

# MODULE 1

## Atomic Diffusion

The Migration of atom from their original lattice sites in a crystal structure to other sites is known as Diffusion

Diffusion involves the movement of atoms ions or molecules from one position to another position and occurs mainly due to thermal agitation or the presence of concentration gradients.

### Fick's I Law of Diffusion

It states that, the flux of atoms J moving across a unit surface area in unit time is proportional to the concentration gradient  $dc/dx$ . Under steady state flow,

$$J = -D \frac{dc}{dx}$$

where,

J = No of atoms/unit area of diffusion per unit time (atoms/m<sup>2</sup> sec)

C = Volume concentration of atoms (atoms/m<sup>3</sup>)

X = Distance between the planes in the direction of flow of atoms (m)

D= diffusion co-efficient or diffusivity (m<sup>2</sup>/sec)

-ve sign = indication that flux moves from higher to lower concentration.

### Fick's II Law of Diffusion

This law relates to the rate of change in concentration with time. This non-steady state condition is represented by a second order differential equation.

It states that,  $\frac{dc}{dt} = D \left[ \frac{d^2c}{dx^2} \right]$

where  $\frac{dc}{dx}$  = concentration gradient

D = diffusion co-efficient

$\frac{dc}{dt}$  = the rate of accumulation of diffusing atoms at a point where the **concentration** gradient is  $dc/dx$  i.e., the rate of compositional change.

Fick's II law is also stated as,

"the rate of compositional change is equal to the diffusivity times the rate of change of the concentration gradient".

## **Diffusivity**

Diffusivity or the co-efficient of diffusion (D) is defined as the amount of substance diffusing in unit time across a unit area through a unit concentration gradient and its unit is  $\text{m}^2/\text{sec}$

The co-efficient of diffusion of various materials vary with crystal structure and temperature.

Factors affecting Diffusion –

- 1) Temperature: High temperature provides the necessary activation energy to the atoms to begin diffusion. So, a higher temperature initiates diffusion faster.
- 2) Crystal Structure: If a crystal structure is distorted, i.e., if there are more imperfections, the rate of diffusion is increased
- 3) Atomic Packing Factor: If APF is high, the rate of diffusion will be decreased. Diffusion is much slower in FCC-iron than in BCC-iron.
- 4) Grain Boundaries: The diffusion process proceeds more rapidly along the grain boundaries since it is a zone of crystal imperfections.
- 5) Grain Size: Since diffusion through grain boundaries is faster than through the grains themselves, a material with finer grains will have a faster rate of diffusion.
- 6) Atomic Size: Diffusion occurs more readily when the size of the diffusing atom is less. Ex: Carbon in iron
- 7) Concentration Gradient: Higher the concentration gradient higher will be the rate of diffusion.

## **Plastic deformation by Slip and Twinning**

### **Plastic Deformation**

If the solid body is loaded beyond the elastic limit, the body will experience a permanent change in its shape and size, even if the load is removed.

This is known as the Plastic behavior of materials. A body which is permanently deformed is said to have undergone Plastic Deformation.

### **Plastic Deformation of Single Crystals**

A single crystal is nothing but a single grain and hence has no grain boundaries example - a whisker grown under special conditions.

A number of such grains come together to form a polycrystalline material and there are grain boundaries between adjacent crystals

Plastic deformation of single crystals involves the study of one single crystal and observing how it behaves under stress

Plastic deformation in single crystals may take place by (i) Slip

(ii) Twinning or

(iii) Combination of both

### i) Plastic deformation by SLIP:

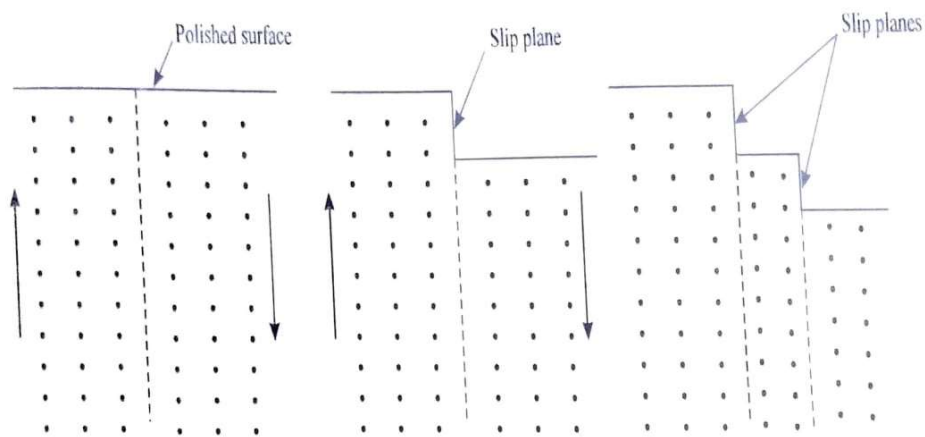
Slip is the most common mode of plastic deformation among crystals.

When a single crystal in tension is stressed beyond its elastic limit, a step appears such that the single crystal divides into two blocks and one block moves with respect to other (fig 1.34).

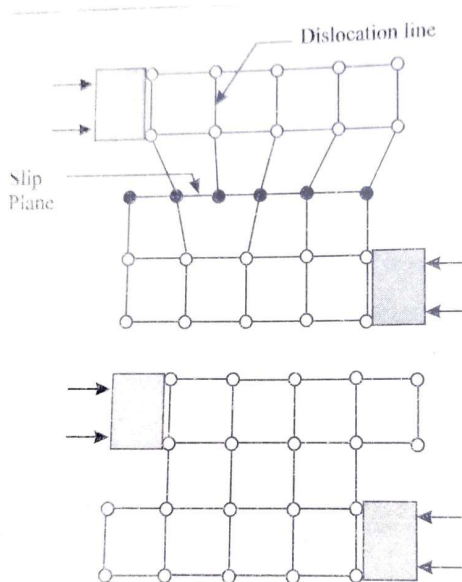
This is due to pure shearing stress that are acting across the specimen irrespective of whether the crystal is subjected to tensile or compressive stresses.

When the tensile load is further increased, the blocks become again divided and relative displacement takes place. Slip can be imagined to a pack of playing cards when they are shuffled.

Slip occurs due to the movement of dislocations through the crystal as shown in fig 1.35.



*Fig. 1.34 : Slip in a single crystal*



*Fig. 1.35 : Slip in a crystal block*

## (ii) Plastic deformation by Twinning:

This is the second important mechanism by which metals plastically deform. In twinning each plane of atoms move through a definite distance in the same direction.

The extent of movement of each plane is proportional to its distance and in the same direction.

The extent of movement of each plane is proportional to its distance from the twinning plane, as shown in fig 1.38 (b).

The distance moved by each successive atomic plane is greater than the previous plane by a few atomic spacings.

The twinning plane is perpendicular to the paper.

When a shear stress is applied, the crystal will turn about the twinning plane in such a way that the region to the left of the twinning plane is not deformed whereas the region to the right (twinned region) is deformed.

The atomic arrangement on either side of the twinned plane is in such a way that they are mirror reflections of each other.

Twins are known as Annealing twins when they are produced during annealing heat treatment and mechanical twins when they are produced during mechanical deformation of metals.

Twinning also occurs on definite crystallographic planes and directions.

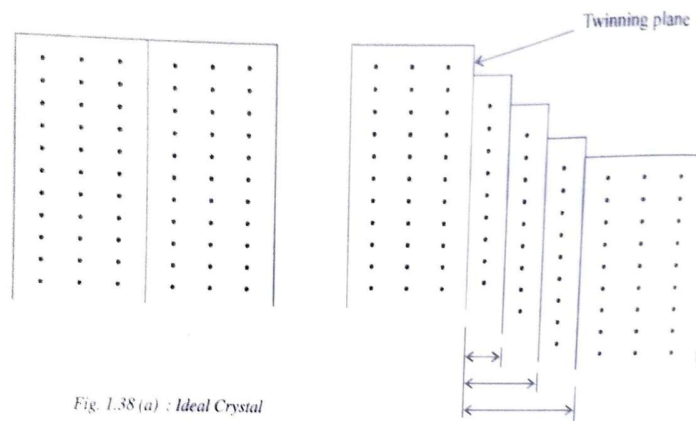


Fig. 1.38 (a) : Ideal Crystal

Fig. 1.38 (b) : Twinned Crystal

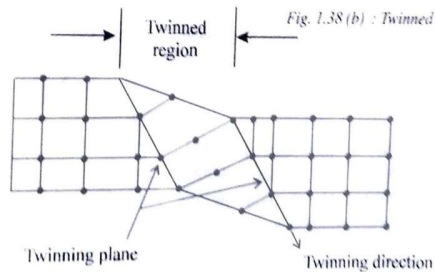
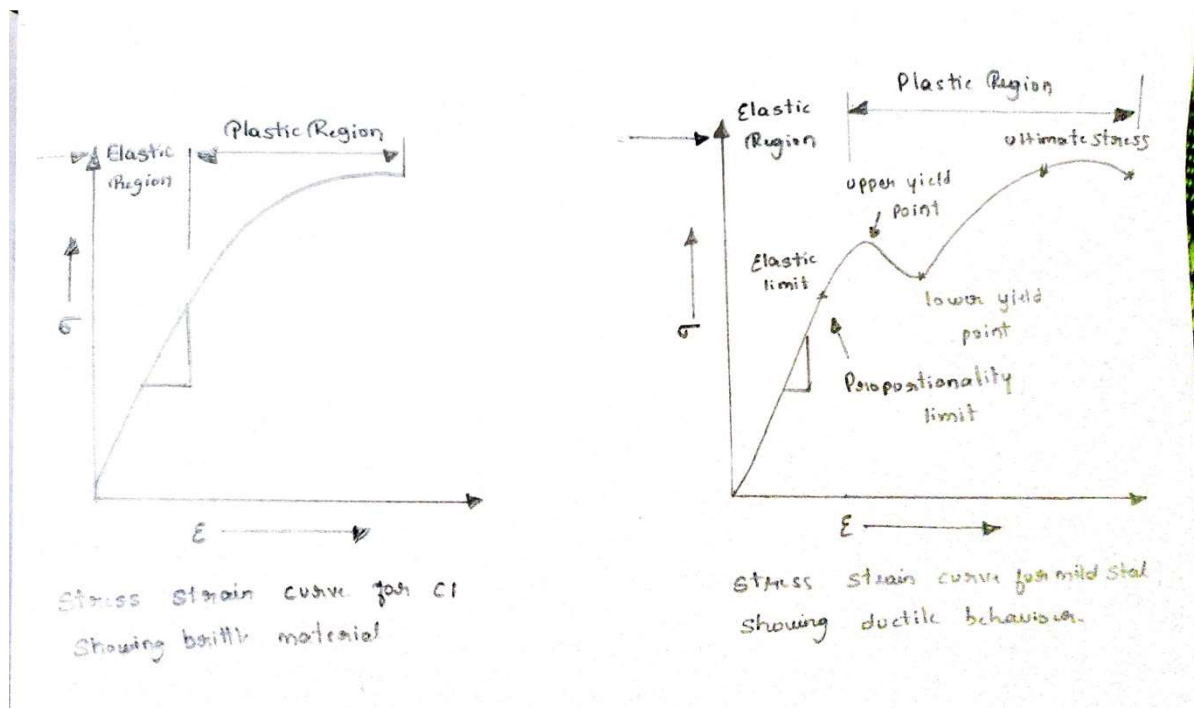


Fig. 1.38 (c) : Twinning

## Differentiate between Slip and Twinning

Slip	Twinning
1. All atoms in one block move over the same fractional distance depending on their plane	Different planes of atoms move fractional distances depending on their plane.
2. Slip appears as thin lines broad or bands	They appear as broad lines or bands
3. There is very little change in lattice orientation	Lattice orientation changes in the twinned region
4. Requires lower shear stress	Requires higher shear stress
5. Occurs in metals having more number of slip systems Ex- Cu (FCC) (12 slip systems)	Occurs in metals having less numbers of slip systems. Ex- Zn (HCP) (3 slip system)
6. More pronounced at higher temperatures and gradual holdings	More pronounced at low temperatures and impact holdings

## Stress - Strain Diagrams showing Ductile & Brittle Behavior



### Elastic Region:

#### Linear Elastic behavior (Proportionality Limit):

When stress is proportional to strain in the elastic region i.e., if the stress-strain relationship is linear (a straight line) then it is known as linear elastic behavior.

**Stiffness (Elastic Limit):**

Stiffness is defined as the resistance offered by the material to elastic deformation.

In this material can take maximum stress without any permanent deformation

Materials having high stiffness show less elastic deformation under load.

The modulus of elasticity or the Young's Modulus (E) itself is the measure of stiffness of a material.

Stiffness (Elastic Limit) is also measured as the slope of the linear portion of the elastic region on a stress strain diagram

**Elastic Strength (Upper Yield Point):**

Elastic Strength corresponds to the highest stress at which the behavior of the material remains elastic.

In other words, it is minimum stress at which plastic deformation first occurs.

**End of elastic Region:**

At the end of elastic region either of the two things might occur – fracture or yielding.

The specimen might break immediately after the elastic limit in case it is a brittle material or the specimen might start yielding as in case of a ductile material.

(Note - If the question is asked for brittle material or cast iron. Write the answer till here and write fracture strength)

**Plastic Range:****Yield Strength (Lower Yield Point):**

Yield strength can be defined as the stress at which plastic deformation (yielding) begins without any appreciable increase in load.

A simple difference between elastic strength and yield strength is that Hooke's Law may still be obeyed at the elastic limit whereas the law is not obeyed at the yield point

**Offset Yield Strength:**

Some materials like mild steel exhibit a definite yield point and hence have a definite yield strength while some other materials like cast iron do not have a definite yield point. So, for such materials which do not exhibit a definite yield point, a quantity called Offset yield strength is determined.

**Ultimate tensile strength:**

After the yield point on the stress - strain curve the specimen undergoes continuous plastic deformation with increasing load.

This load reaches a certain maximum value after which the specimen does not take any more load.

At the point of ultimate load, the area of cross section of stress that specimen starts reducing considerably and is known as necking.

**Fracture strength:**

After the ultimate load is reached, the load drops and at a particular load, fracture takes place.

The stress corresponding to this load, where the actual failure takes place, is known as the fracture strength of the material.

#### **Additional:**

#### **Resilience:**

Resilience is the ability of the material to absorb energy when it is loaded elastically and give back the same energy when the load is removed. So as long as the body remains loaded, it contains stored energy within itself which is called the Strain Energy. As soon as the load is removed, the stored energy is given back, exactly as is observed in a spring.

#### **Ductility:**

Ductility is the ability of the material to undergo plastic deformation under tensile load.

In other words, ductility is that property of a material by which it can be drawn into thin wires

Example - Copper

#### **Malleability:**

Malleability is the ability of the material to undergo plastic deformation under compressive load.

In other words, malleability is that property of the material by which it can be flattened into thin sheets without cracking.

Example – lead

#### **Toughness:**

The toughness of a material is its ability to withstand both elastic and plastic deformation.

In other words, it is the amount of energy a material can withstand before fracture takes place.

For example - If a sudden load is applied to a piece of mild steel and then to a piece of glass, the mild steel piece will absorb more energy before breaking. Thus mild steel is said to have a higher toughness than glass.

### **Fracture**

Fracture is the separation or fragmentation of a solid body into two or more parts under the action of load.

During fracture atomic bonds are broken and new surfaces are formed

#### **Types of Fracture**

Fractures are broadly classified into

(i) Ductile or type I fracture

(ii) Brittle or type II fracture

(iii) Shear or type III fracture

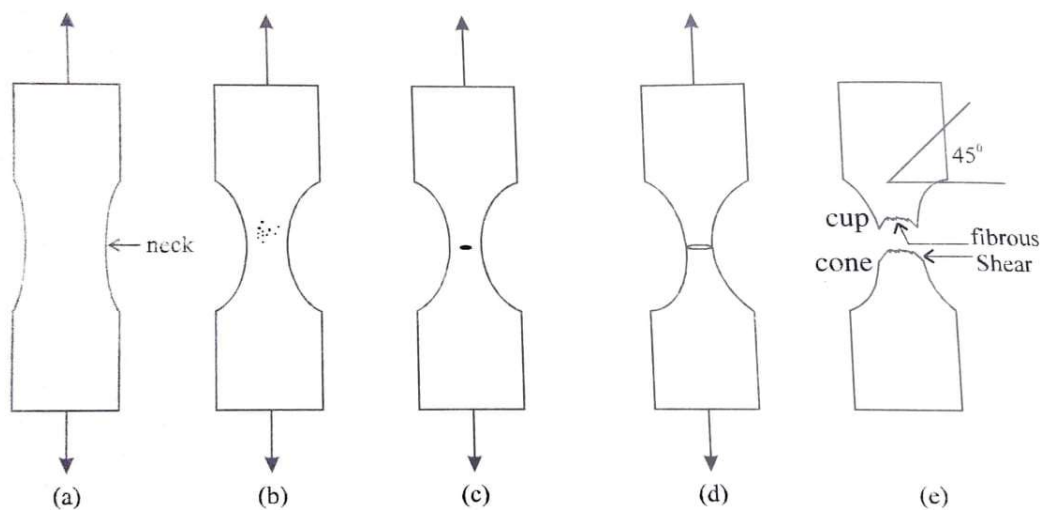
i) Ductile fracture or type I fracture

It is characterized by an appreciable amount of plastic deformation. The fracture proceeds relatively slowly and the fracture surface is dull in appearance. Ductile fracture is of two types:

**a) Highly ductile fracture -**

In these the material necks down to a point fracture and yields to 100% reduction in cross section area.  
ex - soft metals like pure gold, lead etc.

**b) Moderately ductile fracture or Cup and Cone Fracture –**



*Fig. 2.2 : Stages of Cup and cone fracture*

**Stage**

**(a)** - Initial Necking or reduction in cross - sectional area take place.

**(b)** - Small cavities or voids form in the interior of the cross section

**(c)** - As load is increased these minute cavities join together to form an elliptical crack which has its long axis perpendicular to the direction of load.

**(d)** - The crack continues to grow in a direction parallel to its major axis.

**(e)** - Finally, fracture results due to rapid propagation of the crack

**(ii) Brittle fracture or Type II fracture**

Like in ductile fracture, here also small cavities join together to form a crack and this crack propagates.

But all these stages happen instantly, and the material failure takes place suddenly

Tendency for brittle fracture is increased with



- a) decreasing temperature
- b) increasing strain rate or rate of loading
- c) tri-axial stress conditions usually produced by a notch

### **There are two types of Brittle Fracture -**

**(i) Intergranular fracture:** In this the crack propagates along the grain boundaries and fracture occurs.

**(ii) Intragranular fracture:** In this the fracture crack passes through the grains and the fractures surface looks granular. This also known as Trans granular fracture.

Note - Inter and Intra

### **(iii) Shear Fracture or Type III Fracture**

This type of fracture is found in ductile single crystals.

This is promoted by shear stresses and occurs as a result of extensive slip on the active slip plane.

Fracture surfaces are normally at 45 degree to the direction of tensile load and appear shiny owing to extensive slip between fracture.

## **Creep**

### **Creep and Description of the Phenomenon**

When materials under several service conditions are required to sustain steady loads for long periods of time, they undergo a time dependent deformation. This is known as creep and can also be defined as 'the slow and progressive deformation of a material with time at constant stress'.

In other words, creep deformation refers to that permanent deformation which occurs in materials that are exposed to lower values of stress ( $<$  elastic limit) but for a prolonged length of time.

Creep in most of the materials, however, is found to occur predominantly at higher temperatures than at lower temperatures. Generally, temperatures above  $0.4 T_m$  ( $T_m$  = Melting temperature) are considered as higher temperatures.

Therefore, the study of creep is very important for those which are used at higher temperatures like components of gas turbine, furnaces, rockets, missiles etc.

But there are exceptions like lead and plastic which undergo creep at room temperature also.

At elevated temperature, the tensile properties of most engineering metals are very sensitive to both strain rate and time of exposure than at lower temperatures.

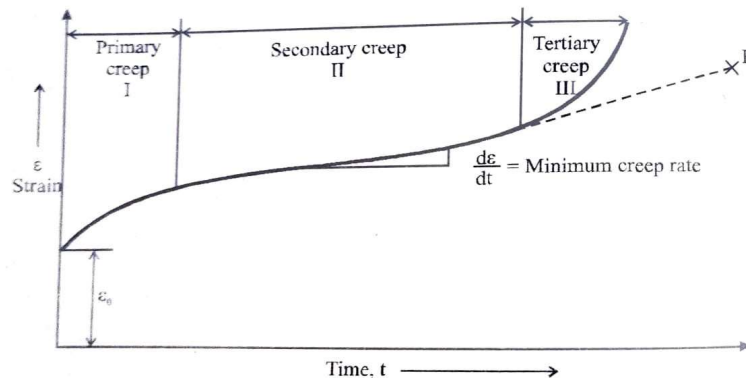
Alternatively, creep is also set to occur at higher homologous temperatures.

### **Three stages of Creep - Through Creep Curve**

The creep curve is obtained by applying a constant tensile load below the yield point to a specimen maintained at constant temperature.

The strain or the elongation of the specimen is then determined as a function of time.

For example, lead is said to creep at room temperature since its melting temperature is 200 degree Celsius. i.e.,  $T/T_m = 298/473 = 0.63$



As soon as the specimen is loaded, there will be an instantaneous strain which is denoted  $\epsilon_0$  on the creep curve.

Further deformation of the metal only after the instantaneous strain is considered **as 'creep deformation'**.

**Creep deformation of materials up to failures are divided into 3 stages:**

**(i) Primary creep**

**(ii) Secondary creep**

**(iii) Tertiary creep**

**(i) Primary Creep:** Thus, is the first stage of the creep which represents a region of decreasing creep rate. In this region the rate at which the material deforms decreases with time until it reaches a constant value.

The creep rate goes on reducing because as the metal deforms it undergoes strain hardening and offers more and more resistance to further elongation. Primary creep is predominantly a period of transient creep.

Primary Creep is important for those materials which undergo creep at room temperature.

**(ii) Secondary Creep:** This stage is a period of nearly constant creep rate. The creep rate is constant because **'strain-hardening'** and **'recovery effects'** balance each other.

This is an important part of the curve because most of the working components will be in this state.

Secondary creep is also known as steady state creep. Creep in this region takes place by the viscous flow in the materials.

### **(iii) Tertiary Creep:**

This stage is a period of increasing strain rate. Tertiary creep occurs when there is an effective reduction in cross-section due to necking or internal void formation. So, the stress at that cross-section increases and consequently the value of strain also increases at a faster rate before the occurrence of fracture.

If the stress is kept constant instead of the load or if the true strain is taken into consideration, then the resulting fracture due to creep would be at 'B'.

## **Creep Properties**

### **(i) Creep Strength:**

It is defined as "the highest stress that a material can withstand without excessive deformation for a specified length of time".

It is also known as 'Creep limit'.

ex. Creep Strength for a steam turbine blade may be that stress which will produce just 0.2% creep for 10,000 hours of working at 800 degree.

### **(ii) Creep Rupture Strength:**

It is defined as "the highest stress that a material can withstand without rupture for a specified length of time".

ex. For the same turbine blade the rupture strength is that stress which produces a fracture in 10,000 hours at 800 degree Celsius. Creep rupture strength is also known as "Stress - rupture strength" or simply rupture strength".

## **Stress Relaxation**

Stress relaxation is the time dependent decrease in stress acting on a body which is constrained to a certain fixed deformation. In other words, it is the reduction in the value of the stress in those components which are not allowed to elongate.

Stress relaxation takes place in a member will reduce after long periods of time.

## **Fatigue**

Fatigue is defined as a process of progressive localized plastic deformation occurring in a material subjected to cyclic stresses and strains at high stress concentration locations that may culminate in cracks or complete fracture after a sufficient number of fluctuations.

## Type of Fatigue loading with examples

### (i) Completely reversed cycles of stress:

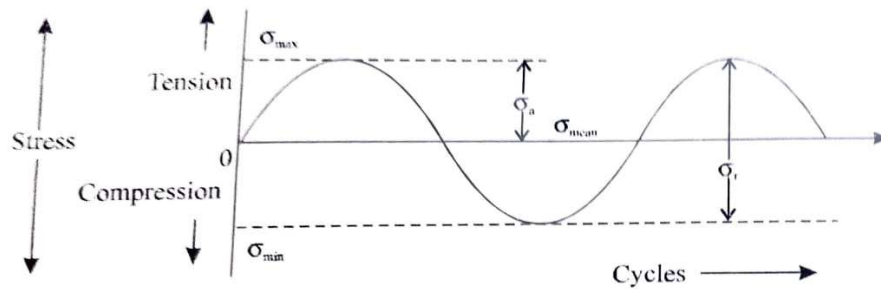


Fig. 2.6 : Alternate tensile and compressive stresses

$\sigma_a$ = Stress amplitude	$\sigma_r$ = range of stress
$\sigma_{max}$ = maximum stress	$\sigma_{min}$ = minimum stress
$\sigma_{mean} = 0$	

Fig 2.6 illustrates the type of fatigue loading where a member is subjected to opposite loads alternatively with a mean of zero.

For example, bending of steel wire continuously in either directions lead to alternate tensile and compressive stresses on its surface layers and failure by fatigue.

### (ii) Repeated stress cycles:

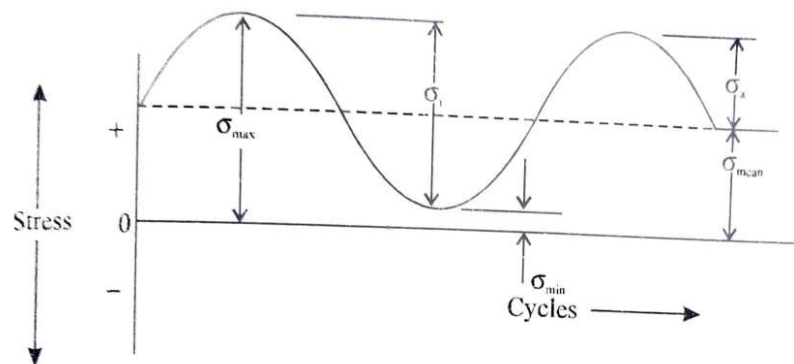


Fig. 2.7 : Various degrees of tension

Fig shows the type of fatigue loading where a member is subjected to only tension but to various degrees.

A spring subjected to repeated tension as in a toy would lead to fatigue failure

### (iii) Irregular or Random stress cycle:

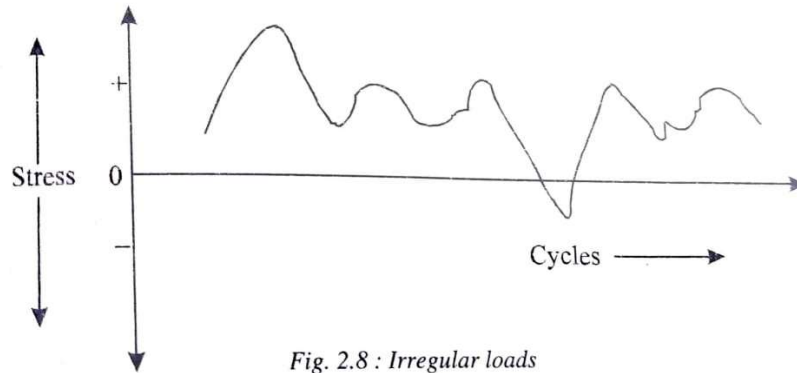


Fig. 2.8 : Irregular loads

Fig 2.8 shows a type of fatigue loading where a member could be subjected to irregular loads just as in the case of an aircraft wing subjected to wind loads

### Stages of fatigue failure

(this section can also be referred for Mechanisms of fatigue (failure))

Let us consider a ductile material which is subjected to simple alternating tensile and compressive stresses.

**Failure by fatigue is found to take place in three stages:**

**(i) Crack nucleation (ii) Crack Growth (iii) Fracture**

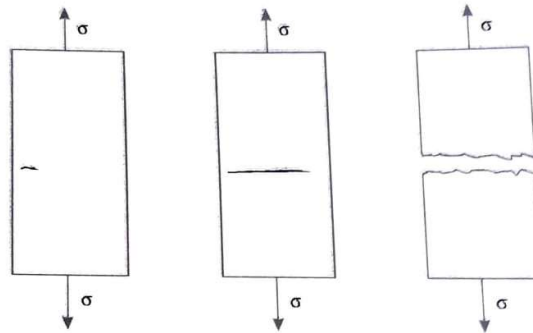


Fig. 2.9 (a) : Crack Nucleation

Fig. 2.9 (b) : Crack growth

Fig. 2.9 (c) : Fracture

#### (i) Crack nucleation:

During the first few cycles of loading, localized changes take place in the structure at various places within the material.

These changes lead to the formation of submicroscopic cracks. These cracks are usually formed at the surface of the specimen.

#### (ii) Crack Growth:

The submicroscopic cracks formed grow as the cycles of loading continue and become microscopic cracks.

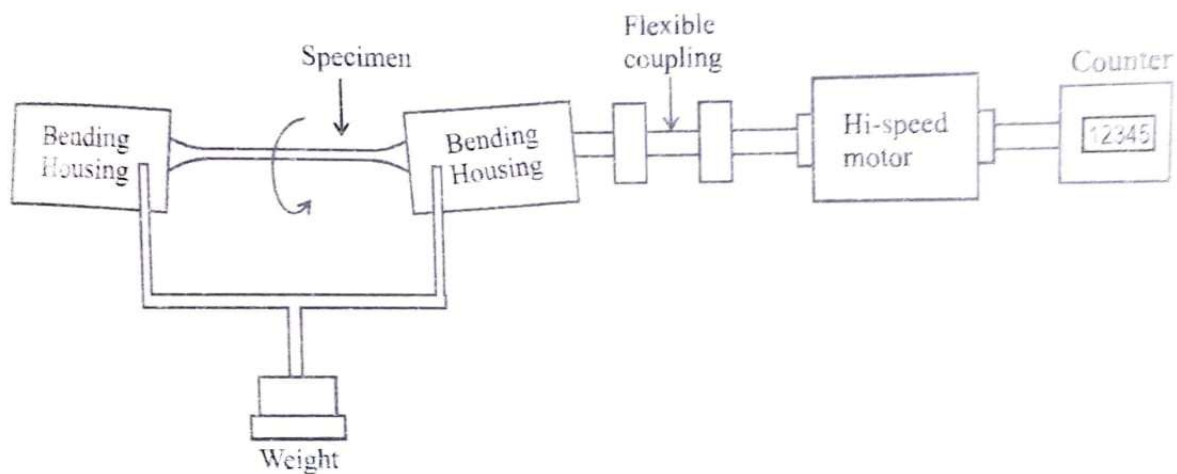
### (iii) Fracture:

When Critical size is reached the crack propagates. The area of cross-section supporting the load gets reduced thus increasing the stress value and fracture finally occurs.

### Fatigue testing

Fatigue failures in engineering materials are observed by conducting the fatigue test which involves the plotting of an S-N diagram. One such test is the R R Moore reversed -bending fatigue testing machine.

Specimens subjected to fatigue test are made to undergo fluctuating or opposite stresses one such test arrangement is shown in the fig. where the specimen is bent with the help of weights as well as rotated. By this, alternate tensile and compressive stresses are imposed on the various layers of the specimen.



*Fig. 2.11 : RR Moore Fatigue Test*

A counter coupled to the motor counts the number of cycles to failure. The experiment could be conducted for different loads, and different number of cycles to fractures are noted to draw the S-N diagram.

### S-N Diagrams

The S-N Curve which gives information on the fatigue behavior of a material is a plot of stress (S) against the number of cycles to failure (N). The value of stress that is plotted can be  $\sigma_a$ ,  $\sigma_{max}$ ,  $\sigma_{min}$ .

The values of N are usually taken along a log scale.

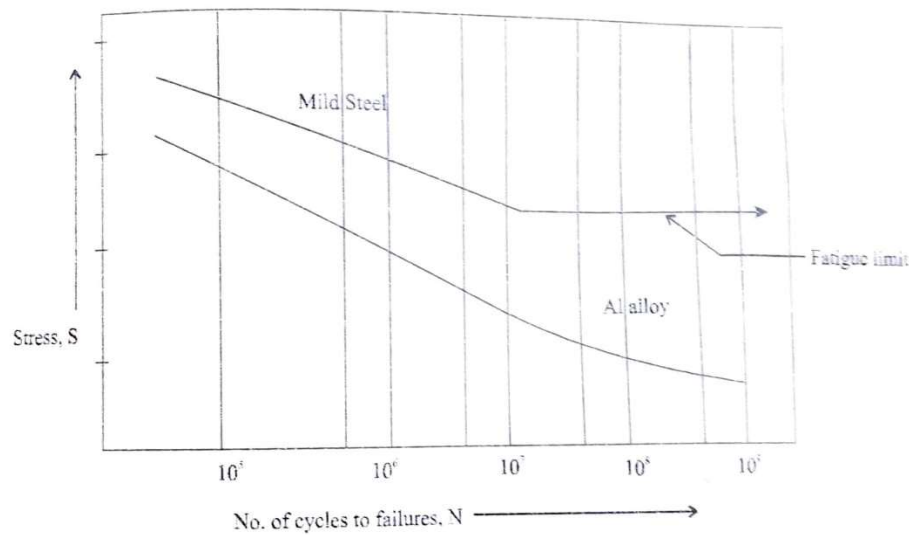


Fig. 2.12 : S-N curves of Mild steel and Alloy

The S-N curve is plotted by applying a cyclic load at any particular value of stress and repeated continuously until the specimen fails. The number of cycles required for failure at that stress is plotted. Specimens would fail for different number of cycles when held at different stresses and hence a number of points are obtained. By joining all these points, a S-N curve typical of that material is obtained.

Fig 2.12 shows the S-N Curve for two metals-mild steel and an aluminum alloy. It is seen from the S-N curves for both metals that the number of cycles which a metal can endure before failure, increases with decreasing stress. But in the case of mild steel, the S-N curve becomes horizontal at a certain limiting stress. Below this limiting stress called fatigue limit or endurance limit, the material can endure an infinite number of cycles, without failure. This means that if the stress is below the materials will never fail for any number of cycles of stresses.

In the case of the non-ferrous aluminum alloy, the S-N curve slopes gradually downward with increasing number of cycles. This material does not have a true fatigue limit because the S-N curve never becomes horizontal.

## Fatigue Properties

### 1) Fatigue Life (N):

It is the total number of cycles required to bring about final fracture in a specimen at a given stress.

Fatigue life for a given condition is a property of the individual specimen and is arrived at after testing a number of specimens at the same stress.

### 2) Fatigue Life for P percent survival (N<sub>p</sub>):

It is the fatigue life for which P percent of the population of samples tested have a longer life than the rest.

For example, N<sub>90</sub> is the fatigue life for which 90% of the samples would be expected to survive and 10% to fail at a particular stress.

### 3) Median Fatigue Life:

It is the fatigue life for which 50% of the population of samples fail and the others 50% survive at a particular stress.

### 4) Fatigue Strength ( $\sigma_n$ ):

It is the stress at which a material can withstand repeatedly 'N': number of cycles before failure. In other words, it is the strength of a material for a particular fatigue life.

### 5) Fatigue Limit or Endurance Limit ( $\sigma_E$ ):

It is the stress below which a material will not fail for any number of cycles.

For ferrous materials it is approximately half of the ultimate tensile strength

For non-ferrous metals since there is no fatigue limit is taken to be the stress at which it endures 'N' number of cycles without failure.

'N' is usually taken as  $5 \times 10^8$  cycles for non-ferrous metals.

## Factors affecting Fatigue Life

### 1) Effect of stress concentration on fatigue:

Stress concentrations are actually responsible for the majority of fatigue failures occurring in practice.

All machine elements contain stress raisers like fillets, keyways, screw threads, porosity etc.

Fatigue cracks are nucleated in the region of such geometrical irregularities.

Fatigue failure by stress concentration can be minimized by reducing the avoidable stress - raisers through careful design and the prevention of stress raisers by careful machining and fabrication.

### 2) Size Effect:

Experiments have shown that fatigue strength of large members is lower than that of small specimens. This may be due to two reasons:

- (i) The larger member will have a larger distribution of weak points than the smaller one and on average, fails at a lower stress.
- (ii) Larger members have larger surface areas. This is important because the imperfections that cause fatigue failure are usually at the surface.

### 3) Surface Roughness

Practically almost all fatigue cracks nucleate at the surface of the members. Therefore, the conditions of the surface such as surface roughness and surface oxidation or corrosion are very important.

Experiments have shown that different surface finishes of the same material can appreciably affect fatigue performance. Smoothly polished specimens have higher fatigue strengths.



# MODULE 2

## TTT Curve or TTT Diagram

Time temperature transformation diagram are plots of temperature versus time (usually on a logarithmic scale)

They are generated from percentage transformation-vs time measurements and are useful for understanding the transformations of an alloy steel at elevated temperatures.

Time temperature transformation diagram is also known as isothermal transformation diagrams

### TTT – DIAGRAM FOR 0.8% C EUTECTOID STEEL

TTT diagram are drawn with temperature along Y -axis and time along X – axis to study the effects of time on transformation of phases. Fig 3.2 illustrates the TTT Diagram for 0.8%C eutectoid steel. From the Fe-Fe<sub>3</sub>C phase diagram we know that steel containing 0.8%C is completely austenitic above 727° C.

This austenite transforms into pearlite upon slow cooling but for much higher rates of cooling other phases like bainite, (upper or lower), martensite or even austenite itself can result in the microstructure. All these appear on TTT Diagram.

TTT diagram basically consists two parallel curves which represent the beginning and ending of transformation of austenite, respectively. Another set of parallel horizontal lines represent the martensite start and finish temperatures respectively

(Fig is shown in a separate page)

## Drawing of TTT Diagram

**The steps followed to determine a TTT diagram are:**

### Step 1 :

A large number of identical samples are cut and prepared from the same bar. The cross section of samples has to be small in order to react quickly to the changes in temperature.

### Step 2:

All the samples are placed in a furnace at the proper austenitizing temperature for sufficient duration until complete austenite phase in the microstructure is ensured

### Step 3:

A set of samples are then transferred to molten salt bath held at a constant subcritical temperature (below 727°C and for example 700°C)

### Step 4:

Each sample in the set held in the molten salt bath at this constant temperature for different intervals of time and then quenched

**Step 5:**

After cooling each sample is checked for hardness and studied microscopically.

**Step 6:**

The above steps are repeated for samples held at different sub-critical temperatures until sufficient points are determined to plot the curves on the diagram

The above procedure is carried out to draw the TTT diagram for one composition of iron and carbon. The entire effort is carried out to draw the TTT diagram for each composition of iron and carbon.

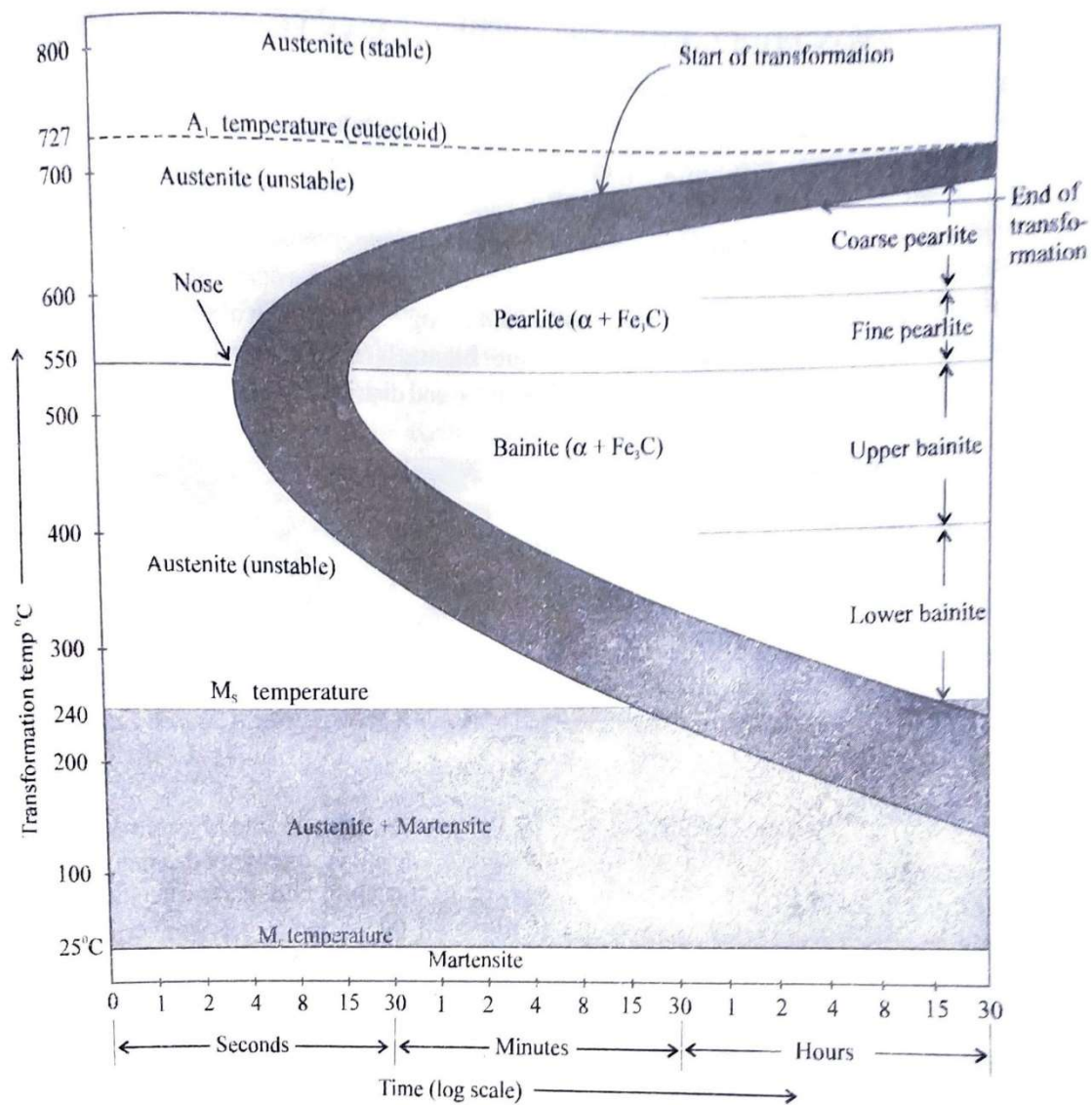


Fig. 3.2 : T-T-T diagram for 0.8% C eutectoid steel

### **Factors affecting TTT Diagram**

1. Grain Size
2. Carbon Content
3. Alloying elements

### **Continuous Cooling Curves (CCT Diagram)**

A **continuous cooling transformation (CCT)** phase diagram is often used when heat treating steel. These diagrams are used to represent which types of phase changes will occur in a material as it is cooled at different rates.

These diagrams are often more useful than time-temperature-transformation diagrams because it is more convenient to cool materials at a certain rate (temperature-variable cooling), than to cool quickly and hold at a certain temperature (isothermal cooling).

### **TTT curve vs CCT curve (Difference between TTT and CCT)**

TTT diagrams are constructed by taking Isothermal transformation whereas CCT diagram is constructed taking continuous cooling into consideration.

Since almost all practical heat treatment cycles make use of continuous cooling, CCT diagram is of more practical use to know the exact transformation temperatures. However CCT diagrams are difficult to draw and therefore reference to TTT Diagram is more common

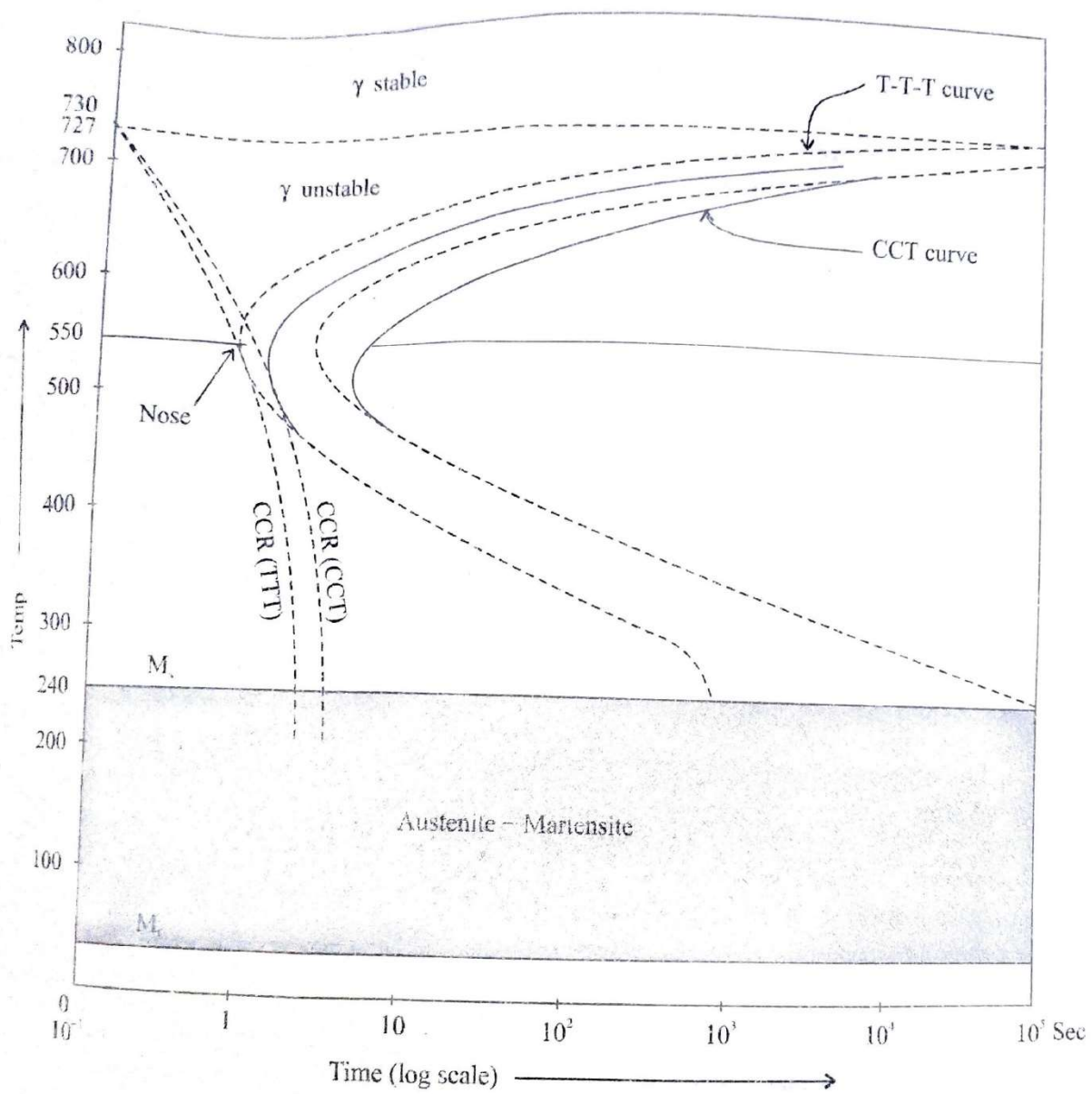


Fig. 3.6 : Continuous cooling transformation diagram

## Annealing and Its Types

Annealing involves heating the specimen to the prescribed temperature, holding it at that temperature and then cooling it down to room temperature at a suitable slow rate. The important objectives of annealing are

- i) Reducing hardness
- ii) Improve machinability
- iii) Facilitate cold working by improving toughness

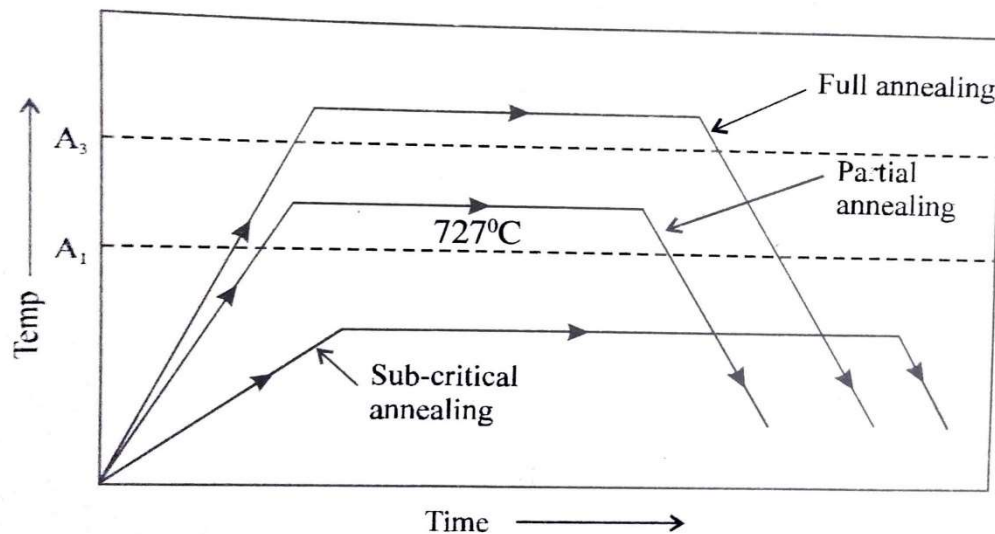


Fig. 3.7 : Types of annealing

### Types of annealing

#### 1) Recrystallisation Annealing

Purpose	To improve ductility To remove strain hardening effects
Temperature Range	Above recrystallization temperature
Holding Time	2-3 minutes per mm of thickness
Cooling Type	Slow cooling
Applications	Steel wires, sheets and strips

#### 2) Full Annealing

Purpose	To remove internal stresses, to improve ductility, for grain refinement
Temperature Range	Above $A_3$ temperature between $940^{\circ}\text{C}$ - $960^{\circ}\text{C}$
Holding Time	Based on size and shape
Cooling Type	Very slow cooling.
Application	Hypo-eutectoid steels
Disadvantage	Expensive because of long cooling cycle

### 3) Partial Annealing

Purpose	To improve machinability
---------	--------------------------

There are two step in the heat treatment procedure

Step 1

Temperature Range	Heat to 940°-960°C
Holding time	Hold until complete austenite is obtained
Cooling Type	Rapid cooling to below A <sub>1</sub> temperature

Step 2

Temperature range	Hold at 600° - 700°C
Holding time	Hold until complete austenite is obtained
Cooling Type	Cooled in air. Rate of cooling is not important because once the temperature is below A <sub>1</sub> temperature, there will be no phase transformation for any rate of cooling
Application	Used for alloy steels
Advantage	Less expensive than full annealing
Disadvantage	Not suitable for heavy components

### 4) Process or Sub-Critical or Stress Relief Annealing:

Purpose	To remove internal stresses To remove strain hardening effect and facilitate further cooling working
Temperature Range	Below A <sub>1</sub> temp in the range of 650°-700°C
Holding Time	Sufficiently long
Cooling Type	Rate of cooling is not important because the temperature range is below A <sub>1</sub> temp and there will be no phase transformation
Applications	Steel Wires, steel sheets and stampings

### 5) Spheroidising Annealing:

Step 1

Temperature Range	Below A <sub>1</sub> temperature in the range of 650°C - 700° C
Holding Time	2-3 minutes per mm of thickness plus 40% more
Cooling Type	Slow cooling

Step 2

Temperature Range	Above and below 727°C (A <sub>1</sub> temp) Alternative heating and cooling
Holding time	2-3 minutes/ mm of thickness + 40% more
Cooling Type	Slow cooling

Step 3

Temperature Range	750°C-780°C *for 0.8% C steel) 780°-800°C (>0.8%C)
Holding Time	Hold till the shape of carbides becomes spheroidal
Cooling Type	Furnace cooling (very slow) to below $A_1$ temperature
Applications	High carbon steels, tool steels, alloy steels etc

## Normalizing

Normalizing consists of heating steels to about 40°C -50°C above upper critical temperature, holding it at that temperature for a short time and then cooling it in still air to room temperature. Cooling in still air is faster than the rate of cooling employed in annealing. That is the reason why normalizing is also called as air quenching.

The type of structure obtained by normalizing will depend largely on the thickness of cross section. Thin sections will give a much finer grain size than thick sections. The microstructure obtained after normalizing will generally be fine pearlitic. The purpose of normalizing is to produce a harder and stronger steel than annealing. Normalizing may also be used to improve machinability, modify and refine cast dendritic structure and grain refinement

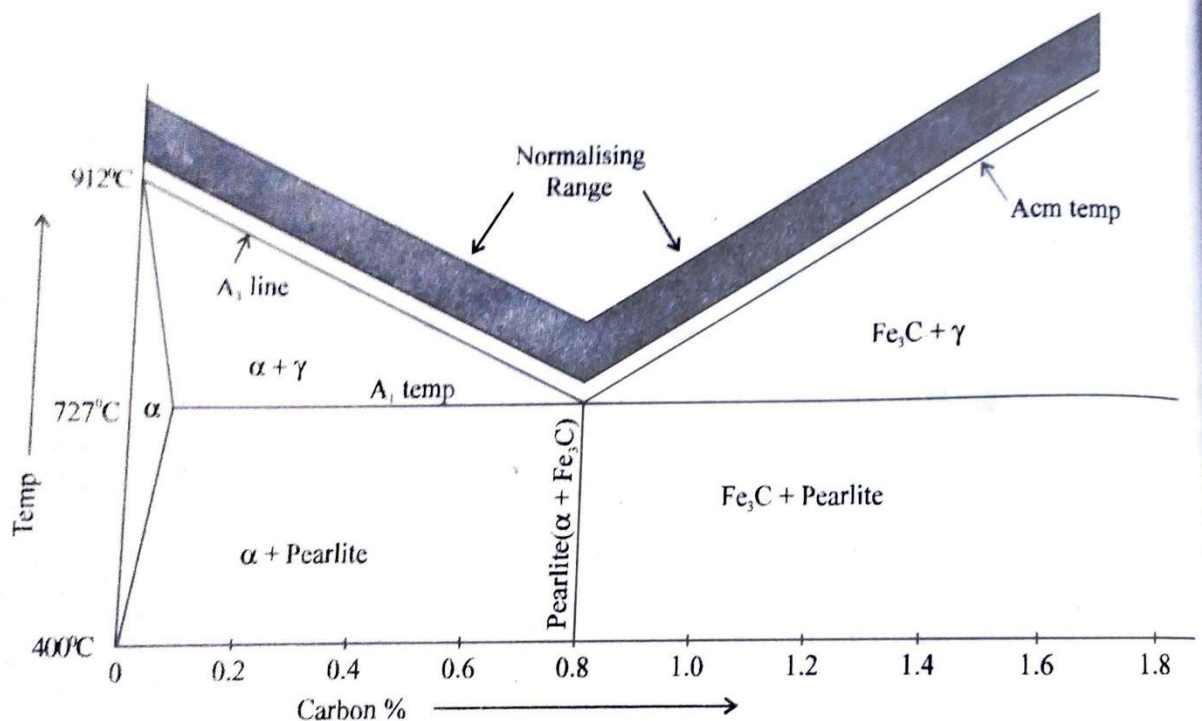


Fig. 3.10 : Normalising Range

### Normalizing vs Annealing

Normalizing	Annealing
Fine pearlite is obtained	Coarse and medium pearlite is obtained
Normalized steels are harder	Less Harder
Finer grain size	Less finer
Less expensive	More expensive
Cooling rates are not critical	Cooling rates are critical
Improves machinability of medium carbon steels	Improves machinability of low carbon steels
Normalized steels are less ductile	More ductile

### Hardening

The heat treatment carried out on metals and alloys in order to increase their hardness is known as hardening.

Hardening involves heating to such a temperature to produce an austenitic structure, hold it at that temperature and quench (sudden cooling by immersing) in water or oil,. By quenching, an extremely rapid rate of cooling is obtained.

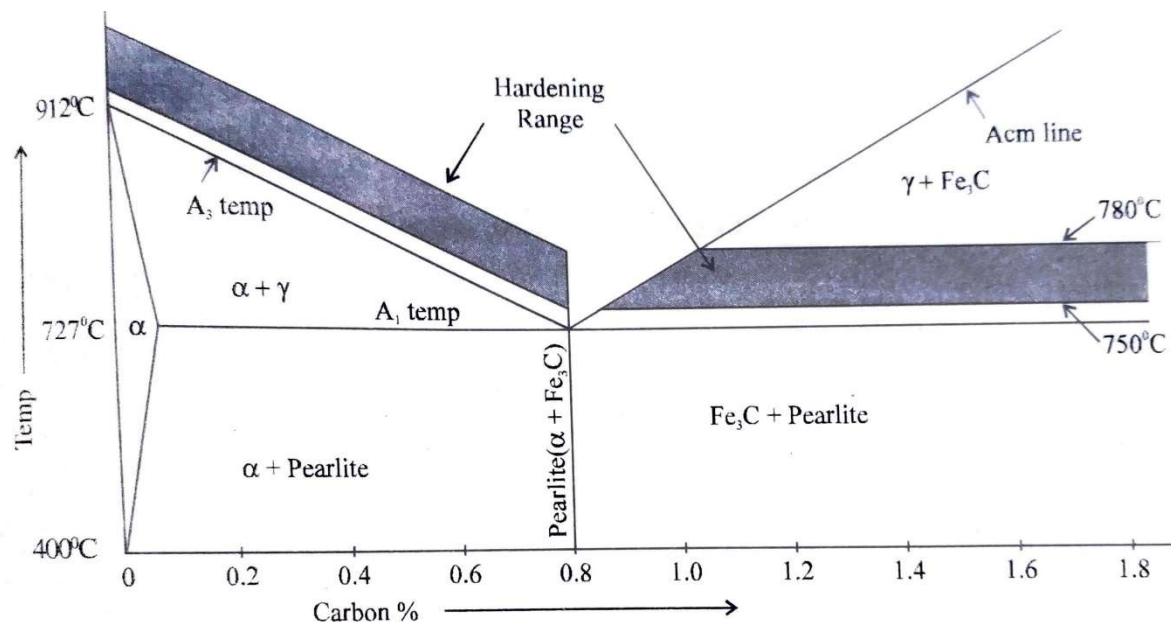


Fig. 3.11 : Hardening range

Fig 3.11 shows the hardening range for steels. Hypo-eutectoid steels (less than 0.8%C) are heated to about 30°-50°C above the critical temperature (A<sub>3</sub> temperature) whereas eutectoid and hyper eutectoid steels are heated to about 30°-50°C above the lower critical temperature.



This means that the hardening range varies for hyper-eutectoid steels of varying carbon content whereas hyper-eutectoid steels are heated to about 30°-50°C above the lower temperatures. This is because a completely austenitic phase is ensured in hypo-eutectoid steels before quenching while in hyper eutectoid steels, only the pearlite phase is allowed to become austenite retaining the other phase cementite, before quenching.

Upon quenching, most of the austenite transforms into martensite in hypo-eutectoid steels whereas the microstructure of hyper- eutectoid steels have martensite and cementite.

## HARDENABILITY

The hardenability of a metal alloy is the depth to which a material is hardened after putting it through a heat treatment process.

The hardenability of steel depends on

- Composition of the steel and the method of manufacture
- Quenching medium and the method of manufacture
- Section (thickness) of steel

## TEMPERING

Tempering is a process of heat treating, which is used to increase the toughness of iron-based alloys. Tempering is usually done after hardening.

The main objectives of tempering are:

- To relieve residual stresses
- To improve ductility, toughness, impact strength
- To reduce hardness
- To convert retained austenite

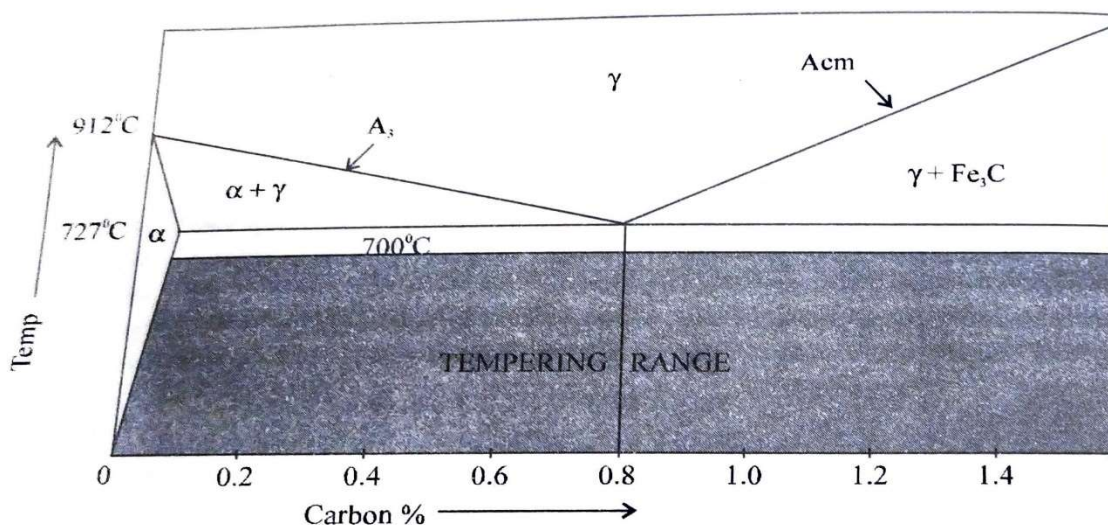


Fig. 3.13 : Tempering range

Fig 3.13 shows the subcritical temperature range of tempering heat treatment. Tempering however is carried out in three stages.

**i) 150 -200°C:**

Immediately after quenching, the specimen is heated in an oil bath to this temperature range in order to relieve the internal stresses and begin the decomposition of retained austenite. Excess carbon also starts precipitating out of martensite.

**ii) 200-450°C:**

Heating in this range increases the toughness at the expense of hardness,

**iii) 450-700°C:**

The fine cementite particles which have precipitated now join together to form larger masses due to which steel becomes more ductile. A structure known as sorbite is obtained which has a coarse spheroidal structure at higher temperature

## Austempering

Austempering is a type of cooling which is employed in order to obtain a 100% bainitic structure. A fully bainitic structure is less harder than the structure containing martensite but possesses a better impact resistance.

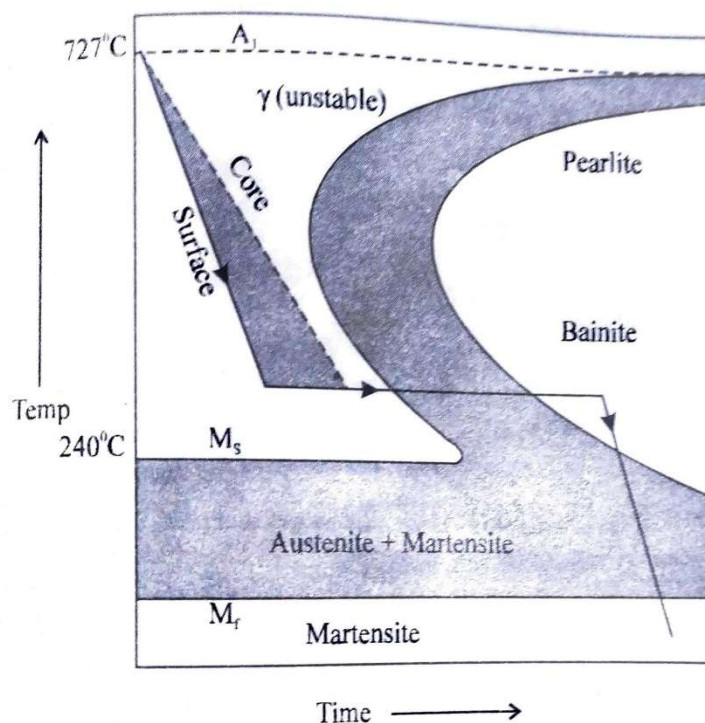


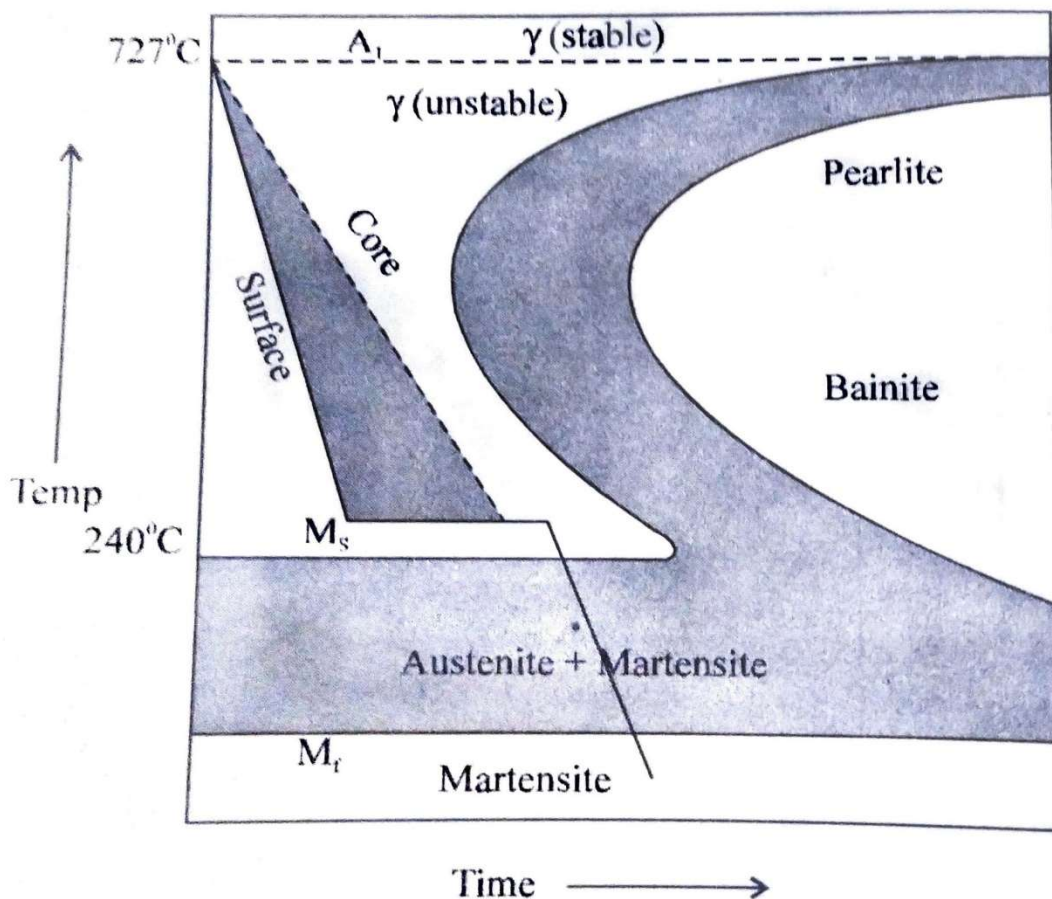
Fig. 3.14 : Austempering

Fig 3.14 shows the TTT diagram on which is drawn the cooling curve, followed during austempering. A 100% bainitic structure is not possible to obtain by continuous cooling. Therefore steel is first quenched down to a temperature within the bainitic zone. It is then held at that temperature in a salt bath until the austenite is completely transformed into bainite.

After this the steel is allowed to cool to room temperature with the rate of cooling being immaterial. The dashed line in the figure shows that the core of the specimen to be austempered takes longer time to arrive at the bainitic zone than the surface.

## MARTEMPERING

Martempering is a type of cooling which is employed in order to obtain a fully martensitic structure with a minimum of distortion and residual stresses in the specimen.



*Fig. 3.15 : Martempering*

Here, the specimen is first cooled at a rate faster than the critical cooling rate to a temperature just above the martensitic start ( $M_s$ ) temperature. It is held at this temperature in a salt bath sufficiently long to make the temperature uniform throughout the volume of the specimen but not long enough to transform into bainite. The specimen is then cooled in air to room temperature.

By air cooling, the martensite will be formed at nearly the same time throughout the specimen. Thus, martempering also minimizes residual stresses and reduces the danger of distortion and cracking.

## **CASE HARDENING**

### **Carburizing**

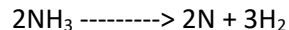
We know that the hardness of steel is increased with the presence of martensite in their microstructures. But the amount of martensite can increase only at higher carbon contents. In case of low carbon steels, the extent to which martensite is formed is reduced owing to lower carbon contents. In such cases, ore carbon is added to their surfaces. These steels whose surfaces are enriched in carbon are further subjected to regular hardening heat treatment as a result of which, more martensite forms at the surface and becomes more harder than in the interior. Carburizing is the term given to all methods of increasing the carbon content at surfaces.

There are three methods of carburizing – Solid, Liquid, Gaseous

### **Nitriding**

Nitriding is the process of obtaining hard and wear resistant surface on components made from alloy steels which contain stable nitride forming elements such as aluminum, chromium, molybdenum, vanadium, tungsten and so on.

In this process the specimen is heated to a temperature of about 500°C and held for considerable duration in an atmosphere of gaseous nitrogen. Nitrogen is produced when ammonia gas passed through the furnace at 550°C, the reaction being

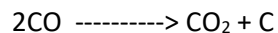
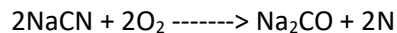


This nascent nitrogen is readily absorbed into the surface of the steel. The holding time depends on the desired depths and size of specimens.

### **Cyaniding**

In this process, steel surfaces are hardened by adding both carbon and nitrogen to the surfaces. The components to be case hardened are immersed in a liquid bath containing sodium cyanide and heated to the temperature range of 800-960°C.

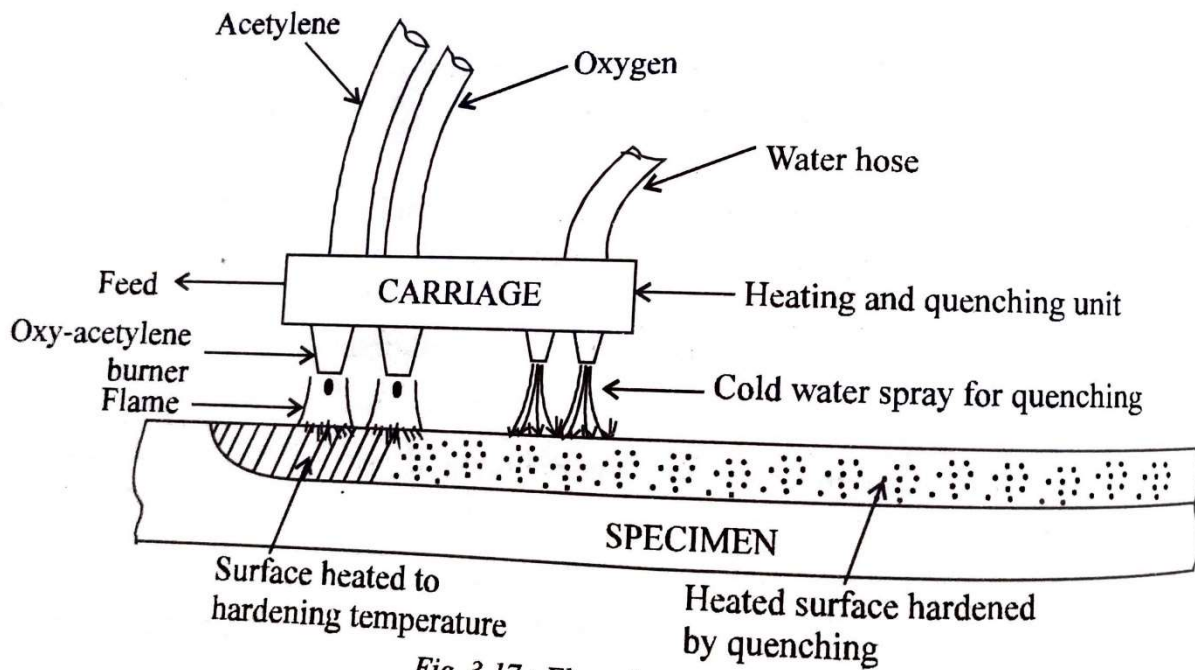
The reaction which take place are,



The nascent nitrogen and carbon produced diffuse into the surface of the steel. Further the components are quenched in order to obtain a hard wear resistant surface with a relatively soft interior.

## SURFACE HARDENING

### FLAME HARDENING

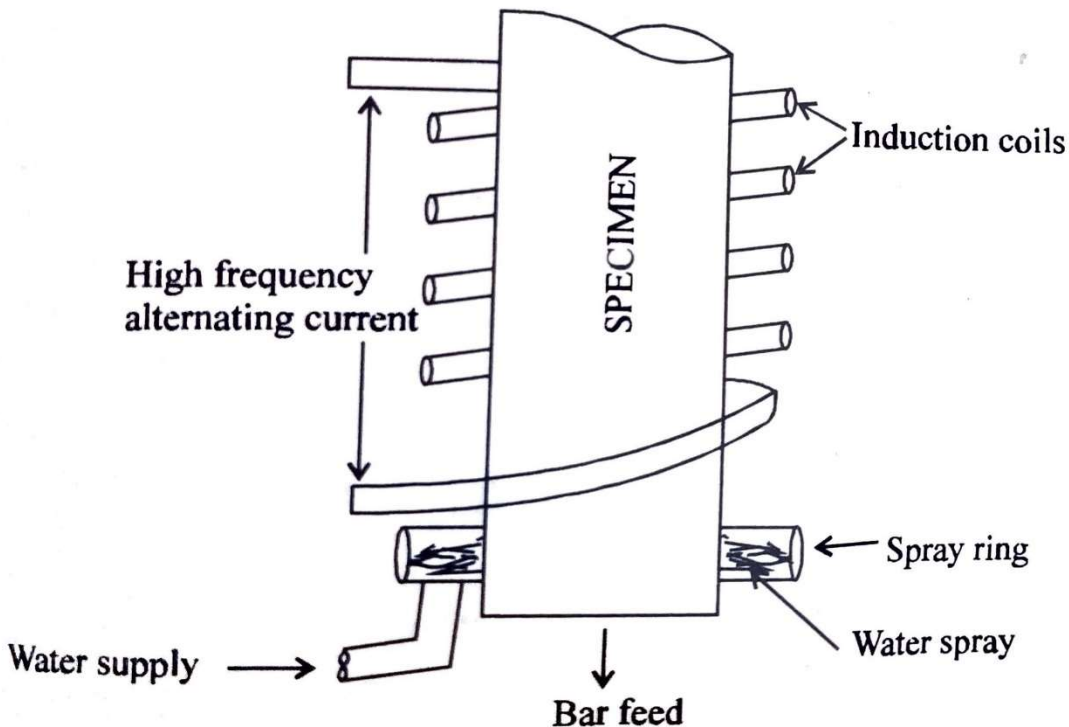


*Fig. 3.17 : Flame hardening*

Flame hardening involves rapid heating of a steel specimen by means of an oxy-acetylene flame to the austenitic range and follow it by quenching. Only the surface gets highly heated and becomes austenitic and upon quenching becomes martensitic. Therefore the surface becomes very hard but the core remains tough.

The carriage in the flame hardening set-up as shown in fig 3.17 contains both heating and quenching units and can run along the length of the specimen. Depth of hardened zone may be controlled by adjusting the flame intensity, heating time and speed of travel of carriage.

## INDUCTION HARDENING



***Fig. 3.18 : Induction hardening***

Induction hardening involves heating of the surface of the component by electromagnetic induction. Here the specimen is passed through induction coils connected to a high frequency alternating current generator.

When high frequency alternating current passes through the induction coils, a high-frequency magnetic field is set up. This magnetic field induces high frequency eddy currents and hysteresis currents in the specimen.

The metallic specimen offers resistance to the passage of these currents and hence gets heated. The high frequency induced currents tend to travel at the surface of the metal. This is known as skin effect. Due to this, it is possible to heat a thin layer of steel without heating the interior. The surface layer is heated almost instantaneously which is quickly followed by quenching by spraying water on the surface of the specimen.

## Ferrous and Non-Ferrous Materials

### Cast Irons

Cast Irons are those alloys of iron and carbon where the carbon content varies between 2.1% and 6.67%. However, since high carbon content tends to make the cast iron very brittle, most commercially available types of cast irons are in the range of 2.5% to 4% carbon.

### Types of Cast Irons

- i) Gray cast irons
- ii) Malleable cast Irons
- iii) S.G iron

#### 1. Gray Cast Iron

Gray Cast irons are the most widely used types of cast irons. They are distinguished by the presence of graphite in the form of flakes. Gray cast iron can be divided into different types based on the average length of the flakes in them.

The general characteristics of gray irons are:

Composition	2.5% -4% carbon 1%-3% silicon, rest iron
Microstructure	$\alpha$ - ferrite and flake graphite's
Properties	High fluidity, very high compressive strength, very effective in damping vibrations, low cost.
Fracture surface	Greyish, blackish surface when fractured (because of graphite flakes) Hence the name gray iron too
Applications	Pressure Vessels, cylinder heads, pistons, clutch plates, base structure for machines, fittings, levers etc.

#### 2. Malleable Cast Iron

Malleable cast iron are those alloys where almost all the carbon is in the free form in the shape of irregular particles known as temper carbon. As the name suggests, they are extremely malleable, and are produced by heat treatment of white cast iron.

The Characteristics of malleable iron are

Composition	1.8% – 3.2% carbon 0.3% - 1.8% silicon, rest iron
Microstructure	Dark graphite rosettes (temper carbon) in an $\alpha$ – ferrite matrix
Properties	Highly malleable, very good machinability, good magnetic properties, wear resistance
Applications	Connecting rods, transmission gears, flanges pipe fittings, differential cases for automotive industry and marine works

### 3. Spheroidal graphite (SG) Iron

S.G Iron is characterized by the presence of free carbon in the shape of compact spheroids or nodules. S.G Iron is also very well known for its ductility. Hence the other names of SG iron are Nodular Iron or Ductile Iron.

Composition	3% - 4% Carbon, 1.6 % -2.8% Silicon, rest iron Very low percentage of phosphorous and Sulphur
Microstructure	Dark graphite nodules surrounded by $\alpha$ - ferrite matrix
Properties	Highly ductile, very good machinability, high corrosion resistance and good properties at elevated temperatures.
Applications	Flywheels, furnace doors, wrenches, lathe chucks, motor frames, pump bodies etc.

## Non- Ferrous Alloys

Different types of non-ferrous alloys are –

1. Copper and its alloys
2. Aluminum and its alloys
3. Magnesium and its alloys
4. Titanium and its alloys

## Copper and its Alloys

The most important copper alloys can be classified as follows:

### 1. Brasses

- a. Alpha brasses
  - a. Yellow alpha brasses
  - b. Red brasses



- b. Alpha plus beta brasses

## 2. Bronzes

1. Tin bronzes ( Phosphor bronze)
2. Silicon bronzes
3. Aluminum bronzes
4. Beryllium bronzes

### 1. Brasses:

Brasses are essentially alloys of copper and zinc. But they may have small amount of other elements such as lead, tin or aluminum added to improve their properties.

#### 1. Alpha Brasses

Composition	Copper + up to 36% zinc
Microstructure	Only solid solution $\alpha$ – brass (FCC structure)
Properties	High corrosion properties, suitable for cold working.
Types of $\alpha$ - brasses	a) Yellow $\alpha$ -brasses b) Red brasses
Applications	Bullet shots, military ammunition, automotive radiator core , storage batteries etc.

#### 2. Alpha Plus Beta Brasses

Composition	Copper + 38 - 46% zinc
Microstructure	Solid solution $\alpha$ – brass (FCC) Electron compound $\beta$ – brass(BCC)
Properties	Suitable for hot working, harder and more brittle at room temperature than $\alpha$ – brass and therefore difficult to cold – work.
Types	a) Muntz metal b) Naval Brass
Applications	Marine hardware, propeller shafts, condenser plates etc.

## 2. Bronzes

Bronzes are those copper alloys which contain up to approximately 12% of the principal alloying element.

### 1. Tin Bronzes (Phosphor bronzes)

Composition	Copper 1-11% Tin +0.01-0.5% P
Microstructure	$\alpha$ - phase and dark $\delta$ - phase
Properties	High strength, toughness, low co-efficient of friction, free from season cracking, high corrosion resistance

Types of tin bronzes	a) Admiralty gun metal b) Bell metal
Applications	Bearings, steam pipe fittings, casting of bells

## 2. Silicon Bronzes

Composition	Copper+ up to 5%silicon
Microstructure	Single $\alpha$ -phase
Properties	Very strong, mechanical properties comparable to those of mild steel, high corrosion resistance
Applications	Corrosion resistant vessels, nuts and bolts, blades, bearings etc

## 3. Aluminum Bronzes

Composition	Copper+4-11% aluminum
Microstructure	Two phases primary $\alpha$ -phase, Eutectoid ( $\alpha + \gamma_2$ )
Properties	Suitable for cold working, good strength combined with corrosion resistance to atmosphere, and water attack
Applications	Corrosion resistant vessels, nuts and bolts, blades, bearings, bushings etc.

## 4. Beryllium Bronzes

Composition	Copper + 1.5 -2% Be +0.2% Co
Microstructure	dark $\gamma$ – phase at the grain boundaries of $\alpha$ - phase
Properties	Excellent formability, good fatigue and creep resistance when hardened, high electrical conductivity
Applications	Diaphragms, surgical instruments, bolts, firing pins etc.

# Aluminum and Its Alloys

## 1. Aluminum Copper Alloys:

Name of the alloy	Duralium
Composition	Al + 4% Cu
Microstructure	Solid solution $\alpha$ – phase, intermediate phase Cu Al <sub>2</sub>
Properties	One of the best non-ferrous alloys for age – hardening, high strength, corrosion resistant etc
Applications	Rivets in air craft construction, electrical cables, automobiles components etc

**2. Aluminum – Silicon alloys:**

Composition	up to 12.5% silicon
Microstructure	Solid solution $\alpha$ -phase + Eutectic ( $\alpha + \beta$ )
Properties	Good forgeability, low co-efficient of thermal expansion, excellent castability and resistance to corrosion
Applications	Intricate castings, food – handling equipment, marine fittings.

**3. Aluminum – Zinc Alloys:**

Composition	Up to 5.6% Zn, 0.6% Mg 0.5% Cr, 0.2 % Ti
Properties	Above composition gives highest mechanical properties without heat treatment. They have good castability, corrosion resistance and good machinability.
Applications	Aircraft structural parts, turret housings, radio equipment

**4. Aluminum Magnesium alloys:**

Composition	Up to 5% magnesium
Properties	Good weldability, good corrosion resistance, moderate strength, poor casting properties
Applications	Architectural extrusions, tubing's for automotive gas and oil lines, fittings for chemical and sewage use etc.

**5. Aluminum Lithium alloys:**

Composition	Up to 2.5% Lithium 1% Mg
Properties	Very low densities (2.5 to 2.6% g/cm <sup>3</sup> ) excellent fatigue strength, low temperature, toughness, high specific modulus
Applications	Aircraft and aerospace industries

**MAGNESIUM ALLOYS**

Composition	Aluminum Zinc, Thorium, Zirconium are common alloying materials
Properties	i) High strength to density ratio ii) Good resistance to deformation at room temperature

Limitations	<ul style="list-style-type: none"> <li>i) Magnesium ignites easily when heated in air. Hence difficult to cast.</li> <li>ii) Relatively brittle because of HCP structure</li> <li>iii) Magnesium alloys have relatively low strength and poor resistance to creep fatigue and wear.</li> <li>iv) Magnesium costs more than Aluminum</li> </ul>
Applications	<ul style="list-style-type: none"> <li>i) Steering wheels and columns, seat frames, transmission cases in automobiles.</li> <li>ii) Handheld devices such as chain saw, power tools etc.</li> <li>iii) Audi-video computer communications equipment's such as laptops, camcorders, cellphones etc</li> </ul>

## TITANIUM ALLOYS

Composition	Aluminum, Tin, Vanadium, Molybdenum are common alloying elements
Properties	<ul style="list-style-type: none"> <li>i) High Strength for its density</li> <li>ii) Can be easily forged and machined</li> <li>iii) Corrosion resistance at room temp is extraordinary</li> <li>iv) Retains strength at higher than room temperatures</li> </ul>
Limitations	<ul style="list-style-type: none"> <li>i) Chemically reacts with other materials at higher temperatures</li> <li>ii) Lower ductility because of HCP structure</li> <li>iii) More expensive than aluminum and Magnesium</li> </ul>
Applications	Air plane structure, space vehicles, surgical implants, Petroleum and Chemical industries etc

# MODULE 3

## **Solidification**

Solidification is the process where liquid metal transforms into solid upon cooling.

The properties of the solidified metal depends on its microstructure and the microstructure in turn depends on the 'Solidification Mechanism' employed to freeze the metal.

Transformation from liquid metal to solid metal is accompanied by a shrinkage in the volume. This volume shrinkage takes place in three stages:

- (i) Liquid-Liquid
- (ii) Liquid-Solid
- (iii) Solid –Solid

## **Mechanism of Solidification in pure metals and alloys**

Solidification of all liquid metals consist of two stages

- A) Nucleation of minute Crystals
- B) Growth of these crystals into grains

### **A) Nucleation:**

This is the starting point of the solidification process of any metal or alloy. In this stage a number of minute crystals nucleate throughout the melt.

Metal in molten condition possesses high energy and the atoms have high mobility.

As the liquid metal cools, the atoms gradually lose their energy and their movements become less vigorous. Then when atoms collide with each other, attractive forces are set up and atomic bonds are reestablished between them.

Therefore, small cluster of atoms, usually consisting of 10 –15 atoms are formed at several places in the molten metal and are known as nuclei.

It is the number of nuclei formed during the stage of nucleation which decides the final grain structure of the solidified metal and therefore some of its properties.

Nucleation in metals and alloys may occur by two mechanisms namely

- (i) Homogenous Nucleation (ii) Heterogeneous nucleation

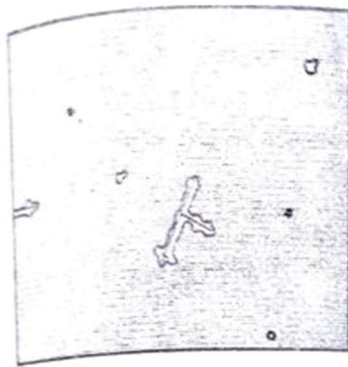
## B) Crystal Growth:

This is the stage where molten metal continues to solidify around the nuclei which are already formed. The nuclei and the metal solidifying around them continuously release latent heat which it had acquired during melting. This heat is absorbed by the surrounding molten metal and therefore for solidification to continue more and more heat has to be extracted i.e., cooling of metals should continue.

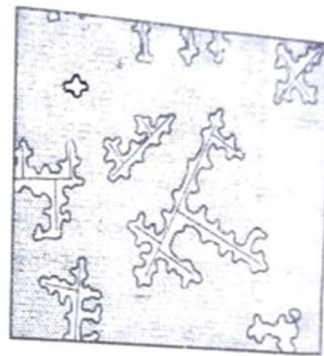
As the temperature decreases due to cooling the nuclei grow rapidly with atoms attaching themselves in identical layers around the nuclei grow rapidly with atoms attaching themselves in identical layers around the nuclei and a dendritic formation takes place.

When more and more atoms attach themselves in a particular direction, they form a trunk like that of a tree. Out of this trunk branches grow out and from these branches some more smaller branches grow out perpendicularly and altogether forms a tree like structure. This type of growth is called the dendritic growth (fig 2.51 a and b)

The dendrites are like skeleton in the microstructure of the solidified metal. When one big dendrite tree meets another, a grain boundary is formed along their border while the dendrites themselves become grains or crystals (fig 2.51c). The liquid metal along the grain boundaries will be the last to solidify and this marks the end of solidification.



*Fig. 2.51 : Nucleation*



*Fig. 2.51 (a) : Crystal growth*



*Fig. 2.51 (b) : Dendrite formation*



*Fig. 2.51 (c) : Grain formation*

## Solidification of Alloys

An alloy is defined as a combination of two or more elements of which at least one of them is a metal and the resulting material should have metallic properties.

Ex: Steel, Cast Iron, Brass, Bronze etc.

Solidification in alloys take place in the same two stages i.e., Nucleation and crystal growth. But most alloys, with some exceptions, solidify over a range of temperatures rather than at a constant temperature as in pure metals.

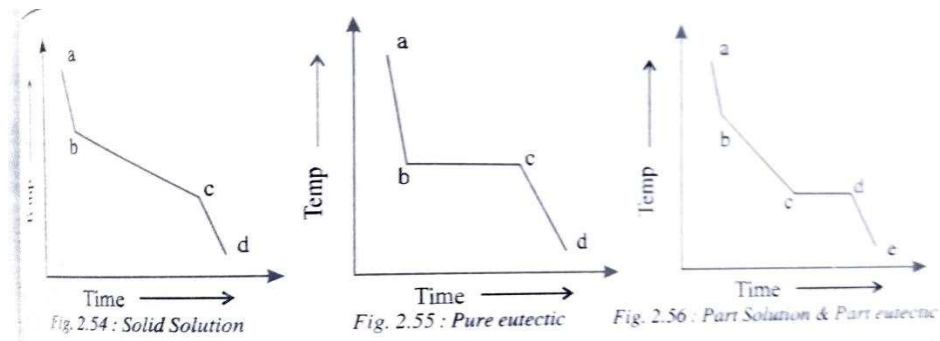
Based on solidification ranges, alloys can be divided into those which: -

i) Begin solidification at one temperature and end at another temperature i.e., solidify over range of temperature (fig 2.54).

E.g.: Solid-solution alloys.

ii) Begin and end solidification at a constant temperature just like in pure metals (fig 2.55). E.g.: Pure eutectics

iii) Begin solidification like a solid – solution but end it like a eutectic i.e., the first half of the solidification is over a range of temperatures and the second half is at a constant temperature (fig 2.56)



## Homogeneous Nucleation

When nucleation takes place in a liquid metal without the help of any impurities, then it is known as homogeneous nucleation.

Homogeneous nucleation occurs in perfectly homogeneous materials such as pure liquid metals.

It is the occurrence of ordered group of 100-200 atoms forming small clusters called nuclei.

For each nucleus so formed to be stable and to grow into a crystal, it must reach a certain size, called the 'Critical Size' or 'Critical radius'.

When solidification takes place, latent heat ( $\Delta f_v$ ) is released by the solidifying atoms.

This is given by,

$$\Delta f_v = -\frac{4}{3}\pi r^2 \Delta G \quad \text{---- (1)}$$

Where  $r$  = radius of the nucleus formed

$\Delta G$  = latent heat energy released / unit volume

(Negative sign because heat is released)

Whenever a new surface is formed, an energy known as surface energy is associated with it. In the melt, the surface energy associated with the newly formed nucleus is given by the relation,

$$\Delta f_s = 4\pi r^2 \gamma \quad \text{--- (2)}$$

Where  $r$  = radius of the nucleus,  $\gamma$  = surface energy / unit area

(positive because heat is absorbed)

Thus, the net energy change for a particle is of radius  $r$  is given by,

$$\Delta f = \Delta f_v + \Delta f_s$$

$$\Delta f = -\frac{4}{3}\pi r^3 \Delta G + 4\pi r^2 \gamma \quad \text{----- (3)}$$

Fig shows the relationship of latent heat energy ( $\Delta f_v$ ) and the surface energy ( $\Delta f_s$ ) with increase in the radius of the nuclei. It is also clear from the fig that as the particle radius increases, the net free energy ( $\Delta f$ ) also increases till the nucleus reaches a critical radius  $r^*$  but with further increase in particle radius the free energy decreases and even becomes negative. In order for the grain growth to take place around a particular nucleus, it should have reached the critical radius

The size of the critical radius can be estimated by differentiating Equation (3) with respect to ' $r$ ' and equating to zero

$$\frac{d}{dr}(\Delta f) = \frac{d}{dr}\left(-\frac{4}{3}\pi r^3 \Delta G + 4\pi r^2 \gamma\right) = 0$$

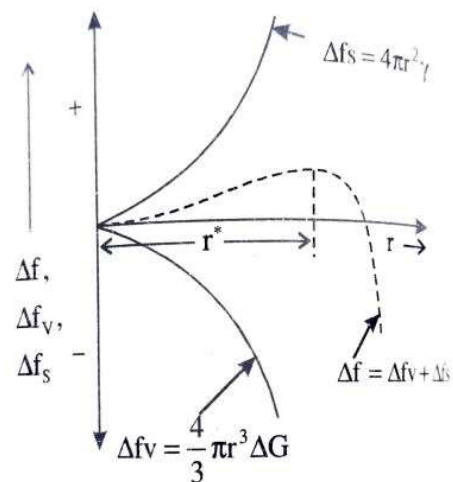


Fig. 2.57 : Variation of latent heat energy, surface energy & net energy with radius of nucleus



$$-4\pi r^2 \Delta G + 8 \pi r \gamma = 0$$

$$r = r^* = \frac{2\gamma}{\Delta G}$$

The net energy change for radius  $r^*$  is given by substituting value of  $r^*$  in equation 3

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

Therefore  $\Delta f^* = 16 \frac{16\pi\gamma^3}{3(\Delta G)^2}$  where  $\Delta f^*$  is also known as activation energy

### Heterogeneous Nucleation

When nucleation takes place in liquid metal with the help of impurities, then it is known as heterogeneous nucleation.

Impurities could be insoluble matter like sand particles, alloy additions to the solidifying metal, even mould walls or any other foreign agent deliberately added to bring about nucleation in order to begin the process of solidification.

Nuclei in heterogeneous nucleation are formed on the surfaces of the above possible surfaces often called the substrate. But for nucleation to actually take place i.e., for a particular surface to serve as a nucleation site for that system, two things must happen

(i) The substrate surface must be actually wetted by the liquid metal. Imagine surfaces like plastic which do not get wetted by water particles which fall on them, and hence do not hold them.

(ii) The contact angle ( $\theta$ ) of the cap-shaped nucleus should be less than  $90^\circ$  theoretically. In general, all liquid particles resting on flat or circular surfaces and wetting them will yield angles less than  $90^\circ$ .

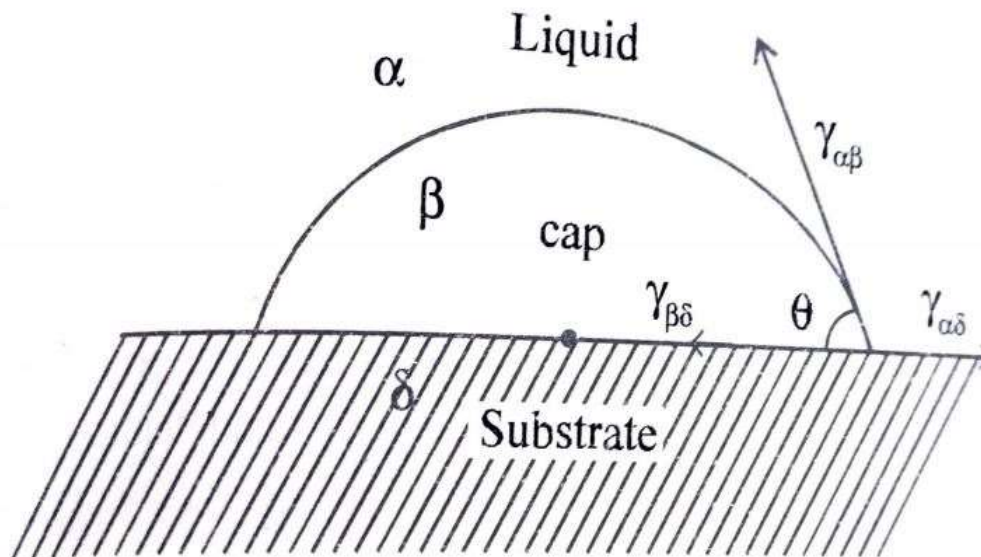


Fig. 2.58 (a) : Heterogeneous Nucleation

## Cast Metal Structures or Ingot Structures

When Molten metal is poured into a mould and allowed to solidify, different grain structures may result in the casting.

In other words, the size and shape of the grains or crystals may differ for each casting and this depends on several factors like

- a) Pouring temperature.
- b) Mould material and its thermal conductivity
- c) Mass of metal
- d) Composition of the alloy

Basically, there are three types of grain structures which can result in ingot castings. They are:

- i) Columnar grains
- ii) Equiaxed grains
- iii) Partially Columnar and Partially equiaxed

### i) **Columnar Grains:**

When molten metal is poured into a mould, the layer which comes in contact with the mould walls cools first and forms fine, hard crystals known as chill crystals. The liquid adjacent to these chill crystals then solidify and start growing in a direction opposite to the direction of heat flow and become columnar grains (fig 2.59). This occurs when there is an absence of nucleation at the centre of the melt and is typical of pure metals.

### ii) **Equiaxed grains:**

Equiaxed grains are obtained when liquid metal which is poured into the mould is cooled suddenly. This type of structure occurs when there is extensive nucleation throughout the melt.

Fig 2.60 illustrates equiaxed grains and is typical of alloys.

### iii) **Partially Columnar and partially equiaxed:**

The solidification here begins like a pure metal and ends like an alloy. In other words solidification begins with chill crystals and growth of columnar grains but before they advance nucleation takes place at the centre and results in equiaxed grains and is typical of solid-solutions alloys (fig 2.61)

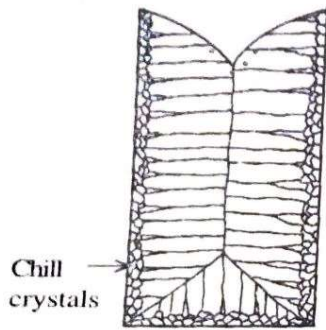


Fig. 2.59 : Columnar grains

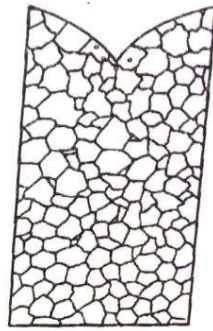


Fig. 2.60 : Equiaxed grains

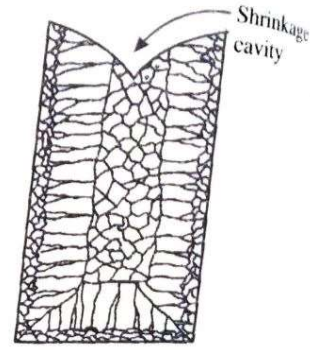


Fig. 2.61 : Partially Columnar and partially equiaxed

## Grain Refinement

Grain refinement is nothing but modifying the size of equiaxed grains in a casting.

Generally, grain refinement refers to decreasing the average grain size. This can be brought about by a number of following ways: -

- i) When the rate of cooling is high.
- ii) Low pouring temperature
- iii) Proper control of alloying elements to promote constitutional super cooling
- iv) Addition of an inoculating agent in the form of a metal powder to the melt while it is being poured
- v) When thermal conductivity of the mould is high.

## Solid Solutions

A solid solution is simply a solution in the solid state and consists of two kinds of atoms in one type of small lattice. In a solid solution, the metal in the major proportion is called the solvent and the metal in the minor proportion is called the solute.

E.g., Cu-Ni, Au-Ag etc.

## Types of Solid Solutions

- 1) Substitutional solid solutions
- 2) Interstitial Solid Solutions

### 1) Substitutional Solid Solution:

In this type of solid solution, the solute atoms substitute the atoms of the solvent in the crystal structure of the solvent. For example in the Au-Ag solid solution, the silver atoms substitute for the gold atoms in the FCC structure of gold. There are two types of substitutional solid solutions.

**a) Orderly Substitutional solid solution:**

In this type, the solute atoms substitute the solvent atoms in an orderly manner, taking up the fixed positions of symmetry in the lattice.

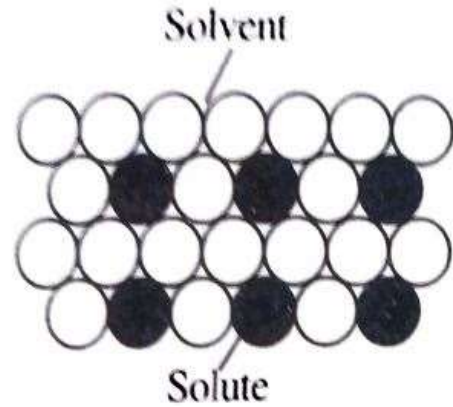
Therefore this type of solid solution has an uniform distribution of solute and solvent atoms.

**b) Disordered substitutional solid solution:**

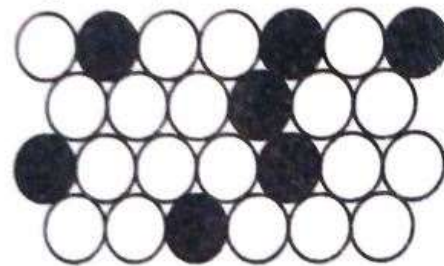
The solute atoms here do not occupy any fixed positions but are distributed at random in the lattice structure of the solvent.

In this type of solid solution, the concentration of solute atoms may vary considerably through out the lattice structure

It is to be noted here that substitutional solid solutions are generally ordered at lower temperatures and disordered at higher temperatures, thus temperature being the deciding factor.



*Fig. 2.21 (a) : Ordered SSS*



*Fig. 2.21 (b) : Disordered SSS*

## Interstitial Solid Solution

These are formed when atoms of small atomic radii fit into the interstitial spaces of the large solvent atoms.

Atoms of elements such as carbon, nitrogen, boron, hydrogen which have very small atomic radii (less than  $1\text{\AA}$ ) are likely to form interstitial solute atoms and may dissolve more readily in transition metals such as Fe, Ni, Mn, Cr etc. than in other metals

For example carbon forms an interstitial solid solution with FCC iron and is called austenite,

Interstitial solid solutions normally have limited solubility and generally are of less importance than substitutional solid solutions with austenite being an exception.



*Fig. 2.22 : ISS*

# **Rules of Formation of Solid Solutions**

## **Or**

## **HUME-ROTHARY Rules**

These rules govern the formation of substitutional solid solutions. In other words, only when these rules are satisfied, a substitutional solid solution can form.

1) Crystal Structure Factor :

For complete solid solubility of two elements, they should have the same type of crystal lattice structure.

For example in Au- Ag solid solution, both have FCC structure

2) Relative Size Factor:

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

3) Chemical -affinity factor :

For a substitutional solid solution to form, the two metals should have very less chemical affinity. Greater the chemical affinity between the two metals, lesser are the chances of forming a solid solution. Generally, the farther apart the elements are in the periodic table, the greater is their chemical affinity.

4) Electro-negativity :

The above point can also be explained in terms of electro negativity (tendency to acquire electrons) of the two elements. Higher the electro-negativity of the two elements, greater will be the chances of forming an intermediate phase rather than a solid solution.

5) Relative valence factor:

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

For example in the Al-Ni alloy system, both metals are faced centred cubic and their relative size difference is less than 15%.

However, Nickel which has a valency of two dissolves 5% aluminum, while on the other hand aluminum which has a valency of three dissolves only 0.004% Ni.

## Intermediate Phases or Intermediate Alloy Phases

Addition of an alloying element to a given metal to an excessive amount than solid solubility results in a second phase appearance with the solid solutions. This second phase is known as Intermediate Alloy Phase.

It differs in both crystal structure and properties from solid solutions

Intermediate phase may range between ideal solid solutions on one hand and ideal chemical compounds on the other hand

Intermediate alloy phases could be either intermediate solid solutions or intermediate compounds.

The three most common intermediate alloy phases are:

1) Intermetallic or valency compounds

When intermediate alloy phases are exclusively metal-metal systems, they are called intermetallic compounds.

These compounds are generally formed between chemically dissimilar metals and are combined by following the rules of chemical valence.

The combination is usually non-metallic and show poor ductility and poor electrical conductivity and may have a complex crystal structure.

E.g.,  $\text{Mg}_2\text{Pb}$ ,  $\text{Mg}_2\text{Sn}$ .

2) Interstitial compounds

These are similar to interstitial solid solutions except that they have more or less a fixed composition.

E.g.:  $\text{Fe}_2\text{C}$ ,  $\text{Tic}$ .

The interstitial compounds are metallic in nature, have high melting points and are extremely hard. Most carbides are interstitial in nature.

3) Electron Compounds

These compounds are of variable composition and do not obey the valency law, but have a definite electron to atom ratio

For example in the compound  $\text{Cu}_9\text{Al}_4$ , each atom of copper has one valence electron and each atom of aluminum has three valence electrons, so that 13 atoms which make up the compound have 21 valence electrons to atom ratio 21:13.

Many Electron compounds have properties resembling those of solid solutions including a wide range of compositions, high ductility and low hardness.

## Gibb's Phase Rule

It states that,  $P + F = C + 2$

Where,

- $P$  = number of phases
- $F$  = number of degrees of freedom
- $C$  = number of components in the system
- Digit 2 = the two system variables, temperature & pressure

(A mnemonic for Gibb's Phase rule would be; Police force = Cops + 2)

**Phase:** A Phase is a homogeneous, physically distinct portion of a system having its own boundary. A solid phase has its own crystal structure and its set of individual properties

**Degrees of freedom:** The number of degrees of freedom of a system is the number of variables that may be changed independently without causing the disappearance of a phase.

In other words, the equilibrium of the system is not disturbed by altering the variable. These variables may be external (temperature) and internal (composition).

## LEVER RULE

The amount or the quantity of each phase present at  $M$  is given by the Lever Rule. It states that, **"The relative amount of each phase is directly proportional to the length of the opposite lever arm"**.

A mechanical analogy to the 'Lever Rule' is shown in fig 2.26.

Consider a lever of length  $OP$  equal to the length of the tie line. A fulcrum is considered to be supporting the lever. A fulcrum is considered to be supporting the lever at point  $M$  which represents the overall composition. In order to keep the lever horizontal i.e., in equilibrium, weights are hung at ends ' $O$ ' and ' $P$ ' which are proportional to opposite lever arms. In other words  $W_L$  represents the weight or the amount of liquid phase and  $W_S$  represents the weight or the amount of solid phase present at.

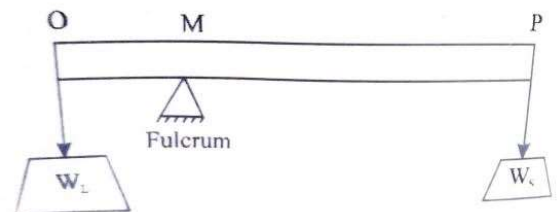


Fig. 2.26 : Lever Rule

## Phase Diagrams

A Phase diagram is essentially a graphical representation of an alloy system. Phase diagrams are also called as Equilibrium diagrams.

Phase Diagrams are classified as:

- Unary phase diagram (one component)

- II) Binary phase diagram (two component)
- III) Ternary phase diagram (three component)

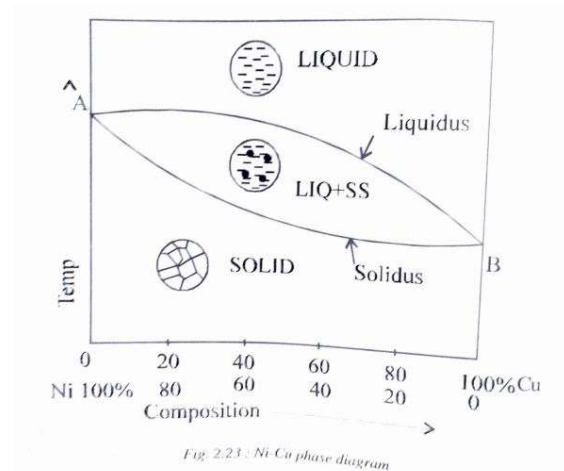
## Binary Phase Diagrams

A binary phase diagram is drawn with temperature on Y axis and various compositions of the two components on the X-axis. Pressure is assumed to be constant at 1 atm for all binary phase diagrams.

Fig 2.23 shows the phase diagram of Ni-Cu system which forms a solid solution for its complete range of compositions.

For all combinations of temperature and compositions above the curve marked liquidus, the mixture is in the liquid state. For all combinations below the solidus curve, the mixture is in the solid state and then we have a mixture of solid and liquid for any combinations between the two curves.

Points A and B represent the melting temperatures of nickel and copper, respectively.



It is to be noted here that phase diagrams show the relationship of the phases with temperature and composition will not change with time. Equilibrium conditions may be approached by extremely slow heating and cooling, so that if a phase change is to occur by varying temperature or composition, sufficient time must be allowed.

## CONSTRUCTION OF PHASE DIAGRAM USING COOLING CURVES

Following are the general steps involved in the construction of a binary equilibrium diagram between any two metals. The example taken here is the Nickel-Copper system which forms a continuous solid solution (Fig 2.24)

1. Cooling curves of pure Nickel and pure Copper are drawn on two parallel vertical axes which represent temperatures.
2. A series of cooling curves of different compositions of Ni and Cu are drawn at appropriate places between the cooling curves of the two pure metals.



3. The cooling curves of all the alloys are typical that of a solid solution i.e., there is liquid-liquid, liquid-solid and solid-solid transformations which make up each cooling curve.
4. Now, a curve is drawn which joins the beginning of solidification points of all the cooling curves of the alloys. A curve is also drawn which joins the end of solidification of all the cooling curves
5. In the cooling curves of pure metals Ni and Cu the mid points are chosen for both beginning and ending of solidification to join the two curves since they are at constant temperatures.
6. Therefore an equilibrium diagram is obtained which is normally shown without the series of cooling curves which helped its construction

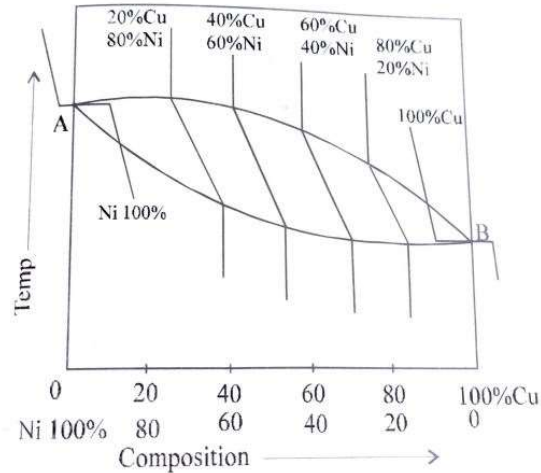


Fig. 2.24 : Construction of phase diagram

# MODULE 4

## Composite Materials

Composite materials are those which are created artificially by combining two or more materials which usually have dissimilar characteristics.

In other words, a composite material can be defined as a *'materials system composed of a combination of two or more constituents that differ in form and chemical composition and which are insoluble in each other'*.

### Role of matrix

1. Matrix transfers the applied load to the reinforcement
2. Matrix protects the reinforcement from mechanical and environmental attacks.
3. Matrix provides for low density in case of FRP
4. Matrix improves the impact and fracture resistance of composite
5. Matrix enables to keep the fibres aligned in a pre-determined direction

### Role of Reinforcement

1. Reinforcement gives strength and stiffness to the composite
2. Reinforcement helps engineers in tailoring composites to the needs of specific applications
3. Reinforcements helps in obtaining properties in composites in the direction preferred
4. Reinforcement deflects crack front in matrix thereby hindering crack growth

## Classification of Composites

Composite materials can be classified in two ways depending on the base matrix material used or depending on the shape of reinforcement used

### According to Base – Matrix material

- i) Polymer composites
- ii) Ceramic composites
- iii) Metal- matrix composites

### According to shape of reinforcement

- i) Fibre / Whiskers
- ii) Laminate
- iii) Particulate

## Types of Matrix Materials

### i) **Polymer – Matrix Composites (PMC's)**

Polymer matrix composites (PMC's) consist of a polymer resin as the matrix material. The term resin is used in the context to denote a high -molecular weight reinforcing plastic.

These materials are used as matrix materials in great diversity of composite applications, as well as in large quantities because of their excellent room - temperature properties, ease of fabrication, highly economical costs and aesthetic values.

Polymer matrices are often dispersed with the reinforcement material in the shape of fibres which are normally stronger and have a higher melting temperature.

Thermoplastic polymers and thermosetting polymers are both used extensively as matrix materials.

### ii) **Ceramic Matrix Composites (CMC's)**

Ceramic materials are very well known for their high temperature properties as well as their resistance to oxidation. But they are very brittle which limits their applications.

Ceramics which are commonly used as matrix materials are silicon nitride ( $\text{Si}_3\text{N}_4$ ), Silicon Carbide ( $\text{SiC}$ ), Alumina ( $\text{Al}_2\text{O}_3$ ), Zirconium dioxide ( $\text{ZrO}_2$ ) but it is a fact that ceramics make better reinforcement material than matrix materials.

### iii) **Metal -Matrix composites (MMC's)**

Metal – matrix composites are those where metals or alloys are used as matrix materials, as the name implies. Metals used are usually ductile in nature and is reinforced with stronger and low-density materials of all shapes -fibres whiskers and particulate.

Such combinations help in obtaining materials with improved stiffness, abrasion resistance, creep resistance, thermal conductivity and dimensional stability.

Some of the advantages of metal – matrix composites include higher operating temperatures, non-flammability and greater resistance to degradation by organic fluids. But MMC's are more expensive than PMC's and therefore, their use is somewhat restricted.

Examples for MMC's include aluminum-alloy matrix reinforced with alumina and carbon fibres used in automobiles as engine components.

Thermo plastic polymers	Thermo setting polymers
1. They have long chain polymers held by secondary bonds	They have 3-D network of bonds
2. Polymerization is linear	Polymerization proceeds in all directions
3. They soften when heated and harden when cooled	They become permanently hard when they are heated and do not soften upon cooling
4. At higher temperatures, these polymers liquify because of the breaking of secondary bonding forces.	At higher temperatures, the strong cross-linked bonds are broken and leads to polymer degradation rather than melting
5. They are relatively soft and ductile	They are harder, stronger and brittle
6. Suitable for use only at low temperatures.	Suitable at both low and high temperature
7. Examples – nylons, PTFE, Polythene	Examples include epoxies, phenolics, polyesters etc.,
8. Applications – toys, bearings, cans, flexible bottles, safety helmets	Applications – electrical moldings, sinks, motor housings, telephones, helmets, chairs etc.

## Types of Reinforcement

### i) Fibre Reinforced Composites

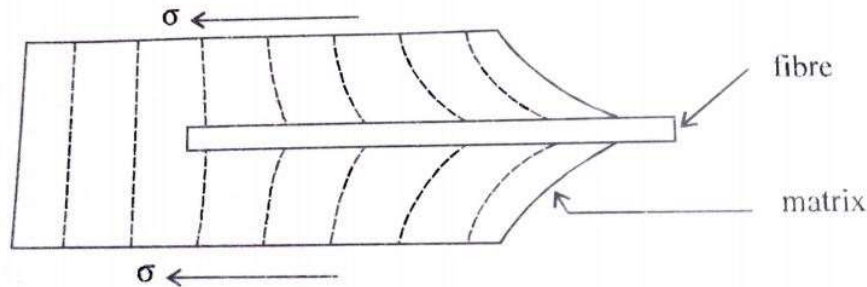
Fibre reinforced composites are those where the reinforcement is in the form of fibres. A natural example for a fibre reinforced composite is wood in which strong cellulose fibres are aligned in a base matrix of lignin which binds the fibres

Technologically the most important type of composites is fibre reinforced ones because of their wide range of applications. The characteristics of fibre reinforced composites are expressed in terms of specific strength and specific modulus parameters.

Fibre reinforcements can be employed in all three types of matrices i.e, plastic ceramic and metal. Usually, a fiber reinforced composite contains high strength and low density fibres in a ductile matrix. However, the combination as a composite can have reasonable strength and good toughness and can still have low density.

The matrix binds the fibres together and protects them from mechanical and chemical damage. The strength of the fibre reinforced composite is determined by the strength of the fibre and the strength of the bond between the fibres and the matrix.

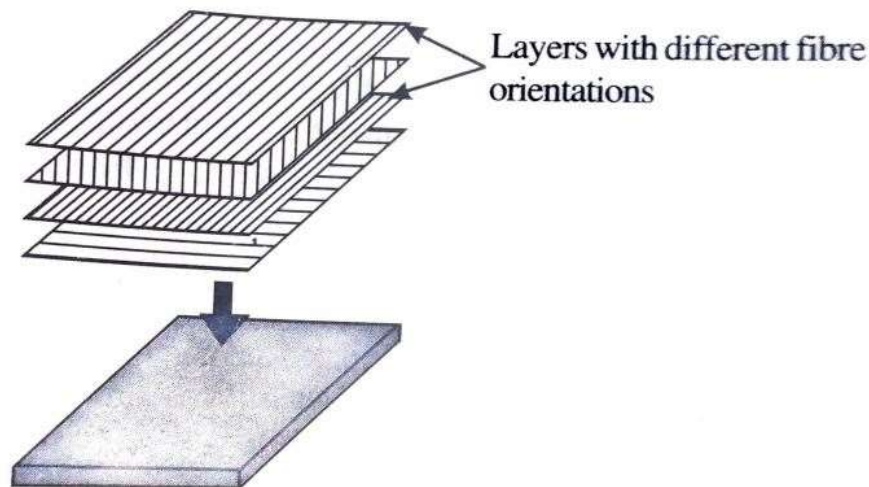
The bond between the fibres and matrix must be strong enough to prevent the fibre pullout under external loads (Fig 4.1), For this to happen the matrix should actually wet the fibres and at the same time there should be no chemical reaction between them.



*Fig. 4.1 : Wetting of fibre by matrix*

## ii) **Laminated Composites**

In fibre-reinforced composites, if the fibres are of uniform alignment, the composites show anisotropic properties i.e., different properties along different directions. But if layers of such composites are stacked and bonded together in such a way that successive layers have their fibres aligned in different directions, the composite overall will have high strength and uniform properties in all directions.(Fig 4.5)



*Fig. 4.5 : Laminated composite*

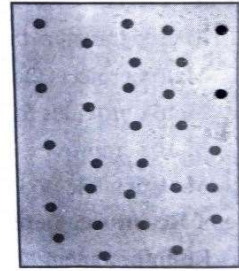
The best example for a laminated composite is plywood where successive layers of wood having different orientation of grains are cemented together and the composite on the whole has better strength in all directions.

Laminated composites can also be made from layers of two different materials that are bonded or clad together.

### iii) **Particulate Reinforced composites**

In this type of composites, particles of varying shape and size of one material is dispersed in a matrix of second material. Particulate composites are similar in construction to dispersion strengthened alloys but differ in particle size and percentage by volume.

Particulate composites are produced with all three types of matrix materials. Important among them are "**Cermets**" which are a group of ceramic - metal combination materials.



*Fig. 4.6 : Particulate composite*

## **Advantages Limitations and Applications of Composite Materials**

### **Advantages**

1. Composite materials possess an excellent combination of mechanical, chemical structural, optical and other desired properties
2. They are generally light weight materials having higher strength to weight ratio and higher modulus to density ratio than the conventional materials.
3. Composites, especially the polymer matrix composites can be moulded to any shape and size
4. They possess excellent anti corrosion and anti-chemical properties
5. They also have good resistance towards severe climatic conditions like heat, cold or rains.
6. Fibre-reinforced composites are virtually replacing every object made of conventional materials due to its low cost and ease of production
7. Wastage can be reduced in the fabrication of composites. Recycling is also possible in many cases.
8. Composites can be designed to obtain aesthetic appearance

### **Limitations**

1. Polymeric composites are not suitable for high temperature applications.
2. They have low flash and fire points
3. Cost of composites is higher when volume of production is less
4. On prolonged exposure to sunlight, the colors of composites generally fade out

### **Applications of Composite materials**

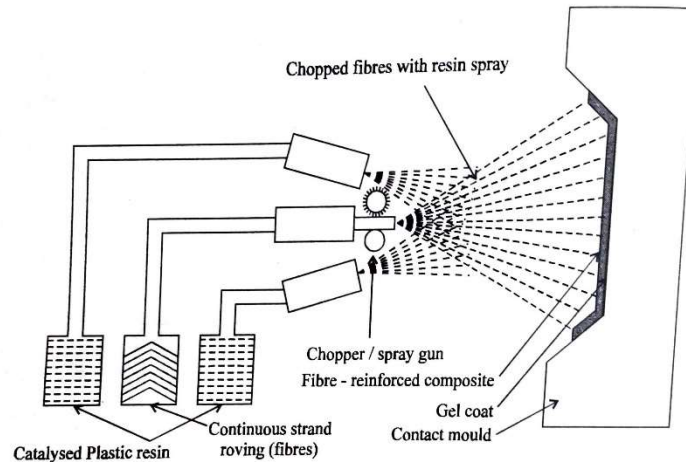
1. In automobile industries (e.g., Steel and Aluminum body)
2. Marine applications like shafts, hulls, spars (for racing boats)
3. Aeronautical application like components of rockets, aircrafts (business and military), missiles etc.
4. Communication antennae, electronic circuit boards (e.g., PCB, breadboard)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

## What is FRP? (Fiberglass reinforced polymer)

FRP (Fiberglass reinforced polymer) is a strong light weight building that resist corrosion

## Open Moulding Processes

### Spray Lay-Up



### Description:

In this process, continuous fibres are first cut into desired length by a chopper. Then a mixture of fibre and resin along with a catalyst is sprayed simultaneously onto a vertical mould. The density of the deposited laminate is later increased with the help of a roller onto a vertical mould. The density of the deposited laminate is sure that the resin completely covers the reinforcing fibres. Multiple layers may be added to produce the desired thickness. Curing is usually at room temperature but may be accelerated by the application of a moderate amount of heat.

### Material Options:

- Resins: Primarily polyester
- Fibres: Glass roving only
- Cores: None. These have to be incorporated separately

### Typical Applications:

Simple enclosures lightly loaded structural panels, e.g. caravan bodies, truck fairings, bathtubs, shower trays, some small dinghies.

### Main Advantages

- Widely used for many years.
- Low-cost way of quickly depositing fibre and resin.

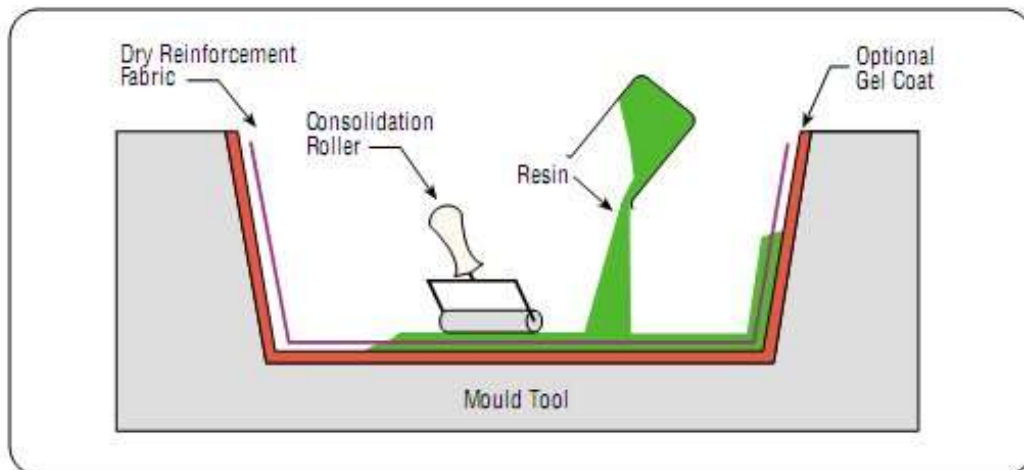
- Low-cost tooling.

#### **Main Disadvantages:**

- Laminates tend to be very resin-rich and therefore excessively heavy.
- Only short fibres are incorporated which severely limits the mechanical properties of the laminate.
- Resins need to be low in viscosity to be sprayable. This generally compromises their mechanical/thermal properties.
- The high styrene contents of spray lay-up resins generally mean that they have the potential to be more harmful and their lower viscosity means that they have an increased tendency to penetrate clothing.

Limiting airborne styrene concentrations to legislated levels is becoming increasingly difficult

#### **Wet/Hand Lay-up**



#### **Description:**

Resins are impregnated by hand into fibres which are in the form of woven, knitted, stitched or bonded fabrics. This is usually accomplished by rollers or brushes, with an increasing use of nip-roller type impregnators for forcing resin into the fabrics by means of rotating rollers and a bath of resin. Laminates are left to cure under standard atmospheric conditions.

#### **Materials Options:**

- Resins: Any, e.g., epoxy, polyester, vinylester, phenolic
- Fibres: Any, although heavy aramid fabrics can be hard to wet-out by hand.
- Cores: Any.

#### **Typical Applications:**

Standard wind-turbine blades, production boats, architectural mouldings.



### Main Advantages:

- Widely used for many years.
- Simple principles to teach.
- Low-cost tooling, if room-temperature cure resins are used.
- Wide choice of suppliers and material types.
- Higher fibre contents and longer fibres than with spray lay-up.

### Main Disadvantages:

- Resin mixing, laminate resin contents, and laminate quality are very dependent on the skills of laminators. Low resin content laminates cannot usually be achieved without the incorporation of excessive quantities of voids.
- Health and safety considerations of resins. The lower molecular weights of hand lay-up resins generally mean that they have the potential to be more harmful than higher molecular weight products. The lower viscosity of the resins also means that they have an increased tendency to penetrate clothing.
- Limiting airborne styrene concentrations to legislated levels from polyesters and vinylesters is becoming increasingly hard without expensive extraction systems.
- Resins need to be low in viscosity to be workable by hand. This generally compromises their mechanical/thermal properties due to the need for high diluent/styrene levels.

### Vacuum Bagging and Pressure bag Moulding

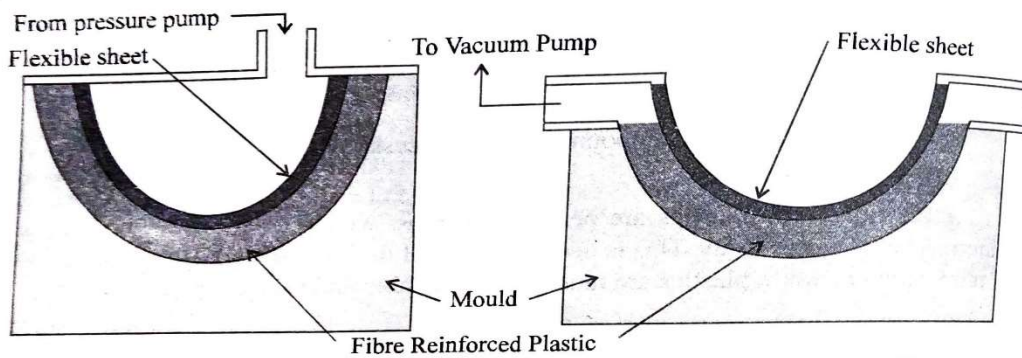


Fig. 4.10 : Pressure bag moulding

Fig. 4.11 : Vacuum-bag moulding

### Description:

Bag moulding is an improvement over the hand lay-up process in that it further removes the entrapped air. The two-basic bag moulding methods are Pressure – bag, Vacuum – bag.

In all the different types of bag moulding, plastic resin is first poured over fibre reinforcement mats placed in an open mould. This mixture of fibre and resin is covered by a flexible sheet. Pressure is then applied to the sheet in various ways so as to compact the fibre and matrix composite. In the case of (i) **pressure bag** moulding high pressure air is used to compact the mixture in the mould cavity. In (ii) **Vacuum- bag**

moulding a vacuum evacuate the mould cavity. The vacuum created results in the elimination of voids, trapped air and excess resin and at the same time has a compacting effect

#### Materials Options:

- Resins: Primarily epoxy and phenolic. Polyesters and vinylesters may have problems due to excessive extraction of styrene from the resin by the vacuum pump.
- Fibres: The consolidation pressures mean that a variety of heavy fabrics can be wet-out.
- Cores: Any.

#### Typical Applications:

Large, one-off cruising boats, racecar components, core-bonding in production boats.

#### Main Advantages:

- Higher fibre content laminates can usually be achieved than with standard wet lay-up techniques.
- Lower void contents are achieved than with wet lay-up.
- Better fibre wet-out due to pressure and resin flow throughout structural fibres, with excess into bagging materials.
- Health and safety: The vacuum bag reduces the amount of volatiles emitted during cure.

#### Main Disadvantages:

- The extra process adds cost both in labour and in disposable bagging materials.
- A higher level of skill is required by the operators.
- Mixing and control of resin content still largely determined by operator skill

#### Filament Winding:

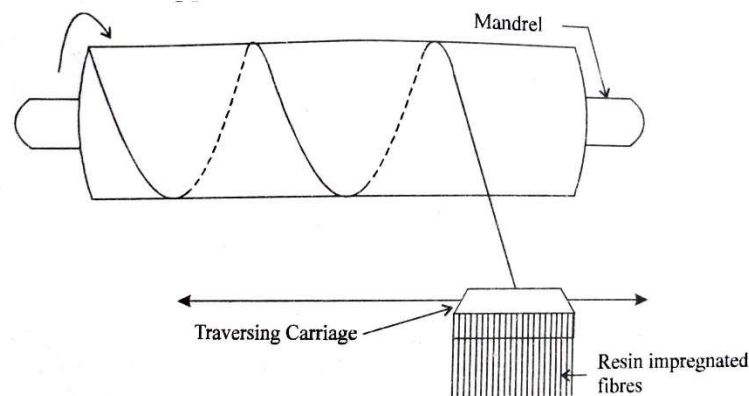


Fig. 4.12 : Filament Winding Process

**Description:**

In this process, strands of fibre reinforcement is fed through a plastic resin bath and then wound on a suitable rotating mandrel in pre-determined orientations. While the mandrel rotates and rolls up the resin impregnated fibres, the traversing carriage runs along the length of the mandrel. The filaments are wound along different orientations so as to utilize their strength in an effective manner.

When sufficient layers have been taken up, the wound mandrel is either cured at room temperature or at an elevated temperature in an oven. The molded composite is then stripped from the mandrel. In some cases the mandrels are usually made of low – melting point alloys and are later melted down.

**Materials Options:**

- Resins: Any, e.g., epoxy, polyester, vinylester, phenolic
- Fibres: Any. The fibres are used straight from a creel and not woven or stitched into a fabric form
- Cores: Any, although components are usually single skin

**Typical Applications:**

Chemical storage tanks and pipelines, gas cylinders, fire-fighters breathing tanks

**Main Advantages:**

- This can be a very fast and therefore economic method of laying material down.
- Resin content can be controlled by metering the resin onto each fibre tow through nips or dies.
- Fibre cost is minimised since there is no secondary process to convert fibre into fabric prior to use.
- Structural properties of laminates can be very good since straight fibres can be laid in a complex pattern to match the applied loads.

**Main Disadvantages:**

- The process is limited to convex shaped components.
- Fibre cannot easily be laid exactly along the length of a component.
- Mandrel costs for large components can be high.
- The external surface of the component is unmoulded, and therefore cosmetically unattractive.
- Low viscosity resins usually need to be used with their attendant lower mechanical and health and safety properties.

## Closed Moulding Process

### Pultrusion Process:

(image)

Pultrusion process is used for producing fibre reinforced plastics of constant cross section such as I-beams, tubes, pipes etc. In this, resin impregnated fibres are first fed into a pre – forming box which gives appropriate orientation to the fibres. These oriented fibres are then fed into a heated steel die which determines the cross section of the composite stock. Thus, continuous lengths of constant cross section can be drawn through the die. Very high strengths in certain directions are possible in the composites because all the fibres run parallel to the length of the stock. A high volume fraction of fibres can be packed into the composite which also contributes to the high strength.

### Advantages:

- The process is suitable for mass production.
- The process is fast and economic.
- Resin content can be accurately controlled.
- Fibre cost is minimized as it can be taken directly from a creel.
- The surface finish of the product is good.
- Structural properties of product can be very good as the profiles have very straight fibres.

### Disadvantages:

- Limited to constant or near constant cross-section components.
- Heated die costs can be high.
- Products with small cross-sections alone can be fabricated.

### Applications:

Beams and girders used in roof structures, bridges, ladders, frameworks

### Pulforming

In this process, the fabrics may also be introduced into the die. The fabrics provide a fibre direction other 0°. Further, a variant of this method to produce a profile with some variation in the cross-section is available. This is known as **pulforming**.

### Injection Molding

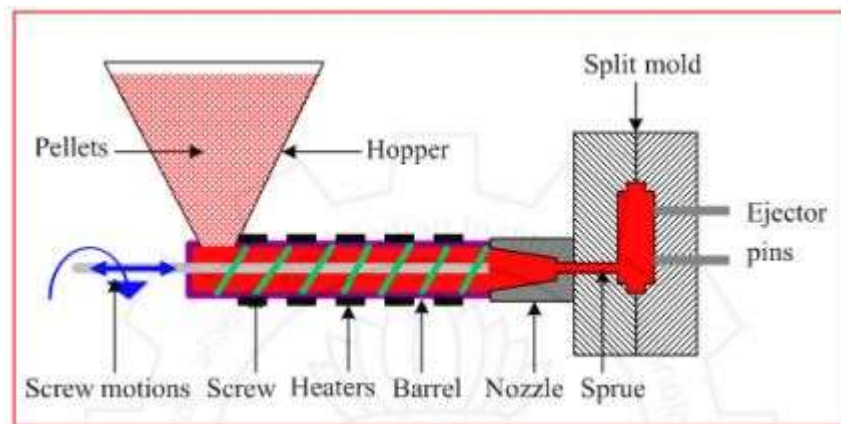
In this process, plastic granules are heated and forced under pressure into a die cavity of desired shape. This process is well suited for producing true three-dimensional shapes such as bottles, toys etc., which

require fine details like holes, snaps, and surface details. Figure 3.7.2 schematically presents an Injection Molding set-up for polymer processing.

Design for gating and feed system for the die is crucial to ensure complete die fill. It is important to design the molding so that solidification does not prevent complete mold filling. The design and location of the gates for entry of polymer is a crucial design details. For large part more than one gate may be required for proper flow of material.

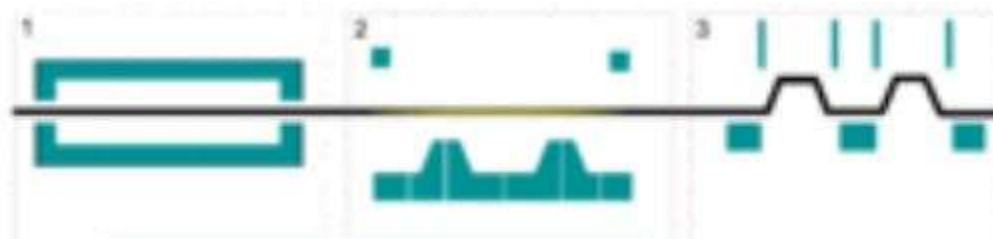
Mold must be designed in such a way that the solid part can be ejected without distortion. By considering proper orientation at the beginning, it may be possible to avoid expensive mold cost. If possible, design the part so that it can be ejected in the direction of mold closure.

To minimize the shrinkage fillers like glass fiber, wood flour, are added during molding. With some part geometries, post mold shrinkage can lead to generation of high residual stress.



### Thermoforming Process

Thermoforming is a manufacturing process where a plastic sheet is heated to a pliable forming temperature, formed to a specific shape in a mold, and trimmed to create a usable product. The sheet, or "film" when referring to thinner gauges and certain material types, is heated in an oven to a high-enough temperature that permits it to be stretched into or onto a mold and cooled to a finished shape.



1- The plastic sheet is heated.

2- The sheet is formed to a specific shape in a mold.

3- The shapes are trimmed.

### **Applications:**

Thermoforming is commonly used for food packaging but has many applications from plastic toys to aircraft windscreens to cafeteria trays.

Thin-gauge (less than 0.060 inches) sheets are mostly used for rigid or disposable packaging, while thick-gauge (greater than 0.120 inches) sheets are typically used for cosmetic permanent surfaces on automobiles, shower enclosures, and electronic equipment.

A variety of thermoplastic materials can be used in this process, including the following:

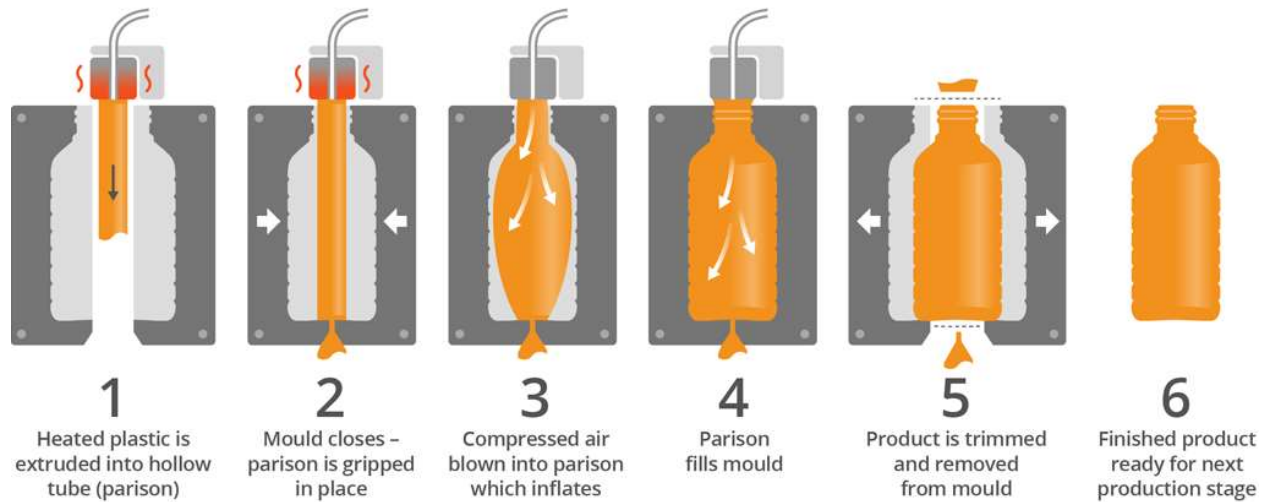
- Acrylic (PMMA)
- Acrylonitrile Butadiene Styrene (ABS)
- Cellulose Acetate
- Low Density Polyethylene (LDPE)
- High Density Polyethylene (HDPE)
- Polypropylene (PP)
- Polystyrene (PS)
- Polyvinyl Chloride (PVC)

### **Blow Moulding**

#### **Extrusion Blow Moulding**

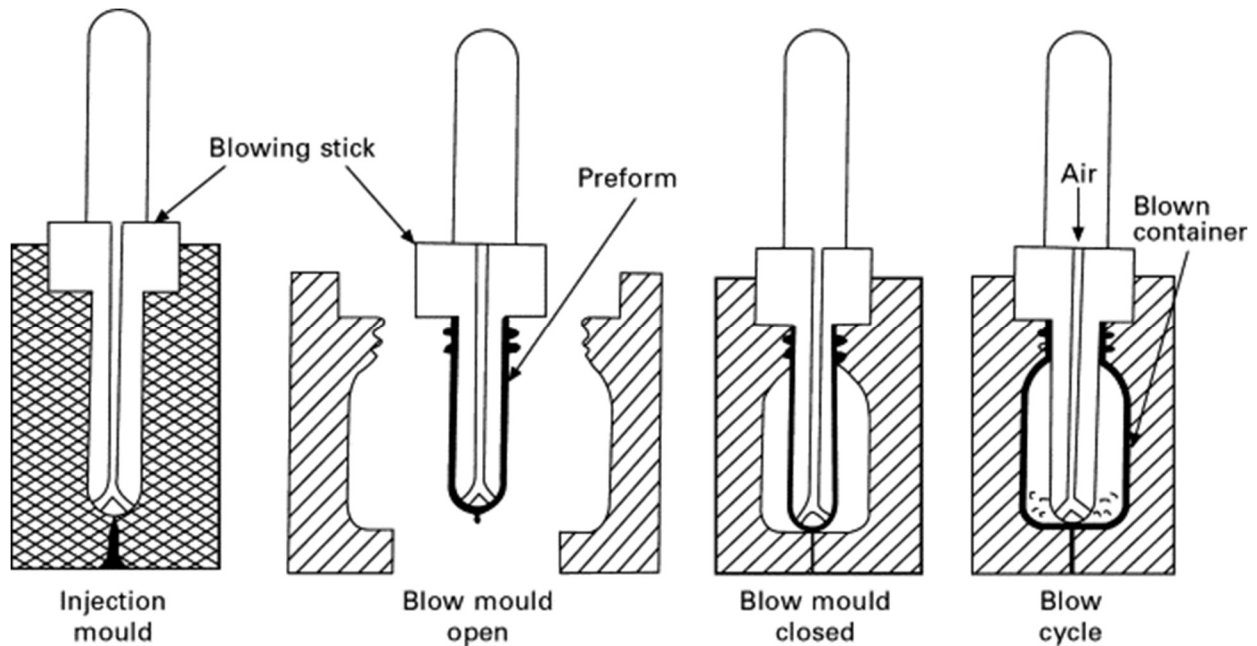
In extrusion blow moulding, a hot tube of plastic material is dropped from an extruder and captured in a water-cooled mould. Once the mould is closed, air is injected through the top of the container.

When the hot plastic blows up and the mould material freezes, it is able to maintain its shape



## Injection Blow Moulding

In this method, hot plastic material is injected into the part of the mould that creates the neck. The injected material is then taken to the next station on the machine where it is blown up into the finished container like in the extrusion blow moulding process.







# Module 5

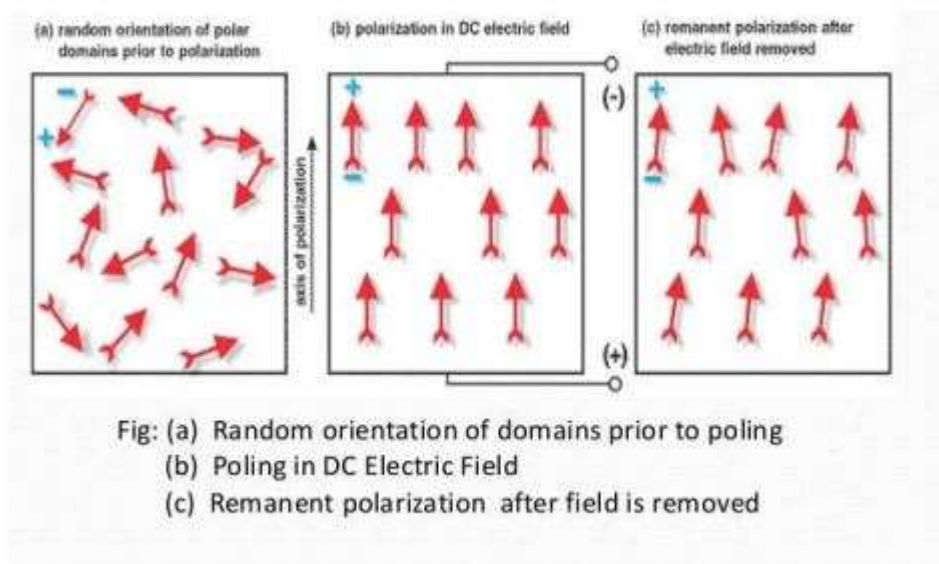
## Smart Materials

### Piezoelectric material

**Piezoelectric Material** uses the application of piezoelectricity that accumulates in certain solid materials in response to mechanical stress

The word piezoelectricity means electricity resulting from pressure and latent heat

The piezoelectric effect is a reversible process: materials exhibiting the piezoelectric effect (the internal generation of electrical charge resulting from an applied mechanical force) also exhibit the reverse piezoelectric effect, the internal generation of a mechanical strain resulting from an applied electrical field.



### Mechanism or working principle

- The nature of the piezoelectric effect is closely related to the occurrence of electric dipole moments in solids.
- The domains are usually randomly oriented, but can be aligned using the process of poling
- Piezoelectric effect is the change of polarization  $P$  when applying a mechanical stress. This might either be caused by a reconfiguration of the dipole-inducing surrounding or by re-orientation of molecular dipole moments under the influence of the external stress.
- Piezoelectricity may then manifest in a variation of the polarization strength, its direction or both, with the details depending on:

1. The orientation of P within the crystal
2. Crystal symmetry
3. The applied mechanical stress

Different types of piezoelectric materials are

Natural – Quartz, Rochelle Salt, Topaz, Sugar etc

Synthetic – Zinc oxide (ZnO), Lead zirconate titanate (PZT), Barium Titanate ( $\text{BaTiO}_3$ ) etc

### Applications –

Piezoelectricity is exploited in a number of useful applications, such as the

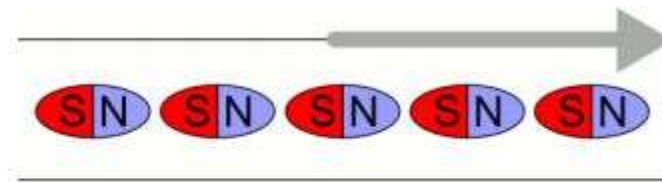
- Production and detection of sound
- Piezoelectric inkjet printing,
- Generation of high voltages
- Clock generator in electronics, Microbalances,
- To drive an ultrasonic nozzle, and ultrafine focusing of optical assemblies.

### Magnetostrictive materials (Magnetostriction)

Magnetostriction is a property of ferromagnetic materials which causes them to expand or contract in response to a magnetic field.

This effect allows magnetostrictive materials to convert electromagnetic energy into mechanical energy.

As a magnetic field is applied to the material, its molecular dipoles and magnetic field boundaries rotate to align with the field. This causes the material to strain and elongate



Molecular dipole rotation during magnetostriction

- Magnetostrictive materials are used to convert electromagnetic energy into mechanical energy and vice versa. This effect can be used to create sensors that measure a magnetic field or detect a force. The magnetic field or force applied would create a strain in the material, which can be measured.
- Transformers also use magnetostrictive materials in conjunction with Faraday's law to convert magnetic fields into an electromotive force. During this process, the change in magnetic flux is converted into an electromotive force (EMF) in the transformer.

This effect is used to increase or decrease AC voltages and to transfer them from one circuit to another. When exposed to a changing magnetic field (wave) the magnetostrictive material responds by rotating

its molecular dipoles in phase with this frequency. The maximum change in length of the material occurs twice per period of the magnetic field. This results in a humming sound, which is commonly heard from transformers.

### **Applications**

A changing magnetic field can also be used in conjunction with magneto-strictive materials to produce vibrations. Such materials are used in

- medical devices and industrial vibrators
- ultrasonic cleaning devices
- underwater sonar
- vibration or noise control systems, and in many other applications.

Similarly, magnetostrictive transducers can be used to transfer ultrasonic energy into other materials.

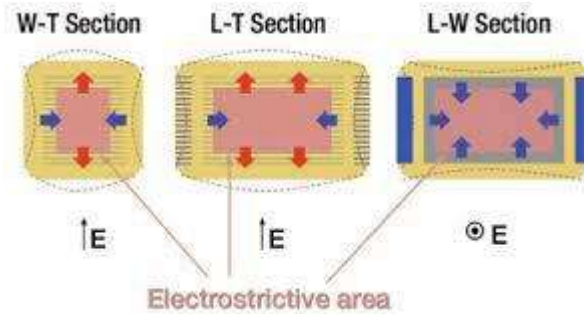
## **Electrostrictive Material**

- Electrostriction is a property of all dielectric materials, and is caused by displacement of ions in the crystal lattice upon being exposed to an external electric field.
- Positive ions will be displaced in the direction of the field, while negative ions will be displaced in the opposite direction.
- This displacement will accumulate throughout the bulk material and result in an overall strain (elongation) in the direction of the field.
- The thickness will be reduced in the orthogonal directions characterized by Poisson's ratio.
- All insulating materials consisting of more than one type of atom will be ionic to some extent due to the difference of electronegativity of the atoms, and therefore exhibit electrostriction.
- The resulting strain (ratio of deformation to the original dimension) is proportional to the square of the polarization. Reversal of the electric field does not reverse the direction of the deformation.

### **Materials**

Although all dielectrics exhibit some electrostriction, certain engineered ceramics, known as relaxor ferroelectrics, have extraordinarily high electrostrictive constants. The most commonly used are

- lead magnesium niobate (PMN)
- lead magnesium niobate-lead titanate (PMN-PT)
- lead lanthanum zirconate titanate (PLZT)

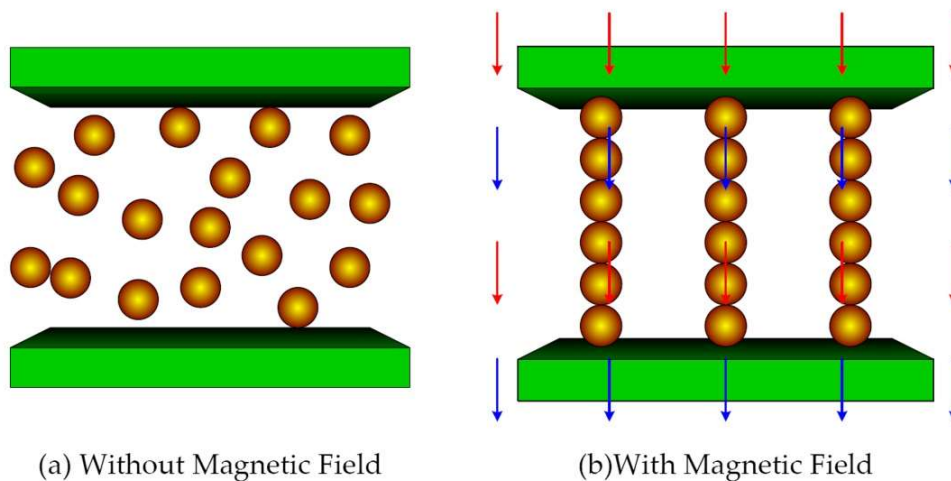


### Applications

- Sonar projectors for submarines and surface vessels
- Actuators for small displacements

### Magnetorheological fluids

A magnetorheological fluid is a type of smart fluid in a carrier fluid, which is when under an influence of a magnetic field, the fluid greatly increases its apparent viscosity, to the point of becoming a viscoelastic fluid



MR fluid is a type of rheological fluid whose yield stress can be varied by an applied magnetic field.

A typical MR Fluid consists of micron sized magnetizable iron/ferrous particles suspended in a base fluid like silicone oil or water

### Functions of MR fluids

1. These are liquids that change their properties when we apply a magnetic field to them
2. When the magnet is in place the MR fluid turns into solid
3. When the magnet is removed the solid instantly reverts to liquid

### Constituents of MR Fluid

- **Carrier Oil**
  1. Parafin Oil
  2. Silicon oil
  3. Water
- **Additives**
  1. Grease
  2. Arabic Gum
- **Magnetic Particles**
  1. Iron Particles
  2. Nickel

### Application of MR fluid

1. Dampers
2. Shock absorbers
3. Rotary brakes
4. Clutches
5. Prosthetic devices
6. Polishing devices
7. Polishing and grinding devices
8. Semiactive control devices

### Electrorheological (ER) fluid

The characteristics of an electrorheological (ER) fluid, as a class of smart soft matter, can be actively and accurately tuned between a liquid- and a solid-like phase by the application of an electric field.

ER materials used in ER fluids are electrically polarizable particles.

#### Properties of ER Fluid

In ER fluids, the carrier liquids should have high electrical resistivity and low viscosity, while the particles are commonly [metal oxides](#), alumina, silicates, silica, organics or polymers, which could be electrically polarized.

As shown in Fig. 1(a), if the ER fluid is free of electric field, the particles are distributed uniformly in the fluid and it can flow as a Newtonian fluid with viscosity  $\mu$ . However, when subjected to a highly intensive electric field, whose intensity could be up to 5 kV/mm, the particles will form a chain-like structure parallel to the electric field direction as shown in Fig. 1(b).

As a result, the flowing resistance or apparent viscosity can be controlled by the intensity of the electric field. Upon the removal of electric field, the original properties of the ER fluids could be recovered.

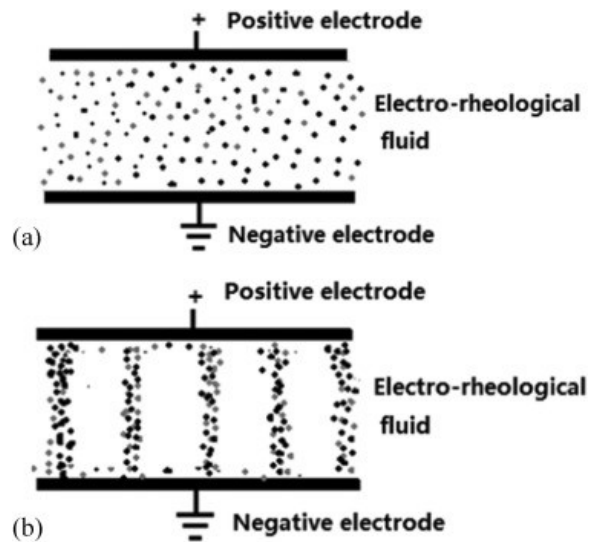


Fig. 1. Distribution of particles in ER fluids: (a) Absence of electric field; (b) presence of electric field.

### Applications

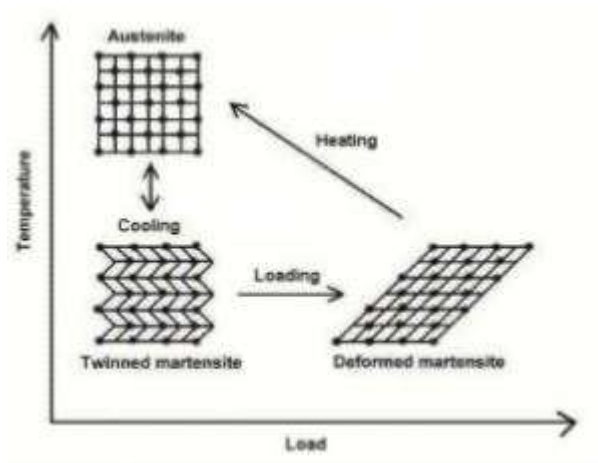
1. The normal application of ER fluids is in fast acting hydraulic valves and clutches,
2. It is used in ER Brakes
3. It is used in shock absorber

### Shape Memory Alloys (Materials)

Shape memory alloys (Materials) are the materials that remember their original shape. If deformed they can recover their original shape upon heating. They can also take large stress without undergoing permanent deformation.

They can be formed into various shapes like bars, wires, plates and rings thus serving various functions

### Working principle



- A molecular rearrangement in the shape memory alloys (materials) austenite phase is responsible for its unique properties
- Martensite is relatively soft and occurs at lower temperatures
- Austenite occurs at higher temperature.
- The shape of austenite structure is cubic
- The un-deformed Martensite phase is the same size and shape as the cubic austenite phase on a macroscopic scale
- No change in size or shape is visible in shape memory alloys until martensite is deformed
- To fix the parent shape, the metal must be held in position and heated to about 500° C
- The high temperature causes the atoms to arrange themselves into the most compact and regular pattern possible resulting in a rigid cubic arrangement (austenite phase)

#### Applications

1. Reinforcement -Shape memory alloy are particularly beneficial for construction in seismic regions
2. Bolted Joints – Shape memory alloy material can be employed in beam column and column foundation joints to reduce their vulnerability by dissipating greater energy through larger plastic deformation and then recovering it on removal of load
3. Prestressing -Shape memory alloy strands are used in pre tensioning and post tensioning, Also Shape memory alloy in prestressing have the potential for creating smart structure
4. Restrainers – By use of shape memory alloy restrainers we can overcome the limitations of unseating as they have larger elastic strain range and can be brought back to its original position even after deformation.