DEPARTMENT MECHANICAL ENGINEERING

ENGINEERING METALLURGY

UNIT NOTES

UNIT-I-CONSTITUTION OF ALLOYS

1.CONSTITUTION OF ALLOYS

Pure metals always have low strength and high ductility and it is practically impossible to use them in industrial applications. Industrial metallic substances are composed of two or more elements in an atomic level as either a compound or a solution for improving the mechanical properties. The value of solid solution was discovered during the ancient times and is commonly known as alloys. Most important industrial solid solutions include alloy steels containing chromium, nickel, manganese, silicon along with carbon. Alloy steels have a wide range of special properties, such as hardness, toughness, corrosion resistance and ductility. Nonferrous alloys, mainly copper–nickel, bronze and aluminium alloys, are used to a great extent in industries.

1.1 SOLID SOLUTIONS

A solid solution is a homogeneous mixture of two or more kinds of atoms in a solid state or more than two types of atoms combined in a single-space lattice. If two or more than two types of metals are mixed in their liquid state, they form a liquid solution. When this mixture is solidified, the solid may retain the homogeneity that was present in the liquid state. In this, the components of different types of atoms form a common crystal lattice. The component whose lattice is retained is called the solvent and the solute atom may occupy a vacant lattice site in the parent metal. It may also exist in between the atoms in the parent lattice as indicated in Figure 1.1

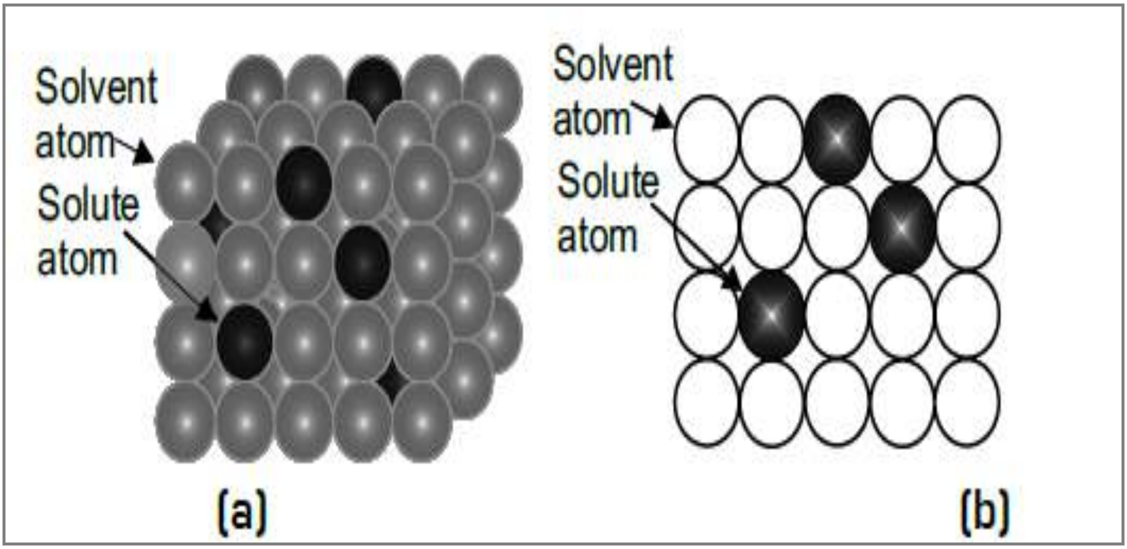


Fig. 1.1 (a) Three-dimensional substitutional solid solution
(b) Two-dimensional substitutional solid solution

Brass is a solid solution of copper and zinc. A typical composition of the brass contains 64% copper and 36% zinc. The copper atoms are solvent atoms and the zinc atoms are solute atoms. The combination of these metals in a lattice structure provides strength, toughness, wear resistance and other desired properties. The solid solutions are of two types—substitutional solid solution and interstitial solid solution. Some other examples of solid solution are Ni–Cu, Au–Ag, Ag–Cu and Fe–C.

1.2 SUBSTITUTIONAL SOLID SOLUTION

In a substitutional solid solution, the solute atom substitutes the atoms of solvent in the crystal structure. The crystal structure of the parent element is unchanged, but the lattice may be distorted by the presence of the solute atoms. In a substitutional solid solution, the two atoms (solvent and solute are equal or approximately equal in diameter and the crystal structure of the two elements must be the same. Brass is alloy of copper and zinc. The atomic diameter of copper is 1.278 Å and that of zinc is1.332 Å and the two metals form substitutional solid solution. Figure 1.1 shows that the zinc atoms replace some copper atoms in the lattice structure of copper. Substitutional solid solutions are further classified into disordered substitutional solid solution and ordered substitutional solid solution.

1.2.1 Disordered Substitutional Solid Solution

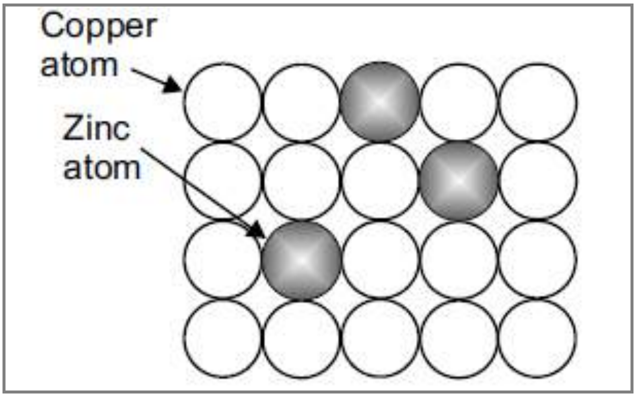


Fig. 1.2 Disordered Substitutional Solid Solution

In a substitutional solid solution, the solute atoms do not follow any specific order, but the atoms are distributed randomly in the lattice structure of the solvent. The concentration of solute atoms can vary throughout the lattice structure. This alloy is said to be in a disordered condition. The disordered substitutional solid solutions crystallize from the molten metal (see Figure 1.2).

1.2.2 Ordered Substitutional Solid Solution

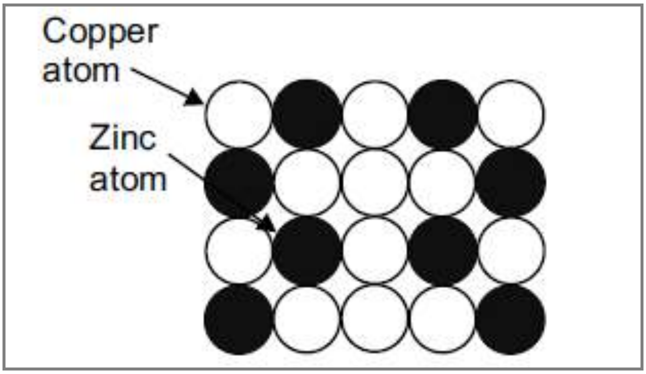


Fig. 1.3 Ordered substitutional solid solution

If the disordered substitutional solid solution is heated to its recrystallization temperature and then cooled very slowly, the atoms are rearranged due to the diffusion that takes place during cooling. This results in uniformity and definite ordering of the atoms in the lattice structure. This structure is said to be ordered substitutional solid solution (see Figure 1.3).

1.2.3 Hume Rothery's Rule

To obtain a metal with desired properties, alloying is essential in metallurgy. However, not all metals can be added to obtain substitutional solid solution. Hume Rothery, a well-known scientist, identified some factors that give complete substitutional solid solution in varying alloying elements. For obtaining a substitutional solid solution, the choice of alloying elements must be based on the following factors.

1. **Relative size factor:** If two metal atoms differ in their sizes by more than 15%, the formation of a solid solution between them will be restricted. To show the solid solubility in each other, it is essential that their atomic diameter shall be similar or the two different atoms differ in their sizes by less than 13% and this is the most important factor to obtain a solid solution.
2. **Chemical affinity factor:** If two metals possess a greater chemical affinity, they prefer to form a chemical compound rather than a solid solution, and lesser are the chances of forming a solid solution and dissolving each other. The two metal atoms should have very less chemical affinity between them to show solid solubility.
3. **Relative valence factor:** In alloying metals, the solute and solvent atoms are different in valence electrons. Hence, a metal of high valence can dissolve only a small amount of lower valence metal but the lower valence metal may have a good solubility than higher valence metal.
4. **Crystal structure factor:** It is found that metals having the same type of crystal lattice form a complete series of solid solution, i.e., the crystal lattice of solvent and solute should be same, otherwise, the solute and the solvent will not merge with each other.

1.3 INTERSTITIAL SOLID SOLUTION

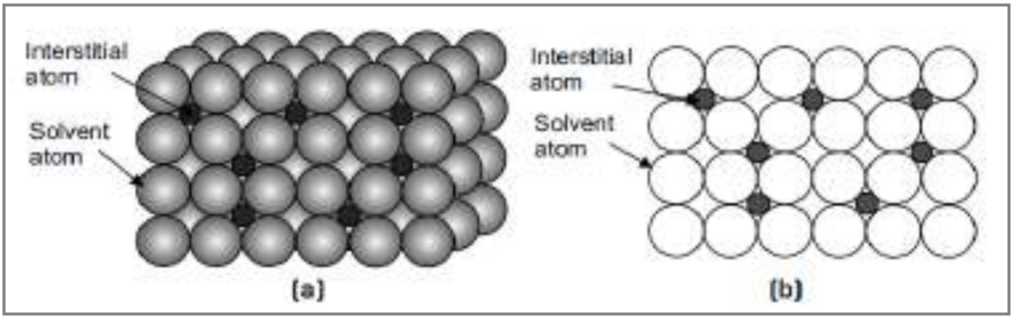


Fig. 1.4 (a) Three-dimensional interstitial solid solution and (b) two-dimensional interstitial solid solution

In an interstitial solid solution, the diameter of the solute atom is very small when compared to the solvent atoms (see Figure 1.4). These are formed when atoms of small atomic radii fit into the void spaces of the larger solvent atoms. The diameters of carbon, boron and nitrogen atoms are less than1 Å and can fit in the crystal structure of iron, nickel and manganese as interstitial solid solution. For example, the atomic diameter of iron is 1.24 Å and that of carbon is 0.77 Å. Because of large difference in the diameters of iron and carbon atoms, the carbon atom is unable to substitute to solventatom and it can fit in the form of interstitial in austenite.

1.3.1 Metallic Compounds (Intermediate Phases)

In the metallurgy process, the alloying elements are added to achieve the desired properties in metals. The intermediate phases are formed in a two-component system when their mutual solid solubility is limited and the chemical affinity is high. When alloying elements are added in excess to solid solubility, a second phase called intermediate phases appears. The intermediate phases are of different types: their metallic compounds, electron compounds and Laves phases. These compounds possess either ionic or covalent bond. These compounds have non-metallic properties and poor ductility, poor electrical conductivity of and higher melting point with complex crystal structure.

1.4 PHASE DIAGRAMS

The solidification of a metal or an alloy is clearly understood by means of a phase diagram. A plot with the temperature on the vertical scale and the percentage of composition by weight on the horizontal scale is termed a phase diagram. A diagram plotted for an alloy system in this fashion is called an equilibrium or a phase diagram. The phase diagram is also known as constitutional diagram. The applications of alloys are wide and ever-increasing in the industry when compared to pure metals. The alloys not only increase the strength of the metals, but many combinations of properties can be obtained by alloying the metals with each other in various proportions. The alloy diagrams are useful in the study of the characteristics of any series of alloys; and it is possible to predict the structure and the physical and chemical properties of any given alloy from these diagrams. In a phase diagram, to specify completely the state of a system in equilibrium, it is necessary to specify the three independent variables—temperature, pressure and composition—which are externally controllable. If there is no variation in pressure, then the metal equilibrium can be expressed in terms of two independent variables, viz., temperature and composition.

1.4.1 Cooling Curves

The phase diagrams are usually constructed from the data of cooling curve obtained by plotting falling temperature versus time for small selected alloys, which are allowed to cool under equilibrium condition. When a metal or alloy solidifies from a state of fusion, it is noticed that at the time of solidification, considerable amount of heat is given out due to changes taking place in the structure of the metal or alloy. The simplest type of curve is obtained by taking the temperature readings at fixed intervals of time with the aid of a pyrometer. This curve is used for studying the changes that occur during the solidification of alloys. If a plot is drawn between temperature and time at a constant composition, the resulting cooling curve shows a change of slope when a phase change occurs.

1.4.2 Cooling Curve for Pure Metals or Solidification of Pure Metals

The pure metals melt and solidify at the same temperature which may be termed as melting point or freezing point. These metals are cooled under equilibrium conditions from the molten state till they solidify. A time–temperature diagram is shown in Figure 1.5(a). Liquid metal cools from A to B. The crystal begins to form at B. From B to C molten metal liberates latent heat of fusion and the temperature remains constant until the entire liquid metal is solidified. Between B and C, the metal is partially solid and partially liquid. On further cooling, i.e., from C to D, solid metal tends to reach the room temperature. In Figure 1.5(a), the horizontal line corresponds to the solidifying or melting temperature of a single-component system at a constant pressure.

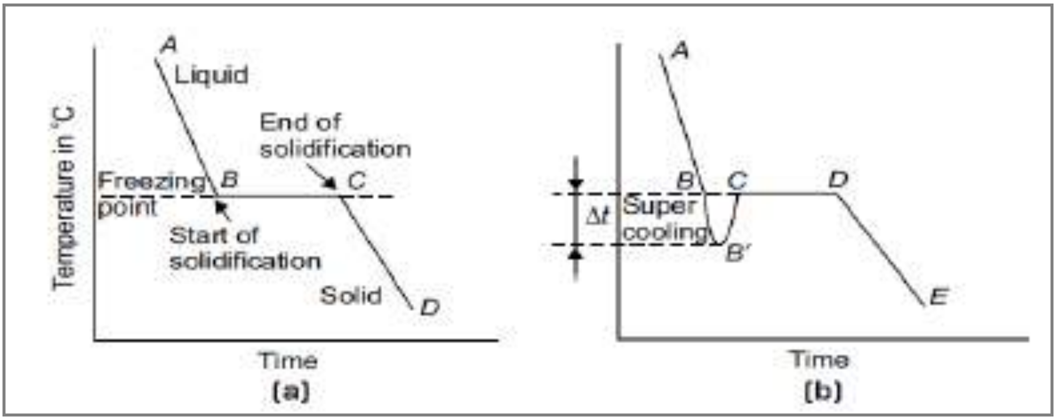


Fig. 1.5 (a) Hypothetical cooling curve and (b) actual cooling curve for pure metals

In real systems, a certain amount of under-cooling occurs before the solidification starts. That is, the melt is maintained in a metastable state at a temperature below the freezing point and most of the cooling curves are as shown in Figure 1.5(b). Nucleation of solid does not start at point B, but it starts at point B′, i.e., liquid metal has super-cooled by an amount Δt. This is known as super-cooling or under cooling.

The extent of under-cooling in terms of temperature and time depends upon several factors.

1.4.3 Cooling Curve for Binary Alloy

1.4.3.1 Solidification of Alloy—Type 1

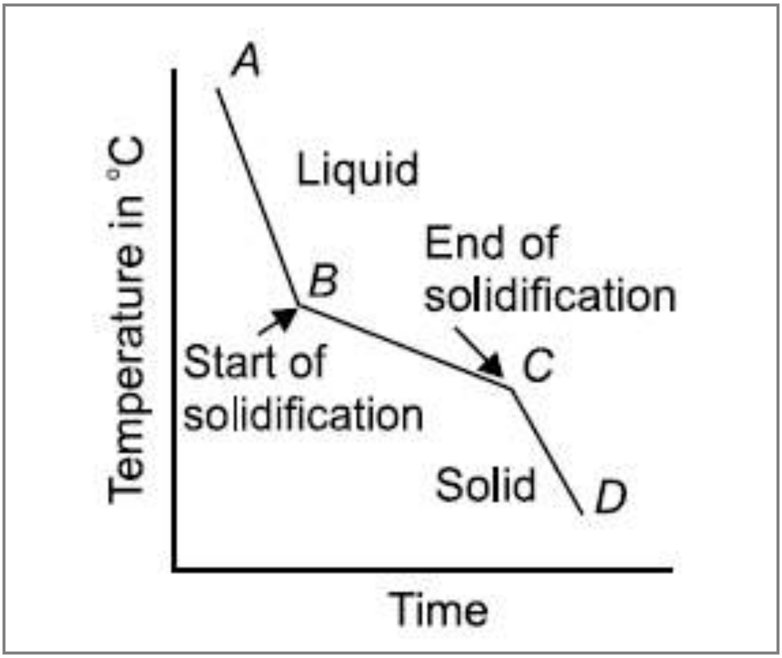


Fig. 1.6 Cooling curve for binary alloy

Consider the solidification of an alloy containing 50% X and 50% Y metals (see Figure 1.6). The alloy which has started cooling is at a temperature A and the metals X and Y are completely soluble in each other. The crystals begin to form at B. In a binary system, during the freezing period, temperature does not remain constant, rather it drops along line BC till the whole mass is solid and cool to room temperature along CD. At the room temperature, the alloy is homogeneous in the solid state similar to in the liquid state. The Cu–Ni system is an example of two metals which form a solid solution.

1.4.3.2 Solidification of Alloy—Type 2 (Eutectic Solidification)

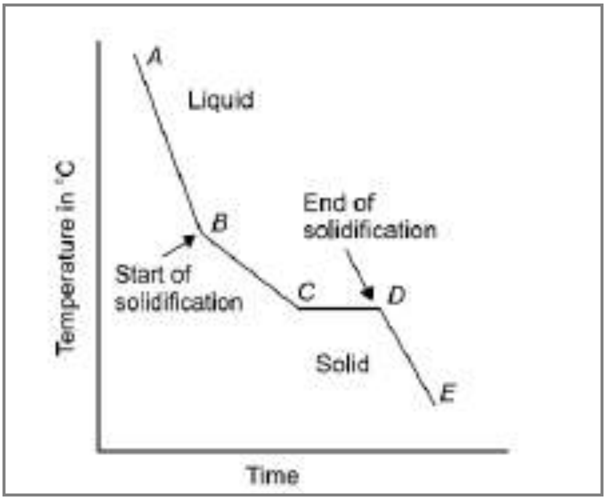


Fig. 1.7 Cooling curve for binary eutectic

In some binary alloy systems, the liquid metal cools along the curve AB until the temperature reaches point B. At point B, one component in excess will crystallize and the temperature will drop along BC as indicated in Figure 1.7. At point C, the residue liquid reaches eutectic composition and the two components crystallize simultaneously from the eutectic mixture. The temperature remains constant until the whole mass is solid between points C and D. From D to E, the metal cools to room temperature. The Cd–Bi system is an example of two metals completely soluble in liquid state but partially soluble in solid state.

1.5 CONSTRUCTION OF PHASE DIAGRAM

The alloy diagram is constructed from a number of cooling curves of a series of alloys of the metals used in the investigation. Thus, while constructing the alloy diagram of the nickel–copper alloys, approximately, the following steps have to be followed:

1. Construct the cooling curve of pure metal A
2. Construct the cooling curve of pure metal B
3. Construct the cooling curves of about 10 different alloys of A and B, for example, an alloy of 90% A with 10% B; an alloy of 80% A and 20% B; and so on.

A and B are mixed in proper proportion and heated above the melting temperature of that alloy. Molten alloys are allowed to cool in equilibrium condition and the temperature at which metal starts to melt (M, M1, M2, …) and the temperature at which metal start to freeze (F, F1, F2, …) are recorded. The cooling curves thus obtained are combined to construct the phase diagram of the metals A and B.

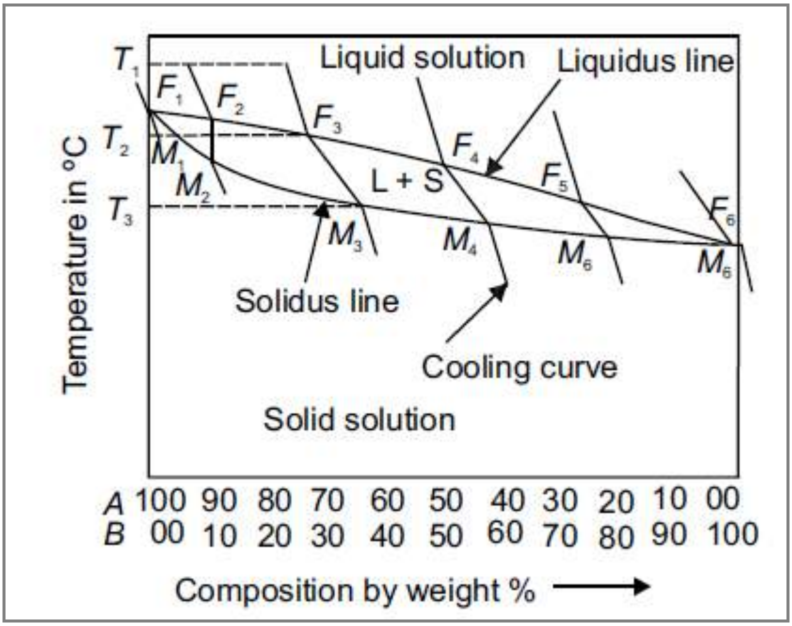


Fig. 1.8 Construction of phase diagram for two metals completely soluble both in liquid and solid phases

The resulting phase diagram as in Figure 1.8 is obtained by joining the points *F*1, *F*2, … and the points *M*1, *M*2, …. The upper line obtained by joining the points showing the beginning of solidification is called the liquid us line. The liquid us line indicates the lowest temperature at which a given alloy of the series in the liquid starts to freeze. The lower line of the diagram is known as the solidus. The area above the liquid us line is a single-phase region. Any alloy in that region consists of a homogeneous liquid solution. At any point in the solidification range, the alloy is partly solid and partly liquid. Similarly, the area below the solidus line is a single-phase region and any alloy in this region consists of a homogeneous solid solution.

1.6 INTERPRETATION OF PHASE DIAGRAM

The following three steps are necessary for the interpretation of phase diagram.

1.6.1 Prediction of Phase

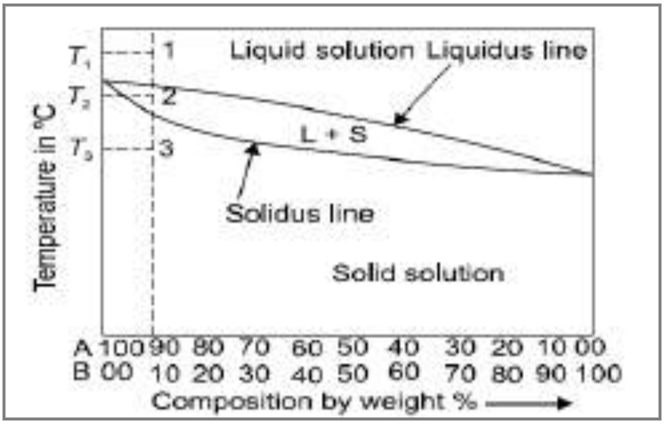


Fig. 1.9 Prediction of phase

Figure 1.9 illustrates the phases that will be present for a given alloy of composition of 90% *A* and 10% *B*. In the phase diagram given in Figure 1.9, the physical states of the alloy at points 1, 2, 3 are as follows. At point 1, since it is above the liquid us line, it consists of only the liquid solution of composition 90% of *A* and 10% of *B* at T_1°C. At point 2, it is between the solidus and liquid us lines. It consists of liquid solid inter phase with 90% of *A* and 10% of *B* at T_2°C. At point 3, it is below the solidus line, so it consists only solid solution of 90% of *A* and 10% of *B* at T_3°C.

1.6.2 Prediction of Chemical Composition of Different Phases for a Given Temperature

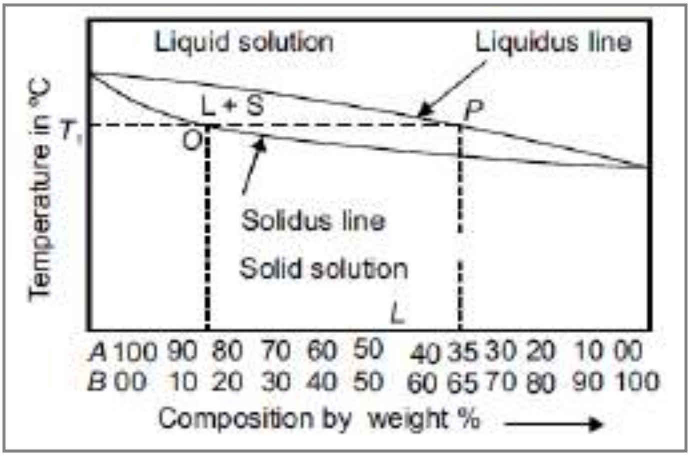


Fig. 1.10 Prediction of chemical composition

Consider the composition at a given temperature, say at T_1°C. Draw a horizontal line. This line intercepts at O and P on solidus and liquid line. From the points O and P, project vertical lines to confirm the composition. In Figure 1.10, at point P, the composition 35% of A and 65% of B starts freezing. The composition 80% of A and 20% of B starts melting.

1.6.3 Prediction of Amount of Phase (Lever-arm Rule)

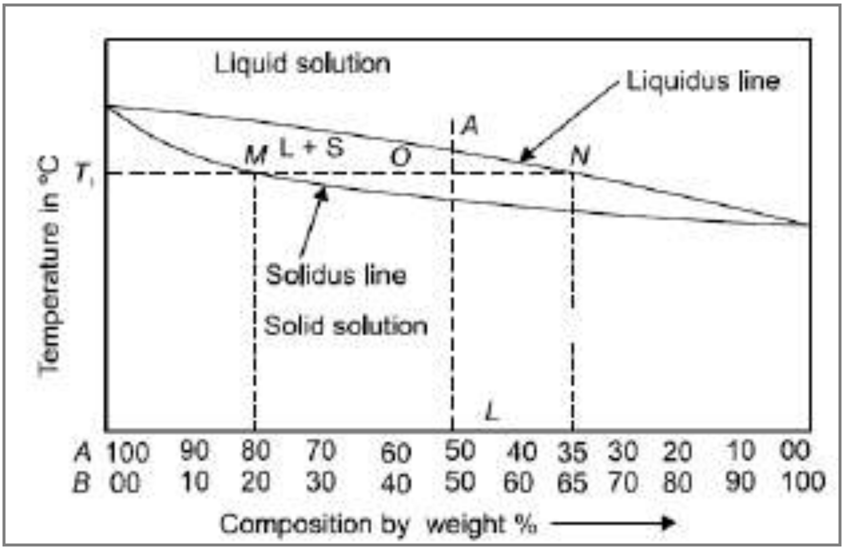


Fig. 1.11 Prediction of amount of phase

The relative amounts of the co-existing phases and their compositions during the process of solidification can be calculated at any temperature by the lever rule. A tie line (isothermal) is drawn intersecting both the solidus and the liquid us lines and the intercepts made by the liquid us and solidus curves with respect to the alloy composition. To determine the relative amount of two phases, consider two lines AL and MN, vertical and horizontal lines in phase diagram, as shown in Figure 1.11. The intersection of these two lines is treated as the fulcrum of a simple lever system. In this, the relative length of lever arms multiplied by amount of phase present must be balanced. This is known as lever rule.

Mathematically, the lever rule can be expressed as

Total amount of solid phase = (ON/MN) × 100

Total amount of liquid phase = (OM/MN) × 100

1.7 GIBBS PHASE RULE

The number of variable factors which define the state of a system is called the degree of freedom. Number of degrees of freedom is the quantity of independent external or internal variables like temperature, pressure and concentration which may change the formation of new phase in the system. Gibbs proved that ‘number of degrees of freedom of a system in equilibrium condition is related to the number of components and the number of phases. Mathematically, it can be expressed as

$$P + F = C + N$$

where P is the number of phases in the system, F is the number of degrees of freedom or number of physical variables, which cause phase change of metal or alloy system, C is the number of components in the system and N is the number of external factors such as temperature and pressure. Usually in metallurgical process, the pressure will not be considered a variable as it is fixed at1 atmospheric pressure. Thus, the above equation becomes

$$P + F = C + 1$$

or

$$F = C + 1 - P$$

The number of degrees of freedom cannot be less than 0. So,

$$C + 1 - P \geq 0$$

or

$$P \leq C + 1$$

The application of phase rule to systems of pure metal is illustrated in Figure 1.12(a).

A pure metal at above melting temperature [at point 1 in Figure 1.12(a)] has single liquid phase.

The degrees of freedom at Point 1 becomes

$$F_1 = C + 1 - P$$

$$F_1 = 1 + 1 - 1$$

$$F_1 = 1$$

This system is said to be mono variant, i.e., only the temperature can be changed to alter the phase. During cooling, liquid metal becomes solid by defusing out the latent heat.

Pure metal during solidification [at point 2 in Figure 1.12(a)] has two (liquid and solid) phases.

The degrees of freedom at Point 2 becomes

$$F_2 = C + 1 – P$$

$$F_2 = 1 + 1 – 2$$

$$F_2 = 0$$

This system is said to be non variant, i.e., we should not vary to change phase of the system. The temperature remains constant during solidification.

Similarly, at Point 3

$$F_3 = C + 1 – P$$

$$F_3 = 1 + 1 – 1$$

$$F_3 = 1$$

The degrees of freedom F = 1 indicate that the pure solid metal becomes liquid only by heating from room temperature to liquid state. During heating, solid metal absorbs latent heat and gets converted into liquid at melting temperature.

The application of phase rule to the system of binary solid solution is illustrated in Figure 1.12(b)).As shown in the figure two metals are completely soluble in the liquid and solid state.

Binary solid solution at the above melting temperature at Point 1 in Figure 1.12 (b) has a single liquid phase.

The degrees of freedom at Point 1 becomes

$$F_1 = C + 1 – P$$

$$F_1 = 2 + 1 – 1$$

$$F_1 = 2$$

This system is said to be divarient, i.e. the phase of a system can be changed by varying the composition and temperature. The figure indicates that by varying the composition the state of the system changes.

In a binary solid system, two phase and two component system (at Point 2) the degrees of freedom will be

$$F_2 = C + 1 – P$$

$$F_2 = 2 + 1 - 2$$

$$F_2 = 1$$

This system is said to be monovariant. This indicates that in a binary solid, during solidification, the temperature drops in opposition to being constant in the case of pure metal as indicated in the above example.

Similarly, at Point 3

$$F_3 = C + 1 - P$$

$$F_3 = 2 + 1 - 1$$

$$F_3 = 2$$

Degrees of freedom 2 indicate that the system is divariant and the binary solid solution becomes liquid by heating and also by varying composition at a certain temperature.

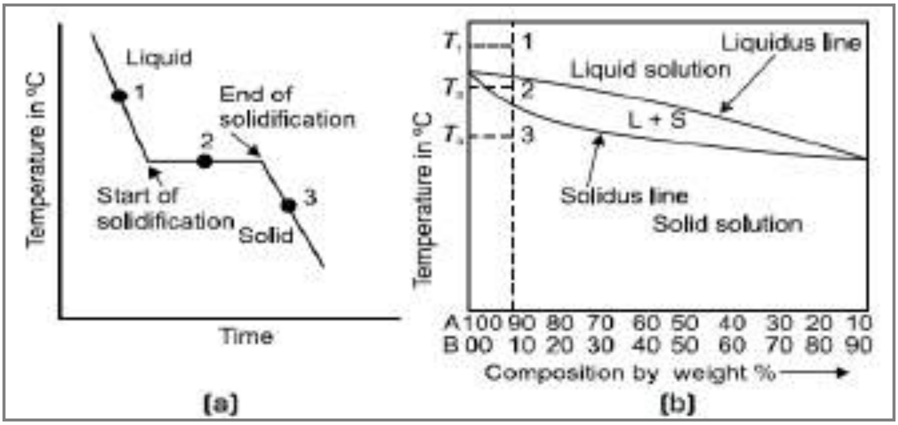


Fig. 1.12 Verification of Gibbs phase rule: (a) Cooling curve for pure metal and (b) phase diagram of two metals completely soluble both in liquid and solid states

1.8 CLASSIFICATION OF PHASE DIAGRAMS

The phase diagrams are classified into two ways:

1.8.1 According to Number of Components in the System

On the basis of number of components in the system, the phase diagrams can be classified as follows:

1. Single-component system has unary diagram
2. Two-component system has binary diagram

3. Three-component system gives rise to ternary diagram and so on

1.8.2 According to Solubility of Components

On the basis of solubility of components, the phase diagrams can be classified as follows:

1. Two metals completely soluble in liquid and solid states
2. Two metals completely soluble in liquid state but partially soluble in solid state
3. Two metals completely soluble in liquid state and insoluble in solid state
4. Two metals incompletely soluble in liquid and solid states

1.8.2.1 Two Metals Completely Soluble in Liquid and Solid States

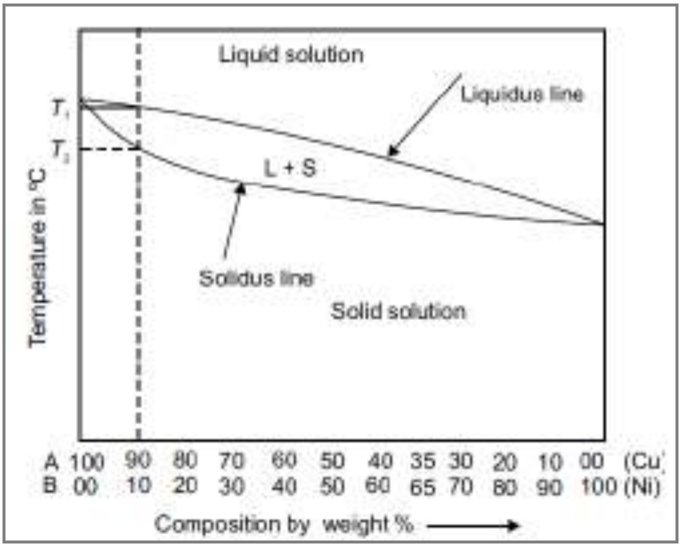


Fig. 1.13 Two metals completely soluble in liquid and solid states

Figure 1.13 shows two metals, Cu and Ni, completely soluble in liquid and solid states. Examples of other systems are antimony–bismuth. The Cu–Ni phase diagram consists of two lines, i.e., liquid us and solidus. Above the liquid us line, there is a uniform liquid solution for any alloy series. Below the solid us line there is a single-solid solution for any alloy. The two metals are completely soluble in the solid state. Hence, substitutional solid solution will be formed.

Consider solidification of alloy containing composition of 90% of copper and 10% of nickel. Solidification now can be started at temperature T1 and as it reaches the liquid us line, it turns into solid at T2. In between temperatures T1 and T2, the metal is partially solid and partially liquid. From T_2 temperature, the metal cools to room temperature.

Problem 1.1

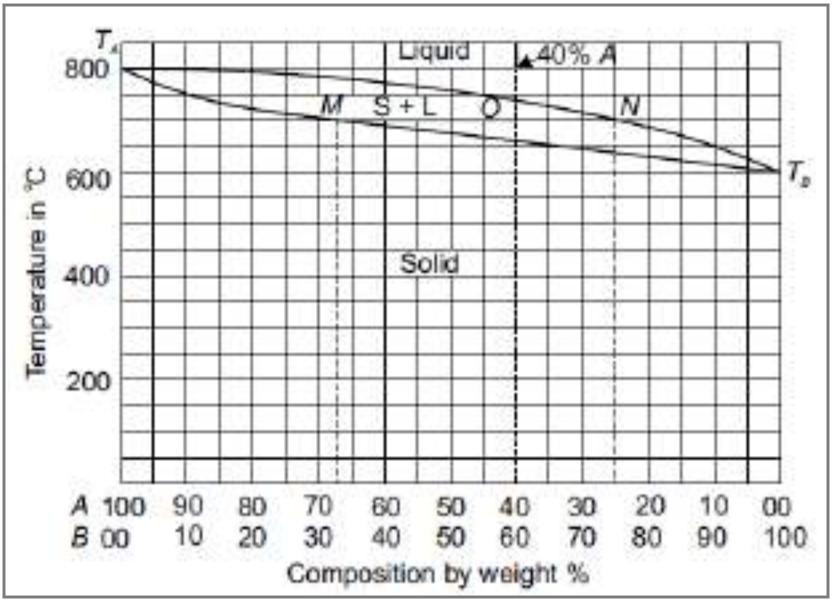
Two metals A and B have 100% mutual solubility in the liquid and solid states. The melting points of pure metals A and B are 800°C and 600°C respectively. Details of the start and end of solidification of various alloys in the series are as follows:

Alloy of Composition	Temperature at Start of Solidification (°C)	Temperature at End of Solidification (°C)
90% A +10% B	798	750
70% A + 30% B	785	705
50% A + 50% B	757	675
30% A + 70% B	715	645
10% A + 90% B	650	615

1. Draw the phase diagram of the series if there are no solid-state reactions and label all regions.
2. Predict the number, type, relative amounts and concentration of phases present in an alloy of40% A and 60% B at 700°C.

Solution

1. The following is the phase diagram.



Alloy	Number Phase	Type	Relative Amounts
40% A and 60% B	02	Solid and liquid	Solid = 70.05% Liquid = 29.95%

For relative amounts, consider the lever-arm rule

$$\% \text{ Solid} = \frac{MO}{MN} \times 100 = \frac{67.5 - 40}{65 - 26} \times 100 = \frac{27.5}{39} \times 100 = 70.05\%$$

$$\% \text{ Liquid} = 100 - 70.05 = 29.95\ \%$$

1.8.2.2 Two Metals Completely Soluble in Liquid State but Partially Soluble in Solid State

Many of the industrial binary alloys form two varieties of crystals when the freezing starts. These crystals carry a certain percentage of the alternate metal as a solid solution. Figure 1.13 shows equilibrium diagram of a system of components that has complete mutual solubility in liquid state and limited solubility in solid state.

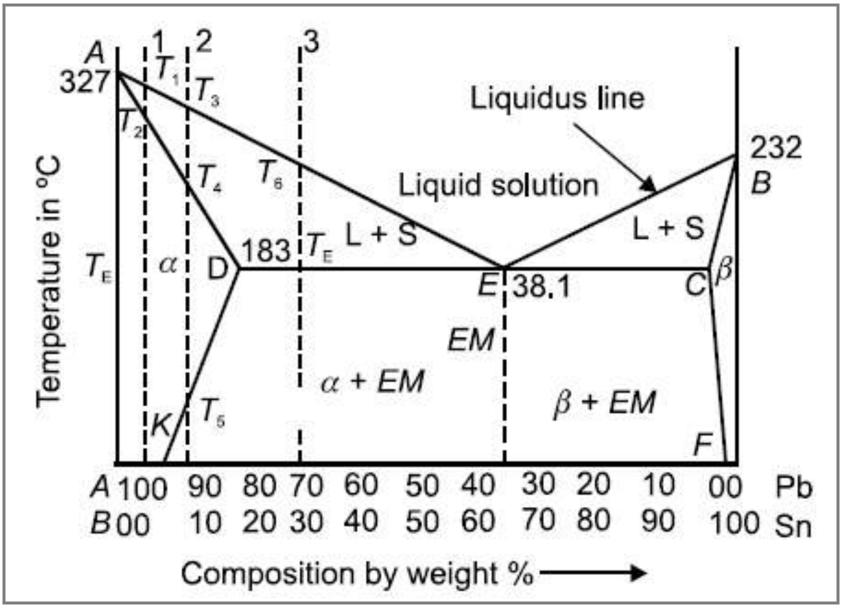


Fig. 1.14 Two metals completely soluble in liquid state and partially soluble in solid state

Consider the solidification characteristics of alloys of lead–tin (Pb–Sn) system. Lead melts at 327°Cand tin melts at 232°C as shown in Figure 1.14. If a small amount of tin is added to molten metallead, freezing point of the resulting alloy decreases as indicated by the line AE on phase diagram. On the other hand, if the small amount of lead is added to tin, the freezing point of the resulting alloy decreases. From this, each metal decreases the freezing point of the other. The line connecting the sefreezing points must intersect at some point called E. This point is the eutectic point in the diagram and represents 38.1% of lead and 61.9% of tin which melts/freezes at eutectic temperature 183°C (TE).The alloy whose composition is represented by eutectic is called as eutectic composition. Lines AE and EB are liquidus lines and lines AD, DEC and CB are solidus lines. Point D shows maximum solubility of metal tin in lead and point C shows maximum solubility of metal lead in tin at eutectic temperature. Points K and F indicate the solubility of metals tin in lead and lead in tin respectively at 0ºC temperature. At point E, solid solution lead and tin simultaneously separate from the liquid phase to form eutectic mixture. From the figure, the metal lead dissolves in tin up to 19.5% and tin in lead 2.6% at eutectic temperature. Similarly, the metal lead in tin dissolves 5% and tin in lead dissolves 6% at 0°C. But these limits of solid solubility apply only up to the eutectic temperature of TE°C. As indicated in the diagram, these solid solutions are alpha (α) and beta (β) solid solution.

Solidification of Alloys: In alloy 1 containing 95% lead and 5% tin, solidification begins at temperatureT1 and completes at temperature T2. Solid solution ‘α’ continuously crystallizes from molten liquid and is cooled to room temperature. Throughout the process, alloy will be ‘α’ solid solution. In alloy 2 containing 8% lead and 92% tin, solidification begins at T3 and completes at T4. Alloy2 consists of only α solid solution till it reaches temperature T5. On further cooling from T5, the solid solution will become supersaturated and solid solution decomposes and is separated at temperature below T5. At the room temperature, the metal consists of solid solution and eutectic mixture. In alloy 3 containing 30% lead and 70% tin, solidification begins at T6 and completes at TE. Initially, α solid solution crystallizes along the solidus line moving towards maximum solubility of lead in it. At temperature TE (eutectic temperature), the residue liquid phase reaches to eutectic composition and then metal completely solidifies in the form of eutectic mixture. The eutectic mixture contains only grains of metal lead and tin after solidifying.

Problem 1.2

Construct a phase diagram using the following data and label all the fields.

Melting point of Ag = 961°C

Melting point of Cu = 1083°C

Eutectic temperature = 780°C

Eutectic composition = 28% Cu

Maximum solubility of Cu in Ag = 9% at 780°C

Maximum solubility of Ag in Cu = 8% at 780°C

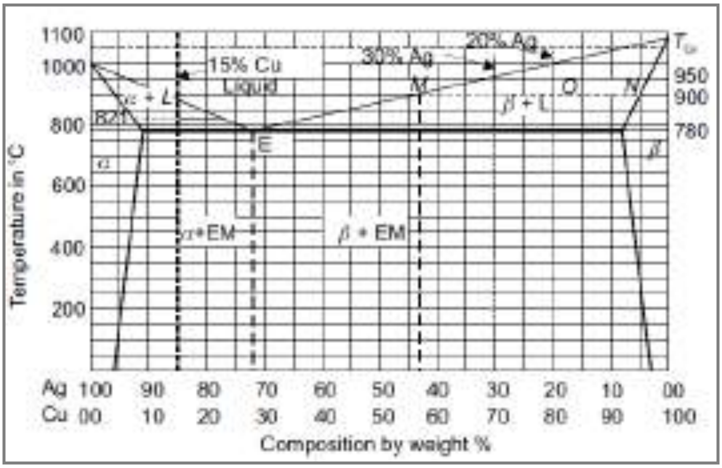
Maximum solubility of Cu in Ag = 2% at 400°C

Maximum solubility of Ag in Cu = 0% at 400°C

Determine the following:

1. Temperatures at which solidification starts and ends for 30% Ag alloy
2. Temperature at which a 15% Cu alloy has 50% liquid phase and 50% solid phase
3. Percentage composition of liquid and solid phases in a 20% Ag alloy at 900°C

Solution



1. For an alloy of 30% silver, solidification starts from 950°C and ends at 780°C.
2. Temperature at which 15% copper is 50% liquid and solid is 821°C.
3. Consider lever-arm rule for an alloy of 20% silver at 900°C

$$\% \text{ Solid} = \frac{MO}{MN} \times 100 = \frac{43.5 - 20}{43.5 - 5} \times 100 = \frac{23.5}{38.5} \times 100 = 61.03\%$$

$$\% \text{ Liquid} = 100 - 61.03 = 38.97\%$$

1.8.2.3 Two Metals Completely Soluble in Liquid State and Insoluble inSolid State

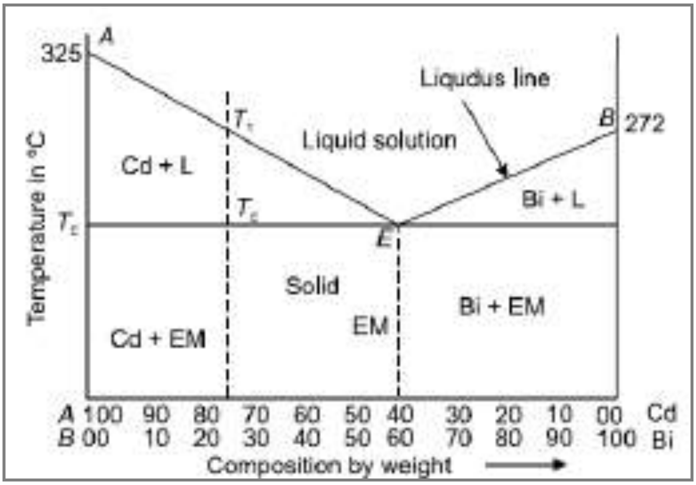


Fig. 1.15 Two metals completely soluble in liquid state and insoluble in solid state

Figure 1.15 shows a phase diagram of *A* and *B* (Bi–Cd system). From the alloy diagram, it can be noted that the melting point of cadmium is 325°C and that of bismuth is 272°C. If a small amount of cadmium is added to molten bismuth, freezing point of the resulting alloy decreases and is indicated by the line *AE* on phase diagram. On the other hand, if a small amount of bismuth is added to cadmium, the freezing point of the resulting alloy decreases. The addition of each metal to another decreases the freezing point of the other. The line connecting these freezing points must intersect at some point called E. This point is the eutectic point in the diagram and represents 40% cadmium and 60% bismuth which melts at eutectic temperature *T*. The alloy whose composition is represented by eutectic is called as eutectic composition. The alloy of eutectic composition melts and freezes at a specific and constant temperature and in this respect behaves as a pure metal. Consider cooling of an alloy of 80% cadmium and 20% bismuth. At *T*1 temperature, pure metal cadmium starts separating and the molten liquid metal gets poorer in cadmium and richer in bismuth. As the temperature further falls, more and more crystals of metal cadmium separate. This process continues until the composition of residue liquid attains eutectic composition (i.e., 60% cadmium and40% bismuth). At this stage, the eutectic composition will solidify at temperature *T*E°C and the alloy will solidify like pure metals. Eutectic consists of alternate layers of metal cadmium and bismuth, which form at eutectic temperature. The eutectic alloys are entirely soluble in each other in the liquid state, but are insoluble in each other in the solid state.

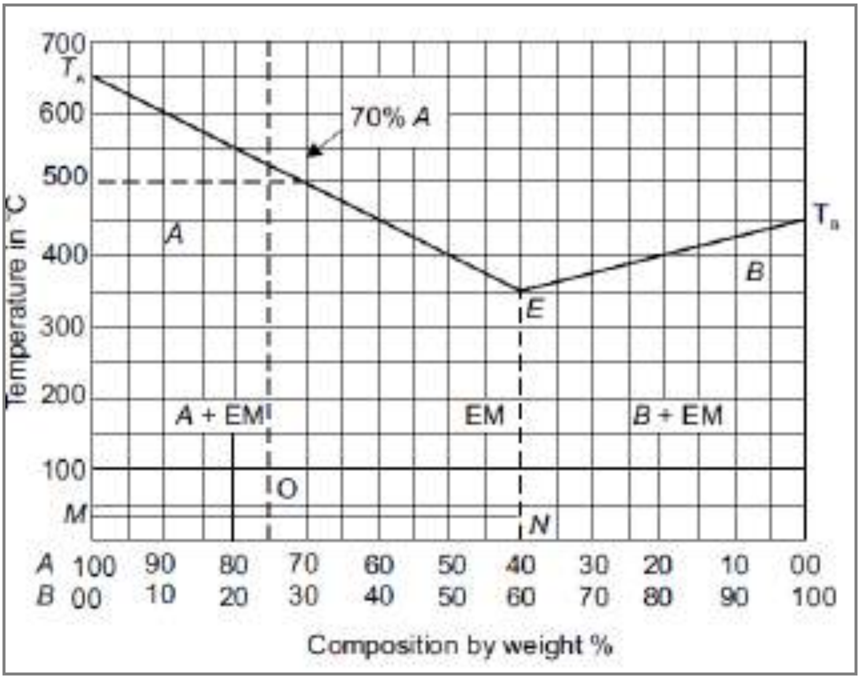
Problem 1.3

Two metals A and B are used to form an alloy containing 70% A and 30% B. Metal A melts at 650°C and B at 450°C when alloyed together. A and B do not form any compound or intermediate phase. The solid solubility of either metal is negligible. The metal pair forms a eutectic of 40% A and 60% B, which solidifies at 350°C. Assume the liquidus and solidus lines to be straight.

1. Draw the phase diagram.
2. Find the temperature at which the alloy starts and completes solidification.
3. Find the percentage of eutectic in the alloy at room temperature.

Solution

1. The following is the phase diagram.



2. The alloy of 70% A and 30% B starts solidification at 500°C and ends at 350°C.
3. Percentage of eutectic

$$= \frac{MO}{MN} \times 100 = \frac{100 - 70}{100 - 40} \times 100 = \frac{30}{60} \times 100 = 50\%$$

1.8.2.4 Two Metals Incompletely Soluble in Liquid and Solid States

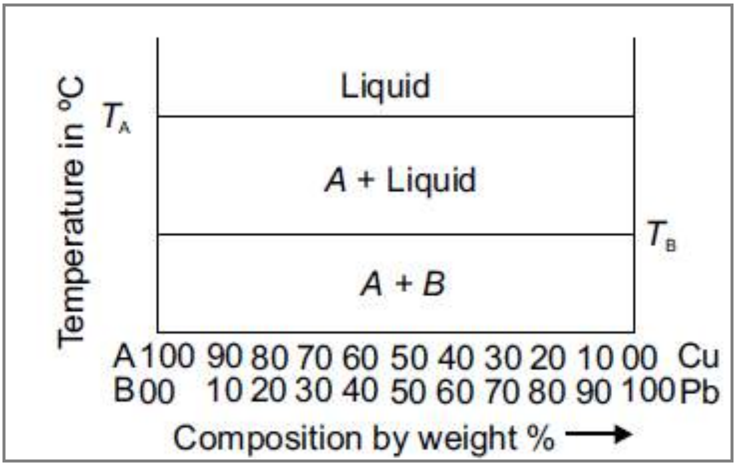


Fig. 1.16 Two metals incompletely soluble in liquid and solid states

All metals are not soluble in each other in the liquid state, e.g., lead and zinc, or lead and copper do not mix with each other when melted (see Figure 1.16). Lead which is heavier settles down at the bottom and the lighter metal zinc or copper, as the case may be, forms a distinct and separable top layer. This property is important commercially while making certain types of bearing alloys. The specific case is that of putting droplets of lead through molten copper and making an emulsion similar to that of oil in water. This emulsion is allowed to solidify and the soft lead globules in suspension in copper for man ideal anti-friction alloy. Practically, however, the two metals are rarely completely insoluble. When the temperature of the mixture is raised beyond a certain limit, these become soluble in each other and on cooling, these separate from each other. This liquid solubility at a high temperature is not of much practical importance.

1.9 LIQUID AND SOLID-STATE TRANSFORMATION

1.9.1 Eutectic Reaction (Transformation)

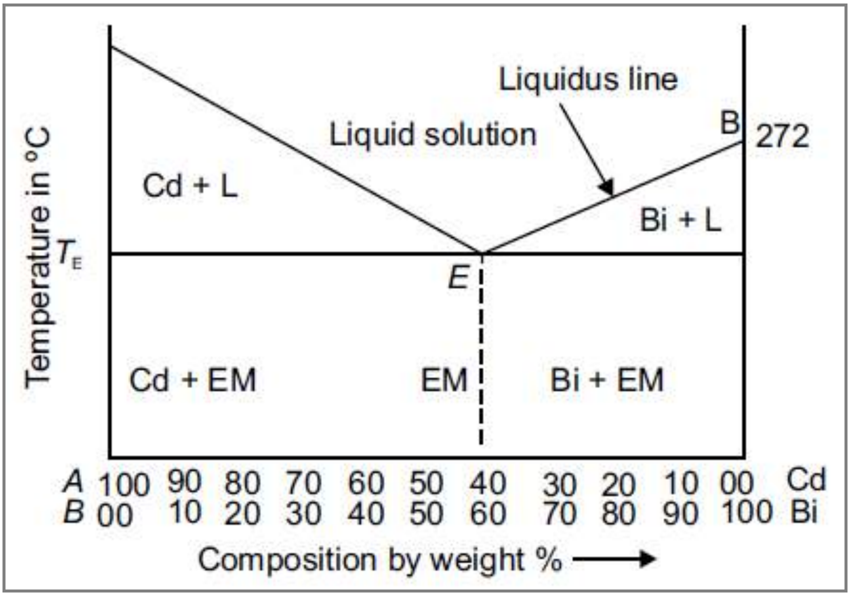


Fig. 1.17 Eutectic reaction in cadmium and bismuth system

In a eutectic reaction, the liquid solution of a fixed composition solidifies at a lower temperature than all other compositions and forms a mixture of two solid phases. This process reverses on heating. An example of metals showing eutectic reaction is bismuth and cadmium at 60% bismuth and 40% cadmium (see Figure 1.17).

$$\text{Liquid}\,\frac{\text{Cooling}}{\text{Heating}} \rightleftarrows \text{Solid1} + \text{Solid2}$$

$$\text{Liquis}\,\frac{\text{Cooling}}{\text{Heatin}} \rightleftarrows A + \text{EM}$$

1.9.2 Peritectic Reaction

Peritectic reaction is the reaction that occurs during the solidification of some alloys. In this reaction, the liquid phase reacts with the solid phase to give a solid phase of different structure, and the reaction occurs at a constant temperature.

Assuming a very slow rate of cooling, the peritectic reaction will occur only in silver and platinum alloys that contain 12–45% Ag (see Figure 1.18). Consider a liquid of composition of 25% silver and75% platinum. The solidification starts at T_1°C and ‘α’ begins to form till peritectic temperature (T_E). At this temperature, the ‘α’ crystals begin to react with remaining liquid and form δ solid solution.

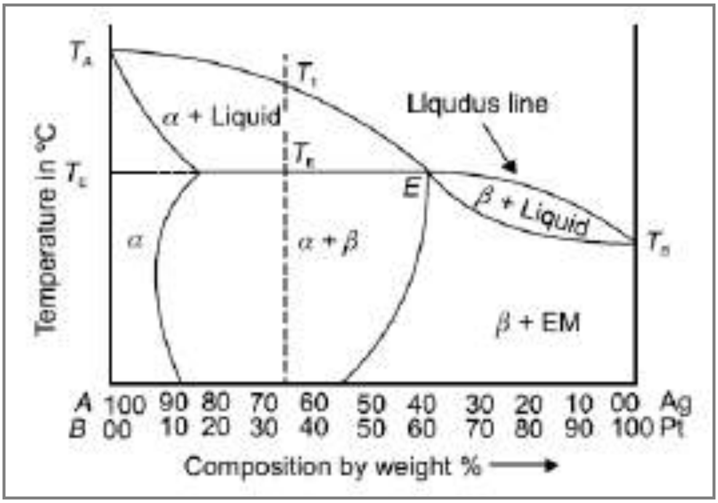


Fig. 1.18 Peritectic reaction in silver and platinum system

In the peritectic reaction, a liquid and a solid react isothermally to form a new solid. This reaction can generally be expressed as follows:

$$\text{Solid} + \text{Liquid}\,\frac{\text{Coling}}{\text{Heating}} \rightleftarrows \text{New Solid}$$

$$\alpha + \text{Liquid}\,\frac{\text{Cooling}}{\text{Heating}} \rightleftarrows \delta$$

The new solid formed is generally an intermediate phase.

1.9.3 Eutectoid Reaction

Allotropy (pure metals) and order–disorder transformation (in alloys) are the phase changes occurring in the solid state. The most important of the solid-state transformations is the eutectoid reaction in which one solid phase decomposes isothermally into a mixture of two solid phases.

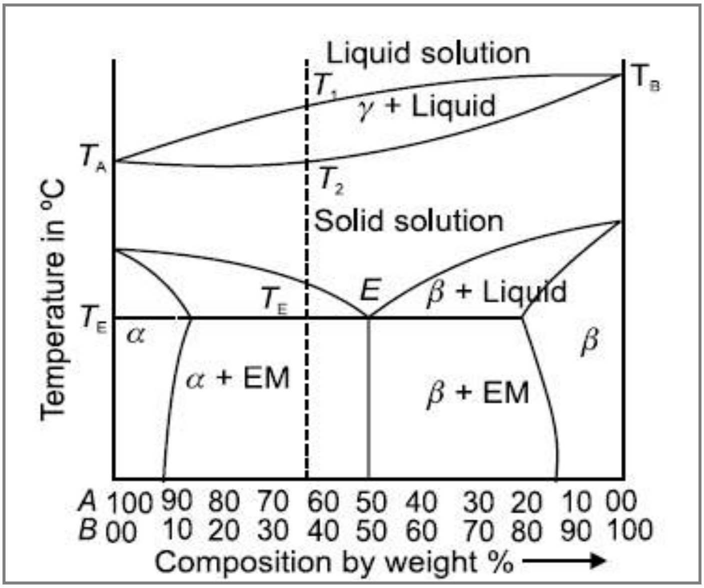


Fig. 1.19 Eutectoid reaction in silver and platinum system

Consider an alloy of 60% A and 40% B. As it is cooled slowly, γ solid solution appears. More and more of γ solid solution appears until it reaches T_2°C. When the alloy reaches eutectoid temp T_E, the γ solid solution now starts changing to ‘α’ solid solution. At the eutectoid temperature, residue γ solid solution is changed into eutectoid mixture. Microstructure at the room temperature consists of primary ‘α’ which was formed between T_3 and T_4 surrounded by a eutectoid mixture of A and B (see Figure 1.19).

$$\text{Solid1} \frac{\text{Cooling}}{\text{Heating}} \rightleftarrows \text{Solid2} + \text{Solid3}$$

$$\gamma \frac{\text{Cooling}}{\text{Heating}} \rightleftarrows \alpha + \text{EM}$$

Another example of eutectoid reaction, which is very common, is austenite decomposing into pearlite (ferrite + cementite).

1.9.4 Peritectoid Reaction

The peritectoid reaction is a very rare reaction. In this reaction, the two solid phases, a pure metal and the other solid solution, react at peritectoid temperature to form a new solid phase.

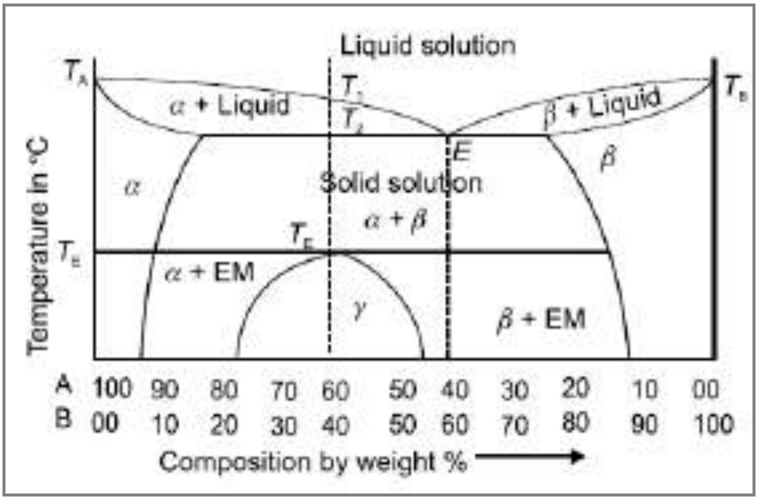


Fig. 1.20 Peritectoid reaction

In Figure 1.20, the solid phases α and β react at peritectoid temperature to form a new phase γ. Peritectoid reaction is the transformation of two solids into a third new solid.

$$\text{Solid1} + \text{Solid2}\ \frac{\text{Cooling}}{\text{Heating}} \rightleftarrows \text{New solid3}$$

$$\alpha + \beta\ \frac{\text{Cooling}}{\text{Heating}} \rightleftarrows \gamma$$

1.10 IRON CARBON EQUILIBRIUM DIAGRAM

The iron carbon equilibrium diagram graphically represents the changes that take place when two variables, such as temperature and overall composition, are varied. It shows the phase present in an alloy for system of different temperatures and for different compositions. This equilibrium diagram has temperature on vertical scale and percentage of composition by weight as horizontal scale. The composition on horizontal scale represents only 6.67% by weight. This is because, a maximum of 6.67% carbon can only be added to molten iron at which it becomes saturated. Any further addition of carbon will not make it dissolve in iron; but it rather floats on the surface due to low density. This phase diagram is also known as iron and iron carbide phase diagram. The iron carbon phase diagram is constructed by using a number of cooling curves with carbon varying from 0 to 6.67% similar to nonferrous diagrams. The effects of carbon addition to iron are shown in Figure 1.21. When carbon dissolves in molten iron, the solidification temperature of the resulting iron carbon alloy decreases. Iron carbon alloys which contain up to 2% carbon are known as steel. Iron carbon alloys holding more than 2% carbon are called cast irons. Up to 0.8% carbon steels are called as hypoeutectoid steels. The carbon content from 0.8% to 2% is called hypereutectoid steel. Similarly, from 2% to 4.43%carbon is called hypoeutectic cast iron and 4.33% to 6.67% cast iron is called hypereutectic cast iron.

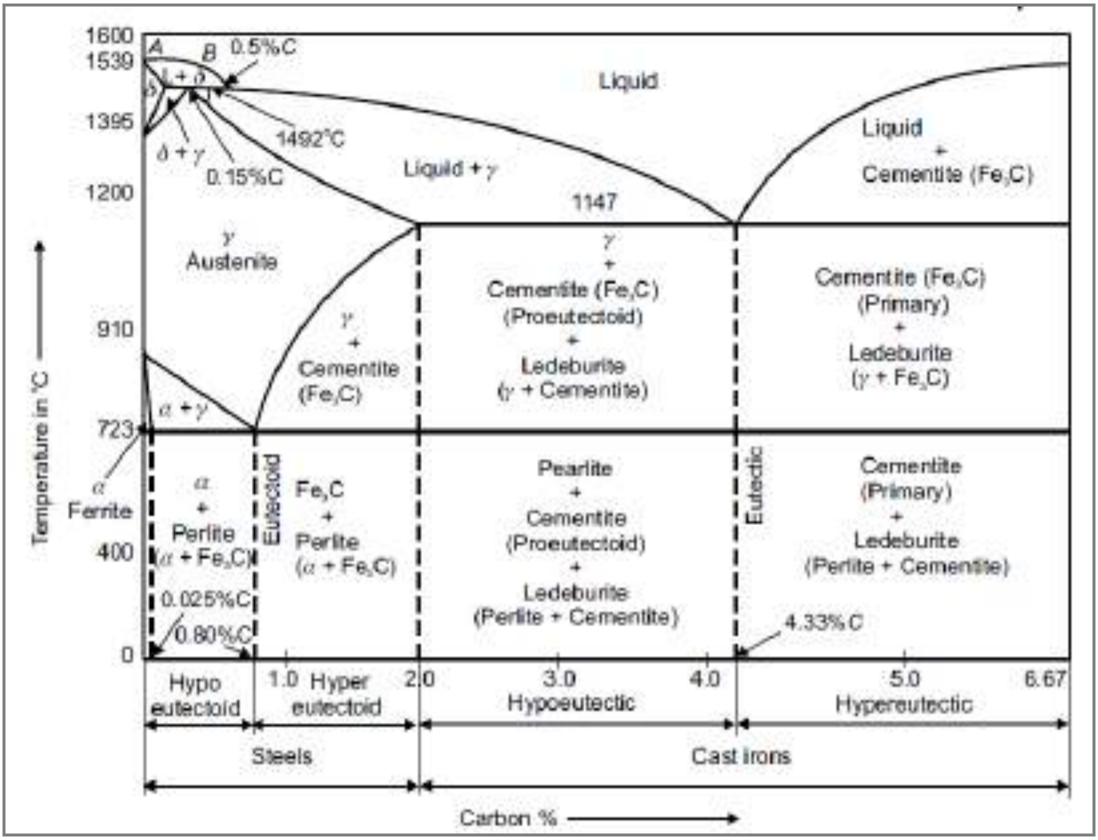


Fig. 1.21 Iron carbon phase diagram

Pure iron melts or solidifies at 1539°C. Further, when up to 4.3% carbon is added to molten iron, the solidification temperature decreases to 1130°C. This is indicated by a line ABC on the diagram. Beyond 4.3% carbon, the temperature increases as shown in the figure. This is represented by a line CD on the diagram. From the figure, the line ABCD represents liquidus line. The melting point of pure iron is marked as point A. Similarly, point D is the melting point of iron carbide. As the temperature of the liquid falls along the line ABCD, crystals of austenite separate from the liquid. In the same way, the crystals of iron carbide separate from liquid along line CD. The complete solidification of iron carbon alloys produces along the line HJECF called the solidus.

1.11 PHASES OF IRON CARBIDE, PHASE DIAGRAM

The phases that occur in iron carbon alloys are molten alloys, austenite, ferrite, cementite, ledeburite and pearlite.

1.11.1 δ-Ferrite

When a low carbon steel crystallizes at 1539°C, the solid that appears is in BCC crystal structure called δ-ferrite. At 1492°C, because of higher temperature the solubility of carbon in δ-ferrite is very small, between 0.1% and 0.15%. It is soft, ductile and converted into γ solid solution by reacting with residue liquid of iron at 1395°C.

1.11.2 Austenite

Austenite is an interstitial solid solution of carbon up to 2% at 1147°C and it is FCC in crystal structure. It is normally unstable at room temperature and is nonmagnetic. On cooling below 723°C,it starts transferring into ferrite and pearlite.

1.11.3 Ferrite

The structural modification of pure iron at room temperature is known as ferrite. It is an interstitial solid solution of small amounts of carbon dissolved in BCC crystal structure. The maximum solubility of carbon is 0.025% at 723°C and 0.008% at room temperature. Ferrite is soft, ductile and is of low strength among all phases of iron carbon alloys.

1.11.4 Cementite

When carbon in iron exceeds the solubility limit, it forms a second phase which is commonly known as cementite. This is also called iron carbide (Fe3C) and it contains up to 6.67% carbon by weight and has orthorhombic crystal structure. It is a typical compound of low tensile strength but high compressive strength and ferromagnetic. It is hardest structure in iron carbide system.

1.11.5 Pearlite

The mechanical mixture of ferrite and cementite formed at 727°C on very slow cooling is known as pearlite. It consists of alternate layers of ferrite and cementite. It is a product of eutectoid formation. Pearlite is fairly soft and its hardness lies between that of ferrite and cementite. It appears like a fingerprint in structure.

1.11.6 Ledeburite

Ledeburite is eutectic lamellar mixture of austenite and cementite. It contains 6.67% carbon and is formed at 1147°C by eutectic reaction. Further, ledeburite is unstable and transfers into ferrite and cementite at 726°C. Cementite is hard but brittle and pearlite is also fairly hard. Therefore, the transformed ledeburite is also hard and brittle.

1.11.7 Solubility of Carbon in Iron

The solubility limit for carbon in ferrite iron is shown by line GPR. This area of diagram is labeled as 'α' (Ferrite). The maximum solubility of carbon in ferrite is 0.025% at 723°C and minimum solubility is 0.008% at room temperature. Austenite is FCC structure iron and is capable of containing up to 2% dissolved carbon. It has definite solubility for carbon, which depends upon the temperature.

1.12 REACTION OF IRON CARBON SYSTEM

There are three invariant reactions that occur in iron carbon phase diagram leading to various phase trans formations and structures. These reactions are peritectic reaction, eutectic reaction and eutectoid reaction.

1.12.1 Peritectic Reaction

The peritectic reaction involves the isothermal transformation of liquid and solid to another solid phase at a constant temperature. In this reaction, the δ-iron reacts with residue liquid and is completely transferred to austenite on cooling at 1492°C. The reaction can be written as

$$\text{Liquid} + \delta \, \frac{\text{Cooling}}{\text{Heating}} \rightleftarrows \gamma \text{ (Austenite)}$$

1.12.2 Eutectoid Reaction

The eutectoid reaction is solid to solid transformation at constant temperature. A solid decomposes into two solid phases. In this reaction, the austenite transfers into ferrite and cementite by eutectoid reaction on cooling at 723°C. The reaction can be written as

$$\gamma(\text{Austenite}) \rightleftarrows \frac{\text{Cooling}}{\text{Heating}} \alpha(\text{Ferrite}) + \text{Fe}_3\text{C}\,(\text{Cementite})$$

1.12.3 Eutectic Reaction

The eutectic reaction is liquid to solid transformation at constant temperature. A liquid is converted into two solids. In this reaction, the liquid solution is transferred into austenite and cementite on cooling at 1147°C. The reaction can be written as

$$\text{Liquid} \frac{\text{Cooling}}{\text{Heating}} \rightleftarrows \gamma(\text{Austenite}) + \text{Fe}_3\text{C}\,(\text{Cementite})$$

1.13 STEELS

Steels contain iron and carbon with the carbon content varying from 0.008% to 2%. In this, carbon is combined with iron in solid solution and no free carbons are present. However, in practice, the carbon range does not exceed 1.7%. Steels can be classified into three types: low carbon steels—0.2%–0.3% carbon, medium carbon steels—0.3%–0.6% carbon and high carbon steels—0.6%–1.7%carbon. Steels with carbon content from 0.025% to 0.8% are called hypoeutectoid steel. Steels with0.8% carbon are known as eutectoid steels and steels with carbon content from 0.8% to 2% are called hypereutectoid steel.

1.13.1 Solidification and Transformation of Hypoeutectoid Steel (0.4% Carbon Steel)

The alloy is liquid above the liquids line. As the temperature decreases from the liquid line (T_1°C), δ-delta iron starts to precipitate from the liquid phase. The δ-iron contains a maximum of 0.1% carbon. At temperature 1427°C or T_2°C, δ-solid solution and molten iron react to get converted into austenite. The austenite region is shown in Figure 1.22. The line GSA in the figure shows that the temperature transformation of austenite to ferrite starts at S, T_3°C. Below this line, ferrite separates out from the austenite. Under very slow cooling conditions, the entire free ferrite separates from austenite when temperature reaches 723°C. At temperature 273°C, the carbon content of the austenite is 0.8%. Slightly below this temperature the austenite of the eutectoid composition decomposes with simultaneous precipitation of ferrite and cementite thus forming pearlite. Upon further cooling at room temperature, microstructure contains a mixture of free ferrite and pearlite.

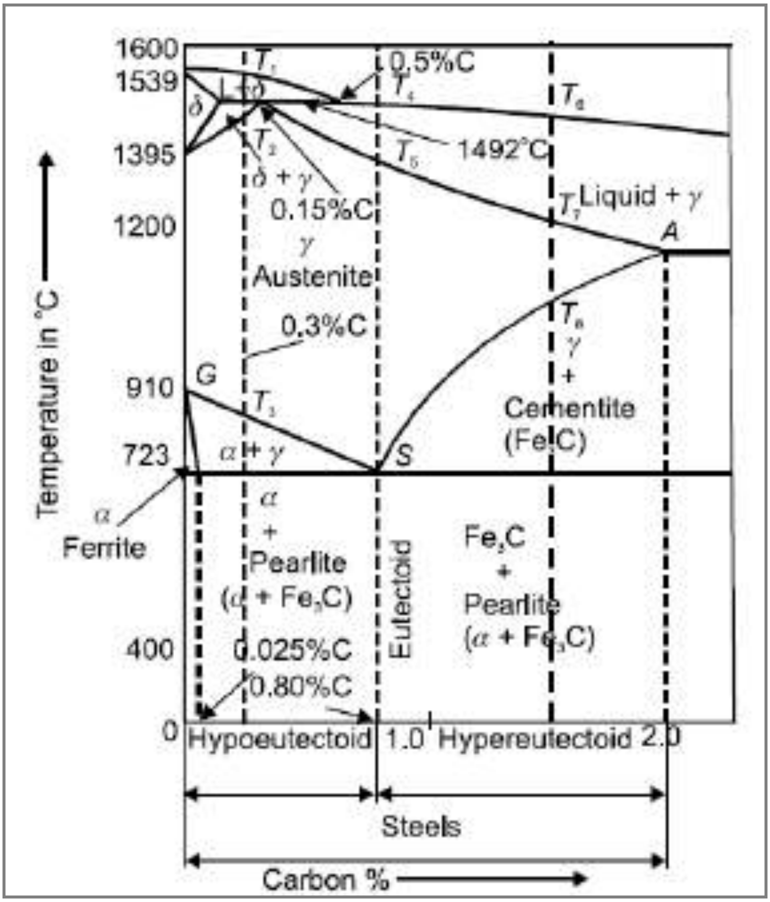


Fig. 1.22 Steel portion of iron carbon phase diagram

1.13.2 Solidification and Transformation of Eutectoid Steel (0.8% Carbon Steel)

The steel containing 0.8% carbon is called eutectoid steel. The alloy is liquid above T_4°C and solidification starts when temperature decreases austenitic range. This process is continuous until temperature reach T_5°C. By the time the temperature reaches T_5, the whole liquid solidifies as austenite 0.8% carbon steel becomes solid solution in the form of austenite between the temperature range of T_5 and 273°C. When temperature 273°C is reached, the carbon content of the austenite is 0.8% and steel undergoes the eutectoid reaction into two new solid phases (ferrite and cementite) called pearlite. On further cooling to room temperature, the microstructure will be pearlite.

1.13.3 Solidification and Transformation of Hypereutectoid Steel (1.5% Carbon Steel)

Hypereutectoid steel contains carbon content from 0.8% to 2%. Any alloy from hypereutectoid steel is liquid above T_6°C. Slightly below this temperature, solidification starts with the separation of austenite crystals. This process is continuous till it reaches a temperature of T_7°C. By time the temperature reaches T_7°C, the whole liquid solidifies as austenite. Hypereutectoid carbon steel becomes solid solution in the form of austenite in the temperature range of T_7 and T_8°C. On further decreasing the temperature, the solubility of the carbon content decreases along the line SA and the excess carbon precipitates as pro-eutectoid cementite up to temperature 273°C. At 273°C, the carbon content of the residue austenite is 0.8% and undergoes the eutectoid reaction and forms two new solid phases (ferrite and cementite) called pearlite. Upon further cooling to room temperature, the microstructure will be proeutectoid, cementite and pearlite.

1.14 CAST IRON

Cast iron is the name given to those alloys of iron carbon which contain more than 2% of carbon. Carbon from 2% to 4.33% is called hypoeutectic, 4.33% cast iron is eutectic and 4.33% to 6.67% cast iron is called hypereutectic cast iron. On the basis of nature of carbon present in cast iron, it may be divided into white cast iron and gray cast iron. In the gray cast iron, carbon is present in freeform as graphite. Under very slow rate of cooling during solidification, carbon atoms get sufficient time to separate out in pure form as graphite. In addition, certain elements promote decomposition of cementite. Silicon and nickel are two commonly used graphitizing elements. In white cast iron, carbon is present in the form of combined form as cementite. In normal conditions, carbon has a tendency to combine with iron to form cementite.

1.14.1 Solidification and Transformation of Hypoeutectic Cast Iron (4% Carbon Cast Iron)

Hypoeutectic cast iron has carbon content between 2% and 4.33% (see Figure 1.23). Hypoeutectic cast iron of any composition solidifies at T_1°C on the liquids line with separation of austenite. Below this line, the alloy is in a two-phase state consisting of liquid and austenite crystals. As solidification progresses, the composition of residue liquid varies along the solids CB and liquids AB respectively. The austenite precipitated between T_1°C and 1147°C has 0.8% carbon. At 1147°C, the residue liquid reduces to eutectic composition (4.33% carbon) and gets converted into eutectic mixture called austenite and cementite. The mixture of austenite and cementite is known as ledeburite. Just below 1147°C, the cast iron consists of austenite crystals and ledeburite. Further cooling involves the separation of cementite from the austenite. The composition of austenite varies along AB. At 727°C, the austenite gets enriched with 0.8% carbon and decomposes into ferrite and cementite. The mixture of ferrite and cementite is called pearlite. The final structure at room temperature consists of ledeburite, cementite and pearlite. These transformations occur when the hypoeutectic cast iron is cooled at a normal rate.

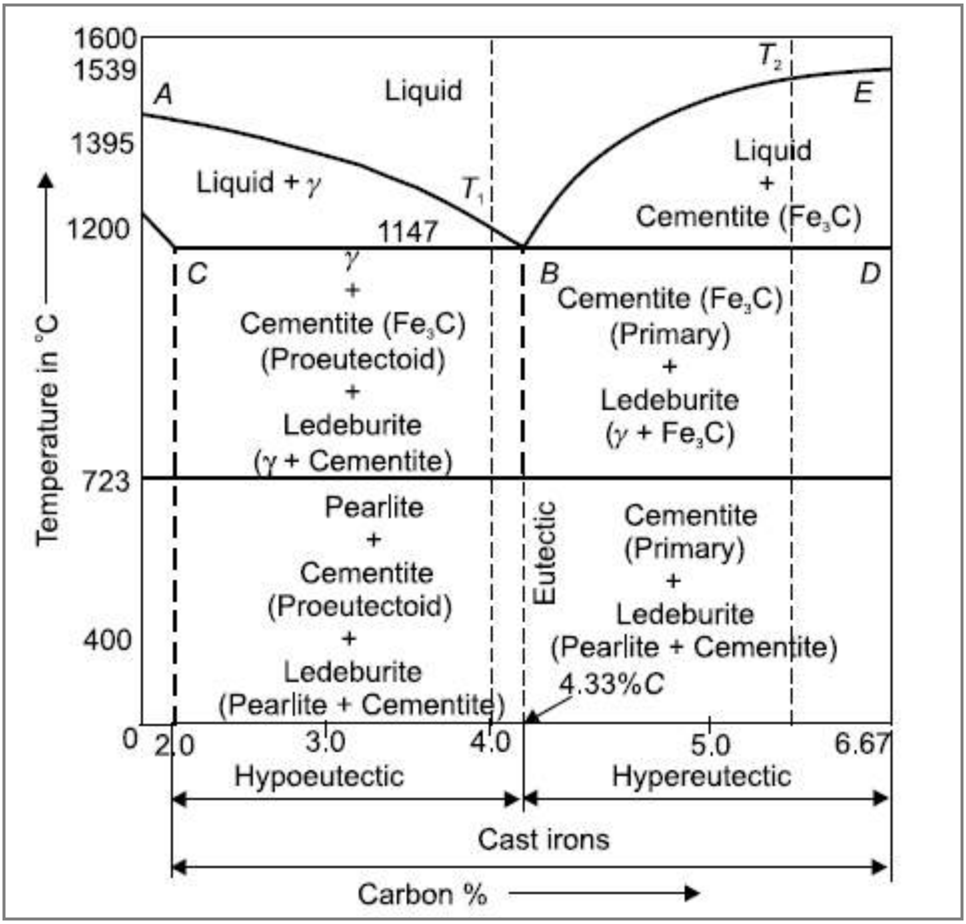


Fig. 1.23 Cast iron portion of iron carbon phase diagram

1.14.2 Solidification and Transformation of Eutectic Cast Iron (4.33% Carbon Cast Iron)

Eutectic cast iron contains 4.33% carbon and it solidifies at a constant temperature of 1147°C.

Below 1147°C, the microstructure consists of austenite and cementite. The mixture of austenite and cementite is also known as ledeburite. As the temperature deceases, the solubility of carbon decreases in austenite as indicated in line AB. On further cooling in temperature range 1147°C to 723°C, excess carbon comes out and gets modified into cementite along with iron. At 723°C, austenite contains 0.8%carbon and transforms into pearlite (ferrite and cementite). The final structure at room temperature consists of ledeburite, cementite and pearlite.

1.14.3 Solidification and Transformation of Hypereutectic Cast Iron (6.23% Carbon Cast Iron)

Hypereutectic cast iron has carbon content between 4.33% and 6.67%. Hypereutectic cast iron of any composition solidifies at T_2°C on the liquids line with the separation of cementite (primary). Below this line, the alloy is in a two-phase state consisting of liquid and cementite crystals. Assolidification progresses, the composition of residue liquid varies along the solidus line BE. The cementite precipitates between T_2°C and 1147°C. At 1147°C, the residue liquid reduces to eutectic composition (4.33% carbon) and gets converted into eutectic mixture called ledeburite (austenite and cementite). Just below 1147°C, the cast iron consists of cementite (primary) crystals and ledeburite. Further cooling involves the separation of cementite from the austenite. At 727°C, the austenite gets enriched with 0.8% carbon and decomposes into ferrite and cementite. The final structure at room temperature consists of cementite, ledeburite and pearlite. These transformations occur when the hypoeutectic cast iron is cooled at a normal rate.

1.15 FERRITE AND AUSTENITE STABILIZERS

Three most common phases in Iron-Carbon Phase diagram are Ferrite, Cementite and Austenite. Stabilising a particular phase primarily means making that phase more available in room temperature. This effect may lead to excessive changes in properties and may make the material fit or unfit for certain application.

Ferrite generally has body centered cubic type of structure. According to Hume Rothery Principle a body centered cubic (B.C.C.) material will stabilise another body centered cubic type of material when mixed with each other. Therefore, Ti, Cr, Mo, Al will help in stabilising ferrite at room temperature.

Austenite generally has face centered cubic type of structure. According to Hume Rothery Principle a face centered cubic (F.C.C.) material will stabilise another face centered cubic type of material when mixed with each other. Therefore, Si, Mn, Ni, C will help in stabilising austenite at room temperature.

UNIT-II-FERROUS AND NON FERROUS ALLOYS

The metallic materials are one of the most important elements that are used for industrial applications in our everyday lifes. The properties of metals and alloys have to be understood before using them. Properties of metals describe the different characteristics of metals when subjected to forces or load. This is used by mechanical engineers to calculate different conditions of metals and it is especially important to people building structures or vehicles or machines. Metals and alloys are safe for humans during their operation in the structures or machines.

The metallic materials can be classified into two main groups ferrous and nonferrous. The ferrous materials are iron based with other constituents. Metals other than iron are called nonferrous materials. The major nonferrous materials are copper, aluminium, magnesium, nickel, tin, lead and zinc.

2.1 FERROUS MATERIALS

2.2 Introduction

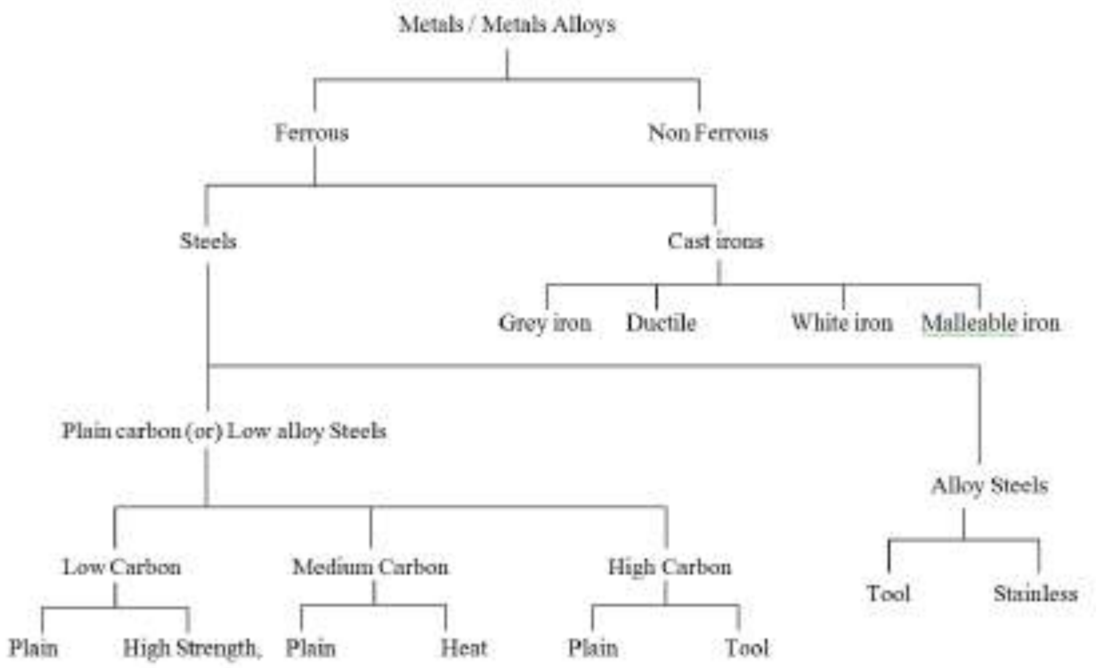
The ferrous materials are those materials which contain iron as their prime constituent. More than 90% by weight of the metallic materials used by human beings are ferrous materials. The ferrous metals are extensively used in engineering due to the following three factors:

- Iron – based components are relatively abundant and are widely distributed throughout the world.
- Ferrous materials can be produced very economically
- Ferrous materials are versatile. Therefore wide range of mechanical and physical properties of ferrous materials can be achieved.

Thus the availability, comparatively low cost, and the wide range of properties that can be achieved have made ferrous materials of great importance. The principal disadvantage of many ferrous alloys is their susceptibility to corrosion.

2.3 Classification of ferrous materials.

A taxonomic classification scheme for the various ferrous materials is presented below.



2.4 STEELS

Steels are alloys of iron and carbon. However, steels contain other elements like silicon, manganese, sulphur, phosphorus, nickel, etc. The alloying elements are either intentionally added or retained during the refining process.

2.5 Plain Carbon Steels

Plain carbon steel includes those steels in which the properties mainly result from the existence of carbon. Additional elements such as manganese, silicon, phosphorous and sulphur may be present in relatively small amounts but do not add to the mechanical properties of the steel. In plain carbon steel, carbon may vary from 0.08% to 1.55%.

Plain carbon steels are classified into three types according to the percentage of carbon.

2.6 Low carbon Steel (Mild Steel)

Steels in which the carbon content ranges from 0.08% to 0.35% are known as mild steels. The microstructure consists of ferrite and small quantity of perlite as shown in Figure 2.1. It is soft, highly ductile and tough. These steels do not respond to hardening and have good machineablity and weldability. Mild steel is mainly used in automobiles, structural fabrication, wires, rivets, nuts, bolts, sheets, tubes and shafts railway axle.

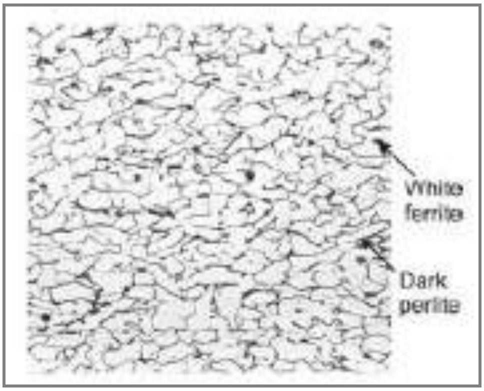


Fig 2.1 Microstructure of low carbon (mild) steel

2.7 Medium Carbon Steel

The steels in which the carbon content ranges from 0.35% to 0.55% are called medium carbon steels. The microstructure consists of perlite and ferrite as indicated in Figure 2.2. It is harder, stronger and less ductile than mild steel. They are used in various steel sections, rail steel, springs, wire ropes and hammer.

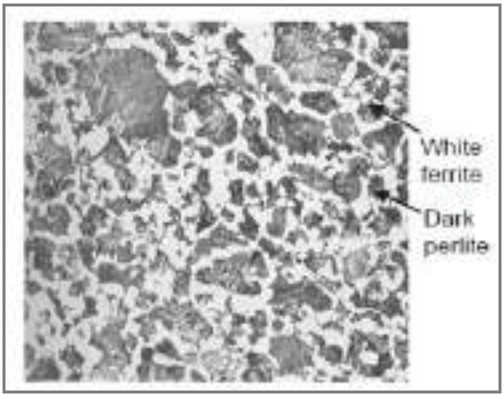


Fig 2.2 Microstructure of medium carbon steel

2.8 High Carbon Steel

The steels in which the carbon content ranges from 0.55% to 1.55% are known as high carbon steel. Hardness and strength are increased by increasing the carbon content. Microstructure consists of cementite and perlite. They are hardest, strongest and low ductile as indicated in Figure 2.3. High carbon is responsible for hardening, and the mechanical properties can be altered by heat treatment. High carbon steels are used for knives, razors, metal-cutting tools, hacksaw blades, hand files, forging dies and drills bits.

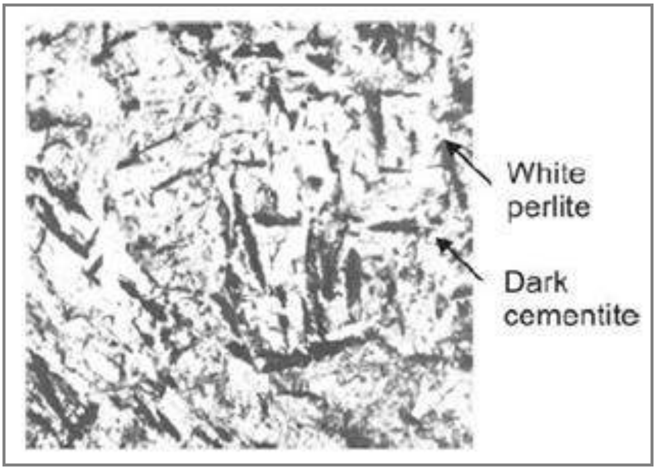


Fig 2.3 Microstructure of high carbon steel

The chemical analyses of some commercial plain carbon steel along with other elements are given in Table 2.1.

Table 2.1 Shows Typical Analysis of Some Commonly used Commercial Steels

Types of Steel	C%	Mn%	Si%	S%	P%
Wrought Iron	0.05	0.05	0.07	0.01	0.01
Low Carbon Steel (Mild Steel)					
(i) Rivet Steel	0.05	0.30	0.07	0.04	0.04
(ii) Structural Steel	0.20	0.08	0.12	0.05	0.05
(iii) Free Cutting Steel	0.13	0.45	0.03	0.12	0.10
(iv) Railway Axle	0.35	0.80	0.20	0.04	0.04
Medium Carbon Steel					
(i) Rail Steel	0.38	1.00	0.08	0.06	0.05
(ii) Railway Spring Steel	0.50	0.85	0.10	0.05	0.05
High Carbon Steel					
(i) Chisel Steel	0.75	0.50	0.08	0.05	0.05
(ii) Carbon Tool Steel	1.30	0.32	0.15	0.02	0.02
(iii) Saws, Razor	1.40	0.50	0.10	0.30	0.05
(iv) Saws for Cutting Steel	1.55	0.40	0.15	0.02	0.02

2.9 Alloy Steels

In the alloy steels, the presence of other elements like manganese, nickel, chromium, etc. along with the carbon improve the mechanical properties, even though carbon still plays a major part in maintaining the superiority of the steels. The alloying elements are added in steels to achieve one or more of the following properties.

1. Increase resistance to corrosion
2. Improve machinability
3. Increase resistance to abrasion
4. Increase high temperature properties

On the basis of the total alloy content, the alloy steels may be classified as low alloy steels and high alloy steels.

The alloy steels in which, generally, the alloying elements are less than 10% are called low alloy steels. The importance of low alloy steels is that the alloying elements like chromium, manganese, nickel, vanadium and boron permit much wider range of physical and mechanical properties. Some alloy steels possess a very high tensile strength, which is impossible with plain carbon steel. Low alloy steels are mainly used as machine components in railway, ship, aeroplane, automobile and other engineering industries. If the alloying elements constitute more than 10%, they are called high alloy steels. The high alloy steels are mainly used as cutting tools, blades, razors and wear-resistant parts in industry. Some common alloy steels are discussed in the following subsections.

2.10 Manganese Steel

Manganese is one of the principal alloying elements using along with steel. Plain carbon contains small trace of manganese ranging from 0.05% to 0.85% and it improves strength and ductility. The use of 1.5%–2% manganese in low alloy steel further increases the strength in heat treated condition. Manganese which amounts between 2% and 10% along with carbon is responsible for brittleness in steel. If the manganese content is increased to 11%–16% along with 1%–1.5% carbon, the alloy produced is hard and wear resistant. This material is known as Hadfield austenitic manganese steel. Manganese steels are used extensively for frogs and switches in railroad, rock crusher and dredge buckets in mining.

2.11 Nickel Steel

Nickel is one of the important alloying elements alloyed with steel. Small quantity of nickel helps to improve the toughness and impact resistance. Nickel content of 1.5%–6% produces much finer grain size than other elements and increases the elastic limit, hardness and tensile strength of steel. The low carbon and 3.5% nickel are used for carburizing as it develops hardness on the surface and toughens the core. Nickel content of 8%–22% improves corrosion resistance and provides additional strength and hardness to steel without affecting the ductility. These steels are used for bolts, gears, axles, nuts and various machine arts. Nickel steel containing 36% nickel is called Invar steel. It is mainly used for measuring instruments.

2.12 Chromium Steel

Chromium is also one of the principal alloying elements in steel. Chromium exists in steel predominantly as carbide which provides hardness and also increases the elastic limit and tensile strength without affecting the ductility. The low carbon chromium steels are suitable for carburizing and produce very hard, wear-resistant alloys and are used for springs, gears, bolts and nuts. Addition of chromium to plain carbon steel improves the hardenability, strength and wear resistance; and both nickel and chromium improve the ductility of steel. It is mainly used in surgical instruments, files, ball and roller bearings, gears and springs.

2.13 Stainless Steel

The proper combination of chromium and nickel will improve some properties of carbon steel. The addition of nickel confirms the increased strength, surface hardness while the depth of hardness is increased by the addition of chromium. Nickel and chromium steel are also called as stainless steel and are classified as follows:

2.13.1 Martensitic Stainless Steel

Martensitic steels typically contain 11.5 to 18 percent chromium and upto 1.2 percent carbon with 1 to 1.2 percent nickel. They are hardenable by heat treatment, have modest corrosion resistance and are employed in surgical instruments, wrenches and turbines. These steels can cold work. They are also used for making springs, steam turbine plates and ball bearings.

2.13.2 Ferritic Stainless Steel

Standard ferrictic steels contain 10.5 to 27 percent chromium and are nickel free; because of their low carbon content (less than 0.2 percent), they are not hardenable by heat treatment. They are resistant to corrosion and have great strength. They are used for household steels, surgical instruments, chemical industries and automobile.

2.13.3 Austenitic Stainless Steel

Austenitic steel which contain 16 to 26 percent chromium and up to 35 percent nickel, usually have the highest corrosion resistance. They are not hardenable by heat treatment and are nonmagnetic. Typical applications include aircraft and the dairy, food processing industries, household equipment, heat exchangers and dairy equipment.

2.14 High-speed Steel

High-speed steels are high-alloyed steel containing large amounts of tungsten, chromium, vanadium and cobalt. They are withstand high temperature without loosing hardness under high cutting speeds. The tools made up of high speed steels can be run at high speeds as compared to tools made up of carbon steels. Drills, milling cutters, tool for lathe are the example for high speed steel.

2.15 Tungsten High-speed Steel

Tungsten is commonly used as alloying elements in high alloy steels. It varies from 1%–20% in the form of ferrite and also carbide. It helps retain hardness and sharp cutting edges at high temperatures. It precipitates as tungsten carbide by reacting with carbon available in the molten steel. One of the most important tool steels is high tungsten alloy called high-speed steel. It has the ability of the steel to maintain a sharp cutting edge even at a red hot condition and used in high-speed machining operations.

2.16 EFFECT OF ALLOYING ELEMENTS IN STEELS

In general, alloying elements are added to steel in small percentages - usually less than 5 percent to improve strength or hardenability. Otherwise, alloying elements are added to steel in much larger amounts usually up to 20 percent to produce special properties such as corrosion resistance or stability at high or low temperatures.

The properties of all steels (or all alloys) are determined by the kinds and amounts of phases of which they are composed, by the properties of the phases, and by the way in which these phases are distributed among one another.

Steels consist of two or more phases known as ferrite, austenite, carbides and graphite. The alloying elements in steels affect the stability of these phases, the relative amounts of the phases, and how the phases are distributed or dispersed throughout one another. Thus, the alloying elements affect and control the properties of steels.

- The alloying elements such as Ni, Mn, Cu and Co tend to stabilize austenite.
- The alloying elements such as Cr, W, Mo, V and Si tend to stabilize ferrite.

- Some alloying elements such as Cr, W, Ti, Mo, Nb, V, and Mn tend to form carbides. Other elements such as Si, Co, Al, and Ni tend to destabilize carbides and form graphite.

The more important effects of the main alloying elements added to steels can be summarized below

2.17 Manganese (Mn)

Manganese is generally used to improve hot ductility. Its effect on the ferrite/austenite balance varies with temperature: at low temperature manganese is an austenite stabilizer, but at high temperatures it will stabilize ferrite. Manganese increases the solubility of nitrogen and is used to obtain high nitrogen contents in duplex and austenitic stainless steels. Manganese, as an austenite former, can also replace some of the nickel in stainless steel.

2.18 Silicon (Si)

Silicon increases resistance to oxidation, both at high temperatures and in strongly oxidizing solutions at lower temperatures. It promotes a ferritic microstructure and increases strength.

2.19 Chromium (Cr)

This is the most important alloying element and it gives stainless steels their basic corrosion resistance. All stainless steels have a Cr content of at least 10.5% and the corrosion resistance increases the higher chromium content. Chromium also increases the resistance to oxidation at high temperatures and promotes a ferritic microstructure.

2.20 Molybdenum (Mo)

Molybdenum increases the hardness penetration of steel, slows the critical quenching speed, and increases high temperature tensile strength.

2.21 Vanadium (V)

Vanadium helps control grain growth during heat treatment. By inhibiting grain growth it helps increase the toughness and strength of the steel.

2.22 Titanium (Ti)

This element, when used in conjunction with Boron, increases the effectiveness of the Boron in the hardenability of steel.

2.23 Aluminum (Al)

If added in substantial amounts aluminum improves oxidation resistance and is used in certain heat-resistant grades for this purpose. In precipitation hardening steels, aluminum is used to form the intermetallic compounds that increase the strength in the aged condition.

2.24 Silicon (Si)

Silicon increases resistance to oxidation, both at high temperatures and in strongly oxidizing solutions at lower temperatures. It promotes a ferritic microstructure and increases strength.

2.25 Copper (Cu)

Copper enhances corrosion resistance to certain acids and promotes an austenitic microstructure. It can also be added to decrease work hardening in grades designed for improved machinability. It may also be added to improve formability.

2.26 Tungsten (W)

Tungsten is present as an impurity in most stainless steels, although it is added to some special grades, for example the super duplex grade 4501, to improve pitting corrosion resistance.

2.27 SOME IMPORTANT ALLOY STEELS

Though there are number of alloy steels available, the study of the following four alloy steels are very important from our subject point of view.

1. Stainless steels.
2. Tool steels
3. HSLA steels
4. Maraging steels.

2.28 Stainless steels

Stainless steels are alloys of iron, chromium, and other elements that resist corrosion from many environments. Stainless steels are also known as corrosion-resistant steels or chromium-bearing steels. All true stainless steel contain minimum of about 12% Cr. This 12% Cr permits a thin protective Surface layer of chromium oxide to form when the steel is exposed to oxygen. To enhance corrosion resistance, the stainless steels often contain other elements such as Cu, Al, Si, Ni and Mn.

2.28.1 Types of Stainless Steels

There are different types of stainless steels: when nickel is added, for instance, the austenite structure of iron is stabilized. This crystal structure makes such steels virtually non-magnetic and less brittle at low temperatures. For greater hardness and strength, more carbon is added. With proper heat treatment, these steels are used for such products as razor blades, cutlery, and tools. Significant quantities of manganese have been used in many stainless steel compositions. Manganese preserves an austenitic structure in the steel, similar to nickel, but at a lower cost.

The stainless steels are divided into three classes on the basis of the predominant phase constituent of the microstructure as

1. Austenitic: stainless steels
2. Ferritic stainless steels
3. Martensitic stainless steels

2.28.1.1Austenitic: stainless steels

The austenitic stainless steels have the austenite structure retained at room temperature. Austenitic: stainless steels have an austenitic crystalline structure, which is a face-centered cubic crystal structure. Austenite steels make up over 70% of total stainless steel production. They contain a maximum of 0.15% carbon, a minimum of 16% chromium and sufficient nickel and/or manganese to retain an austenitic structure at all temperatures from the cryogenic region to the melting point of the alloy.

Composition

Typical composition of austenitic stainless steel is given below

C - 0.03 to 0.15%
Mn - 2 to10%
Ni - 3.5 to 22%
Si - 1 to 2%
Cr - 16 to 26%
P and S - Normal
Mo and Ti in some cases

Properties

- Highest corrosion resistance
- Good strength and scale resistance at high temperature
- Non-magnetic
- Good ductility at cryogenic temperature i.e., below 0°C
- Very tough and can be welded

Applications

The typical applications of austenitic stainless steels include aircraft industry (engine parts), chemical processing (heat exchanger), food processing (kettles, tanks), household (cooking utensils), dairy industry (milk cans), transportation industry (trailers and railway cars), etc

2.28.1.2 Ferritic stainless steels

Ferritic stainless steels generally have better engineering properties than austenitic grades, but have reduced corrosion resistance, because of the lower chromium and nickel content. They are also usually less expensive. Ferritic stainless steels contain between 12 to 25% of chromium and less than 0.1 % of carbon.

Composition

Typical composition of ferritic stainless steel is given below

C - 0.08 to 0.10%

Mn - 1 to 1.5%

Si - 1%

Cr - 12 to 25%

Properties

- They are magnetic
- They have good ductility
- They have great strength, toughness, and good resistance to corrosion
- These steels can be welded, forged, rolled, and machined

Applications

The typical applications of ferritic stainless steels include lining for petroleum industry, heating elements for furnaces, interior decorative work, screws and fittings, oil burner parts, etc

2.28.1.3 Martensitic stainless steels

Martensitic stainless steels are not as corrosion-resistant as the other two classes but are extremely strong and tough, as well as highly machinable, and can be hardened by heat treatment. Martensitic stainless steels contain between 12 and 25% of chromium, together with carbon contents ranging from 0.1 to 1.5%.

Composition

C - 0.1 to 1.5%

Mn - 1%

Si - 1%

Cr - 12 to 25%

Properties

- Good hardness, ductility and thermal conductivity
- Good toughness and corrosion resistance

Applications

The typical applications of martensitic stainless steels include pumps and valve parts, rules and tapes, turbine buckets, surgical instruments, etc

2.29 Tool Steels

Tools steels are metals used to make tools and dies for cutting farming, or otherwise shaping a material into a component or part for a specific application. In other words, tool steels are metals designed to provide wear resistance and toughness combined with high strength. They are basically high-carbon alloys, where the chemistry provides the balance of toughness and wear desired.

Properties

- Good toughness
- Good wear resistance
- Very good machinability

- Slight change of form during hardening
- Little risk of cracking during hardening
- Resistance to softening on heating
- Resistance to decarburisation.
- A definite hardening temperature
- A definite cooling rate during hardening

Applications

Tool steels are used for cutting, pressing, extruding, coining, of metals and other materials. Their use for applications like injection molding due to their resistance to abrasion is an important criterion for a mold that will be used to produce hundreds of thousands of parts is essential.

2.30 HSLA steels (high strength low alloy steels)

HSLA steels, also known as micro-alloyed steels, are low carbon steels containing small amounts of alloying elements. The primary purpose of HSLA steels is weight reduction through increased strength. For structural applications, high yield strength, good weldability, and corrosion resistance are most desired, with only limited ductility and virtually no hardenability.

The increase in strength, coupled with resistance to martensite formation in a weld zone of a HSLA steel, is obtained by adding low percentages of several elements, such as manganese, silicon, niobium, vanadium, etc. About 0.20% Cu is, usually added to improve corrosion resistance

Composition

They have a carbon content between 0.05–0.25% to retain formability and weldability. Other alloying elements include up to 2.0% manganese and small quantities of copper, nickel, niobium, nitrogen, vanadium, chromium, molybdenum, titanium, calcium, rare earth elements, or zirconium. Copper, titanium, vanadium, and niobium are added for strengthening purposes.

Properties

- HSLA steels have very high yield strength
- They can be welded without becoming brittle

- These are very light i.e., weight savings upto 20 to 30% can be achieved without compromising its Strength.
- They have high corrosion resistance
- They are ductile, formable and machinable

Applications

They are used in cars, trucks, cranes, bridges, roller coasters and other structures that are designed to handle large amounts of stress or need a good strength-to-weight ratio.

2.31 Maraging steels

Maraging steels are low-carbon, highly alloyed steels .The term maraging is derived from the strengthening mechanism, which is transforming the alloy to martensite with subsequent age hardening. Air cooling the alloy to room temperature from 820°C creates a soft iron nickel martensite, which contains molybdenum and cobalt in supersaturated solid solution.

In the martensitic condition, these steels can be cold worked and can be hardened by precipitation at temperatures below the austenitizing temperature to achieve high tensile strength.

Composition

It contain 17–19 wt.% nickel, 8–12 wt.% cobalt, 3–5 wt.% molybdenum, and 0.2–1.6 wt.% titanium.

Properties

- Maraging steels have very high tensile strength and impact strength.
- These steels combine considerable toughness with high strength and are far superior than conventional alloy constructional steels.
- They are also very suitable for surface hardening by nitriding.
- They can be welded, if welding is followed by the full solution and ageing treatment.

Applications

- Aerospace, e.g. undercarriage parts and wing fittings

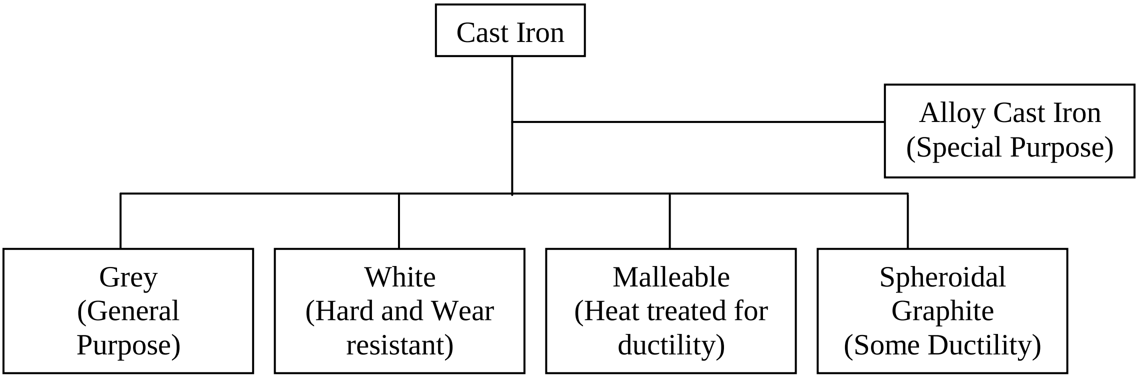
- Tooling & machinery ,e.g. extrusion press rams and mandrels in tube production, gears ordnance components and fasteners.

2.32 CAST IRON

An alloy of iron that contains 2%–4% carbon along with varying amounts of silicon and manganese and traces of impurities such as sulphur and phosphorus is called cast iron. It is made by reducing iron ore in a blast furnace. The liquid iron is cast into crude ingots called pig iron, and the pigs are subsequently remelted along with scrap and the alloying elements in cupola furnaces and recast into moulds for producing a variety of products. Commercially, cast irons have the carbon range between 2.2% and 4.3%. All cast irons are low in terms of ductility and hence, cannot be rolled. The fluidity of cast iron is very good, and therefore can be cast into any complicated shapes. Cast irons have high compressive strength.

2.33 Types of Cast irons

According to the shapes of the free carbon available in the microstructure, the cast irons are classified into following types



2.34 GREY CAST IRON

Grey cast iron basically is an alloy of iron and carbon. It contains 2.5%–3.8% carbon, 1.1%–2.8% silicon, 0.4%–1% manganese, 0.15% phosphorous and 0.10% sulphur. Microstructure consists of ferrite and flake graphite as shown in Figure 2.4. It can be cast into any shape in a sand mould, and it possess the lowest melting point of the ferrous alloys. It provides excellent casting quality for producing simple and complex shapes. It has high resistance to wear, high compressive strength and high vibration damping capacity. Grey cast iron is mainly used for water pipes, manhole covers, IC engine blocks, piston rings and machine components.

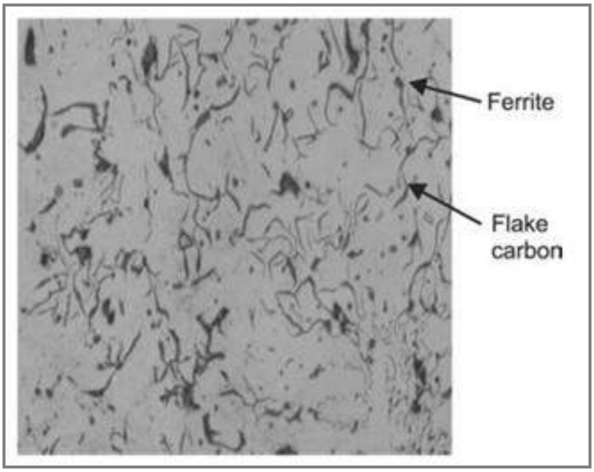


Figure 2.4 Microstructure of grey cast iron

2.35 WHITE CAST IRON

White cast iron derives its name from the fact that its freshly broken surface shows a bright white fracture. This is because, the carbon present in them is in combined form as cementite and perlite. Carbon is chemically bonded with the iron as iron carbide. White cast iron contains 1.8%–3.6% carbon, 0.5%–2% silicon, 0.2%–0.8% manganese, 0.18% phosphorus and 0.10% sulphur. Microstructure consists of iron carbide along with perlite as shown in Figure 2.5. It has excellent abrasive wear resistance and brittleness. It can be cast only in sand moulding and is mainly used for producing malleable cast iron and wear-resistance component machine component.

Figure 2.5 Microstructure of white cast iron

2.36 MALLEABLE CAST IRON

Malleable cast iron is obtained from hard and brittle white iron through controlled heat conversion (malleabilasztion) process. It is having all the carbon in the free form in irregular shapes as shown in Figure 2.6. Malleable cast iron contains 2.3% carbon, 0.6%–1.3% silicon, 0.2%–0.6% manganese and 0.15% phosphorous. Microstructure consists of dark graphite in a ferrite matrix as shown in Figure 2.6. Malleable cast iron possesses high yield strength and high Young's modules and it possesses good wear resistance. It is mainly used for railroad, agricultural implements and conveyor chain links.

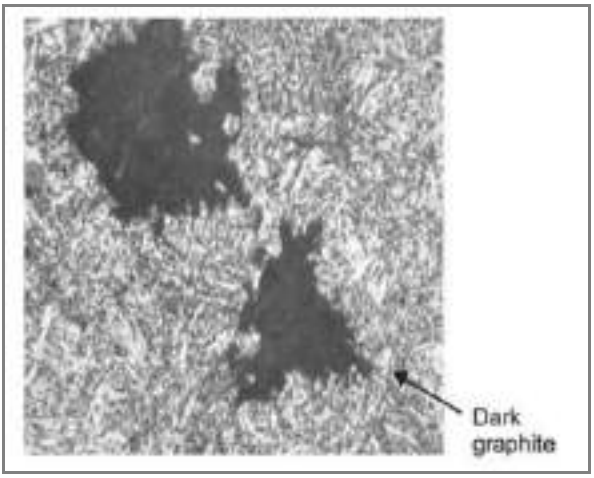


Figure 2.6 Microstructure of malleable cast iron

2.37 SPHEROIDAL GRAPHITE CAST IRON

Spheroidal graphite (SG) cast iron is also known as '**nodular cast iron**'or as '**ductile iron**'. In nodular cast iron, graphite appears as round shape instead of flakes as in grey cast iron. Nodular shaped graphite is obtained by adding small amounts of magnesium or cerium in the molten grey cast iron. Nodular cast iron contains 3.2%–4.2% carbon, 1.1%–3.5% silicon and 0.3%–0.8% manganese. Figure 2.7 shows the microstructure of nodular cast iron. Microstructure consists of nodules surrounded by ferrite. It is highly ductile and machinable with excellent castability and wear resistance. It is mainly used in internal combustion engine, earth moving machinery, valves and fittings, pipes and flywheels.

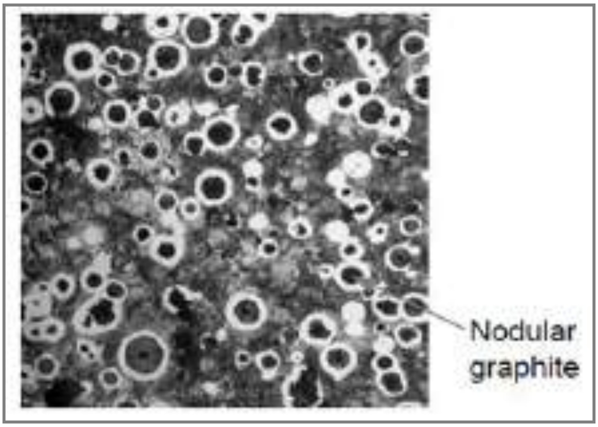


Figure 2.7 Microstructure of spheroidal graphite cast iron

2.38 ALLOY CAST IRON

The cast irons discussed so far are called plain cast irons, in the sense that the above cast irons contain only small amounts of impurities. The alloy cast irons, like alloy steels, can be produced by adding alloying elements like Ni, Cr, Mo, Cu, Si, and Mn. In general, the effects of alloying elements on the properties of cast iron are similar to the effects of same elements on the properties of steel.

Purpose

Alloy cast irons have been produced to give high strength materials, hard and abrasion-resistant materials, corrosion resistant irons, and irons for high-temperature service.

Effects of Alloying Elements in Cast Iron

Table 2.2 presents some of the alloying elements and their primary effects on the cast iron.

Table 2.2 Effects of Alloying Elements in Cast Iron

S.No.	Alloying Element	General Effects
1	Nickel (Ni)	♦ It has graphitizing effect on cementite. So it tends to produce a grey iron. ♦ It has a grain-refining effect, which helps to prevent the formation of coarse grain. ♦ It also toughens thin sections

2	Silicon (Si)	It has same effects as that of nickel
3	Chromium (Cr)	It is a carbide stabilizer, so it is used for hard and wear-resistant irons.
4	Molybdenum (Mo)	It increases the hardness of thick sections. It also improves toughness.
5	Vanadium (V)	It increases both strength and hardness. It promotes heat-resistance in cast irons, by stabilizing carbides.
6	Copper (Cu)	It improves resistance to corrosion.

Applications

Cylinder blocks, brake drums, clutch, casings, piston rings for areo, automobile and diesel engines. Hard, strong and tough, used for automobile crank shaft.

2.39 NON - FERROUS MATERIALS

All the metallic elements other than iron are referred to as non- ferrous materials. In other words, non-ferrous materials are those metals which contain elements other than iron as their chief constituent. Even though non-ferrous materials are not produced in as great tonnages and are more costly than ferrous materials (steel and cast iron), the non-ferrous materials are widely employed in current engineering industries due to the following characteristics

- Lighter in weight.
- Higher electrical and thermal conductivity.
- Better resistance to corrosion.
- Ease of fabrication (casting, rolling, forging, welding and machining).
- Colour.

The most important nonferrous metals and alloys are discussed in the following subsections,

2.40 COPPER

Copper is an important engineering metal. Pure copper is reddish in colour and is available in the earth as pure and as ore as well. It is highly malleable, ductile and is a good conductor of heat and electricity. In pure state, its application lies in the electrical industries because of its high electrical conductivity. It is widely used in wire and some industrial applications like heat exchanger, bearing, etc.

Table 2.3 Principal properties of pure copper

Melting point	1083°C
Crystal structure	FCC
Density	8.93×10^{3} kg/m^{3}
Young's Modulus, E	122.5 Gpa
Tensile strength	220 MPa
Electrical resistivity	$1.67 * 10^{-8}$ Ωm at 20°C
Corrosion resistance	Very good

2.41 COPPER ALLOYS

Copper may be alloyed with a number of elements to provide a range of useful alloys. The copper alloys possess a number of unique superior characteristics: High thermal and electrical conductivity, high corrosion resistance, high ductility and formability and interesting colour for architectural uses.

The important copper alloys are:

1. Brasses (copper-zinc alloys)
2. Bronzes (copper-tin alloys)
3. Gun-metals (copper-tin-zinc alloys)
4. Cupro nickels (copper-nickel alloys)

2.42 BRASSES

Brass is an alloy of copper and zinc containing at least 50% copper. It is bright yellow to golden in colour. It is soft and ductile and is stronger than copper. It has good casting properties and is resistant to corrosion. Figure 2.8 shows a microstructure of copper–zinc. It is used for making plumbing fittings, bushes, bearings and pumps.

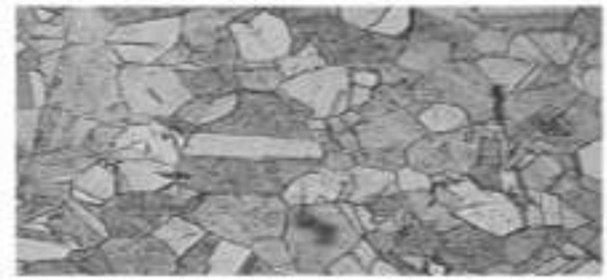


Figure 2.8 Microstructure of brass

Types of brasses

There are various types of brasses, depending upon the proportion of copper and zinc Table 2.4 presents composition, properties, and applications of some commonly used brasses.

Table 2.4 Composition, Properties and uses of Various Brasses.

S.No.	Type	Composition	Properties	Uses
1	Yellow brass	65% Copper 35% Zinc	High Ductility, good strength, high resistant to corrosion.	Plumbing, lamp fixtures, grill works, rivets, tubes
2	Red brass or Red metal	85% Copper 15% Zinc	Better corrosion then yellow brass, superior to copper to handling water.	Plumbing lines, electrical sockets.
3	White brass	10% Copper 90% Zinc	Hard and strong	Used for or namental work
4	Muntz metal (Alpha and Beta brass)	60% Copper 40% Zinc	More brittle, suitable for hot working	Used for casting condenser tubes, suitable for hot working, rolling, extrusion etc.
5	Naval brass	69% Copper 30.25% Zinc 0.75% Sn	High strength, high resistance to corrosion	Architectural work, condenser tubes, brazing rods etc.
6	Leaded yellow brass	67% Copper 29% Zinc 3% Lead 1% Sn	High strength, high resistance to corrosion	Furniture hardware, radiator, light fittings etc.

2.43 BRONZES

The bronze is an alloy of copper and tin. They have higher strength than copper and can be cast to any shape. They are noncorrosive and wear resistant. The commercial bronzes are made up of copper, tin and aluminium.

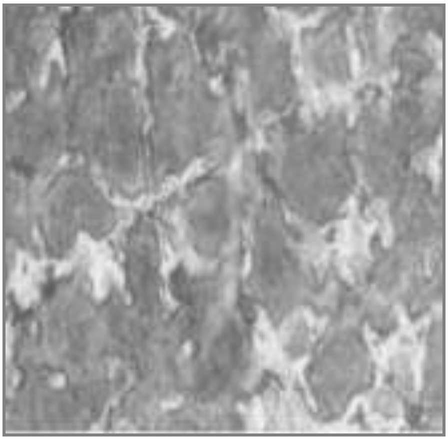


Figure 2.9 Microstructure of bronze

Table 2.5 Composition, Properties and uses of various bronzes

S.No	Type	Composition	Properties	Uses
1	Bell metal	82% Copper 18% Tin	Hard and brittle. It posses resonance	Making bells
2	Gun metal	88% Copper 10% Tin 2% Zinc	Hard, tough and strong. Corrosion resistant to water	Bearings, bolts, nuts, naval applications.
3	Phosphor bronze	89% Copper 10% Tin 1% Phosphorous	High endurance limit, hard, strong, corrosion resistant to seawater.	Gears, springs, bearings etc.
4	Speculum metal	67% Copper 33% Tin	High reflective surface after surface finishing	Used for telescope
5	Silicon bronzes	95% Copper 5% Silicon	Strong, high corrosion resistances	Tanks, presser vessels,
6	Beryllium bronzes	88% Copper 1.5 Beryllium 0.2% Cobalt	Good fatigue, creep resistance, high electrical conductivity.	Surgical instruments, bolts, etc.
7	Aluminum bronzes	80% Copper 20% Aluminium	Hard, strong, light, malleable.	Corrosion resistant vessels, blades, bearings etc.

2.44 SILVER

Silver is a chemical element with Ag as its symbol. It belongs to group 11 of the periodic table and its atomic number is 47. Silver is lustrous, soft, very ductile and malleable metal. It has the highest electrical conductivity of all metals, but it is not widely used for electrical purposes as it is very expensive. Silver is not a chemically active metal; however nitric acid and hot concentrated sulfuric acid will react with it. Silver can be obtained from pure deposits as well as from silver ores such as horn silver and argentite. It can also be obtained as a by-product along with deposits of ores containing gold, copper, or lead. Silver does not oxidize in air; however it reacts with hydrogen sulfide in the air, causing the metal to tarnish due to the formation of silver sulfide. Hence silver products require regular cleaning. Silver is stable in water.

Properties

The mechanical properties of silver are tabulated below.

Table 2.6 Properties of Silver

Tensile strength	140 MPa
Poisson’s ratio	0.37
Modulus of elasticity	76 GPa
Shear modulus	27.8 GPa
Hardness, Vickers	25

Silver Alloys

- Argentium sterling silver (silver, copper, germanium)
- Britannia silver (silver, copper)
- Goloid (silver, copper, gold)
- Shibuichi (silver, copper)
- Sterling silver (silver, copper)

Argentium sterling silver

Argentium silver (originally patented in 1998) is a brand of modern tarnish-resistant silver alloys, containing either 93.5% or 96% silver. Argentium alloys replace some of the copper in the traditional sterling silver alloy (92.5% silver + 7.5% copper) with the metalloid germanium. Argentium's patents refer to percentages of zinc and boron present in Argentium silver.

Britannia silver

Britannia silver has a millesimal fineness of at least 958. The alloy is 95.84% pure silver and 4.16% copper or other metals. The Britannia standard was developed in Britain in 1697 to help prevent British sterling silver coins from being melted to make silver plate. It was obligatory in Britain between 1697 and 1720, when the sterling silver standard was restored. It became an optional standard there after.

Goloid

Goloid is an alloy of silver, gold and copper patented by Dr. William Wheeler Hubbell on May 22, 1877. The patent specifies 1 part gold (about 3.6%), 24 parts silver (about 87.3%), and 2.5 parts copper (about 9.1%, all by weight); however, the patent also states that "The proportions may be slightly varied" and goes on to specify that the silver portion can range from 20 times to 30 times that of the gold, and the copper could range from one-eighth to one-twelfth (from 12.5% to 8.33%) of the total mixture. The patent specifies that the metals be separately melted, then mixed, along with "sulphate of sodium or sulphate of potassium" in the amount of one part sulfate to one thousand parts metal.

Shibuichi

Shibuichi is a traditional Japanese copper / silver alloy. The name translates into English as “one quarter”. Shibuichi was often used to decorate a samurai sword’s handle and scabbard. Shibuichi has a nominal composition of 75% copper and 25% silver but can range from 5% – 60% silver. At 75% copper / 25% silver it has a pale copper color. In traditional Japanese work it was typically patinated to various shades of grey.

Sterling silver

Sterling silver is an alloy of silver containing 92.5% by weight of silver and 7.5% by weight of other metals, usually copper. The sterling silver standard has a minimum millesimal fineness of 925. Fine silver (99.9% pure) typically is too soft for practical objects. Alloying with copper maintains the silvery color of the metal while increasing its strength. However, the copper is much more susceptible to oxidation and corrosion, so sterling silver tarnishes more easily than fine silver.

Other metals that may be used in sterling silver include zinc, platinum, and germanium. Silicon or boron may be added to improve the properties of the metal. Although these metals and additions may improve the resistance of the sterling silver to firesale and tarnish, most sterling silver is still made using copper.

Applications

The following are the application areas of silver:

- In photography
- In dentistry
- As cutlery and mirrors
- As a catalyst in oxidation reactions
- In high-capacity zinc long-life batteries
- As a precious metal to make coins and jewelry
- In electrical and electronic industries for items such as printed circuits and computer keyboards

2.45 Gold

Gold was undoubtedly one of the first metals used by man as it occurs in native form in various parts of the earth's surface and is sufficiently ductile in this form to be fashioned into jewelry and ceremonial utensils. Its ornamental use and esthetic appeal is deeply imbedded into man's ancient and modern cultures. The ability to refine gold into a pure metal and to fabricate it into convenient forms, its durability and imperviousness to atmospheric or chemical attack, and its relative scarcity have given gold the pre-eminent position as a monetary medium throughout recorded history.

Gold is a heavy metal: its density is 19.32 kg/m^3. Gold melts at the temperature of 1063ºC and its boiling point is 2940ºC.

Properties

Gold is a bright, yellow, soft, and very malleable metal. Its special properties include corrosion resistance, good reflectance, resistance to sulfidation and oxidation, freedom from ionic migration, ease of alloying with other metals to develop special properties, and high electrical and thermal conductivity. Gold is easy to fashion, is pleasing in color, is non allergenic, and remains tarnish free indefinitely. This explains why it is much used in jewelry, and for similar reasons it is also used in dentistry.

Table 2.7 Properties of Gold

Young's modulus	80GPa
Tensile strength	131MPa
Proportional limit	3.4MPa
Elongation	50%
Solid surface tension	1400mNm^{-1}
Liquid surface tension at 1200°C	1070mNm^{-1}
Fatigue strength at 10^7 cycles reversed bending	31.7MPa

Gold Alloys

Table 2.8 Compositions of Various alloying elements of Gold

Color of Gold	Alloy Composition
Yellow Gold (22K)	Gold 91.67%, Silver 5%, Copper 2%, Zinc 1.33%
Red Gold (18K)	Gold 75%, Copper 25%
Rose Gold (18K)	Gold 75%, Copper 22.25%, Silver 2.75%
Pink Gold (18K)	Gold 75%, Copper 20%, Silver 5%
White Gold (18K)	Gold 75%, Platinum or Palladium 25%
White Gold (18K)	Gold 75%, Palladium 10%, Nickel 10%, Zinc 5%
Gray-White Gold (18K)	Gold 75%, Iron 17%, Copper 8%
Soft Green Gold (18K)	Gold 75%, Silver 25%
Light Green Gold (18K)	Gold 75%, Copper 23%, Cadmium 2%
Green Gold (18K)	Gold 75%, Silver 20%, Copper 5%
Deep Green Gold (18K)	Gold 75%, Silver 15%, Copper 6%, Cadmium 4%
Blue-White or Blue Gold (18K)	Gold 75%, Iron 25%
Purple Gold	Gold 80%, Aluminum 20%

Applications

Gold is used in electronic devices, particularly in printed circuit boards, connectors, keyboard contactors, and miniaturized circuitry. Because electronic devices employ low voltages and currents, the listed components must remain free from tarnish films and be chemically and metallurgically stable for the life of the equipment.

Gold is a good reflector of infrared radiation, and therefore gold films are used in radiant heating and drying devices as well as in thermal-barrier windows for large buildings and space equipment.

2.46 Platinium

Platinum with the atomic number 78 and an atomic mass of 195 in the periodic table is an extremely rare element found in the crust of the earth. The word Platinum is derived from Platina (Spanish word meaning ‘little silver’), because of its grey-white silvery colour. With an availability of 5g/kg in the earth’s crust, it is one of the rarest elements and is highly valuable for the same reason. Although it was discovered relatively later by European scientists, it has been found in Egyptian tombs dating back to 1200 BC.

Properties

Table 2.9 Properties of Platinium

Tensile strength	125-165 MPa
Modulus of elasticity	171 GPa
Bulk modulus	230 GPa
Shear modulus	62 GPa
Poisson’s ratio	0.39
Elongation at break	35%
Hardness, Vickers	40

- Physically, platinum is a soft, lustrous, silver-coloured metal.
- It is highly dense (21.5 g/cc), malleable and ductile (there is an ongoing debate if it is the most ductile).
- It is also highly corrosion resistant and has a high boiling point (around 1700 degrees Celsius or 3220 degrees Fahrenheit).
- Chemically, platinum is one of the most stable elements in nature. It is often referred to as Noble metal because of its high stability.

Platinium Alloys

- Platinum-Iridium alloys
- Platinum-Cobalt alloys
- Platinum-Palladium alloys
- Platinum-Gold alloys
- Platinum-Tungsten alloys

Platinum-Iridium alloys

Pure platinum is rarely used in jewelry because of its low hardness (about 40 Vickers in annealed state). Alloying platinum with iridium (Ir) has a strong hardening effect even at relatively low iridium concentrations.

Pt950/Ir is the alloy containing 5%wt. of iridium (950 parts of platinum and 50 parts of iridium). The hardness of the alloy is 80 HV in annealed state and may reach 160 HV in cold worked state. On the other hand the alloy is very malleable and ductile what makes it easy to fabricate. Pt950/Ir alloy is used for fabrication handmade pieces and parts resistant to mechanical impacts. Because of its softness the alloy has poorer resistance to scratches.

Platinum-Cobalt alloys

Alloying platinum with cobalt (Co) results in significant hardness increase due to the grain refining effect of cobalt. Pt950/Co is the most popular Pt-Co alloy. It is the best platinum alloy for fabricating cast pieces due to its excellent Casting properties - fine and detailed products may be fabricated from the alloy. Pt950/Co has a high hardness (135 HV as annealed and up to 185 HV in cold worked state) and good scratch resistance.

Platinum-Palladium alloys

Platinum-palladium alloys are traditionally popular in Japan and Hong Kong. The Pt-Pd alloys are relatively soft therefore the pieces made of them are cold worked (burnished) in order to increase the surface hardness by cold. The alloys have grey color. Rhodium Electroplating is used to improve their appearance.

Pt950/Pd contains 5% of palladium (Pd). It is the softest Pt-Pd alloy with hardness 60 HV. It is used for fabricating fine and detailed castings.

Platinum-Gold alloys

Platinum-Gold alloys are heat treatable which means that they may be strengthened by precipitation hardening method: solution treatment at a temperature 1100-1800ºF (599-982ºC) followed by quenching and aging. In hardened state Pt-Au alloys are brittle and not suitable for Forging. Pt950/Au is a general purpose alloy with the hardness 92 HB which may be increased to 143 HB by heat treatment.

Platinum-Tungsten alloys

From all alloying elements tungsten (W) exerts the greatest effect on the platinum alloy hardness. Platinum-tungsten alloys are used for fabricating springs (e.g. a tongue of a bracelet lock). The alloys are heat treatable and may be strengthed by precipitation hardening (solution treatment-quenching-aging). Hardness 300 HV may be achieved by the heat treatment.

Applications

The most common use of platinum is as a catalyst in chemical reactions. It is used as a catalytic converter in automobiles, which allows for complete combustion of unburned hydrocarbons from the exhaust.

It is extensively used for jewelry, usually as a 90–95% alloy, due to its inertness and shine. It is manufactured into metal gauzes for producing nitric acid, and used as a catalyst to enhance fuel cell efficiency. Platinum-cobalt, an alloy of roughly three parts platinum and one part cobalt, is used to make relatively strong permanent magnets. Platinum-based anodes are employed in steel piers, pipelines and ships.

2.47 PRECIPITATION STRENGTHENING TREATMENT (AGE HARDENING)

Precipitation hardening; also known as age hardening, is the most important method of improving the physical properties of some of the non-ferrous alloys by solid state reaction. It is mostly applicable to the alloys of aluminium, magnesium and nickel, It is occasionally used for the alloys of copper and iron.

The phenomenon of hardening is found in nonferrous alloys like aluminium and copper. By controlling the precipitant from the solid solution, we can achieve varying properties for such alloys. The heat treatment process to achieve this consists of the following:

1. Solution treatment
2. Ageing treatment (precipitation treatment)

1. Solution treatment

The aim of solution heat treatment is to distribute the solute atoms uniformly in the solvent atoms to achieve uniform cast structure to improve corrosion resistance and casting ductility. When Al–3%Cu alloy is heated above a certain temperature, the Cu in the alloy goes into what is known as solid solution and the alloy exists in the form of single α-phase. This operation is called solution treatment. At this point, the alloy is soft and malleable. Slow cooling of the alloy will cause formation of relatively coarse particles of $CuAl_2$ phase. In the solution treatment, the components of Al–Cu alloys are heated to about 530 ^oC in a heat treatment furnace and are soaked for a predetermined length of time. Then the components are quenched in an oil or water bath at about 60 ^oC–80 ^oC. On such rapid cooling, there is not enough time for the diffusion of copper atoms to form the precipitate particles. Therefore, a supersaturated solid solution is obtained at room temperature. Solid solution in this non equilibrium state is called supersaturated solid solution (see Figures 2.10 and 2.11).

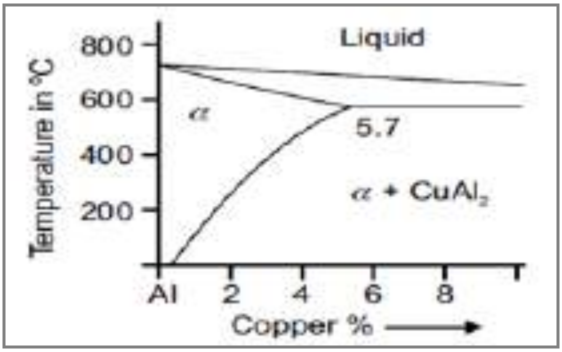


Fig 2.10 Aluminium portion of Al—4%Cu phase diagram

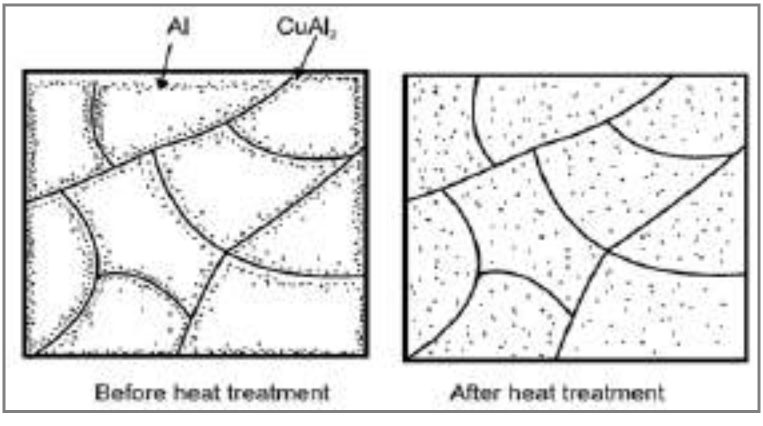


Fig 2.11 Solution heat treatment for Al—4%Cu alloy

2. Ageing treatment (precipitation treatment)

Strengthening by the precipitation of fine particles of a second phase from a supersaturated solid solution is called precipitation or age hardening. This heat treatment would be used to increase the strength and hardness of a part by precipitating second phase. Solubility of one metal in the other decreases with decreasing temperature and supersaturated with respect to the solute at lower temperatures. Then the solute atoms are precipitated from the matrix and reacts with the matrix atoms in the form of precipitate particles. The precipitation hardening mechanism in Al 3%Cu alloys may be illustrated by the phase diagram of Al–Cu system. When an Al–3%Cu alloy is heated to above 548 ^{o}C, all $CuAl_2$ particles are dissolved and the alloy exists in the form of single-phase solid solution (α-phase). Slow cooling of the alloy will cause formation of relatively coarse particles of $CuAl_2$ intermetallic phase. Precipitation from supersaturated solid solution occurs in several steps. The Cu atoms are segregated into plane clusters. These clusters are called Guinier-Preston zones (G-P zones). This phase is coherent with the matrix. This phase provides maximum hardening and it is called artificial ageing. It usually takes a time of several hours to one day. When the ageing is conducted at the room temperature, it is called natural ageing. Natural ageing takes several days or more. The ageing process done at room temperature is often called natural ageing, which takes a prolonged period of time in terms of several days. However, ageing at higher temperatures of 100 ^{o}C–200 ^{o}C accelerates the precipitation process and the time required is reduced considerably.

UNIT-III-NON- METALLIC MATERIALS

3.1. Introduction

Non-metallic materials (polymers and composites) play a major role in oil and gas production as material option to reduce corrosion failures, weight, and cost. These materials have been widely used for decades and have the potential to expand both in new projects and rehabilitation of existing assets. Non-metallic materials same as metals have their advantages and limitations; corrosion resistance and light weight are the most attractive properties, whereas their limited mechanical properties, temperature rating, and chemical resistance remain a distracting feature in limiting their wider use and acceptability. Lack of common design data and models to predict longer term behavior of these materials hinders the progress in development of the high-grade materials to rendering them more cost competitive with corrosion-resistant alloys.

3.2. POLYMERS

The word mer means a ‘‘unit.’’ In this context, the term mer refers to a unit group of atoms or molecules that defines a characteristic arrangement for a polymer. A polymer can be thought of as a material made by combining several mers or units. Polymers are materials consisting of giant or macromolecules, chain-like molecules having average molecular weights from 10,000 to more than 1,000,000 g/mol. They are built by joining many mers or units through chemical bonding. Molecular weight is defined as the sum of atomic masses in each molecule. Most polymers, solids or liquids, are carbon-based; however, they can be inorganic (e.g., silicones based on a Si-O network). Plastics are materials that are composed principally of polymers containing additives such as glass fibers, fillers, pigments, and the like that further enhance their properties. Plastics include thermoplastics (commodity and engineering), thermoset materials, and elastomers (natural or synthetic). In this book, we use the terms plastics and polymers interchangeably.

Polymers such as polyethylene, polypropylene, PVC etc which does not have excellent mechanical and thermal properties are used in high volume in non-structural applications are termed commodity polymers. Polymers which possess properties such as

i) Excellent mechanical properties over temperatures from below -40°C (-40°F) to above 148°C (300°F),

ii) Self-extinguishing, non-dripping characteristics,

iii) Excellent durability, dimensional stability and low water absorption,

iv) Resistance to aqueous chemical environments.

v) Excellent impact strength.

3.2.1. Applications of Polymers:

1. Toys.
2. Home appliances.
3. Structural and decorative items.
4. Coatings, paints, adhesives.
5. Automobile tyres.

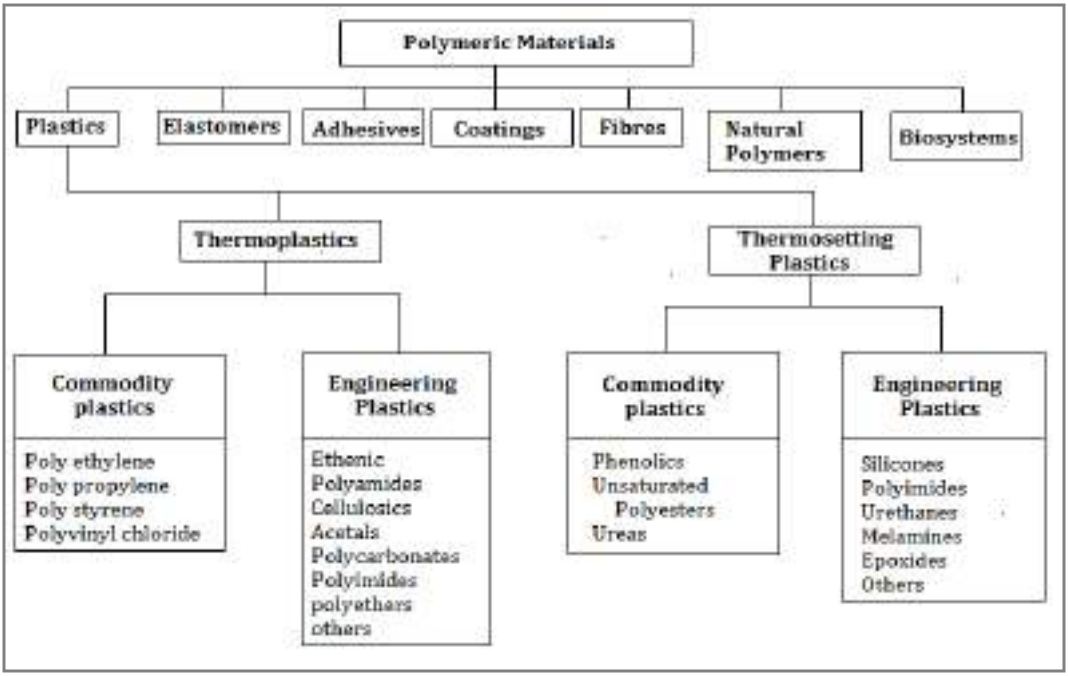


Fig.3.1. Classification of Polymers

3.2.2. Terminology used in polymers

1. ***Monomer:*** It is a small molecule consisting of a single mer i.e., a single unit/blocking block.
2. ***Polymer:***It is a macromolecule formed by the repeated linking of many monomers.
3. ***Polymerisation:*** It is the process of forming a polymer.
4. ***Homopolymer:*** It is a polymer made out of identical monomer.

   In other words, when all the repeating units along a chain are of the same type, the resulting polymer is called a homopolymer

   $$—M—M—M—M— \qquad —M_1—M_2—M_1—M_2—M_1—M_2—$$

   Homopolymer Copolymer

5. ***Copolymers:*** consist of chains with two or more linkages usually implying two or more different types of monomer units.

   These may be represented as:- [A-B-A-B-A-B]-

6. ***Degree of polymerization***: - It is the number of repetitive units (or mers) present in one molecule of a polymer, it is a parameter used to designate the average chain size of a polymer. Mathematically,

$$\textit{Degree of polymerization} = \frac{\textit{Molecular weight of a polymer}}{\textit{Molecular weight of a single monomer}}$$

7. ***High-polymers:***Solid polymers which have very high molecular weights (ranging between 10,000 and1,000,000 g/mol) are called high-polymers.
8. ***Oligo-polymers***: Oligo-polymers or oligomers are liquid/gas polymers with very short chains (having molecular weights on the order of 100 g/mol).

Types of Homopolymers

9. ***Linear polymers***: Linear polymers are those in which the mer units are joined together end to end in single chains, as shown in Fig.3.2 For linear polymers, there may be extensive Van der Waals boundary between the chains.

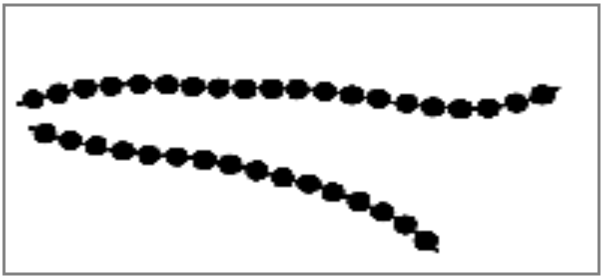


Fig.3.2. Schematic representations of linear polymers

10. ***Branched polymers:*** Branched polymers are those in which side-branch chains are connected to the main ones, as shown in Fig.3.3

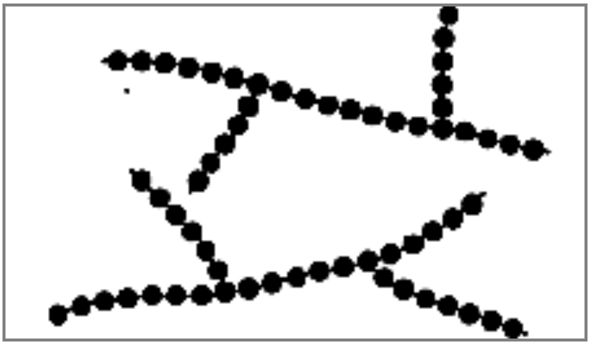


Fig.3.3. Schematic representations of Branched polymers

11. ***Cross-linked polymers:***In cross-linked polymers, adjacent linear chains are joined one to another at various positions by covalent bonds, as shown in Fig.3.4

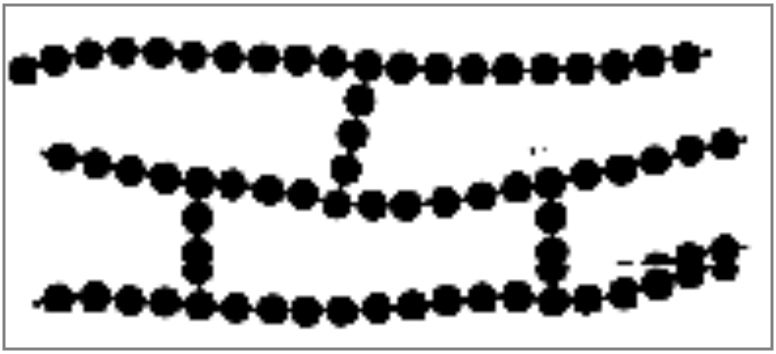


Fig.3.4. Schematic representations of Cross-linked polymers

12. ***Network polymers:*** Network polymers have three active covalent bonds, which form three dimensional networks instead of the linear chain framework, as shown in Fig.3.5

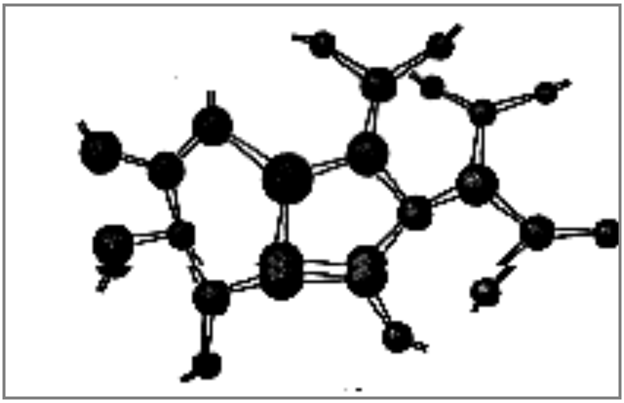


Fig.3.5. Schematic representations of Network polymers

Types of copolymers

13. ***Random copolymer*:** In this, the two different units are randomly dispersed along the chain, as shown in Fig.3.6

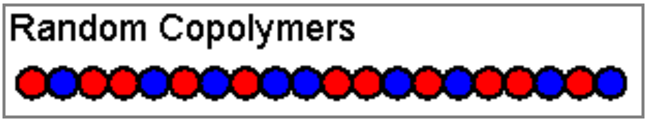


Fig.3.6. Schematic representations of Random copolymer

14. ***Alternating copolymer:*** In this, the two mer units alternate chain positions, as shown in Fig 3.7

Fig.3.7. Schematic representations of alternating copolymer

15. ***Block copolymer:*** In this, the identical mers are clustered in blocks along the chain, as shown in Fig.3.8

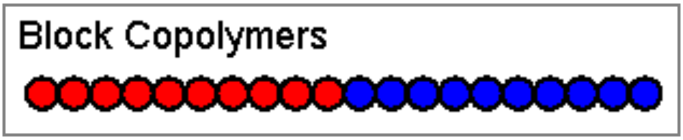
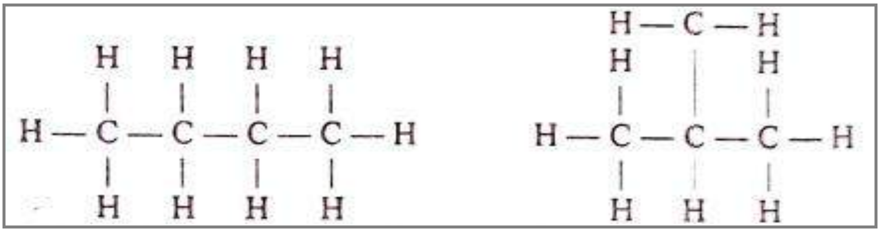


Fig.3.8. Schematic representations of Block copolymer

16. ***Graft copolymer:*** In this, homopolymer side branches of one type may be grafted to homopolymer main chains that are composed of a different mer, as shown in Fig.3.3

17. ***Isomerism:*** It is a phenomenon wherein different atomic configurations are possible for the same configuration. For example, there are two isomers for butane (C_4H_{10}) as shown in Fig.3.9

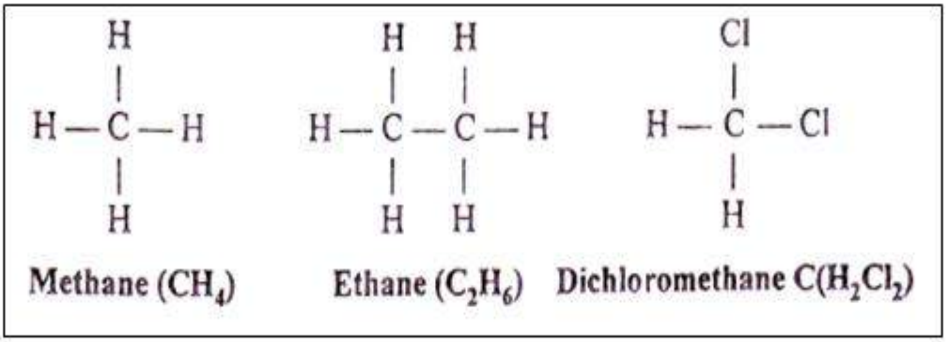


(a)Structure of normal butane (b) Structure of a molecule of isobutane

Fig.3.9. Isomers of butane

3.2.3. Molecular Structure of Polymers

- As we know, most polymers are organic in origin: many organic materials are hydrocarbons. In other words, most polymers are hydrocarbons.
- In hydrocarbons, carbon and hydrogen combine in the relationship $C_n H_{2n+2}$, known as **paraffins.**
- Theoretically, the hydrocarbons can be linked together indefinitely to form very large molecules, as lustrated n Fig.3.10. The bonds between the atoms are single pairs of covalent electrons. Because there is no provision for additional atoms to be added to the chain, such molecules are said to be saturated.
- In other words, a compound in which all the valence bonds of the carbon atoms are satisfied is said to be saturated. Such saturated molecules have strong intermolecular bonds, but the intermolecular bonds are much weaker.



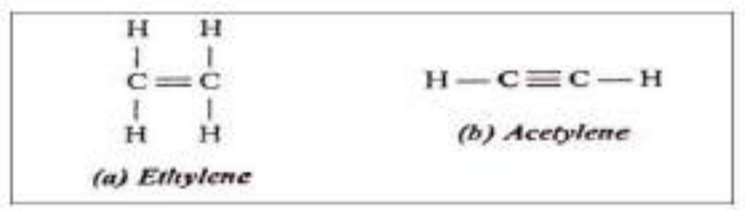
Methane (CH_4) Ethane (C_2H_6) Dichloromethane $C(H_2Cl_2)$

Fig.3.10. Linking of hydrogen and carbon in saturated compounds. The single lines (–) represent single covalent bonds.

- A bond between two carbon atoms may involve the sharing of two pairs of electrons.This is termed as a **double bond**. For example, in ethylene (C_2H_4), the two carbon atoms are doubly bonded together, and each is also bonded to two hydrogen atoms, as illustrated in Fig.3.11.(a). In some cases, triple bonds also exist. For example, in acetylene (C_2H_2),there is a triple bond between two carbon atoms, as shown in Fig.3.11.(b)

- In these double and triple covalent bonds molecules, each carbon atom is not bonded to the, maximum other atoms. So these compounds are termed as **unsaturated**.

- In other words, a compound in which the valence bonds of the carbon atoms are not satisfied is said to be unsaturated, Such unsaturated molecules are important in the polymerisation i.e., joining together of small molecules into large ones having the same constituents.



(a) Ethylene

(b) Acetylene

Fig.3.11.Unsaturated compounds: Covalent bonds in ethylene and acetylene molecules. The two parallel lines (═) and three parallel lines (≡) represent a double and triple covalent bonds between atoms

3.3 POLYMERISATION

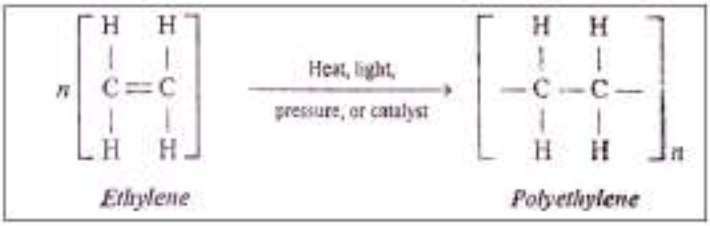
The polymerisation mechanism can be divided into two categories as:

1. Addition polymerisation.
2. Condensation polymerisation.

3.3.1. Addition Polymerisation

- Addition polymerisation, also known as chain reaction polymerisation, is a process by which two or more chemically similar monomers are polymerised to form long chain molecules.

- Polymerisation takes place only in unsaturated organic compounds. In this process, their double covalent bonds are broken and single bonds are formed in its place.
- Addition polymerisation yields a product that is an exact multiple of the original monomeric molecule,
- Addition polymerisation is usually instigated by the application of heat, light, pressure or a catalyst, as shown in Fig.3.12
- It should be noted that in addition polymerisation process there is no loss of any substance.



3.3.1.1. THREE STAGES IN ADDITION POLYMERISATION:

1. Initiation.
2. Propagation.
3. Termination.

These three stages are demonstrated for polyethylene formation from ethylene monomer.

Stage 1: Initiation of addition polymerisation

- During the initiation stage, an initiator (such as benzoyl peroxide) is added to the molecule.
- The initiator forms free radicals with a reactive site that attracts one of the carbon atoms of an ethylene monomer, as shown in Fig.3.13.

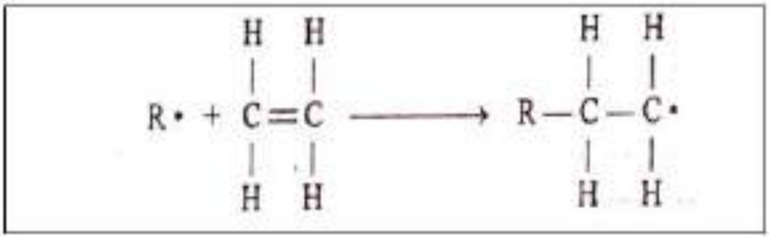


Fig.3.13. Initiation of polyethylene chain H by producing free radicals from initiators. R• represents the active initiator, and • is an unpaired electron.

Stage 2: Propagation of the addition chain

- Once the chain is initiated, repeat units are added onto each chain at a high rate, as shown in Fig.3.14.

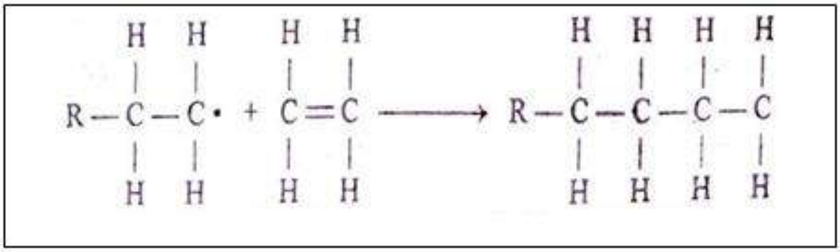


Fig.3.14. Growth of the addition chain

Stage 3: Termination of addition polymerisation

The chains may be terminated by two mechanisms. They are:

1. The active ends of two propagating chains may react or link together to form a non-reactive molecules, as shown in Fig.. This process is called combination**. *This terminates the growth of each chain.***

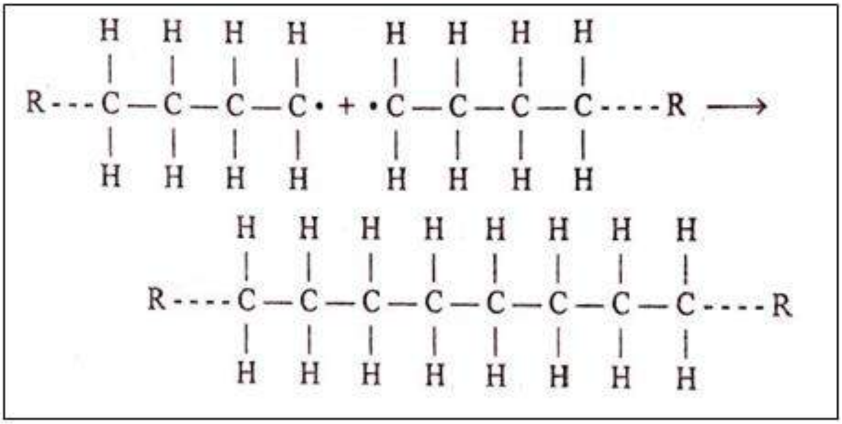


Fig.3.15. Termination of polyethylene chain growth by combination process

2. The active end of one chain may remove a hydrogen atom from a second chain by a process known as disproportionation. This reaction terminates two chains, as shown in Fig.3.16.

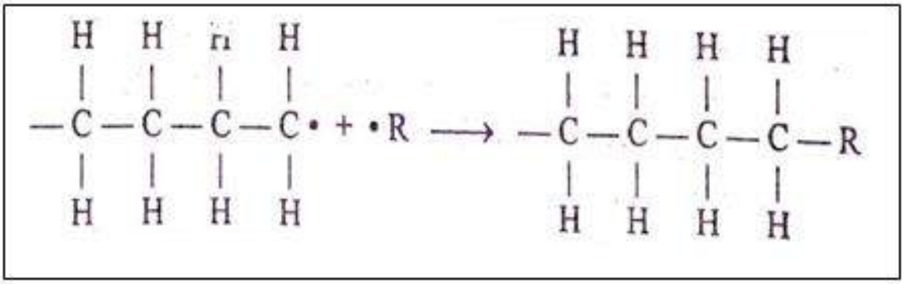


Fig.3.16. Termination of polyethylene chain growth by disproportionation process

3.3.2. Condensation Polymerisation

- ❖ Condensation polymerisation, also known as step-growth polymerisation, is the formation of polymers by stepwise intermolecular chemical reactions that normally involve at least two different monomers.
- ❖ In contrast to addition polymerisations, the condensation polymerisations form a small molecular weight by-product such as water or $CH_3$0H in addition to the polymer final product.

1. Formation of polyester from the reaction between ethylene glycol and adipic acid is illustrated in Fig. 3.17.

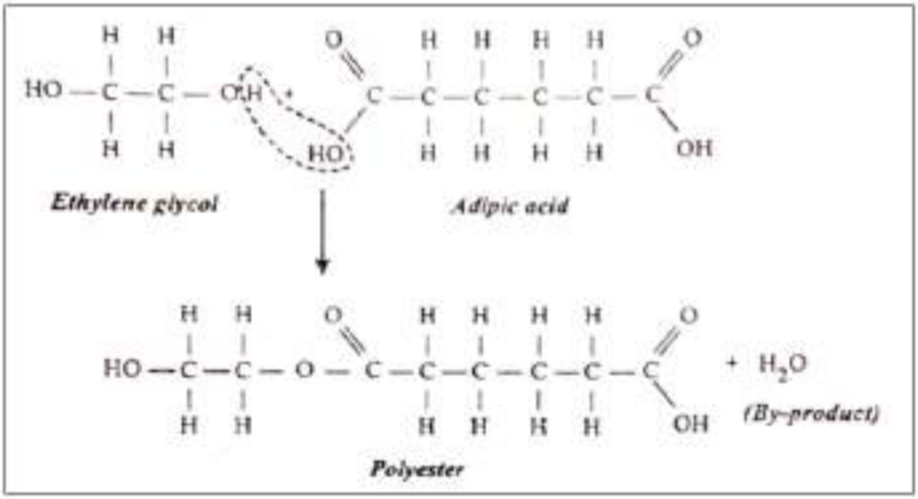


Fig.3.17.Condensation polymerisation of polyester

2. The condensation polymerisation of Bakelite i.e., phenol formaldehyde is illustrated in Fig.3.18.

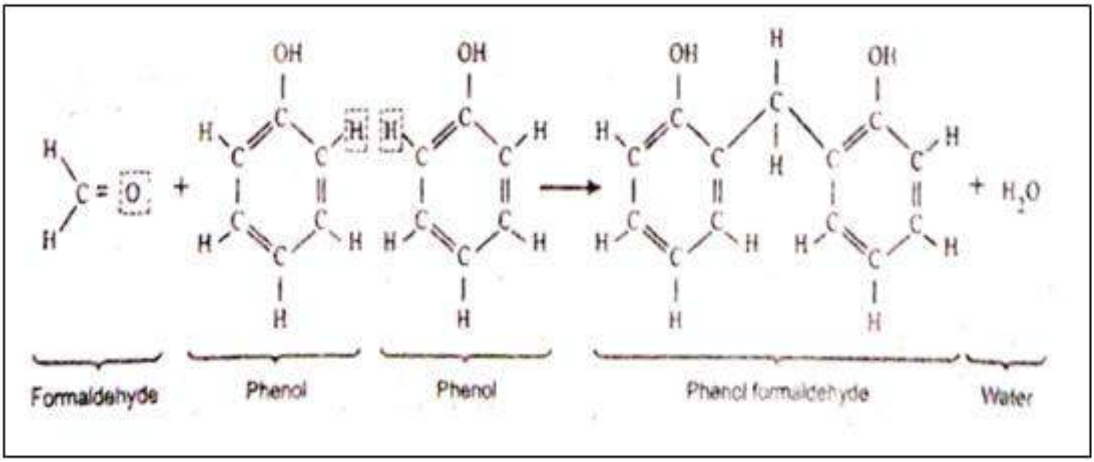


Fig.3.18. Formation of phenol-formaldehyde by condensation polymerization

3.3.2.1. Characteristics of Condensation Polymerisation

- The reaction times for condensation are generally larger than for addition polymerisation.
- Like addition polymerisation, various chain length can be produced, yielding a molecular weight distribution.
- Condensation reactions of ten produce tri functional monomers capable offering cross-linked and network polymers.

3.3.2.2. Applications

The condensation polymerisation is used in the synthesis of thermosetting polyesters and phenol formaldehyde (Bakelite), the nylons, and the polycarbonates.

3.4. POLYMER ADDITIVES

Polymers use additives to improve their properties and performance.

Additives are added to polymers:

(i) To improve mechanical properties.

(ii) To reduce the cost.

(iii) To improve the thermal processing such as moldability.

(iv) To improve surface and chemical characteristics.

(v) To improve the appearance and aesthetic properties.

The various polymer additives include:

1. Filler materials,
2. Plasticizers,
3. Stabilizers,
4. Colorants,
5. Flame retardants,
6. Reinforcements, and
7. Lubricants.

3.5. PLASTICS

3.5.1. What are Plastics?

- A plastic may be defined as an organic polymer, which can be moulded into any desired shape and size with the help of heat, pressure, or both.
- Now a days plastics are extensively used in engineering applications due to their important properties such as low price, colour range, toughness, water resistance, low electrical and thermal conductivity, ease of fabrication, etc.
- Standard forms in which plastics are available include powders, sheets, films, rods, tubes, and liquids.

3.5.2. Sources of Raw Materials for Plastics

The three main sources of raw materials used in the manufacture of plastics are:

1. Animal and vegetable by-products [such as casein (from cow's milk), cellulose (mainly from cotton fibres), and wood pulp - (cellulosics)].
2. Coal by-products (obtained during the destructive distillation of coal to produce coal gas).
3. Petroleum by-products (obtained during the refining of crude oil).

3.5.3. Classification of Plastics

The plastics can be broadly classified into two groups:

1. Thermoplastics, and

2. Thermosetting plastics.

1. Thermoplastics

- Thermoplastics, also known as thermoplastics, are the plastics whose plasticity increases with the increase in temperature.
- It means that thermoplastics soften (i.e., liquidity) when heated, and harden when cooled. -
- Thermoplastics may be solidified and.reheated as many time as desired. But their characteristics remain the same.
- Thermoplastics are relatively soft and ductile.
- Since thermoplastics have low melting temperatures and can be repeatedly moulded and remoulded to the desired shape, they have a good resale/scrap value.

Mechanism: It may be noted that most of the thermoplastics are formed by addition poly1nerisation. We know that the addition polymerisation produces only linear polymers i.e., chain molecules or linear molecules. Therefore thermoplastics can be mechanically deformed and softened at high temperature. Also they can be easily moulded due to the absence of cross links. On cooling, they are hardened and they regain their original low temperature properties.

Examples: Some of the important thermoplastics are:

1. Polythenes,
2. Polystyrenes,
3. Polyvinyls,
4. Acrylics,
5. Polyamides (Nylones),
6. Polytetrafluoro ethylenes (Teflon), and
7. Cellulosics.

2. Thermosetting Plastics

- Thermosetting plastics, also known as thermosets, are plastics which become permanently hard when heat is applied and do not soften upon subsequent heating.
- That is, thermosetting plastics once set cannot be soften on heating. Thus they cannot be remoulded /reshaped again and again.That's why they donot have a resale/scrap value.
- The thermosetting plastics are generally stronger, harder, more brittle more resistant to heat and solvents than thermoplastics.

Mechanism: Itmay be noted that most of the thermosetting plasticsareformed by condensation polymerisation. We know that the condensation polymerisation produces cross linked molecules. Cross linked molecules are composed of long molecules linked to each other in three dimensions by primary or valence bonds. They are not broken by heat until the compound is decomposed. Once the product is heated to an excessive temperature, where cross-links are broken, an in eversible decomposition takes place. Moreover, due to these cross linked molecules the thermosetting plastics cannot be softened once they are moulded, even at high temperatures,

Examples: Some of the important thermosetting plastics are:

1. Polyesters,
2. Phenolic,
3. Urea formaldehyde,
4. Melamine formaldehyde, and
5. Epoxides

3.6. COMMODITY AND ENGINEERING PLASTICS

As shown in Fig.3.1, both the thermoplastics and thermosetting plastics, in turn, can be classified, from the usage point of view; into two groups. They are:

1. Commodity plastics.
2. Engineering plastics.

3.6.1. Commodity Plastics

- The widely usedplastics are called as commodity plastics.
- Commodity plastics generally have lower cost.
- Most commodity plastics are used for throwaway items such as hot/cool drink cups, plastic bags, boxes, etc.
- In simple terms, the plastics which are not used for engineering applications are known as commodity plastics.
- Examples for commodity are listed below.

Thermoplastics

1. Polyethylenes
2. Polypropylene
3. Polystyrene
4. Polyvinyl chloride (PVC)

Thermosetting

1. Phenolics
2. Unsaturated polyesters
3. Ureas

3.6.2. Engineering Plastics

- The plastics which are used in engineering applications are known as engineering plastics.
- Engineering plastics have higher strength, greater environmental resistance, and better physical properties.
- Engineering plastics are more costlier than commodity plastics.

Thermoplastics

1. Ethenic

2. Polyamides
3. Cellulosics
4. Acetals
5. Polycarbonates
6. Polyimides

Thermosetting plastics

1. Silicones
2. Polyimides
3. Urethanes
4. Melamines
5. Epoxides

3.7. PROPERTIES AND APPLICATIONS OF THERMOPLASTICS

1. Polyethylene (PE)

- Polyethylene,also known commonly as polythene, is made by the polymerisationof ethene i.e., ethylene (CH_2= CH_2).
- Polyethylene is made from petroleum or natural gas feed stocks.
- The properties and application of PE vary over wide ranges depending on the molecular weight, the method of manufacture, and differences in structure and density.

Types of polyethylenes: Based on density, there are four classifications of polyethylene :

1. Low density polyethylene (LOPE),
2. High density polyethylene (HOPE),
3. Linear low density polyethylene (LLOPE), arid
4. Ultra-high-molecular weight polyethylene (UHMWPE).

Characteristics of PEs:

- They have excellent resistance to most solvent and chemicals.
- It has a good flexibility property.
- They are non-toxic

Applications of PEs:

- Polyethylene used in packaging film, coating and laminations.
- It used to produced gaskets and seals.
- It is used for Cable coating and insulation tapes.
- They are used for transporting water and various other chemicals.
- Polyethylene containers are used as packaging material for pharmaceuticals**,** corrosive chemicals, and cosmetics.

2. Polypropylene (PP)

- Polypropylene (thermoplastic, melting temperature: 174ºC; glass transition temperature: -17ºC) is a versatile commodity polymer.
- It serves double duty, both as a plastic and as a fiber. As a plastic it's used to make things like dishwasher-safe food containers. It can do this because it doesn't melt below 160ºC, or 320ºF.
- Polyethylene, a more common plastic, will anneal at around 100ºC, which means that polyethylene dishes will warp in the dishwasher. As a fiber, polypropylene is used to make indoor-outdoor carpeting, used around swimming pools and miniature golf courses. It doesn't absorb water, like nylon does.
- It is slightly more susceptible than polyethylene to strong oxidizing agents. It offers the best stress crack resistance of the polyolefins.
- Products made of polypropylene are brittle at 0°C and may crack or break if dropped from bench top height.
- Polypropylene can be made from the monomer propylene by Ziegler-Natta polymerization and by metallocen cetalysis polymerization.

3. Polystyrene (PS)

- This plastics account for about 20% of all the thermoplastics in commercials use.
- Polystyrene is made from ethyl benzene.
- A large benzene ring replaces a hydrogen atom on an ethylene molecule.

Properties of PSs:

- PS possesses good dimensional stability
- Low cost.
- Dielectric resistance is satisfactory.
- Mechanical properties within the operating temperature limit.
- It is soluble in many hydrocarbons.
- It is easy thermoform ability.

Applications of PSs:

- It is used for household items such as imitation glass and cut glass varieties.
- PS is also used in refrigeration components and many applications.
- PS are used in the insulation of cold storage warehouse, building foundations.
- Packaging items for delicate instruments such as cameras, calculators.
- Other application includes automobile interior parts dials and knobs.

4. Poly Vinyl Chloride (PVC)

- The widely used acronym for polyvinyl chloride is PVC.
- It is one of the most widely used plastics in terms of volume produced.
- PVC is made by reacting acetylene gas with hydrochloride (HCL) acid in the presence of a suitable catalyst.

Properties of PVCs:

- PVC has a relative high density (52.5 – 63 [g/cm3]).
- Medium heat deflection temperature. (52 -82 °C)

- Good electrical properties.
- High solvent resistance, flame and chemical resistance.
- PVC is a high rigid and brittle material.

Applications of PVCs:

- Non plasticized PVC grade are widely used for manufacturing of pipes.
- PVC finds use in furniture and automobile, shaped cushion, interior wall coverings, rainwear, shoes, luggage and shower curtains.
- PVC is used for auto top covering, electric wires insulation, floor mats and interior and exterior trim.
- Other applications include garden hoses, refrigerator gaskets

5. Poly methyl methacrylate (PMMA)

- This complicated name applies to a polymer that everyone is familiar with. Poly methyl methacrylate is the polymer used to make the clear, sheet material in unbreakable windows.
- It may be more readily recognized by the trade name Plexiglass.

Characteristics of PMMAs:

1. They are hard, rigid, and high impact strength thermoplastic.
2. They are highly transparent to light.
3. They can be easily formed.
4. They can be readily coloured and they have excellent decorative properties.

Applications of PMMA:

Typical applications of PMMAs include camera lenses, flash lights, safety glasses, drafting equipment, instrument panels, display signs, transparent aircraft enclosures, and windows.

6. Polyethylene Terephthalate (PET)

Thermoplastics polyesters have been used for about 35 years, predominantly in films for packaging and in fibers. Everyone is familiar with polyester clothing and polyester auto tire reinforcement. These are thermoplastics polyester, usually polyethylene terephthalate.

Properties of PETs:

- PET has good injection characteristics and mechanical properties similar to nylon.
- It has a use temperature above that of most nylons, and it does not have the moisture absorption problems of nylon.
- PET and POYL BUTYL TETRAPHATALATE are closely related polymers in use properties with only subtle difference.
- PET is slightly stronger and lower in cost.

Applications of PETs:

- Structural application in appliances, automobiles, and consumer products.
- About 45% of the production of PET goes into films for photography and packaging.
- PET has been used for plastics liter-size beverage bottles.

7. Polycarbonates (PC)

- Polycarbonates are really polyester, since both are ester of carbonic acid and an aromatic biphenol.
- The polycarbonate is amorphous linear polyesters with excellent mold ability and impact strength.
- It is made from the condensation of bisphenol and carbonic acid.

Properties of PCs:

- PCs possess excellent dimensional stability over a wide range of temperature.
- Good ductility properties
- It has electrical and chemical resistance properties.

- They have a good strength and rigidity and because of high modulus of elasticity, possess good creep resistance.

Applications of PCs:

- PCs are used in the manufacture of helmets, safety shields, street lamp cover, factories and school windows, machine guard, gears and cams.
- PCs find uses as housing for high voltage lamps, aircraft parts, and instruments panel.

8. Polyamides (PA)

- It is otherwise called as nylon.
- An important polymer family that forms characteristics amid linkage (CO-NH) during polymerization is called the polyamides (PA).

Properties of PAs:

- Nylon is strong, highly elastics, tough abrasion resistant, and self – lubricating.
- It retain good mechanical properties
- It is very strong and tough

Applications of PAs:

- Nylon is commonly a good substitute for metals in bearings, gear, and similar parts.
- The majority of applications of nylon (about) are in fiber for carpets.

9. Polyimides (PI)

- Polyimides are a group of linear aromatic polymers
- They are produced in condensation reaction

Characteristics of PIs:

- Good mechanical properties
- Excellent thermal resistance up to 250ºC
- Good resistance to organic solvents expect, alikies and concentrated acids

Applications of PIs:

- High temperature electrical cables.
- Printed circuit boards,
- Turbine blades and other components requiring fire resistance, strength at high temperatures and good electrical properties.

10. Polyamide- Imide (PAI)

- It is similar to polyimide, is also a linear aromatic polymer for use of high temperature.

Properties of PAIs:

- The distinguishing characteristic of this family of polymers is high strength and a high maximum operating temperature.
- Polyamide imides have a high modulus of elasticity. .
- They have excellent thermal resistant up to 250 ˚ Celcius.
- Used in spark ignition engines.

Applications of PAIs:

- Most electrical application.
- Valves made from PAI replace bronze castings in hot water plumbing systems.
- Polyamide imides are premium engineering plastics.
- They should be used where elevated temperature strength and injection mold ability are important selection factors.

11. Poly Phenylene oxide(PPO)

Poly(p-phenylene oxide) or poly(p-phenylene ether) (PPE) is a high-temperature thermoplastic. It is rarely used in its pure form due to difficulties in processing. It is mainly used as blend with polystyrene, high impact styrene-butadiene copolymer or polyamide. PPO is a registered trademark of SABIC Innovative Plastics IP B.V. under which various polyphenylene ether resins are sold.

Properties of PPOs:

PPE is an amorphous high-performance plastic. The glass transition temperature is 215°C, but it can be varied by mixing with polystyrene. Through modification and the incorporation of fillers such as glass fibers, the properties can be extensively modified.

Applications of PPOs:

- PPE blends are used for structural parts, electronics, household and automotive items that depend on high heat resistance, dimensional stability and accuracy. They are also used in medicine for sterilizable instruments made of plastic.
- The PPE blends are characterized by hot water resistance with low water absorption, high impact strength, halogen-free fire protection and low density.

12. Poly phenylene sulfide

Polyphenylene sulfide (PPS) is an organic polymer consisting of aromatic rings linked by sulfides. Synthetic fiber and textiles derived from this polymer resist chemical and thermal attack.

PPS is used in filter fabric for coal boilers, papermaking felts, electrical insulation, film capacitors, specialty membranes, gaskets, and packings. PPS is the precursor to a conductive polymer of the semi-flexible rod polymer family. The PPS, which is otherwise insulating, can be converted to the semiconducting form by oxidation or use of dopants.

Characteristics of PPSs:

- PPS is one of the most important high temperature thermoplastic polymers because it exhibits a number of desirable properties.
- These properties include resistance to heat, acids, alkalies, mildew, bleaches, aging, sunlight, and abrasion.
- It absorbs only small amounts of solvents and resists dyeing.

13. Polyether ether ketone (PEEK)

- It is a linear crystalline hetro chain polymer for High temperature plastics

Characteristics of PEEKs:

- Melting temperature is high.
- Low flammability and low smoke emission.
- Good fatigue and chemical resistance.

Applications of PEEKs:

- High temperature engineering components, high temperature electrical coatings and aerospace applications.

14. Poly tetra fluoro ethylene or Teflon (PTFE)

Fluorocarbons are a family of polymers based on a fluorine atom substructure. The oldest fluorocarbon, Polytetrafluoroethylene may be more familiar under the trade name Teflon.

Properties of PTFEs:

- PTFE has an outstanding resistance to chemicals and is insoluble in all organics except a few fluorinated solvents.
- It has a high service temperature.
- Its impact strength is high even at sub-zero temperatures.
- Though its tensile strength, wear resistance and creep resistance.
- It has non sticking property and is flexible.
- It also has excellent electrical resistance.

Applications of PTFEs:

- PTFE is used in chemical resistant pipe and pump parts, tank lining, filter media, valve seats, high temperature cable insulation, non-stick coating on frying pans and special surgical blades, bearings, etc.
- High temperature electronic components, piston rings and bearings.

3.8. ENGINEERING CERAMICS

3.9.1. Introduction

Ceramic materials are inorganic, non-metallic materials. Most ceramics are compounds between metallic and non-metallic elements for which the interatomic bonds are either totally ionic or predominantly ionic but having some covalent character. The term ceramic comes from the Greekword keramikos, which means burnt stuff, indicating that desirable properties of these materials are normally achieved through high-temperature heat treatment process called firing.

Ceramic materials are important in today's society. Consider the ceramic engine and what advantages it offers in terms of fuel economy, efficiency, weight savings and performance. Below are three gif's showing a montage of a prototype ceramic engine and some of the internal automotive components made from ceramics.

3.9.2. Characteristics of ceramics

- Used in high temperature places.
- It is strong, hard and brittle.
- High melting point.
- Good thermal and electrical insulators.
- Resistant to oxidation and corrosion.
- Having high compressive strength but are weak in tension.

3.9.3. Classification of engineering ceramics

1. Alumina (Al_2O_3)
2. Silicon Carbide (SiC)
3. Silicon Nitride (Si_3N_4)
4. Partially stabilized Zirconia
5. Sialons

1. Alumina (Al_2O_3)

Alumina is the most cost effective and widely used material in the family of engineering ceramics. The raw materials from which this high performance technical grade ceramic is made are readily available and reasonably priced, resulting in good value for the cost in fabricated alumina shapes. With an excellent combination of properties and an attractive price, it is no surprise that fine grain technical grad alumina has very wide range of applications.

Key Properties

- Hard, wear-resistant.
- Excellent dielectric properties from DC to GHz frequencies.
- Resist strong acid andalkali attack at elevated temperatures.
- Good thermal conductivity.
- Excellent size and shape capability.
- Highstrength and stiffness.
- Available in purity ranges from 94%, an easily metallizable composition, to 99.5% for the most demanding high temperature applications.

Typical Uses

- Gas laser tubes
- Wear pads
- Seal rings
- High temperature electrical insulators
- High voltage insulators
- Furnace liner tubes
- Thread and wire guides
- Electronic substrates
- Ballistic armor
- Abrasion resistant tube and elbow liners
- Thermometry sensors
- Laboratory instrument tubes and sample holders
- Instrumentation parts for thermal property test machines

- Grinding media

General Information

Aluminum oxide, commonly referred to as alumina, possesses strong ionic interatomic bonding givingrise to it's desirable material characteristics. It can exist in several crystallinephases which all revert to the most stable hexagonal alpha phase at elevated temperatures. This is the phase of particular interest for structural application and the material availablefrom Accuratus.

Alpha phase alumina is the strongest and stiffest of the oxide ceramics. Its high hardness, excellent dielectric properties, refractoriness and good thermal properties make it the material of choice for a wide range of applications.

High purity alumina is usable in both oxidizing and reducing atmospheres to 1925°C. Weight loss invacuum ranges from 10^{-7} to 10^{-6} g/cm^2.sec over a temperature range of 1700° to 2000°C. It resists attack by all gases except wet fluorine and is resistant to all common reagents except hydrofluoric acid and phosphoric acid. Elevated temperature attack occurs in the presence of alkali metal vapors particularly at lower purity levels.

2. Silicon Carbide (SiC)

Sintered alpha silicon carbide is produced by initially mixing fine (sub-micron) and pure silicon carbide powder with non-oxide sintering aids. The powdered material is formed or compacted byusing most of the conventional ceramic forming processes such as die pressing, isostatic pressing and injection moulding. Following the forming stage the material is sintered in an inert atmosphereat temperatures above 2000°C. The sintered silicon carbide can then be machined to precise tolerances using a range of precision diamond grinding or lapping techniques. As with mostadvanced ceramics the cost of the component is reduced if the amount of diamond grinding isreduced i.e. either the material manufacturer can achieve the required tolerances "as sintered" or the designer removes unnecessary tolerances.

Key Properties

The major properties of sintered silicon carbide of interest to the engineer or designer are as follows:

- High hardness (second only to diamond).

- Low density 40% the density of steel – approximately the same as aluminium.
- Low porosity.
- Good wear resistance in sliding and abrasive environments.
- Excellent corrosion resistance in most chemical environments.
- Low thermal expansion and high thermal conductivity leading to excellent thermal shock resistance.

Applications

- As a abrasives for grinding wheel.
- As a coating material.
- As a refractory tubes.
- In nuclear reactor.
- In bearings.
- And in very high temperature places.

3. Silicon Nitride (Si_3N_4)

Silicon nitride is a man made compound synthesized through several different chemical reaction methods. Parts are pressed and sintered by well developed methods to produce a ceramic with a unique set of outstanding properties. The material is dark gray to black in color and can be polished to a very smooth reflective surface, giving parts with a striking appearance. High performance silicon nitride materials were developed for automotive engine wear parts, such as valves and cam followers and proven effective. The cost of the ceramic parts never dropped enough to make the ceramics feasible in engines and turbochargers. The very high quality bodies developed for these demanding high reliability applications are available today and can be used in many severe mechanical, thermal and wear applications.

Key Properties

- High strength over a wide temperature range.
- High fracture toughness.
- High hardness.
- Outstanding wear resistance, both impingement and frictional modes.

- Good thermal shock resistance.
- Good chemical resistance.

Typical Uses

- Rotating bearing balls and rollers
- Cutting tools
- Engine moving parts — valves, turbocharger rotors
- Engine wear parts — cam followers, tappet shims
- Turbine blades, vanes, buckets
- Metal tube forming roll and dies
- Precision shafts and axles in high wear environments

General Information

The material is an electrical insulator and is not wet by nonferrous alloys. Silicon nitride is a rather expensive material, but it’s performance to cost benefit ratio is excellent in the applications where it can outperform the normally utilized materials with long life and very reliable low maintenance operation.

4. Partially stabilized Zirconia (PSZ)

Zirconia is an extremely refractory material. It offers chemical and corrosion inertness to temperatures well above the melting point of alumina. The material has low thermal conductivity. It is electrically conductive above 600°C and is used in oxygen sensor cells and as the subsector (heater) in high temperature induction furnaces. With the attachment of platinum leads, Nernst glowers used in spectrometers can be made as a light emitting filament which operates in air.

Key Properties

- Use temperatures up to 2400°C.
- High density.
- Low thermal conductivity (20% that of alumina).
- Chemical inertness.
- Resistance to molten metals.

- Ionic electrical conduction.
- Wear resistance.
- High fracture toughness.
- High hardness.

Typical Uses

- Precision ball valve balls and seats.
- High density ball and pebble mill grinding media.
- Thread and wire guides.
- Hot metal extrusion dies.
- Powdercompacting dies.
- Marine pump seals and shaft guides
- Oxygen sensors.

5. Sialons

- Sialon, a fine grain nonporous technical grade engineering material, is a silicon nitride ceramic with a small percentage of aluminum oxide added.
- Sialon is outstanding in nonferrous metal contact. It is highly thermal shock resistant, strong, and is not wet or corroded by aluminium, brass, bronze, and other common industrial metals.

Key Properties

- Excellent thermal shock resistance.
- Not wetted or corroded by nonferrous metals.
- High strength.
- Good fracture toughness.
- Good high temperature strength.
- Low thermal expansion.

- Good oxidation resistance.

Typical Uses

- Thermocouple protection tubes for nonferrous metal melting.
- Immersion heater and burner tubes.
- Degassing and injector tubes in nonferrous metals.
- Metal feed tubes in aluminum die casting.
- Welding and brazing fixture and pins.

General Information

The combination of silicon nitride and aluminum oxide produces a material with the excellent strength, hardness, fracture toughness and low thermal expansion of silicon nitride, enhanced by corrosion resistance, good high temperature strength and oxidation.

The SiAlONs were developed as a more economical alternative to hot pressedsilicon nitride.

SiAlONs have a complex chemistry and should be thought of as a family of alloys with a wide range of properties. They are formed when silicon nitride (Si_3N_4), aluminium oxide (Al_2O_3) and aluminium nitride are reacted together. The materials combine over a wide compositional range.

3.9. Glass Annealing

Annealing is a process of slowly cooling hot glass objects after they have been formed, to relieve residual internal stresses introduced during manufacture. Especially for smaller, simpler objects, annealing may be incidental to the process of manufacture, but in larger or more complex products it commonly demands a special process of annealing in a temperature-controlled kiln.

Annealing of glass is critical to its durability. Glass that has not been properly annealed retains thermal stresses caused by quenching, which indefinitely decrease the strength and reliability of the product. Inadequately annealed glass is likely to crack or shatter when subjected to relatively small temperature changes or to mechanical shock or stress. It even may fail spontaneously.

To anneal glass, it is necessary to heat it to its annealing temperature, at which its viscosity, η, drops to 10^{13} Poise (10^{13} dyne-second/cm²). For most kinds of glass, this annealing temperature is in the range of 454–482 °C (850–900 °F), and is the so-called stress-relief point or annealing point of the glass. At such a viscosity, the glass is still too hard for significant external deformation without breaking, but it is soft enough to relax internal strains by microscopic flow in response to the intense stresses they introduce internally. The piece then heat-soaks until its temperature is even throughout and the stress relaxation is adequate. The time necessary for this step varies depending on the type of glass and its maximum thickness. The glass then is permitted to cool at a predetermined rate until its temperature passes the strain point ($\eta = 10^{14.5}$ Poise), below which even microscopic internal flow effectively stops and annealing stops with it. It then is safe to cool the product to room temperature at a rate limited by the heat capacity, thickness, thermal conductivity, and thermal expansion coefficient of the glass. After annealing is complete the material can be cut to size, drilled, or polished without risk of its internal stresses shattering it.

At the annealing point ($\eta = 10^{13}$ Poise), stresses relax within several minutes, while at the strain point ($\eta = 10^{14.5}$ Poise) stresses relax within several hours. Stresses acquired at temperatures above the strain point, and not relaxed by annealing, remain in the glass indefinitely and may cause either short-term or much delayed failure. Stresses resulting from cooling too rapidly below the strain point largely are considered temporary, although they may be adequate to promote short-term failure.

3.10. COMPOSITES

3.10.1. Introduction

A composite material is a multiphase material, which is composed of at least two basic elements working together to produce material properties that are different to the properties of those elements on their own. In practice, most composites consist of a bulk material (the ‘matrix‘), and a reinforcement of some kind, added primarily to increase the strength and stiffness of the matrix. This reinforcement is usually in fibre form. Composites maintain an interface between components and act in concert to provide improved specific or synergistic characteristics not obtainable by any of the original components acting alone.

The definition will allow the inclusion of natural materials such as wood which consists of cellulose fibers bonded together with lignin and other carbohydrate constituents, as well as the silk fiber spun by a spider which is as strong as steel on a weight basis consisting of a gel core encased in a solid protein structure as composite materials.

Composites include:

(1) Fibrous (composed of fibers, and usually in a matrix),

(2) Laminar (layers of materials),

(3) Particulate (composed of particles or flakes, usually in a matrix),

(4) Hybrid (combinations of any of the above).

Today, the most common man-made composites can be divided into three main groups:

1. **Polymer Matrix Composites (PMC's)** – These are the most common and will be discussed here. Also known as FRP - Fibre Reinforced Polymers (or Plastics) – these materials use a polymer-based resin as the matrix, and a variety of fibres such as glass, carbon and aramid as the reinforcement.
2. **Metal Matrix Composites (MMC's)** - Increasingly found in the automotive industry, these materials use a metal such as aluminium as the matrix, and reinforce it with fibres such as silicon carbide.
3. **Ceramic Matrix Composites (CMC's)** - Used in very high temperature environments, these materials use a ceramic as the matrix and reinforce it with short fibres, or whiskers such as those made from silicon carbide and boron nitride.

It is when the resin systems are combined with reinforcing fibres such as glass, carbon and aramid that exceptional properties can be obtained. The resin matrix spreads the load applied to the composite between each of the individual fibres and also protects the fibres from damage caused by abrasion and impact. High strengths and stiffness, ease of moulding complex shapes, high environmental resistance all coupled with low densities, make the resultant composite superior to metals for many applications. Since PMC‘s combine a resin system and reinforcing fibres, the properties of the resulting composite material will combine something of the properties of the resin on its own with that of the fibres on their own.

Overall properties of the composite are determined by the,

1) Properties of the fibre,

2) Properties of the resin,

3) Ratio of fibre to resin in the composite (Fibre Volume Fraction (FVF)

4) Geometry and orientation of the fibres in the composite

3.10.2. Constituents of composites

Composite is considered to be any multiphase materials that exhibits a significant proportion of the properties of both constituent phases such that a better combination of properties is realized.

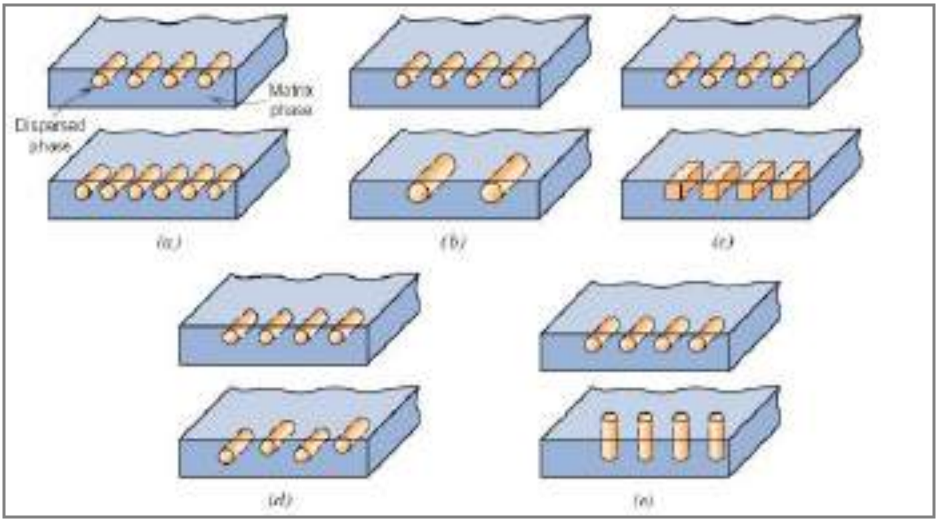


Fig.3.18 Constituents of composites

3.10.3. Classification of composites

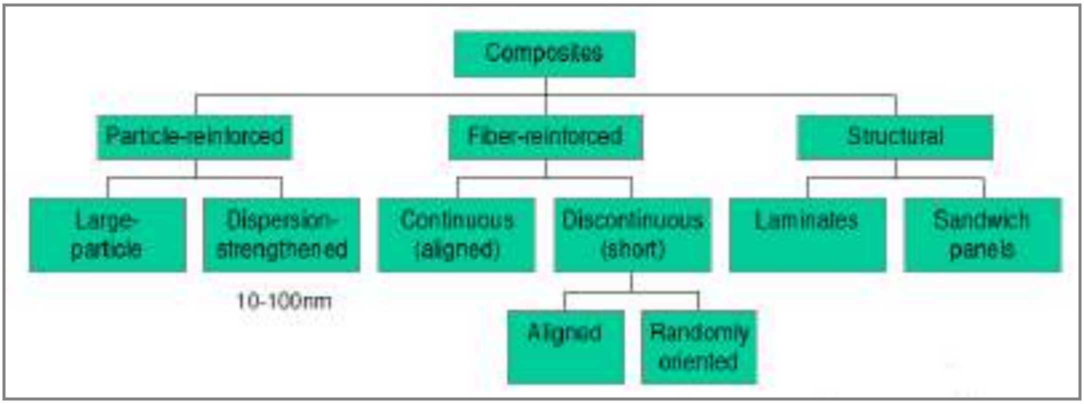


Fig.3.19 Classification of composites

3.10.4. PARTICULATE RE-INFORCED COMPOSITES

The particulate composite consists of particles of various sizes and shapes randomly dispersed within the matrix. The particles are 1 μm or less in size and the volume concentration is in between 20% and 40%. Typical examples include use of metallic partials in metallic matrices (lead particles in copper alloys to improve machinability), non-metallic particles in metallic matrices (silicon carbide particles in aluminium to improve high temperature properties), non-metallic particles in a non-metallic matrices (brittle polymer reinforced with rubber) and metallic reinforcement in non-metallic matrices (aluminium particles in rubber used in rockets). These are usually isotropic and are added randomly. Particulate composite have advantages such as improved strength, increased operating temperature, low density and improved wear resistance.

- Its consist of particles of one material dispersed in a matrix of a second material
- The fine dispersion particle posses good strength in composites.
- The size, distribution and orientation of particles define the strength of the composite.

Types particulate reinforced composite

1. Dispersion strengthened composites
2. Large particle composites

1. Dispersion strengthened composites

- The particles are smaller and having diameter 0.01 – 0.1 microns and volume concentration 1 – 15 % of fiber.
- This method is similar to that for precipitation hardening.
- Due to this, the composites have good yield and tensile strength. And the plastic deformation is restricted.

2. Large particle composites

- The particles diameter greater than 1 micrometer and volume concentration are greater than 25 %.
- Here the load on this composite is shared by both matrix and particles.
- It posses good strength.
- Tungsten carbide or Titanium carbide embedded in a metal matrix of cobalt or nickel.

- These composites used as a cutting tool.

3.10.4. FIBER RE-INFORCED COMPOSITES

The fibre reinforced composites consist of matrices reinforced by discontinuous (short fibre) or continuous (long) fibre. In any case, the second phase is in the form of fibres with the length many times larger than their diameter. A discontinuous fibre composite consists of short fibre in matrices and it can be oriented in one direction or randomly. These fibres are anisotropic. Carbon nanotube reinforced epoxy composite is the best example for short fibre reinforced composites.

- Here the dispersed phase is in the form of fibers.
- These fibre reinforced composites having improved strength, fatigue resistant, stiffness and strength-to-weight ratio.

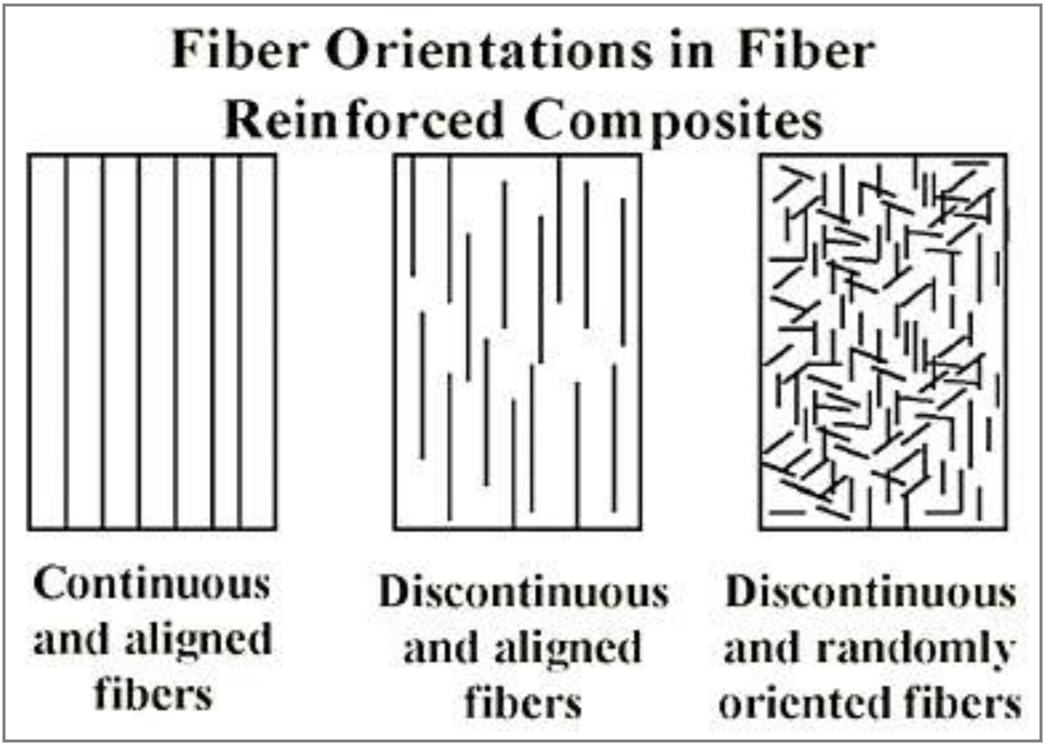


Fig.3.20. **Fibre orientations infibre reinforced composites**

3.10.5. Applications of Composites

There are many reasons for the growth in composite applications, but the primary impetus is that the products fabricated by composites are stronger and lighter.

Today, it is difficult to find any industry that does not utilize the benefits of composite materials. In the past three to four decades, there have been substantial changes in technology and its requirement. This changing environment created many new needs and opportunities, which are only possible with the advances in new materials and their associated manufacturing technology. In the past decade, several advanced manufacturing technology and material systems have been developed to meet the requirements of the various market segments. Broadly speaking, the composites market can be divided into the following industry categories:

1. Aerospace,
2. Automotive,
3. Construction,
4. Marine,
5. Corrosion resistant equipment,
6. Consumer products, appliance/business equipment, and
7. Others

UNIT-IV-HEAT TREATMENT

Most of the engineering properties of metals and alloys are related to their structure. Varying the relative properties of micro constituents can change the mechanical properties. In practice, change in mechanical properties can be achieved by a process called heat treatment. Heat treatment can be defined as a heating and cooling operation applied to metals and alloys in solid state so as to obtain the desired properties. The heat treatment is an important process in the final fabrication of many engineering components. Almost all metals and alloys respond to some form of heat treatment. Practically, all steels respond to one or more types of heat treatment. The strength of nonferrous alloys namely Al, Cu, Ni, Mg, etc. can be strengthened to various degrees by using the heat treatment technique.

4.1 HEAT TREATMENT PURPOSES

The heat treatment can be undertaken for the following purposes:

1. Improvement in ductility
2. Relieving internal stress
3. Refinement of grain
4. Increasing the hardness
5. Improvement in machinability
6. Alteration in magnetic and electrical properties
7. Improvement in toughness

A number of factors are to be considered when heat treating a metal or an alloy. These are known as heat treatment process variables and they are discussed in the following subsections.

4.1.1 Temperature up to which the Metal or Alloy is heated

The heat treatment temperature is governed mainly by the chemical composition of the alloy, prior heat treatment, if any, and the ultimate properties desired. Heat treatment temperature for steels can be determined with the help of iron–carbon diagram. The rate of heating is also important in heat treatment operations. It depends on the size, shape of the object and the thermal conductivity of the alloy. The larger the objects, the lower is the rate of heating. It avoids development of internal stresses due to thermal gradient and ensures homogeneity of the structure.

4.1.2 Length of time the Metal or Alloy is held at this Temperature (Holding Time)

For an object of variable thickness, the holding time is determined on the basis of the thickest section. Holding time is generally provided at a rate of 2–3 minutes per millimetre of the section thickness. Heat treatment temperature and holding time are somewhat related. Increasing the rate of heat treatment temperature reduces the holding time. Similarly, lowering of heat treatment temperature results in increase of holding time.

4.1.3 Rate of Cooling

The mode of cooling as well as the rate of cooling is governed by those factors which control the heating mode and the rate. Objects with heavy section, complicated shapes and variable section thickness are cooled slowly. The size, shape, distribution and relative properties of micro constituents can be controlled over a wide range of varying cooling rates. By increasing the cooling rates beyond the limits, the structure produced will be non equilibrium products like martensite developed by sudden quenching.

4.1.4 Quenching Media

Quenching is the rapid cooling of a metal or an alloy from a suitable elevated temperature. This is usually accomplished by immersing in water, oil or in a brine used. Commonly used quenching media is air, water, oil and brine. The choices of quenching medium depend upon the type of steel being treated and the resultant properties desired.

Selection of Quenching Medium

The selection of quenching medium is based on the following factors:

1. Desired rate of heat removal.
2. Required temperature interval.
3. Boiling point.
4. Viscosity.
5. Flash point (if combustible).
6. Stability under repeated use.
7. Possible reactions with the material being quenched.

8. Cost.

Stages of Quenching

The three stages of quenching are:

Stage 1: Vapour-Jacket Stage

When a piece of hot metal is first inserted into a tank of liquid quenchant, that adjacent to the metal vapourises and forms a gaseous layer separating the metal and liquid. In this stage cooling is slow since all heat transport must be through a gas (by conduction and radiation). This stage occurs when the metal is above the boiling point of the quenchant.

Stage 2: Vapour-Transport Cooling Stage

This stage starts when the hot metal is cooled to a temperature at which the gaseous layer is no longer stable. In this stage, bubbles nucleate and remove the gaseous layer; liquid contacts the metal and vapourises it and thus the process of bubbles formation continues. This second stage of quenching provides rapid cooling as a result of the large quantities of heat removed by the mechanism.

Stage 3: Liquid Cooling Stage

Third stage begins when the metal cools below the boiling point of the quenchant. In this stage, all heat transfer occurs through conduction across the solid-liquid interface, aided by convection or stirring within the quenchant. The third stage of quenching provides the slowest rate of cooling.

4.2 HEAT TREATMENT OF STEEL

The object of heat treatment is to make the steel suitable for some specific application. Steel is an important engineering material as it can be given a wide range of mechanical properties by heat treatment. Heat treatment can alter the properties of steel by changing the size and shapes of the grains, and by altering the micro constituents. The shape of the grains can be altered by heating the steel to a temperature above that of recrystallization and the duration of heating and the rate of cooling.

Heat treatment process can be broadly classified into following:

1. Treatment that produces equilibrium condition
2. Treatment that produces non equilibrium condition

4.2.1 Treatments that Produce Equilibrium Condition

When steel is heated to a temperature up to 500°C, small residual stresses will be relieved to a small extent to cause only a slight reduction in hardness and strength. On reaching 500°C, recrystallization takes place producing new small grains. If heating is continued, the grains become enlarged and ductility will be increased. If temperature is high enough to produce the austenite structure and if cooling rate is low enough, new grains that relieve stress will be produced. The mechanical properties of steel at the end of heat treatment will depend upon the carbon content, the heat treatment temperature, the holding time and the cooling rate. The principal heat treatments in this group are stress reliving, annealing, normalizing, etc.

4.2.1.1 Annealing

Annealing can be defined as heating and holding the material at a suitable temperature following by cooling at a suitable rate to get softness, to improve its strength and to remove stress.

The purposes of annealing are specified as follows:

1. To improve mechanical properties
2. To improve machinability
3. To restore ductility, particularly after the steel has been subjected to cold working
4. To remove or minimize segregation of the essential constituents of steel
5. To alter the microstructure to make it suitable for hardening
6. To relieve the internal stresses

Depending upon specific purposes, annealing can be classified as follows:

4.2.1.1.1 Full Annealing

In fact, the actual definition of annealing describes only the full annealing. That is, full annealing consists of heating the steel to a temperature at or near the critical point, holding there for a time period and then allowing it to cool slowly in the furnace itself.

The main objects of full annealing are:

(i) To soften the metal,

(ii) To refine its crystalline structure, and

(iii) To relieve the stresses.

Material: The full annealing is specially adopted for steel castings and steel ingots:

Process of Full Annealing

`In full annealing, hypoeutectoid steels (less than 0.77% C) are heated to 30 to 60°C above the upper critical point i.e., A_3 line (i.e., between 723°C and 910°C), as shown in Fig.4.1. This is to convert the structure to homogeneous single-phase austenite of uniform composition and temperature, held at this temperature for a period of time, and then slowly cooled to room temperature,

Cooling is usually done in the furnace itself by decreasing the temperature 10 to 30°C per hour to at least 30°C below the A_1 line (Fig.4.1). Then, the alloy is removed from the furnace and air cooled to room temperature. Now the resulting structure is coarse pearlite with excess ferrite. In this condition, the steel is quite soft and more ductile.

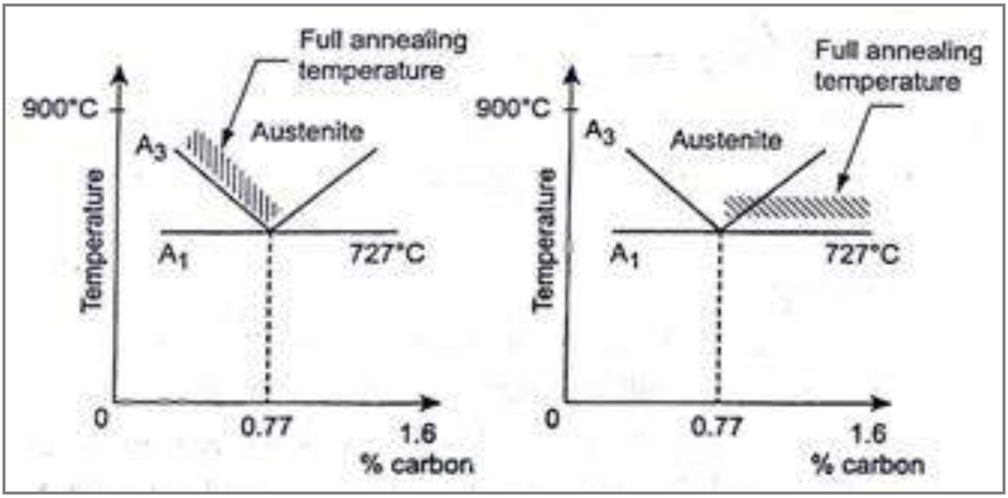


Fig 4.1 Full annealing temperatures for hypo eutectoid steel & hyper eutectoid steel

The procedure for hypereutectoid steels (i.e., greater than 0.77% C) are the same, except that the hypereutectoid steels are heated to 30 to 60°C above the A_1 line (i.e., between 723°C and 1138°C), as shown in Fig.

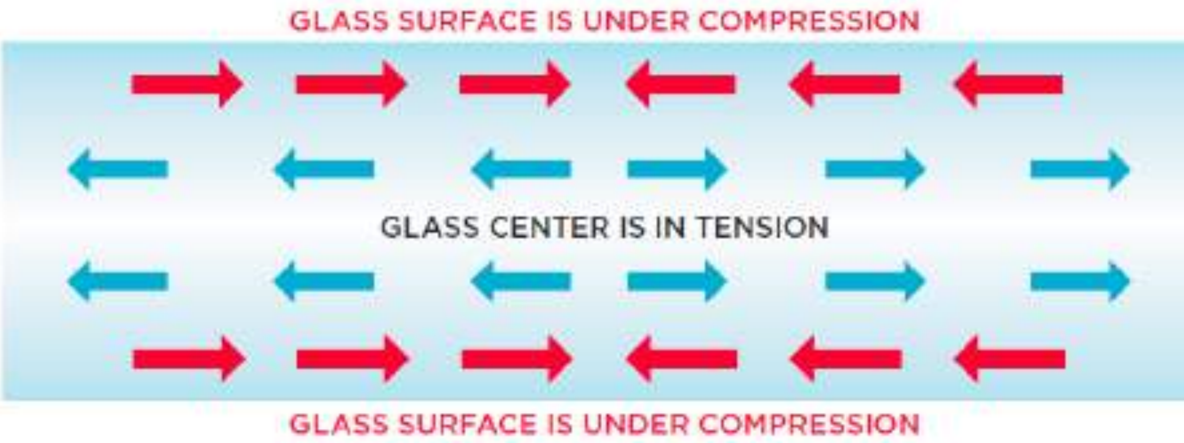
In this case, the resulting structure of a hypereutectoid steel will be coarse pearlite plus excess cementite in dispersed spheroidal form. This structure imparts much improvement in mechanical properties, high ductility and high toughness.

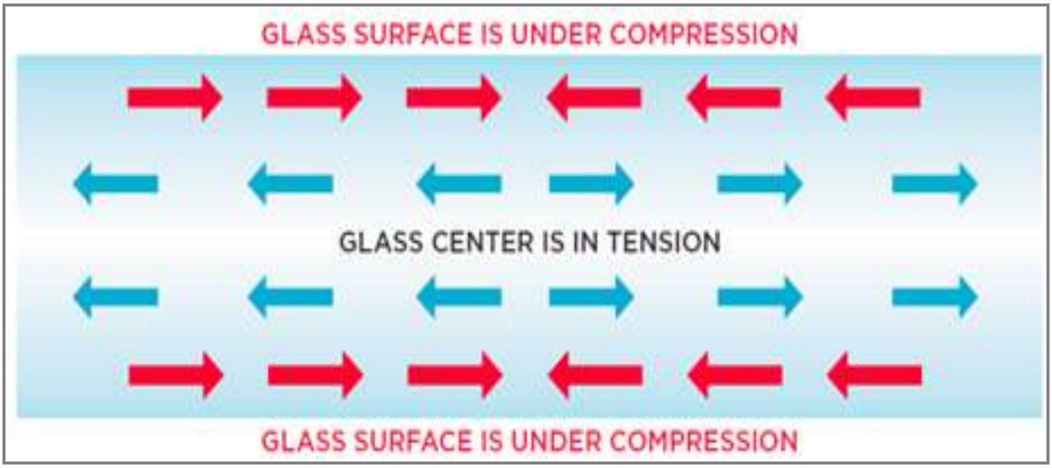
4.2.1.1.2 Glass Annealing

Glass annealing is a controlled process of slowly cooling glass to relieve these internal stresses. First, the glass is heated to its annealing point; the temperature at which the residual stresses in a glass are reduced over a matter of minutes. It is then slowly cooled to room temperature. To ensure maximum stress removal, each product design requires a unique annealing schedule that takes into consideration the glass composition, coefficient of thermal expansion, and thickness. Following production, glass lenses can be inspected with equipment like a polariscope to ensure well annealed, minimally stressed glasses.

Heat Strengthening and Tempering of Glass

Conversely, there are times when you want to introduce stress in a controlled way to improve a glass' thermal and mechanical properties. Glass can be heat-strengthened or tempered through a controlled heating and cooling process. This is accomplished by first heating the glass above its glass transition temperature. According to the standard ASTM C1048, a heat-strengthened glass has a surface compression of 3500 to 7500 psi, while a tempered glass must have a surface compression of at least 10,000 psi. The compressive layer is responsible for improving the thermal and mechanical resistance of the glass; any shock or impact would have to overcome this stress before catastrophic failure could occur.





Surface compression improves the thermal shock resistance, as well as mechanical resistance of a glass.

4.2.1.1.3 Recrystallization or Stress-relieving Annealing

This process is used to relieve internal stress which develops during different operations like welding, solidification of casting, machining, etc. The process of recrystallization annealing consists of heating steel uniformly to a temperature 50°C–80°C below 723°C as indicated in Figure 4.2 and holding at this temperature for sufficient time followed by slow cooling. Uniform cooling is most important as non uniform cooling results in the development of internal stress.

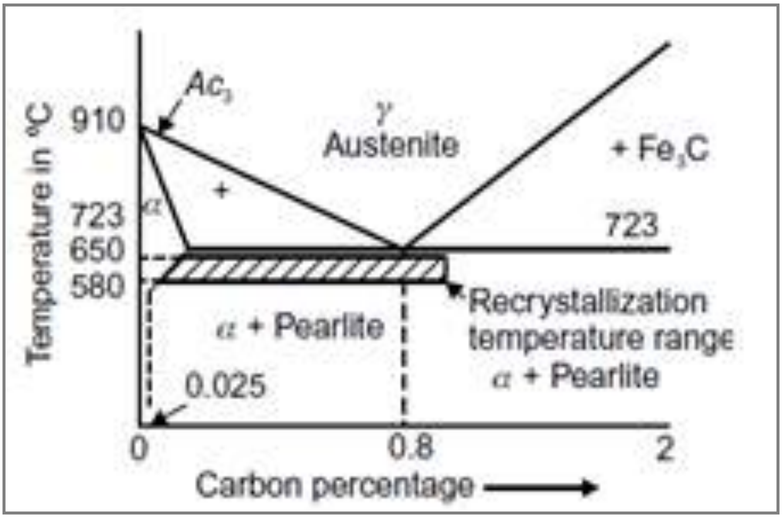


Fig. 4.2 Fe—Fe_3C diagram for Recrystallization annealing

4.2.1.1.4 Process Annealing

Process annealing is usually carried out to remove the effects of cold working and to soften the steel. Process of annealing consists of heating steel uniformly to a temperature of 650°C–723°C (see Figure 4.3) and holding at that temperature for sufficient time, followed by slow cooling.

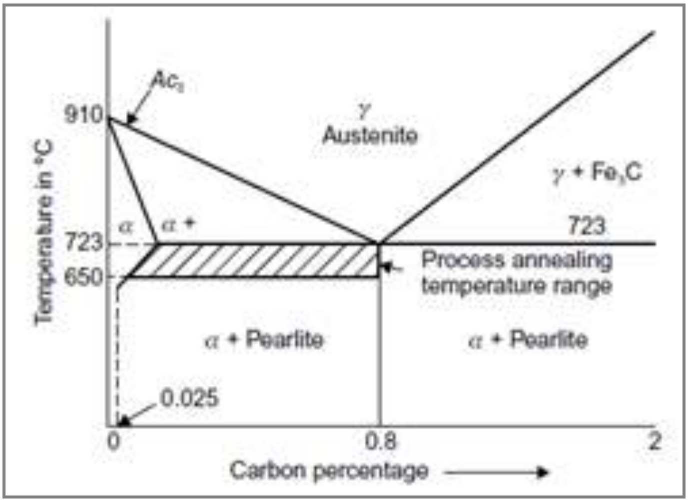


Fig. 4.3 Fe—Fe_3C diagram for Process annealing

4.2.1.1.5 Spheroidal Annealing

In spheroidal annealing, graphite with iron in the granular form is produced. The prolonged heating causes the cementite to coalesce into spheres, completely destroying the pearlitic formation.

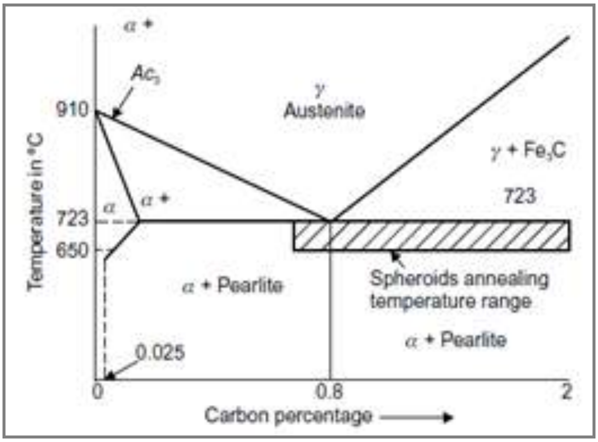


Fig. 4.4 Fe—Fe_3C diagram for spheroidal annealing

4.2.1.1.6 Normalizing

The normalizing is a process of heating steel about 40°C – 50°C above the A_3 temperature, 'soaked' for a specified period of time, depending upon the size and section thickness, and then allowed to cool in still air. The normal rate of cooling in air is about 50°C–80°C per minute, depending upon the section, size and air conditions. This cooling rate is fast enough to produce a sorbite structure in steel which results in increased tensile strength and yield point. Free cooling will produce a finer structure than that produced by annealing. After normalizing, the microstructure obtained will be pearlite (see Figure 4.5). The normalizing of low carbon steels is usually done for stress relief, grain size refinement and for improvement in toughness, tensile strength and ductility. Normalized steels are generally stronger and harder than annealed steels.

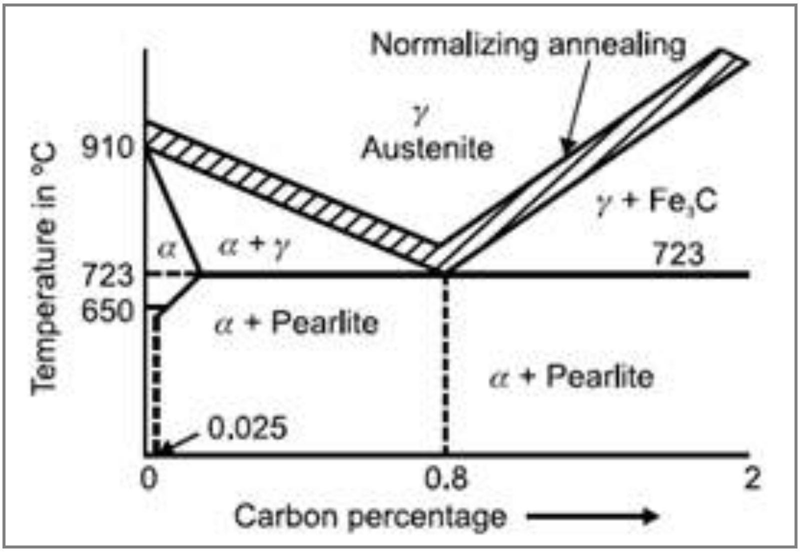


Fig. 4.5 Fe—Fe_3C diagram for Normalization

4.2.2 Treatments that Produce Non equilibrium Condition

Certain applications demand high hardness values so that the components may be successfully used for heavy-duty purposes. High hardness values can be obtained by a process known as hardening process. Steel is heated to produce austenite structure held at that temperature and then quenched in water. The high hardness developed by this process is due to the transformation of austenite at considerable low temperature known as martensite and this metal is known as non equilibrium condition. The properties produced by this method depends on the carbon content of the steel, temperature, holding time and quenching media. To produce a change in properties, sufficient carbon must be retained in solid solution after quenching to produce the necessary lattice distortion. If the carbon is less than 0.15%, there will be no appreciable change in the properties after quenching. However, as the carbon content is increased, there will be a corresponding increase in the hardness and strength as a result of quenching due to the formation of martensite. An example for the treatment that produces non equilibrium condition is hardening of steel.

4.2.2.1 Hardening of Steels

Certain applications demand high hardness value so that the components may be successfully used for heavy-duty purpose. High hardness values can be obtained by a process known as hardening process.

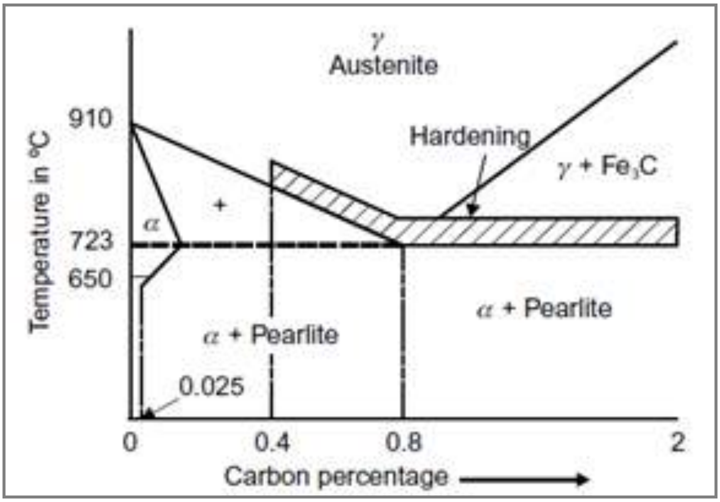


Fig. 4.6 Fe—Fe$_3$C diagram for spheroids hardening process

When steels are heated above the A$_3$ temperature and drastically quenched in water, maximum hardness is obtained. The structure so obtained is called martensite. The hardness obtained depends upon the composition of the steel. When the carbon content of the steel is 0.80%, the maximum hardness obtained is 66 Rockwell C. When the carbon content is increased to more than 0.80%, the maximum hardness obtained remains the same, i.e., 66 Rockwell C. When the carbon content is decreased, the maximum hardness that is obtained gradually decreases and with mild steels it is highly impossible to get a superficial surface hardness of about 40 Rockwell C, however drastic the quenching may be. Also, faster the cooling, greater is the hardness; and, slower the cooling, lower is the hardness. The structures obtained with different rates of cooling will differ fundamentally with respect to appearance under the metallurgical microscope as well as in physical properties like tensile strength, yield point, hardness, etc. (see Figure 4.6).

If steel is cooled at a certain minimum rate, called the ‘critical rate’, all the austenite will be transformed into martensite and thus produces maximum hardness. If the cooling rate is slightly lower than the critical rate, troostite will be formed. If the cooling rate is still lower but is higher than the critical rate, it will allow pearlite formation and sorbite is formed.

The products of decomposition between pearlite and martensite are often termed as bainite. This means that sorbite, troostite and acicular troostite are the same as bainite.

Water and oil are the most common quenching mediums adopted in heat treatment. Some of the alloy steels are hardened by simply cooling in the air. Such steels are known as air-hardening steels. The quenching medium used depends upon the specification and the section of the steel. Plain carbon steels are usually water hardened. Such steels are called water-hardening steels. Most of the low and high alloy steels are oil hardened. Such steels are known as oil-hardening steels. Air-hardening steels are few and their heat treatment has to be carefully handled. When thick piece is heated and quenched, only outside will be martensite and core will be of pearlite. The condition of the surface of the steel also affects hardening. The presence of oil, grease, scale, etc. reduces the cooling rate of the metal than the treated surface which may lead to incomplete hardening.

To produce high hardness, sufficient carbon must be retained in solid solution after quenching to produce necessary lattice changes. Hypo eutectoid steels are heated to about 30°C–50°C above the upper critical temperature, whereas hyper-eutectoid steels are heated to about 30°C–50°C above the lower critical temperature. Duration of heating depends upon the thickness of material. The steel components are cooled at a certain minimum rate called critical cooling rate.

In the hardening process, steel is heated to produce an austenite structure held at that temperature and then quenched in water or oil. The high hardness developed is due to the transformation of austenite at considerable low temperature into non equilibrium product known as martensite.

4.2.2.2 Tempering

Steels are hardened by heating them above the critical temperature and quenching in water or oil. The quenching process brings about great stresses in the hardened steels. Hardening treatment develops maximum hardness, excellent wear resistance and high strength in steels. At the same time, it affects properties such as ductility, impact strength, etc. because of internal stresses developed by quenching. A process which consists of heating hardened steel below the lower critical temperature followed by air cooling is known as tempering which reduces internal stresses and degree of brittleness.

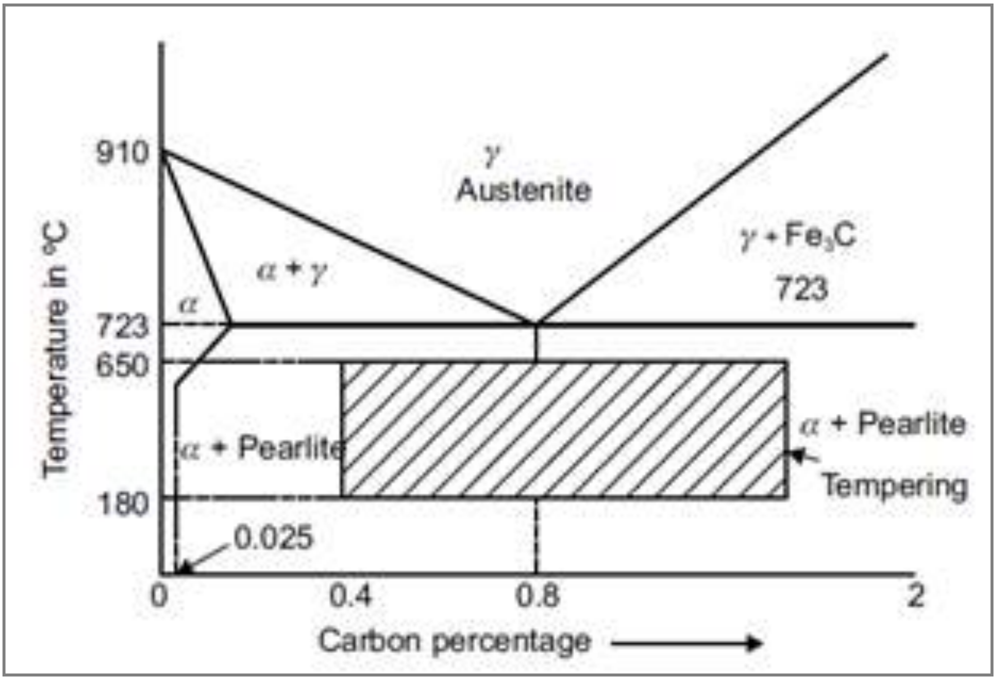


Fig. 4.7 Fe—Fe_3C diagram for tempering process

The tempering temperature is determined by the specification of steel and the final hardness and toughness desired. The tempering temperature depends on the properties required, but it is between 180°C–550°C, and duration of heating depends upon the thickness of the materials. The tempering temperature below 220°C relieves the hardening stress, but at the tempering temperature above 220°C, the martensite structure transfers into a fine pearlite structure (see Figure 4.7).

By the tempering operation, the following changes occur:

1. The quenching stresses are mostly relieved.
2. The hardness in the piece is equalized, as far as possible.

3. The hardness is reduced to the desired extent and the toughness proportionately restored.

For tempering, the hardened steel is again heated in a furnace or in heavy oil or in molten salts and held long enough for the heat to penetrate to the centre. For most steels, cooling after the tempering operations is of little consequence and in practice the cooling after tempering is usually done in the air.

4.3 ISOTHERMAL AND CONTINUOUS COOLING TRANSFORMATION DIAGRAMS

The properties of steel are mainly dependent upon micro constituents or phases present in the structure. Austenite is unstable below 723°C and it undergoes phase transformation into pearlite, bainite or martensite. In the beginning, austenite is transformed into a-iron but this iron is unable to hold Fe_3C in solid solution. The Fe_3C, which is held in the ferrite, is diffused out as free cementite. This requires heat energy and sufficient time. If sufficient heat and time are not allowed, the process of Fe_3C diffusion is decreased and in some cases, altogether arrested. So austenite undergoes transformation depending upon temperature and time. The relationship between structure and rate of cooling (time taken to decompose) can be studied for given steel with the help of a set of isothermal austenite transformation curves, which are popularly known as Time–Temperature–Transformation diagram or TTT diagram. In this diagram, the temperature is plotted on the vertical axis and time is plotted on a logarithmic scale along the horizontal axis. This curve is also known as S curve, C curve or isothermal curve.

4.3.1 CONSTRUCTION OF TTT DIAGRAM

For eutectoid composition of steel, TTT diagram can be constructed as follows.

Obtain a large number of relatively small specimens, cut from the same bar of given steel sample (composition should not change). The samples are made as thin as possible to bring in the temperature changes uniformly throughout the section. Place the samples in a molten salt bath (brine solution) and heat the eutectoid steel to a temperature above 723°C . Specimens are kept in the molten salt bath for long enough to form complete austenite. Time is an important factor in dissolving the Fe_3C in solid solution.

Withdraw the specimens from the molten salt bath and quickly transfer into another bath which is at a temperature lower than 723°C. For example, bath temperature is maintained at 700°C. Samples are held for varying lengths of time to transfer austenite into pearlite before being quenched to room temperature. Pearlite is the result of isothermal heat treatment and its amount depends upon the time permitted for isothermal reaction to continue. Specimens are held in the bath for varying periods of time, which may vary from 1 s to as long as several hours. More time given to a sample to react isothermally, the more pearlite is formed. Isothermal reaction stops by quenching in cold water or ice to get untransformed austenite into martensite. Martensite is the result of water quenching of the specimen after the isothermal heat treatment (see Figure 4.8).

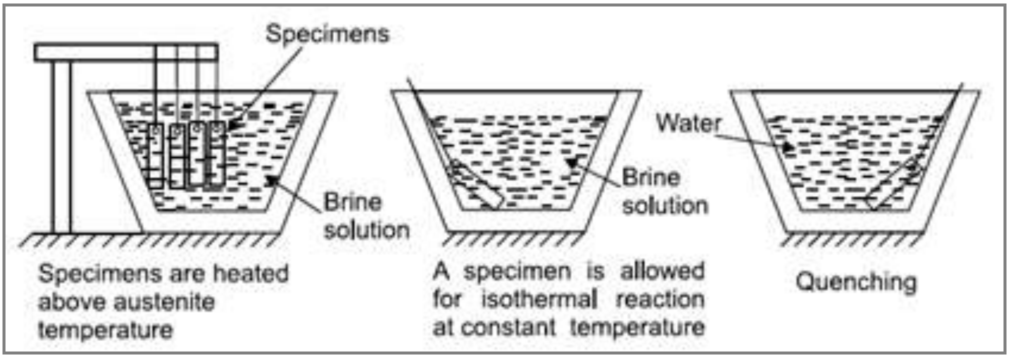


Fig. 4.8 Isothermal heat treatment arrangement

Observe the microstructure of the specimens under the microscope. It shows both the pearlite and martensite. Based on the structure, predict the amount of pearlite in specimens. When a large numbers of specimens which isothermally react at 700°C for varying time periods are metallographically observed, the result is the reaction or S curve as shown in Figure , curve is plotted with time on the horizontal axis and pearlite percent on the vertical axis.

Austenite is stable above 723°C and below this temperature it is unstable, i.e., it can transform into pearlite, bianite or martensite. Transformation at temperature approximately between 723°C to 550°C results in the characteristics of microstructure of pearlite. The transformation within this range takes place by nucleation and growth of cementite and ferrite respectively. The ferrite formed at slightly below the 723°C is coarse structure due to high temperature and long time is available for diffusing Fe_3C. However, as the temperature is reduced, i.e., just above the nose of the curve, the pearlite becomes fine pearlite.

At temperature between 550°C and 240°C, the transformation product is bainite. Austenite decomposes into ferrite and cementite. Below the nose temperature, bainite looks feathery and above this temperature, it is dark acicular. These are called as upper bainite and lower bainite respectively.

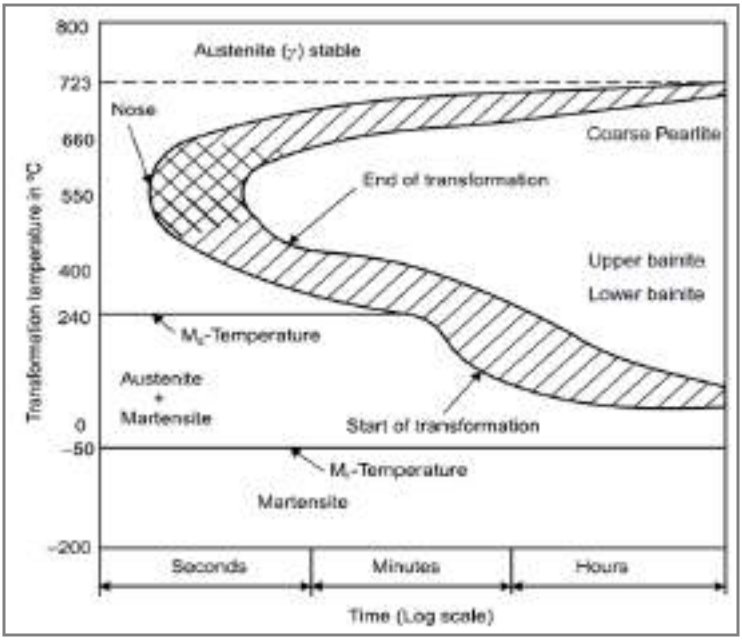


Fig. 4.10 Time, temperature and transformation for eutectoid steel

Below 240°C, the austenite transferred is martensite. Martensite is an acicular, supersaturated interstitial solid solution of iron and carbon. At the foot of TTT diagram, there are two lines M_s and M_f at temperatures 240°C and –50°C respectively. M_s represents the temperature at which formation of martensite starts. M_f is the temperature at which the formation of martensite finishes during the cooling of austenite.

4.3.2 EFFECT OF COOLING RATE ON TTT DIAGRAM

Figure 4.11 shows the effect of cooling rate on the formation of different reaction products in eutectoid steel. Austenite transforming into pearlite, bainite and martensite with different cooling rates is an example of this.

When a metal is heated above 723°C, held for a suitable time and cooled very slowly, it cools as per the curve A (becomes annealing) as shown in figure. A transformation starts at point 1, ends at 2 and the product is coarse pearlite with a low hardness and high ductility. This process is known as annealing. Cooling curve B involves a faster cooling rate than curve A and it becomes normalizing heat treatment. In curve B, the austenite transformation starts at point 3 with the formation of coarse pearlite and ends with fine pearlite at point 4. Curve C is a result of further increase in cooling rate.

The transformation of austenite is a mixture of pearlite and bainite. It is typical air quench. Hardness of this structure is higher then the structure obtained in the annealing process. Curve D represents the intermediate cooling rate and some amount of austenite starts to transfer as fine peralite between points 7 and 8. The residue austenite will transform into martensite when cooled at M_s line. Final structure consists of a mixture of peralite and martensite.

When the cooling curve (E) touches the nose of the TTT diagram, then this curve is called critical rate of cooling curve as shown in Figure 4.12. If the curve touches the nose of the TTT diagram and has enough time, austenite transfers into fine bainite. If the curves miss the nose of the diagram, austenite is directly transferred in to martensite. When the material is dipped in oil or water, the substance remains austenite until it reaches the M_s line and changes to martensite between M_s and M_f lines.

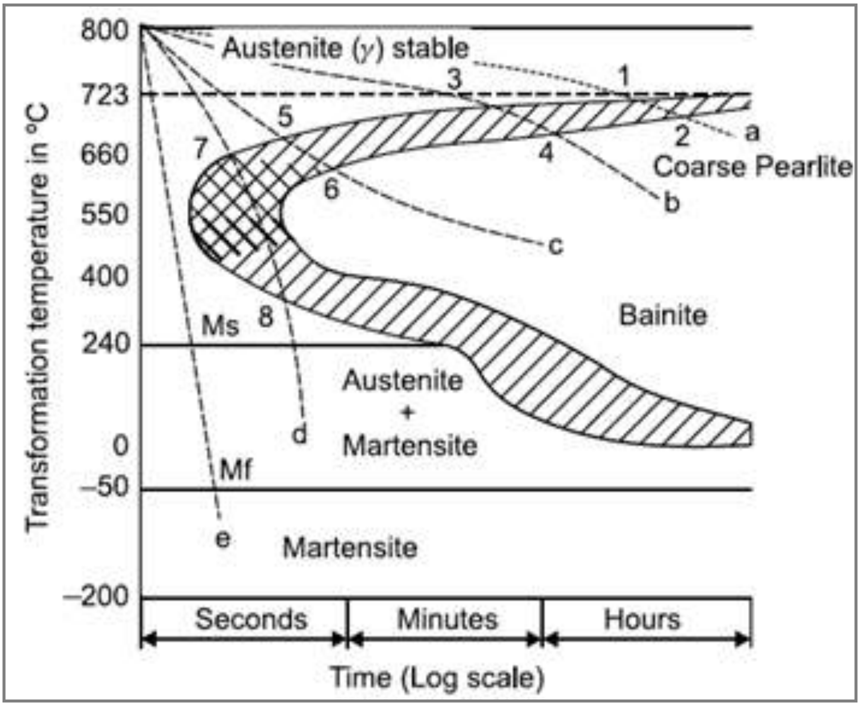


Fig. 4.11 Effect of cooling curve on TTT diagram

4.4 CONTINUOUS COOLING TRANSFORMATION (CCT) CURVE

The TTT diagrams hold good for isothermal transformation of austenite. It has limited application because in most of the heat treatment processes, the transformation of austenite takes place at continuous cooling and not at constant temperature or isothermal transformation. When the steel is cooled continuously, the TTT curve shifts to the right and downwards.

To construct a continuous cooling diagram of eutectoid steel, a large number of samples are heated above 723°C to get a complete austenite structure. From this temperature, specimens are cooled at a constant cooling rate of some definite temperature and then quenched in water. The specimens are studied for their microstructure and the time of start and end of pearlite are determined. By repeating the process, different sets of start and end points of pearlite are obtained. On joining the start and end points, two curves, similar to those of TTT diagram, are obtained as shown in Figure 4.12. This diagram gives the end product of pearlite, bianite and martensite at different cooling rates and at different temperatures. This diagram is widely useful in heat treatment process.

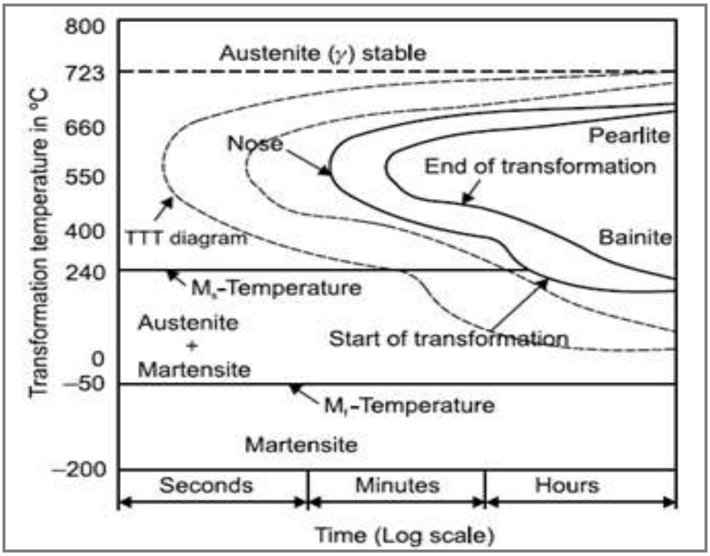


Fig. 4.12 Continuous cooling curve for eutectoid steel

4.5 EFFECT OF CARBON CONTENT AND ALLOYING ELEMENTS

The TTT curves explained are those of 0.8% C steel (eutectoid steel). The change in carbon content above or below this and the addition of alloying elements tend to displace the curves. A reduction in carbon content moves the curve to the left and an increase in carbon content (and alloying elements) tends to move the curve to the right as shown in Figure 4.13 (a) to (c).

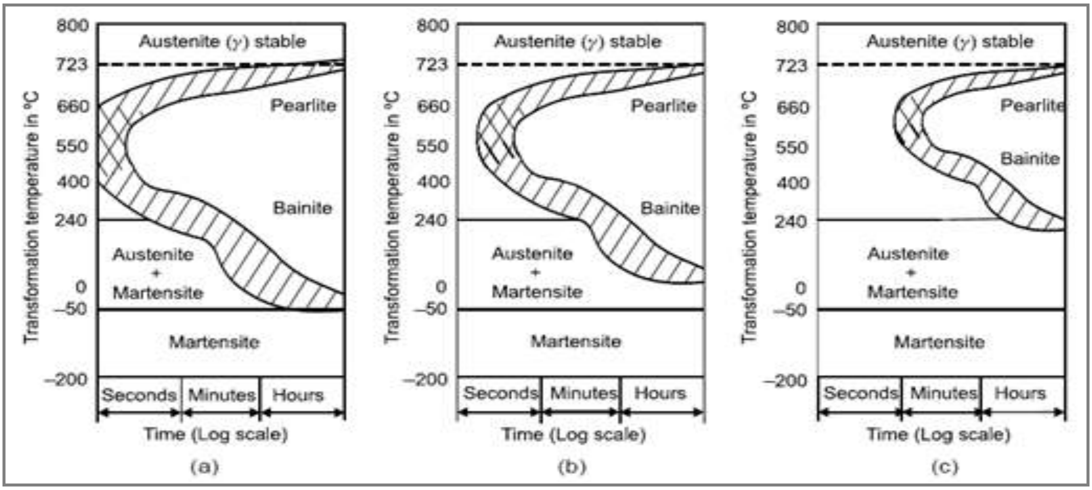


Fig. 4.13 Effect of carbon on TTT diagram: (a) Low carbon steel, (b) eutectoid steel and (c) high carbon steel

As the carbon content decreases, the nose of the curve moves left. At lower carbon content, austenite transformation results in more ferrite than Fe_3C. Ferrite is soft and does not respond to heat treatment, and the time available for quenching decreases so that the critical cooling rate required for producing a totally martensitic structure will be greater.

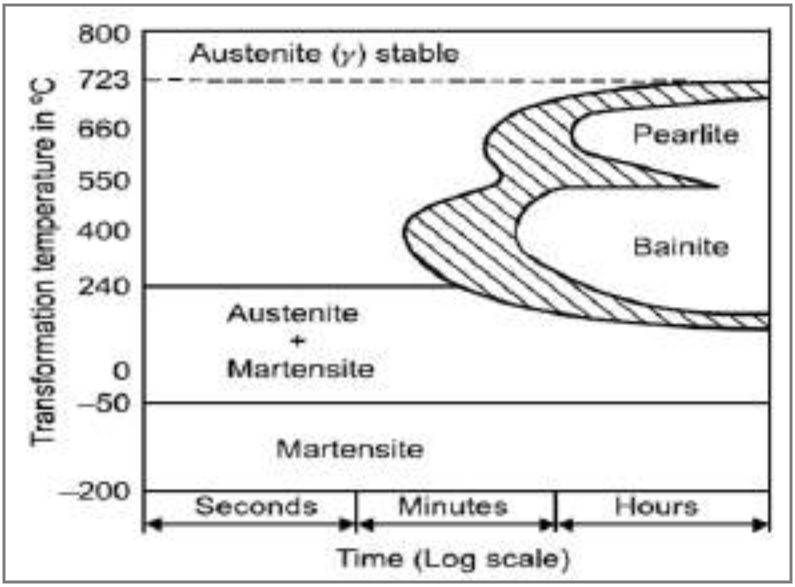


Fig. 4.14 Effect of alloying elements on TTT diagram

On the other hand, an increase in carbon content or the addition of alloys will shift the nose of the curves to the right (see Figure 4.13 (b) and (c)). This tends to increase the time required for quenching, the hardness and the depth of hardening. Addition of carbon and alloying elements helps to precipitate Fe_3C more and more. The TTT curve for a low alloy steel is shown in Figure 4.14. This needs a reduced rate of cooling to produce a martensitic structure. This makes it possible to oil-quench (or even to air harden) a suitable steel and obtain a hard martensitic structure throughout.

4.6 CRITICAL COOLING RATE

Definition: The slowest rate of cooling of austenite that will result in 100% martensite transformation is known as the critical cooling rate.

Importance: The critical cooling rate is most important in hardening. In order to obtain a 100% martensitic structure on hardening, the cooling must be much higher than the critical cooling rate.

Factors affecting the critical cooling rate are:

1. Chemical composition of steel,
2. Hardening temperature, and
3. Metallurgical nature (i.e., purity) of steel.

4.7 HARDENABILITY

Hardenability can be defined as the ability to harden the metal and it determines the depth and distribution of hardness induced by quenching. Steel, so quenched, will be hardened throughout. This property of steels of acquiring hardness throughout the section by means of heat treatment is known as hardenability. Hardness is a measure of resistance to plastic deformation; while hardenability is the ease with which the hardness may be attained.

In any steel, maximum hardness is obtained only when 100% martensite is formed. Thus, the steel is said to possess good hardenability when it is possible to get uniform hardness all through its section thickness upon quenching. However, in practice, the hardness values decrease along the cross section as we go away from the quenched end.

4.7.1 Jominy End-Quench Tests

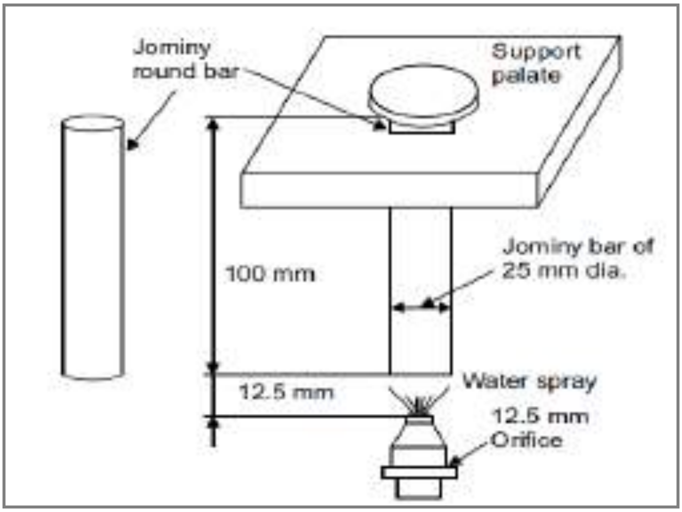


Fig. 4.15 Jominy end-quench for eutectoid steel

When steel is quenched, the cooling rate decreases from the surface to the interior and the hardness is highest at the surface and lowest in the central portion. There is a standard test called the Jominy end quench test to determine the hardenability of steel. In this test, a round bar of a specified size is heated to form austenite and is then end quenched with water stream of specified flow rate and pressure as shown in Figure 4.15.

4.8 MARTEMPERING (INTERRUPTED QUENCHING)

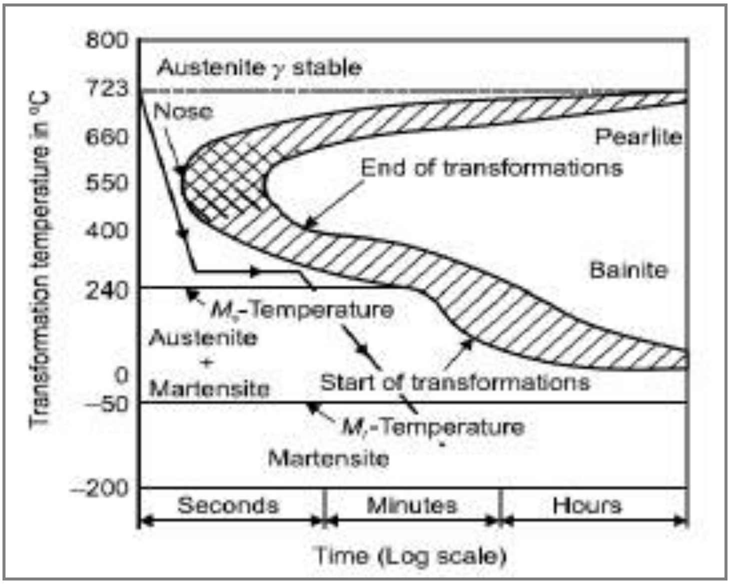


Fig. 4.16 Martempering process for eutectoid steel

Martempering, also known as marquenching, is an interrupted cooling procedure used for steels to minimize the stresses, distortion and cracking of steels that may develop during rapid quenching.

The martempering process consists of the following steps:

Step 1: Austenitizing the steel, i.e., heating the steel above its critical range to make it all austenite.

Step 2: Quenching the austenitized steel in hot oil or molten salt at a temperature just slightly above the martensite start temperature (M_s).

Step 3: Holding the steel in the quenching medium until the temperature is uniform throughout and stopping this isothermal treatment before the austenite-to-bainite transformation begins.

Step 4: Cooling at a moderate to room temperature (usually in air) to prevent large temperature differences between center and surface.

4.9 AUSTEMPERING (ISOTHERMAL TRANSFORMATION)

- Austempering is another type of interrupted quenching that forms bainite structure.
- The austempering is an isothermal heat treatment process, usually used to reduce quenching distortion and to make a tough and strong steels.

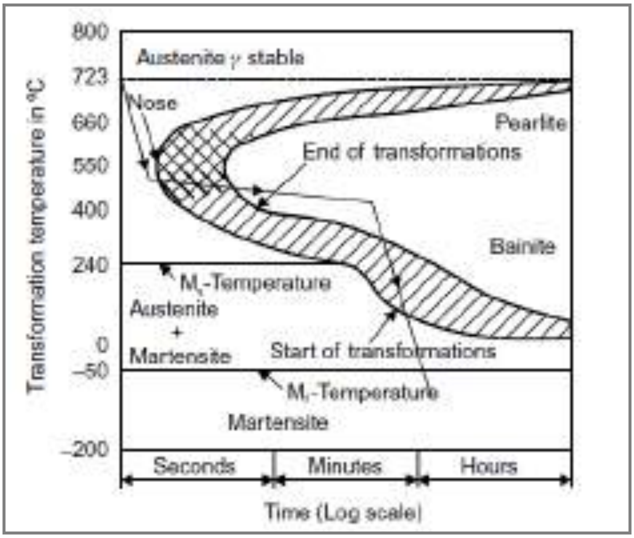


Fig. 4.17 Austempering process for eutectoid steel

The austempering process consists of the following steps:

Step 1: Austenitizing the steel.

Step 2: Quenching the austenitised steel in a molten salt bath at a temperature just above the martensite starts temperature (M_s) of the steel.

Step 3: Holding the steel isothermally to allow the austenite-to- bainite transformation to take place.

Step 4: Slow cooling to room temperature in air. Fig.4.17 shows a cooling path for the austempering process.

The resulting microstructure of the austempering process is bainite. Unlike martempering, tempering is rarely needed after austempering.

4.10 CASE HARDENING (OR SURFACE HARDENING)

Many components like gear, camshafts and piston pins require a very hard-wearing surface to withstand the constant wear in service conditions and at the same time, a tough core which will withstand the shock loads. The treatments given to steels to achieve this are called surface heat treatments. This combination of widely differing properties can be combined in a single piece of steel by surface hardening.

The classification of surface heat treatments is as follows:

1. Method in which the whole component is heated
2. Methods in which only the surface of the component is heated

4.11 Method in which Whole Component Is Heated

In this method, the hardness of the surface is improved by diffusing interstitial elements like carbon, nitrogen or both into the surface of steel components by heating the whole component. Only on heat treating, the surface of the component will respond to the treatment depending on its diffusing elements chosen.

Diffusion treatment can be classified as follows:

1. Carburizing
2. Nitriding
3. Cyaniding
4. Carbonitriding

4.11.1 Carburizing

Carburising is the process in which carbon atoms introduced onto the surface of low carbon steels to produce a hard case of surface, while the interior or core remains soft. Steels for carburising should have carbon from 0.10 to 0.20%.

In carburisation, when a piece of low-carbon steel is placed in a carbon saturated temperature, then the carbon will diffuse or penetrate into the steel and carburising it.

The carburising i.e., the process of adding carbon to a metal surface, can be accomplished by the following three methods.

1. Pack carburising,

2. Gas carburising, and

3. Liquid carburising (or cyaniding).

4.11.1.1 Pack (or solid) carburising

In solid carburizing process, mild steels and low-alloy steels of high tensile strength but with low carbon content are used. This method of carburizing is also known as pack carburizing. Here, the steel component to be heat treated is packed with 80% granular coal and 20% barium carbonate and heated at 930°C in a furnace for a specific period of time which depends on case depth required. Even ordinary charcoal mixed with $BaCO_3$ serves the purpose. But it is preferable to purchase patented carburizing compounds from reputed firms for this purpose.

Once the components to be heated and carburising mixture are packed into steel boxes, then lids are fixed on the boxes. Then they are heat treated to the carburising temperature. They are maintained at this temperature for up to six hours according to the depth of case hardening required. When carburising is complete, the components are either quenched or allowed to cool slowly in the box. The pack carburising process is illustrated in Fig. 4.18.

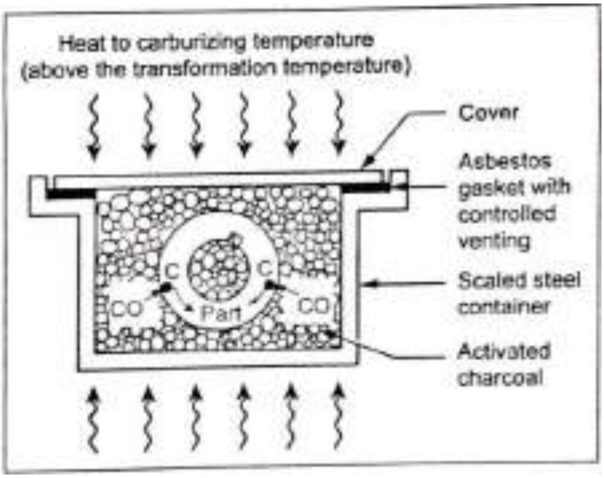


Fig. 4.18 Pack carburising

During the process of carburizing, the $BaCO_3$ splits up. At high temperature, the following reactions take place:

$BaCO_3$ decomposes and to give CO to steel surface.

$$BaCO_3 \rightarrow BaO + CO_2$$

$$CO_2 + C \rightarrow 2CO$$

Carbon reacts on surface of steel

$$2CO + Fe \rightarrow Fe(C) + CO2$$

The carbon dioxide formed in step in this reaction reacts with the carbon in the coal.

$$CO_2 + C \rightarrow 2CO$$

Generally, carburizing time varies from 4 to 8 hours and case depth obtained varies from 1 to 3 mm.

4.11.1.2 Gas Carburizing

This is the most widely used method of carburizing. The gaseous hydrocarbons most widely used in gas carburizing are natural gas (methane), town gas and any other gas containing CO and hydrocarbons which decompose at red heat and deposit the carbon on the surface of the steel. The thickness of the case formed depends upon the rate of flow of the gases into the retorts and also upon the temperature. It is carried out in a closed-type furnace. These furnaces are gas fired or heated electrically and the temperature varies from 900°C to 950°C. A mixer of propane or methane with air is injected to hot chamber to form a gas. The approximate compositions of this gas are N_2—40%, H_2—7.5%, CO—20%, water vapour—7.5% and O_2—balanced.

Carburizing occurs mainly due to conversion of CO to CO_2. That is,

$$2CO \rightarrow CO_2 + C$$

$$C + Fe \rightarrow Fe(C)$$

In gas carburizing, the overall time taken for the whole cycle including packing, charging, etc. is very much shorter. More uniform results with regard to case depth are obtained.

4.11.1.3 Liquid Carburizing

In solid carburizing, time is excessively long and uniform depth of penetration by the carbon is not always assured. Hence, the alternative process of liquid carburizing is adopted. It is also known as salt bath carburizing. In this process, carburizing occurs through molten cyanide. The bath contains NaCN or KCN and $BaCl_2$, which acts as a catalyst. Low-carbon steels are heated between 900°C and 910°C and reactions in cyanide bath are as follows:

$$BaCl_2 + NaCN \rightarrow Ba\,(CN)_2 + NaClO$$

$$Ba\,(CN)_2 + Fe \rightarrow Fe(C) + Ba\,(CN)_2$$

In this heating, time is short and the clean hardened layer is up to 3 mm thickness.

4.11.2 Nitriding

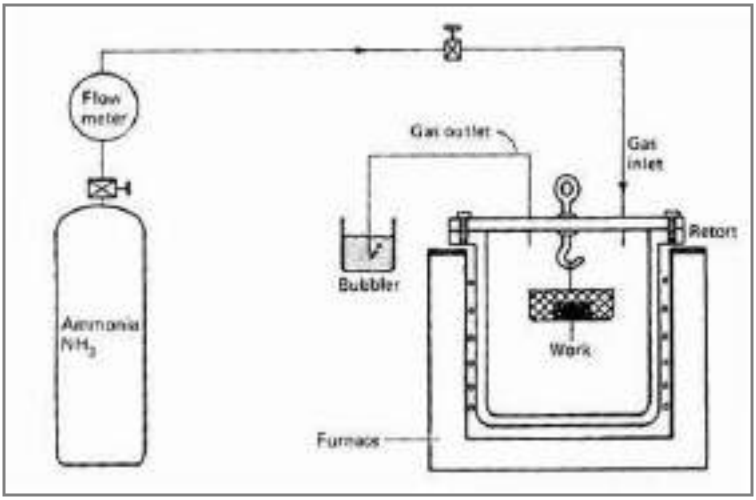


Fig. 4.19 Schematic of gas nitriding system

Nitriding can be defined as a surface hardening in which the special alloy steel is heated in the atmosphere of gaseous nitrogen. The process consists of heating the finished machined articles in a closed container into which the ammonia gas is forced under pressure at a temperature of about 450°C–540°C. The ammonia gets dissociated into nitrogen and hydrogen. The nitrogen then combines with the surface layer of steel to form complex nitrogen compounds with iron and other elements present in the steel. Nitriding is carried out in a ferritic region, i.e., NH_3 gas is passed into the furnace at 550°C where it dissociates into nitrogen and hydrogen.

$$2NH_3 \rightarrow 3H_2 + 2N$$

Nitrogen is readily absorbed by the surface of steel. The treatment time varies from 90 to 110 hours. After nitriding, the steel components are allowed to cool or quenched

But nitriding is done on finished articles. Nitriding is a very costly process and is resorted to for the following purposes:

1. To get a really super-hard-wearing surface
2. To resist corrosion
3. Where resistance to softening of the hardened surface at elevated temperatures is desired, as in the case of parts used for steam turbines, aircraft engines, etc.

A typical basic nitriding setup is illustrated in Fig.4.19

The hardness obtained in nitriding is the highest that can be obtained in all the known methods of heat treating steel.

4.11.3 Cyaniding

This is a process of introducing both nitrogen and carbon on the surface of low-carbon steel components. It is carried in a liquid bath of solid cyanide (NaCN). Here the steels are heated up to about 800°C in a molten sodium cyanide bath for a period of 30 min to 3 hours depending upon the thickness required. At this temperature, sodium cyanide dissociates to give carbon and nitrogen in the atomic form, which goes in to the surface of the steel component.

The basic reactions in the bath are as follows:

$$2NaCN + O_2 \rightarrow 2NaCNO$$

$$2NaCNO + O_2 \rightarrow Na_2CO_3 + CO + 2N$$

$$2CO \rightarrow CO_2 + C$$

Quenching completes the formation of hard, wear-resistant case with a relatively soft core. The cyanide bath consists of 30% NaCN, 40% NaCO and 30% NaCl. A case depth of up to 2.5 mm is obtained.

4.11.4 Carbonitriding

As we know, in the carburising process the diffusing hardening element is carbon. In nitriding process, the diffusion involves nitrogen. As the name suggests, carbonitriding is a surface- hardening process that involves the diffusion of both nitrogen and carbon into the steel surface. Carbonitriding is also known as gas-cyaniding or dry-cyaniding, because it makes use of a mixture of hydrocarbons and ammonia.

The carbonitriding process is carried out in a gas-atmosphere furnace using a carburising gas such as propane or methane mixed with the ammonia. The organic gas serves as the source of carbon and the ammonia gas serves as the source of nitrogen. The workpiece is heated to 850°C in the mixture of above gases for 2 to 10 hours.A typical carbonitriding system is illustrated in Fig.4.20.

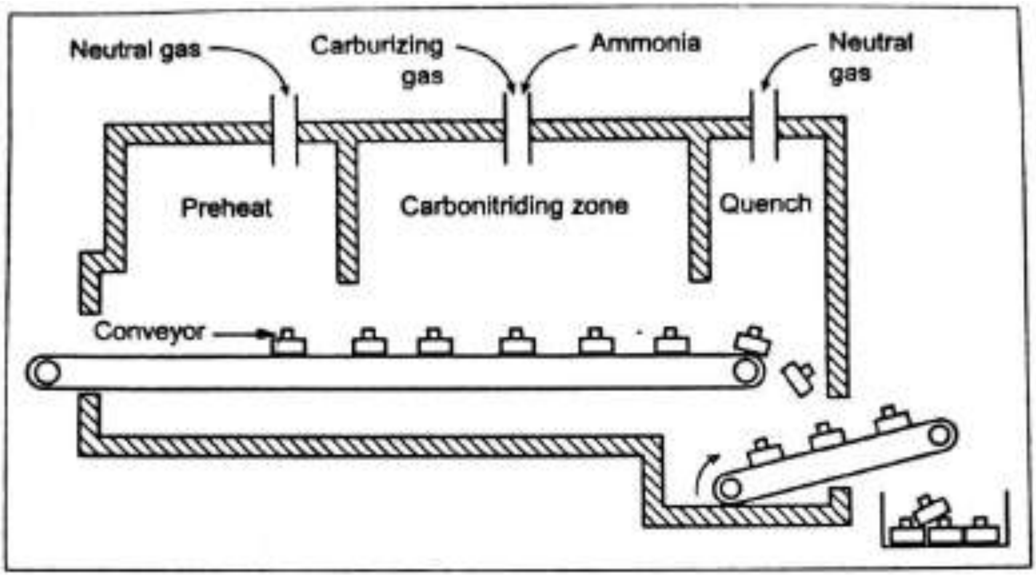


Fig. 4.20 Carbonitriding Process

4.12 Method in which Only Surface of Component is heated

In this method, only the surface of steel components is heated to temperatures above the upper critical temperature and is suddenly quenched to get martensite on the surface which gives higher hardness. The following two methods employ local heating:

1. Flame hardening
2. Induction hardening

4.12.1 Flame hardening

- Flame hardening is the process of selective hardening with a combustible gas flame as the source of heat for austenitizing

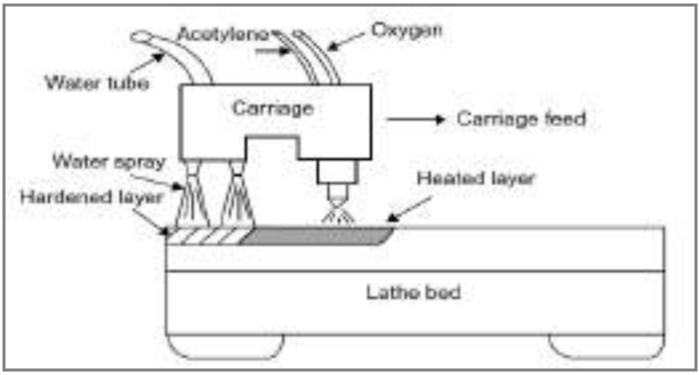


Fig. 4.21 Flame hardening process for lathe bed

It is the simplest form of surface hardening treatment. Localized surface hardening can also be achieved in medium high carbon steel and by rapid local heating and quenching. Figure 4.21 shows the principle of flame hardening.Thus, the surface of work piece is heated and quenched before its core can rise to the hardening temperature. This process is known as flame hardening treatment.

4.12.2 Induction Hardening Process

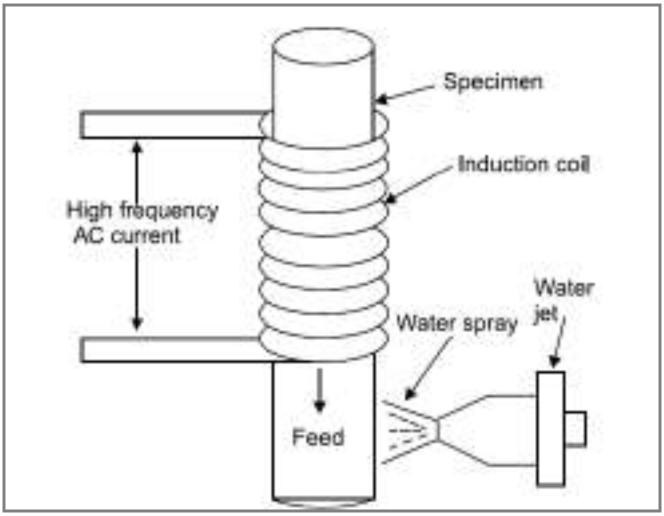


Fig. 4.22 Induction hardening process for small shaft

- The mechanism and purpose of induction hardening are same as for flame hardening. The main difference is that in induction hardening the source of heat input is an induced electric current instead of using a flame.
- In other words, the induction hardening is a process of selective hardening using resistance to induced eddy currents as the source of heat.

Figure 4.22 shows the induction hardening of steel shaft. Induction hardening process may be used for local surface heat treatment. Generally, it is used to surface harden the crank shafts, gears, etc. In this process, heating of the component is achieved by electromagnetic induction. Induction coil is connected to a high frequency AC current, which induces high frequency, eddy current in the component causing it to become hot. When the hardening temperature has been reached, water spray quenches the component. The induction coil can be made from copper tube, which also carries quenching water. In induction hardening process, the component is heated usually for a few seconds. Due to quenching, a martensite structure is formed which makes the outer surface hard and wear resistant. Here a very close control can be exercised on the depth of hardness required which is one of the major advantages of this process over flame hardening.

UNIT-V-TESTING OF MECHANICAL PROPERTIES

5.1 DEFORMATION OF METALS

In the mechanical working on metals, numerous metallic shapes are formed by different processes to form proper shapes and dimensions. The different processes used are rolling (for rails, beams, plates, etc.), forging (for crankshafts, axles), spinning or drawing (for tanks, tubes and other light shapes),extrusion (for rods, tubes, etc.), machining, etc. The basic reasons for the use of metallic substances as materials of construction are due to the property of plastic flow or the ability of the solid material to be permanently deformed without rupture. The deformation of metals is necessary to form various metallic shapes without rupture.

Deformation often referred to strain, is the change in the size and shape of an object due to the change in temperature or an applied force. Depending on the size, material and the force applied, various forms of deformation may occur. Based on these factors, deformation is classified into the following:

- **Elastic Deformation** – The deformation caused is reversible, and the deformation disappears after the removal of applied forces. A classic example of elastic deformation is the stretching of a rubber band.
- **Plastic Deformation** – The deformation is irreversible and it stays even after the removal of the applied forces. Example, bending of steel rods.

5.2 MECHANISM OF PLASTIC DEFORMATION

Plastic deformation is defined as a process in which the object due to applied force changes its size or shape in a way that is not reversible. Plastic deformation is seen in many objects, including:

- Plastics
- Metals
- Soils
- Rocks
- Concrete

The mechanisms that cause plastic deformation differ widely. Plasticity in metals is a consequence of dislocations while in brittle materials such as concrete, rock and bone, plasticity occurs due to the slippage of micro cracks. There are two prominent mechanisms of plastic deformation in metals and they are

- Slip
- Twinning

5.2.1 Deformation by Slip

Slip is the prominent mechanism of deformation in metals. A slip involves the sliding of blocks of crystal over one another along different crystallographic planes known as slip planes. The particular crystallographic planes are called slip planes and the preferable direction is called the slip direction. There are one or more slip planes and one or more- slip directions in each crystal.

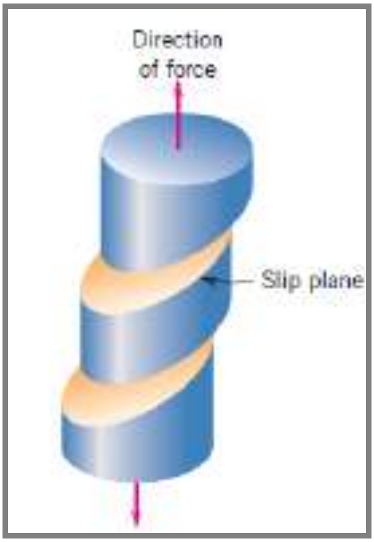


Figure 5.1 Slip in a single crystal

5.2.1.1 Mechanism of Slip

- The slip occurs by translatory motion along sliding planes and rotation of the specimen.
- Fig.5.2 illustrates the mechanism of slip.
- Fig.5.2 (a) depicts the layers of planes of an ideal crystal. Let us consider the shear stress acting on the crystal, as indicated by the arrows.
- When the shear stress exceeds the critical value, then the slipoccurs, as shown in Fig.5.2 (b).

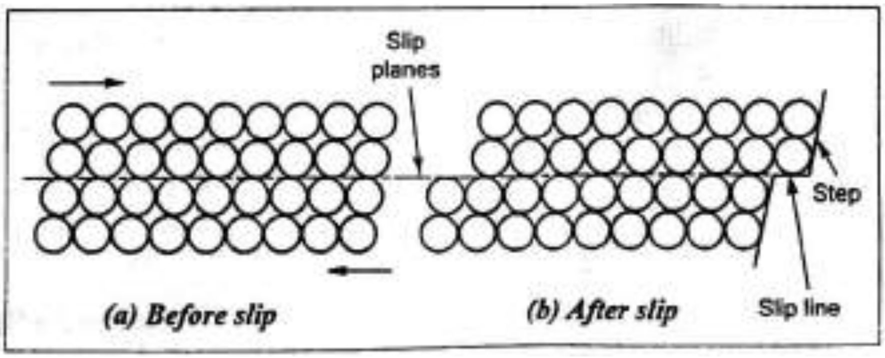


Figure 5.2 Mechanism of Slip

- It is experimentally proved that the mechanism of slip is actually due to the movement of dislocations in the crystal lattice.
- The Energy of a dislocation line is given by the relation

$E \alpha G . 1 . b^2$ …… (5.1)

G = Shear modulus

l = Length of dislocation line

b = Unit slip vector, also known as Berger’s vector

5.2.1.2 Critical Resolved Shear Stress for Slip

- The extent of slip in a single crystal depends on the magnitude of the shearing stress produced by external loads, the geometry of the crystal structure, and the orientation of the active slip planes with respect to the shearing stresses.
- Slip begins when the shearing stress on the slip plane in the slip direction reaches a threshold value called the critical resolved shear stress.

Consider a cylindrical single crystal subjected to an axial load as shown in Fig.5.3.

Let P = Axial load applied along the crystal axis

A = Area of cross-section of the crystal

ϕ = Angle between the normal to the slip plane and the tensile axis

λ = Angle which the slip direction makes with the tensile axis

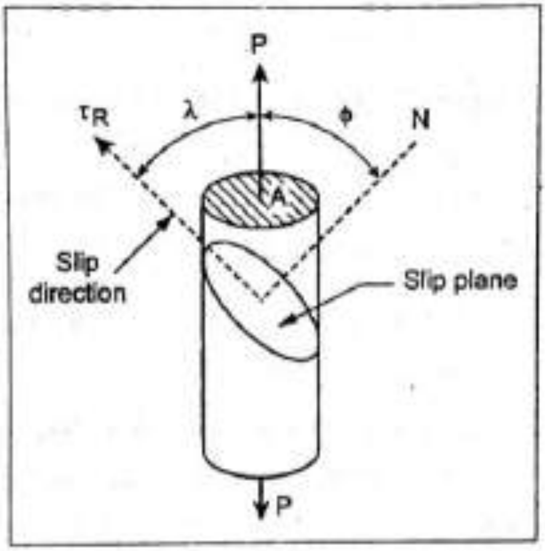


Figure 5.3 Cylindrical single crystal subjected to an axial load

The area of the slip plane inclined at the angle ϕ = $\frac{A}{\cos\phi}$

The component of the axial load acting in the slip plane direction = P cos λ

Critical resolved shear stress = $\frac{\text{Load}}{\text{Area}}$

$$\tau_{cr} = \frac{P\cos\lambda}{A/\cos\phi} = \frac{P}{A}\cos\phi\cos\lambda$$

$$\tau_{cr} = \sigma\cos\phi\cos\lambda \qquad \text{…... (5.2)}$$

Where σ = Applied tensile stress = $\frac{P}{A}$

- The stress required at a given temperature to initiate slip in a pure and perfect single crystal, for a material is constant. This is known as Schmid's Law.
- In equation (5.2), the term 'cosϕ cos λ' is known as the Schmid's factor.

5.2.2 Deformation by Twinning

- The second important mechanism by which metals deform is the process known as twinning.

- Twinning is the process in which the atoms in a part of a crystal subjected to stress, rearrange themselves so that one part of the crystal becomes a mirror image of the other part.

- Like slip, twinning almost takes place in special planes called twinning planes.

- In most plastic deformation, twinning is relatively insignificant, but it may have considerable influence on the total amount of deformation.

- It should be noted that twinning differs from slip in that everyplane of atoms suffers some movement, and the crystallographic orientations of many unit cells are altered.

5.2.2.1 Mechanism of Twinning

- Fig.5.4 (a) depicts the arrangement of atoms before twinning.

- Fig.5.4 (b) depicts the arrangement of atoms after twinning. In Fig.5.4 (b), the planes AB and CD are known as twining planes.

- The crystals twin about the twinning planes. The twinning occurs due to the growth and movement of dislocations in the crystal lattice.

- It can be noted from the Fig.5.4 (b) that the arrangement of atoms on either side of the twinning planes remain unaffected

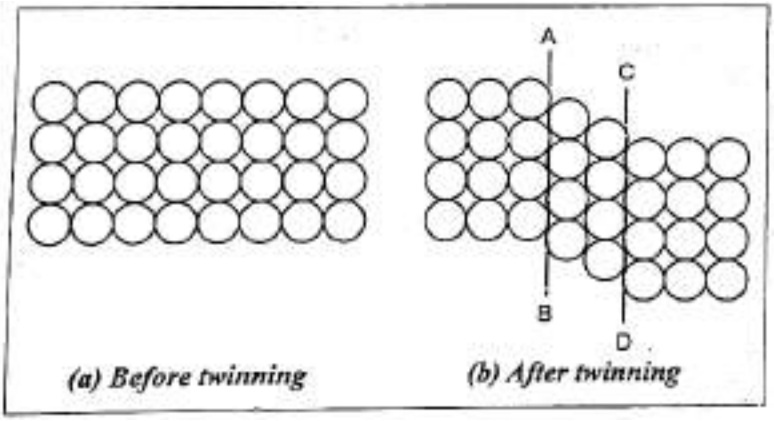


Figure 5.4 Mechanism of twinning

5.2.2.2. Types of Twins (Causes of Twins)

Two types of twins are:

1. Mechanical twins:
    - Twins that are produced by mechanical deformation are called mechanical twins.
    - Mechanical twins are produced in BCC or HCP metals, under the conditions of decreased temperature and shock loading.
2. Annealing twins:
    - Twins that are produced by annealing are called annealing twins.
    - Most of FCC metals form annealing twins.

5.3 SLIP VS TWINNING

S.No.	Slip	Twinning
1	Occurs in discrete multiples of atomic spacing	The movement of atoms is lesser in atomic spacing
2	The orientation of the crystal above and below the slip plane is the same after deformation as before.	Orientation difference takes places across the twin plane
3	Occurs over a wide plane	Every atomic plane is involved
4	Slip occurs when shearing stress on the slip plane in the slip direction strikes a threshold value known as the critical resolved shear stress.	No critical resolved shear stress for twinning.
5	Takes places in several milliseconds	Takes place in few microseconds
6	Slip lines are present in even or odd numbers	Twin lines occur in pair

Table 5.1 Slip Vs Twinning

5.4. FRACTURE AND ITS PREVENTION

5.4.1. Fracture

- Fracture is the mechanical failure of the material which will produce the separation or fragmentation of a solid into two or more parts under the action of stresses.

- The understanding of various phenomenons of fracture is necessary to minimise and prevent the fracture.

5.4.2. Cause of Fracture

The fracture is caused due to the presence of sub microscopic defects known as cracks. Then the initial crack is propagated to cause complete failure.

5.4.3. Types of Fractures

1. Brittle fracture
2. Ductile fracture,
3. Fatigue fracture, and
4. Creep fracture

5.5. BRITTLE FRACTURE

- Brittle fracture defined: A brittle fracture may be defined as a fracture which takes place by the rapid propagation of crack with a negligible deformation.
- It may be noted that in amorphous materials such as glass, the fracture is completely brittle whereas in crystalline materials, the fracture occurs after a small deformation.

5.5.1. Mechanism of Brittle Fracture: Griffith's Theory

5.5.1.1. Introduction

It is proved that the stress at which a material fractures is far below the lower value of the ideal breaking strength calculated from the atomic strength. In other words, the fracture strength of real materials is far lower than (about 104 MPa) the theoretical minimum value foran ideal solid.

5.5.1.2. Griffith Theory

- In a brittle material, there are many fine cracks. These cracks concentrate the applied stress at their tips or ends.
- When the stress at the tips of a crack exceeds the theoretical stress values, the crack expands and fracture occurs.

5.5.1.3. Explanation of Mechanism of Brittle Fracture

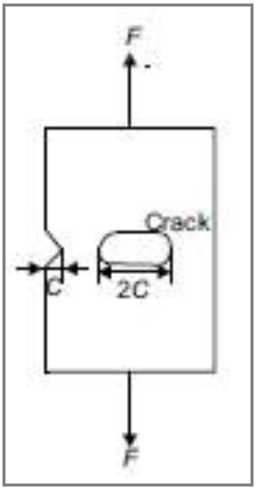


Figure 5.5 Griffith's model for brittle fracture

The brittle fracture occurs with little or no plastic deformation. Crack appears suddenly and the metal gets fractured at unpredictable stress level. Griffith proposed a model, as shown in Figure 5.5, for understanding the discrepancy between the theoretical strength and the actual fracture strength of thebrittle material. He assumed that the brittle materials will contain a number of fine cracks which act as a notch to raise the stress due to the stress concentration. When a metal is stressed under tensile stress, then theoretical cohesive strength can be attained at this localized area with this stress concentration. `The theoretical cohesive strength is reached at these regions even at a nominal stress which is well below the theoretical value of the cohesive strength.

Griffith established the following criteria for the propagation of crack, 'A crack will propagate when the increase in elastic strain energy is at least equal to the energy required to create a new crack surface.' In this theory, the energy method is employed to estimate the stress necessary to cause the crake propagation.

The elastic strain energy per unit volume is given by

$$U_e = -\frac{\sigma^2}{E} \times Width \times Area$$

$$U_e = -\frac{\sigma^2}{E} \times 2C \times \pi C = -\frac{2\pi C^2 \sigma^2}{E}$$

where σ is the tensile stress acting normal to crack and E is the Young's modulus. Here, negative sign indicates decrease in the elastic strain energy.

The surface energy of the flat crack of length 2C and that of unit width is

$$U_s = (2\gamma C)\,2 = 4\gamma C$$

Where γ is surface energy per unit area of crack surface. This equation is multiplied by 2 because there are two new crack surfaces.

Applying Griffith's criteria, if the crack is to propagate in length, it does not change the net energy of the system. In addition to this, it will propagate and produce brittle fracture. The total energy change during the process is

$$U = U_e + U_s$$

$$U = -\frac{2\pi C^2\sigma^2}{E} + 4\gamma C$$

To know the maximum stress at which the crack begins, differentiate the above equation and equate it to zero.

$$-\frac{d\left(\frac{2\pi C^2\sigma^2}{E}\right)}{dc} + \frac{d(4\gamma C)}{dc} = 0$$

$$\frac{2\pi\sigma^2 C}{E} = 4\gamma$$

$$\sigma^2 = \frac{2\gamma C E}{\pi C^2}$$

$$\sigma = \sqrt{\frac{2\gamma E}{\pi C}}$$

The above equation shows that the stress necessary to cause brittle fracture and limitation of Griffith's theory is applicable only for brittle fracture. It can be seen from this equation that the stress required to fracture a metal is lower if the existing crack is longer and the energy consumed in plastic deformation is smaller. It is believed that in some cases, micro-cracks exist in the metal due to solidification or hot working. Such cracks will accumulate as barriers to dislocation movement. They, in turn, propagate and contribute brittle failure. The increase in the work temperature promotes plastic deformation making the metal ductile.

5.6. DUCTILE FRACTURE

- ❖ Ductile fracture defined: Ductile fracture may be defined as the fracture which takes place by a slow propagation of crack with appreciable plastic deformation.

- When a ductile specimen is subjected to tensile stress, the stress-strain curve can be
obtained as shown in Fig.5.6.
- In Fig.5.6, at point F the fracture takes place.

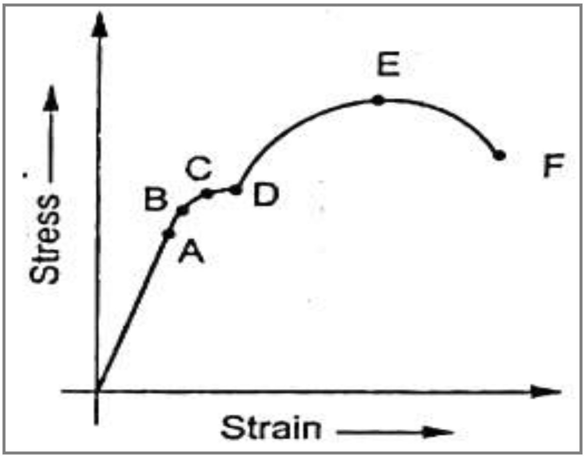


Figure 5.6.Ductile Fracture

.5.6.1. Mechanism of Ductile Fracture

- The various stages in the development of a ductile fracture, also called cup-and-cone fracture is shown in Fig.5.7.
- Fig.5.7 (a) indicates the formation of a neck, when a ductile specimen is subjected to tensile stress. When the tensile stress is increased beyond the ultimate tensile stress (i.e., at point E in Fig.5.6), a neck is formed in the specimen.
- The continuation of the plastic deformation produces many fine cavities in the specimen, as shown in Fig.5.7 (b).
- Under continued straining, these cavities grow and form central crack, as shown in Fig.5.7 (c).
- The crack grows in a direction perpendicular to the axis of the specimen until it approaches the surface of the specimen. It then propagates to the surface of the specimen to form the cone part of the fracture, as shown in Fig.5.7 (d).
- The central “cup' region of the fracture has a very fibrous appearance, as shown in Fig.5.7.

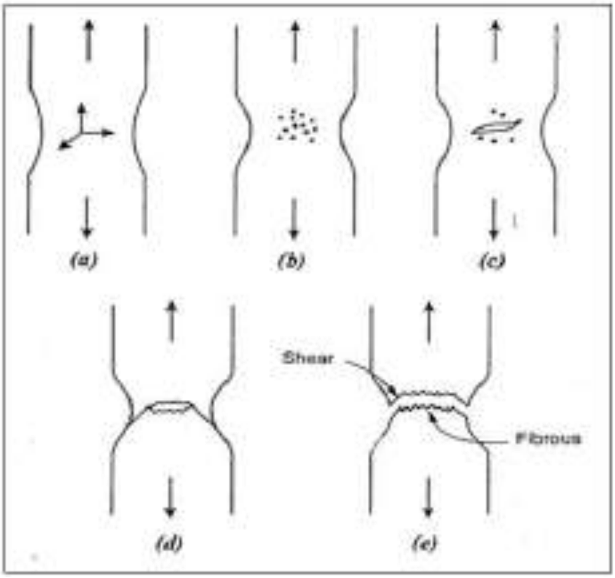


Fig.5.7. Stages in the formation of a cup-and-cone fracture

5.6.2. Brittle Fracture Vs Ductile Fracture

S.No.	Brittle fracture	Ductile fracture
1	It occurs with negligible plastic deformation.	It occurs with large plastic deformation.
2	The rate of crack propagation is rapid.	The rate of crack propagation is slow.
3	It occurs at the point where micro crack is more	It occurs in some localised region where the deformation is very large.
4	Failure is due to the direct stress.	Failure is due to the shear stress.
5	It is characterised by separation of normal to tensile stress	It is characterised by the formation of cup and cone.

Table.5.2 Comparison between brittle and ductile fractures

5.6.3. Prevention of Ductile Fracture

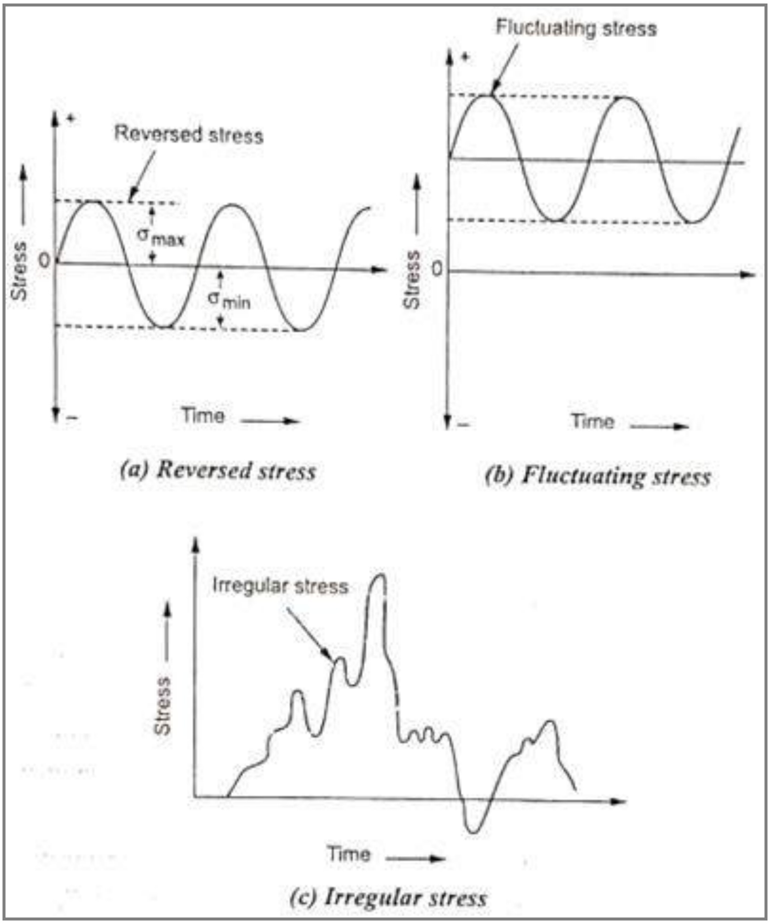
- The material should have fine grains.
- It should have higher hardness value.
- It should have higher Young's modulus and cohesive energy.
- It should not have any defects/dislocations.

5.7. FATIGUE FRACTURE

- *The fatigue fracture is defined as the fracture which takes place under repeatedly applied fatigue stresses.*

Stress Cycles

- Fig.5.8 (a) shows the arrangement of the reversed stress.
- Fig.5.8 (b) shows the arrangement of the fluctuating stress.
- Fig.5.8. (c) shows the arrangement of the irregular stress.



(a) Reversed stress *(b) Fluctuating stress*

(c) Irregular stress

Fig.5.8. Stress cycles for fatigue loading

Mechanism of Fatigue Fracture

- Fatigue fracture begins at irregularities on the surface imperfections such as machine marking and slip steps. The nucleation of micro crack is due to the slip movements. The slip movement starts within few cycles of loading. The micro cracks act as the points of stress concentration.

S-N Diagram

The S-N diagram can be obtained by plotting the number of cycles of stress reversals (N) required to cause fracture against the applied stress level (S),

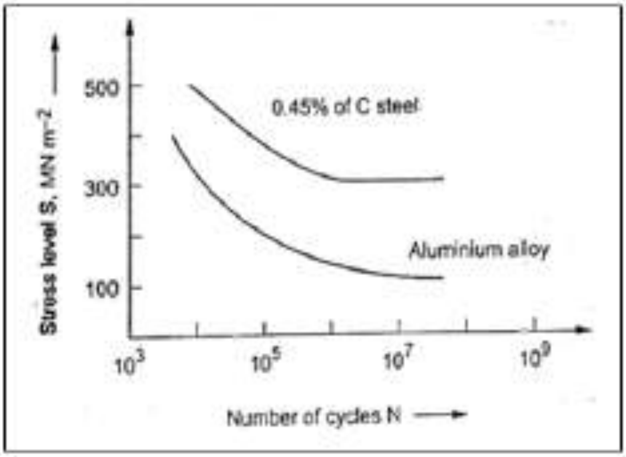


Fig.5.9.The S-N curves for different materials.

Factors Affecting Fatigue Strength

1. Fatigue strength is influenced by many factors such as chemical composition, grain size, and amount of cold working.
2. Fatigue strength is high at low temperatures and gradually decreases with rise in temperature.
3. Environmental effects such as corrosion of the product by moisture decreases the fatigue strength.
4. The design of the product also influences the fatigue strength. Because changes in shape/size may change the stress gradients and residual stresses of the materials.

Prevention of Fatigue Failure

The following methods can be adopted to prevent the fatigue failure.

1. Use of good design to avoid stress concentration by eliminating sharp recesses and severe stress raisers.

2. Control of the surface finish by avoiding damage to surface machining, punching, stamping, shearing, etc.
3. Reduction of corrosion environmental effects by surface heat treatments like polishing, coating, carburizing, nitriding, etc.
4. The material should have fine grain structure and also it should be free from residual stresses and dislocations.

5.8. CREEP

The creep is defined as the property of a material by virtue of which it deforms continuously under a steady load.

The property of creep is important in :

(a) The soft metals used at about room temperature such as lead coverings on telephone cables and white metal bearings.

(b) The metals used at high temperature such as furnace parts, turbine blades, pressure vessel parts, rocket and missiles, supersonic jets, etc.

- When a material is subjected to a constant loading, then the time-dependent strain occurring under the constant stress is known as creep.
- Some materials such as zinc, lead and tin creep more at room temperature. Some other materials such as iron, nickel, and copper creep more at elevated temperatures only.

5.8.1. Creep Curve

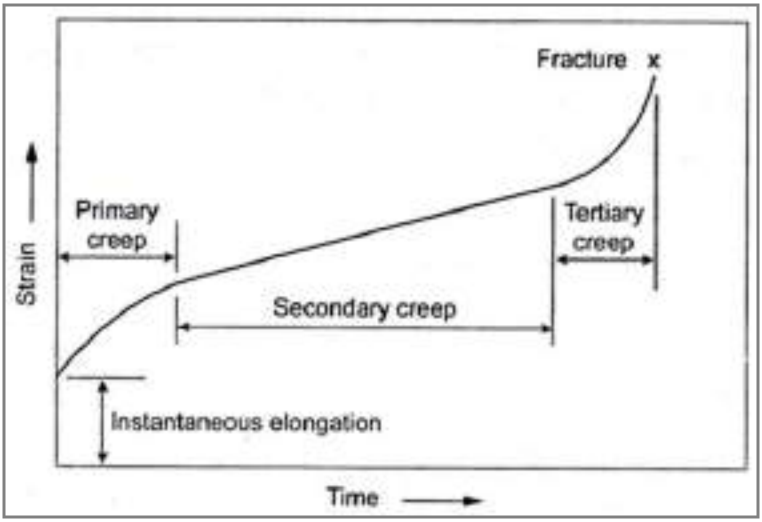


Fig.5.10.Creep curve for a long time, and high temperature

A creep curve is a plot of the creep strain versus the time taken to fracture the specimen. The plot is obtained by conducting creep test. During the test, the creep strain at various time intervals is measured and plotted as a function of elapsed time. The curve drawn between the total creep deformation and the time duration is shown in Figure 5.10. The creep curve shows the three stages of the creep—primary, secondary and tertiary. These stages are identified based on the deformation behaviour of the metal with time.

5.8.2. Different Stages in Creep Curve

1. **Primary Creep**

   The stage of the creep during which the creep rate decreases with time due to the work hardening (strain hardening) because of the plastic deformation is called primary creep. It usually occurs in the elastic region of the material. This creep is also called transient creep or cold creep. The material can revert to its original dimensions if it is unloaded in this stage.

2. **Secondary or Steady-state Creep**

   The stage of the creep in which the creep rate is minimum is called secondary or steady-state creep. As the rate of creep decreases to an essentially constant value, the metal enters the second stage of creep and this stage is of longest duration in the creep curve. The metal constantly deforms because the rate of re-softening balances the rate of strain hardening. In this stage, a balance exists between the rate of strain hardening and rate of softening due to recrystallization. In this stage, the creep rate is constant and hence, the curve is linear. The second stage of creep is also known as hard creep. The creep deformation at this stage is shown by a steady-state or a constant slope in the curve.

3. **Tertiary or Viscous Creep**

   The tertiary creep is marked by a rapid increase in the creep rate and failure of the specimen for a short duration of time. If the magnitude of constant load and the temperature are sufficiently high, this creep results. In this stage, the creep deformation accelerates as viscous flow until the material is fractured. Failure by creep is usually referred by the term rupture or creep rupture. This is shown by the increasing the slope up to the fracture in the curve.

5.8.3. MECHANISM OF CREEP

The following are the mechanisms that will take place during the process of creep:

1. Climb of dislocation
2. Sliding of grain boundary
3. Diffusion of vacancy

1. Dislocation Climb

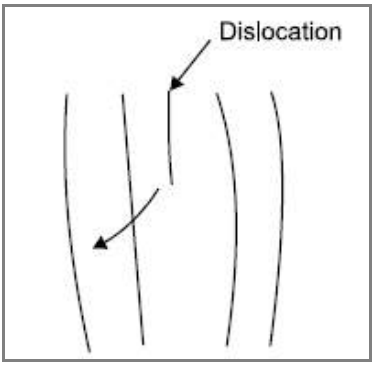


Fig.5.11. Dislocation climb in creep behaviour of metals

At a high temperature, a considerable atomic movement causes the dislocation to climb up or down. In a climb of edge dislocation, there may be diffusion of atoms due to the applied stress. Thus, the edge dislocation is moved from one end to the other and the rate of creep is governed by the rate of escape (movement of) of dislocation beyond the obstacles (see Figure 5.11).

2. Sliding of Grain Boundary

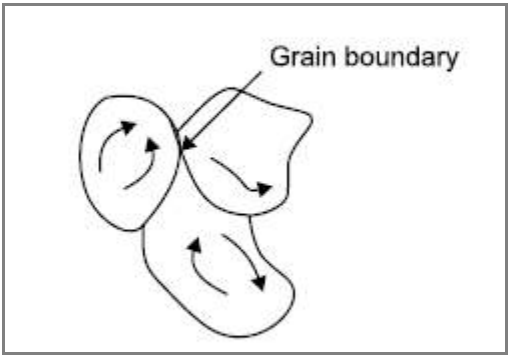


Fig.5.12. Grain sliding in creep behavior of metals

The grain boundaries become soft at low temperatures and at high strength. The grain boundary plays a major role in the creep of polycrystals at high temperature as they slide through each other. At a high temperature, the ductile metals begin to lose their ability to strain harden and become viscous because of sliding of grain boundary (see Figure 5.12).

3. Diffusion of Vacancy

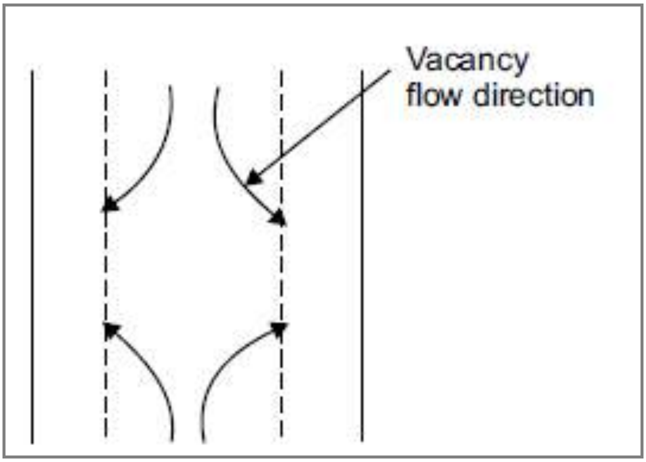


Fig.5.13. Diffusion of atoms in a vacancy mechanism in creep behaviour

In the diffusion of vacancy mechanism, atom vacancies control the creep rate. It depends on the migration of vacancies from one side of the grain to another. Vacancies move in response to the applied stress in the direction as shown in Figure 5.13.

5.9. MECHANICAL TESTS OF METALS

- Testing is an essential part of any engineering activity. Testing is applied to materials, components, and assemblies.
- It consists of measurement of fundamental properties or measurement of responses to particular influences such as load, temperature, and corrodants.
- It can be noted that the tests need to be conducted according to standard procedures so that one can have confidence in published test results.

5.9.1. Classification of Mechanical Tests

Mechanical tests may be grouped into two classes as :

1. Destructive tests, and

2. Non-destructive tests.

5.10. TENSILE TEST

A tensile test of a material is performed on ductile materials todetermine tensile properties such as:

(i) Limit of proportionality,

(ii) Yield point or yield strength,

(iii) Maximum tensile strength,

(iv) Breaking strength,

(v) Percentage elongation,

(vi) Percentage reduction in area, and

(vii) Modulus of elasticity.

The tensile test is usually carried out with the help of a 'Universal Testing Machine' (UTM).

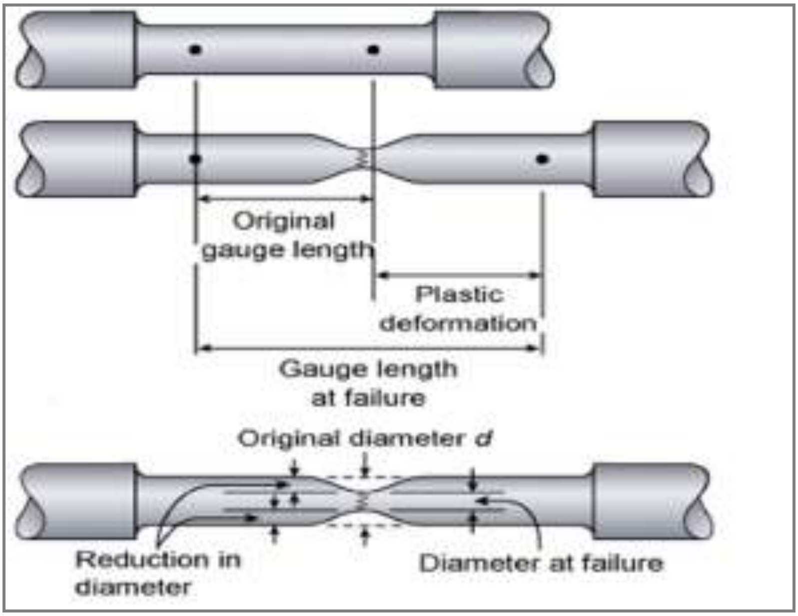


Fig.5.14. Standard tension specimen

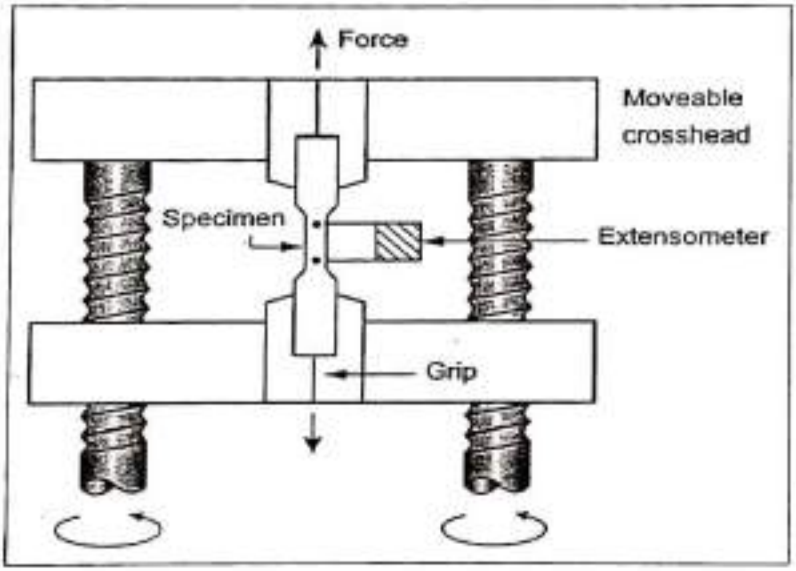


Fig.5.15. Schematic arrangement of a UTM

5.10.1. Testing Procedure

The specimen to be tested is fastened to the two end-jaws of the UTM. Now the load is applied gradually on the specimen by means of the movable cross head, till the specimen fractures.

5.10.2. Stress-Strain Curve

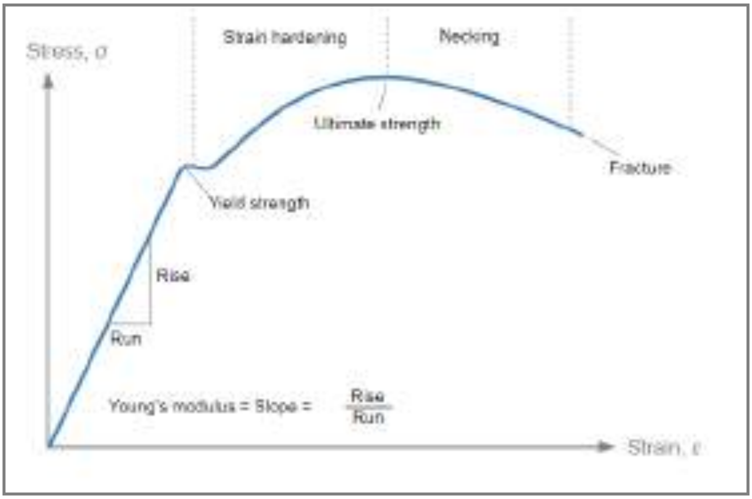


Fig.5.15. Stress-Strain Curve

Stress–strain curve for a material gives the relationship between stress and strain. It is obtained by gradually applying load to a test coupon and measuring the deformation, from which the stress and strain can be determined (see tensile testing). These curves reveal many of the properties of a material, such as the Young's modulus, the yield strength and the ultimate tensile strength.

5.10.3. Results of Tensile Test

1. **Elastic stress (or Elastic strength) (σ_e)**

$$\sigma_e = \frac{\text{Elastic load}}{\text{Original cross} - \text{sectional area}} = \frac{P_e}{A_0}$$

$A_0 = \left(\frac{\pi}{4}\right) D_0^2$

D_0 = Initial diameter of the given specimen.

2. **Strain (ε)**

$$\varepsilon = \frac{\text{Change in length}}{\text{Original length}} = \frac{L_f - L_0}{L_0}$$

where

L_0 – initial gauge length

L_f - final gauge length

3. **Yield stress (or Yield strength) (σ_s)**

$$\sigma_s = \frac{\text{Yield load}}{\text{Original cross} - \text{sectional area}} = \frac{P_s}{A_0}$$

4. **Ultimate stress (or Ultimate tensile strength)**

$$\sigma_u = \frac{\text{Ultimate load}}{\text{Original cross} - \text{sectional area}} = \frac{P_u}{A_0}$$

5. **Percentage elongation**

$$\%\ \text{elongation} = \frac{\text{Final length} - \text{Original length}}{\text{Original length}} \times 100$$

$$= \frac{L_f - L_0}{L_0} \times 100$$

6. Percentage reduction in area

$$\%\ \text{reduction in area} = \frac{\text{Original area} - \text{Final area}}{\text{Original area}} \times 100$$

$$= \frac{A_0 - A_f}{A_0} \times 100$$

7. Young's modulus of elasticity (E)

$$E = \frac{\text{Stress at any point within elastic limit}}{\text{Strain at that point}} = \frac{\sigma_\varepsilon}{\varepsilon}$$

8. Breaking/Fracture stress (or Breaking strength)

$$\sigma_b = \frac{\text{Breaking load}}{Final\ cross - sectional\ area}$$

9. Modulus of toughness

$$\text{Modulus of toughness} = \text{Ultimate tensile strength} \times \%\ \text{elongation}$$

5.10.4. Problems on Tensile Test

Example 5.1 A steel specimen is tested in a standard tension test to evaluate several mechanical properties. The dimensions of the specimen and observations made during the test are given below:

Diameter of the specimen = 12.5 mm

Gauge length = 62.5 mm

Load at yield point =: 41 kN

Maximum load = 72.5 kN

Fracture load = 51.25 kN

Gauge length at fracture = 80.5 mm

Diameter of fracture section = 9.5 mm

Strain at a load of 20 kN = 7.764×10^{-4} mm/mm

Determine:

(a) The yield strength,

(b) The ultimate tensile strength,

(c) The % elongation,

(d) Modulus of elasticity,

(e) % reduction in area,

(f) Fracture stress, and

(g) Modulus of toughness.

Solution:

The original area of cross-section,

$$A_0 = \frac{\pi}{4}(12.5)^2 = 122.72\ \text{mm}^{2\backslash}$$

1. Yield stress (or Yield strength) (σ_s)

$$\sigma_s = \frac{\mathit{Yield\ load}}{\mathit{Original\ cross - sectional\ area}} = \frac{P_s}{A_0} = \frac{41 \times 10^3}{122.72} = 334.1\ N/mm^2$$

2. Ultimate stress (or Ultimate tensile strength)

$$\sigma_u = \frac{\mathit{Ultimate\ load}}{\mathit{Original\ cross - sectional\ area}} = \frac{P_u}{A_0} = \frac{72.5 \times 10^3}{122.72} = 590.77\ N/mm^2$$

3. Percentage elongation

$$\%\ \text{elongation} = \frac{\text{Final length} - \text{Original length}}{\text{Original length}} \times 100$$

$$= \frac{L_f - L_0}{L_0} \times 100 = \frac{80.5 - 62.5}{62.5} \times 100 = 28.8\%$$

4. Young's modulus of elasticity (E)

$$E = \frac{\text{Stress at 20KN}}{\text{Strain at 20KN}} = \frac{\left(\frac{20 \times 10^3}{122.72}\right)}{7.764 \times 10^{-4}} = 2.1 \times 10^5\ N/mm^2$$

5. Percentage reduction in area

$$\%\ \text{reduction in area} = \frac{\text{Original area} - \text{Final area}}{\text{Original area}} \times 100$$

$$= \frac{A_0 - A_f}{A_0} \times 100$$

$$Where, \quad A_f = Area\ of\ fracture\ section$$

$$= \frac{\pi}{4}(9.5)^2 = 70.88\ \text{mm}^2$$

$$\%\ \text{reduction in area} = \frac{122.72 - 70.88}{122.72} \times 100$$

$$= 42.24\%$$

6. Breaking/Fracture stress (or Breaking strength)

$$\sigma_b = \frac{\text{Breaking load}}{Final\ cross - sectional\ area}$$

$$= \frac{51.25 \times 10^3}{70.88} = 723\ \text{N/mm}^2$$

7. Modulus of toughness

$$\text{Modulus of toughness} = \text{Ultimate tensile strength} \times \%\ \text{elongation}$$

$$= 590.77 \times 0.288$$

$$= 170.14\ \text{N/mm}^2$$

5.11. COMPRESSION TEST

A compression test determines behavior of materials under crushing loads. The specimen is compressed and deformation at various loads is recorded. Compressive stress and strain are calculated and plotted as a stress-strain diagram which is used to determine elastic limit, proportional limit, yield point, yield strength and for some materials, compressive strength.

5.11.1. Why Perform a Compression Test?

"Axial compression testing is a useful procedure for measuring the plastic flow behavior and ductile fracture limits of a material. Measuring the plastic flow behaviour requires frictionless (homogenous compression) test conditions, while measuring ductile fracture limits takes advantage of the barrel formation and controlled stress and strain conditions at the equator of the barreled surface when compression is carried out with friction.

Axial compression testing is also useful for measurement of elastic and compressive fracture properties of brittle materials or low-ductility materials. In any case, the use of specimens having large L/D ratio should be avoided to prevent buckling and shearing modes of deformation.

5.11.2. Testing Procedure

For compression tests, specimens are made of cubical or cylindrical shape to avoid eccentric loading. The specimen to be tested is fitted in between compression plates of the universal testing machine. Now the compression load is gradually applied on the specimen and the corresponding reduction in lengths of the specimen are recorded.

Using the recorded values of loads and their corresponding values of change in length, one can find the various compressive properties in the same manner as that of the tensile test.

Axial compression testing is also useful for measurement of elastic and compressive fracture properties of brittle materials or low-ductility materials. In any case, the use of specimens having

5.11.3. Typical Materials

The following materials are typically subjected to a compression test.

- Concrete
- Metals
- Plastics
- Ceramics
- Composites

5.12. SHEAR TESTS

There are two main types of test which may be used for the determination of the properties of a material in shear. They are:

- Test performed using a pure shear force, and
- Test performed using the application of a torque to a cylindrical specimen i.e., torsion test.

5.12.1. Shear Test Using a Pure Shear Force

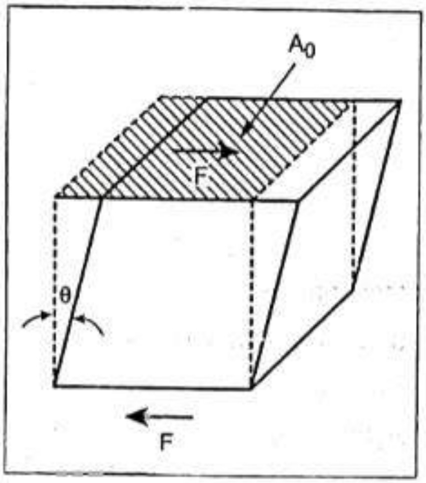


Fig.5.16. Schematic representation of shear strain

Fig.5.16. illustrates the shear test, performed using a pure shear force. In this type, the force is imposed parallel to the upper and lower faces of the body.

Shear stress: The shear stress or shear strength is the value of load applied tangentially to shear it off across the resisting section. Mathematically,

Shear stress, $\tau = \frac{F}{A}$

Where, F = Shear force applied, and

A = Area of shear

Shear strain: The shear strain is defined as the tangent of the strain angle θ.

Shear strain, $\gamma = \tan\theta$

5.12.1.1. Testing Methods

Three main systems used for shear tests are:

- Double shear system for round bar test-pieces using a fork and eye device.
- Double knife shear system for specimens with a rectangular section.
- The shearing of a disc from sheet materials using a punch and die.

The test equipment generally takes the form of attachments which can be used in conjunction with a universal testing machine.

5.12.1.2. Disadvantages

- Always there will be bending of the test-piece, therefore the stresses within the material will not be of the pure shear type, but they include bending stresses.
- Very difficult to obtain accurate quantitative data from them.

5.13. Torsion Test

- Torsion is a variation of pure shear, wherein a structural member is twisted in the manner of Fig.5.17.
- Torsional forces produce a rotational motion about the longitudinal axis of one end of the member relative to the other end.

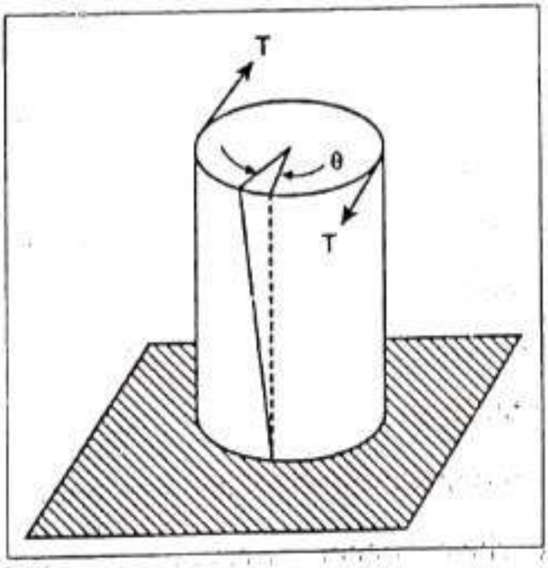


Fig.5.17. Schematic representation of torsional deformation

- To determine the shear strength t, the following general torsion equation can be applied within the elastic range:

$$\frac{\tau}{r} = \frac{T}{J} = \frac{G\theta}{L}$$

T = Shear stress,

r = Radius of the cylinder,

T = Applied torque,

J = Second polar moment of area,

G = Modulus of rigidity of the material,

ϴ =Angle of twist in radians, and

L= Gauge length of the test-piece.

5.14. HARDNESS TESTS

- Hardness may be defined as the ability of a material to resist scratching, abrasion, cutting or penetration.
- The hardness test is performed on a material to know its resistance against indentation and abrasion.

5.14.1. Types of Hardness Tests

1. Brinell hardness test,
2. Vickers hardness test, and
3. Rockwell hardness test.

5.15. BRINELL HARDNESS TEST

- One of the earlier standardised methods of measuring hardness was the Brinell test.
- In the Brinell test, a hardened steel ball indenter is forced into the surface of the metal to be tested. The diameter of the hardened steel (or tungsten carbide) indenter is 10 mm.
- Standard loads range between 500 kg and 3000 kg in 500 kg increments. During a test, the load is maintained constant for 10 to 15 seconds.

5.15.1. Testing Arrangement and Procedure

- A Brinell hardness testing machine is depicted in Fig.5.18.

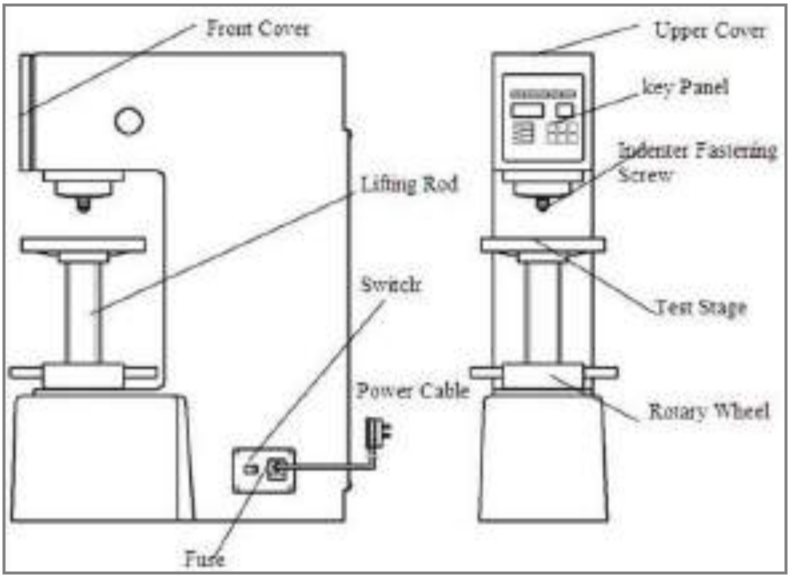


Fig.5.18. Brinell hardness testing machine

The Brinell's hardness test is performed by pressing a steel ball, also known as indenter, into the specimen as shown in Fig.5.19.

The diameter of the resulting impression is measured with the help of a calibrated microscope.

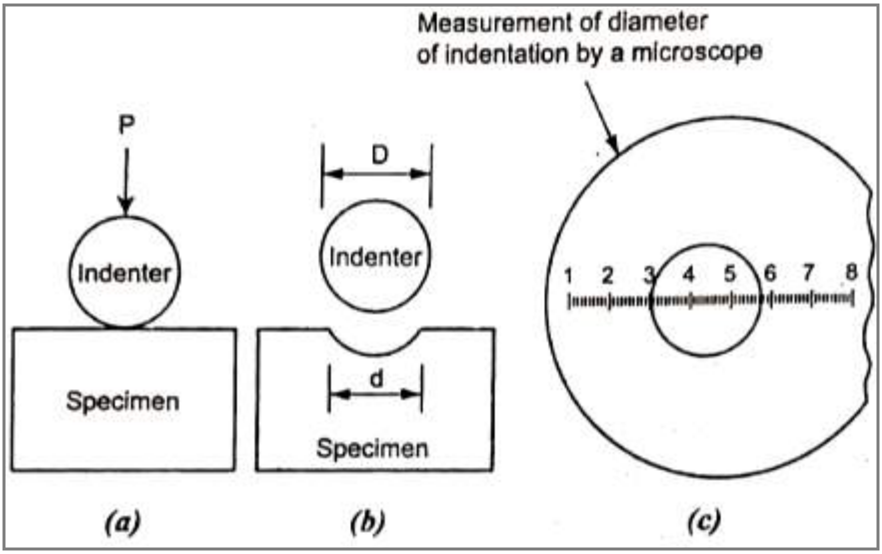


Fig.5.19. Brinell hardness test

- **Brinell hardness number (BHN):** The measured diameter isconverted into the equivalent Brinell hardness number using thefollowing relation.

$$BHN = \frac{\text{Load on the ball}}{Area\ of\ indentation\ of\ steel\ ball}$$

$$= \frac{P}{\frac{\pi D}{2}\left[D - \sqrt{D^2 - d^2}\right]}$$

P = Load applied on indenter in kg,

D = Diameter of steel ball indenter in mm, and

d = Diameter of ball impression in mm.

- If the BHN value is higher, then the material is said to be harder. If BHN is less, then the metal is soft.

5.15.2. Limitations

- It cannot be used on very hard or very soft materials.
- The test may not be valid for thin specimens.
- The test is not valid for case-hardened surfaces.
- The test should be conducted on a location far enough.

5.16. VICKERS HARDNESS TEST

- The Vickers hardness test is similar to the Brinell test, with a square-based diamond pyramid being used as the indenter.
- The Vickers hardness test method consists of indenting the test material with a diamond indenter, in the form of a right pyramid with a square base and an angle of 136 degrees between opposite faces subjected to a load of 1 to 100 kgf. The full load is normally applied for 10 to 15 seconds. The two diagonals of the indentation left in the surface of the material after removal of the load are measured using a microscope and their average calculated. The area of the sloping surface of the indentation is calculated. The Vickers hardness is the quotient obtained by dividing the kgf load by the square mm area of indentation.

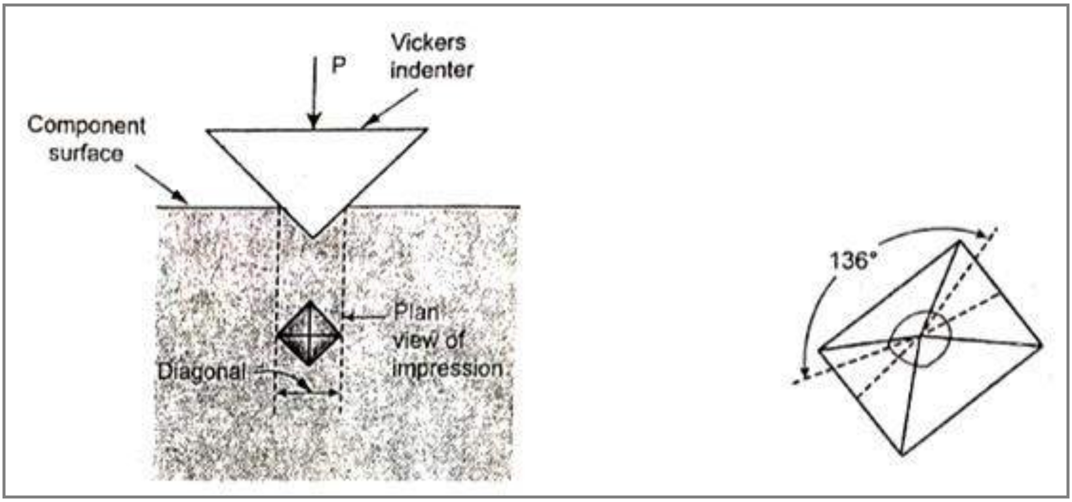


Fig.5.20. Vickers indenter and impression

$$VHN = \frac{\text{Applied load}}{\text{Surface area of impression}} = \frac{2P\sin\frac{\theta}{2}}{D^2}$$

$\theta = 136^0$

$$= \frac{1.8544\,P}{D^2}$$

Where P = Applied load in kg,

θ = Angle between the opposite faces of diamond = 136°,

D = Mean diagonal length in mm.

5.16.1. Advantages of Vickers Hardness Test

The Vickers test has the following advantages over the Brinell test.

1. The diagonals of the square indentation can be measured more. accurately than the diameters of the circles.
2. This method is suitable for hard materials as well as for soft materials.
3. The Vickers indenter is capable of giving geometrically similar impression with different loads. Thus, the hardness number is independent of the load applied.

5.16.2. Limitations of Vickers Hardness Test

The Vickers test has the following limitations.

1. The impression is very small and also it requires careful surface preparation of the specimen.
2. It takes a relatively long time to perform a Vickers hardness test.

5.17. ROCKWELL HARDNESS TEST

- The Rockwell hardness test is probably the most widely used methods of hardness testing.
- The principle of the Rockwell test differs from that of the others in that the depth of the impression is related to the hardness rather than the diameter or diagonal of the impression, as shown in Fig.5.21.
- Rockwell test are widely used in industries due to its accuracy, simplicity and rapidity. In this test; the dial gives a direct reading of hardness; no need for measuring indentation diameter or diagonal length using the microscope.

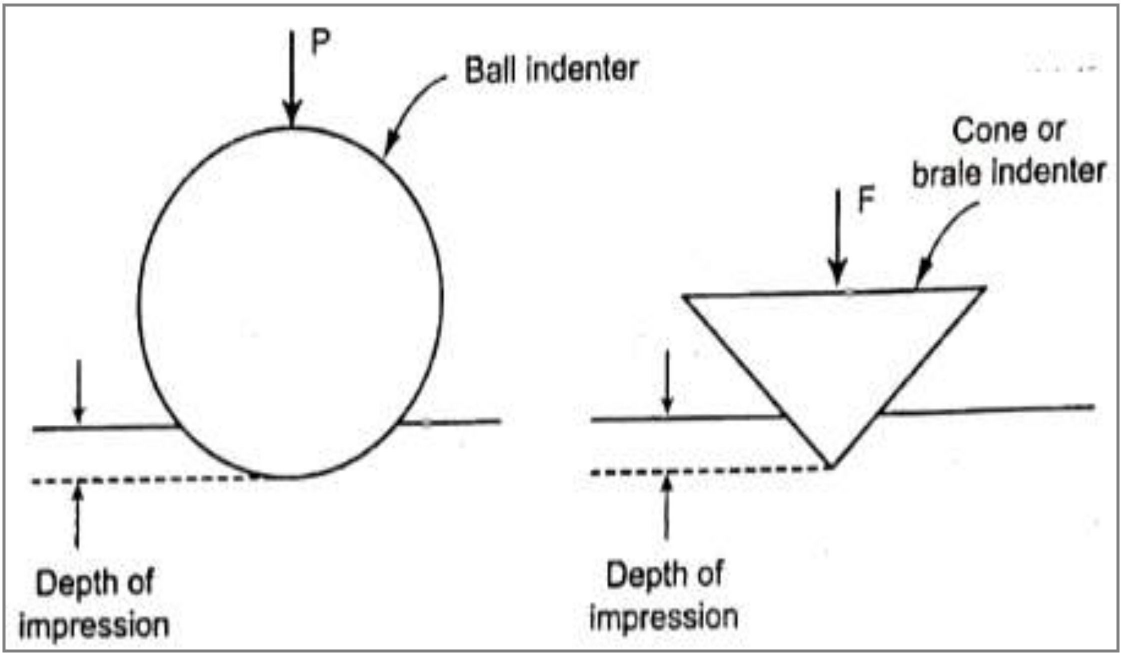


Fig.5.21. Rockwell indenter

5.17.1. Rockwell Scales

1. B-scale (1/16 inch diameter steel ball indenter; 100 kg load), used to measure the hardness (HRB) of non-ferrous metals.

2. C-scale (120° diamond cone indenter, called a BRALE; 150 kg load), used to measure the hardness (HRC) of steels.

Scale	Symbol	Indenter	Total indenting load	Material for which the scale is used
A	HRA	Diamond cone	60 kg	Thin hardened steel strip
B	HRB	$\frac{1}{16}$ inch diameter steel ball	100 kg	Mild Steel and non- heat treated medium carbon steels
C	HRC	Diamond cone	150 kg	Hardened and tempered steels and alloy steels
D	HRD	Diamond cone	100 kg	Case hardened steels
E	HRE	$\frac{1}{8}$ inch diameter steel ball	100 kg	Cast iron, aluminium alloys and magnesium alloys
F	HRF	$\frac{1}{16}$ inch diameter steel ball	60 kg	Copper and brass
G	HRG	$\frac{1}{16}$ inch diameter steel ball	150 kg	Bronzes, gun metal and beryllium copper
H	HRH	$\frac{1}{8}$ inch diameter steel ball	60 kg	Soft aluminium and thermoplastics
K	HRK	$\frac{1}{8}$ inch diameter steel ball	150 kg	Aluminium and magnesium alloys
L	HRL	$\frac{1}{4}$ inch diameter steel ball	100 kg	Thermoplastics
R	HRR	$\frac{1}{2}$ inch diameter steel ball	60 kg	Very soft thermoplastics

Table 5.3. Rockwell hardness scales

5.17.2. Testing Procedure

The step by step procedure for measuring Rockwell hardness is given below:

- The material to be tested is held on the anvil of the machine.

- The test piece is raised by turning the hand wheel, till it just touches the indenter.
- A minor load of 10 kg is applied to seat the specimen. Then the dial indicator is set at zero.
- Now the major load (100 kg for B-scale or 150 kg for C- scale) is applied to the indenter to produce a deeper indentation.
- After the indicating pointer has come to rest, the major load is removed.
- With the major load removed, the pointer now indicates the Rockwell hardness number on the appropriate scale of the dial.

5.17.3. Advantages of Rockwell Hardness Test

The advantages of the Rockwell test are as follows:

1. Very simple to use.
2. Hardness can be read directly in a single step.
3. Each' measurement requires only a few seconds.
4. Since it can be conducted very fast, it is suitable for routine tests of hardness in mass production.
5. It can be used to test materials over a greater range of hardness because of the many combinations of indenters and loads which are available.
6. It can be used on metallic materials as well as on plastics..

5.17.4. Limitations of Rockwell Hardness Test

The Rockwell test is not as accurate as the Vickers test. That's why the Vickers test is usually preferred for research and development works.

5.18. IMPACT TESTS

- The impact test is performed to study the behaviour of materials under dynamic load i.e., suddenly applied load.
- Impact strength defined: The capacity of a metal to withstand blows without fracture, is known as impact strength or impact resistance.

- The impact test indicates the toughness of the material i.e., the amount of energy absorbed by the material during plastic deformation.
- The impact test also indicates the notch sensitivity of a material. The notch sensitivity refers to the tendency of some normal ductile materials to behave like brittle materials in the presence of notches.
- In an impact test, a notch is cut in a standard test piece which is struck by a single blow in a impact testing machine. Then the energy absorbed in breaking the specimen can be measured from the scale provided on the impact testing machine.

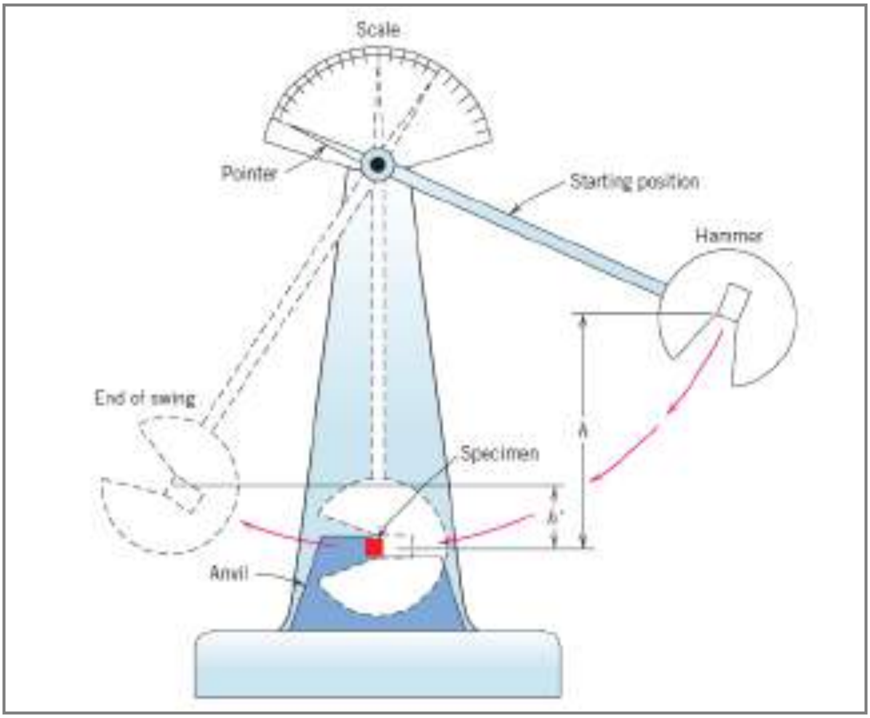


Fig.5.22. Impact testing machine

5.18.1. Types of Impact Tests

Based on the types of specimen used on impact testing machine the impact tests can be classified into:

1. Izod test.
2. Charpy test.

It can be noted that the impact testing machines are designed so that both types of test can be performed on the same machine with only minor adjustments.

5.18.2. Izod Test

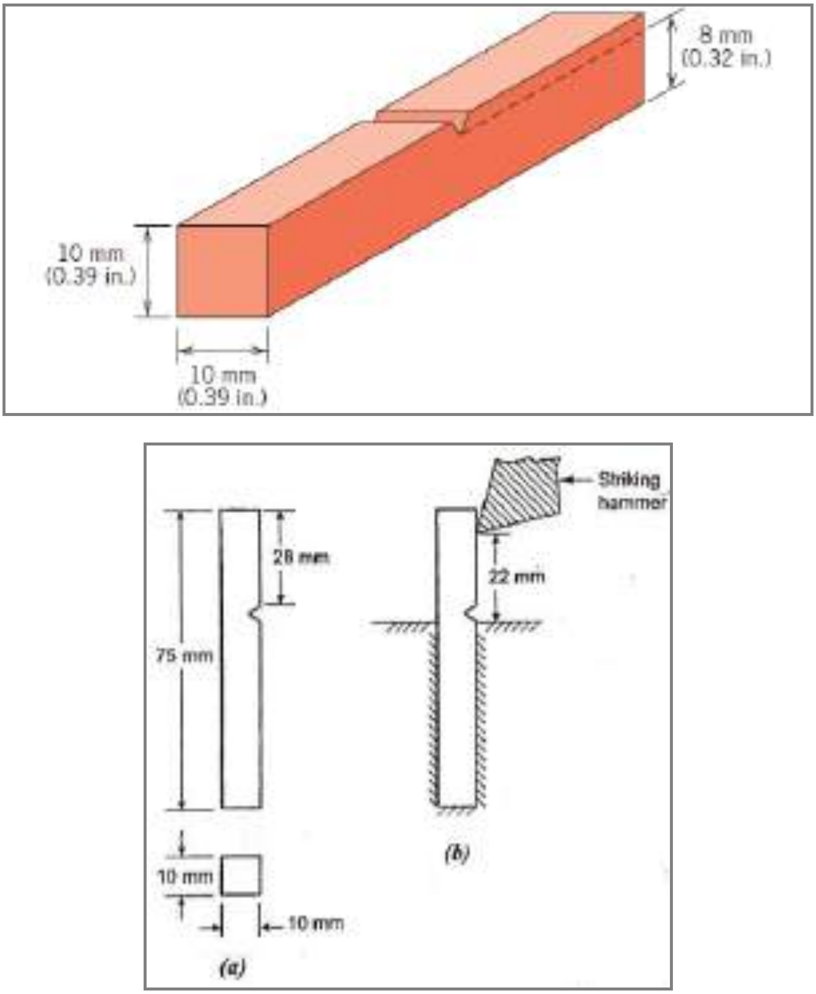


Fig.5.23. Specimen for Izod test

- Izod test uses a cantilever specimen of size 75 mm x 10 mm x 10 mm, as shown in Fig.5.23 (a). The V-notch angle is 45º and the depth of the notch is 2 mm.
- The Izod specimen is placed in the vise such that it is a cantilever, as shown in Fig.5.23 (b).

5.18.3. Charpy Test

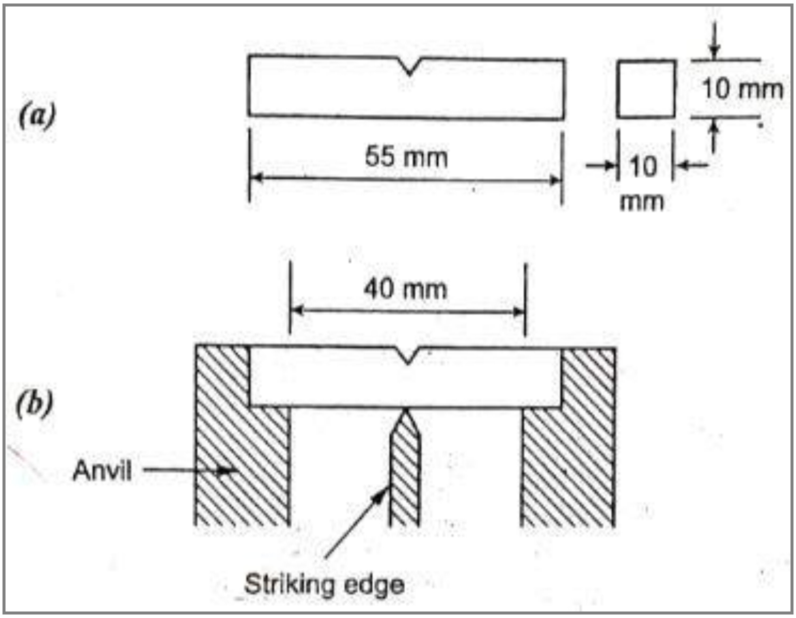


Fig.5.24. Specimen for Charpy test

- The Charpy test uses a test specimen of size 55 mm x 10 mm x 10 mm, as shown in Fig.5.24 (a). The V-notch angle is 45° and the depth of the notch is 2 mm.
- The Charpy specimen is placed in the vise as a simply supported beam, as shown in Fig.5.24 (b).

5.18.4. Testing Procedure

The general procedure to conduct an impact test is given below:

- The specimen is placed in the vice of the anvil.
- The pendulum hammer is raised to known standard height depending on the type of specimen to be tested.
- When the pendulum is released, its potential energy is converted into kinetic energy just before it strikes the specimen.
- Now the pendulum strikes the specimen. It may be noted that the Izod specimen is hit above the V-notch and the Charpy specimen will be hit behind the V-notch.
- The pendulum, after rupturing the specimen, rises on the other side of the machine.

- The energy absorbed by the specimen during breaking is the weight of the pendulum times the difference in two heights of pendulum on either side of the machine.
- Now the energy i.e., the notched impact strength, in foot pounds or metre-kg, is measured from the scale of the impact testing machine.

5.18.5. Calculation

- The energy used in rupturing the specimen in both Izod and Chary tests, using the Fig.5.25, is calculated as given below:

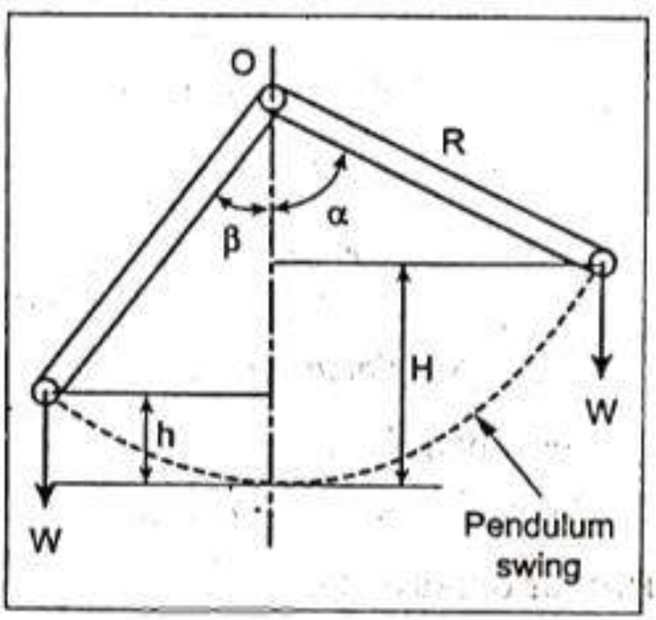


Fig.5.25. Impact test - calculation of energy relations

W = Weight of the pendulum,

α = Angle through which the pendulum falls,

β = Angle through which the pendulum rises,

R = Distance between the centre of gravity of the pendulum and the axis of rotation,

H = Height of fall of centre of gravity of pendulum, and

h = Height of rise of centre of gravity of pendulum after striking specimen.

Initial energy = W.h

= Potential energy

= Kinetic energy of striking specimen

Remaining energy afterstriking specimen = K.E of carrying the pendulum to the lowest position

= W.h

Energy delivered to the specimen = Impact value of energy in fracturing specimen

= W.H – W.h

= W (H – h)

In terms of angles, the energy required to break away the specimen

$$= W\,R(\cos\beta - \cos\alpha)$$

5.18.6. Factors Affecting Impact Strength

The factors affecting the impact strength are:

1. Angle of notch,
2. Shape of notch,
3. Impact velocity,
4. Temperature of the specimen, and
5. Dimensions of notch specimen.

5.19. FATIGUE TESTS

- Fatigue tests determine the resistance of material to repeated pulsating or fluctuating loads.
- Fatigue defined: The capacity of material to withstand repeatedly applied stresses is known as fatigue.
- The resistance of a material to fatigue failure is characterised by its fatigue or endurance limit.

- The endurance limit or endurance strength is defined as the maximum stress which a specimen can endure without failure when this stress is repeated for a specified number of cycles.

5.19.1. Arrangement

The schematic arrangement of the most commonly used rotating beam fatigue testing machine is shown in Fig.5.26

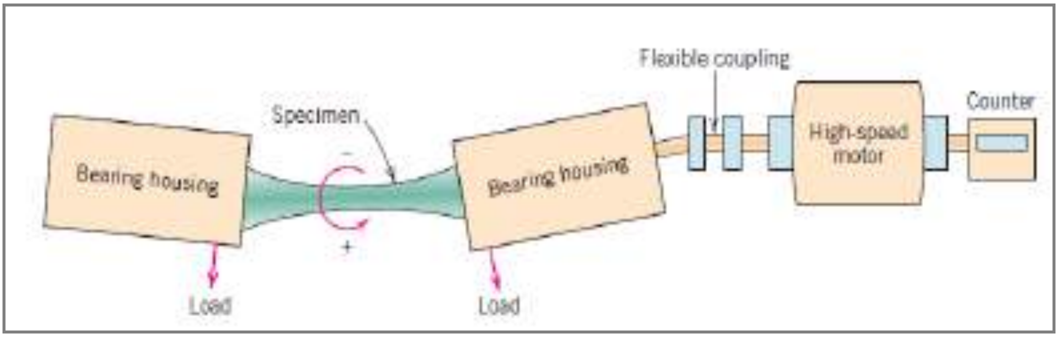


Fig.5.26. Rotating beam fatigue testing machine

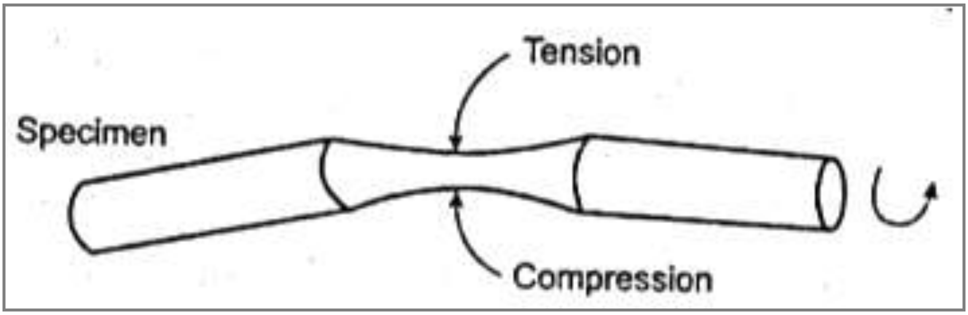


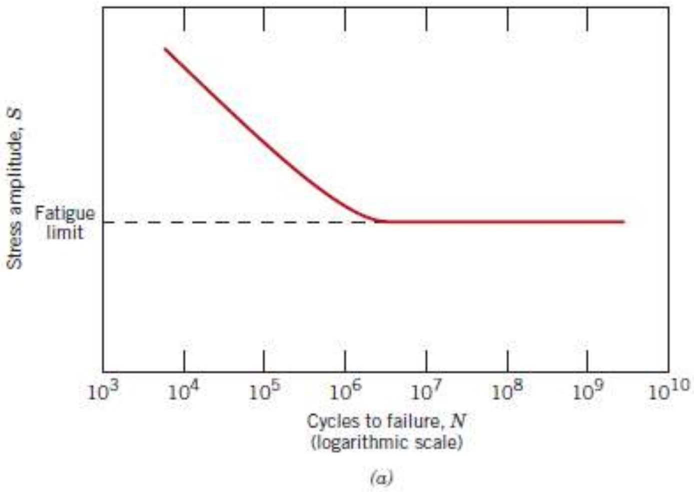
Fig.5.27. Fatigue test specimen

5.19.2. Testing Procedure

The step by step procedure for fatigue testing is given below:

- The test specimen is placed on the machine.
- Now the specimen is rotated using an electric motor.
- When the specimen is rotating, it can be noted that the upper surface of the specimen is subjected to tension and its lower surface experiences compression, as shown in Fig.5.27.

- As the specimen rotates, there is sinusoidal variation of stress between a state of maximum tensile stress and a state of maximum compressive stress.
- The cycles of stress are applied until the specimen fractures. A reduction counter records this number of stress cycles.
- Now a number of specimen of the same material (at least six specimens) are tested in the same manner under different stress levels and the results are plotted on S-N graph.
- The S-N graph is drawn on a semi logarithmic scale with the number of cycles (N) required to cause failure of the specimenon the X-axis and the stress (S) on the Y-axis. The resulting curve in a S-N graph is called as S-N curve.
- The Fig.5.28 shows the S-N curves obtained on testing different materials.



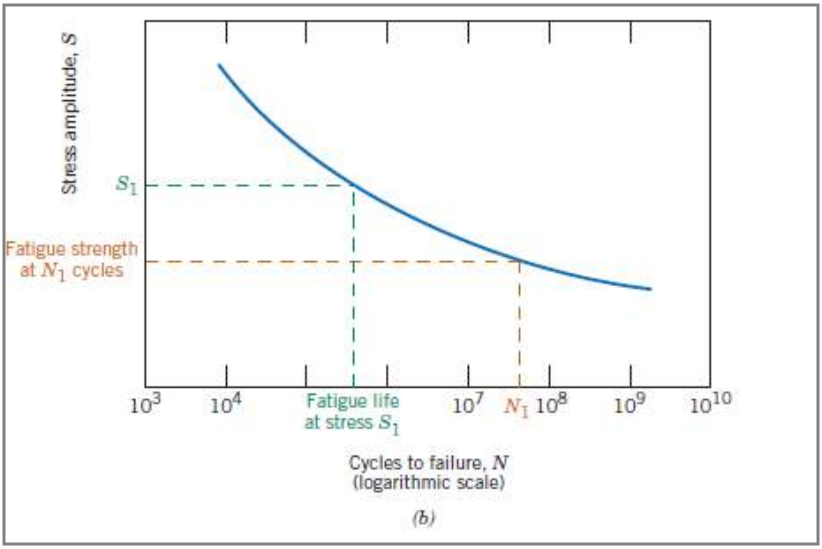


Fig.5.28. Stress amplitude (S) versus logarithm of the number of cycles to fatigue failure (N) for (a) a material that displays a fatigue limit, and (b) a material that does not display a fatigue limit.

5.19.3. Results of the Fatigue Test

- The fatigue test can tell us show long a part may survive or the maximum allowable loads that can be applied to prevent failure.
- The fatigue test is useful in setting the design criterion with the use of the endurance limit. Endurance limit is stress below which there is a 50% probability that failure by fatigue will never occur, which is the common design criterion.
- Fatigue life tells us how long a component survives at a particular stress. From the S-N curve, one can find the fatigue life (N) for the applied stress.

$$\text{Endurance ratio} = \frac{\text{Endurance limit}}{\text{Tensile strength}} = 0.5$$

5.20. CREEP TESTS

- Creep defined: The continuous deformation of a metal under a steady load is known as creep.

- The purpose of creep tests is to determine the creep limit. The creep limit or the limiting creep stress is defined as the stress that will not break the specimen when applied for an infinite period at a specific constant temperature.
- The creep tests require the measurement of four variables, stress, strain, temperature, and time.
- The creep tests are simply tension tests run at constant load and constant temperature. Then the value of strain of the test piece is noted as a function of time.

5.20.1. Arrangement of creep test

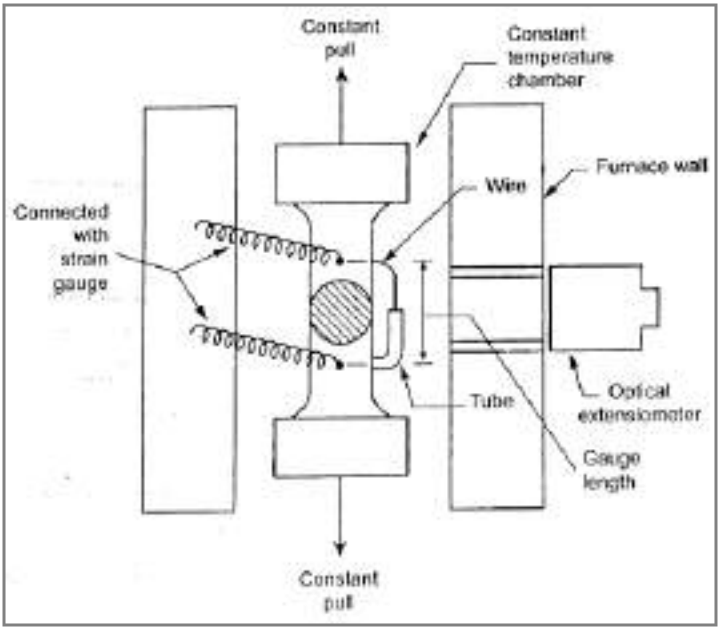


Fig.5.29. Creep test

The specimens for creep testing are usually the same as for conventional tensile tests.

The basic requirements for a creep testing machine are:

- It must possess means for applying and maintaining a constant tensile load.
- There must be a furnace capable of keeping the temperature of the test-piece at the desired value to within very close limits.
- There should be means for the accurate measurement of test- piece extension.