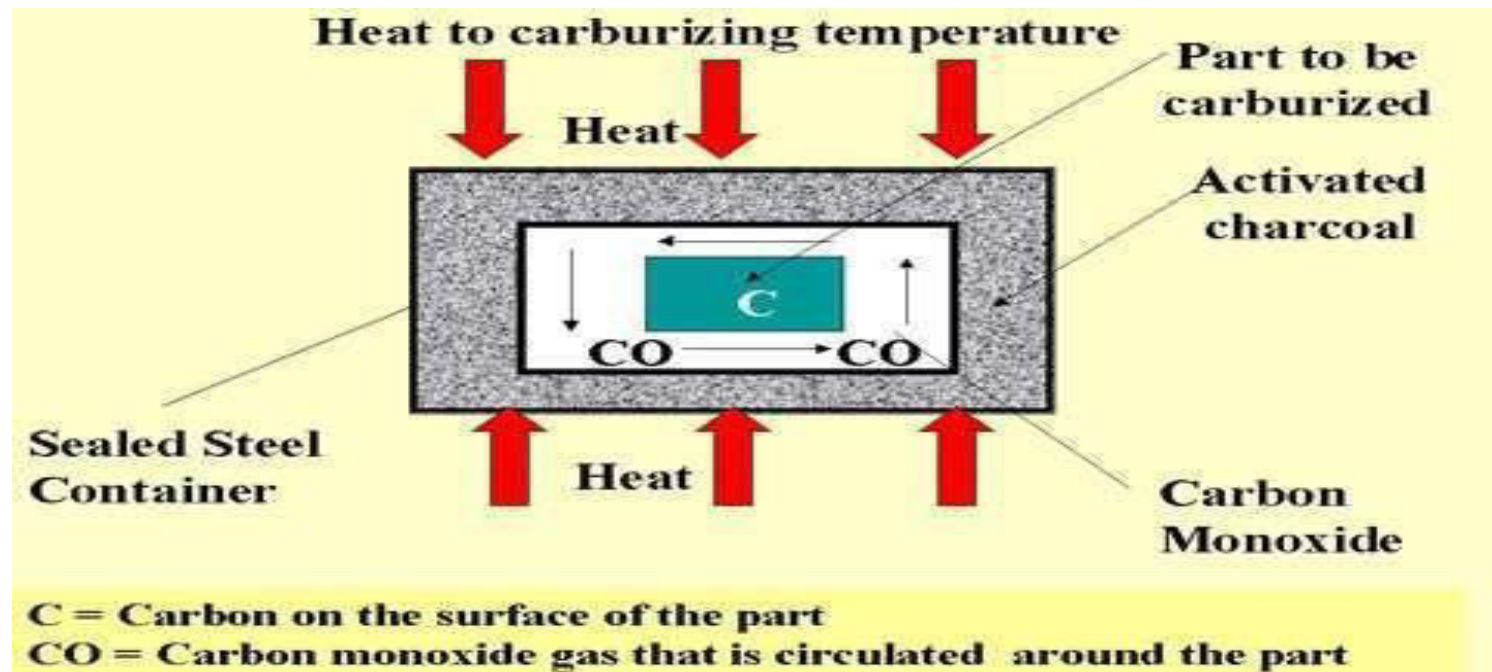


Fig. 4.8 Pack Carburizing

- **Advantages:**

- It is simple method and less capital investment.
- No atmosphere control furnace is required.

- **Disadvantages:**

- Carburizing time is very long.
- Difficult to control surface carbon & case depth.

4. LIQUID CARBURIZING :-

- Sample is placed in molten cyanide's bath so that carbon will diffuse into the sample.
- Diffusion of carbon into sample is greater than nitrogen.
- Low temperature salt bath contains 20% cyanide & operate between 1550°F to 1650°F.
- High temperature salt bath contains 10% cyanide & operate between 1650°F to 1750°F.



Fig. 4.9 Liquid Carburizing

- **Advantages:**

- Freedom from oxidation & soot problems.
- A rapid rate of penetration.

- **Disadvantages:**

- Proper composition is necessary to obtain uniform case depth.
- Parts must be washed after doing the process.

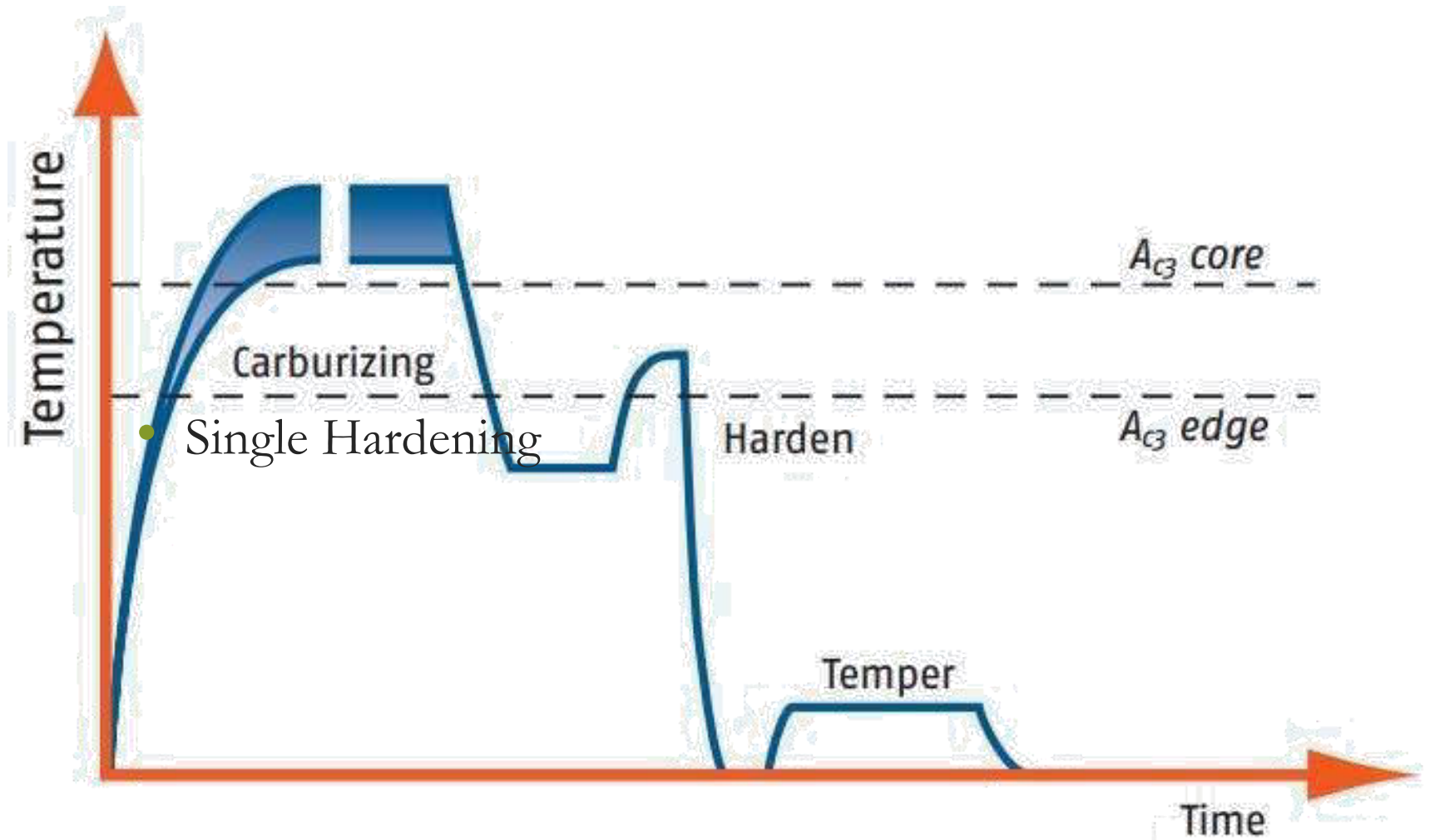


Fig. 4.9 Temperature-time relation of carburizing (single hardening)

4.4.3 APPLICATIONS

- Fly wheels
- Ball bearings
- Gear wheels & pinion blanks
- Railway wheels
- Crankshaft
- Shackles of lock
- Bevel Gears

4.5 NITRIDING AND CARBO-NITRIDING :-

NITRIDING :-

- Nitriding is a heat treating process that diffuses nitrogen into the surface of a metal to create a case hardened surface.
- Nitriding of steels produces less distortion and deformation than either carburizing or conventional hardening.
- These processes are most commonly used on low-carbon, low-alloy steels.
- However they are also used on medium and high-carbon steels, titanium, aluminum and molybdenum.

MECHANISM OF NITRIDING :-

- Case-hardening process.
- Solid ferrous alloy.
- Diffuse nitrogen.

- There are three main methods of nitriding :-
- Gas nitriding .
- Salt bath nitriding.
- Plasma nitriding.



Fig. 4. 9 Salt bath nitriding and Gas nitriding

4.5.1 MECHANISM OF NITRIDING :-

4.5.1.1 GAS NITRIDING

1. Case-Hardening Process
2. Nitrogen Introduction
3. Surface of a Solid Ferrous Alloy
4. Nitrogenous Gas
5. Ammonia

CHEMICAL REACTION

1. Nitrogen & Iron
2. Core Properties Not Effected

TEMPERATURE RANGE

1. 495 - 565 °C
2. Below Tempering Temperature

WHITE LAYER BY-PRODUCT

1. Thin
2. Hard Iron Nitride

1. CHEMICAL REACTION :-

Possible reactions taking place at the steel surface:

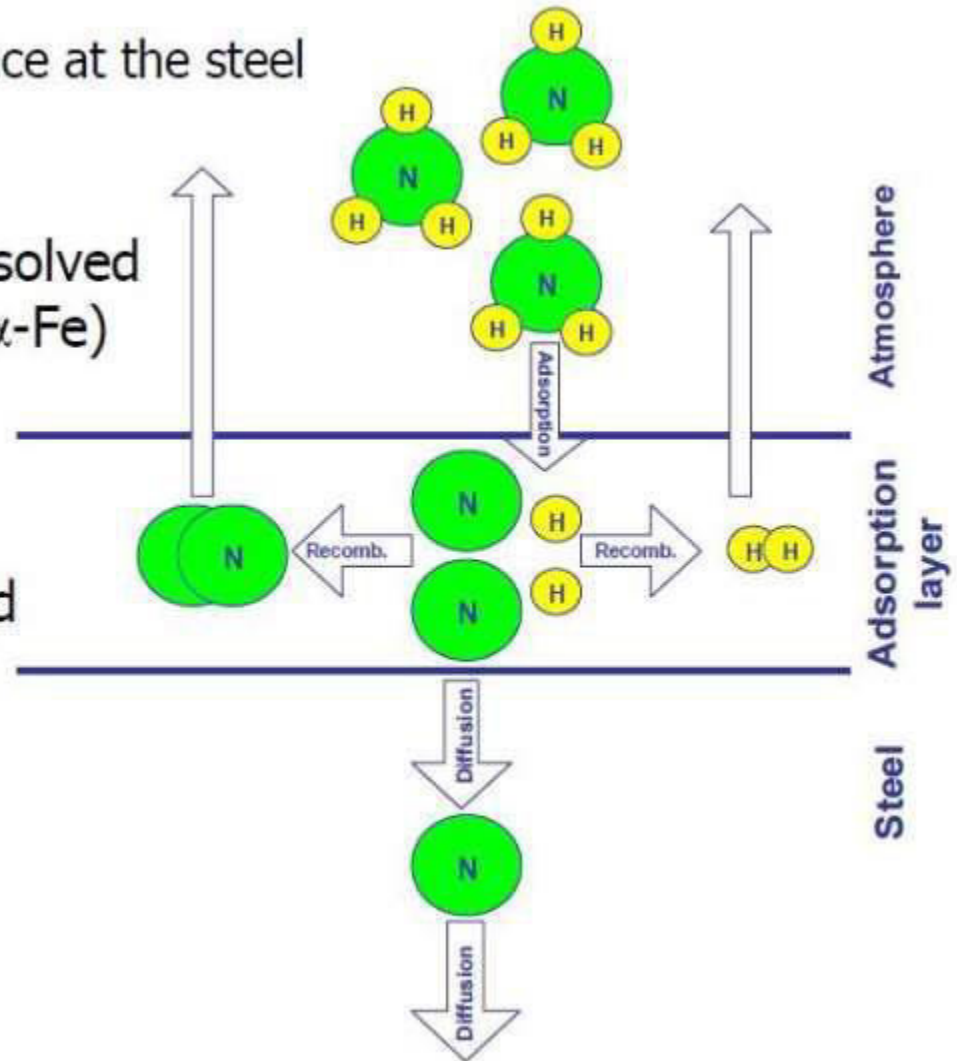
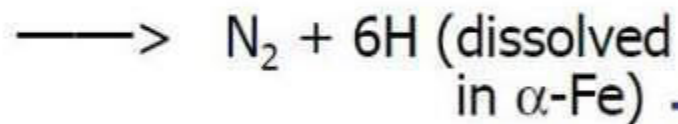
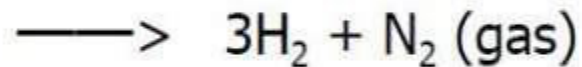
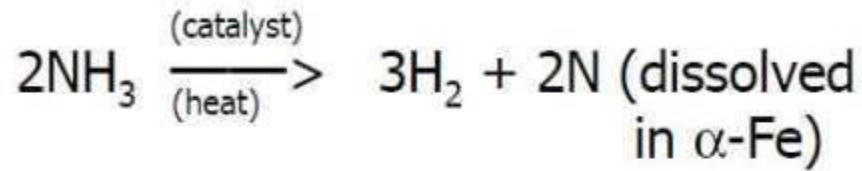


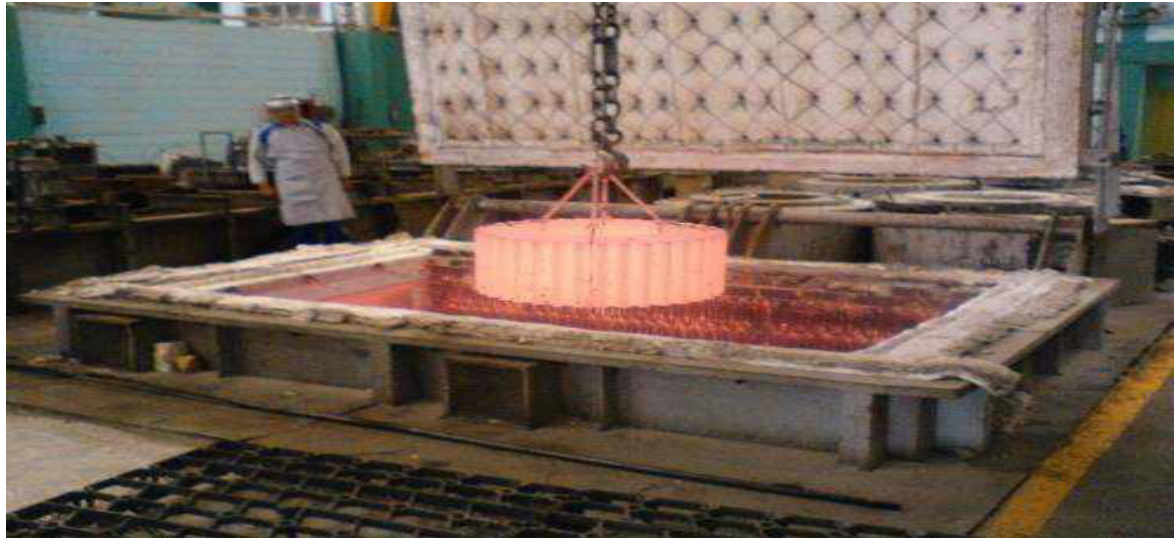


Fig. 4. 10 Nitriding flask

4.5.1.2 SALT BATH NITRIDING :-

- Thermo-chemical Diffusion Treatment
- Hardening Components With
- Repeatability.
- Use salt nitrogen-containing
- Salt Bath, at sub-Critical Temperatures.
- Higher diffusion nitrogen
- Corrosion Protection

Fig. 4.11 Salt bath nitriding



4.5.1.3 PLASMA NITRIDING :-

VACUUM CHAMBER :-

1. Pressure = 0.64 Pa
2. Pre-Heat Cycle
3. Surface Cleaning
4. Intense electric field.
5. Control Gas Flow
6. N, H, CH₄
7. Ionization by Voltage
8. Blue-Violet Glow

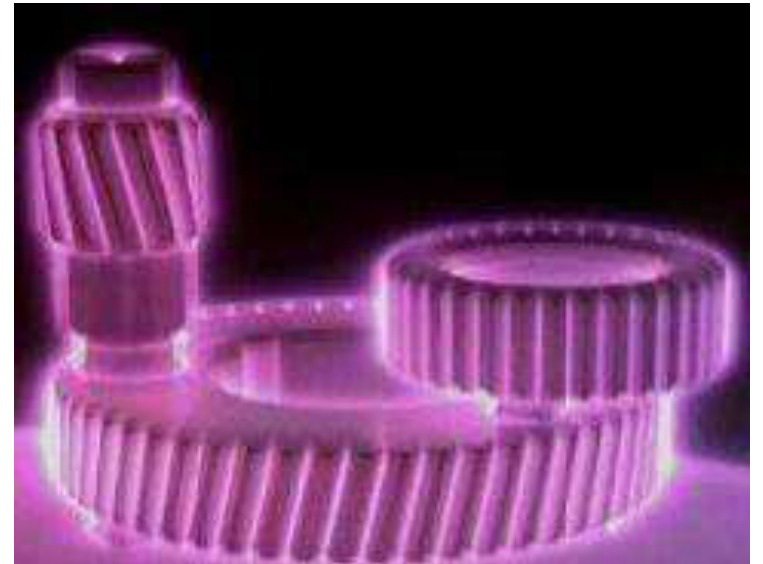


Fig. 4.11 Plasma nitriding

4.6 CARBONITRIDING :-

MECHANISM OF CARBONITRIDING :-

- Carbonitriding is similar to gas carburization with the addition of ammonia to the carburizing atmosphere, which provides a source of nitrogen.
- Nascent nitrogen forms at the work surface by the dissociation of ammonia in the furnace atmosphere; the nitrogen diffuses into the steel simultaneously with carbon.
- Typically, carbonitriding is carried out at a lower temperature and for a shorter time than is gas carburizing, producing a shallower case than is usual in production carburizing.
- carbonitriding in FC-35 atmosphere
- Ammonia and CO₂ flows are maintained constant throughout the process during Carbonitriding in the FC35 process.

- A typical Carbonitriding process cycle using the FC35.
- Carbonitriding (around 850 °C / 1550 °F) is carried out at temperatures substantially higher than plain nitriding (around 530 °C / 990 °F) but slightly lower than those used for carburizing (around 950 °C / 1700 °F) and for shorter times.
- A typical Carbonitriding process cycle using the FC35

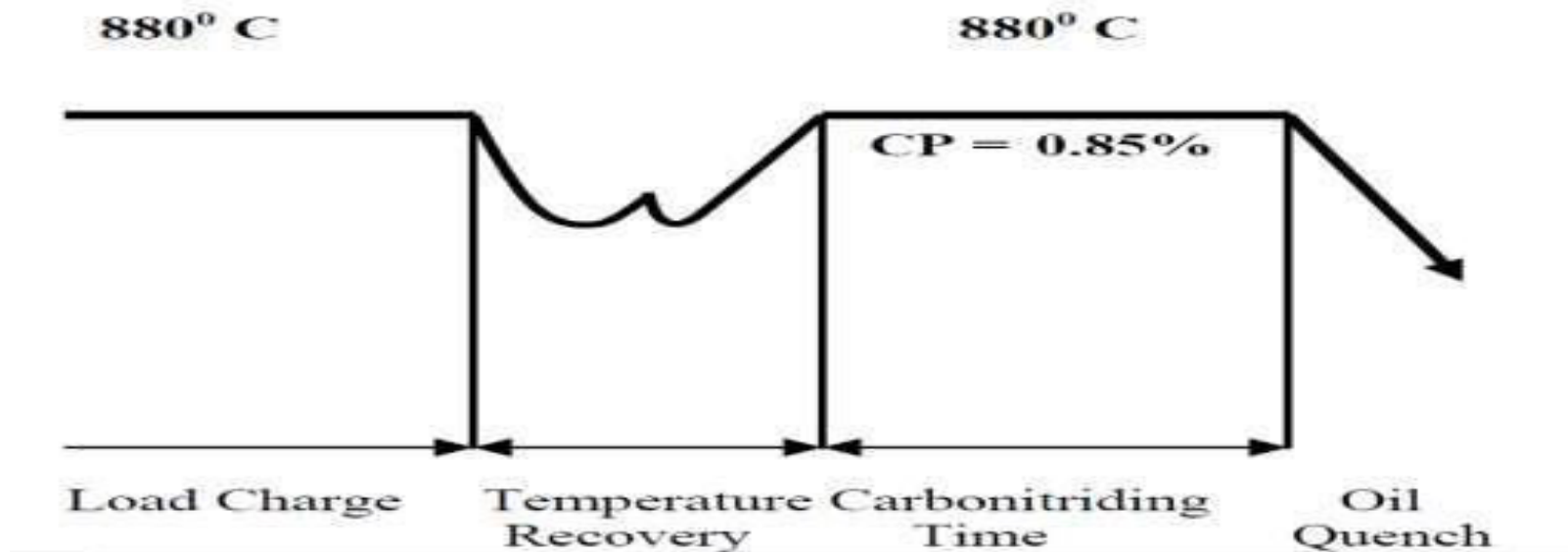


Fig. 4.12 Phases of Carbonitriding process

- Carbonitriding forms a hard, wear-resistant case, is typically 0.07mm to 0.5mm thick.
- Maximum case depth is typically restricted to 0.75mm; case depths greater than this take too long to diffuse to be economical.
- Its carried out in a salt bath or in a furnace gas atmosphere.
- FOR EXAMPLE :- Aircraft Industry, Military technology, Automotive Industry, Internal combustion engines, Compressors, Crank Shafts, Cam shafts, Gears etc

ADVANTAGES OF CARBONITRIDING PROCESS:-

- It gives high surface hardness.
- Nitriding increase wear resistance.
- It increase the tensile strength and yield point.
- Improves fatigue life by 30% to 100%.
- It is good for high temperature applications.
- It has a greater resistance to softening during Tempering.
- The carbonitrided case has better wear and temper resistance than a straight carburized case.
- It is carried out at a lower temperature and for a shorter time than is gas carburizing.
- Reduced distortion due to lower temperature.

- Since nitrided parts are not quenched, this minimizes distortion or cracking.
- Whereas in a carburized part, hardness begins to fall at about 200°C, a nitrided part retains hardness up to 500°C.
- No machining is required after nitriding.
- Some complex parts which are not carburized satisfactorily, can be nitrided without difficulty.

DISADVANTAGES OF CARBONITRIDING PROCESS:-

- Asymmetric products could buckle due to unequal cooling effects
- Maximum dimensions are determined by the furnace dimensions Blind holes cannot be treated during plasma - nitriding.
- Toughness and impact resistance decrease.

- It is not possible to obtain higher core hardness and deeper case depths.
- Only useful for Plain carbon steel or Low alloy Steel.
- Ammonia can produce harmful effects.
- Long cycle times (40 to 100 hours).
- The brittle case formed is Brittle.
- Only special alloy steels (containing Al, Cr and V) can be satisfactorily treated.
- High cost of the nitriding process.
- Technical control required.
- If a nitrided component is accidentally overheated, the surface hardness will be lost completely and the component must be nitrided again.

4.7 CYANIDING :-

1. Hardening the surface of steel with carbon and nitrogen obtained from a bath of liquid cyanide solution.
2. Steel is heated in molten cyanide at about 850 C followed by quenching.
3. Carbon and nitrogen are absorbed by steel.
4. It is a process of producing hard surface on lowcarbon or medium carbon steels by immersing the steel in amolten salt bath containing cyanide maintained at 800 to 900 degree celcius and then quenching the steel in water or oil.
5. The hardness produced by this treatment is due to the presence of components of nitrogen as well as carbon in the surface layer.
6. A bath containing one-third each of sodium chloride, sodium carbonate` and sodium cyanide is used for the cyaniding treatment. Under average conditions, a depth of case of 0.125mm will be produced in about 15 minutes at 850 degree celcius.

6. But special salt composition are available which enables much thicker cases to be obtained, if required.
7. Cyaniding is used chiefly for cases not exceeding about 0.8mm in thickness.
8. One advantages of tis process is that the bright finish of machined part can, if required, be maintained;
9. Second the distortion is more easily avoided.
10. Third, is that change in hardness from the case of core is more gradual and flaking of the core is eliminated.



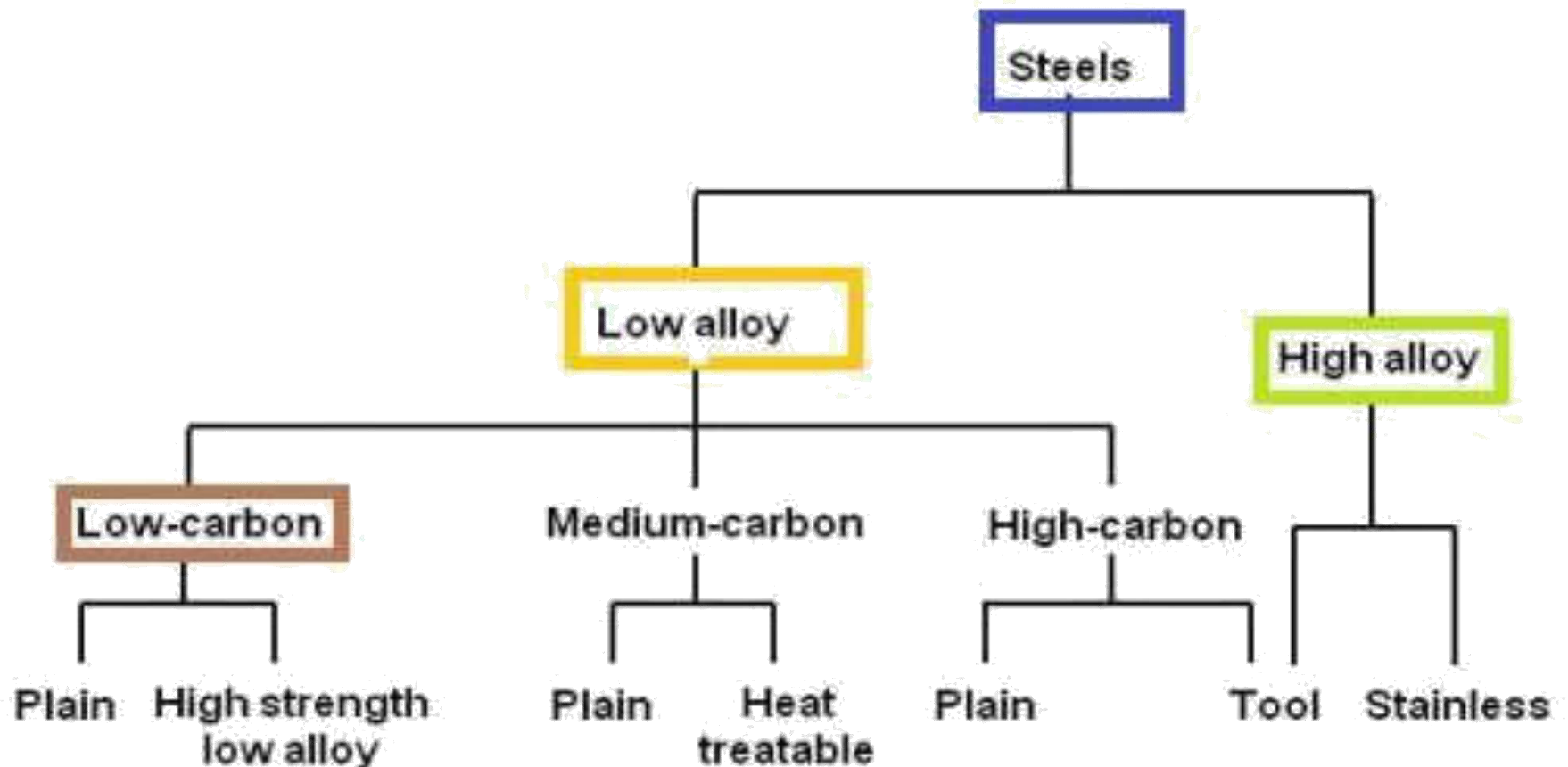
Fig. 4.13 Cyaniding surface treatment

CONTENTS :-

UNIT-5 EFFECT OF VARIOUS ALLOYING ELEMENT ON STEEL AND PLASTIC PROCESSING :-

- *Effects produced by Alloying element on the structures and properties of steel*
Distribution of alloying elements (Si, Mn, Ni, Cr, Mo, Co, W, Ti, Al) in steel,
structural classes of steel.
- *Classification of steels, BIS Standards. Fibre reinforced plastic composites:*
Various fibres and matrix materials, basic composite manufacturing methods,
applications of composite materials.

5.1 CLASSIFICATION OF STEEL :-



5.1.1 FERROUS MATERIAL – STEELS :-

- Steels - alloys of iron-carbon.
 - May contain other alloying elements.
- Several grades are available
- Low.Alloy (<10 wt%)
 - Low Carbon (<0.25 wt% C)
 - Medium Carbon (0.25 to 0.60 wt% C)
 - High Carbon (0.6 to 1.4 wt% C)
- HighAlloy
 - Stainless Steel (>11 wt% Cr)
 - Tool Steel

5.1.2 EFFECT OF CARBON ON PROPERTIES OF STEELS :-

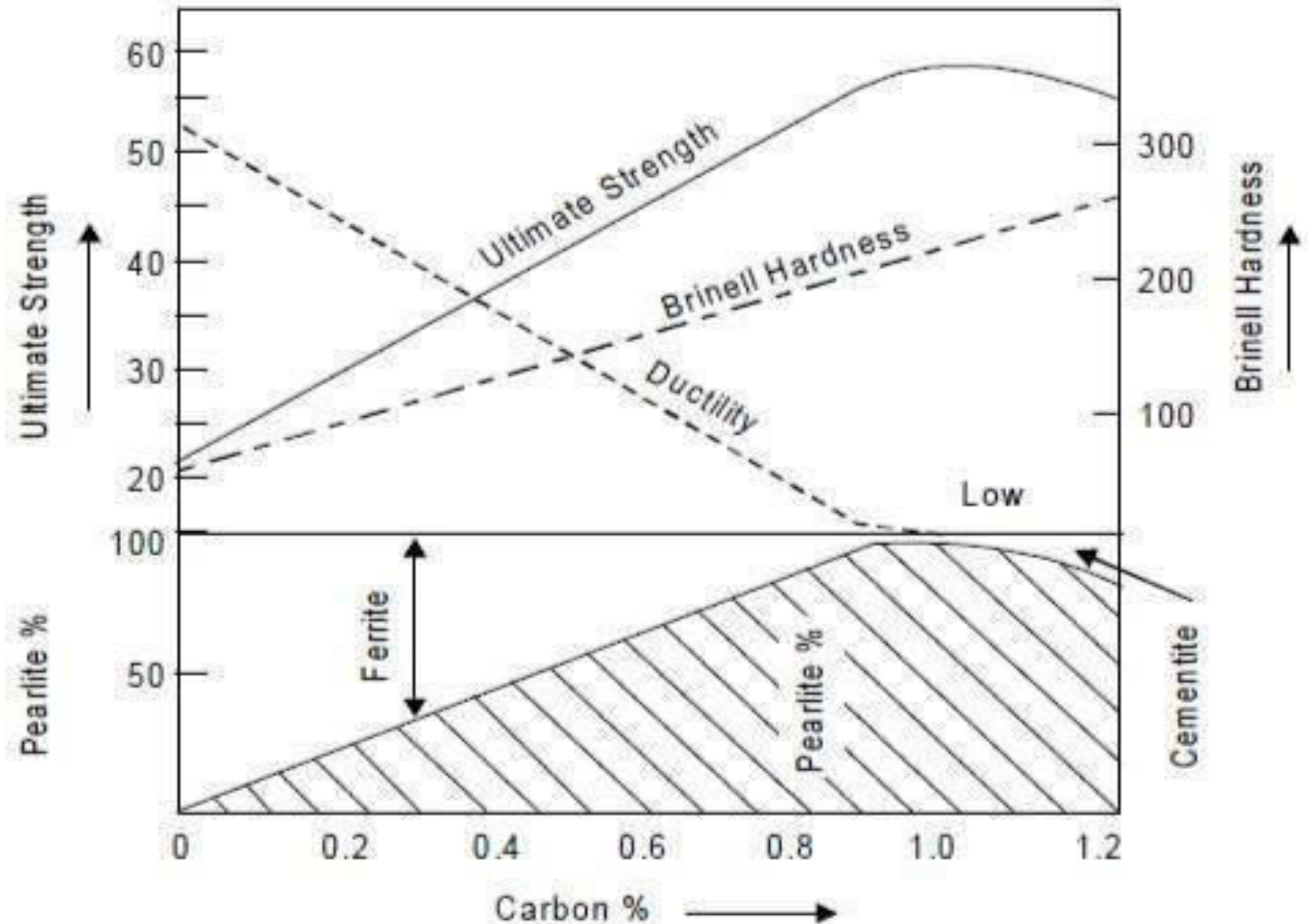


Fig. 5.1 Effect of carbon on properties of steels

5.1.3 LOW CARBON STEEL :-

- Also known as Mild Steel.
- Tensile strength of 555 N/mm.
- Hardness of 140 BHN.
- Bright fibrous structure.
- Tough , malleable , ductile and more elastic than wrought iron.
- Melting point 1410.
- Plain carbon steels - very low content of alloying elements and small amounts of Mn.
- Most abundant grade of steel is low carbon steel – greatest quantity produced; least expensive.
- Not responsive to heat treatment; cold working needed to improve the strength.
- Good Weldability and machinability

<i>Designation</i>		<i>Composition (wt%)</i>		
<i>AISI/SAE or ASTM Number</i>	<i>UNS Number</i>	<i>C</i>	<i>Mn</i>	<i>Other</i>
<i>Plain Low-Carbon Steels</i>				
1010	G10100	0.10	0.45	
1020	G10200	0.20	0.45	
A36	K02600	0.29	1.00	0.20 Cu (min)
A516 Grade 70	K02700	0.31	1.00	0.25 Si
<i>High-Strength, Low-Alloy Steels</i>				
A440	K12810	0.28	1.35	0.30 Si (max), 0.20 Cu (min)
A633 Grade E	K12002	0.22	1.35	0.30 Si, 0.08 V, 0.02 N, 0.03 Nb
A656 Grade 1	K11804	0.18	1.60	0.60 Si, 0.1 V, 0.20 Al, 0.015 N

Table 5.1 Compositions of some low carbon and low alloy steels

<i>AISI/SAE or ASTM Number</i>	<i>Tensile Strength [MPa (ksi)]</i>	<i>Yield Strength [MPa (ksi)]</i>	<i>Ductility [%EL in 50 mm (2 in.)]</i>	<i>Typical Applications</i>
<i>Plain Low-Carbon Steels</i>				
1010	325 (47)	180 (26)	28	Automobile panels, nails, and wire
1020	380 (55)	210 (30)	25	Pipe; structural and sheet steel
A36	400 (58)	220 (32)	23	Structural (bridges and buildings)
A516 Grade 70	485 (70)	260 (38)	21	Low-temperature pressure vessels
<i>High-Strength, Low-Alloy Steels</i>				
A440	435 (63)	290 (42)	21	Structures that are bolted or riveted
A633 Grade E	520 (75)	380 (55)	23	Structures used at low ambient temperatures
A656 Grade 1	655 (95)	552 (80)	15	Truck frames and railway cars

Properties and typical application of some low carbon and low alloys steels

Applications



1. Mild steel containing 0.15 to 0.20% carbon

It is used in structure steels, universal beams, screws, drop forgings, case hardening steel, bars, rods, tubes, angles and channels etc.

2. Mild steel containing 0.20-0.30% carbon

It is used in making machine structure, gears, free cutting steels, shafts and forged components etc.

5.1.4 MEDIUM CARBON STEEL :-

- Carbon content in the range of 0.3 – 0.6%.
- Can be heat treated - austenitizing, quenching and then tempering.
- Most often used in tempered condition – tempered martensite
- Medium carbon steels have low hardenability
- Addition of Cr, Ni, Mo improves the heat treating capacity Heat treated alloys are stronger but have lower ductility Typical applications – Railway wheels and tracks, gears, crankshafts.
- Bright fibrous structure when fractured
- Tough and more elastic in comparison to wrought iron
- Easily forged , welded , elongated due to ductility, Good malleability
- Its tensile strength is better than cast iron and wrought iron
- Compressive strength is better than wrought iron but lesser than cast iron

Composition of some alloyed medium carbon steels

<i>AISI/SAE Designation</i>	<i>UNS Designation</i>	<i>Composition Ranges (wt% of Alloying Elements in Addition to C)</i>			
		<i>Ni</i>	<i>Cr</i>	<i>Mo</i>	<i>Other</i>
10xx, Plain carbon	G10xx0				
11xx, Free machining	G11xx0				0.08–0.33S
12xx, Free machining	G12xx0				0.10–0.35S, 0.04–0.12P
13xx	G13xx0				1.60–1.90Mn
40xx	G40xx0			0.20–0.30	
41xx	G41xx0		0.80–1.10	0.15–0.25	
43xx	G43xx0	1.65–2.00	0.40–0.90	0.20–0.30	
46xx	G46xx0	0.70–2.00		0.15–0.30	
48xx	G48xx0	3.25–3.75		0.20–0.30	
51xx	G51xx0		0.70–1.10		
61xx	G61xx0		0.50–1.10		0.10–0.15V
86xx	G86xx0	0.40–0.70	0.40–0.60	0.15–0.25	
92xx	G92xx0				1.80–2.20Si

Applications

➡ steels having carbon % 0.30 to 0.45. Axles, special duty shafts, connecting rods, forgings, machinery steel, spring clips, turbine, rotors, gear shafts, key stock, forks and bolts.

➡ steels having carbon % 0.45 to 0.60. Railway coach axles, crank pins, crankshafts, axles, spline shafts, loco tyres.

5.1.5 HIGH CARBON STEEL :-

- High carbon steels – Carbon content 0.6 – 1.4%
- High C content provides high hardness and strength. Hardest and least ductile.
- Used in hardened and tempered condition
- Strong carbide formers like Cr, V, W are added as alloying elements to form carbides of these metals.
- Used as tool and die steels owing to the high hardness and wear resistance property

5.1.6 APPLICATIONS :-

HCS containing 0.7 to 0.8% carbon

for making cold chisels, drill bits, wrenches, wheels for railway service, jaws for vises, structural wires, shear blades, automatic clutch discs, hacksaws etc.

Steel containing 0.8 to 0.9% C possesses hardness of 500 to 600 BHN. This steel is used for making rock drills, punches, dies, railway rails clutch discs, circular saws, leaf springs, machine chisels, music wires,

Steel containing 0.90 to 1.00% carbon is also known as high carbon tool steel and it possesses hardness of 550-600 BHN. Such steel is used for making punches, dies, springs keys and shear blades.

Steel containing 1.0 to 1.1 % C is used for making railway springs, mandrels, taps, balls, pins, tools, thread metal dies.

Steel containing 1.1 to 1.2% C is used for making taps, twist drills, thread dies, knives.

Steel containing 1.2 to 1.3% carbon is used for making files, reamers Files, dies for wire drawing, broaches, saws for cutting steel, tools for turning chilled iron.

Compositions and Application of some Tool steels

AISI Number	UNS Number	<i>Composition (wt.%)</i>						Typical Allpications
		C	Cr	Ni	Mo	W	V	
M1	T11301	0.85	3.75	0.30 max	8.70	1.75	1.20	Drills, saws, lathe and planer tools
A2	T30102	1.0	5.15	0.30 max	1.15	-	0.35	Punches, embossing dies
D2	T30402	1.5	12	0.30 max	0.95	-	1.10 max	Cutlery, drawing dies
O1	T31501	0.95	0.50	0.30 max	-	0.50	0.30 max	Shear blades, cutting tools
S1	T41901	0.50	1.40	0.30 max	0.50 max	2.25	0.25	Pipe cutters, concrete drills
W1	T72301	1.10	0.15 max	0.20 max	0.10 max	0.15 max	0.10 max	Balcksmith tools

Table 5.2 Compositions and application of some tool steels

5.2 STRUCTURAL STEELS :-

- Possess high strength and toughness
- Resistance to softening at elevated temperatures
- Resistance to corrosion
- Possess weld ability, workability & high harden ability
- Principle alloying elements chromium, nickel , manganese

Applications

They are used for structural members of bridges, buildings, rail road, cars etc. They are also used for manufacturing components subjected to static and dynamic loads. These components include valves, pins, studs, gears, clutches, bushes, shafts etc.

5.4 EFFECT OF MAGNESSIUM (M) :-



Manganese increases hardenability and tensile strength of steel, but to a lesser extent than carbon. It is also able to decrease the critical cooling rate during hardening, thus increasing the steels hardenability much more efficient than any other alloying elements. Manganese also tends to increase the rate of carbon penetration during carburizing and acts as a mild deoxidizing agent. However when too high carbon and too high manganese accompany each other, embrittlement sets in. Manganese is capable to form Manganese Sulphide (MnS) with sulphur, which is beneficial to machining. At the same time, it counters the brittleness from sulphur and is beneficial to the surface finish of carbon steel.

Manganese could be the second most important element after Carbon on steel. Mn has effects similar to those of carbon, and the steel producer uses

these two elements in combination to obtain a material with the desired properties. Manganese is a necessity for the process of hot rolling of steel by its combination with oxygen and sulfur.

- Its presence has below main effects:
- It is a mild de-oxidant acting as a cleanser taking the sulphur and oxygen out of the melt into the slag.
- It increases the harden ability and tensile strength but decreases ductility.
- It combines with sulphur to form globular manganese sulphides, essential in free cutting steels for good machinability.
- Steels usually contain at least 0.30% manganese, however, amounts of up to 1.5% can be found in some carbon steels.
- Manganese also tends to increase the rate of carbon penetration during carburizing and acts as a mild deoxidizing agent. However when too high carbon and too high manganese accompany each other, em-brittlement sets in.

5.5 EFFECT OF PHOSPHORUS ¹⁵P_{30.973761}

- Phosphorus increases strength and hardness, but at the expense of ductility and impact to toughness, especially in higher carbon steels that are quenched and tempered. As such its content in most steel is limited to a maximum of 0.05%. Phosphorus prevents the sticking of light-gage sheets when it is used as an alloy in steel. It strengthens low carbon steel to a degree, increases resistance to corrosion and improves machinability in free-cutting steels. In terms of welding, phosphorus content of over 0.04% makes weld brittle and increases the tendency to crack. The surface tension of the molten weld metal is lowered, making it difficult to control.
- Although it increases the tensile strength of steel and improves machinability it is generally regarded as an undesirable impurity because of its embrittling effect.
- Effect of phosphorus element will have various effects on steel depending on concentration.

- The maximum amount of phosphorus in higher grade steel is between 0.03 to 0.05% due to the fact that is detrimental. Up to 0.10% of phosphorus in low-alloy high-strength steels will increase the strength as well as improve the steel's resistance against corrosion. The possibility of brittleness increases when the content in hardened steel is too high. Even though the strength and hardness is improved, the ductility and toughness decreases.
- The machinability is improved in free-cutting steel, but weld brittle and/or weld cracks can occur during welding if the phosphorus content is more than 0.04%. Phosphorus also affects the thickness of the zinc layer when galvanising steel.

5.7 EFFECT OF SILICON ¹⁴Si_{28.0855}

- Silicon increases strength and hardness but to a lesser extent than manganese. It is one of the principal deoxidizers used in the making of steels to improve soundness, i.e. to be free from defects, decays or damages. Silicon is present in all steels to a certain extent. Its content can be up to 4% for electric sheets that are widely used in alternating current magnetic circuits.
- In welding, silicon is detrimental to surface quality, especially in the low carbon, resulphurized grades. It aggravates cracking tendencies when the carbon content is fairly high. For best welding condition, silicon content should not exceed 0.10%. However, amounts up to 0.30% are not as serious as high sulphur or phosphorus content.
- For galvanizing purposes, steels containing more than 0.04% silicon can greatly affect the thickness and appearance of the galvanized coating.

- This will result in thick coatings consisting mainly zinc-iron alloys and the surface has a dark and dull finish. But it provides as much corrosion protection as a shiny galvanized coating where the outer layer is pure zinc.
- Silicon is one of the principal deoxidizers for steel. Silicon helps to remove bubbles of oxygen from the molten steel. It is the element that is most commonly used to produce semi- and fully killed steels, and normally appears in amounts less than 0.40 percent, usually only small amounts (0.20%) are present in rolled steel when it is used as a deoxidizer. However, in steel castings, 0.35 to 1.00% is commonly present.
- Silicon dissolves in iron and tends to strengthen it. Some filler metals may contain up to 1% to provide enhanced cleaning and deoxidation for welding on contaminated surfaces. When these filler metals are used for welding on clean surfaces, the resulting weld metal strength will be markedly increased. Silicon increases strength and hardness but to a lesser extent than manganese. The resulting decrease in ductility could result in cracking problems.

5.7 CHROMIUM (CR) :-

- Chromium is a powerful alloying element in steel. Cr presents in certain structural steels in small amounts. It is primarily used to increase hardenability of steel and increase the corrosion resistance as well as the yield strength of the steel material. For that reason often occurs in combination with nickel and copper. Stainless steels may contain in excess of 12% chromium. The well-known “18-8” stainless steel contains 8 percent of nickel and 18 percent of chromium.
- When the percent of chromium in the steel exceeds 1.1% a surface layer is formed that helps protect the steel against oxidation.

5.8 TUNGSTEN (W) :-

- It is used with chromium, vanadium, molybdenum, or manganese to produce high speed steel used in cutting tools. Tungsten steel is said to be "red-hard" or hard enough to cut after it becomes red-hot. After heat treatment the steel maintains its hardness at high temperature making it particularly suitable for cutting tools.
- Tungsten in the form of tungsten carbide
- Gives steel high hardness even at red heats.
- Promotes fine grains
- Resists heat
- Promote strength at elevated temperatures

5.9 MOLYBDENUM (MO) :-

- Molybdenum has effects similar to manganese and vanadium, and is often used in combination with one or the other. This element is a strong carbide former and is usually present in alloy steels in amounts less than 1%. It increases hardenability and elevated temperature strength and also improves corrosion resistance as well as increased creep strength. It is added to stainless steels to increase their resistance to corrosion and is also used in high speed tool steels.

5.10 COBALT (CO) :-

- Cobalt improves strength at high temperatures and magnetic permeability.
- Increases hardness, also allows for higher quenching temperatures (during the heat treatment procedure). Intensifies the individual effects of other elements in more complex steels. Co is not a carbide former, however adding Cobalt to the alloy allows for higher attainable hardness and higher red hot hardness.

5.11 NICKEL (Ni) :-

- In addition to its favorable effect on the corrosion resistance of steel, Ni is added to steels to increase hardenability. Nickel enhances the low-temperature behavior of the material by improving the fracture toughness. The weldability of the steel is not decreased by the presence of this element. The nickel drastically increases the notch toughness of the steel.
- Nickel is often used in combination with other alloying elements, especially chromium and molybdenum. It is a key component in stainless steels but at the low concentrations found in carbon steels. Stainless steels contain between 8% and 14% nickel.
- One more reason Ni is added to an alloy is that it creates brighter portions in damascus steels.

5.12 ALUMINUM (AL) :-

- Aluminum is one of the most important deoxidizers in very small amounts in the material, and also helps form a more fine-grained crystalline microstructure and increase the steel grade's toughness. It is usually used in combination with silicon to obtain a semi- or fully killed steel.

5.13 TITANIUM (Ti) :-

- Ti is used to control grain size growth, which improves toughness. Also transforms sulfide inclusions from elongated to globular, improving strength and corrosion resistance as well as toughness and ductility.
- Ti is a very strong, very lightweight metal that can be used alone or alloyed with steels. It is added to steel to give them high strength at high temperatures. Modern jet engines use titanium steels.
- It prevents localized depletion of chromium in stainless steels during long heating
- Prevents formation of austenite in high chromium steels
- Reduces martensitic hardness and hardenability in medium chromium steels.

5.14 TEMPER EMBRITTLEMENT :-

- Temper embrittlement refers to the decrease in notch toughness of alloy steels when heated in, or cooled slowly through, a temperature range of 400°C to 600°C. Temper embrittlement can also occur as a result of isothermal exposure to this temperature range. The occurrence of temper embrittlement can be determined by measurement of the change in the ductile to brittle transition temperature with a notched bar impact test, before and after heat treatment. In most cases, the hardness and tensile properties of the material will not show any change as a result of embrittlement, but the transition temperature can be raised by as much as 100°C for embrittling heat treatments.
- Temper embrittlement is caused by the presence of specific impurities in the steel, which segregate to prior austenite grain boundaries during heat treatment. The main embrittling elements (in order of importance) are antimony, phosphorous, tin and arsenic. The fracture surface of a material embrittled by these elements has an intergranular appearance.

- Plain carbon steels with less than 0.5% Mn are not susceptible to temper embrittlement. However, additions of Ni, Cr and Mn will cause greater susceptibility to temper embrittlement. Small additions of W and Mo can inhibit temper embrittlement, but this inhibition is reduced with greater additions.
- The original toughness of a steel which has suffered temper embrittlement can be restored by heating to above 600°C, and then cooling rapidly to below 300°C. However, the best method of avoidance is to reduce the embrittling impurities through control of raw materials and steel production.
- Temper embrittlement has been also related to reheat cracking and low-ductility creep fractures, and a number of types and mechanisms have been proposed, considering carbide precipitation as well as grain boundary embrittling elements.
- The loss of ductility caused in certain steels when they are held in or slowly cooled through the temperature range 300° to 600°C. This effect is commonly seen in nickel-chromium steels and is due to the precipitation of carbides in the areas between the crystals in their structure (grain boundaries). It can be overcome by adding 0.2% to 0.3% molybdenum. This effect is called temper brittleness since it occurs in the normal tempering range of steels.

5.15 OVERHEATING :-

- The term "overheating" has been loosely used in the past to indicate the structure associated with austenitic grain growth, for instance the precipitation of ferrite in a Widmanstätten pattern. In view of the temporary nature of the effects of this phenomenon it is desirable to differentiate it from overheating as described below, the effects of which are persistent.
- Inferior mechanical properties of a steel resulting from coarse austenite grains can be improved by hot working and grain refining treatments. The effects of overheating and burning, on the other hand, are difficult to remove. Burning may damage the steel beyond resuscitation; it may also impair the forging properties of the

steel. **SYMPTOM** :-

- When a steel is heated above a certain temperature, generally known as the overheating temperature, changes which take place at the austenitic grain boundaries reduce the resistance of these regions to fracture.

- After the steel is reheated, quenched and tempered so that the resistance to fracture of the matrix is increased, the steel will break, during notched impact test, along the previous grain boundaries giving rise to a fracture containing a number of matrix crystal facets in a fibrous structure. These facets correspond to the previous grain interfaces.
- The optimum heat-treatment required to develop the facets in an overheated steel depends on the composition of the steel. In general, oil quenching from the austenite range followed by tempering at 600° C for 1 hour is most suitable for alloy steels. No systematic investigation has been published for plain carbon steels; tempering at 200°C has been reported as suitable for a mild steel.
- The size and the number of facets in a fracture increase with increasing temperature

EFFECTS :-

- The ductility and impact toughness of a steel are reduced by overheating, but the tensile strength is not affected except when it is severely overheated.
- That fatigue strength of steel is lowered. Premature failure in aeroengine components, such as connecting rods, has been attributed to overheating during forging.
- The austenitizing temperature above which the symptom of overheating appear after suitable heat treatment is known as the overheating temperature. It varies from steel to steel, even from one heat to another for a steel of the same specification, but it normally lies above 1200° C. There are indications that the overheating temperature decreases when the carbon content of the steel is increased.
- The overheating temperature of a steel is lower and hence the susceptibility to overheating is higher, the fewer the inclusions. Probably for this reason, electric steels generally have a lower overheating temperature than open hearth steels.

- Therefore it can be determined only for a set of fixed conditions, including the technique of etching and repolishing. The only effective methods of reclaiming the steel known at present are :-
 1. Reheating the steel to the original heating temperature, followed by cooling at a rate not greater than 3°C . per minute through the overheating range.
 2. Repeatedly austenitizing the steel at successively lower temperatures at $100\text{-}150^{\circ}\text{C}$ intervals. The properties of overheated steel can be improved by repeatedly normalizing, but no full recovery is possible without the above treatment.

5.15.1 CAUSES :-

- The appearance of overheated structures occurs when numerous fine manganese sulphide inclusions are observed on the grain interface (Fig. 10), which can be exposed by suitable techniques.
- Ko and Hanson concluded that the solubility of sulphur in austenite in the presence of manganese increases with increasing temperature. When a steel has been heated to high temperatures, sulphide inclusions are dissolved during heating, and subsequently, during cooling to below the overheating temperature, reprecipitated
 - (i) on residual sulphide inclusions,
 - (ii) on austenite grain interfaces, and
 - (iii) sometimes on (100) crystallographic planes of austenite.
- The presence of inclusions at the grain boundaries of small curvature weakens the resistance to fracture of these planes and, when the matrix is toughened by suitable heat treatment, the fracture will propagate along these planes of sulphide precipitation

5.15.2 BURNING :-

- The term "burning" is misleading as it implies the effect of combustion in air or oxygen.
- In fact, burning, similar to overheating, is independent of the furnace atmosphere,

SYMPTOM :-

- The burning of steel is indicated by the presence of a light etching network outlining the austenite grain boundaries, (Fig. 12), when the steel is etched with alcoholic solution of nitric acid, and of a dark-etching network when picric acid is used.
- The structure in burnt steel revealed by etching with nitrosulphuric acid and ammonium nitrate are the reverse of those obtained in the overheated steel, (Fig. 13 and 14). Strings of sulphide inclusions can often be seen along the grain boundaries (Fig. 15), which are covered with a two dimensional network of iron manganese sulphide.
- The sulphide was precipitated as one component of a eutectic during cooling after burning, (Fig. 16), the other component being iron. Burning can occur at a temperature well below the solidus of an alloy- of the same chemical composition but free front

EFFECTS:-

- The presence of a liquid at the high temperature, as evidenced by the presence of eutectic after cooling, reduces the ductility, and tensile strength, and in severe cases the steel may disintegrate during forging giving fractures of distinctly intergranular appearance.
- But the liquid at the grain interface is not necessarily present as a continuous film covering the whole interface. The eutectic at the grain interface in a severely burnt steel is often observed in colonies and hot tensile tests made by Winterton of British Welding Research Association on a eutectoid carbon steel (Steel T mentioned in Ko and Hanson's paper) well above the solidus showed that, unlike commercially pure aluminium, considerable ductility remained at these temperatures :

Testing Temperature °C	Tensile Strength Tons per sq. in	Elongation on in.	Reduction in Area
955	4.7	77	99
1302	1.7	76	100
1351	1.2	100	100
1388	1.0	77	88
1397	0.9	24	58

CAUSES :-

Investigation made with pure materials showed that burning is chiefly associated with the formation of a sulphur-rich liquid at the grain interface at high temperatures. When phosphorus is present as is usually the case in steels, it congregates in the liquid, and, after cooling, gives rise to an iron net-work rich in phosphorus, revealed by the various etching reagents as a network.

Burning is normally observed at unexpectedly low temperatures, which had led various investigators to suggest that burning could not be caused by incipient fusion. Ko and Hanson showed that in sulphur-free iron carbon alloys burning does not occur below the solidus, and they suggested that the solidus of the steel has been exceeded when burning takes place.

5.16 BIS (BUREAU OF INDIAN STANDARDS) :-

- The **Bureau of Indian Standards (BIS)** is the national Standards Body of India working under the aegis of Ministry of Consumer Affairs, Food & Public Distribution, Government of India. It is established by the Bureau of Indian Standards Act, 1986 which came into effect on 23 December 1986. The Minister in charge of the Ministry or Department having administrative control of the BIS is the ex-officio President of the BIS.
- As a corporate body, it has 25 members drawn from Central or State Governments, industry, scientific and research institutions, and consumer organisations. Its headquarters are in New Delhi, with regional offices in Kolkata, Chennai, Mumbai, Chandigarh and Delhi and 20 branch offices. It also works as WTO-TBT enquiry point for India

5.16.1 ASSOCIATION WITH INTERNATIONAL STANDARDS BODIES :-

- BIS is a founder member of International Organisation for Standardization (ISO).
- It represents India in the International Organization for Standardization (ISO), the International Electrotechnical Commission (IEC) and the World Standards Service Network (WSSN).
- One of the major functions of the Bureau is the formulation, recognition and promotion of the Indian Standards. As on 31 August 2016, 26552 Standards formulated by BIS, are in force. These cover important segments of economy, which help the industry in upgrading the quality of their products and services.

5.16.3 LABORATORIES

- To support the activities of product certification, BIS has a chain of 8 laboratories. These laboratories have established testing facilities for products of chemical, food, electrical and mechanical disciplines. Approximately, 25000 samples are being tested in the BIS laboratories every year. In certain cases where it is economically not feasible to develop test facilities in BIS laboratories and also for other reasons like overloading of samples, equipment being out of order, the services of outside approved laboratories are also being availed. Except for the two labs, all the other labs are NABL (National Accreditation Board for Testing and Calibration Laboratories) accredited. It operates a laboratory recognition scheme also.

5.16.4 PRODUCT CERTIFICATION SCHEME :-

- Product Certifications are to be obtained voluntarily. For, some of the products like Milk powder, Drinking Water, LPG Cylinders, etc., certification is mandatory. Because these products are concerned with health and safety.

5.16.5 FOR FOREIGN MANUFACTURERS :-

- All foreign manufacturers of products who intend to export to India are required to obtain a BIS product certification license. Towards this, BIS launched its Product Certification Scheme for overseas manufacturers in the year 1999. Under the provisions of this scheme, foreign manufacturers can seek certification from BIS for marking their product(s) with BIS Standard Mark. If or otherwise, the foreign manufacturer has not signed an MoU with BIS, it has to set up a liaison office in India with the permission of Reserve Bank of India. Otherwise, an authorised representative or agent needs to be appointed by the foreign firm.

5.16.6 MANAGEMENT SYSTEM CERTIFICATION :-

- Management System Certification Scheme IS/ISO 9001.
- Environmental Management System Certification Scheme IS/ISO 14001.
- Occupational Health and Safety Management System Certification Scheme IS 18001.
- Hazard Analysis and Critical Control Scheme IS/ISO 22000.
- Service Quality Management System Certification Scheme IS 15700.

5.16.7 OBJECTIVES :-

- The main objectives of the proposed legislation are:-
- To establish the Bureau of Indian standards(BIS) as the National Standards Body of India.
- The Bureau to perform its functions through a governing council, which will consist of President and other members.
- To include goods, services and systems, besides articles and processes under the standardization regime.
- To enable the government to bring under the mandatory certification regime for such articles, processes or service which it considers necessary from the point of view of health, safety, environment, prevention of deceptive practices, consumer security etc. This will help consumers receive ISI certified products and will also help in prevention of import of sub-standard products.

5.17 PROCESSING OF PLASTICS : -



Plastic is a material consisting of any of a wide range of synthetic or semi-synthetic organic that are malleable and can be moulded into solid objects of diverse shapes.



Plastics are typically organic polymers of high molecular mass,

but they often contain other substances.



They are usually synthetic, most commonly derived from petrochemicals.



The world's first fully synthetic plastic was Bakelite, invented in



Fig. 5.2 Example of plastics

5.17.1 TYPES OF PLASTIC :-

1. THERMOSETTING PLASTIC:-

- The molecules of thermosetting plastics are heavily cross-linked. They form a rigid molecular structure
- Although they soften when heated the first time, which allows them to be shaped they become permanently stiff and solid and cannot be reshaped.
- **Ex. Polyester resin and urea formaldehyde**

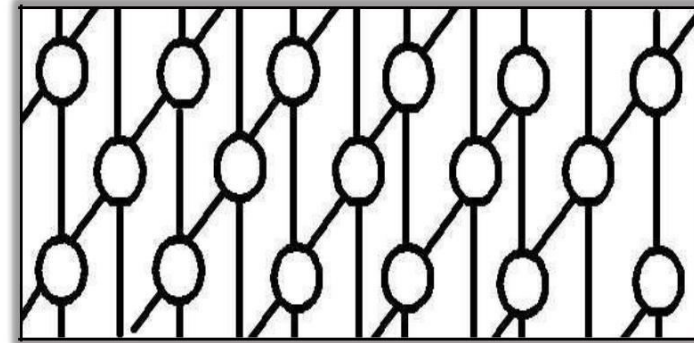
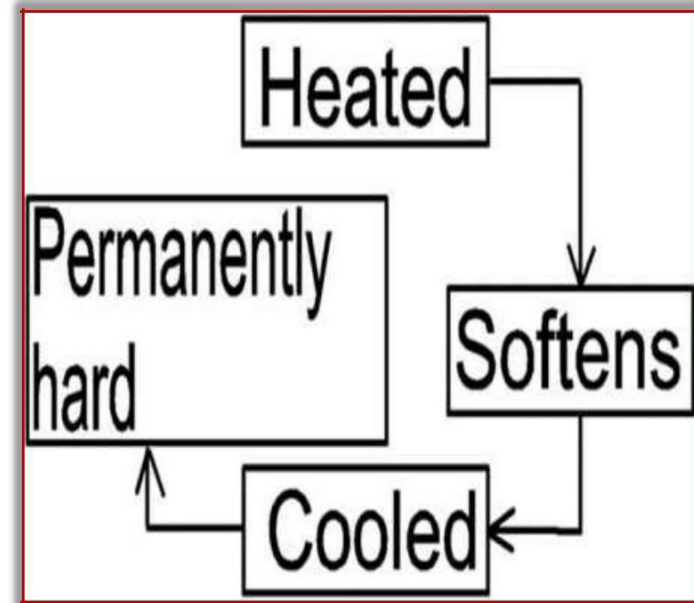


Fig. 5.17.2 Cross-linked molecules



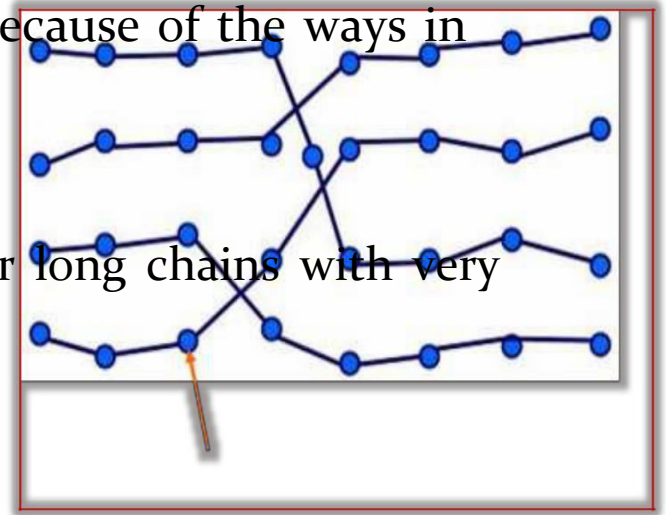
2. THERMOPLASTIC: -



Thermoplastics can be heated and reshaped because of the ways in which the molecules are joined together.



The molecules of thermoplastics are in lines or long chains with very few entanglements.



When heat is applied the

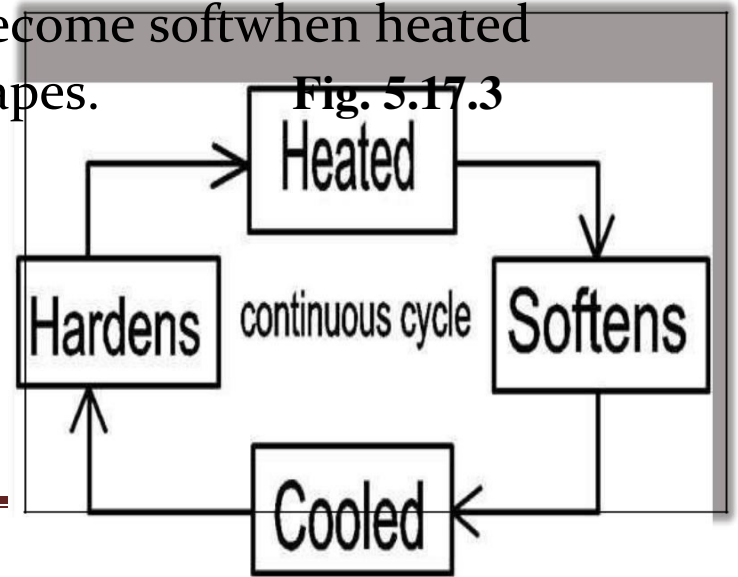


molecules move apart, which increases the distance between them, causing them to become untangled. This allows them to become soft when heated so that they can be bent into all sorts of shapes.

Individual monomer molecule



Ex. Polyvinyl chlorides (PVC), Nylons,



5.17.3 PROCESSING OF PLASTICS: -

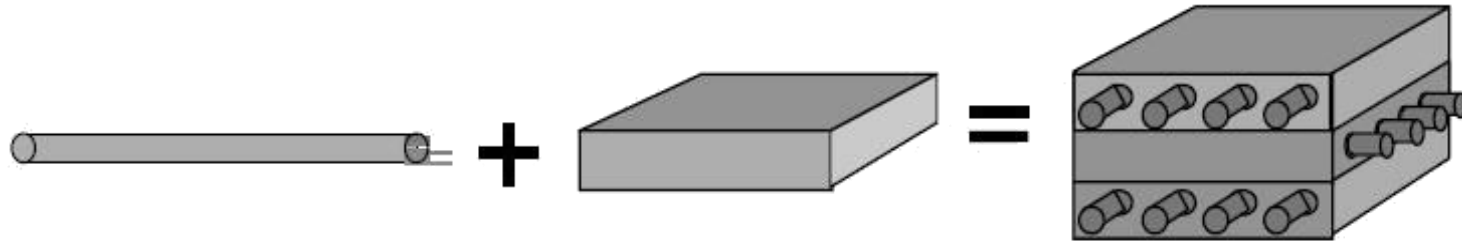
1. COMPRESSION MOULDING
2. TRANSFER MOULDING
3. INJECTION MOULDING
4. EXTRUSION MOULDING
5. BLOW MOULDING
6. CALENDARING
7. THERMOFORMING
8. ROTATIONAL MOULDING
9. LAMINATING

5.18 WHAT ARE “COMPOSITES” :-

- Composite: Two or more chemically different constituents *combined macroscopically* to yield a useful material.
- Examples of naturally occurring composites permeated with holes filled with liquids
 - Wood: Cellulose fibers bound by lignin matrix
 - Bone: Stiff mineral “fibers” in a soft organic matrix permeated with holes filled with liquids
 - Granite: Granular composite of quartz, feldspar, and mica.
- 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.

- Composite materials are materials made from two or more constituent materials with significantly different properties, that when combined, produce a material with characteristics different from the individual components.
- Composite materials consist of two or more chemically distinct constituent on a macro scale having a dispersed interface separating them and having bulk performance which is considerably different from those of any of its individual constituents.
- Examples: Cement, Concrete, Fiber-reinforced polymer, etc.
- Some examples of man-made composites
 - Concrete: Particulate composite of aggregates (limestone or granite), sand, cement and water
 - Plywood: Several layers of wood veneer glued together
 - Fiberglass: Plastic matrix reinforced by glass fibers
 - Cemets: Ceramic and metal composites

Composition of Composites



**Fiber/Filament
Reinforcement**

Matrix

Composite

- High strength
- High stiffness
- Low density

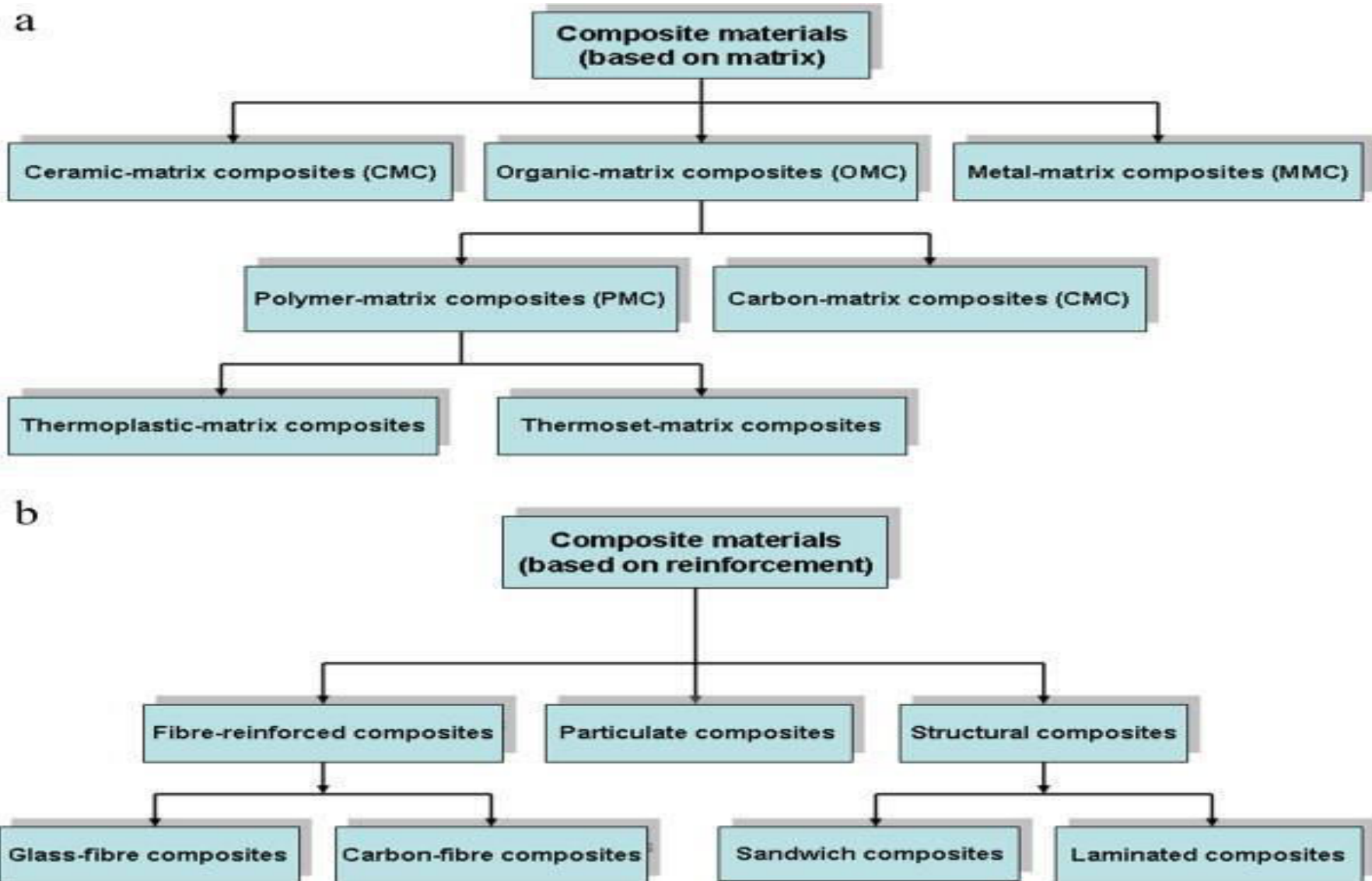
- Good shear properties
- Low density

- High strength
- High stiffness
- Good shear properties
- Low density

5.18.1 WHERE ARE COMPOSITES USED?

- Sports: Lighter, stronger, toughness, better aesthetics, higher damping properties
 - Tennis Bicycles
 - Badminton
 - Boats
 - Hockey
 - Golfing Motorcycles
 - Railway coaches Bridges
 - Ships and boats
 - Dams
 - Truck bodies and floors
 - RV bodies
 - Biomedical industry

5.19 CLASSIFICATION OF COMPOSITES :-



5.19.1 ORGANIC MATRIX COMPOSITES (OMCS) :-

- **Polymer Matrix Composites (PMC)/Carbon Matrix Composites or Carbon-Carbon Composites :-**

Polymers make ideal materials as they can be processed easily, possess lightweight, and desirable mechanical properties. It follows, therefore, that high temperature resins are extensively used in aeronautical applications.

- Two main kinds of polymers are **thermosets and thermoplastics:-**

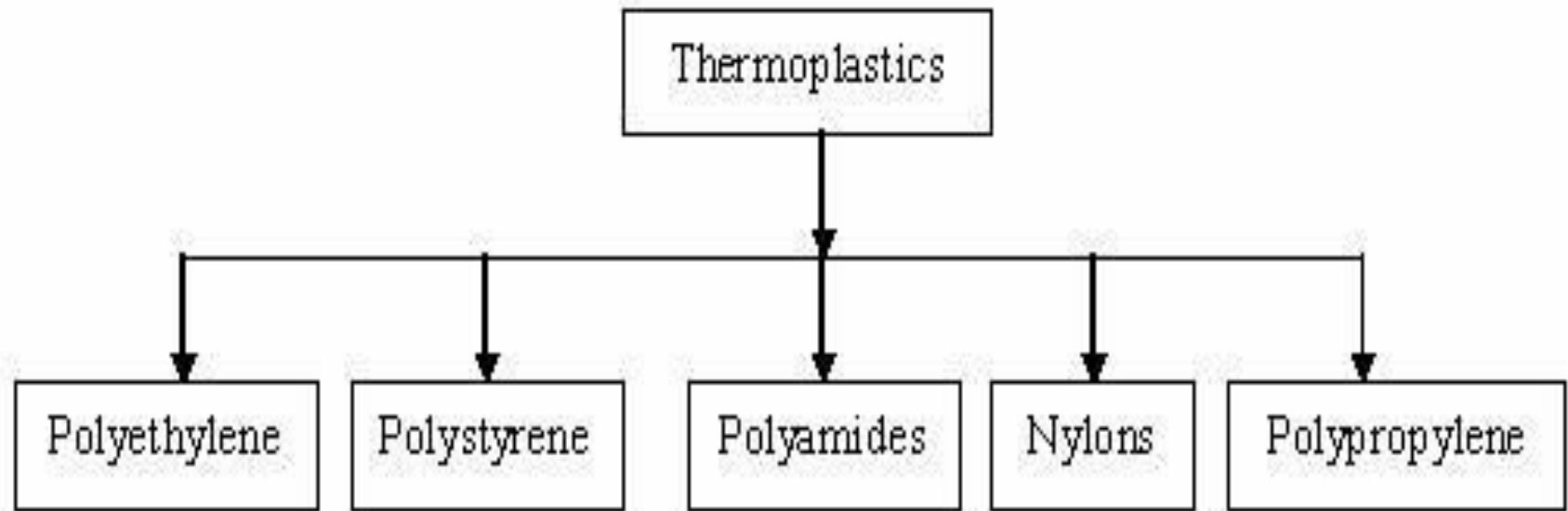
Thermosetting plastics :-

1. Thermosets have qualities such as a well-bonded three-dimensional molecular structure after curing.
2. This polymer is hard and infusible on heating.
3. These are not soft on heating under pressure and they are not remoluded.
4. These polymers are cross linked or heavily branched molecules
5. These polymers we cannot reused or recycle.

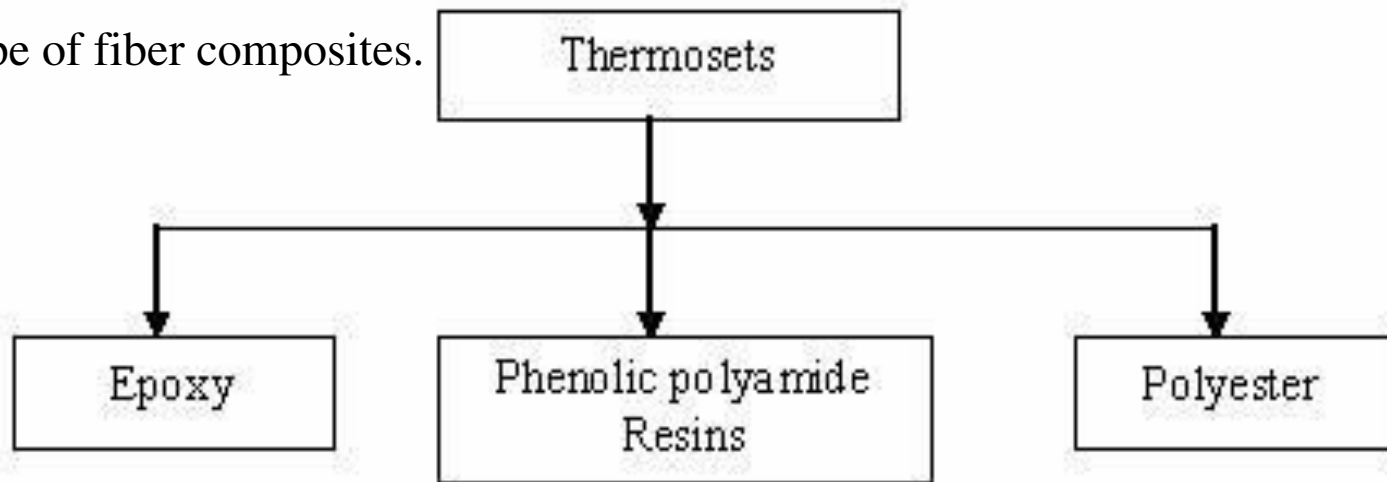
Ex. Some common examples are bakelite, urea-formaldelyde resins, etc

- **Thermoplastic polymers :-**

1. These are the polymers having intermolecular forces between elastomers and fibres.
2. They are those polymers which can be softened on heating and hardened on cooling room temperature.
3. They may be linear or branched chain polymers.
4. These polymer can be recycled many times. Ex , Polythene, polyesterne, PVC.



- A small quantum of shrinkage and the tendency of the shape to retain its original form are also to be accounted for. But reinforcements can change this condition too. The advantage of thermoplastics systems over thermosets are that there are no chemical reactions involved, which often result in the release of gases or heat. Manufacturing is limited by the time required for heating, shaping and cooling the structures.
- Thermosets are the most popular of the fiber composite matrices without which, research and development in structural engineering field could get truncated. Aerospace components, automobile parts, defense systems etc., use a great deal of this type of fiber composites.



5.19.2 METAL MATRIX COMPOSITES (MMC) :-

- Metal matrix composites, at present though generating a wide interest in research fraternity, are not as widely in use as their plastic counterparts. High strength, fracture toughness and stiffness are offered by metal matrices than those offered by their polymer counterparts. They can withstand elevated temperature in corrosive environment than polymer composites. Most metals and alloys could be used as matrices and they require reinforcement materials which need to be stable over a range of temperature and non-reactive too.
- However the guiding aspect for the choice depends essentially on the matrix material. Light metals form the matrix for temperature application and the reinforcements in addition to the aforementioned reasons are characterized by high moduli.

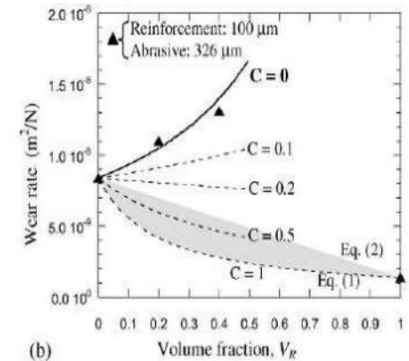
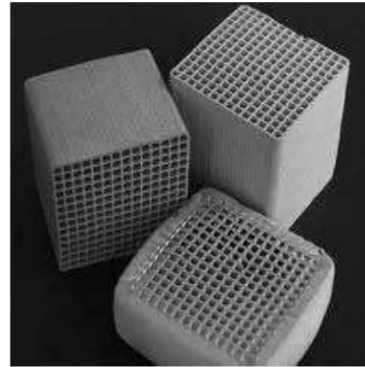
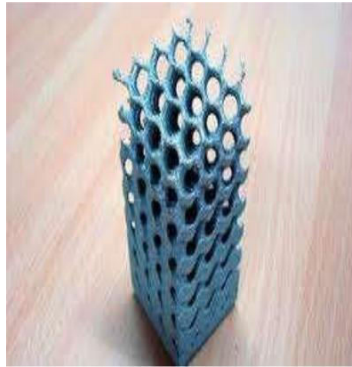
- Most metals and alloys make good matrices. However, practically, the choices for low temperature applications are not many. Only light metals are responsive, with their low density proving an advantage.
- Titanium, Aluminium and magnesium are the popular matrix metals currently in vogue, which are particularly useful for aircraft applications.
- The melting point, physical and mechanical properties of the composite at various temperatures determine the service temperature of composites

5.19.3 CERAMIC MATRIX MATERIALS (CMM) :-

- Ceramics can be described as solid materials which exhibit very strong ionic bonding in general and in few cases covalent bonding. High melting points, good corrosion resistance, stability at elevated temperatures and high compressive strength, render ceramic-based matrix materials a favourite for applications requiring a structural material that doesn't give way at temperatures above 1500°C. Naturally, ceramic matrices are the obvious choice for high temperature applications.
- High modulus of elasticity and low tensile strain, which most ceramics possess, have combined to cause the failure of attempts to add reinforcements to obtain strength improvement. This is because at the stress levels at which ceramics rupture, there is insufficient elongation of the matrix which keeps composite from transferring an effective quantum of load to the reinforcement and the composite may fail unless the percentage of fiber volume is high enough.

- A material is reinforcement to utilize the higher tensile strength of the fiber, to produce an increase in load bearing capacity of the matrix. Addition of high-strength fiber to a weaker ceramic has not always been successful and often the resultant composite has proved to be weaker.
- When ceramics have a higher thermal expansion coefficient than reinforcement materials, the resultant composite is unlikely to have a superior level of strength.
- In that case, the composite will develop strength within ceramic at the time of cooling resulting in microcracks extending from fiber to fiber within the matrix. Microcracking can result in a composite with tensile strength lower than that of the matrix.

5.13.4 PARTICLE REINFORCED COMPOSITES :-



- One form of composites is particulate reinforced composites with concrete being a good example. The aggregate of coarse rock or gravel is embedded in a matrix of cement. The aggregate provides stiffness and strength while the cement acts as the binder to hold the structure together.
- There are many different forms of particulate composites. The particulates can be very small particles (< 0.25 microns), chopped fibres (such as glass), platelets, hollow spheres, or new materials such as Bucky balls or carbon nano-tubes. In each case, the particulates provide desirable material properties and the matrix acts as binding medium

LARGE-PARTICLE COMPOSITE

- Some polymeric materials to which fillers have been added are really large- particle composites. The fillers modify or improve the properties of the material. Example of large-particle composite is concrete, which is composed of cement (the matrix), and sand and gravel (the particulates). Particles can have quite a variety of geometries, but they should be of approximately the same dimension in all direction (equated).
- For effective reinforcement, the particles should be small and evenly distributed throughout the matrix. The volume fraction of the two phases influences the behavior; mechanical properties are enhanced with increasing particulate content.
- Rule of mixture: equation predict that the elastic modulus should fall between an upper and lower bound as shown:
- Example:** Fig. 1.1 plots upper and lower bound E_c – versus V_p curves for a copper – tungsten composite; in which tungsten is the particulate phase.

- Where:-

E_c : elastic modulus of

composite E_p : elastic

modulus of particle E_m :

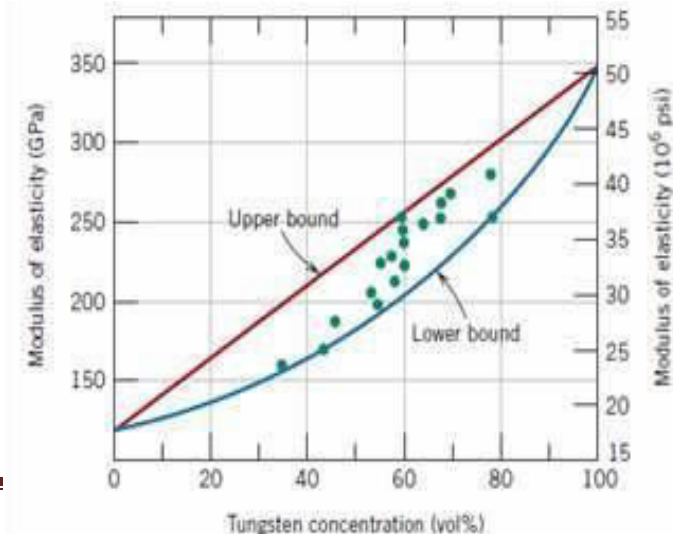
elastic modulus of matrix

V_m : volume fraction of

matrix V_p : volume fraction of particle

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

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

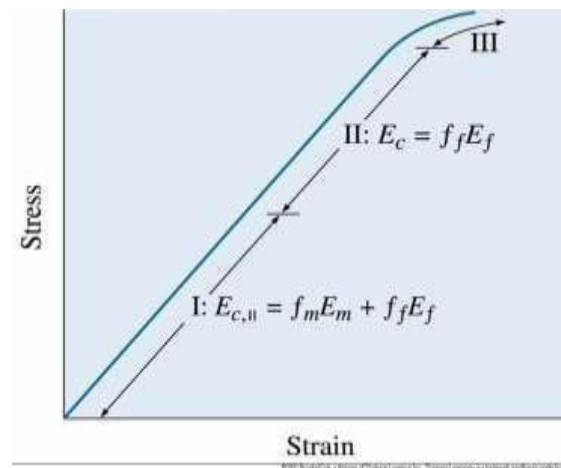


(ON THE BASIS OF REINFORCEMENT) FIBER-REINFORCED COMPOSITES

- The Rule of Mixtures in Fiber-Reinforced Composites

$$\rho_c = f_m \rho_m + f_f \rho_f$$

- Strength of Composites - The tensile strength of a fiber-reinforced composite (TS_c) depends on the bonding between the fibers and the matrix.

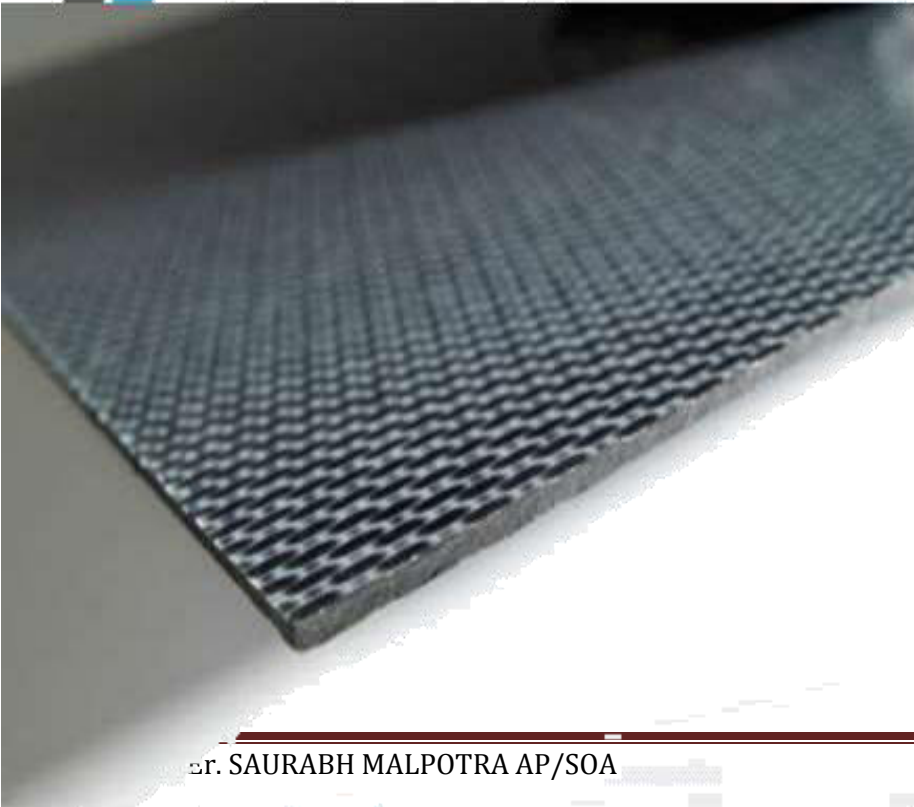


- Figure 1.3 The stress-strain curve for a fiber-reinforced composite. At low stresses (region I), the modulus of elasticity is given by the rule of mixtures. At higher stresses (region II), the matrix deforms and the rule of mixtures is no longer obeyed.

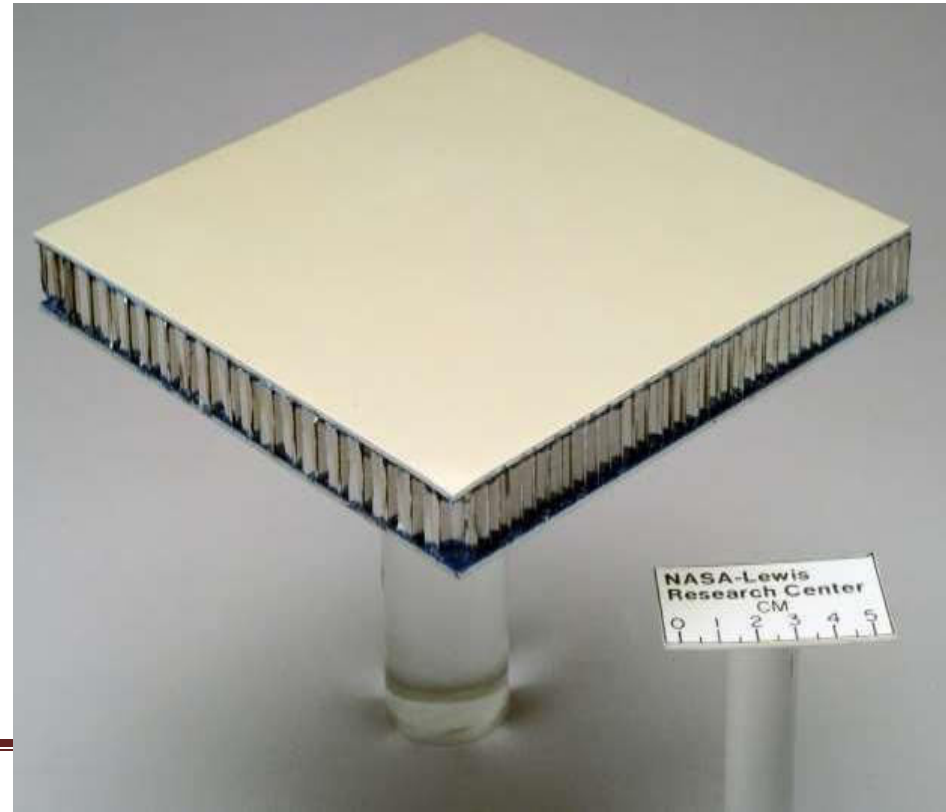
STRUCTURAL COMPOSITES

- A structural composite consists of both homogeneous and composite material. Their properties depend on, the characteristic properties of the constituent materials as well as the geometric design.
- Structural composites are of two types:-

1. Laminar composite panel

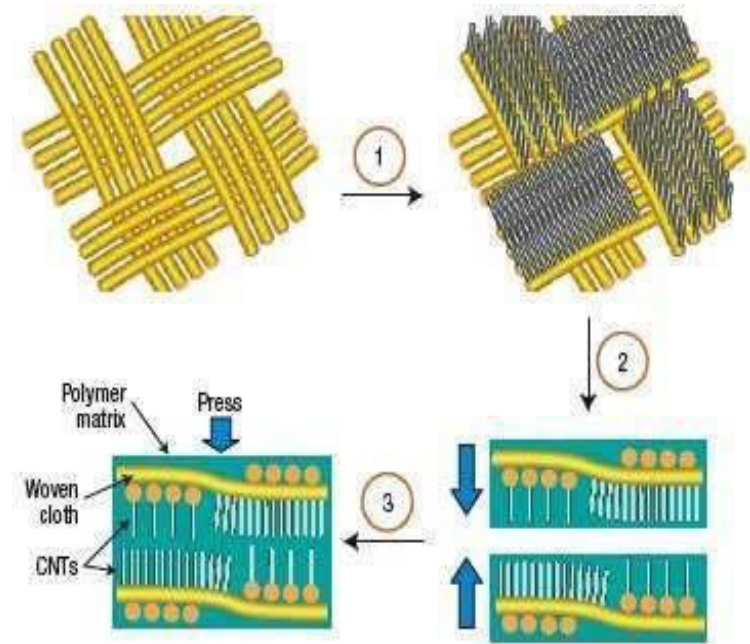
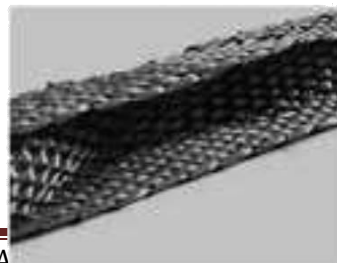


2. Sandwich



LAMINAR COMPOSITE

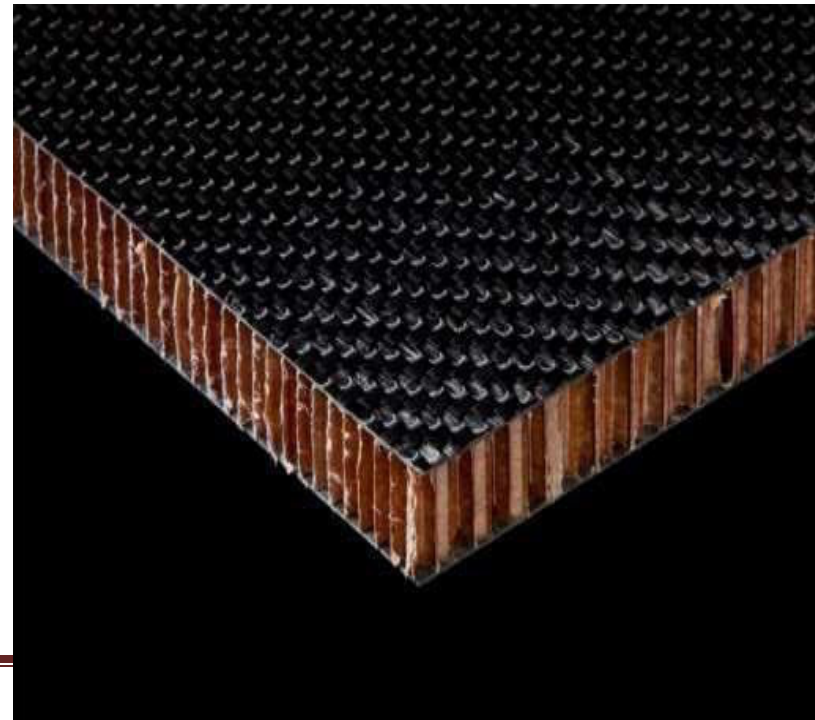
- It consists of panels or sheets which are two dimensional. These panels possess preferred directions to achieve high strength.



- Such successively oriented layers are stacked one above with preferred directions and then are cemented. Such an arrangement or orientation ensures varying highest strength with each successive layer involved in material.
- For example :- Plywood

SANDWICH PANEL

- Sandwich panel is also a kind of layered composite. It consists of 'faces' and 'core'
- With increase in thickness of core, its stiffness increases as seen in the most common sandwich panel 'honeycomb'.
- **Faces:**-They are formed by two strong outer sheets.
- **Core:**-Core is layer of less dense material.
- **Honeycomb:**-Structure which contain thin foils forming interlocked hexagonal cells with their axes oriented at right angles in the direction of face sheet.



APPLICATIONS OF COMPOSITE MATERIAL

1. In automobile industries (e.g. Steel & Aluminium body)
2. Marine applications like shafts, hulls, spars (for racing boats)
3. Aeronautical application like components of rockets, aircrafts (business and military), missiles etc.
4. Communication antennae, electronic circuit boards (e.g. PCB, breadboard)
5. Safety equipment like ballistic protection and Air bags of cars.



Aerospace



Automobile



Boat building



Infrastructure



Wind power



Recreation

<u>S.No</u>	Cellulosic fibres/Vegetable fibre	Synthetic fibres
1.	Low resiliency: Fabric wrinkles unless any finishing is given	High resiliency: Less wrinkles after washing and wearing
2.	High water absorbency: Comfortable for summer wears, good for towel, hand kerchief and diapers.	Low moisture absorption: Easily washable and easy spot removing.
3.	Cellulosic fibres are good conductors of heat.eg: Cotton is a better conductor of heat but less than that of rayon.	Synthetic fibres are also good conductors of heat they <u>melt</u> with hot or iron touch with hot <u>objects</u> .
4.	Identification: Cellulose fibres ignite quickly, burns freely with smoke and have an afterglow and after burning forms a grey feathery ash.	Identification: Readily burns and melts giving a distinct plastic burning odour.
5.	Cellulosic fibres have high affinity for dyes.	Synthetic fibres have low affinity for dyes.
6.	Cellulosic fibres are resistant to moth but less susceptible to mildew hence damp clothes should not be stored.	Highly resistant to moths, mildew and insects.

Fibers

1. Fabric is made of fibers.
2. Fibers are made of twisted filaments.
3. Types of fibers and fabric:
 - Natural—*animal, vegetable, or inorganic*
 - Artificial—*synthesized or created from altered natural sources.*

- TYPES OF FIBERS :

- Synthetic

Rayon

Nylon

Acetate

Acrylic

Spandex



Natural

Silk

Cotton

Wool

Mohair

Cashmere

CLASSIFICATION OF FIBERS

NATURAL FIBERS ARE CLASSIFIED ACCORDING TO THEIR ORIGIN:

1. Vegetable or cellulose
2. Animal or protein
3. Mineral



CELLULOSE FIBERS

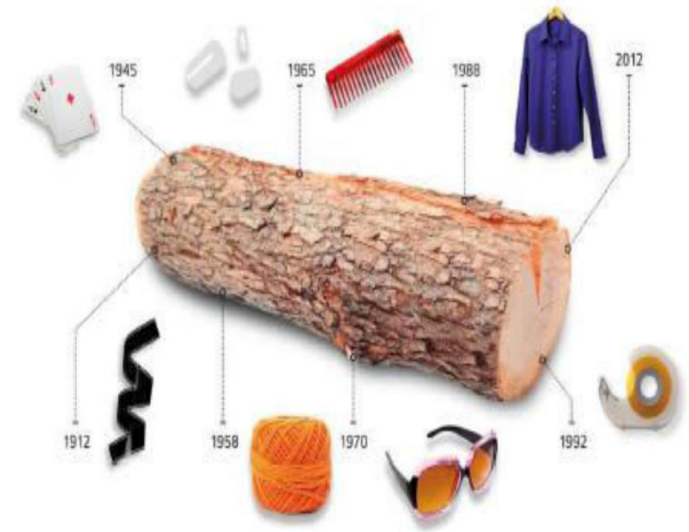
1. **Cotton**—vegetable fiber; strong, tough, flexible, moisture-absorbent, not shape-retentive
2. **Rayon**—chemically altered cellulose; soft, lustrous, versatile
3. **Cellulose acetate**—cellulose that is chemically altered to create an entirely new compound not found in nature.



Cotton



Rayon



Cellulose acetate

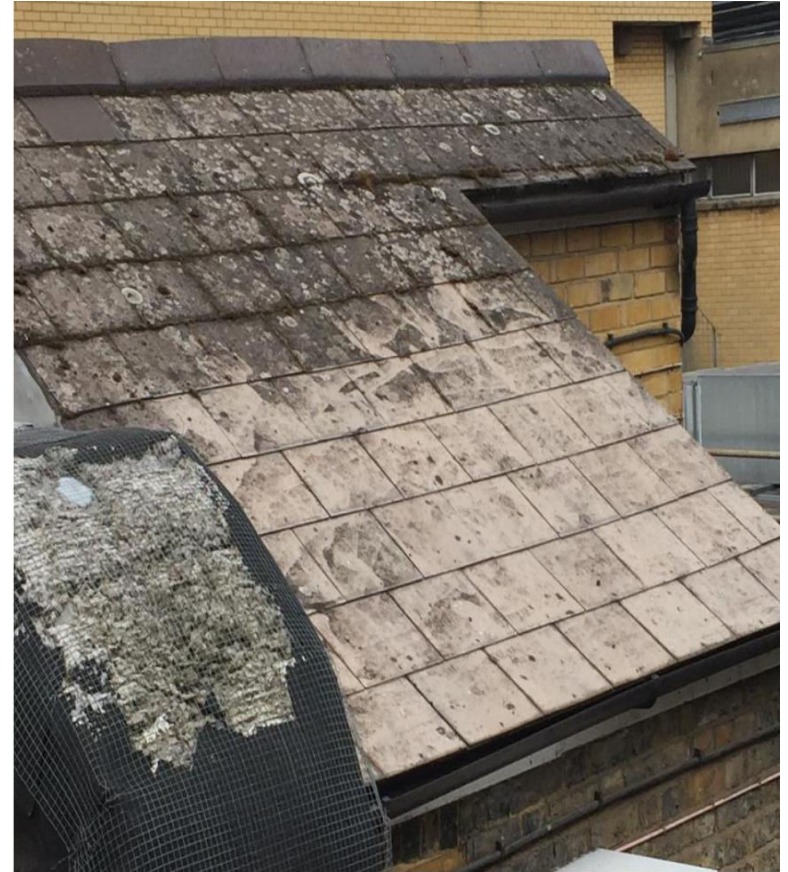
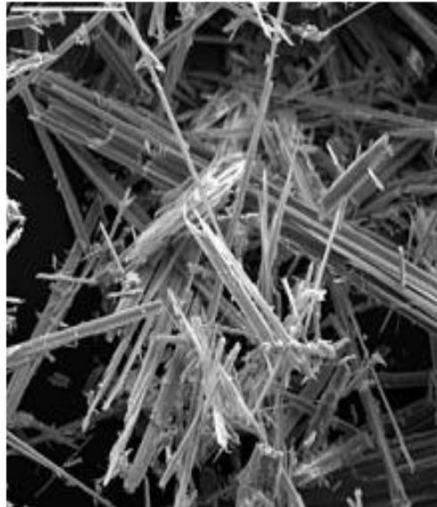
PROTEIN FIBERS

1. **Wool**—animal fiber coming most often from sheep, but may be goat (mohair), rabbit (angora), camel, alpaca, llama, or vicuña
2. **Silk**—insect fiber that is spun by a silkworm to make its cocoon; the fiber reflects light and has insulating properties.



MINERAL FIBERS

1. **Asbestos**—a natural fiber that has been used in fire-resistant substances
2. **Rock wool**—a manufactured mineral fiber
3. **Fiberglass**—a manufactured inorganic fiber

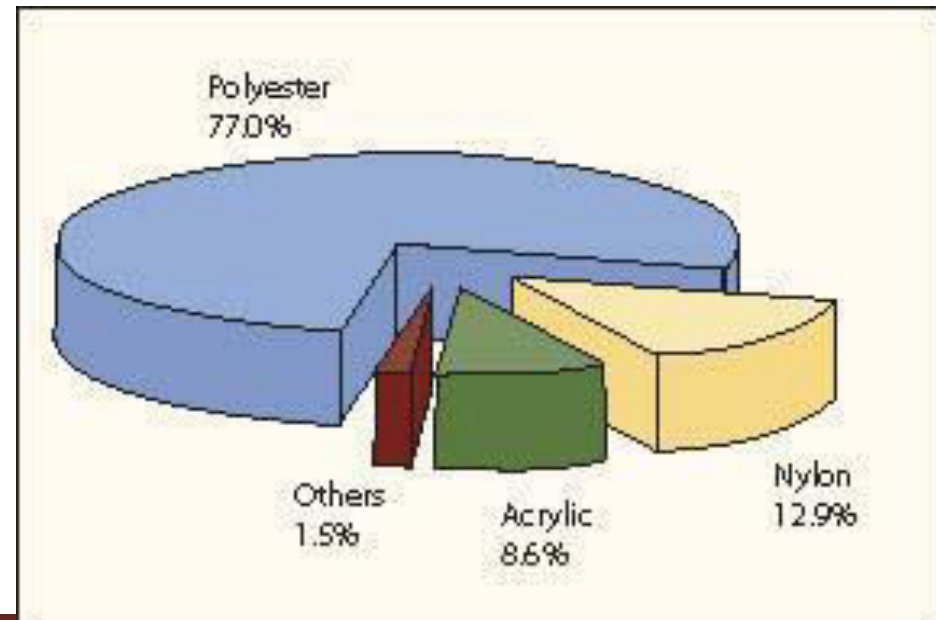


Asbestos

SYNTHETIC FIBERS

Made from derivatives of petroleum, coal, and natural gas.

1. **Nylon**—most durable of man-made fibers; extremely lightweight
2. **Polyester**—most widely used man-made fiber
3. **Acrylic**—provides warmth from a lightweight, soft, and resilient fiber
4. **Spandex**—extreme elastic properties



MATRIX MATERIAL

- While the principal strength and stiffness of the composite is provided by the fibres, the matrix material also has a large part to play in the overall mechanical properties. The matrix is not designed to bear much of the load. Instead, the matrix binds the fibres together and distributes the load. It also provides ductility and protects the fibres from surface damage. It separates the fibres and prevents propagation of cracks from one fibre to the next. Also, unless the matrix chosen is a particularly flexible one then it will assist in prevention of the fibres buckling under compression.
- The requirements of a good matrix material are that it can infiltrate between the fibres and form a strong interfacial bond. It is also essential that there is no chance of chemical reaction between the matrix material and fibres and that the matrix material does not cause damage to the fibres.

- There are three main types of composites based on the type of matrix they employ –
 1. polymer matrix composites (PMC)
 2. ceramic matrix composites (CMC) and
 3. metal matrix composites (MMC).
- The most common type are polymer matrix composites. They are produced in the largest quantities, due to their good room temperature properties, ease of manufacture and low cost.
- There are two main types of polymer composite matrix materials, thermoplastics and thermosetting resins.
- Fibers and whiskers in composites are held together by a binder known as *matrix*. This is required since fibers by themselves:
 - Given their small cross-sectional area, cannot be directly loaded.

- Further, they cannot transmit load between themselves.
- This limitation is addressed by embedding fibers in a matrix material.
- Matrix material serves several functions, the important ones being:
 - Binds fibers together.
 - Transfers loads and stresses within the composite structure.
 - Support the overall structure
 - Protects the composite from incursion of external agents such as humidity, chemicals, etc.
 - Protects fibers from damage due to handling.
- Matrix material also significantly limits a composite's maximum permissible operating temperature.
- Most of the matrix materials are relatively lighter, more compliant, and weaker vis-à-vis fibers and whiskers.

- However, the combination of fibers/whiskers and matrix can be very stiff, very strong, and yet very light.
- Thus most of modern composites have very high specific strengths, i.e. very high strength/density ratios.
- This makes them very useful in aerospace applications, where weight minimization is a key design consideration.

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