

## MODULE-1

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### Q- MECHANICAL BEHAVIOUR

MSM U-9

Learning objectives:- (After studying this chapter you should be able to do the following).

- \* What is Strain and Strain in materials?
- \* What is tensile test and how to plot a Stress-Strain diagram for different materials when they are subjected to tensile test.
- \* What are zones coming into picture when Stress-Strain diagram is plotted.
- \* How the tensile properties are classified?
- \* What are the properties coming under linear elastic properties & Non linear elastic properties.
- \* What are the properties observed in the plastic region.
- \* How the Stress-strain curve varies with ductile and brittle material.
- \* Difference between ductile and brittle material.
- \* What is true stress and give the relationship between true stress and engineering stress.
- \* What is true strain and give the relationship between true strain and engineering strain.
- \* How does the Stress-Strain curve varies for engineering & true stress-strain.
- \* What is plastic deformation and explain the different modes of plastic deformation.
- \* Explain slip and twinning & plot the difference b/w slip & twinning.

\* what is essentially residual stress and derive an expression for it.

## INTRODUCTION:-

Every material when in service (working), will be subjected to forces or loads. For example an aluminium alloy from which an airplane wing is constructed and the steel in the automobile will be subjected to different amount of loads daily. In such situation it is necessary to know the characteristics or the properties of the material in order to know the maximum load the material can take to prevent it from failure.

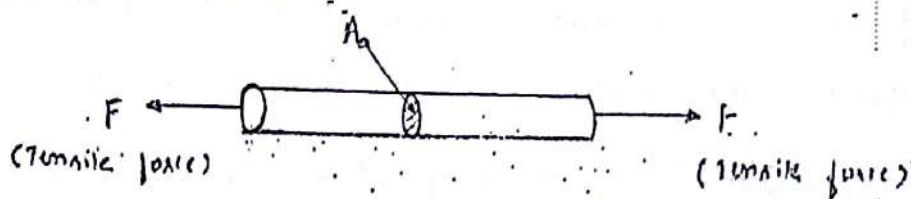
### 1. What is Stress and Strain?

Stress or conventional stress is also known as engineering stress. When any engineering material is subjected to forces or loads, the material experiences deformation (change in shape & size).

The term stress ( $\sigma$ ) is used to express the loading intensity. It is force applied to a certain cross-sectional area of an object.

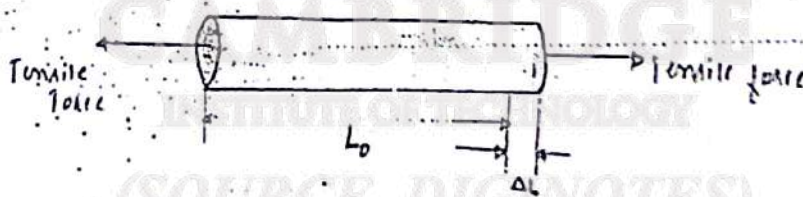
From the loading point of view, stress is the applied force that tends to deform a body. From the view of what's happening within a material, stress is the internal distribution of forces within a body that balances and react to the loads applied to it.

In simple stress can be defined as the force acting on a unit (cross-sectional area).



$$\text{Stress, } \sigma = \frac{\text{Force}}{\text{Cross-sectional area}} = \frac{F}{A_0}$$

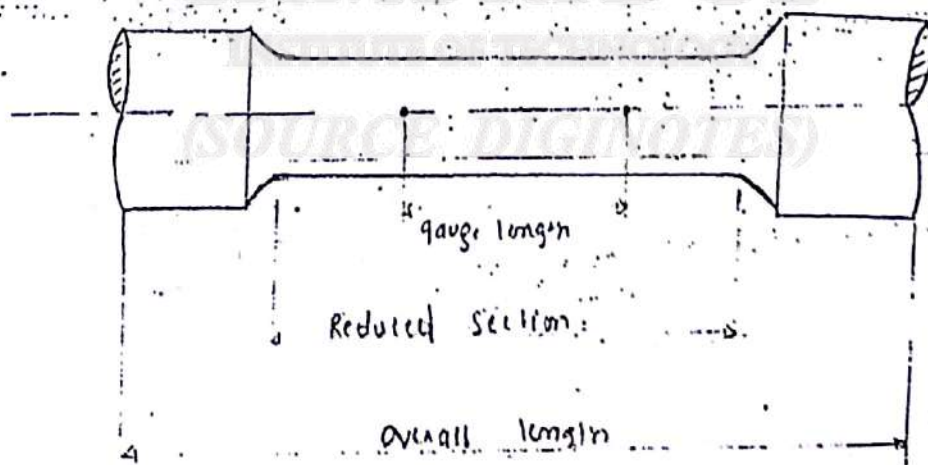
Strain or conventional strain is also known as the engineering strain. When a material is loaded with a force, it produces a stress, which causes the material to deform. Strain can be defined as the amount of deformation in the direction of the applied force divided by initial length of the material. Strain is a dimensionless quantity.



$$(\epsilon) \text{ Strain} = \frac{\text{Elongation or Deformation or Change in length}}{\text{original length}} = \frac{\Delta L}{L_0}$$

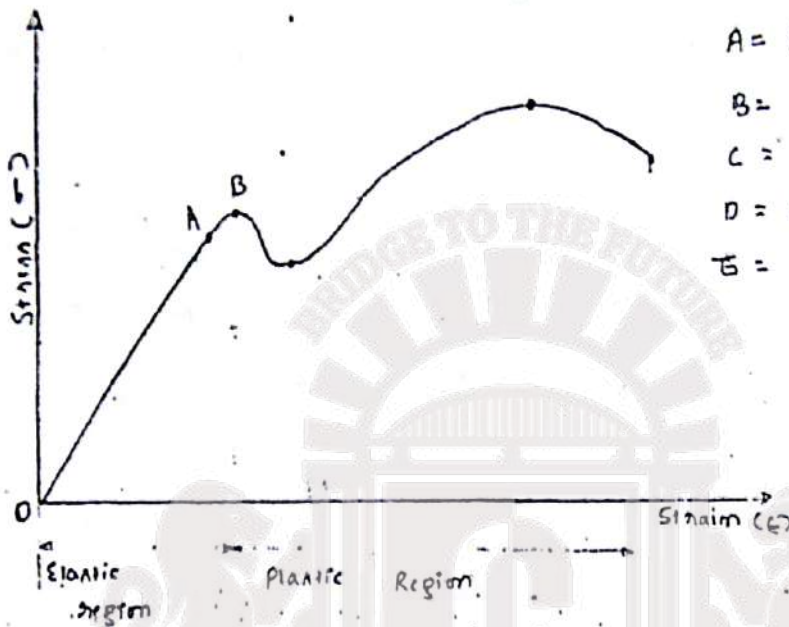
## 2. Stress - Strain diagram for ductile material.

One of the most common mechanical tests is the stress - strain test. The tension test or tensile test can be used to get several mechanical properties of materials that are important for design. The standard tensile test specimen is as shown in the figure below. The specimen is mounted by its ends into the holding grips of the testing apparatus. Then the specimen is subjected to gradually increasing tensile force and simultaneously observations are made from the elongation of the specimen (deformation) until the fracture or break of the specimen takes place. A graph of stress vs strain is drawn by calculating stress & strain for each load (force) value to study various properties of the material.



Standard tensile test Specimen (Round)

The following figure shows the stress-strain curve for ductile material such as mild steel.



- A = Proportionality limit
- B = upper yield point
- C = lower yield point
- D = ultimate stress
- E = Fracture point.

The following salient points are observed on stress-strain curve.

(1) Proportionality limit (limit of proportionality) - point A.

It is the limiting value of the stress upto which stress is proportional to strain, i.e., maximum stress level upto which stress is proportional to strain. The graph OA is a straight line on the stress-strain curve, which shows the material obeying Hooke's law till point A is reached.

(2) Elastic limit:-

This is the limiting value of stress upto which if the material is strained and then released (unloaded) strain disappears completely and the original length is regained. This point is slightly beyond

the limit of proportionality. The graph OB on the stress-strain curve represent that the material behaves in an elastic manner, beyond which any additional loading will cause permanent (plastic) deformation in the material.

3. Point B & C - upper yield point and lower yield point.

The point 'B' represents the upper yield pt, which is the stress at which the load starts reducing and the deformation increases. This is known as yielding of material, which continues till the point 'C' (lower yield pt). At the lower yield-pt, even though stress remains same, deformation of the material increases for some time. It is now clear that till the pt 'B' the material behaves elastic and once the yielding of the material starts at 'B', the material starts deforming plastically. Hence to avoid the permanent deformation in the materials, it is essential to have a knowledge on the yield pt of a material from the designer point of view.

4. Ultimate Stress - Point 'D'.

It is the maximum stress the material can withstand before it fails or fractures. Once after the yielding, any increase in the stress will cause a considerable or notable increase in the deformation of a material and the curve reaches a point 'D'. The stress corresponding to the point 'D' is known as ultimate stress.

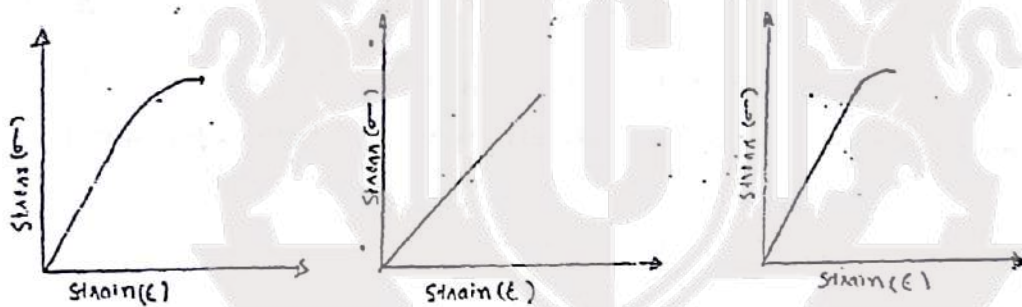
5. Fracture point - point 'E' (Breaking point).

If the material is loaded beyond the maximum load that it can take, the  $\sigma_a$  area decreases rapidly in the localized region by forming

the necking. The specimen finally reaches a point 'E' where the fracture or failure or breaking of the specimen occurs. The stress corresponding to the point 'E' is known as fracture stress.

3. Stress - strain curve for brittle material.

A material is brittle if, when subjected to stress, it breaks without significant deformation (strain). They absorb very less energy before fracture, even those of high strength. There is no yield point & no necking takes place. ultimate point and breaking point are the same. The typical stress-strain curve for brittle material (for cast iron) is as shown below.

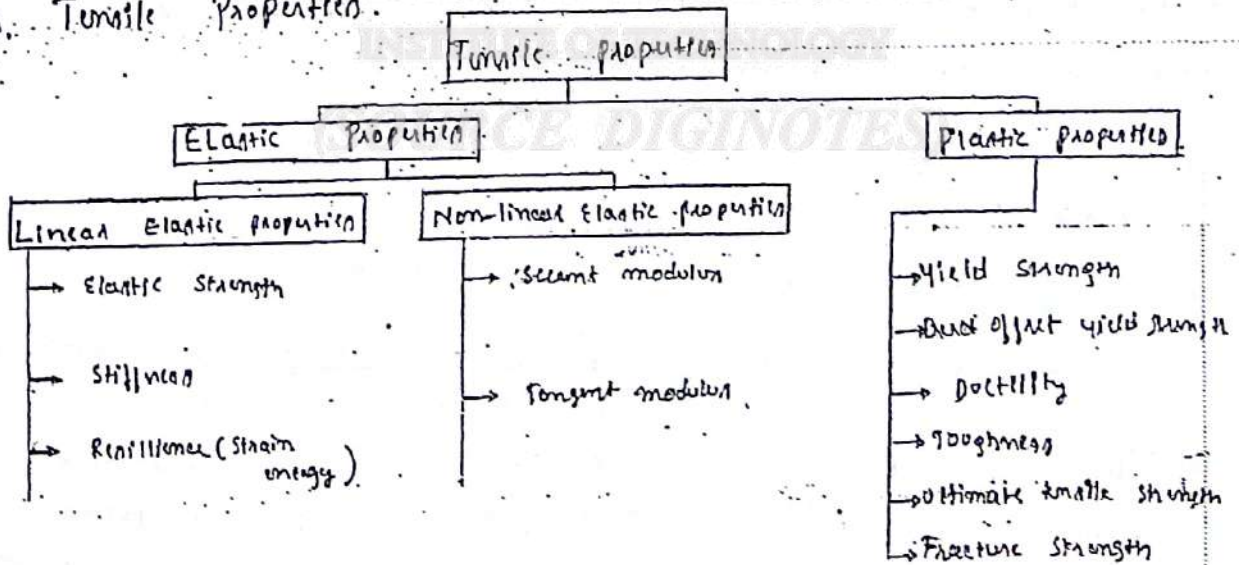


(a) cast iron.

(b) plates & pipes

(c) glass.

4. Tensile Properties.



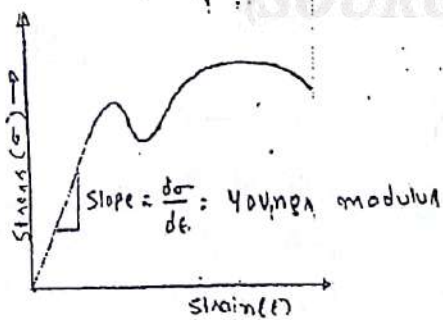
## Elastic Properties

Linear elastic properties: The properties which obey Hooke's law are coming under this classification.

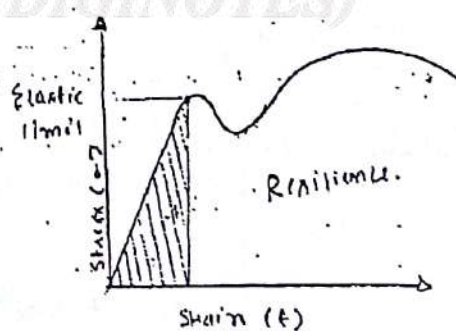
(a) Elastic Strength: It is the maximum stress upto which the behaviour of the material remains elastic i.e., material regains its shape upon removal of load. It is hard to measure the elastic strength of a material and hence it is generally taken as the stress at the end of proportionality limit.

(b) Stiffness: It is the ability of a material to resist elastic deformation. i.e., Higher the stiffness of a material, lower the elastic deformation of a material. The slope of the stress-strain curve gives the Young's modulus (modulus of elasticity) of a material, which is used to measure the stiffness of the material. Higher the Young's modulus, stiffer the material, lesser the elastic deformation of a material.

(c) Resilience (Strain energy): It is the ability of a material to absorb energy when it is loaded within the elastic limit and giving back the same energy (absorbed) when the load is removed. It is mainly considered when the material is subjected to shock or impact loading. It is measured by the area under the elastic region of the stress-strain curve.



(b) Stiffness (Young's modulus) or (Elastic modulus)



(c) Resilience.



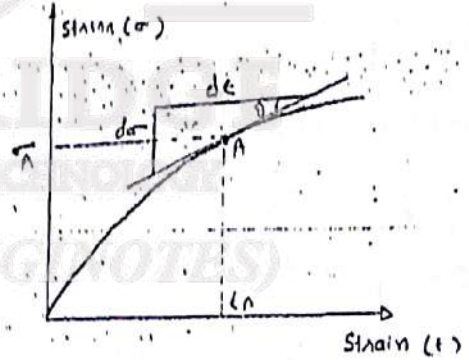
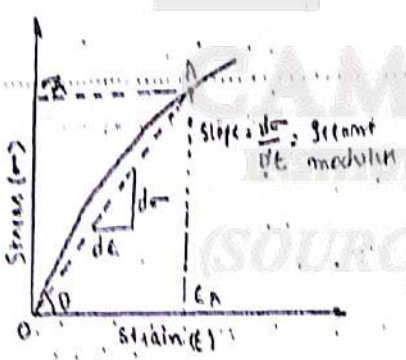
• Modulus of Resilience: It is the strain energy stored by the material per unit volume.

$$\text{Modulus of Resilience } (U_A) = \frac{\sigma^2}{2E} \quad \left[ \begin{array}{l} \text{where } \sigma = \text{stress at elastic limit} \\ E = \text{Young's modulus} \end{array} \right]$$

\* Non-Linear Elastic Properties: Some materials like grey cast iron, soft copper, aluminum, concrete etc., do not obey Hooke's law in the elastic range of elastic region of the stress-strain curve. But to find the stiffness parameter  $E$ , Young's modulus, the stress-strain curve must be linear, hence stiffness in these kind of materials is found by secant modulus  $E_s$  & tangent modulus.

(a) Secant modulus: Secant modulus is used when the non-linearity of the curve is not much. It is the measure of average stiffness at any given stress value.

Consider a non-linear curve (stress-strain) as shown below. Mark a point 'A' on the curve and then draw a line from the origin O to intersect the point A on the curve.  $\sigma_A$  &  $\epsilon_A$  be the corresponding stress & strain. The average slope of the line OA gives the secant modulus at the given stress  $\sigma_A$ .



(a) Secant modulus =  $E_{sec} = \left[ \frac{\sigma}{\epsilon} \right] = \tan \theta$       (b) Tangent modulus =  $E_{tan} = \left[ \frac{d\sigma}{d\epsilon} \right] = \tan \theta$

(b) Tangent modulus: Tangent modulus is considered when the non-linearity of the curve is too much. Mark a point 'A' on the curve and  $\sigma_A$  &  $\epsilon$  be the corresponding stress & strain. Draw a line tangent to the non-linear curve and passing through point 'A'. Slope of the tangent drawn gives the tangent modulus.

at given stress value ( $\sigma_A$ ).

Plastic Properties:- The properties which don't obey Hooke's law are classified under this category.

(a) Yield Strength:- It is the stress required to produce a small, specified amount of plastic deformation. The deformation of the material is elastic, when it is loaded prior to yield point and when the loading is changed beyond yield point the plastic or permanent deformation occurs. Hence to avoid the permanent deformation in the materials, it is essential to have knowledge on the yield point of a material from designing point of view.

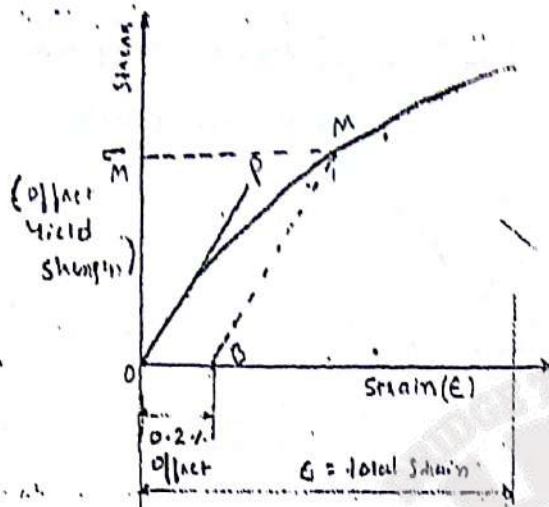
$$\text{Yield Stress } (\sigma_y) = \frac{F_y}{A_0}$$

where  $F_y$  = load at yield point (usually lower yield point)

$A_0$  = Original cross area of specimen.

(b) Offset Yield Strength:- For some materials which do not show a well defined yield point, yield stress is found by offset method and hence the name offset yield strength or proof stress. It is defined as the stress corresponding to the intersection of the stress-strain curve and a line drawn parallel to the linear part of the curve offset by a specified strain.

It is recommended from Bureau of Indian Standards to use 0.2% offset in general. Consider a stress-strain curve and draw a line of tangent to the curve from origin O. Mark a point 'B' on the strain axis at a distance of 0.2% of total strain. Now draw a line parallel to the OP, to intersect the curve at point M. The stress corresponding to the point 'M' gives the offset yield strength or proof stress of a material.



(b) off set yield strength.

(c) Ductility:- It is a measure of the degree of plastic deformation that has been sustained at fracture. It indicates the extent to which a material can be deformed without fracture. A knowledge of ductility of materials is important for at least two reasons. First, it indicates to a designer the degree to which a structure will deform plastically before fracture. Second, it specifies the degree to which allowable deformation during fabrication operations.

Ductility is measured by the percentage elongation or percentage reduction in area before rupture of the specimen taken place.

$$\% \text{ Elongation} = \left[ \frac{\text{Increase in length}}{\text{original length}} \right] \times 100 = \left[ \frac{L_f - L_0}{L_0} \right] \times 100$$

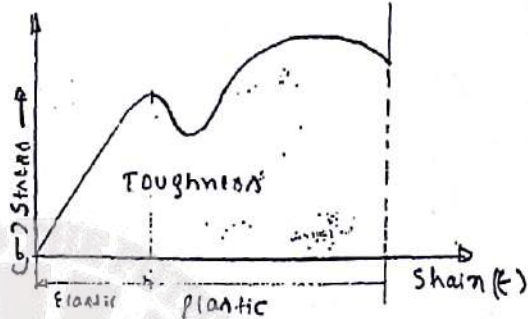
where  $L_f$  = final length  
 $L_0$  = original length.

$$\% \text{ reduction in c/a area} = \left[ \frac{A_0 - A_f}{A_0} \right] \times 100$$

where  $A_0$  = original c/a area

$A_f$  = final c/a area.

(b) Toughness:- It is defined as ability of a material to absorb energy upto fracture. It is ability of a material to withstand both elastic and plastic deformation. Area under the curve upto fracture gives the toughness of material.



(c) Ultimate tensile strength:- It is the maximum stress the material can withstand before it fractures, or it is simply known as tensile strength.

$$\text{Ultimate stress } (\sigma_u) = \frac{\text{Ultimate load } (F_u)}{\text{Original c/n area } (A_0)}$$

(d) Fracture strength:- It is the stress at which the actual fracture of the material takes place.

$$\text{Fracture stress } (\sigma_f) = \frac{\text{Load at fracture point } (F_f)}{\text{Original c/n area } (A_0)}$$

## 5. True Stress & True Strain:-

\* True stress:- It is defined as the local stress on the specimen at any instant, divided by the c/n area of the specimen at that instant.

$$\text{True stress } (\sigma') = \frac{\text{Force } (F)}{\text{Instantaneous c/n area } (A')}$$

where  $A'$  = area of the specimen at any instant of loading, or actual area of specimen.

\* True strain:- It is defined as sum of all the ~~instantaneous~~ ~~elongations~~ strains.

It is determined by the change in length to the immediate previous length of the specimen. It is summation of the ratios of each increment in length to the immediately preceding length.

$$\text{True Strain } (\epsilon') = \sum \frac{L_1 - L_0}{L_0} + \frac{L_2 - L_1}{L_1} + \frac{L_3 - L_2}{L_2} + \dots$$

$$\therefore \epsilon' = \int_{L_0}^{L_i} \frac{dL}{L} = \ln\left(\frac{L_i}{L_0}\right)$$

where  $L_i$  = instantaneous length of the specimen.

5.1. Relationship between engineering stress & true stress.

$$\text{Engineering stress} = \sigma = \frac{F}{A_i}$$

We know that for constant volume,  $A_i L_i = A_0 L_0 \Rightarrow A_i = \frac{A_0 L_0}{L_i}$

$$\begin{aligned} \sigma' &= \left(\frac{F}{A_0}\right) \cdot \left(\frac{L_i}{L_0}\right) \\ &= \sigma \left(1 + \frac{L_i - L_0}{L_0}\right) \end{aligned}$$

where  $A_0$  = original area

$A_i$  = instantaneous area

$L_i$  = instantaneous length

$L_0$  = original length.

$$\sigma' = \sigma (1 + \epsilon)$$

5.2. Relationship between engineering strain & true strain.

$$\text{Engineering strain} = \epsilon = \frac{\Delta L}{L_0}$$

$$\epsilon = \frac{L_i - L_0}{L_0}$$

where  $L_0$  = original length

$L_i$  = instantaneous length.

$$\epsilon = \frac{L_i}{L_0} - 1$$

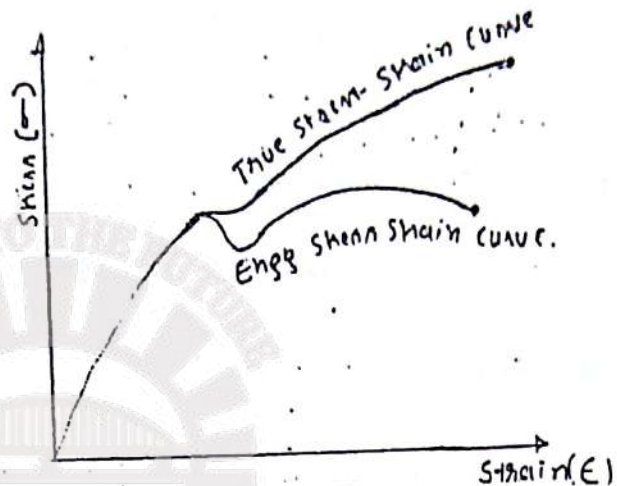
$$\epsilon + 1 = \frac{L_i}{L_0}$$

Taking ln on both sides,  $\ln(\epsilon + 1) = \ln\left(\frac{L_i}{L_0}\right)$

$$\epsilon' = \ln(\epsilon + 1)$$

∴ 5.3. Comparison between True Stress-strain & Engineering Stress-strain.. with diagrams.

Engg Stress-strain curve has been drawn with the help of original CA area of specimen, whereas for the true stress-strain curve marks use of instantaneous dimensions of specimen at any instant of load.



The curve is similar till the

elastic limit for both engineering & true stress-strain, but once load goes beyond the elastic limit, curves for both take their own path.

This is because, till the elastic limit the material will experience a negligible or small deformation but once load crosses elastic limit

substantial change in dimensions of specimen can be observed. As the loading

continues beyond elastic limit, strain becomes large and CA area of specimen

decreases and hence true stress will be much larger than engineering stress.

6. Plastic deformation:- when a material is loaded beyond the elastic limit, it experiences a deformation such that even after removing the load, the material cannot regain its original shape. This type of deformation is known as plastic or inelastic or permanent deformation.

Many crystals in grains come together to form a polycrystalline material & it is hard to study the mechanism of plastic deformation in polycrystalline material as each crystal has its own orientation due to the huge number of crystals. Hence it is preferred to study the behaviour of each single crystal under stress and then applying this study to polycrystalline materials.

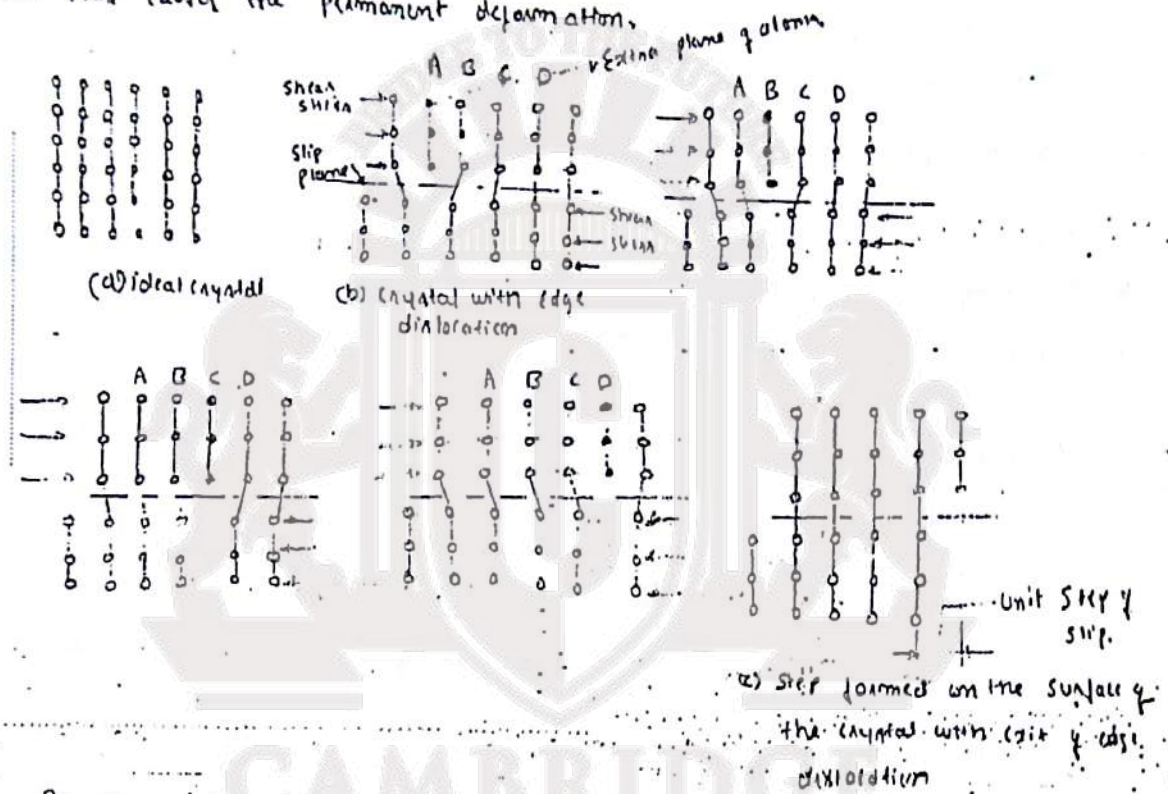
There are three modes or ways by which a single crystal can experience a plastic deformation. They are:-

- \* Slip
- \* Twinning
- \* Combination of slip and twinning.

6.1. Plastic deformation by slip:- All metals and alloys contain some dislocations that were introduced during solidification or due to the presence of thermal stresses that result from rapid cooling. If the material experiences plastic deformation by the movement of these dislocations then it is termed as slip. The plane along which the dislocation line moves is known as slip plane.

Let us consider an edge dislocation which helps in explaining how slip occurs. An edge dislocation moves in response to a shear stress applied in a direction perpendicular to its line. The mechanics of the dislocation motion (slip) is as shown in figure below. Fig (a) shows a perfect crystal and let the initial extra plane (half-plane) of atoms be plane 'A' which is as shown in fig (b). When the shear stress is applied as indicated in fig (b), plane A is forced to the right; this in turn pushes the top halves of planes B, C, D and so on, in the same

direction. so in the process of slipping, the movement of the dislocation, across the plane will cause the top half of the crystal to move with respect to the bottom half. Due to the actual movement of atomic blocks, no return to the original lattice shape is possible even after withdrawal of force. This causes the permanent deformation.



6.2 Plastic deformation by twinning: Twinning occurs when a portion of crystal takes up an orientation that is related to the orientation of the rest of the untwinned lattice in a definite, symmetrical way. i.e., the twinned portion of the crystal is a mirror image of the parent crystal. The plane of symmetry is called twinning plane.

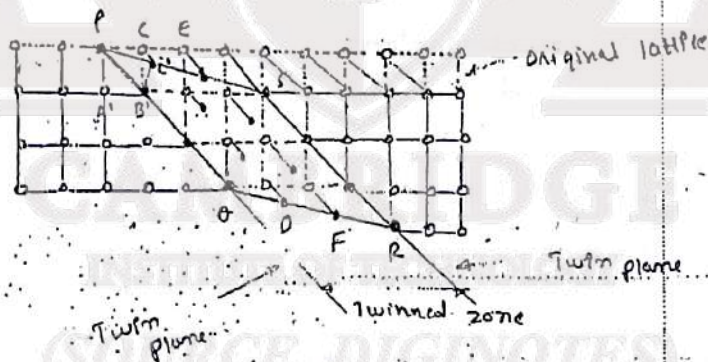
Figure shows the plastic deformation by twinning. In the figure PB and RS are called twin boundaries and twin planes, which separates the deformed and undeformed parts of metal lattice. The region PARS is known as twinned region. The part of the atomic lattice deformed in



the twinned region is a mirror image of the undeformed lattice.

In twinning, one plane of atoms slides over the next and the extent to which the each plane of atoms moves in the twinned region is proportional to the distance of plane of atoms from the twinning plane. Let's say the first plane CD moves one-third of an interatomic distance, the second plane EF moves two-thirds of the interatomic distance and the third plane SR moves SR moves an entire spacing.

Notice that the atom C gets displaced to C' exactly the same distance from each side of the twin plane.  $PC = B'C = B'A$ .  $PC'B'$  in the twinned region is mirror image of  $PA'B'$  in the undeformed region. Similar will be the case with respect to other atoms in the twinned region.



---PLASTIC DEFORMATION BY TWINNING

### 6.3 Difference between slip & twinning.

Description	Slip	Twinning
Stress	Shear stress required to cause slip is less	Shear stress required to cause twinning is high.
Critical Resolved Shear Stress	Plays a crucial role to cause slipping	has no role in twinning.
Atomic movement	Moves from one corner to another corner of the unit cell	Moves over fractional distance of atomic spacing.
Crystal orientation	Same above & below the slip plane	Differs across the twin plane.
Time required	Milli seconds	Microseconds
Occurrence	on many slip systems simultaneously	on particular plane for each crystal.
Microscopic appearance	As thin lines	As wide bands.

### 7. CRITICALLY RESOLVED SHEAR STRESS.

Even though a material is subjected to pure tensile stress, the presence of shear components can be seen, but these shear components are parallel or perpendicular to the applied stress direction. These are known as resolved shear stress.

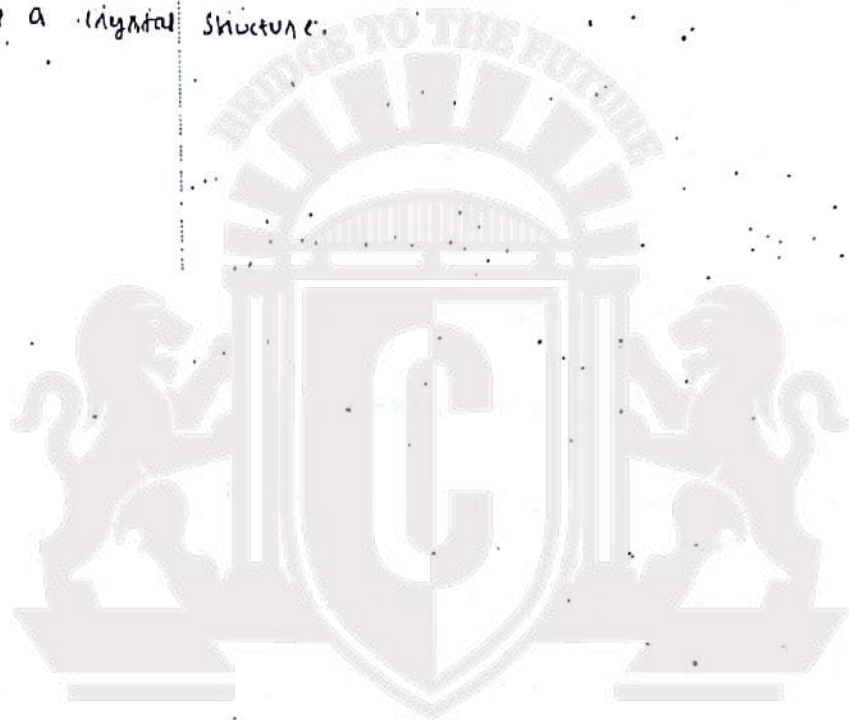
The magnitude of shear stress (resolved) depends on the applied stress, orientation of both the slip plane & direction with respect to the applied stress.

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Important questions from VU Question Paper.

- (1) Define engineering stress and engineering strain and obtain a relationship between true strain and engineering strain.
- (2) What are the slip systems in FCC and BCC crystals?
- (3) Explain Brinell hardness testing, with sketch & eqn.
- (4) Define (i) Resilience (ii) Tensile strength (iii) Hardness (iv) Ductility.
- (5) With the help of stress-strain curves show for the engineering stress-strain and true stress-strain. Explain briefly.
- (6) Explain Rockwell hardness with sketch & eqn.
- (7) Find out the relationship between true stress & engineering stress.
- (8) Explain slip & twinning with figures.
- (9) Draw the stress-strain diagram of mild steel and describe how the following properties can be obtained from the diagram:
  - (i) Elastic modulus
  - (ii) Ductility
  - (iii) Toughness
- (10) Draw stress-strain diagram for a ductile material and explain the salient points.
- (11) Explain non-linear elastic properties when a material is subjected to static tension.
- (12) What is work hardening? Explain the reasons for the same.
- (13) Explain in detail the mechanical properties in elastic & plastic region.

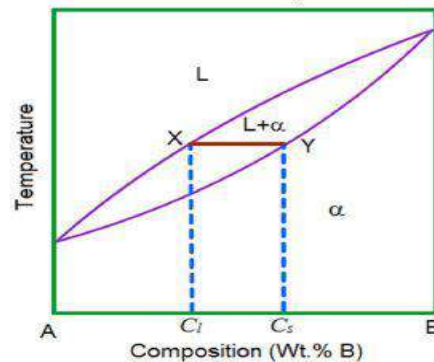
- (4) Discuss how the slip phenomenon differs in case of a polycrystal to the single crystal.
- (5) Derive an expression for critical resolved shear stress for slip in a crystal structure.



(SOURCE: DIGINOTES)

## Module-2

### SOLIDIFICATION



#### OBJECTIVES:

- To learn and understand the concepts of solidification
- Solid Solution and types
- Phase and phase equilibrium
- Nucleation and types of nucleation
- Crystal growth
- Phase diagrams

#### OUT COMES

The student should be able to understand the mechanism of solidification

#### Introduction

The solidification of metals and alloys is an important industrial process since most metals are melted and then cast in to a semi finished or finished shape. When molten metals are cast, solidification starts at the walls of the mould as it is being cooled. The solidification of alloy takes place not at a specific temperature but over a range of temperatures. While the alloy is in this range, it has a pasty form that consists of solid, tree like structures called dendrites and liquid metals. The size and shape of the dendrites depends on the cooling rate. The study of dendrites is important because they influence compositional variations, porosity and segregation and therefore properties.

**Component** – is either pure metal and/or compounds of which an alloy is composed. The components of a system may be elements, ions or compounds. They refer to the independent chemical species that comprise the system.

**System** – it can either refer to a specific body of material under consideration or it may relate to the series of possible alloys consisting of the same components but without regard to alloy composition.

**Solid solution** – it consists of atoms of at least two different types where solute atoms occupy either substitutional or interstitial positions in the solvent lattice and the crystal structure of the solvent is maintained.

**Solubility limit** – for almost all alloy systems, at a specific temperature, a maximum of solute atoms can dissolve in solvent phase to form a solid solution. The limit is known as solubility limit. In general, solubility limit changes with temperature. If solute available is more than the solubility limit that may lead to formation of different phase, either a solid solution or compound.

**Phase equilibrium** – it refers to the set of conditions where more than one phase may exist. It can be reflected by constancy with time in the phase characteristics of a system. In most metallurgical and materials systems, phase equilibrium involves just solid phases. However the state of equilibrium is never completely achieved because of very slow rate of approach of equilibrium in solid systems. This leads to non-equilibrium or meta-stable state, which may persist indefinitely and of course, has more practical significance than equilibrium phases. An equilibrium state of solid system can be reflected in terms of characteristics of the microstructure, phases present and their compositions, relative phase amounts and their spatial arrangement or distribution.

### **Kinetics of nucleation and growth**

Structural changes in metallic systems usually take place by nucleation and growth whether it is just a phase change within one of the three states, or a simple structural rearrangement within a single phase, or a phase transformation. An equilibrium phase diagram presents the phases and phase changes expected under equilibrium conditions, but it provides no information about the rates of transformation. Although changes in pressure, composition, or temperature can cause phase transformations, it is temperature changes that are more important. From a micro structural standpoint, the first process to accompany a phase transformation is nucleation (i.e. the formation of very small particles or nuclei of the product phase from the parent phase) of the new phase particles which are capable of growing. The second stage is growth, in which the nucleated particles increase their size. The transformation reaches completion if growth of these new phase particles is allowed to proceed until the equilibrium fraction is attained.

Both nucleation and growth require that the accompanying free energy change be negative. Consequently, the super-heating or super-cooling that is necessary for a phase change is to be expected. That is a transformation cannot take place precisely at the equilibrium transformation

temperature because at that temperature free energies of phases are equal. In addition to temperature, two other factors that affect transformation rate – first, diffusion controlled rearrangement of atoms because of compositional and/or crystal structural differences; second, difficulty encountered in nucleating small particles via change in surface energy associated with the interface. Diffusion limits both the nucleation and growth rates in many cases.

With the nucleation of new particle, new interface is created between the particle and liquid. This interface will have positive energy that must be supplied during the transformation process. A tiny particle has a large surface area to volume ratio and therefore be unstable. Thus energy of the surface can effectively prevent the initial formation of a tiny particle. A particle said to have nucleated when it becomes stable and will not disappear due to thermal fluctuations. After a particle attained a critical size, it can grow further with a continuous decrease in energy. The surface energy is no longer a dominant factor in the growth process.

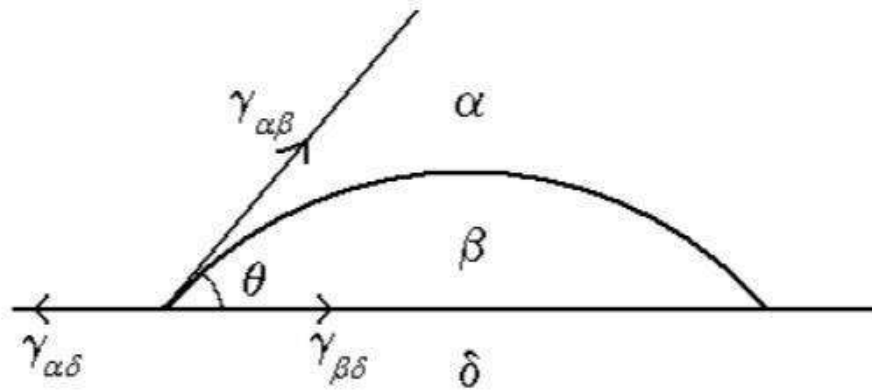
## Nucleation

**Homogeneous** nucleation, the probability of nucleation occurring at any given site is identical to that at any other site within the volume of the parent phase. When a pure liquid metal is cooled below its equilibrium freezing temperature to a sufficient degree, numerous homogeneous nuclei are created by slow-moving atoms bonding together. Homogeneous nucleation usually requires a considerable amount of *under cooling* (cooling a material below the equilibrium temperature for a given transformation without the transformation occurring). Under cooling enhances the formation of nuclei that eventually grow. If  $f$  is the free energy change accompanying the formation of a spherical new phase particle,

$$\Delta f = \frac{4}{3} \pi r^3 \Delta g + 4\pi r^2 \gamma$$

where  $r$  is the radius of the particle,  $g$  is the Gibbs free energy change per unit volume and  $\gamma$  is the surface energy of the interface.

**Heterogeneous nucleation**, the probability of nucleation occurring at certain preferred sites is much greater than that at other sites. During solidification, inclusions of foreign particles (*inoculants*), walls of container holding the liquid provide preferred sites. Irregularities in crystal structure such as point defects and dislocations possess strain energy. In solid-solid transformation, foreign inclusions, grain boundaries, interfaces, stacking faults and dislocations can act as preferred sites for nucleation as the strain energy associated with them will be reduced. The released strain energy can reduce the energy requirements for free energy change,  $f$ . Therefore, nucleation proceeds with a smaller critical radius. A majority of reactions are initiated by some type of heterogeneous nucleation which is common among the two types.



**Figure-:** Schematic of heterogeneous nucleation.

## Crystal Growth

Many transformations occur as a result of continuous formation of critical nuclei in the parent phase and the subsequent growth of the particles. Growth is the increase in size of the particle after it has nucleated i.e. growth kinetics become important once an embryo has exceeded the critical size and become a stable nucleus. Growth may proceed in two

radically different manners. In one type of growth, individual atoms move independently from the parent to the product phase, thus it is diffusion controlled and is thermally activated. In the other type of growth that occurs in solid-solid transformations many atoms move cooperatively without thermal assistance. Growth that is diffusion controlled is more common the other. Growth usually occurs by the thermally activated jump of atoms from the parent phase to the product phase. The unit step in the growth process thus consists of an atom leaving the parent phase and jumping across the interface to join the product phase. At the equilibrium temperature, both phases have the same free energy, hence the frequency of jumps from parent phase to product phase will be equal to that from product phase to parent phase i.e. the net growth rate is zero. At lower temperatures, product phase is expected to have lower free energy, and thus a net flow of atoms from parent phase to product phase. This net flux of atoms results in interface motion i.e. growth rate is taken as the rate of increase of a linear dimension of a growing particle. As a function of temperature, the growth rate first increases with increasing degree of super cooling, but eventually slows-down as thermal energy decreases. This is same as for nucleation; however the maximum in the growth rate usually occurs at a higher temperature than the maximum in the nucleation rate.

## Solid Solution

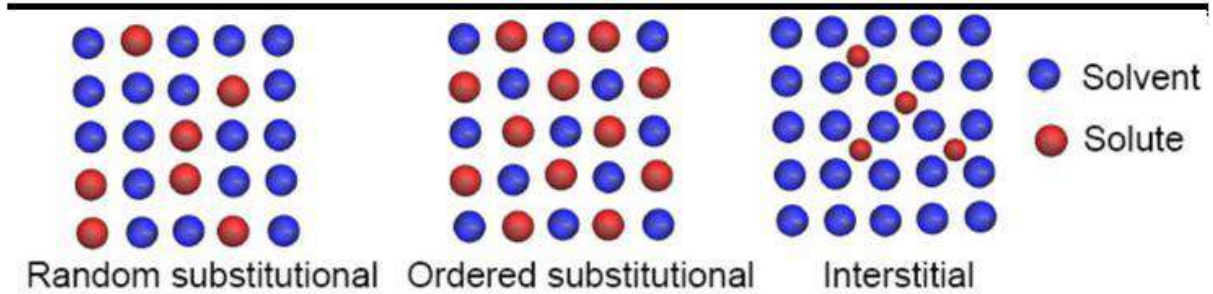
When two metals are mixed together they form an alloy if one metal is soluble in the other one in solid state. Therefore, an alloy is a solid solution of two or more metals.

Primarily there are two types of solid solutions -

**Substitutional** – Solute atoms occupy the regular lattice sites of the parent metal (solvent). Substitutional solid solutions can be random (Cu-Ni) or ordered (Cu-Au).

**Interstitial** – Solute atoms occupy the interstitial positions (Steel – C solute atoms in Fe) .





## Hume-Rothery Rules

Formation of substitutional solid solutions between two metals is governed by a set of rules known as **Hume-Rothery rules**

- Size difference between the atoms of solute and the parent metal should be less than 15%.
- The electronegativity difference between the metals should be small (minimum chemical affinity to each other).
- The solubility of a metal with higher valence in a solvent of lower valence is more compared to the reverse situation e.g. Zn is much more soluble in Cu than Cu in Zn.
- For complete solubility over the entire range of compositions the crystal structures of the solute and the solvent must be the same.

## Phase

A phase can be defined as a physically distinct and chemically homogeneous portion of a system that has a particular chemical composition and structure.

Water in liquid or vapor state is single phase. Ice floating on water is an example two phase system.

## Gibbs Phase rule

The number of degrees of freedom,  $F$  (no. of independently variable factors), number of components,  $C$ , and number of phases in equilibrium,  $P$ , are related by Gibbs phase rule as

$$F = C - P + 2$$

Number of external factors = 2 (pressure and temperature).

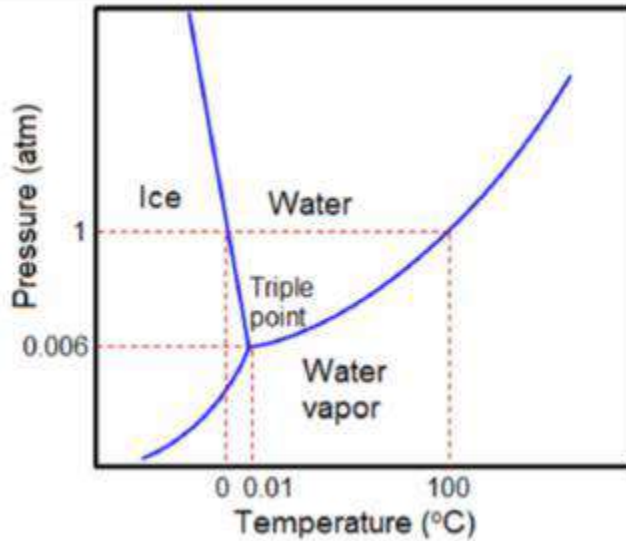
For metallurgical system pressure has no appreciable effect on phase equilibrium and hence,  $F = C - P + 1$

## Phase Diagrams

### One component system

The simplest phase diagram is the water which is a one component system. It is also known as pressure-temperature or P-T diagram. Two phases exist along each of the three phase boundaries.

At low pressure (0.006 atm) and temperature (0.01<sup>0</sup>C) all the three phases coexist at a point called triple point.

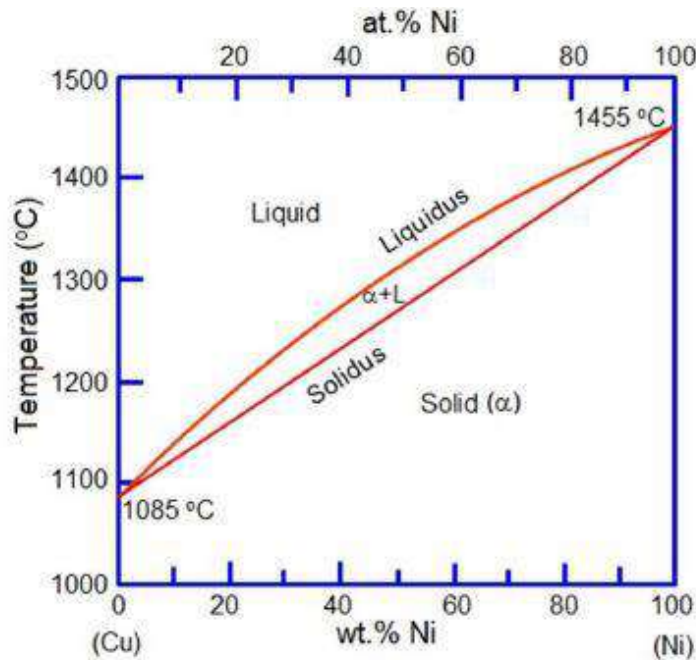


Water phase diagram

### Binary Phase diagrams

A binary phase is a two component system. Binary phase diagrams are most commonly used in alloy designing.

The simplest binary system is the Cu-Ni which exhibits complete solubility in liquid and solid state.



Cu-Ni equilibrium phase diagram

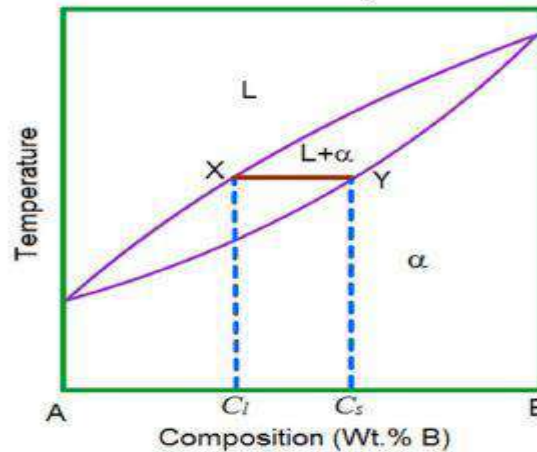
- The line above which the alloy is liquid is called the liquidus line. At temperature just below this line crystals of  $\alpha$  solid solution start forming.
- The line below which solidification completes is called solidus line. Hence, only  $\alpha$  solid solution exists at any temperature below the solidus line.
- The intermediate region between liquidus and solidus lines is the two-phase region where liquid and solid coexists.

- It can be noted that the two metals are soluble in each other in the entire range of compositions in both liquid and solid state. This kind of system is known as 'Isomorphous' system.

### The Tie line

The composition of phases in the two-phase region is not same.

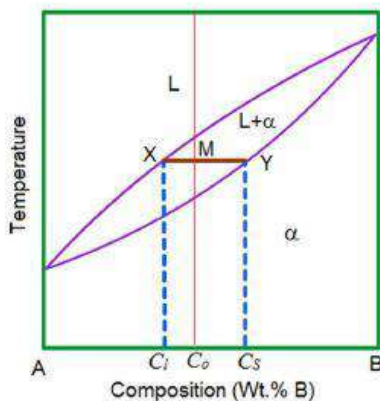
To find the composition of the individual phases in the two phase region, a horizontal line (XY), called tie line, is drawn and its intercepts on the liquidus and solidus lines,  $C_l$  and  $C_s$ , are taken as the composition of the liquid and solid respectively.



### Lever rule

The relative fractions of the phases at a given temperature for an alloy composition  $C_o$  is obtained by the lever rule. This rule gives the fraction of a phase by the ratio of the lengths of the tie line between  $C_o$  and composition of the other phase to the total length of the tie line. For example, fraction solid,  $f_s$  is given by

$$f_s = \frac{MX}{XY} = \frac{C_o - C_l}{C_s - C_l}$$



Similarly fraction liquid,  $f_l$

$$f_l = \frac{MY}{XY} = \frac{C_s - C_o}{C_s - C_l}$$

### Phase diagrams- Limited solubility

Not all metals are completely soluble in each other. Distinctions can be made between two types of solid solutions with limited solubility – (i) **Eutectic** and (ii) **Peritectic**.

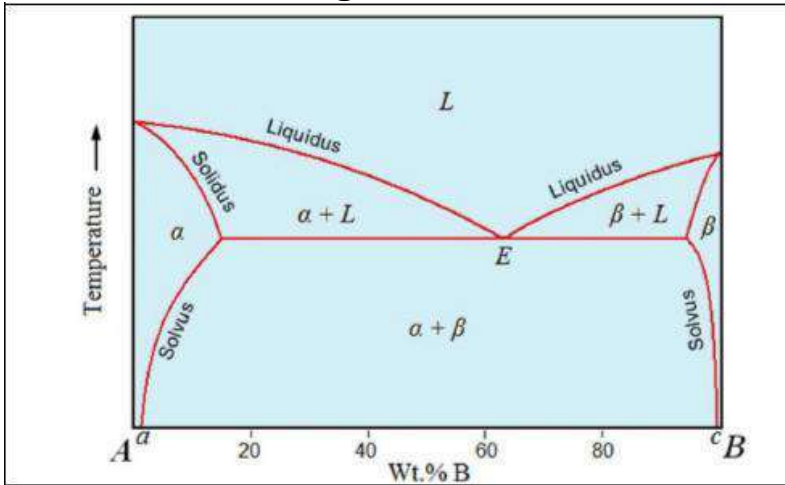
When the melting points of two metals are comparable, a eutectic system forms while a peritectic results when melting points are significantly different.

**A eutectic** reaction is defined as the one which generates two solids from the liquid at a given temperature and composition,  $L \rightarrow \alpha + \beta$

**Peritectic** is Liquid + Solid 1  $\rightarrow$  Solid 2 ( $L + \alpha \rightarrow \beta$ )

In both the cases three phases (two solids and a liquid) coexist and the degrees of freedom  $F = 2 - 3 + 1 = 0$ . This is known as invariant ( $F = 0$ ) reaction or transformation.

### Eutectic Phase diagram



Three phases ( $L + \alpha + \beta$ ) coexist at point  $E$ . This point is called eutectic point or composition. Left of  $E$  is called hypoeutectic whereas right of  $E$  is called hypereutectic.

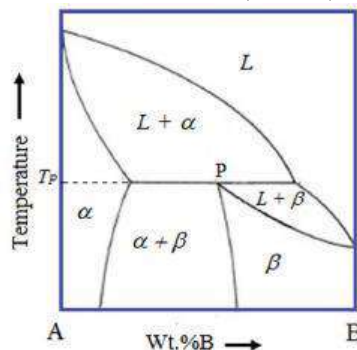
A eutectic composition solidifies as a eutectic mixture of  $\alpha$  and  $\beta$  phases. The microstructure at room temperature (RT) may consist of alternate layers or lamellae of  $\alpha$  and  $\beta$ .

In **hypoeutectic** alloys the  $\alpha$  phase solidifies first and the microstructure at RT consists of this  $\alpha$  phase (called proeutectic  $\alpha$ ) and the eutectic ( $\alpha + \beta$ ) mixture. Similarly hypereutectic alloys consist of proeutectic and the eutectic mixture. The melting point at the eutectic point is minimum. That's why Pb-Sn eutectic alloys are used as solders. Other eutectic systems are Ag-Cu, Al-Si, Al-Cu.

### Peritectic Phase diagram

$L + \alpha \rightarrow \beta$ . An alloy cooling slowly through the peritectic point,  $P$ , the  $\alpha$  phase will crystallize first just below the liquidus line. At the peritectic temperature,  $T_P$  all of the liquid and  $\alpha$  will convert to  $\beta$ . Any composition left of  $P$  will generate excess  $\alpha$  and similarly compositions right of  $P$  will give rise to an excess of liquid.

Peritectic systems – Pt - Ag, Ni - Re, Fe - Ge, Sn-Sb (babbitt).

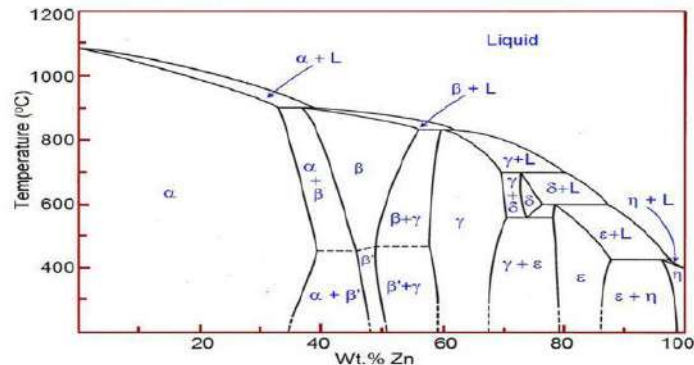


### Phase diagrams with intermediate phases

Binary system can have two types of solid solutions/phases – *terminal phases* and *intermediate phases*. Terminal phases occur near the pure metal ends, e.g.  $\alpha$  and  $\beta$  phases in the eutectic system. Intermediate phases occur inside the phase diagram and are separated by two-phase regions. The Cu-Zn system contains both types of phases.  $\alpha$  and  $\eta$  are terminal phases and  $\beta$ ,  $\gamma$ ,

$\delta$  and  $\epsilon$  are intermediate phases. Intermediate phases form in ceramic phase diagrams also. For example, in the  $\text{Al}_2\text{O}_3 - \text{SiO}_2$  system an intermediate phase called mullite ( $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ ) is formed.

### Intermediate phases - Cu-Zn Phase diagram



Cu-Zn phase diagram.  $\alpha$  and  $\eta$  are terminal phases and  $\beta$ ,  $\gamma$ ,  $\delta$  and  $\epsilon$  are intermediate phases.

### Summary

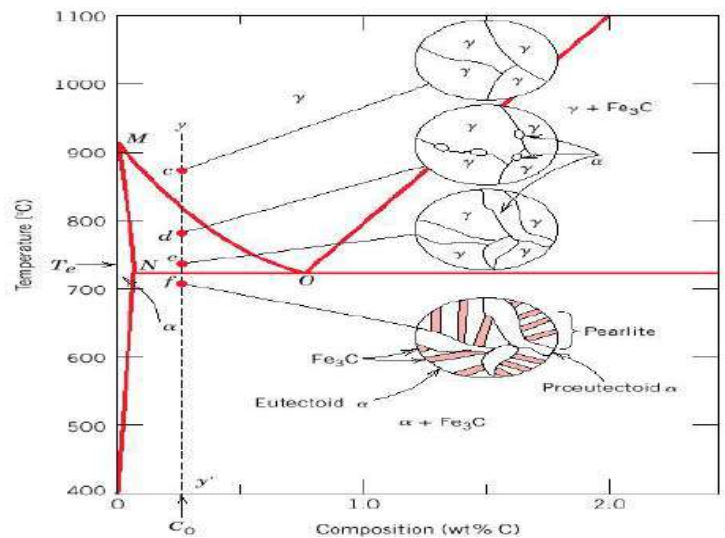
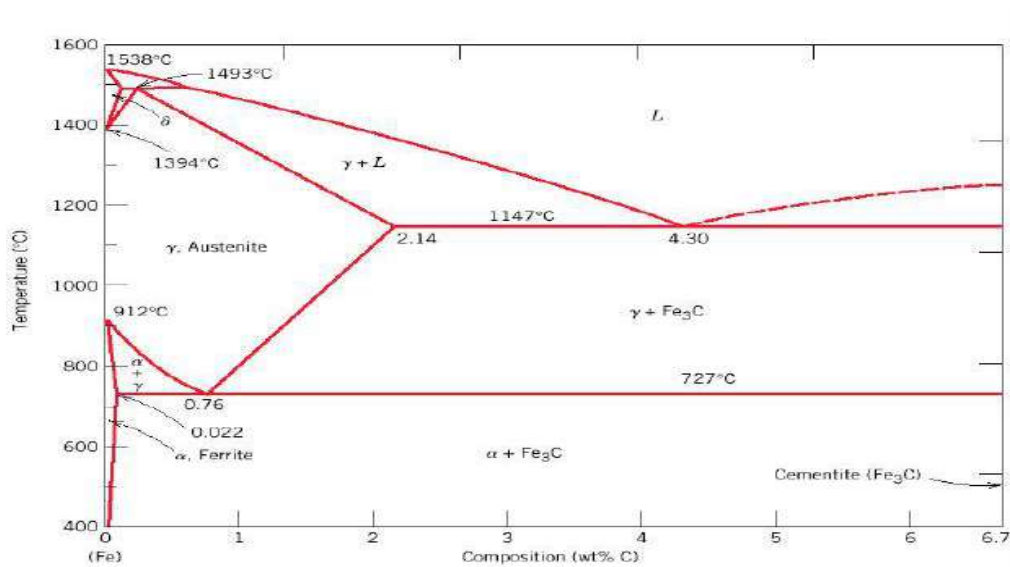
The solidification of alloy takes place not at a specific temperature but over a range of temperatures. While the alloy is in this range, it has a pasty form that consists of solid, tree like structures called dendrites and liquid metals. Formation of substitutional solid solutions between two metals is governed by a set of rules known as **Hume-Rothery rules**. The relative fractions of the phases at a given temperature for an alloy composition are obtained by the lever rule. A eutectic reaction is defined as the one which generates two solids from the liquid at a given temperature and composition,  $L \rightarrow \alpha + \beta$ . Peritectic is  $\text{Liquid} + \text{Solid 1} \rightarrow \text{Solid 2}$  ( $L + \alpha \rightarrow \beta$ )

In both the cases three phases (two solids and a liquid) coexist and the degrees of freedom  $F = 2 - 3 + 1 = 0$ . This is known as invariant ( $F = 0$ ) reaction or transformation.

### Self assessment questions

1. Define nucleation. Derive an expression for the critical size of the nucleus for homogeneous nucleation.
2. State and explain Gibb's phase rule. How it can be applied to a unary phase diagram? Show that degrees of freedom at triple point are zero.
3. Describe the solidification mechanism in pure metal. Distinguish between homogeneous and heterogeneous nucleation.
4. Discuss the factors worked out by Hume-Rothery that governs the formation of an ideal solid solution.
5. What are the different types of solidification
6. Explain with neat sketches the different stages of mechanisms of solidification.
7. Define solid solution. Explain substitutional and interstitial solid solution.
8. Explain the factors governing the formation of substitutional solid solution.
9. With the help of cooling curves explain the solidification of pure metal and binary eutectic alloy
10. A binary alloy A-50% B contains at a particular temperature two solid phases  $\alpha$  and  $\beta$  are 5% B and 95% B respectively. calculate the amount of  $\alpha$  and  $\beta$  in the alloy.

## IRON CARBON DIAGRAM



### OBJECTIVES:

- To construct equilibrium diagrams involving complete and partial solubility,
- To understand lever rule
- To understand Iron carbon equilibrium diagram description of phases,
- To know solidification of steels and cast irons invariant reactions.

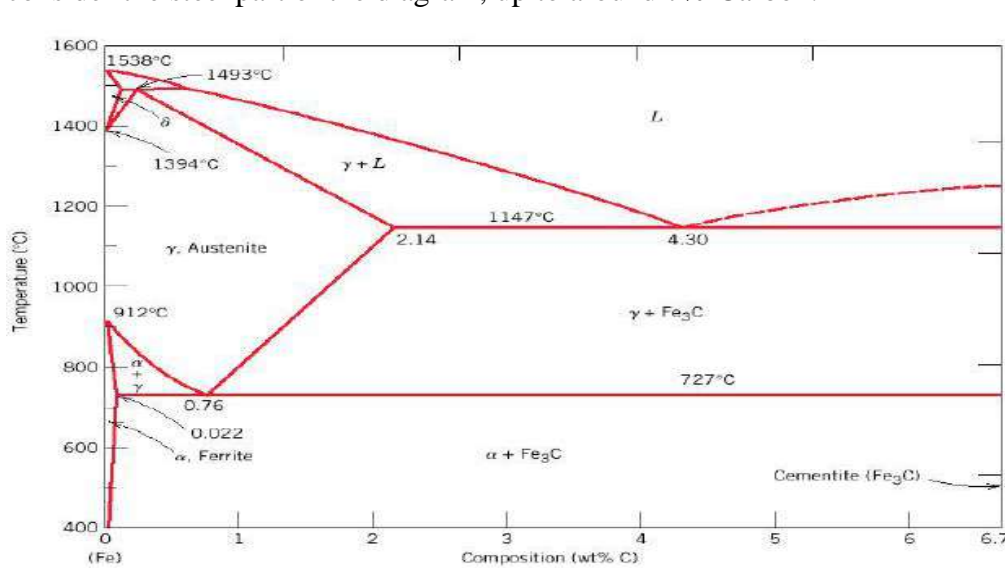
### Outcomes:

1. Student can better understand the phase diagrams those are important to design and control of heat treating process and to obtain desirable microstructures.

## Introduction

A phase in a material is a region that differs in its microstructure and /or composition from another region. Phase diagrams are graphical representations of what phases are present in a materials system at various temperatures and pressures and compositions. Most phase diagrams are constructed by using equilibrium conditions and used by engineers and scientists to understand and predict many aspects of the behaviour of materials.

**The Iron–Iron Carbide (Fe–Fe<sub>3</sub>C) Phase Diagram** In their simplest form, steels are alloys of Iron (Fe) and Carbon (C). The Fe-C phase diagram is a fairly complex one, but we will only consider the steel part of the diagram, up to around 7% Carbon.



### Phases in Fe–Fe<sub>3</sub>C Phase Diagram

- α-ferrite - solid solution of C in BCC Fe**
- Stable form of iron at room temperature.
- The maximum solubility of C is 0.022 wt%
- Transforms to FCC γ-austenite at 912 °C

### γ-austenite - solid solution of C in FCC Fe

- The maximum solubility of C is 2.14 wt %.
- Transforms to BCC δ-ferrite at 1395 °C
- Is not stable below the eutectic temperature (727 °C) unless cooled rapidly (Chapter 10)

### δ-ferrite solid solution of C in BCC Fe

- The same structure as α-ferrite
- Stable only at high T, above 1394 °C
- Melts at 1538 °C

### Fe<sub>3</sub>C (iron carbide or cementite)

- This intermetallic compound is metastable, it remains as a compound indefinitely at room T, but decomposes (very slowly, within several years) into α-Fe and C (graphite) at 650 - 700 °C

### Fe-C liquid solution

### A few comments on Fe–Fe<sub>3</sub>C system

C is an interstitial impurity in Fe. It forms a solid solution with α, γ, δ phases of iron. Maximum solubility in BCC α-ferrite is limited (max. 0.022 wt% at 727 °C) - BCC has relatively small

interstitial positions. Maximum solubility in FCC austenite is 2.14 wt% at 1147 °C - FCC has larger interstitial positions.

**Mechanical properties:** Cementite is very hard and brittle - can strengthen steels. Mechanical properties also depend on the microstructure, that is, how ferrite and cementite are mixed.

**Magnetic properties:**  $\alpha$ -ferrite is magnetic below 768 °C, austenite is non-magnetic

**Classification.**

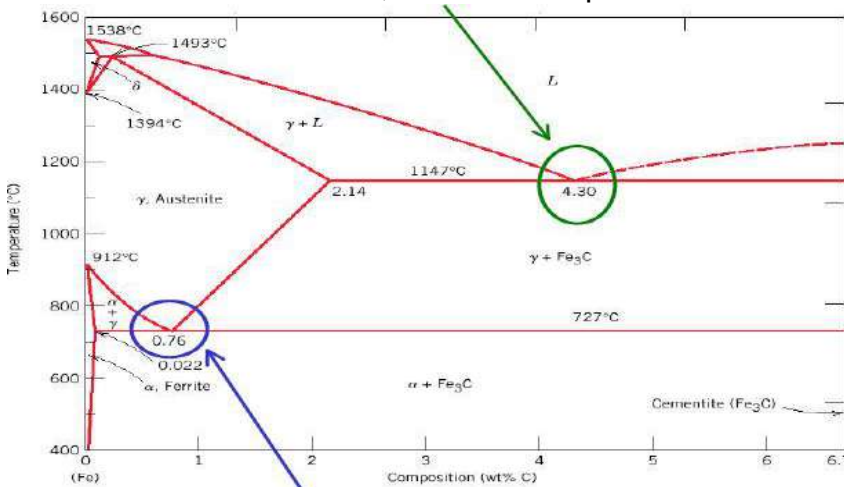
**Three types of ferrous alloys:**

- Iron: less than 0.008 wt % C in  $\alpha$ -ferrite at room T
- Steels: 0.008 - 2.14 wt % C (usually < 1 wt %)  $\alpha$ -ferrite + Fe<sub>3</sub>C at room T
- Cast iron: 2.14 - 6.7 wt % (usually < 4.5 wt %)

**Eutectic and eutectoid reactions in Fe-Fe<sub>3</sub>C**

**Eutectoid:** 0.76 wt %C, 727 °C  $\gamma(0.76 \text{ wt\% C}) \leftrightarrow \alpha(0.022 \text{ wt\% C}) + \text{Fe}_3\text{C}$

**Eutectic:** 4.30 wt% C, 1147 °C  $L \leftrightarrow \gamma + \text{Fe}_3\text{C}$



**Eutectoid:** 0.76 wt %C, 727 °C

$\gamma(0.76 \text{ wt\% C}) \leftrightarrow \alpha(0.022 \text{ wt\% C}) + \text{Fe}_3\text{C}$

**Fe<sub>3</sub>C Eutectic:** 4.30 wt% C, 1147 °C

$L \leftrightarrow \gamma + \text{Fe}_3\text{C}$

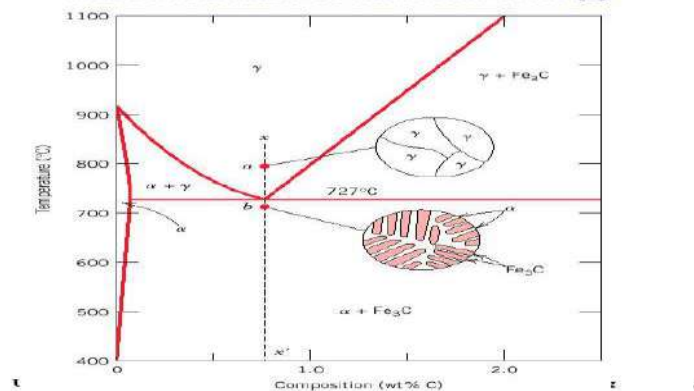
Eutectic and eutectoid reactions are very important in heat treatment of steels

**Development of Microstructure in Iron - Carbon alloys**

**Microstructure depends on composition (carbon content) and heat treatment.**

In the discussion below we consider slow cooling in which equilibrium is maintained.

**Microstructure of eutectoid steel (D)**



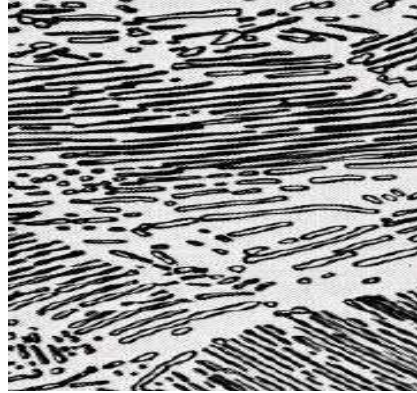


### Microstructure of eutectoid steel (II)

When alloy of eutectoid composition (0.76 wt % C) is cooled slowly it forms **pearlite**, a lamellar or layered structure of two phases:  $\alpha$ -ferrite and cementite ( $\text{Fe}_3\text{C}$ ). The layers of alternating phases in pearlite are formed for the same reason as layered structure of eutectic structures: redistribution C atoms between ferrite (0.022 wt%) and cementite (6.7 wt%) by atomic diffusion. Mechanically, pearlite has properties intermediate to soft, ductile ferrite and hard, brittle cementite.

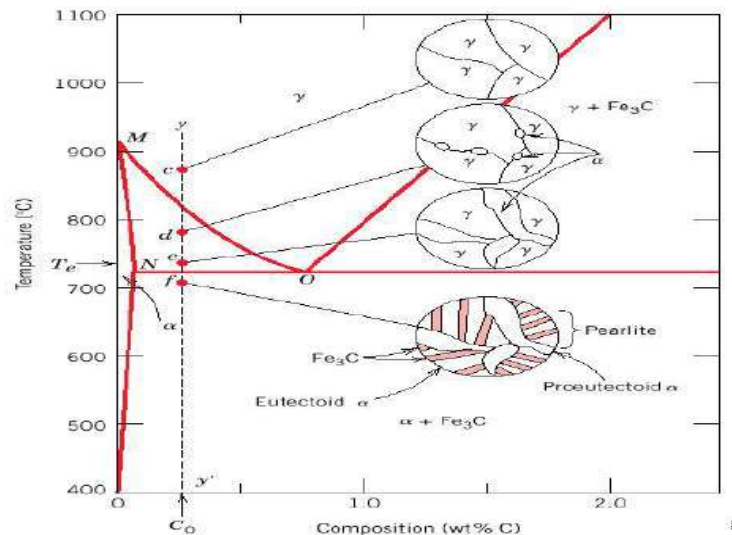
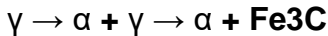
### Microstructure of eutectoid steel (II)

In the micrograph, the dark areas are  $\text{Fe}_3\text{C}$  layers, the light phase is  $\alpha$ -ferrite



### Microstructure of hypo eutectoid steel (I)

Compositions to the left of eutectoid (0.022 - 0.76 wt % C) **hypo eutectoid** alloys.

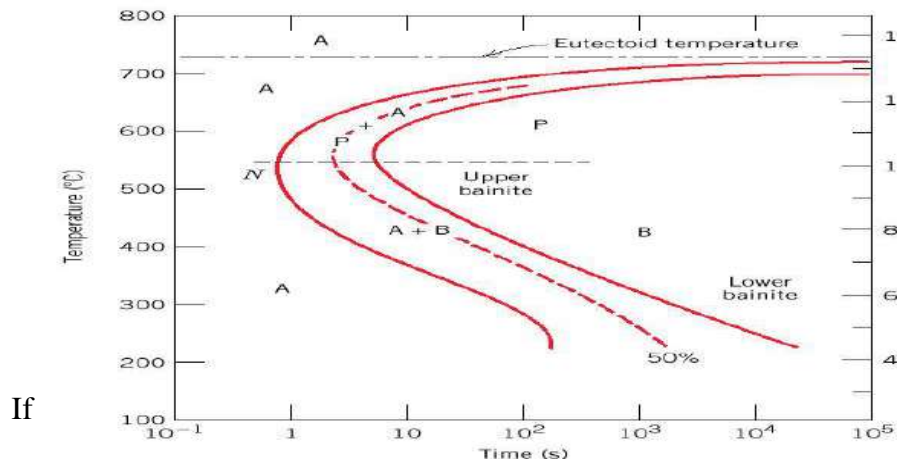


### TTT Diagrams

- The family of S-shaped curves at different T is used to construct the TTT diagrams. The TTT diagrams are for the **isothermal** (constant T) transformations (material is cooled quickly to a given temperature before the transformation occurs, and then keep it at that temperature).
- At low temperatures, the transformation occurs sooner (it is controlled by the rate of nucleation) and grain growth (that is controlled by diffusion) is reduced.
- Slow diffusion at low temperatures leads to fine-grained microstructure with thin-layered structure of pearlite (**fine pearlite**).

- At higher temperatures, high diffusion rates allow for larger grain growth and formation of thick layered structure of pearlite (**coarse pearlite**).
- At compositions other than eutectoid, a proeutectoid phase (ferrite or cementite) coexist with pearlite.
- Additional curves for proeutectoid transformation must be included on TTT diagrams.

## Formation of Bainite Microstructure (I)

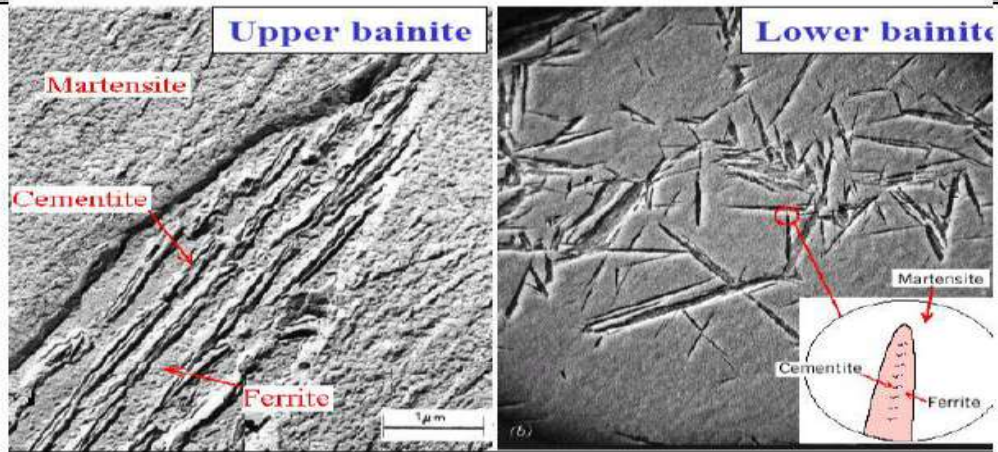


## Formation of Bainite Microstructure (II)

- For  $T \sim 300\text{-}540^\circ\text{C}$ , **upper bainite** consists of needles of ferrite separated by long cementite particles
- For  $T \sim 200\text{-}300^\circ\text{C}$ , **lower bainite** consists of thin plates of ferrite containing very fine rods or blades of cementite
- In the bainite region, transformation rate is controlled by microstructure growth (diffusion) rather than nucleation.
- Since diffusion is slow at low temperatures, this phase has a very fine (microscopic) microstructure.
- Pearlite and bainite transformations are competitive; transformation between pearlite and bainite not possible without first reheating to form austenite

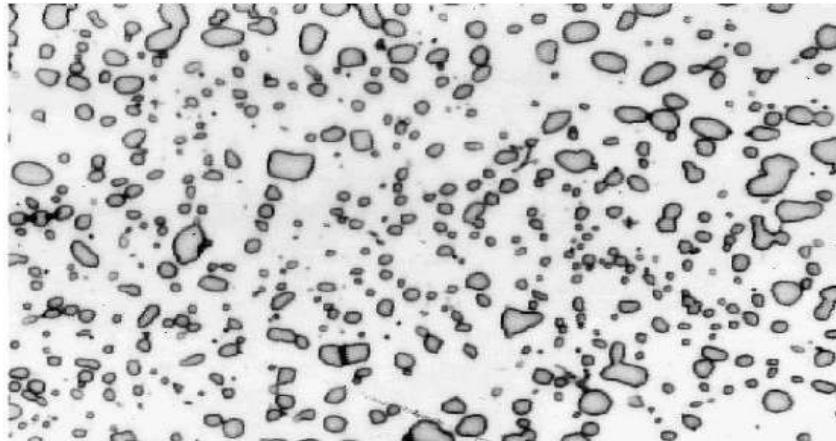
## Upper bainite Lower bainite Spheroidite

- Annealing of pearlitic or bainitic microstructures at elevated temperatures just below eutectoid (e.g. 24 h at 700 C) leads to the formation of new microstructure – **spheroidite** - spheres of cementite in a ferrite matrix.
- Composition or relative amounts of ferrite and cementite are not changing in this transformation; **only shape of the cementite inclusions is changing**.
- Transformation proceeds by C diffusion – needs high T.
- Driving force for the transformation - reduction in total ferrite - cementite boundary area



### Martensite (I)

- Martensite forms when austenite is rapidly cooled (quenched) to room T.
- It forms nearly instantaneously when the required low temperature is reached. The austenite-martensite does not involve diffusion → no thermal activation is needed, this is called a **thermal transformation**.
- Each atom displaces a small (sub-atomic) distance to transform FCC  $\gamma$ -Fe (austenite) to martensite which has a Body Centered Tetragonal (BCT) unit cell (like BCC, but one unit cell axis is longer than the other two).
- Martensite is metastable - can persist indefinitely at room temperature, but will transform to equilibrium phases on annealing at an elevated temperature.
- Martensite can coexist with other phases and/or microstructures in Fe-C system
- Since martensite is metastable non-equilibrium phase, it does not appear in phase Fe-C phase diagram



### Summary

- A phase in a material is a region that differs in its microstructure and /or composition from another region. Phase diagrams are graphical representations of what phases are present in a materials system at various temperatures and pressures and compositions. Most phase diagrams are constructed by using equilibrium conditions and used by engineers and scientists to understand and predict many aspects of the behaviour of materials. The different forms of iron and carbon are  $\alpha$ -ferrite,  $\gamma$ -austenite,  $\delta$ -ferrite. TTT diagrams are

for the isothermal (constant T) transformations (material is cooled quickly to a given temperature before the transformation occurs, and then keep it at that temperature).

### Self assessment questions

- 1) Draw iron carbon equilibrium diagram and mark on it all salient temperatures, composition and phases involved. Elaborate the invariant reactions.
- 2) Construct a phase diagram using the following data and label all the fields  
Melting point of Ag = 961°C      melting point of copper = 1083°C Eutectic temperature = 780°C  
Eutectic composition = 28%Cu maximum solubility of Cu in Ag = 9% at 780°C  
maximum solubility of Cu in Ag = 2% at 0°C. Determine the following. Solidification start and end of temperature for 30% Ag alloy, temperature at which a 15% Cu alloy has 50% liquid phase and 50% solid phase
- 3) What is a phase diagram?. Clearly explain the different predictions that can be made from phase diagram.
- 4) Draw the iron carbon equilibrium diagram and label all the parts.
- 5) With the help of a iron carbon diagram explain cooling of steel with 0.6% carbon showing the microstructure at different stages.
- 6) What is an invariant reaction? Write the following binary invariant reactions 1) Eutectoid 2) peritectic
- 7) Calculate the amount of proeutectoid ferrite, total ferrite and cementite in 0.6% C steel at room temperature.
- 8) Draw the TTT diagram for eutectoid steel and explain the different microstructures obtained at various cooling rates.
- 9) What is critical cooling rate?
- 10) Two metals A and B melt at 600°C and 400°C respectively. They do not form any intermediate phase. The maximum solid solubility in each other is 4% down to 0°C. an eutectic reaction takes place at a composition of 65%A-35%B at 300°C. Draw the phase diagram and label all regions. Find the temperature at which a 20% A-80%B alloy starts and completes solidification. Find the temperature at which the same alloy is 50% solid and 50% liquid.

### Module 3

1. **What is a solid solution? Explain the Hume-Rothery rules for the formation of substitutional solid solution with examples** Jan 16/ July 15/ Jan 15/ July 14

A solid solution is, a solid-state solution of one or more solutes in a solvent. Such a mixture is considered a solution rather than a compound when the crystal structure of the solvent remains unchanged by addition of the solutes, and when the mixture remains in a single homogeneous phase

#### Hume-Rothery rule

While developing an alloy, it is frequently desirable to increase the strength of the alloy by adding a metal that will form a solid solution. Hume-Rothery has framed empirical rules that govern the choice of alloying elements in the formation of substitutional solutions. We may note that if an alloying element is chosen at random, it is likely to form an objectionable intermediate phase instead of a solid solution. Extensive solid solubility by substitution occurs, when

- (i) the solute and solvent atoms do not differ by more than 15% in size, i.e. diameter. Within this limit of size factor, each of the metals will be able to dissolve appreciably (to the order of 10%) in the other metal. However, if the atomic size factor is greater than 15%, solid solution formation tends to be severely limited and is usually only a fraction of one percent.
- (ii) the electronegativity difference between the elements is small. If the chemical affinity of two metals is greater, then the solid solubility will be more restricted. When the chemical affinity of two metals is great, they tend to form an intermediate phase rather than a solid solution.

the valency and the crystal structures of the elements are the same. If the alloying element has a different valence from that of the base metal, the number of valence electrons per atom (called the electron ratio), will be changed by alloying. We may note that the crystal structures are more sensitive to a decrease in the electron ratio than to an increase. Obviously, a metal of high valence can dissolve only a small amount of lower valence metal; whereas the lower valence metal may have good solubility for a higher valence metal.

Moreover, only metals that have the same type of lattice (for example FCC) can form a complete series of solid solutions. For complete solubility, it is found that the size factor must usually be less than 8%. Examples of binary and ternary systems exhibiting complete solid solubility are Cu-Ni and Ag-Au-Pt respectively

2. Compare homogenous and heterogeneous nucleation with sketches

Jan 16/July 14/June 16

**Homogeneous nucleation**

In homogeneous nucleation the stability of a nucleus is controlled by two factors (i) the free energy change during the liquid – solid transition, and (ii) the value of the surface energy of the nucleus thus formed. As a result, the total free energy change associated with the embryo formation is given by

$$\text{Volume free energy } G = (4/3)\pi r^3 \Delta G_V \quad \text{----- (1)}$$

$\Delta G_V$  Where  $V$  = free energy change between liquid and solid per unit volume

$\gamma$  = specific surface energy

$r$  = radius of an embryo considered to be spherical

At temperature, below the melting temperature  $T_s$ ,  $\Delta G_V$  is negative, and hence the first term on the right of equation (1) is negative. Since  $\gamma$  is always positive the second terms representing the surface energy between the embryo, and the matrix is positive. For a spherical embryo the term (FORMULA), which is the driving force for the creation of solid – liquid interface decreases as  $r^3$  increases. However the retarding force, which is the surface energy, increases as  $r^2$  increases.

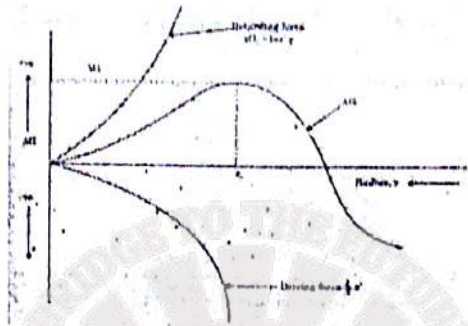


Fig Variation of free energy with the radius of a nucleus

Fig shows a plot of free energy  $\Delta G$  versus the embryo radius  $r$ . the maximum  $\Delta G$  equal to  $\Delta G^*$  is reached for  $r=r_c$  where  $r_c$  is the critical radius of the embryo. at the critical radius, the volume free energy decreases, just equals the surface free energy of the nucleus.

Differentiating equation (1) with respect to  $r$  and equating it to zero, will give

$$4\pi r^2 \Delta G_v + 4\pi \times 2r_c \times \gamma = 0$$

$$r_c = \frac{-2\gamma}{\Delta G_v}$$

When  $r > r_c$  the free energy of the system decreases initiating the formation of crystal.

It is seen that upon the formation of a nucleus of a size less than the critical value  $r_c$ , the free energy of the system increases because the increment of free energy due to the formation of a new interface exceeds reduction in free energy due to the formation of a nucleus of solid metal. Therefore a nucleus of a size less than  $r_c$  cannot grow and soon dissolve in the liquid metal. If a nucleus appears with a size exceeding  $r_c$ , it will be stable and will be capable of growth because the free energy of the system reduces as the size of the nucleus increases.

Heterogeneous nucleation

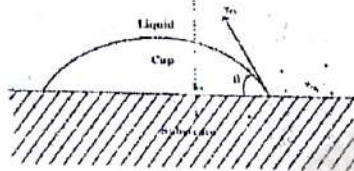


Fig Heterogeneous nucleation.

Most frequently, the source about which nuclei are formed on solid particles are always present in the melt. If the particles of the impurity have a crystal lattice of a structure more or less closely resembling that of the solidifying metal, then they play the part of ready centers of crystallization. Such surfaces or impurities are "wet" by both liquid and solid lowering the net energy associated with the formation of nucleus. Fig illustrates mechanism of heterogeneous nucleation. The heterogeneous nucleus is considered as a spherical cap on a solid, flat substrate. The volume of the cap depends on the contact angle  $\theta$  at the nucleus - liquid- substrate junction. If the contact angle is less than  $180^\circ$  a particular surface will serve as nucleation catalyst for that system. The change in free energy associated with the formation of the embryo is given by,

$$\Delta G = V\Delta G_v + A_{cl}\gamma_{cl} + \pi r^2\gamma_{sc} - \pi r^2\gamma_{sl}$$

Where  $V$  = volume of the spherical cap (nucleus).

$A_{cl}$  = the interfacial surface area between liquid and the cap.

$r$  = the radius of the cap (nucleus)

$\gamma_{CL}$ ,  $\gamma_{SC}$  and  $\gamma_{SL}$  are interfacial surface tension between Cap (nucleus) liquid, cap substrate and substrate liquid respectively. In homogeneous nucleation, the critical size of the nucleus given by

$$r_c = \frac{-2\gamma_{cl}}{\Delta G_v}$$

and it is independent of contact angle. In heterogeneous nucleation, however, the value of  $\gamma_{CL}$ , the interfacial surface tension, is much smaller, therefore the critical size of the nucleus



will be much smaller. As a result, the number of atoms that must be crystallized before the critical radius size  $r_c$  is reached is much less for heterogeneous nucleation than for the homogeneous one, and hence smaller amount of undercooling is required.

3. Write a short notes on intermediate phases

Jan 16

Equilibrium Diagrams Having Intermediate Phases or Compounds: A terminal phase or terminal solution is one that exists in the extremes of concentration (0 and 100%) of the phase diagram. One that exists in the middle, separated from the extremes, is called an intermediate phase or solid solution. An important phase is the intermetallic compound, that has a precise chemical compositions. When using the lever rules, intermetallic compounds are treated like any other phase, except they appear not as a wide region but as a vertical line.

4. Define solidification and explain nucleation and grain growth of a metal or alloy with neat sketch

July 15/Jan 15/Jun 16

Solidification is one of the most important phase transformations in materials, and its proper understanding is essential in control of many fabricating processes. The transformation of a metal from the liquid to the solid state is often called primary crystallization.

Solidification proceeds owing to the conversion of matter to a more stable thermodynamic state with less free energy  $E$ . Free energy is reversibly changed upon changes in temperatures, allotropic transformations, fusion (melting) etc. At temperature  $T_s$  amount of free energies are equal in the liquid and in solid state. This is the equilibrium temperature of solidification (or melting) of the substances of which both phases (liquid or solid) may exist simultaneously

Solidification of pure metals is considered to take place in two stages namely nucleation and crystal growth. Nucleation It is seen that the atoms are not chaotically arranged in a liquid metal as they are in the gaseous state; but at the same time they do not have the regular orderly characteristic of a solid (crystal) body.

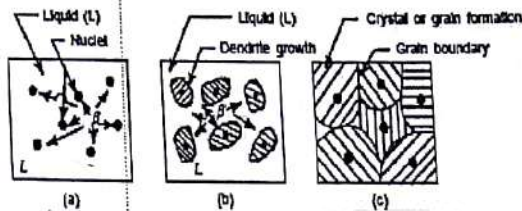


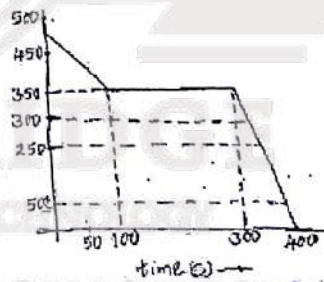
Illustration of solidification process of the liquid to  $\beta$ -crystals by nucleation and growth

Fig mechanism of solidification

At a temperature somewhat lower than  $T_s$  (melting temperature), micro volumes having atomic arrangement similar to that in the solid metal acquire higher stability and become centers of crystallization (nuclei or embryos). Nuclei of a great variety of size appear during the solidification process. Not all nuclei, however are capable of further growth. This is due to the fact that the free energy of the system is reduced in solidification when a certain volume of the increased owing to the formation of an interface with which a certain amount of free energy is associated. Nucleation may occur by two mechanisms namely homogeneous nucleation and heterogeneous nucleation.

5. A cooling curve is shown in fig below determine the following Jan 15

- The pouring temperature
- Solidification temperature
- The super heat
- Cooling rate
- Total solidification time
- Local solidification time



- The pouring temperature =  $475^{\circ}\text{C}$
- Solidification temperature =  $350^{\circ}\text{C}$
- The super heat =  $475 - 350 = 125^{\circ}\text{C}$
- Cooling rate =  $1.13^{\circ}\text{C}/\text{sec}$
- Total solidification time = 300sec
- Local solidification time = 200sec

Sp. Sub

MATERIAL SCIENCE3<sup>rd</sup> Sem Mechanical.IREETHAMIS T  
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15

MODULE-4 - "OTHER MATERIALS,  
MATERIAL SELECTION"

SYLLABUS: CERAMICS: Structure, types, Properties and application of Ceramics. Mechanical / Electrical behaviour & Processing of Ceramics.

PLASTICS: Various types of polymers / plastics & their application. Mechanical behaviour and processing of plastics, Failure of plastics.

OTHER MATERIALS:- Brief description of other materials such as optical and thermal materials, smart materials - fibre optic materials, piezo electric, shape memory alloys. Shape memory alloys - Nitinol, superelasticity. Biological applications of smart materials - materials used as implants in human body. Selection of materials; Performance of materials in service, Reliability, life assessment - use of non destructive testing. Economics, Environment & Sustainability.

CERAMICS:-

Definition - Ceramic materials are inorganic, non metallic materials that consist of metallic and non metallic elements bonded together primarily by ionic and/or covalent bonds.

The properties of ceramic material varies greatly due to the difference in bonding. But in general ceramic materials are hard & brittle with low toughness & ductility. They are also good thermal & electrical insulators & possess high melting temperatures & chemical stability because of stability of their strong bonds.

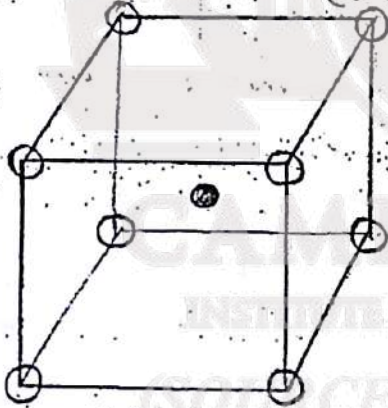
## STRUCTURE :-

Like all other materials, the properties of ceramics are also dictated by its crystal structure, i.e., type of atoms present, type of bonding, how the atoms are packed together, and the way the atoms are packed together.

The bonding in ceramic material is either ionic or covalent or combination of ionic and covalent. The strength of ionic bond depends on the size of the charge on each ion and on the radius of each ion, whereas the strength of the covalent bond depends on the number of electrons being shared.

### Examples for crystal structure in ceramics

#### A- Calcium chloride ( $\text{CaCl}_2$ ) Crystal Structure.



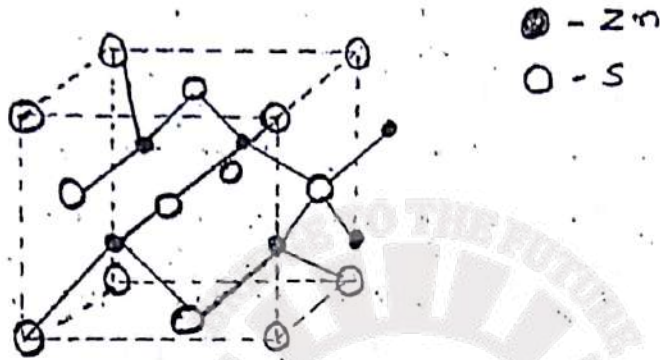
- - Chloride ion
- - calcium ion

The calcium chloride ( $\text{CaCl}_2$ ) is basically ionic bonded ceramic material. Consisting of equal number of  $\text{Ca}^{2+}$  &  $\text{Cl}^-$  ions. The radius ratio for  $\text{CaCl}_2$  is 0.94, cubic coordination number = 8. i.e., 8 chloride ions surround a central calcium ion in the  $\text{CaCl}_2$  unit cell.

For ceramic materials, where it is dominated by ionic bond, the crystal structure is defined by,

- Magnitude of electrical charge on each ion.
- Relative size of the cations & anions.

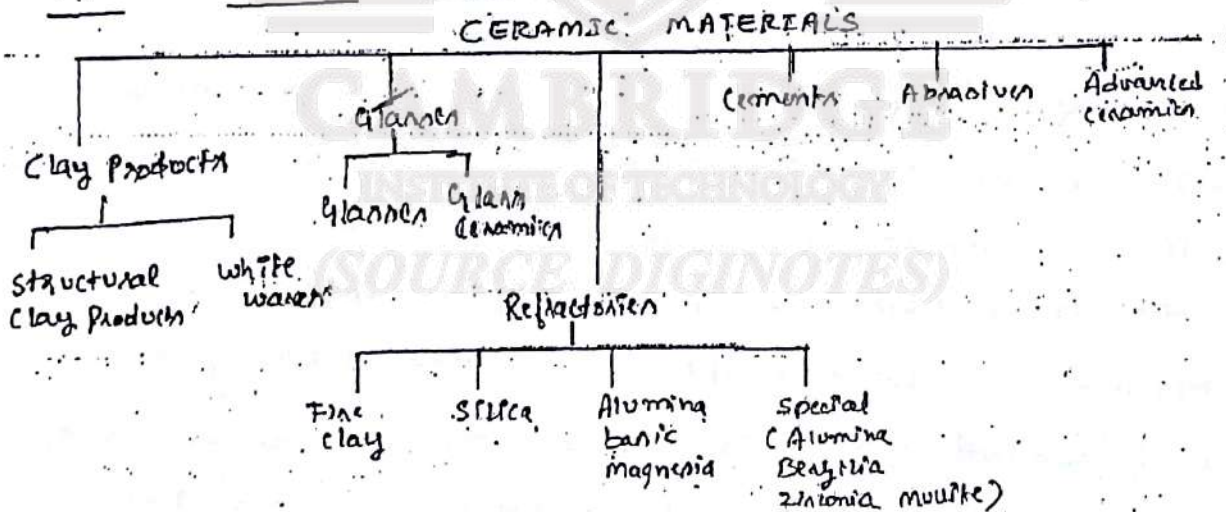
\* Zinc blende structure ( $ZnS$ )



Zinc blende structure [Both Dominated by covalent bond]

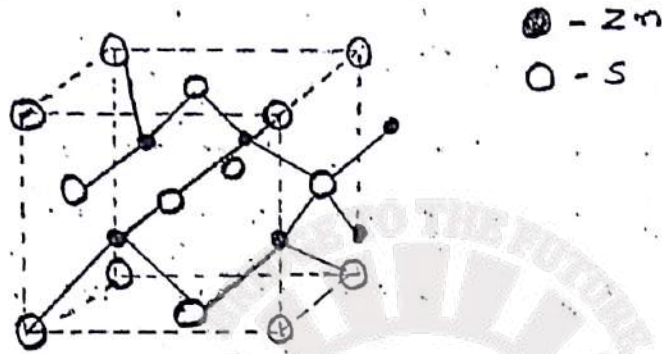
The zinc blende structure has the chemical formula  $ZnS$  and the unit cell is as shown in the fig. above. The unit cell has four zinc and four sulphur atoms. Each Zn or S atom has a co-ordination number of 4 and is tetrahedrally covalently bonded to other atoms.

Types, Properties and application of ceramics :-



1. Clay Products:- Clay is one of the most widely ceramic raw material, which can be used as mined without any upgrading of quality.

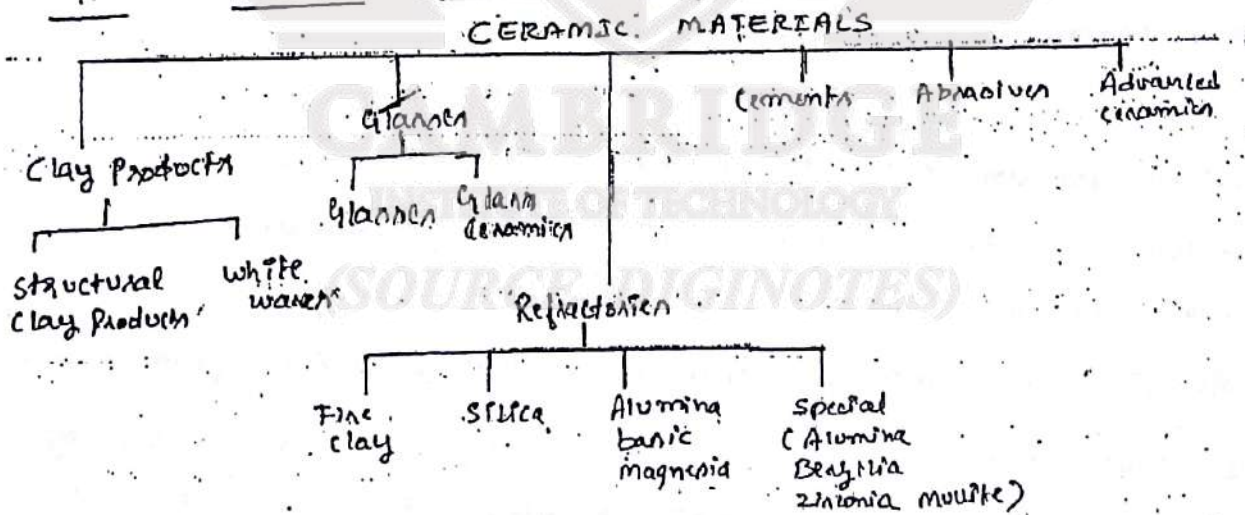
Zinc blende structure (ZnS)



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Types, Properties and application of ceramics



1. Clay Products:- Clay is one of the most widely ceramic raw material, which can be used as mined without any upgrading of quality.

Clay based products are categorized as

(i) white wares - The white ware ceramics becomes white after high temperature firing.

Applications:- porcelain, pottery, tableware, china & plumbing fixtures.

(ii). Sand clay products:- These products are made from common clay by using soft-mud process, salt glazing.

Applications:- Building bricks, tiles, sewage pipes & floor pots.

2. Glasses:- Glass is an amorphous, hard, brittle & transparent material which is obtained by fusing a mixture of a number of metallic silicates, commonly sodium, potassium, calcium boron etc.;

#### Types of Glasses

1.a - Toughened glass

2.a. Glass ceramics

1.b - Laminated glass

1.c - Foams or cellular glass.

1.a - Toughened glass:- It is made by dipping steel hot articles in an oil bath so that the outer layers of the article to shrink and acquire state of compression while inner layers are in state of tension.

Applications:- window screens in moving vehicles, funnels etc.;

1.b - Laminated glass:- It is made by pressing or bonding together two or more sheets of glass. They are shatter proof, shock proof & can withstand changes in temperature.

Applications:- Bullet proof glass, safety glass in aircrafts, helicopters, submarines etc.;

1.6.1. Foam glass:- It is made by heating a mixture of pulverized glass and a foaming agent.

Applications:- used as insulating materials.

2.6.1. Glass (ceramic):- These are the most sophisticated ceramic materials. They combine the nature of crystalline ceramics with glass. They possess good mechanical & thermal shock resistance, low coefficient of thermal expansion, high thermal conductivity.

Applications:- kitchen ware, table ware, heat exchangers & regenerators.

3. REFRACTORIES:- Refractory are ceramic material that can withstand high temperature without suffering a deformation. on the basis of composition of refractory ceramic, they are classified as lime clay, silica, basic and special refractories.

\* Fine clay refractories:- Fine clay bricks are made from high purity fine clays, silica & Alumina mixtures [55%  $\text{SiO}_2$  & 35%  $\text{Al}_2\text{O}_3$  to 55%  $\text{Al}_2\text{O}_3$  & 40%  $\text{SiO}_2$ ].

Applications:- Furnace lining.

\* Silica refractories:- Silica is the major ingredient in the silica refractories. They can withstand high temperature as high as  $1600^\circ\text{C}$ .

Applications:- Roof of steel & glass making furnaces, lining of acid converters & containment vessels etc.



\* **Basic Refractories:** These refractories are rich in Magnesia. They also contain calcium, chromium & iron compounds. They possess good crushing strength, resistance to attack by slag.

**Applications:** Lining of basic converters, reverberatory furnaces for smelting lead, copper, antimony ores etc.

\* **Special Refractories:** Special refractories are ceramic materials made from beryllia, zirconia, carbide compounds in addition to carbon & graphite.

**Applications:** Beryllia refractories are used as moderator in nuclear reactors, zirconia refractories are used in high frequency electric furnaces. Carbon & graphite refractories are used as material for construction of electrodes, linings of atomic reactors, chemically resistant furnaces.

4. **CEMENTS:** The characteristic feature of the cement is that when mixed with water, they form a paste that subsequently sets & hardens. The cement forms a bonding phase that chemically binds particulate aggregate into a single cohesive structure. Cement is produced by a process called calcination.

**Applications:** Largely used in civil engg construction.

5. **ABRASIVES:** Abrasive ceramics are used to grind, cut or wear away other materials which are necessarily softer. Abrasive ceramic material includes expensive material like natural & synthetic diamonds & other materials like silicon carbide, tungsten carbide, aluminium oxide & silica.

### \* Electrical behaviour of ceramics

Ceramics are probably the best known electrical insulators. They are also known as piezoelectrics that can generate an electrical response to the applied mechanical force or vice versa. Ceramic materials because of their dielectric properties find applications in personal computers, electronic devices etc., they are widely used in capacitors.

### PROCESSING OF CERAMICS

Processing of ceramics cannot be formed by Rolling, extrusion or drawing because of their inherent brittleness. Their high melting temperature also adds restrictions on the use of casting techniques. Processing of ceramics can take place through Powder Metallurgy (P.M.) techniques.

The basic steps for the processing of ceramics by agglomeration of particles are

- \* Material preparation
  - \* Forming or casting
  - \* Thermal treatments by drying and firing.
- \* Material preparation: Most ceramic products are made by the agglomeration of particles. The raw materials for these products vary depending on the required properties of the finished product. The particles & other ingredients such as binders & lubricants may be blended wet or dry. Sometimes wet & dry

**Applications:-** Abrasive powders are coated on some type of paper or cloth, loose abrasive grains are used for grinding, lapping & polishing wheels.

6. **ADVANCED CERAMICS:-** Advanced ceramics are just beginning to be used in applications ranging from automobile I.C. engines to gas turbine engines. Advanced ceramic material includes Silicon Carbide, Silicon nitride, Zirconia, Alumina, Sapphire, Tungsten Carbide etc.:

## MECHANICAL & ELECTRICAL BEHAVIOUR OF CERAMICS:-

1. **MECHANICAL BEHAVIOUR:-** Mechanical behaviour of ceramic materials explains how a material responds to mechanical forces. As a class of <sup>ceramic</sup> materials, ceramics are relatively brittle. The tensile strength of ceramic materials vary from very low values of less than 0.69 MPa to about  $7 \times 10^3$  MPa. They also have a large difference b/w their tensile & compressive strength, with compressive strength usually being about 5 to 10 times higher than tensile strength.

Many ceramic materials are hard & have low impact resistance due to their ionic-covalent bonding. However, there are many exceptions to these generalizations. For example plasticized clay is a ceramic material that is soft & easily deformable due to weak secondary bonding forces b/w layers of strongly ionic-covalently bonded atoms.

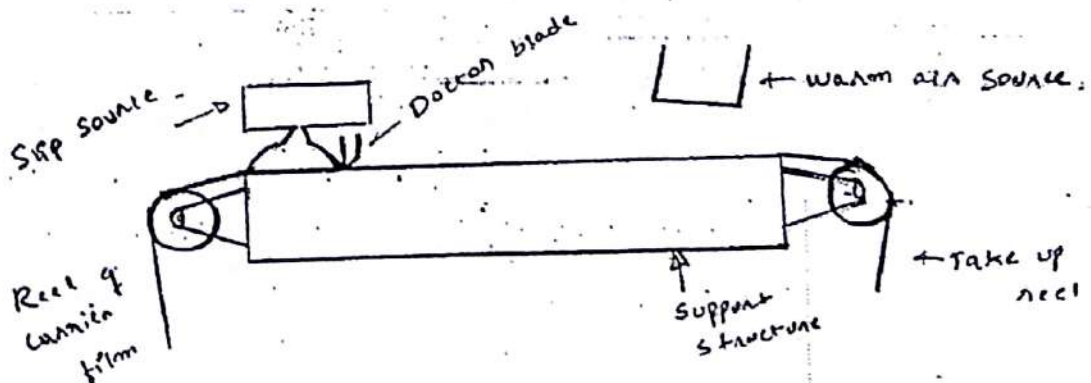
Processing are combined.

\* **Forming**:- Ceramic products made by the agglomeration of particles may be formed by variety of methods in dry, plastic or liquid conditions. Pressing, slip casting, tape casting and extrusion are commonly used ceramic forming methods.

(a) **Pressing**:- Ceramic particulate raw materials can be pressed in the dry, plastic or wet condition into a die to form shaped products.

(b) **Slip casting**:- In this process, aqueous slurry of ceramic powder is poured into planks of porous mold. As water begins to move out due to capillary action, thick meniscus builds along mold wall. It is possible to form solid piece by pouring more slurry.

(c) **Tape casting**:- Tape casting is also known as doctor blade process used for making thin ceramic tapes. In this, slurry of ceramic powder + binder + plasticizer is spread over plastic substrate. Tape is then dried using hot air. Later tape is subjected to binder burnout & sintering.



(A) Extrusion/ Viscous mixture of ceramic particles, binders & other additives is fed through an extruder where continuous shape of green ceramic is produced. Then the product is dried & sintered.

(B) Thermal treatments:-

(a) Drying & binder removal:- The purpose of drying ceramic is to remove water from the plastic ceramic body before it is fired at higher temperatures. Then the bulk of organic binders can be removed from ceramic parts by heating in the range of 200 to 300°C.

(b) Sintering:- The process by which small particles of a material are bonded together by solid-state diffusion is called sintering. Sintering results in the transformation of porous compact into a dense, coherent product. In the sintering process, particles are coalesced by solid-state diffusion at very high temperature but below the melting point of the compound being sintered.

## PLASTICS

The word plastic comes from Greek word *plastikos*, meaning "able to be shaped and molded". Plastics can be broadly classified into two major groups on the basis of their chemical structure, i.e., thermoplastics and thermosetting plastics.

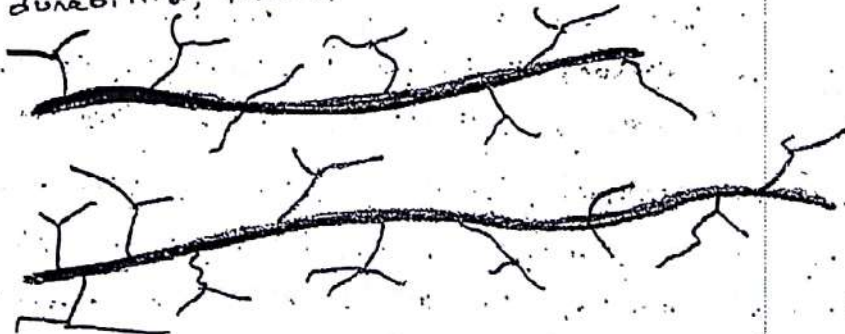
### Types of Plastics:-

(1) Thermoplastics

(2) Thermosetting plastics.

(1) **Thermoplastics**: The material that softens when heated above the melting temperature and becomes hard after cooling is called thermoplastic. Thermoplastics can be reversibly heated, melted by heating & solidified by cooling in limited no. of cycles without affecting the mechanical properties. In the molten state, they are liquids and for the solid state they are glassy or partially crystalline. The molecules are joined end to end into a series of long chains, each chain being independent of the other. Above the melting point, all crystalline structures disappear & the long chain becomes randomly scattered.

The important properties of thermoplastics are high strength, toughness, better hardness, chemical resistance, durability, transparency & water proofing.

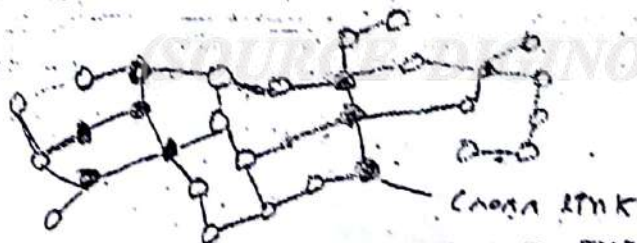


MOLECULAR STRUCTURE OF THERMOPLASTICS

Types of thermoplastics: Acrylonitrile Butadiene Styrene (ABS), Acetate, Acrylic, Cellulose, polystyrene, polyacrylonitrile, Polyethylene (PE) etc.,

Applications:- Dashboards, car mirrors, toys, phones, handles, electrical products, bearings, gears, rope, hinges, glass frames etc.,

(2) THERMOSETS:- The property of material becoming permanently hard and rigid after swelling when heated above the melting temperature is called thermosetting. The solidification process of plastics is known as curing. The transformation from the liquid state to the solid state is an irreversible process. The thermosets can't be recycled. During curing, the small molecules are chemically linked together to form a complex inter-connected network structure as shown in the fig. below. This cross-linkage prevents the slipping of individual chains. Therefore, the mechanical properties are not temperature dependent as compared to thermoplastics. Hence, thermosets are generally stronger than thermoplastics.



MOLECULAR STRUCTURE OF THERMOSETS

Different types:- Alkyds, Allylics, Amides, Bakelite, epoxy, phenolic polyester, silicone, polyurethane (PUR), Vinyls etc.,

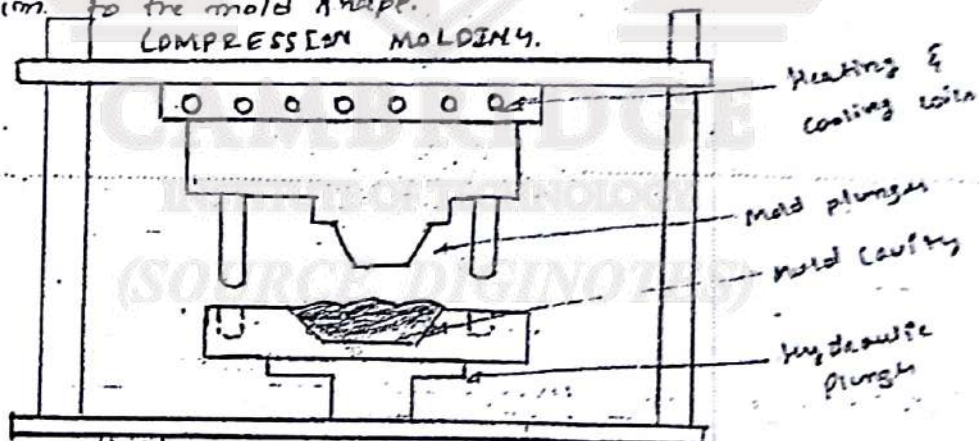
Applications:- High temperature applications like electrical equipments, motor brush holders, printed circuit boards, kitchen utensils, Spectacle lenses, encapsulation etc.,

**PROCESSING OF PLASTICS!** - There are different <sup>13</sup> molding techniques available for producing plastic components. The selection of a particular technique depends upon the following factors. (1) Type of material (thermoplastic or thermosetting)

- (2) If thermoplastic, the temperature at which it becomes soft and deformable
- (3) Size and geometry of the finished product.
- (4) Stability of the material being formed at atmospheric conditions.

Some of the common molding techniques used include compression molding, transfer molding, injection molding and extrusion molding.

- (a) **Compression molding:** In compression molding, pre-determined quantity of plastic ingredients in proper proportions are placed in the lower female cavity. Both the mold pieces are heated. The mold is closed, heat & pressure are applied which causes the plastic to become viscous and conform to the mold shape.

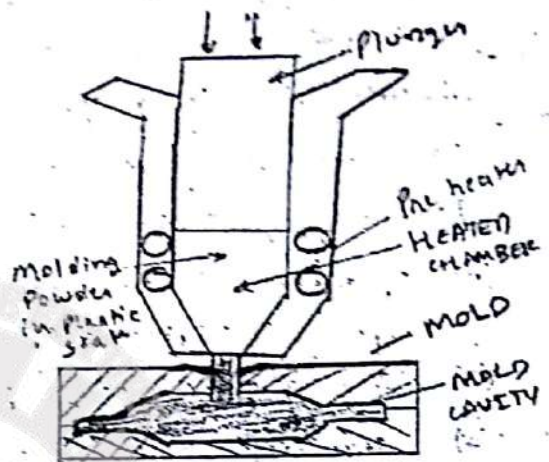


(b) **Transfer molding!**

- (1) In this method pelletized plastic is placed inside heated chamber maintained at the minimum temperature at which molding powder just begins to become plastic. This plastic material is then injected through an orifice into the mold by a plunger working at higher pressure. Due to very high friction developed at the



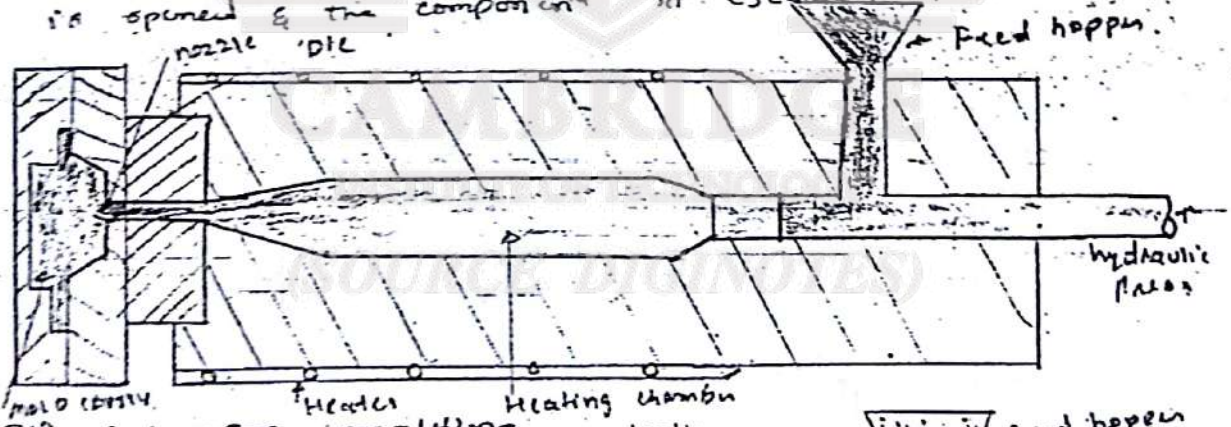
orifice, the temperature rises to such an extent that molding powder becomes viscous liquid & consequently flows into the mold & cools at that temperature. The molded component is then ejected mechanically.



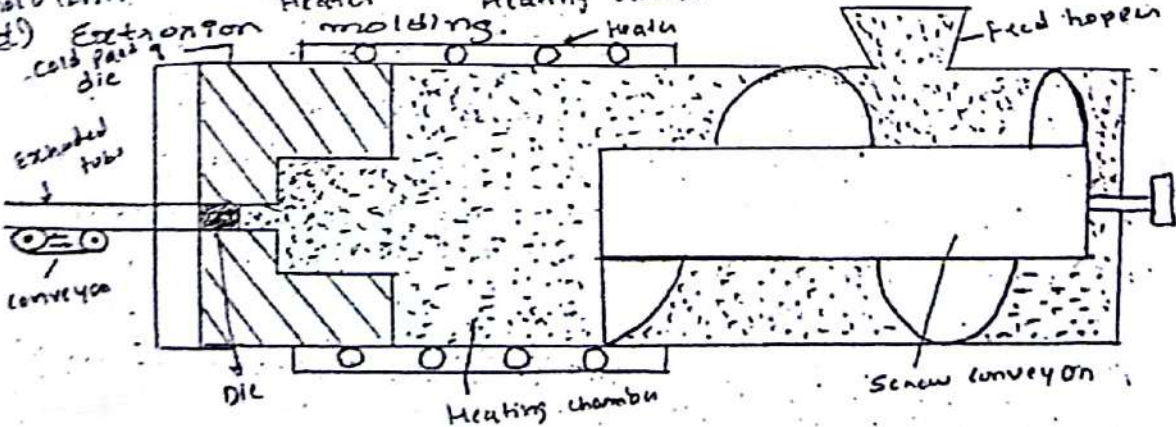
TRANSFER MOLDING

(C) Injection molding:

It is the most widely used technique for molding thermoplastics. The measured amount of pelletized material is fed from a hopper into the heating chamber, where it is melted to form a viscous liquid. The molten plastic is then injected into the mold cavity through nozzle by means of plunger. The pressure is maintained until the plastic is completely solidified. Finally the mold is opened & the component is ejected.



(D) Extrusion molding:



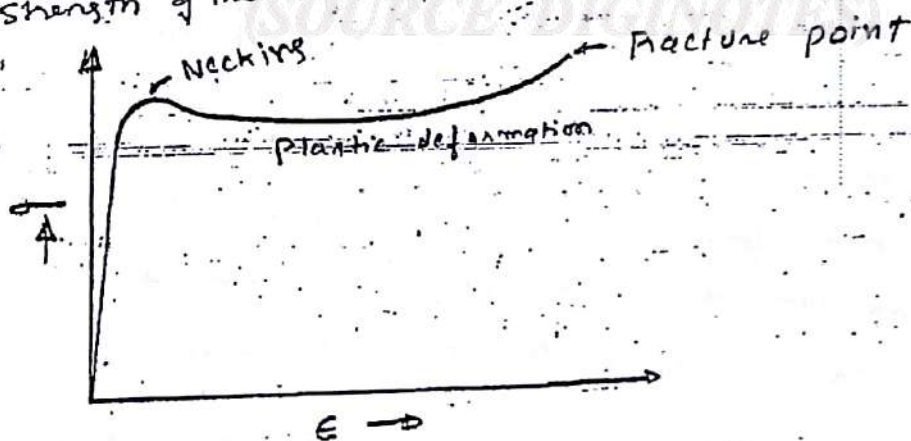
Here in Extrusion moulding, the granules or pelletized plastic material is fed from a hopper into a chamber through which it is forced by a mechanical screw into a heated die. Extrusion takes place as this molten plastic is forced through a die orifice. Extruded length is solidified by water spray or by using blower.

## MECHANICAL BEHAVIOUR OF PLASTICS

Mechanical behaviour of plastic explains how a plastic response to mechanical force or load & what are its mechanical properties.

- ① **Hardness**:- Plastics are not very hard. The hardness of commonly used plastics is in the range of 5-50 BHN. Generally thermosets are harder than thermoplastics.
- ② **Stress-strain behaviour**:- When the plastic is subjected to uni-axial load, it deforms permanently & ultimately fails as shown in the fig below. Tensile strength of plastics may be in the range of 10 to 100 MPa, whereas Young's modulus ranges from 10 MPa to 400 MPa. Tensile

strength of the material decreases with increasing temperature.



Stress-strain behaviour of plastic.

① Fatigue behaviour:- Fatigue failure of thermoplastics is brittle in nature, but in case of thermoplastic failure occurs due to initiation of crack propagation. The flexural fatigue strength of plastics may be in the range of  $10^5 - 10^7$  no. of cycles to failure at room temperature ( $20^\circ\text{C}$ ).

FAILURE OF PLASTICS:- Failure of plastic materials can be viewed in 3 different ways i.e., mechanical, thermal and Environmental. Mechanical failure occurs when a product is exposed to external forces that are greater than the product is designed to handle. Thermal failure occurs when a product fails due to exposure to extreme temperatures. Environmental failure occurs when a product is failed to perform desired function when it is subjected to undesirable Environmental conditions.

i.e., Exposure to UV rays, extreme weather, pollution etc. 2 factors to be considered for the failure of plastic material.

→ Material Selection:- It is essential to choose a proper material for a particular application.

→ Design:- A sound design must be done by keeping in mind the working conditions of material. Poor design leads to failure of product.

→ Manufacturing Process:- It is essential to choose a proper manufacturing process depending upon the particular application of product.

## SMART MATERIALS

17

Smart materials are designed materials that have one or more properties that can be significantly changed in a controlled fashion by external stimuli, such as stress, temperature, moisture, pH, electric or magnetic fields.

The present section deals with some of those smart materials like optical materials, optical fibres, shape memory alloys, piezoelectrics.

\* OPTICAL MATERIALS :- Optical materials are substances that are used to manipulate the flow of light. This can include reflecting, absorbing, focusing or splitting of an optical beam. Let us now discuss the properties of few optical materials.

(a) BK7 :- BK7 is the most common borosilicate crown glass used for visible and near infrared optics.

Its high homogeneity, low bubble and inclusion content &

straightforward manufacturability makes it a good choice

for transmissive optics. The transmission range for

BK7 is 380 - 2100 nm. It is not recommended for

temperature sensitive applications, such as precision

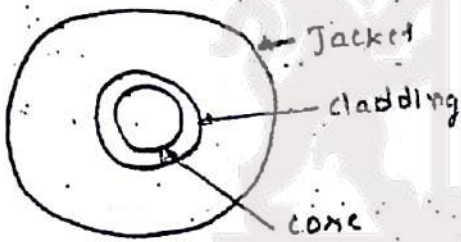
mirrors. BK7 is relatively hard and possesses good

scratch resistant properties.

Fibre optic communication is based on the principle that light in a glass medium can carry more information over longer distances than electrical signals can carry in a copper or coaxial medium or radio frequencies through a wireless medium.

Basically fibre optics is a applied science & engineering concerned with design and application of optical fibres.

Optical fibres:- An optical fibre is a very thin and flexible medium of cylindrical shape. The three principal sections of fibres are (a) core (b) cladding and (c) the jacket.

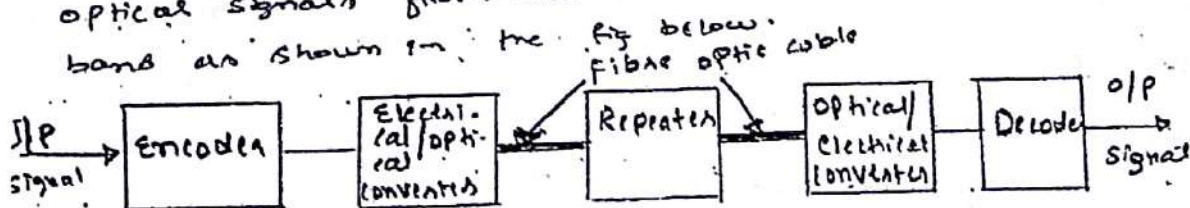


The innermost section, core is made up of glass or plastic. The cladding which surrounds the core is also made up of glass or plastic. The jacket is made up of plastic or polymer and other

materials which protect the structure from moisture, abrasion, mechanical shocks & other environmental hazards. The optical properties of cladding are different from that of jacket.

The actual working structure of the optical fibre is the core. The light entering the core at an suitable angle propagates through it, suffering a number of total internal reflections at the core-cladding interface.

Optical fibres serve as cables for communications to carry optical signals from one end to the other over a wide band as shown in the fig below.



THE COMPONENTS OF OPTICAL FIBRE COMMUNICATION S/M.

Generally high purity silica glass is used as fibre material. Fibre diameters normally range b/w 5 to 100  $\mu\text{m}$ . Fluoroaluminate and chalcogenide glasses and sapphire are the materials which can be used as fibre optic material.

Advantages :-

- \* They can carry more data

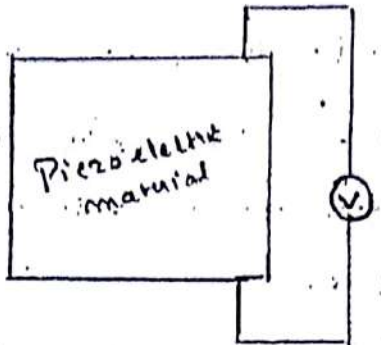
- \* They are less susceptible than metal cables to interference
- \* They are much thinner & lighter
- \* Data can be transmitted digitally rather than analogically.

Applications :- Fibre optics is used in myriad applications. Due to its low weight, high bandwidth, capacity & immunity to electromagnetic and RF interference, fibre optics is used extensively in avionics on both military & commercial aircraft systems. Applications include radar links, video links, sensor networks, & in-flight entertainment links.

## PIEZOELECTRIC MATERIALS

The piezoelectric effect was discovered in 1880 by the Jacques and Pierre Curie brothers. They found out that when a mechanical stress was applied on crystals such as tourmaline, tourmaline topaz, Quartz, Rochelle salt and cane sugar, an electrical charge appeared, and this voltage was proportional to the applied stress. So piezoelectric materials are those which produce an electric field when subjected to mechanical force (vice-versa).

Piezoelectric effect :-



Let us consider a sample of piezoelectric material, when this material is subjected to mechanical force like tension or compression, depending upon the applied load, the charge density at the ends of the sample changes, which further changes voltage difference b/w the ends of the sample.

Piezoelectric materials :-  $\text{BaTiO}_3$  (Barium Titanate) is commonly used piezoelectric material. Quartz is also a well known piezoelectric material. Few other piezoelectric material includes lead zirconate ( $\text{PbZrO}_3$ ), lead titanate ( $\text{PbTiO}_3$ ).

Applications :- Medical, Aerospace, nuclear instrumentation, fields etc. SONAR, Scanning probe microscope, ultrasonic transducers, quartz clocks etc.,

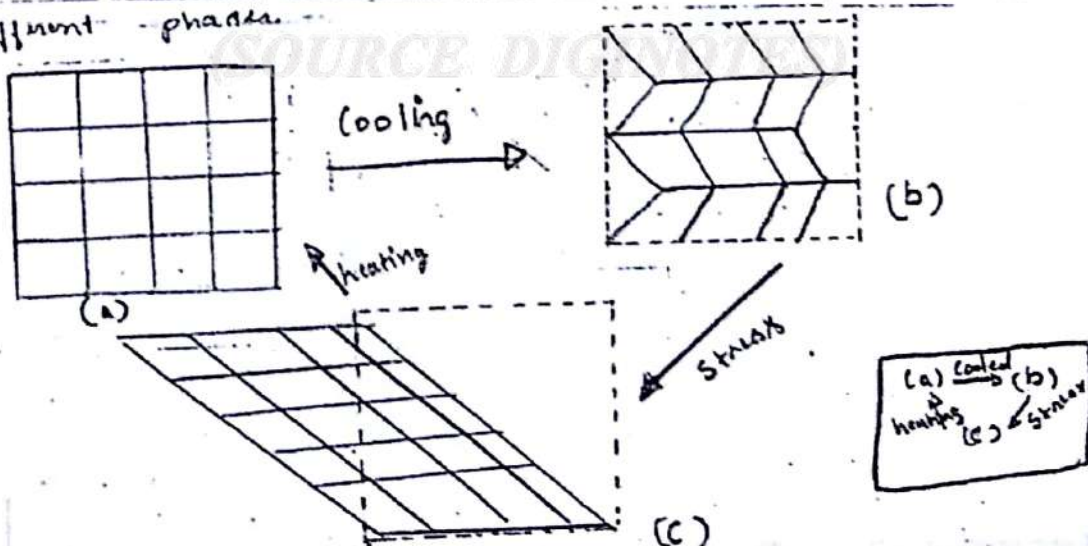
CAMBRIDGE

(SOURCE DIGINOTES)

## SHAPE MEMORY ALLOYS (SMA's)

A Swedish physicist Åke Brander discovered the "Shape Memory Effect" (SME) in gold-cadmium alloy in 1932. The alloy was deformed when cooled & then heated to return to original remembered shape. This effect is called SME, the alloy which shows this effect are called SMA's. So basically "SMA is an alloy that remembers its original shape and this alloy when deformed, can remember & return to its original shape when it is heated."

PRINCIPLE OF OPERATION :- The SME occurs due to a temperature & stress dependent shift in the material's crystalline structure b/w two different phases, Martensite (low temp phase) & Austenite (high temp phase). The temperature where the phase transformation occurs is called transformation temperature. Fig below shows a simplified representation of material's crystalline arrangement during different phases.



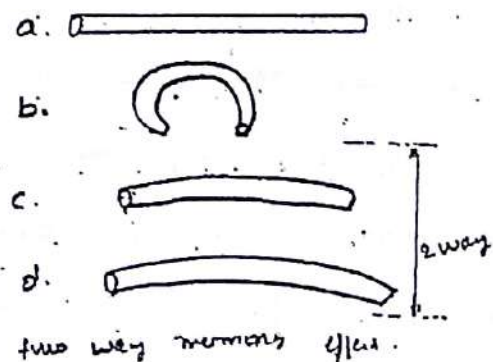
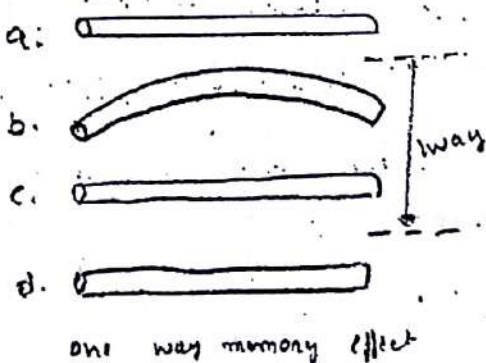


Here when SMA's, in its austenite phase, the structure of the material is symmetrical i.e., each grain of the material is cubic with right angles as shown in the fig (a). When this alloy cools, it forms a martensite phase & collapses to a structure with different shape as shown in fig (b). Now if any external stress is applied, the alloy will yield and deform to an alternate state as shown in the fig (c). If this alloy is now heated again above the transformation temperature, the austenite phase will be formed & the structure of the material returns to the original cube form (a).

### One way and two way memory effect

One way memory effect:- If the shape memory alloy (SMA) recovers a specific shape upon heating and retains the same shape even when it is cooled. The effect is known as one way memory effect.

Two way memory effect:- The SMA recovers a specific shape upon heating and then returns to an alternate shape when cooled (below transition temperature). The effect is known as two way memory effect.



NITNOL: Researchers of U.S. Naval Ordnance Laboratory found SME in nickel-titanium alloy (NiTi) in 1961 by accident, while studying the heat & corrosion resistance of NiTi alloy. Today NiTi alloys are commonly referred as "Nitinol" for NiTi Naval Ordnance Laboratory.

The shape memory effect must be programmed into the SMA with an appropriate thermal procedure. The alloy is formed into desired austenite form and heated into a specific temperature. The temperature & the duration of the heating depends on the alloy & required properties. For NiTi alloy, generally 500°C and over 5 minutes are used.

SUPERELASTICITY: In the SMA's instead of the phase transformation due to temperature, this transformation of phase occurs due to mechanical stress. When SMA's are loaded in the austenite phase, the material will transform to the martensite phase above a critical stress, proportional to the transformation temperature. Upon continued loading, the twinned martensite will begin to deform, allowing the material to undergo large deformations. Once the stress is released, the martensite transforms back to austenite & the material recovers its original shape.

Some SMA's :- Ag-Cd, Au-Cd, Cu-Al-Ni, Cu-Sn, Cu-Zn, In-Ti, Ni-Al, Ni-Ti, Fe-Pt, Mn-Cu & Fe-Mn-Si. 25

Applications, Bioengineering, especially for broken bones, orthopaedic implants, cardiovascular devices. Fire & Security: slim lines, eye glasses, helicopter blades.

### SMART MATERIALS - BIOMEDICAL APPLICATIONS

(Implants in human body)

- The bio compatibility of the SMA's is one of the important points which makes them suitable for biomedical applications, as orthodontic devices, orthopaedic implants, cardiovascular devices, surgical instruments & endodontic files.

- Broken bones can be mended with SMA's.

- Memory metals can also apply to hip replacements.

- For clogged blood vessels, an alloy tube is crumpled & inserted into the clogged veins. Since the memory metal has a memory transfer temperature close to body heat, the memory metal expands to open the clogged arteries.

SMA's find applications in Dental braces & dental arch wires.

## Residual life assessment of materials (RLA)

Residual life of an engineering material is the time period during which it shall retain the fitness for service characteristics. Traditionally, "visual inspection" has been the method for carrying out RLA studies, but soon it was realized that a scientific method or approach was required for assessing the residual life of extremely costly equipments. With respect to this, Non-destructive testing are considered, besides other techniques.

Conducting RLA is an important process to maintain the efficient operation of a power plant unit & to avoid the failure of critical equipments, which lead to costly downtime problem. RLA studies are done on power plant components, aircraft components & other machines which are subjected to fatigue / creep loading conditions.

RLA makes use of NDT test results with the operational parameters to estimate the residual life of any equipment.

## NON - DESTRUCTIVE TESTING (NDT) <sup>Def</sup>

As the name suggests, Non destructive testing (NDT) techniques includes all types of testing techniques in which, the material / product under test is not destroyed and may be reused.

Sometimes abbreviation NDE (NON DESTRUCTIVE EVALUATION) is used to describe NDT techniques. However it would be more appropriate to call those techniques as NDE, which are meant for evaluation of material properties such as fiber volume fraction, composition of alloys, grain size, fatigue behaviour etc. Other techniques that are used for inspection of incoming materials, inspection of voids, porosity etc., should be called as NDT Techniques.

We know that no material can be categorized as absolutely perfect, i.e., having zero defect. So one should be able to locate and assess the severity of the defect present in any material or component without impairing their future usefulness. To meet this various NDT techniques are used. They are:

- (1) Radiography
- (2) Ultrasonic Testing
- (3) Acoustic Emission Testing
- (4) Eddy-current Testing
- (5) Magnetic Method
- (6) Liquid Penetrant Inspection. etc.

## Module-5

# Composite Materials

### Objectives:

To learn about composites such as

- Classification of Composites
- Types of matrix materials & reinforcements,
- Production of FRP's and MMC's
- Advantages and application of composites.

### Outcomes:

1. Today's composite materials often outshine traditional materials; they are lightweight, corrosion-resistant, and strong. Used in everything from aircraft structures to golf clubs, and serving industries from medicine to space exploration, composites are an exciting field of study for students, engineers, and researchers around the world. New applications of these versatile materials are being found daily.

## INTRODUCTION TO COMPOSITE MATERIALS

**Composite materials** (or **composites** for short) are engineered materials made from two or more constituent materials with significantly different physical or chemical properties and which remain separate and distinct on a macroscopic level and are not soluble to each other. one constituent is called the MATRIX and the other is called the REINFORCING phase. examples; concrete, fibre glass, wood

**Composite material** is a material composed of two or more distinct phases (matrix phase and dispersed phase) and having bulk properties significantly different from those of any of the constituents

The idea is that by combining two or more distinct materials one can engineer a new material with the desired combination of properties (e.g., light, strong, corrosion resistant). The idea that a better combination of properties can be achieved is called the principle of combined action. New - High-tech materials, engineered to specific applications

**Properties that can be improved by forming a composite material are (Advantages of composites**

Strength Stiffness Corrosion Resistance Wear Resistance Attractiveness lessWeight  
Fatigue life Fatigue life Temperature dependent behavior Thermal insulation Thermal  
conductivity, Acoustical Insulation

### Limitations

High cost of production, Anisotropy, Mechanical characterization  
difficult Debonding, Delamination, Fiber pullout

Repair of flaws- difficult in  
metals Recycling-PMC

### Historical Background

addition of straw to clay in making of mud huts -4000bc

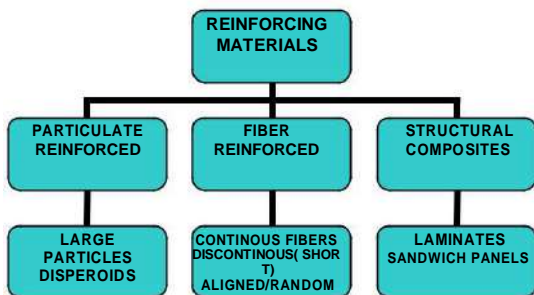
glue laminated wood 500 bc

medieval swords and armor made with layers different metals

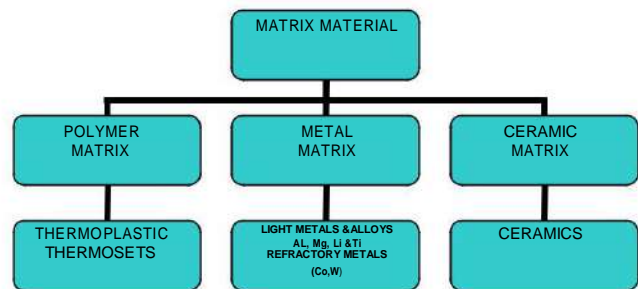
reinforced cement concrete-1800 ad

### Classification of composites

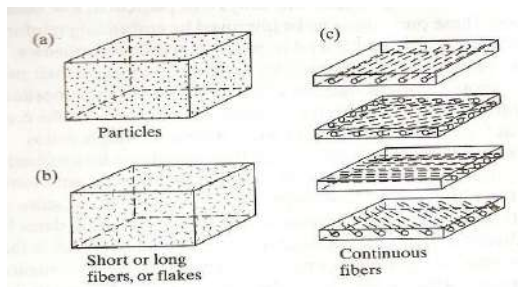
#### Based on reinforcing materials



#### Based on matrix material



**Matrix phase** The primary phase, having a continuous character, is called matrix. Matrix is usually more ductile and less hard phase. It holds the dispersed phase and shares a load with it



:  
Reinforcement Phase Discontinuous phase,

### Particle Reinforced composites Fiber reinforced composites

Particulate reinforced composites consist of particles of one or more materials suspended in a matrix of another material. The particles can be either metallic or non metallic as can the matrix.

The four different combinations are

#### Nonmetallic particles in Nonmetallic Matrix

Concrete- a mixture of sand, gravel, cement & water

Glass flakes in plastic resins

**Metallic particles in Non metallic matrix**

Copper in Epoxy resin increases the conductivity Aluminum paint – Suspension of aluminum flakes in Paint

Metallic additives to plastics improves the thermal conductivity, lowers the coefficient of thermal expansion and reduces the wear

**Metallic particles in Metallic Matrix**

Lead alloys in copper alloys to improve machinability, where lead is a natural Lubricant Tungsten, Chromium (hard materials) suspended in ductile materials

**Non metallic particles in Metallic Matrix**

Chromium carbide in a Cobalt matrix has high corrosion and abrasion resistance Uranium oxide in stain less steel as a control rod in nuclear reactors Ceramics suspended in metal matrix called as cermets.

**Fiber reinforced composites:**

Fibers are one of the oldest engineering materials in use. Jute, flax, hemp have been used for such products as rope, nets, water hose, and containers since antiquity. Plant fibers and animal fibers are used for papers, brush, or heavy structural cloth. Many synthetic fibers have been developed to replace natural fibers, because synthesis has more predictability and uniform in size. For engineering purposes glass, metallic, and organically derived synthetic fibers are most significant. Nylon is used for belting, nets, hose, rope, parachute, ballistic cloths and reinforcement in tyres.

**FIBERS**

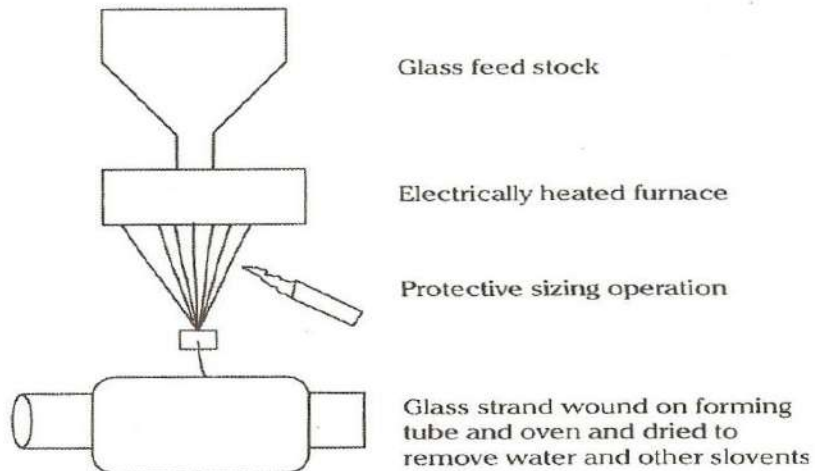
Glass-high strength low stiffness, high density lowest cost  
Graphite-high strength low cost less dense than glass Boron-high strength & stiffness high density, highest density Aramids-highest strength to weight ratio of all fibers, high cost

Other fibers nylon silicon carbide silicon nitride aluminum oxide boron carbide boron nitride tantalum carbide aramids/ Kevlar

**Chemical composition of different glass fibers**

Constituents	E-glass	S-glass	C-glass
SiO <sub>2</sub>	54	64	65
Al <sub>2</sub> O <sub>3</sub>	15	25	4
CaO	17	<1	14
MgO	4.5	10	3
B <sub>2</sub> O <sub>3</sub>	8	-	5
Others	1.5	0.8	8





*Wet Spinning Technique*

### Factors for Glass fiber selection

- Thermal properties
- Fiber cost
- Type of manufacturing process
- Forms of reinforcement

### Thermal properties of Glass fibers

- Glass fibers lose tensile strength as temp increases.
- At high temp performance of C glass is inferior to E glass & S glass.
- Fibers with high CTE expand more as temp increases.
- S-glass has much lower CTE than E glass & C glass

### Glass Fiber Manufacturing

Sand, Limestone &  $Al_2O_3$  is fed to Feed stock & heated to  $14000C$ . The melt is stirred at a constant temperature. The melt passes through the platinum nozzles containing around 934 nozzles of  $10\mu m$  dia. The yarn coming out is wrapped up in the forming tube at a speed of  $25m/s$ . Before the yarn is drawn, sizing is done

Sizing solution consists of

1. organic binders- to allow packing of strands
2. Lubricants- to prevent abrasion of filaments
3. Coupling agents-for better bonding with polymers.

Fibers are drawn in to strands; each strand consists of more than 204 filaments. The wound array of strands are dried in an oven to remove water & other solvents

### Forms of Glass fibers

Continuous strands (group of 204 fibers)

Rovings (group of parallel strands)

Chopped strands (5 to 50mm length)

Chopped rovings (5 to 50mm length)

**Tow** (group of over 10000 fibers). **A strand** is a collection of continuous filaments

**A roving** is a collection of untwisted strands. **Yarns** are collection of filaments or strands twisted together.

**Reinforcing fibers** for PMC's are generally Glass, graphite, aramids, boron, and other fibers.

---

**Graphite;** graphite fibers are more expensive than glass fibers. They have a combination of low density, high strength and high stiffness

All graphite fibers are made by pyrolysis of organic precursors commonly polyacrylonitrile (PAN) because of its low cost. Rayon and pitch (the residue from catalytic crackers in petroleum refining) can also be used as precursors.

**Pyrolysis** is a process of inducing chemical changes by heat-by burning a length of yarn and causing the material to carbonize and become black in color. The temperatures for carbonizing range up to about 1500 deg C: for graphitizing, to 3000 deg C.

The difference between graphite and carbon fibers depends on the temperature of pyrolysis and purity of material. Carbon fibers are usually 80-95%, graphite fibers are 99% carbon.

**Conductive Graphite fibers:** are used to increase the thermal and electrical conductivities of the reinforced plastic components. The fibers are coated with metals, usually nickel, by continuous electroplating process. The coating will be around 5 micron thick on a 7 micron graphite fiber core. Applications include electromagnetic and radio frequency shielding and lightening –strike protection.

**Aramids:** are produced from aromatic polyamide fibers. The trade name is **Kevlar** produced by DuPont. Kevlar fibers are compounds based on benzene rings. It is manufactured by a process called Dry jet wet spinning process.

**Boron:** boron fibers consist of boron deposited on tungsten fibers by chemical vapor deposition. These fibers have desirable properties like high strength and stiffness both in tension & compression & resistance to high temperature. Because of the high density of the tungsten they are heavy, expensive.

**Other fibers:** Nylon, silicon carbide, silicon nitride, aluminum oxide, sapphire, steel, tungsten, molybdenum, boron carbide, boron nitride, and tantalum carbide.

**Whiskers** are also used as reinforcing fibers. They are needlelike single crystals that grow to from 1 micron to 10 micron in diameter. They have aspect ratios ranging from 100-15000. (**Aspect ratio** is defined as the ratio of fiber length to fiber diameter.)

Because of their small size whiskers are free of defects. The elastic modulus ranges from 400 GPa -700 GPa and their tensile strength ranges from 15GPa to 20GPa.

**Mats** - is a non-woven fabric that provide equal strength in all directions Mats are of two types

- 1.Chopped strand-randomly distributed fibers cut in 1.5-2.5 inch, held with a chemical binder (styrene)-used in hand lay up, continuous laminating, closed molding application
2. Continuous strand-formed by swirling continuous strands of fiber onto a moving belt, finished with a binder are stronger than chopped strand.

These mats are used in compression molding, resin transfer molding, pultrusion

TABLE 9.2 Typical Properties of Reinforcing Fibers

Type	Tensile strength (MPa)	Elastic modulus (GPa)	Density (kg/m <sup>3</sup> )
Boron	3500	380	2600
Carbon			
High strength	3000	275	1900
High modulus	2000	415	1900
Glass			
E type	3500	73	2480
S type	4600	85	2540
Kevlar			
29	2800	62	1440
49	2800	117	1440

Note: These properties vary significantly depending on the material and method of preparation.

**Desirable characteristics of fiber reinforced composites.**

While designing a fiber reinforced composites, the following factors have to be considered. Length of the fibers

Diameter of the fibers

Orientation of the fibers

Amount or volume fraction of the fibers

Physical and Mechanical properties of Matrix

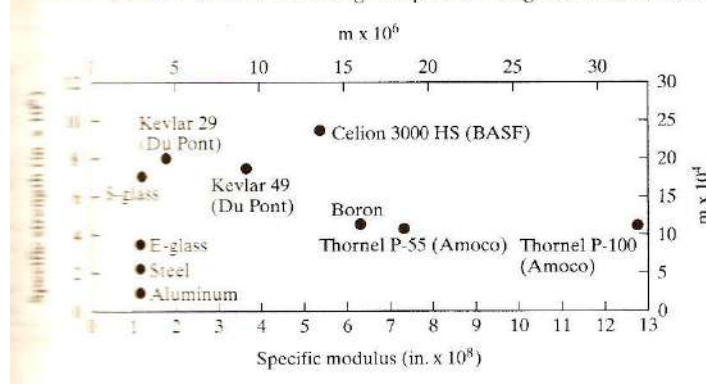
Bonding between matrix and fibers.

**Length of fibers:** Usually the ends of fibers have lower load carrying capability and hence more no of ends will lower the load carrying capacity of the composite. Longer the fiber, no of ends will be lower and hence the load carrying capacity will be higher. An important parameter characterizing the length of the fiber is the aspect ratio (l/d). if the aspect ratio is greater than 15, the fiber is termed as continuous, otherwise it is termed as discontinuous.

**Diameter of fibers:**

Reducing the diameter of fibers has the following advantages. The numbers of defects are reduced and the strength is increased

FIGURE 9.3 Specific tensile strength (tensile strength-to-density ratio) and specific tensile modulus (modulus of elasticity-to-density ratio) for various fibers used in reinforced plastics. Note the wide range of specific strengths and stiffnesses available.



## LAMINAR COMPOSITES

Of all the composites devised the laminar type is the oldest. It differs from the other types by the presence of layers. They are made up of films or sheets. Laminar composites consist of two or more different layers bonded together. The layers constituting a composite can differ in material, form and / or orientation. Laminar composites are anisotropic in nature.

In plywood, though the layers are often of the same material, the orientation differs. A reinforced plastic sheet may be clad with copper to make a printed circuit board

A **Lamina** is a single layer of uni-directional fibers or woven fibers arranged in a matrix.

The constituents of lamina ie fiber and matrix exhibit different types of stress strain behaviour. Fibers generally show linear elastic behaviour. The fibers or filaments, the main load carrying agent, are strong and stiff. The matrix may be plastic ceramic or metallic. Its function is to transfer the load , support and protect the fibers.

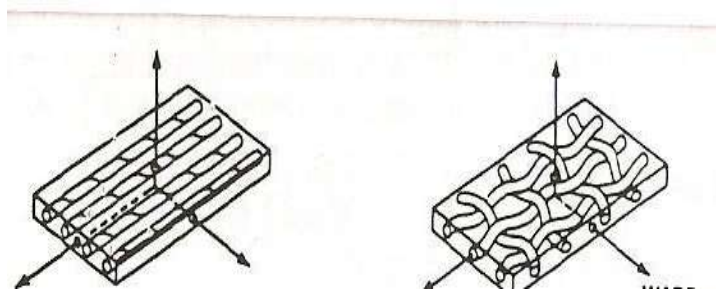


Fig 1 Lamina with unidirectional fibers.

Fig 2 Lamina with woven fibers

**Laminates** are defined as composite materials consisting of two or more superimposed layers bonded together. Laminate is a stack of plies of composites. Each layer can be laid at various orientations and can be different material systems. Laminate is a stack of laminae.

Generally laminates are designed to protect against corrosion, high temp oxidation, to cut costs, to improve appearance etc

Laminar composites can be divided in to laminates and sandwiches.

A major purpose of lamination is to tailor the directional dependence of strength and stiffness of a material to match the loading environment of the structural element.

**Sandwiches** a special case of laminates, consists of a thick low-density core (such as honey comb or foamed material) between thin faces of comparatively higher density. In sandwich composites the primary objective is to improve the structural performance.

**Matrix materials:**

## POLYMER MATRIX COMPOSITES

Polymers make ideal matrix material as they can be processed easily, possess light weight and have desirable mechanical properties. Polymers in general have poor strength and modulus. They get degraded on prolonged exposure to ultra-violet rays. They also cannot withstand high temperatures. They are poor conductors of electricity and have high coefficient of thermal expansion. Polymers do not have fixed melting point. The temp at which the crystallinity is destroyed is called glass transition temperature. There are two types of polymers a) Thermo plastics b) Thermosets

Matrix materials are usually thermosets. Commonly used are epoxies, polyester, phenolic, fluorocarbons, polyether sulphone or silicone. The most commonly used are epoxies and (80%)

and poly esters, which are less expensive than epoxies. Polyamides which resist exposure to temperature in excess of 300 deg C are being developed for use with graphite fibers. PEEK (polyetheretherketone) is also used as matrix material. They have higher toughness than thermosets, but their resistance to temperature is being limited to 100 deg-200deg C.

The matrix in reinforced plastics has three functions.

- a) To support the fibers in place and transfer the stresses to them, while they carry most of the load
- b) To protect the fibers against physical damage and the environment.
- c) To reduce the propagation of cracks in the composites, by virtue of the greater ductility and toughness of the plastic material.

**METAL MATRIX COMPOSITES:**

Metal matrix composites have a metal as a matrix usually a light metal such as Al, Mg, or Ti or a super alloy ( Ni based or Co based super alloy). The reinforcement materials include Boron, Silicon Carbide, carbon, Graphite, alumina, boron carbide, boron nitride. The form of reinforcement material can be either a fiber or whisker or particulate. Metals are reinforced to either to increase certain properties like elastic modulus and tensile strength or decrease certain properties like coefficient of thermal expansion and thermal conductivities.

**CERAMIC MATRIX COMPOSITES:**

They are hard and brittle, have low toughness, low thermal coefficient of expansion, very low mechanical shock resistance. Examples are

1. SiC particles in alumina matrix used as tool materials.
2. SiC particles in SiC matrix used as cutting tool inserts.
3. Glass fibers in alumina matrix used in aircraft engine parts.

**FIBER REINFORCED PLASTIC**

**PROCESSING:** Need for development of composite materials Advantages of composites:

1. High specific Strength and modulus – aerospace industries, automobiles.
2. Advantage of moulding in to desired shape and size using open or closed moulding process.

TABLE 9.3 Metal-Matrix Composite Materials and Applications

Fiber	Matrix	Applications
Graphite	Aluminum	Satellite, missile, and helicopter structures
	Magnesium	Space and satellite structures
	Lead	Storage-battery plates
	Copper	Electrical contacts and bearings
Boron	Aluminum	Compressor blades and structural supports
	Magnesium	Antenna structures
	Titanium	Jet-engine fan blades
Alumina	Aluminum	Superconductor restraints in fission power reactors
	Lead	Storage-battery plates
	Magnesium	Helicopter transmission structures
Silicon carbide	Aluminum, titanium	High-temperature structures
	Superalloy (cobalt-base)	High-temperature engine components
Molybdenum, tungsten	Superalloy	High-temperature engine components

**DEFINITIONS**

**Aspect ratio:** The ratio of length to diameter of the fiber.

**Coefficient of elasticity:** the reciprocal of Young’s modulus in a tension test.

**Coefficient of expansion:** The fractional change in dimension of a material for a unit change in temperature.

**Coefficient of friction:** A measure of the resistance to sliding of one surface in contact with another surface.

**Felt:** A fibrous material made from interlocked fibers by mechanical or chemical action, moisture, or heat, made from asbestos, cotton, and glass.

**Flexural modulus:** The ratio within the elastic limit, of the applied stress on a test specimen in flexure to the corresponding strain in the outer most fibers of the specimen.

**Flexural rigidity:** For fibers this is a measure of the rigidity of individual strands or fibers. The force couple required to bend a specimen to unit radius of curvature. For plates the measure of rigidity is  $D = EI$  where  $E$  is the modulus of elasticity and  $I$  is the moment of Inertia,

$D = E h^3 / 12(1-\nu)$  mm/N where  $E$ - modulus of elasticity,  $h$ - thickness of plate,  $\nu$ - Poisson's ratio

**Flexural strength:** The resistance of a material to breakage by bending stresses

**Notch sensitivity:** The extent to which the sensitivity of a material to fracture is increased by the presence of surface inhomogeneity such as notch, a sudden change in section, a crack, or a scratch. Low notch sensitivity is usually associated with the ductile materials and high notch sensitivity with brittle materials.

**Poisson's ratio:** A constant relating change in cross-sectional area to change in length when a material is stretched.

**Resilience:** The ratio of energy returned on recovery from deformation to the work input required to produce the deformation- expressed as percentage. 2) The ability to regain an original shape quickly after being strained or distorted.

**Stiffness:** A term often used when the relationship of stress to strain doesn't confirm to the young's modulus of elasticity.

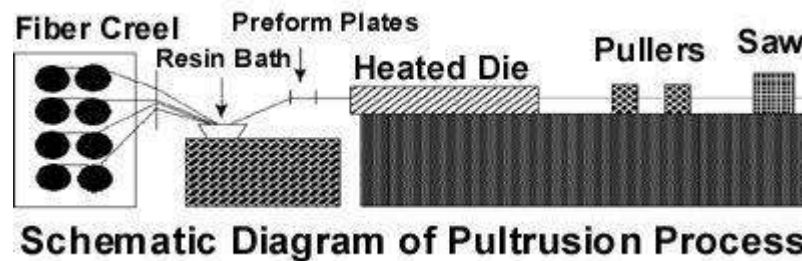
### **Boron Fibers**

**Definition:** Filaments produced by a chemical vapor deposition process. Boron can be deposited on a tungsten wire core, and on a glass or graphite filament core. The filaments thus produced have nominal diameters ranging from 0.1-0.2 mm. They are characterized by low density, high tensile strength and high modulus of elasticity. They are extremely stiff, e.g., five times stiffer than glass fibers. This stiffness makes boron filaments difficult to weave, braid, or twist, but they can be formed into resin impregnated tapes for hand lay-up and filament winding processes. The high cost of boron filaments has limited their use to experimental aircraft and aero-space applications

**Pultrusion:** Pultrusion is a continuous, automated closed-moulding process that is cost effective for high volume production of constant cross section parts. Due to uniformity of cross-section, resin dispersion, fibre distribution & alignment, excellent composite structural materials can be fabricated by pultrusion. The basic process usually involves pulling of continuous fibres through a bath of resin, blended with a catalyst and then into pre-forming fixtures where the section is partially pre-shaped & excess resin is removed. It is then passed through a heated die, which determines the sectional geometry and finish of the final product. The profiles produced with this process can compete with traditional metal profiles made of steel & aluminum for strength & weight.

**Pultrusion: Process Technology** The process begins when reinforcing fibres are pulled from a series of creels. The fibres proceed through a bath, where they are impregnated with formulated resin. The resin-impregnated fibres are preformed to the shape of the profile to be produced. This composite material is then passed through a heated steel die that has been machined precisely to the final shape of the part to be manufactured. Heat initiates an exothermic reaction thus curing the thermosetting resin matrix. The profile is continuously pulled and exits the mould as a hot, constant cross sectional member. The profile cools in ambient or forced air, or assisted by water.

The product emerges from the puller mechanism and is cut to the desired length by an automatic, flying cutoff saw. A schematic representation of pultrusion process is given in following figure:



## THERMOPLASTIC COMPOSITE PROCESING

**THERMO FORMING** Thermo forming consists of heating a thermoplastic material to its softening point and forming it against the contour of the mold. Fiber reinforced thermoplastic such as ABS, nylons, polycarbonates polysulphones, polybuteneterephthalate and PET are used in this method, since they exhibit good melt characteristics even with fiber reinforcements and filler contents of 40% volume or more. Parts are formed by heating the sheet of reinforced thermoplastics to a temperature above the glass transition temperature of the resin and then mechanically forming the sheet in to a mould or over a mandrel. The formed parts cool to a temperature below the plastic range and are removed from the mold. At this point the part is still hot and is placed on a fixture to cool to the room temperature. Cycle time varies between seconds to mins.

### Thermoforming methods;

There are at least dozen methods of thermoforming

Vacuum assisted forming

Pressure forming

Plug assisted forming

Drape forming

Matched mold forming

Slip forming

Free forming

### INJECTION MOLDING.

Compared with low pressure molding and mechanical mixing the reaction injection molding offers the following advantages.

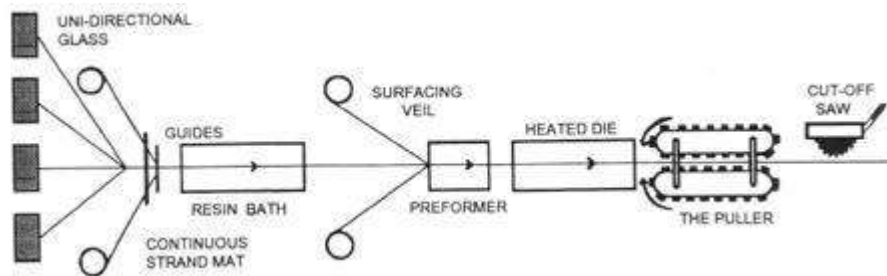
Since the mixing head is self cleaning, no solvent flush is required, as it is in low pressure molding. Since there is no mechanical mixing, outputs are higher and faster-reacting urethane mixes can be used. Since reaction time is faster, mold residence time is reduced because the material cures more rapidly, in turn reducing mold cycle time by as much as 75%. Since high pressure impingement mixing reduces air entrapment in the reaction mixture, part appearance is improved and surface defects eliminated.

### Vacuum Bag Molding

Vacuum bag molding, a refinement of hand lay-up, uses a vacuum to eliminate entrapped air and excess resin. After the lay-up is fabricated on either a male or female mold from precut plies of

glass mat or fabric and resin, a non adhering film of polyvinyl alcohol or nylon is placed over the lay-up and sealed at the mold flange. A vacuum is drawn on the bag formed by the film while the composite is cured at room or elevated temperatures. Compared to hand lay-up, the vacuum method provides higher reinforcement concentrations, better adhesion between layers, and more control over resin/glass ratios. Advanced composite parts utilize this method with preimpregnated fabrics rather than wet lay-up materials and require oven or autoclave cures.

### Pultrusion



Pultrusion is a continuous method of manufacturing various reinforced plastic shapes of uniform cross sections. Glass reinforcements, such as unidirectional rovings or multi-directional glass fiber mat, are guided through a liquid resin bath to thoroughly wet every fiber. The reinforcements are then guided and formed, or shaped, into the profile to be produced before entering a die. As the material progresses through the heated die, which is shaped to match the design profile, the resin changes from a liquid to a gel, and finally, into a cured, rigid plastic.

A pulling device grips the cured material and literally pulls the material through the die. Hence, the name pultrusion. It is the power source for the process. After the product passes through the puller, it is sawed into desired lengths. Although pultrusion is ideally suited for custom shapes, some standard products include rods, bars, angles, channels, and I-beams.

### Summary

Composite materials (or composites for short) are engineered materials made from two or more constituent materials with significantly different physical or chemical properties and which remain separate and distinct on a macroscopic level and are not soluble to each other. One constituent is called the MATRIX and the other is called the REINFORCING phase. Based on reinforcement they are classified as Particle Reinforced composites Fiber reinforced composites. Based on matrix they are classified as PMC, MMC and CMC. Composites have the following advantages over metals such as specific strength, specific weight, design tailorability, use of existing manufacturing process.

### Self assessment questions

- 1) Define composite material and give the classification of composite briefly?
- 2) Describe the features of fibrous composite, laminated composite and particulate composite?
- 3) Using neat sketches, explain the process of preparation of MMC?



- 4) Discuss the role of matrix and reinforcement in a composite material. Write a short note on FRP?
- 5) Explain autoclave & filament winding methods for production of FRP.
- 6) Compare MMC's with PMC's.
- 7) How the mechanical advantage of composite is measured. What are the limitations of composite materials?
- 8) What are the applications of composite material?
- 9) What are FRP's? Give at least four examples.
- 10) Discuss briefly advantages and applications of MMC's and FRP's.
- 11) Compare MMC's with PMC's.
- 12) Why and how are composite superior to conventional materials.
- 13) What are the main types of synthetic fiber used in FRP's?
- 14) List at least three commonly used matrix material and reinforcement fibers used in the production of FRP's.
- 15) Discuss the role of FRP's in space, naval and aeronautical engineering

**TEXT BOOKS:**

1. Smith, Foundations of Materials Science and Engineering, 4th Edition, McGraw Hill, 2009.
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2. Donald R. Asklund and Pradeep.P. Phule, The Science and Engineering of Materials, Cengage Learning, 4th Ed., 2003.
3. George Ellwood Dieter, Mechanical Metallurgy, McGraw-Hill.
4. ASM Handbooks, American Society of Metals.

