ENGINEERING METALLURGY QUESTION - ANSWER WAY !!

CONTENTS

Lesson 1.

CRYSTALLINE NATURE OF METALS

Q. 1.1.:- Distinguish clearly between crystalline and amorphous materials.

Ans.:- All meterials are aggregates of atoms held together by the inter-atomic forces forming bonds. In some materials the arrangement of atoms is haphazard, disorderly or without any regular repetitive pattern. The atoms are randomly distributed. Such materials are known as amorphous materials. On the contrary there are solids in which the atoms are arranged in a regular, repetitive three-dimensional pattern in a very orderly fashion. Such materials are known as crystalline materials. All metals are crystalline and there are some well recognized geometrical patterns on which metal atoms are arranged. Thus, crystals are aggregates of atoms which are arranged in a regular repetitive pattern in three dimensions.

Q. 1.2.:- What is a crystal lattice ?

Ans.:- The arrangement of atoms in crystals can be understood in terms of the arrangement of points in three dimensional space. A space lattice is a regular distribution of points in such a way that each point has identical surroundings. A perticular type of arrangement of points gives a perticular type of space lattice. When the atoms actually occupy specific positions, on, or in relation to, these lattice points, we get a crystal lattice. Hence a crystal lattice is a regular distribution of atoms in space, each atom having identical surroundings.

Q. 1.3.:- What do you understand by a " unit cell " ?

Ans.:- A unit cell is the smallest regular shape in space, which when repeated, generates the whole crystal lattice.Thus unit cell is the basic shape with respect to which the atomic arrangement in a given type of crystal is understood. Naturally a given type of arrangement in space would be characterized by the shape and size of its unit cell. The shape and size of a unit cell can be completely defined by the help of three vectors a,b,c;specifying the vector lengths and the angles α, β, and γ, between them, Fig. 1.1.(3) shows a unit cell and its lattice vectors.

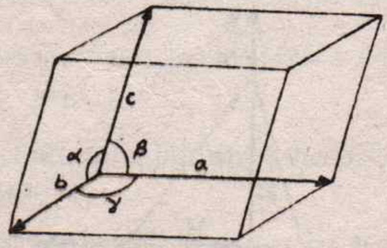


Fig. 1.1.(3)

Q. 1.4: Enumerate the different types of crystal systems and mention the characteristics of their lattice vectors and inter-vector angles.

Ans. As outlined in the above answer, each crystal system is characterised by the shape and size of its unit cell and each type of unit cell is characterized by the vector lengths a,b,and c, and the angles a, b, and g, respectively, between them. On this basis, seven CRYSTAL SYSTEMS have been recognized. They are as given below :-

CRYSTAL SYSTEM	VECTOR LENGTHS RELATION	ANGLES' RELATION
CUBIC	$a = b = c$	$\alpha = \beta = \gamma = 90^0$
TETRAGONAL	$a = b \neq c$	$\alpha = \beta = \gamma = 90^0$
ORTHORHOMBIC	$a \neq b \neq c$	$\alpha = \beta = \gamma = 90^0$
RHOMBOHEDRAL	$a = b \neq c$	$\alpha = \beta = \gamma \neq 90^0$
HEXAGONAL	$a = b \neq c$	$\alpha = \beta = 90^0$ $\gamma = 120^0$
MONOCLINIC	$a \neq b \neq c$	$\alpha = \gamma = 90^0 \neq \beta$
TRICLINIC	$a \neq b \neq c$	$\alpha \neq \beta \neq \gamma \neq 90^0$

Q. 1.5. What are Miller's indices? Explain how Millers indices of a crystallographic plane are derived.

Ans. The easiest way to denote a crystallographic plane would be to note the intercepts it makes on the three crystallographic axes and mention them. For example the crystallographic plane shown in Fig. 1.2.(5), making intercepts X, Y and Z on x, y and z axes, respectively can be described by noting the intercepts in that order. However, we are faced with a difficulty when a plane is parallel to an axis. In this case the intercept made by this plane on the axis to which it is parallel, would be infinity. Since α is indeterminate,it should not be used in the definition of a plane.

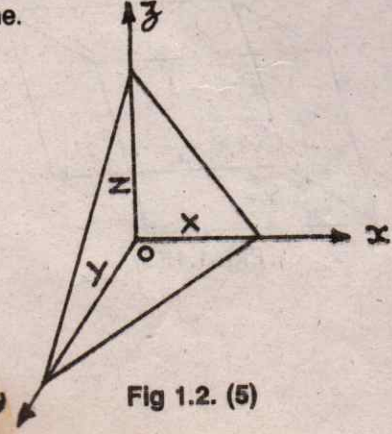


Fig 1.2. (5)

Miller devised a method to represent crystallographic planes and directions, using a set of three integers, without involving . These integers, a set of three (one for each axis), are known as Miller's indices.

Consider the plane shown in Fig. 1.2.(5). The method of finding out Miller's indices of this plane is given below :-

(a) Mark the intercepts made by the plane - X Y Z

(b) Convert the intercepts into " partial axial intercepts " by dividing each intercept with the vector length or axial length of that axis. (Suppose a,b,c are the axial lengths of x, y and z axes) :-

$$\frac{X}{a} \qquad \frac{Y}{b} \qquad \frac{Z}{c}$$

(c) Find the reciprocals of these partial axial lengths : -

$$\frac{a}{X} \qquad \frac{b}{Y} \qquad \frac{c}{Z}$$

(d) Find the set of three smallest integers - say h k l , which are in the same ratio as the reciprocals of partial axial lengths i.e.,

$$\frac{a}{X} : \frac{b}{Y} : \frac{c}{Z} :: h : k : 1$$

These three integers h k l are the Miller's indices of the plane under consideration, and the plane is hence represented by writing down these indices in rounded brackets - (h k l).

Q. 1.6.:- Explain how Miller's indices of a crystallographic direction are found.

Ans.:- For finding out the Miller's indices of a given crystallographic direction, we draw a line passing through the origin such that this line is parallel to the direction and also points towards the same direction. Then any one point on this line is taken and its three coordinates are found. Suppose these coordinates are m, n and p. Then, a set of three smallest integers u v and w is found such that

$$u : v : w :: m : n : p.$$

These three integers u v w become the Miller's indices of the direction and the direction is represented as [u v w].

Q. 1.7. :- What are the crystal structures into which the metals crystallize ? Explain them with the help of neat sketches.

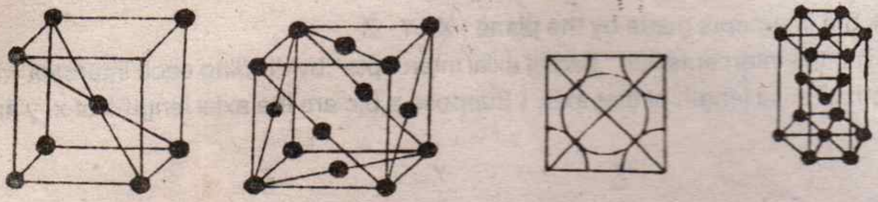
Ans.:- Approximately 75% of the elements known are metals and a majority of metals crystallize into one of the three relatively simple crystal structures, namely -

(a) Body centred cubic,

(b) Face centred cubic, and

(c) Close-packed hexagonal or hexagonal close-packed.

(a) **Body centred cubic structure :** The unit cell is a cube and at the eight corners there are eight atoms,and, one atom at the centre of the cube. The atoms are arranged so that all the corner atoms are touching the central atom. Hence the arrangement, illustrating BCC structure in Fig.1.3.(7) (a) is only schematic - the central atom MUST be touching all the corner atoms. Examples of metals with BCC structure are - Fe, Cr, W, V, etc.



(a) **(b)** **(c)** **(d)**

Fig.1.3(7)

(b) **Face Centred Cubic Structure :** The unit cell is again a cube. There are atoms at all the eight corners along with six atoms at the centres of the six faces of the cube as shown in Fig. 1.3(7)(b). The figure is only schematic, not exact, because each facial atom MUST touch the corner atoms surrounding it. Hence the actual picture of any cube face must look like one shown in Fig.1.3(7)(c). Examples of metals with FCC structure are - Fe, Cu, Al, Au, Ag, etc.

(c) **Hexagonal Close Packed :** The arrangement of atoms in hexagonal close packed unit cell is shown in Fig.1.3.(7)(d). There are six atoms at the six corners of the two hexagonal faces and one each at their face-centres. Furthermore, there are three atoms in the middle layer, touching all the atoms in two hexagonal layers. Examples of metals with HCP structures are - Mg, Zn, Cd, etc.

Q. 1.8.:- Calculate the number of atoms belonging to BCC and FCC unit cells.

Ans.:-

(a) **BCC Unit Cell :** In this unit cell there are eight corner atoms. Each corner atom is shared by eight cubes. The atom at the centre of the cube wholly belongs to the given unit cell. Hence the total number of atoms belonging to the BCC unit cell,N, is -

$$N = \frac{8}{8} + 1 = 2$$

(b) **FCC Unit Cell :** In this unit cell, the eight corner atoms are shared by eight units cells. Each face-centred atom is shared by two unit cells, and there are six face-centred atoms. Hence the number of atoms belonging to a FCC unit cell, N, is -

$$N = \frac{8}{8} + \frac{6}{2} = 1 + 3 = 4$$

Q. 1.9.:- Calculate the packing efficiency of BCC crystal structure.

Ans.:- From the geometry of atomic arrangement shown in Fig.1.4.(9), it is clear that cube diagonal AD is given by

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

$$\therefore r = \frac{\sqrt{3}a}{4} \qquad \text{(a)}$$

where r is the atomic radius and a is the length of the cube edge. The packing efficiency of a crystal structure. , P.E, is defined as:-

$$\text{P.E.} = \frac{\text{Volume of the atoms belonging to a unit cell}}{\text{volume of the unit}}$$

The number of atoms belonging to the BCC unit cell is 2. Hence -

$$\text{P.E.} = \frac{2 \times \frac{4}{3}\pi\left(\frac{\sqrt{3}a}{4}\right)^3}{a^3}$$

$$= 0.68$$

Q. 1.10. Calculate the packing efficiency of the FCC crystal structure.

Ans. From the geometry of atomic arrangement in FCC crystals, shown in Fig.1.5.(10), we see that -

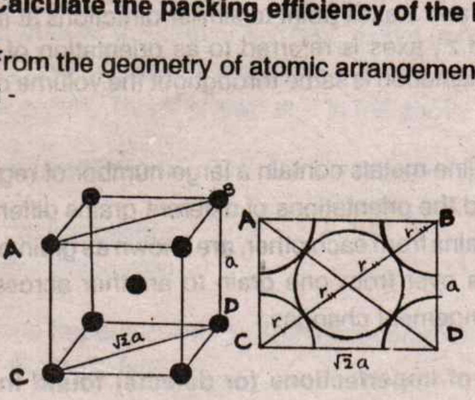


Fig. 1.4.(9)

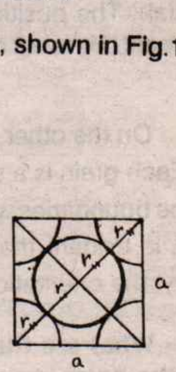


Fig.1.5.(10)

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

$$\therefore r = \frac{a}{2\sqrt{2}}$$

The number of atoms belonging to the FCC unit cell is 4.

Hence, the packing efficiency,P.E.,of the FCC crystal is -

$$\text{P.E.} = \frac{\text{volume of atoms belonging to a unit cell}}{\text{volume of the unit cell}}$$

$$= \frac{4 \times \frac{4}{3}\pi \left[\frac{a}{2\ \sqrt{2}}\right]^3}{a^3}$$

$$= 0.74$$

Hence, FCC crystals are said to be more closely packed than BCC crystals.

Q. 1.11.:- What is "polymorphism" or "allotropy" in metals ? Explain it with the example of iron.

Ans.:- Some metals exist in more than one crystal structure, each type of crystal structure existing in a limited temperature range. This phenomenon is known as " polymorphism " or " allotropy " For example metal iron exists in BCC form at 900 C. At this temperature, it changes its structure to FCC form which is stable between 900 C.and 1400 C. At 1400 C, it again reverts back to BCC structure and retains this form upto melting point.

Q. 1.12.:- Distinguish clearly between " single crystal " and polycrystalline metal."

Ans.:- In a single crystal, the atomic arrangement is continous throughout the volume of the crystal in such a fashion that the x, y and z axes point to similar directions at any place in the crystal. The positioning of x, y and z., axes is referred to as orientation of the atomic arrangement. Hence it means that the orientation is same throughout the volume of the single crystal.

On the other hand,polycrystalline metals contain a large number of regions,called grains. Each grain is a single crystal, and the orientations of different grains differ from each other. The boundaries which separate grains from each other, are known as grain boundaries. Hence it is evident that when we cross over from one grain to another across the grain boundary, the orientation of atomic arrangement changes.

Q.1.13.:- What are the various types of imperfections (or defects) found in crystals? Explain the point imperfections (or defects) with the help of a neat sketch.

Ans.:- The atomic arrangement in actual crystals is never perfect. They contain various types of imperfections. The imperfections in crystals are classified according to their geometry. Basically three types imperfections are recognized -

(a) point imperfections
(b) line imperfections
(c) surface imperfections

(a) **Point imperfections :-**

These are point-like regions of distortion in the crystal lattice. There are four types of point defects --

(i) **Vacancy :-** A vacancy is a lattice site from which the atom is missing as shown in Fig.1.6.(13), at A.

(ii) **Interstitialcy :-** An interstitialcy is a point defect at which a lattice atom is displaced from a regular site to an interstial site, as shown at B in the above figure.

(iii) **Interstitial impurity :-** An interstitial impurity is a small atom that occupies any interstitial void or interstitial space in between the parent atoms of the crystal, as shown at C in the above figure.

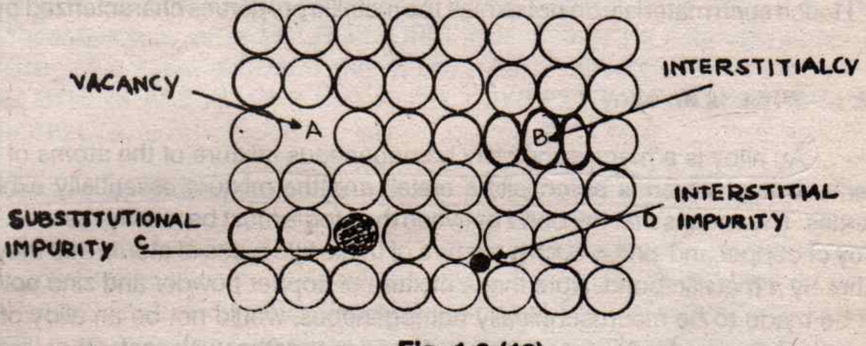


Fig. 1.6 (13)

(iv) **Substitutional impurity:-** A substitutional impurity atom is an impurity atom, relatively comparable in size to parent atom of the crystal, that has taken the regular place of a parent atom of the crystal. This is shown at D in the above figure.

(b) **Line imperfections :-** There are two basic types of line imperfections :-

(i) edge dislocations.
(ii) screw dislocations.

(c) **Surface imperfections :-** The most common surface imperfection found in crystals is known as " Stacking fault ".

Lesson 2.

BINARY PHASE DIAGRAMS

Q.2.1.:- **What are metals ? How do they differ from other types of materials ?**

Ans. :- All materials are aggregates of atoms. In these aggregates, the atoms are bonded together due to interatomic forces between the atoms constituting the aggregate. The bonds formed due to the interatomic forces are classified basically as metallic bond, covalent bond, ionic bond and Van der waals bond. Metals are made of the atoms of such elements whose atoms are bonded by metallic bond. Hence metals are those elements which exhibit metallic bond. Metallic bond is characterized by high electical conductivity, lustre, high ductility or deformability and good thermal conductivity. On the other hand materials like ceramics or polymers have either ionic bond, covalent bond, or a mixture of such bonds, or Van der waals bond. Hence such materials do not exhibit the metallic properties characterized by the metallic bond.

Q.2.2. :- **What is an alloy ?**

Ans. :- An alloy is a macroscopically homogeneous mixture of the atoms of two or more elements, one of which is essentially a metal; and the mixture essentially exhibits metallic properties. This means that the bond between the atoms must be mostly metallic. For example an alloy of copper and zinc is such a mixture of these two types of atoms that they are bonded together by a metallic bond. Note that a mixture of copper powder and zinc powder, though might be made to be macroscopically homogeneous, would not be an alloy of copper and zinc because the two kinds of atoms are not bonded together with each other through metallic bond. Sodium Chloride is not an alloy because , though macroscopically homogeneous, the two kinds of atoms are not bonded with each other by metallic bond. The bond in this case is ionic. On the other hand steel is an alloy of iron and carbon because the bond between iron and carbon atoms is metallic to a high degree, thus giving metallic properties.

Q.2.3.:- **What are the various types of phases found in the alloys ? Enumerate them.**

Ans. :- The most common phases found in alloys are -

(a) Random substitutional solid solutions ✓
(b) Ordered solid solutions ✓
(c) Interstitial solid solutions ✓
(d) Intermetallic compounds ✓
(e) Electron compounds ✓

Normally the random substitutional solid solutions may be found at one or both of the pure-metal-ends of a binary phase diagram, i.e., "TERMINALS" of a diagram. Hence such substitutional solid solutions, which are almost always random, are known as primary solid solutions or terminal solid solutions. In some cases the arrangement of solute atoms and solvent atoms may not be random, but ordered. These are the ordered substitutional solid solutions. The other types of phases like intermetallic compounds and electron compounds are offen found in the intermediate portions of the diagram and hence they are called intermediate phases. Intertstitial solid solutions are a special variety of solid solutions in which the solute atoms are very small as compared to solvent atoms.

Q.2.4. :- Define a solid solution.

Ans. :- A solid solution is a microscopically homogeneous mixture of the atoms of two or more elements, one of which is essentially a metal and the mixture exhibits all metallic properties. It means that in case of a solid solution, we can not find any heterogeneity; we find only one and one type of phase. Note that in case of the definition of an alloy, the mixture need be homogeneous only on a MACROSCOPIC level. It may be heterogeneous on a MICROSCOPIC level (i.e. it may show two phases under the microscope). Thus it is clear that ALL SOLID SOLUTIONS ARE ALLOYS BUT ALL ALLOYS NEED NOT ESSENTIALLY BE SOLID SOLUTIONS ONLY.

Q.2.5.:- What is a substitutional solid solution ? What are their two types ?

Ans. :- A substitutional solid solution is homogeneous mixture of the atoms of two elements, right down to the atomic scale, the two elements being such that their atoms are nearly identical in their size, i.e., diameter and electrochemical nature. The two kinds of atoms are so much alike that, supposing we could see them through a microscope, we would not be able to distinguish between one type of atom and the other in their mixture. Because of this similarity between the solute (the element whose proportion is less) atoms and the solvent (the element which is more in proportion) atoms, the solute atoms occupy the lattice sites of the solvent atoms; i.e., they SUBSTITUTE the solvent atoms on their lattice sites. This is schematically shown in Fig. 2.1.(5). If the two kinds of atoms are arranged in a haphazard fashion on the lattice sites, as in the above figure, we get a RANDOM substitutional solid solution. On the other hand if the solute atoms and solvent atoms are arranged in an orderly fashion as shown in Fig. 2.2.(5), we get ORDERED substitutional solid soultion.

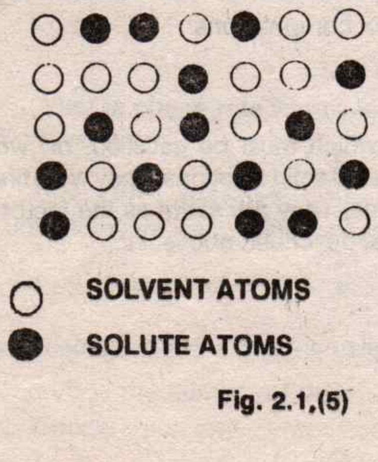


Fig. 2.1,(5)

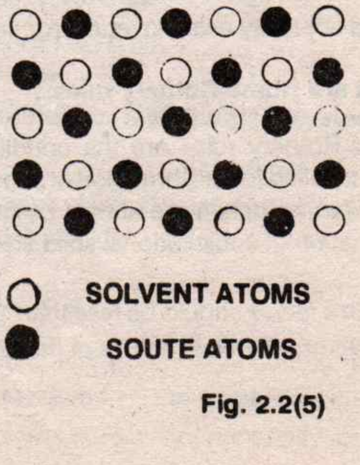


Fig. 2.2(5)

Q.2.6. :- What are the factors which govern the formation of substitutional solid solutions ?

Ans. :- Substitutional solid solutions are formed when the solute atoms and solvent atoms are identical in their sizes and electrochemical natures. Hence the factors which govern the formation of substitutional solid solutions are-

(1) The size factor :- For the formation of a substitutional solid solution, the size factor should be less than 15%. If the atomic radius of the solute atom is R and the atomic radius of solvent atom is R , then the size factor is defined as -

$$\frac{R_A - R_B}{R_A}$$

$$\text{It means that} \quad \left| \frac{R_A - R_B}{R_A} \right| \times 100 < 15\%$$

for the formation of substitutional solid solutions. If the size factor is more than 15%, the formation of substitutional solid solution is less favoured.

(2) Electro-chemical nature :- For the formation of substitutional solid solutions, the electro- chemical natures of the solvent element and the solute element should also be identical. For example, if the solvent element is strongly electropositive the solute element should also be strongly electropositive. A large difference in electrochemical nature does not allow the formation of substitutional solid solutions.

(3) Valency :- An element with lower valency dissolves more of the element with higher valency and vice versa. This is known as relative valency effect.

Apart from these factors, if the crystal structures of the elements are same, substantial solid solubility exists over a large range of compositions.

Q.2.7. :- What are Hume-Rothery rules ?

Ans. :- Hume-Rothery rules are the conditions which must be satisfied, or, which are observed to be satisfied for the formation of substitutional solid solutions. They were first stated by Hume-Rothery and hence are known by his name. They are same as the factors which govern the formation of substitutional solid solutions, described above. i.e.,-

(a) The size factor should be less than 15%.

(b) The electrochemical nature of the solute element and solvent element should be identical, and

(c)

The ralative valency effect which states that a metal with lower valency dissolves more of the metal of higher valency as compared to the case of metal with a higher valency which dissolves relatively less amount of a solute of lower valency.

Q.2.8. :- What is an interstitial solid solution ? what are the - factors that govern its formation ?

Ans. :- When the size of the solute atoms is so small that they can easily be accomodated in the interstitial space (the space in between the atoms of the solvent), we get an interstial solid solution. This is schematically shown in Fig. 2.3.(8). The best examples of interstitial solid solutions are found in alloys of iron with carbon, nitrogen and hydrogen. The atoms of carbon,nitrogen and hydrogen are much smaller in size as compared to the iron atom. As such, all these three elements form insterstitial solid solutions with iron. It has been shown that the formation of interstitial solid solutin is favoured if the radius ratio of the solute atom to solvent atom is less than 0.6., i.e.,

$$\frac{R_{\text{Solute}}}{R_{\text{Solvent}}} < 0.6$$

The radius ratio is the most important factor that governs the formation of interstitial solid solutions. The other factor is electrochemical nature. The electrochemical nature of the solute should not be extremely different from that of the solvent element. For example, although the radius ratio is favourable for the formation of an interstitial solid solution of oxygen in iron, it is not formed because oxygen is highly electronegative as compared to iron which is electropositive in nature.

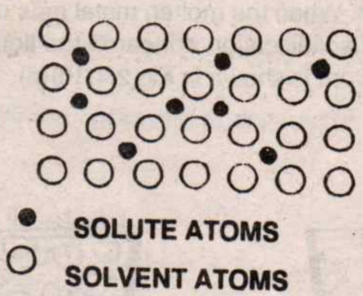


FIG.2.3.(8)

Q.2.9.:- What is phase rule ? How is it modified for metallurgical systems ? Define all the terms involved.

Ans. :- Gibb's phase rule gives us the conditions satisfied when an isolated system is under equilibrium. Mathematically, Gibb's phase rule is stated as -

$$P + F = C + 2$$

Where P is the number of phases in equilibrium, C is the number of components forming the system, and F is the number of degrees of freedom i.e., the number of such variables as pressure, temperature and composition which can be independently changed without changing the other variables. In other words, degrees of freedom are the variables which must be specified to completely define the system.

A phase is defined to be a microscopically homogenous and physically distinct portion of a system with well defined boundaries separating that portion from its surroundings. For example vapour, water and ice are three different phases. A phase is characterized by its structure - the atomic arrangement in it.

The number of components is the number of elements of which the system is made up of. For example, a binary system is a two component system and a ternary system is a three component system. That is, for a binary system, $C = 2$, and for a ternary system, $C = 3$.

In metallurgical alloy systems, the vapour pressure of metals is negligibly small and hence the effect of pressure can be ignored. HENCE FOR METALLURGICAL SYSTEMS, GIBB'S PHASE RULE IS MODIFIED, NEGLECTING PRESSURE AS A VARIABLE. The MODIFIED EXPRESSION for Gibb's phase rule for metallurgical alloy systems is given by-

$$P + F = C + 1$$

(remembered as Police (for P) Force (for F) is equal to Cops (for C) plus one).

Q.2.10.:- Explain the solidification of a pure metal.

Ans. :- Consider a crucible containing molten pure metal well above its melting point. Let it cool slowly to room temperature. Nothing happens till the temperature of the molten metal reaches its melting point. When the molten metal gets undercooled slightly below its melting point, certain centres of solidification appear in the liquid at random at various sites. These are called nuclei. This event is shown in Fig.2.4(10)(a).

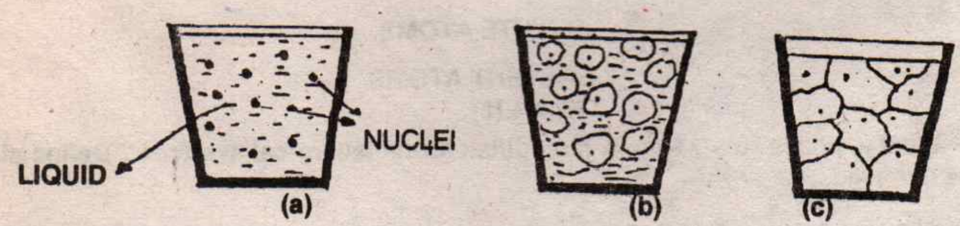


Fig.2.4.(10)

As soon as these nuclei form (or say the nucleation occurs), the temperature of the molten metal rises to its melting point. At this constant temperature, these nuclei grow in size, thus increasing the proportion of solid metal. Finally after sometime all the liquid is consumed and the solidification is over. These steps are shown in Fig. 2.4.(10) (b) and Fig. 2.4.(10) (c). The temperature of the metal further falls only when the solidification is completed.

Fig.2.5.(10) shows the overall cooling curve for the solidification of pure metal.

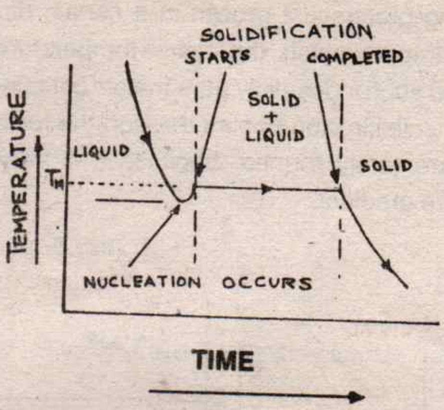


Fig. 2.5.(10)

Q.2.11.:- Apply phase rule to the solidification of a pure metal and explain why the solidification of a pure metal occurs at a constant temperature.

Ans. :- During the solidification of pure metal, solid metal and liquid metal are in equilibrium. Hence the number of phases in equilibrium is 2. Since it is a pure metal, it is a single component system i.e., C = 1. Phase rule for alloy system is stated as

$$P + F = C + 1$$

where F is the number of degrees of freedom. Applying phase rule for the solidification of a pure metal, we get

$$2 + F = 1 + 1$$

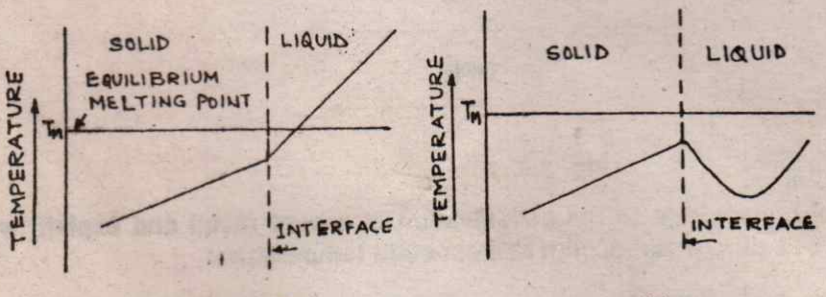
$$F = 0$$

Which means that during the solidification of a pure metal, the temperature does not change; it remains constant. Thus the solidification of a pure metal occurs at constant temperature, the melting point or freezing point of the metal.

Q. 2.12. :-What are dendrites ? How are they formed ?

Ans. :- When crystals are growing into liquid metal, one can identify a boundary - an interfacee between the liquid and solid. Normally the temperature gradient across the interface - from solid into liquid is positive as shown in Fig.2.6.(12)(a), the liquid being hotter than the interface, and interface being hotter than solid. In such a case columnar crystals (or grains) grow. However, under certain conditions an inverse temperature gradient is set up as shown in Fig.2.6.(12)(b). Under these conditions, it can be seen that the interface is hotter than solid and liquid. Thus the growth is taking place into undercooled liquid. Under these circustances, growth is faster in certain preferential directions and the crystals grow to larger dimensions in certain directions as compared to others. This gives rise to a branch like shape of crystal longer in a particular direction, as shown in Fig.2.6.(12)(c).

These crystals showing preferential growth in a certain direction are known as dendrities. In alloys and relatively impure metals, the inverse temperature gradients are almost always set up. Hence in alloys and such industrially pure metals containing impurities, always the solidification is dendritic- i.e. solidification occurs through the formation of dendrites. In highly pure metals, dendrites are rarely formed, because it is very difficult to produce conditions for inverse temperature gradient.



(a) (b)

Fig.2.6(12)

Q.2.13. :- Describe the solidification of a liquid metal in an ingot mould.

Ans. :- As soon as liquid is poured into the ingot mould, the liquid in contact with the mould is chilled to a depth and a large number of nuclei are heterogeneously nucleated on the mould wall and grow to give small grains called "Chilled grains". Chilled grains are formed immediately adjacent to the mould wall. Then, nuleation again takes place on the surface of these chilled grains and the nuclei grow into the liquid because the heat from the melt is being abstracted through the mould wall and chilled grain layer. These grains preferentially grow longer in the normal direction to the mould wall. These elongated grains look like "coloumns" and hence they are called columnar grains. During the growth of columnar grains, the liquid in the interior is continuously getting cooled and at one stage its temperature is suppressed below its melting/freezing temperature.

At this instant, homogeneous nucleaction occurs in this liquid. These nuclei grow nearly equal in all directions and give rise to equi-axed grains. All these types of grains are shown in Fig. 2.7.(3). After the solidification is completed, one finds a depression in the centre at the top of the ingot. This is the shrinkage cavity known as "pipe" and forms because the specific volume of the liquid is larger than that of the solid.

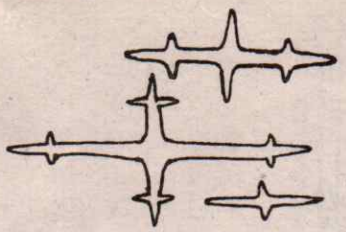


Fig. 2.6.(12) C

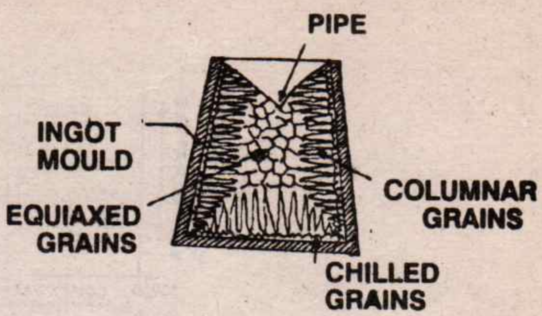


Fig.2.7.(13)

Q.2.14. :- Distinguish clearly betweenhomogenous nucleation and heterogeneous nucleation.

Ans. :- When the probability of the formation of a nucleus is same through out the volume of the liquid at every place, we call it homogeneous nucleation. Homogeneous nucleation requires that the liquid is supercooled below its melting/freezing point. The degree of undercooling required is also high.

In heterogeneous nucleation, nuclei are preferentially formed at certain sites like the surfaces of the mould wall, surfaces of solid impurity particles suspended in the liquid metal,etc. It means that the process of nucleation is catalysed due to the presence of the catalyst surfaces mentioned above. As such the nucleation is made easier and requires a lesser degree of undercooling, or, no undercooling at all, as compared to homogenous nucleation. Naturally in heterogeneous nucleation, the number of nuclei formed per unit volume of liquid, per unit time, is much larger than that in case of homogeneous nucleation.

Q.2.15.:- What is binary phase diagram ?

OR

What is a binary equilibrium diagram ? What information does it - provide ?

Ans. :- A binary phase diagram or binary equilibrium diagram is a plot of various phases in equilibrium at different temperatures for alloys of different compositions in the entire range form one pure metal to the other. It can be considered as a map showing the various phases present at different composition-temperature conditions for an alloy system. The Y axis represents the temperature and the X axis represents the composition. The composition can be given either in weight percent (i.e. described in terms of proportion by weight) or in atom% (i.e., in terms of the relative proportions of the two types of atoms). Fig. 2.8.(15) schematically shows the nature of the reference frames.

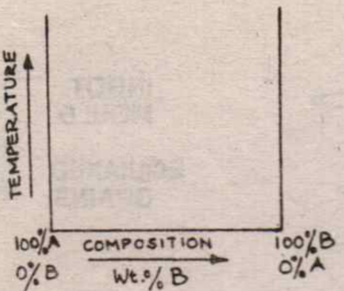


Fig. 2.8(15)

An equilibrium diagram tells us -

(a) the various changes that occur on cooling an alloy from a higher temperature to room remperature.

(b) the condition of an alloy in terms of the phases present in that alloy at any given temperature.

(c) various solidification reactions and reactions that occur in solid state.

(d) temperature at which solidification begins and ends for any given alloy.

Q.2.16.: - Describe an isomorphous system.

OR

Draw and explain a binary phase diagram for two elements A and B which are completely soluble in each other in solid state.

OR

Describe a diagram exhibiting complete solid solubility or complete miscibility in solid state.

Ans. :- An equilibrium diagram showing complete solid solubility or solid miscibility is known as an ISOMORPHOUS system because the crystal structure of any alloy between the limits of the two pure metals - i.e. from 100% A to 100% B - is same (iso-meaning "same" or "identical" and morphous indicating "structurally"). Such an equilibrium diagram is shown in Fig. 2.9.(16). The boundary line separating the liquid region from solid + liquid region is known as the LIQUIDUS line, and the boundary line separating the solid + liquid region from solid region is known as SOLIDUS line. The liquidus line indicates the variation of freezing point of the alloy with composition. A given alloy is exhibited by a vertical line indicating its compostion. The intersection point of this composition line with the liquidus line indicates the temperature at which, on cooling the liquid alloy, its solidification STARTS. Similarly the intersection point of the composition line with solidus line indicates the temperature at which the solidification of the alloy is COMPLETED. For example, as shown in the Fig. 2.9.(16), the solidification of an alloy containing C%B, starts at temperature T_1 and is completed at temperature T_3 (Note that T_A and T_B are the melting points of elemrnts A and B).

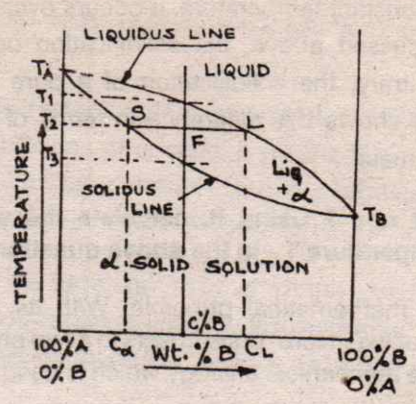
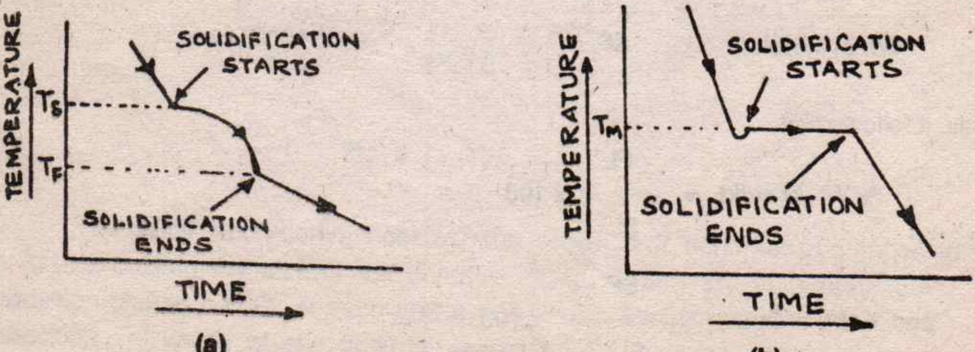


Fig. 2.9.(16)

From the diagram we see that, whatever be the composition, we get a solid solution only. Thus the solid solubility is COMPLETE. Further more, if the crystal structures of A and B are, say, FCC, the crystal structure of any alloy of A and B (always a solid soluction in this case) will also be FCC.

Q.2.17.:- Discuss the solidification of any alloy in the above phase diagram. How does it differ from the solidification of a pure metal ?

Ans. :- Consider an alloy containing C%B. As indicated in Fig. 2.9.(16),the solidification is dendritic and the first dendrites of solid solution, which form, have a composition C as shown in the figure. On cooling further, more solid solution dendrites are formed and the already formed dendrites grow to large size. At any temperature T , we have dendrites of solid solution of composition C and liquid melt of composition C . These compositions are given by the intersection points of the temperature horizontal-line drawn at T , with the solidus line and liquidus line, respestively, as indicated in the figure. At temperature T ,the solidification of the alloy is completed and there is no further change.



(a)

(b)

Fig.2.10.(17)

From the above discussion it is evident that the solidification of a solid solution type alloy does not occur at a constant temperature. It occurs over a range of temperatures. For example, in the alloy discussed above, the solidification occurred between T and T temperatures. On the contrary, the solidification of a pure metal occurs at a constant temperature. Fig. 2.10.(17) shows this difference in terms of the cooling curve of a solid solution and that of a pure metal.

Q.2.18. :- What is LEVER rule ? Using it, calculate the weight proportions of solid solution and liquid at temperature T in the above question, for the alloy discussed.

Ans. :- Lever rule is a mathematical principle. With its help one can calculate the proportions of two phases or two micro- constituents in a two phase region. This rule is known as lever rule because of the mechanical analogy which is used in calculation.

In this rule it is assumed that, the weights of the two phases under consideration, are suspended from the ends of a tie-rod. The ends and fulcrum are given by the intersection points of the temperature-horizontal-line (corresponding to the temperature at which the calculation is required) with the phase boundaries of the two phases, and, the compositon vertical, respectively.

For example, in the case of the alloy of Q.2.17, containing C%B, suppose we want to calculate the proportions of solid solution and liquid, at temperature T .We draw the temperature- horizontal line SFL, as shown in the Fig.2.9.(16) which corresponds to temperature T .This line cuts the composition vertical at F, and cuts the solidus line (the -phase boundary), at S, and liquidus line at L. Hence the tie rod is the line SFL, with the fulcrum at F. The weight of solid solution is supposed to be suspended at S and the weight of the liquid is supposed to be suspended at L. Under equilibrium, the moments must be balanced.

Hence; wt. of solid x SF = wt. of liquid x FL

$$\text{Hence;}\quad \frac{\text{Wt. of solid}}{\text{Wt. of liquid}} = \frac{FL}{SF}$$

From this, it follows that

$$\%\ \text{Wt. of solid} = \frac{FL}{SL} \times 100$$

$$\text{and}\ \%\ \text{Wt. of liquid} = \frac{SF}{SL} \times 100$$

Q.2.19. :- Explain the terms "Liquidus temperature" and "Solidus temperature "

Ans. :- The solidification of an alloy (e.g. a solid solution) occurs over a range of temperatures.

Liquidus temperature is the temperature at which the solidification of such an alloy just starts, under equilibrium conditions of cooling. It means that no solid phase is presnt above this temperature. Since liquidus temperature of the alloy is governed by its composition, it is obvious that the liquidus temperatures of alloys of different compositions are different.

Solidus temperature is the temperature at which the given alloy has just solidified completely. It means that the solidification of the alloy is just finished. It is obvious that there would be no liquid left below this temperature. Solidus temperature also varies with the composition of the alloy.

In Fig. 2.9.(16), T is the liquidus temperature of an alloy containing C%B, while its solidus temperature is T .

Q.2.20 :- What is coring ? Why does it occur ? How can it be eliminated ?

Ans. :- Coring is the formation of grains or dendrites which are nonuniform in their composition from their interior to their outermost regions. This happens due to the non-equilibrium cooling rate, i.e., faster cooling rate during solidification. Consider the solidifiation of an alloy C in Fig. 2.11.(20).

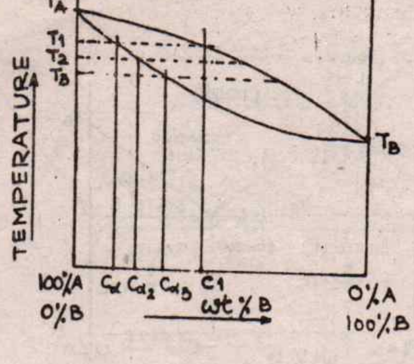


Fig. 2.11.(20)

The solidification commences with the formation of dendrites of composition C . With further cooling the size of the dendrite increases and say at temperature T ,its composition should be C at each and every place. Similarly at temperature T , the composition of whole of any dendrite should be C .It means that with decrease in temperature, the composition of the dendrites of solid solution should get richer in the solute element B. This is only possible when atoms of B from the liquid surrounding the dendrites, are drawn into solid and diffuse into its nooks and corners to change its compositon at every place to the desired level in element B. This diffusion requires time and when cooling rate is faster during solidification, sufficient time is not available for diffusion to take place. This results in that, different layers of a dendrite have different compositions - the outer layers being richer in B than the interior. This layer like -onion like - heterogeneity in composition is "CORING" and the dendrites are said to be "cored". The nonuniformity in composition of cored dendrites is easily seen in terms of gradual variation in the contrast from the outer perifery to the interior -core - of the dendrites, in their microstructure.

The cored nonuniform structure can be eliminated by -

(a) prolonged annealing at higher temperature - the homogenization anneal, or

(b) cold working the structure, breaking the dendrites into smaller grains and then annealing it at high temperature.

The second method is much faster.

Q.2.21 :- Draw a phase diagram for two metals A and B which are completely soluble in liquid state but are completely insoluble in each other in solid state, and explain it.

OR

Draw and explain a phase diagram exhibiting eutectic reaction.

Ans. :- When the two elements A & B are completely insoluble (immiscible) in solid state, they form an equilibrium diagram showing eutectic reaction. The phase diagram in this case is one shown in Fig. 2.12.(21).

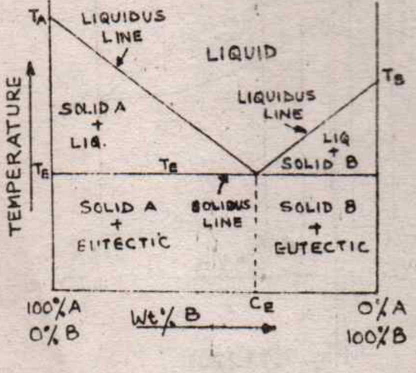


Fig.2.12.(21)

We see that whether element A is added to B. or, B to A,. the melting point of the alloy is always decreased, till the composition reaches a specific composition. C , for which the melting point is minimum. This composition is known as "**Eutectic**" **composition**, and the point - eutectic point. The melting point of such an alloy is called **Eutectic temperature,- a** constant temperature.

When an alloy of eutectic composition is cooled from, say a temperature T, from liquid condition, nothing happens till the eutectic temperature is reached. At this temperature T_E ,the liquid of eutectic composition C_E solidifies at constant temperature T_E to form a solid comprising of an intimate mechanical mixture of solid A and solid B.This is known as eutectic reaction, and the mixture is known as eutectic mixture. The reaction is written as-

$$\text{Liquid } (C\,\%\,B) \xrightarrow[T\,=\,T_E]{\text{Cooling}} \text{Solid A} + \text{Solid B}$$

The word EUTECTIC is derived from Greek word "eutectus" meaning easy to melt. This type of diagram is shown by Al-Si,Sn- Zn and Al-Sb systems.

Q.2.22 :- Draw a phase diagram exhibiting partial solid solubility between two elements A and B, which form a eutetic, and explain it.

OR

Draw and explain the equilibrium diagram formed between two elements which are partially soluble in each other in solid state and form a eutetic.

Ans. :- Two elements exhibiting partial solid solubility may either form a eutetic or give a peritectic reaction. Consider two elements A and B which are partially soluble in solid state and form a eutectic. The equilibrium diagram for these two elements is shown in Fig.2.13.(22).

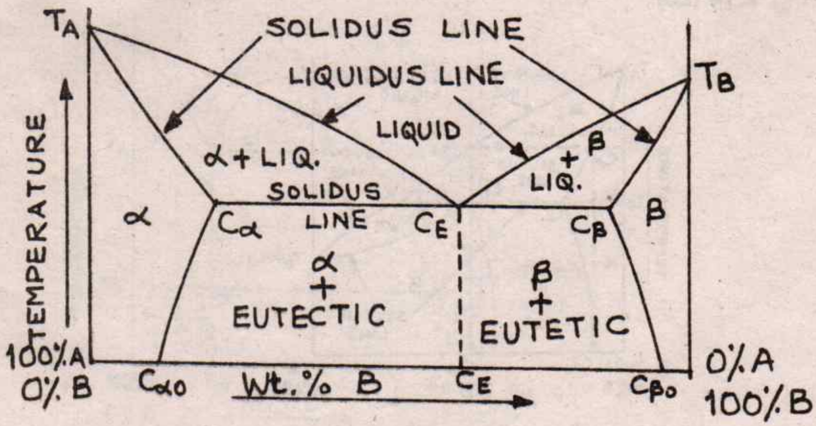


Fig. 2.13.(22)

C_ε is the eutectic composition and T is the eutectic temperature. The diagram shows two solid solutions α and β at both the ends. This means that both A and B are soluble in each other in solid state - but to a limited extent. α is the substitutional solid solution of B in

A and β is the substitutional solid solution of A in B. The solubility of β in is $C_{\alpha 0}$ at 0° C and C_α at eutectic temperature. The solubility of A in β is given by $C_{\beta o}$ at 0° C and C_β at T_ε. If an alloy of eutectic composition C_ε is cooled from a higher temperature in molten condition, nothing happens till the temperature of the melt reaches T_ε . At this temperature, the liquid solidifies giving an intimate mechanical mixture of α solid solution of composition containing C_α % B and β solid solution containing C_β % B (i.e. [100 - C_β] %A) through the eutetic reaction as shown below :-

$$\text{Liquid } (C_\varepsilon \text{ \% B}) \xrightarrow[T\ =\ T_\varepsilon]{\text{Cooling}} \alpha\,(C_\alpha \text{ \% B}) + \beta\,(C_\beta \text{ \% B})$$

The eutectic reaction occurs at a constant temperature.

It can be seen that in this case the eutectic is a mixture of two solid solutions, while in case of complete immiscibility in solid state, the eutectic is a mixture of two pure metals (elements) as discussed in the previous answer. This type of diagram is found in Cu-Ag, Pb-Sn and Pb-Sb systems.

Q.2.23 :- Explain a phase diagram with a peritectic reaction.

OR

Write in brief on peritectic reaction.

Ans. :- In certain cases, two elements which are completely soluble in liquid state but partially soluble in each other in solid state may exhibit a PERITECTIC REACTION in their equilibrium diagram. A phase diagram for two elements A and B exhibiting peritectic reaction is shown in Fig. 2.14.(23).

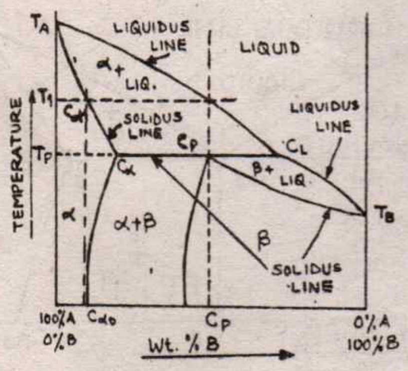


Fig.2.14.(23)

C_P represents the peritectic composition and T_P is the peritectic temperature. The peritectic reaction can be best understood by considering the solidification of an alloy of peritectic composition - C_P . Suppose a melt of peritectic composition C_P is being cooled from a higher temperature. The solidification of this alloy starts at temperature T_1 through the formation of dendrites of composition $C_{\alpha 1}$ .As the temperature is decreased below T_1 , more and more dendrites form, and the composition of α changes along the solidus line $T_A C_\alpha$ while the composition of the liquid changes along the liquidus line $T_A C_L$ as shown in the figure. At the peritectic temperature, the composition of α solid solution is C_α and the composition of the liquid is C_L . At this temperature T_P ,all the solid solution reacts with all the liquid to form another solid solution - β of composition C_P . The reaction can be represented by -

$$\alpha(C\alpha\ \%\ B) + \text{Liquid}\ \beta(C\beta\ \%\ B) \xrightarrow[T\ =\ T_P]{\text{Cooling}} \beta\ (C\beta\ \%\ B)$$

It can be seen that on further cooling no change takes place in B and it remains as it was when it formed.

The reaction is known as peritectic because the reaction between the solid solution and the liquid starts at the PERIPHERY of a dendrite and progresses. Peritectic reaction is found in Cu - Zn, Cu - Sn, Sb - Sn and Fe - C systems.

Q.2.24. :- Draw a phase diagram showing monotectic reaction and explain it :

Ans. :- Fig. 2.15.(24) shows an equilibrium diagram with a MONOTECTIC reaction. Monotectic reaction is exhibited by two such elements which show a liquid region in which the two elements are immiscible. They are said to show a miscibility gap in liquid condition. Normally, such metals are insoluble in solid state and show a eutectic reaction also as indicated in the figure.

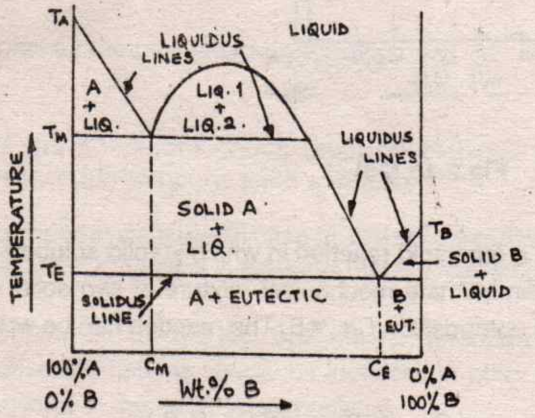


Fig.2.15.(24)

Consider an alloy of composition C_M which is the monotectic composition. When an alloy of C_M composition is cooled from liquid state at higher temperature, nothing happens till the temperature reaches T_M - the monotectic temperature. At this constant temperature, the liquid of composition C_M decomposes into solid A and the liquid of composition C_M .The reaction is represented as given below :-

$$\text{Liquid } (C_M \ \% \ B) \xrightarrow[T\,=\,T]{\text{Cooling}} \text{Solid A Liq. } (C_L \ \% \ B)$$

After the reaction, the composition of the liquid changes along C_L C_E by the solidification of more solid A, till the eutectic temperature T_E is reached when the liquid of C % B undergoes eutectic reaction to give the eutectic mechanical mixture of solid A and solid B.

Q.2.25. :- Write a short note on eutectoid reaction.

Ans. :- Eutectoid reaction is a solid state reaction in which a solid solution of a definite composition decomposes into an intimate mechanical mixture of two solid phases. The two solid phases may be any of the alloy phases like solid solution, intermetallic compound or an electron compound.

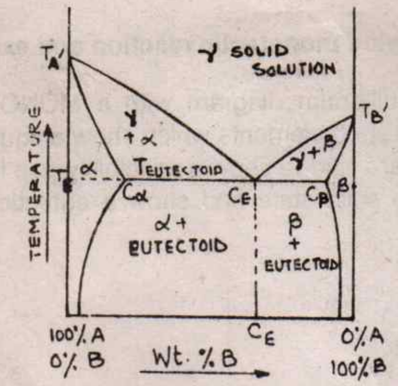


Fig.2.16.(25)

Fig. 2.16.(25) shows a eutectoid reaction in which γ solid solution of composition C_E %B is decomposing into an intimate mechanical mixture of two solid solutions - α of compositions C_α %B and β of composition C_β %B. The reaction can be written as -

$$\gamma \ (C_E \ \% \ B) \xrightarrow[T\,=\,T]{\text{Cooling}} \alpha \ (C_\alpha \ \% \ B) + \beta (C_\beta \ \% \ B)$$

EUTECTOID

During the reaction, the temperature remains constant. The temperature at which it occurs is known as eutectoid temperature. The composition of γ solid solution exhibiting eutectoid reaction is known as eutectoid composition (C_E) and the mechanical mixture formed is known as the eutectoid mixture. Eutectoid reaction is seen in Fe-C, Cu-Sn and Cu-Al systems.

Q.2.26. :- Write a short note on peritectoid reaction.

Ans. :- Peritectoid reaction is a solid state reaction in which one solid phase of a definite composition reacts with another solid phase of a definite composition at a constant temperature to give a third solid phase of a definite composition.

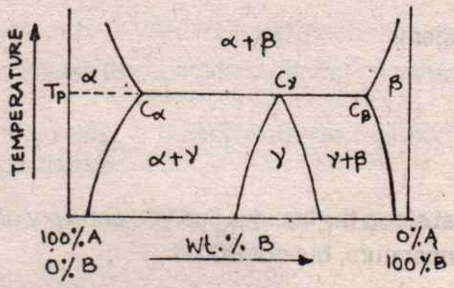


Fig.2.17.(26)

Fig. 2.17.(26) schematically shows a peritectoid reaction in which α solid solution of a composition C_α %B reacts with β solid solution of composition C_β %B at temperature T_P to give a third solid phase γ of C_γ %B. The reaction is represented by -

$$\alpha(C_\alpha\ \%\,B) + \beta(C_\beta\ \%\,B) \xrightarrow[T = T_P]{\text{Cooling}} \gamma(C_\gamma\ \%\,B)$$

C_γ is known as the peritectoid composition and T_P is known as the peritectoid temperature.

Q.2.27.:- What are the conditions which must be satisfied for the formation of an isomorphous system,or,for complete solid solubility ?

Ans. :- An isomorphous system is exihibited by two elements which are completely soluble in each other in solid state. For this, it is essential that the following conditions be satisfied :-

(a) The size factor between the two elements must be less than 15%.

(b) Their electrochemical natures should be identical. In other words both the elements should be electro-positive to the SAME extent or level.

(c) Their valencies must be identical.

(d) Their crystal structures must be same.

Examples of isomorphous systems are Cu-Ni, Fe-Ni, V-Ti system, etc.

Q.2.28. :- Show that in binary systems, liquidus line is always - monovariant while the solidus line can be monovariant or invariant.

Ans. :- A liquidus line indicates the liquidus temperature; i,e., the temperature at which solidification just begins. Hence, whatever be the nature of the equilibrium diagram,the number of phases in equilibrium along liquidus is two only, the liquid and the solid. Hence applying phase rule -

$$P + F = C + 1$$

With P = 2 and C = 2 (binary system)

we get $2 + F = 2 + 1$

Hence $F = 1$

I.e, liquidus is monovariant, meaning that along the liquidus line you can vary only one of the two variables, either composition or temperature, but not BOTH.

However, in case of solidus line, the number of phases in equilibrium can be two or three. For example, in the solidus line of Fig.2.9.(16), or the solidus line for alloys between 100% A and C %B in Fig.2.13.(22) and Fig.2.14.(23), the number of phases in equilibrium is only two, the liquid and the solid. Hence these solidus lines are monovariant.

However, if we consider the solidus line of Fig.2.12.(21), or alloys of composition between C %B and C %B in Fig.2.13.(22), we find that the number of phases in equilibrium is three; A + B + Liquid in case of Fig.2.12.(21), and + B + Liquid in case of Fig.2.13.(22). Hence applying phase rule, we get:-

$$3 + F = 2 + 1$$

Hence, $F = 0.$

Therefore the solidus line is invariant in such cases.

Q.2.29. :- Explan why a peritectic reaction occurs at a constant temperature ?

Ans. :- A peritectic reaction in binary phase diagrams can be represented by :-

$$\text{(Solid) + liquid} \xrightarrow[T = T]{} \beta\text{(Solid)}$$

It means that during the reaction, three phases are in equilibrium. since it is a binary system, the number of components is two. The phase rule for metallic systems in equilibrium is :-

$$P + F = C + 1$$

Where P is the number of phases in equilibrium, F is the number of degrees of freedom, and C is the number of components in the system.

In case of peritectic reaction in binary systems, $P = 3$ and $C = 2$

Hence applying phase rule :-

$$3 + F = 2 + 1$$

i.e. $F = 0$

Hence the system is INVARIANT and hence the peritectic reaction occurs at a constant temperture, because the conditions cannot be varied as $F = 0$.

Q.2.30. :- Explain why a binary eutectic reaction occurs at a fixed composition and constant temperature.

Ans. :- A eutectic reaction is given by the relation -

$$\text{Liq.} \xrightarrow[T = T_E]{\text{Cooling}} \text{Solid 1} + \text{Solid 2}$$

Hence the number of phases in equilibrium during the eutectic reaction is 3. Since it is a binary eutectic reaction, the number of componets in the system is 2. Phase rule for a metallic system is

$$P + F = C + 1$$

where

P = No. of phases in equilibrium

C = No. of components, and

F = No. of degrees of freedom

For the binary eutectic reaction, $P = 3$ and $C = 2$. Applying phase rule to this eutectic reaction, we get-

$$3 + F = 2 + 1$$

i.e. $F = 0$

i.e., the number of degrees of freedom is zero for a binary eutectic reaction. This means that the conditions under which the eutectic reaction is taking place can not be varied. Hence a binary eutectic reaction occurs at a fixed compostion and constant temperature.

Q.2.31. :- Apply phase rule to show that a binary eutectic in a ternary system is monovariant.

Ans. :- Since the system is ternary, the number of components in the system,. C, is 3. A binary eutectic reaction has three phases in equilibrium, i.e., P = 3. Applying phase rule for metallic systems

$$P + F = C + 1\text{, we get } 3 + F = 3 + 1$$

$$F = 1$$

Hence the binary eutectic in a ternary system is monovariant.

Q.2.32. :- What are the various types of intermediate phases formed in alloys ?

Ans. :- Elements with partial solid solubility may form certain phases other than the primary solid solutions. These phases are normally found in the "intermediate" region of the equilibrium diagrams and hence they are known as intermediate phases.

In general, three types of intermediate phases, or "compounds", are formed in alloy systems. They are-

(i) Electrochemical compounds
(ii) Electron compunds
(iii) Size factor compounds or Laves phases.

Electrochemical or valency compounds form at certain fixed composition according to the rules of normal valency. They melt at a fixed temperature.

Electrochemical compounds are formed at or around certain composition given by fixed valence-electron/atom ratios. Three such valence-electron/atom ratios are indentified. They are 3/2,21/13 and 7/4. Electron compounds with a given valence- electron/atom ratio exhibit identical crystal structures.

Size factor compounds are formed in certain particular systems, only when the size factor is such that the average coordination number can be more than 12- the maximum possible in close packed systems. These are also known as Laves phases. Examples of such size factor compounds are Cu_2 Mg, Ni_2 Mg, Be_2 Ag, Au_2 Pb, etc.

Q.2.33. :- What are electrochemical compounds or valence compounds ? Explain their characteristic properties.

Ans. :- Valence compounds or electrochemical compounds are formed in alloy systems, following normal rules of valency. Usually the bond is mixed bond,metallic and ionic or metallic and covalent. Such compounds are formed when there is a substantial difference in the electrochemical nature of the two elements. Examples are Mg Pb, AlSb, ZnS, MgSe etc. Normally they exist at a fixed composition - not over a range of compositions. These compounds have usually a high melting point - sometimes higher than the melting points of both the elements of which the compound is formed.They are hard and brittle, particularly if they are of those elements which have a high degree of covalent bond. They melt at constant temperatures.

Q.2.34. :- What are electron compounds ? Explain their characteristics.

Ans. :- When the difference in the electrochemical nature of two elements is not markedly different, electron compounds are formed in their phase diagram. The compounds form around specific valence- electron/atom ratios of 3/2, 21/13 and 7/4. Generally the electron compounds are formed in systems where the size factor is favourable for the formation of substitutional solid solutions, but complete solid solubility is not possible due to slight difference in the electrochemical nature between the two elements.

Electron compounds are similar in their properties to primary solid solutions. They have enough ductility and electrical conductivity. Hence electron compounds are sometimes known as "secondary solid solutions". A number of electron compounds form ordered structures. Unlike valency compounds, they usually form over a range of compositions determined by the valence- electrom/atom ratio.

Examples of electron compounds are-

3/2 - CuZn, Cu_3Al, FeAl etc.

21/13 - Cu_5Zn_8, $Cu_{31}Sn_8$

7/4 - $CuZn_3$, Cu_3Sn

Q.2.35. :- Draw cooling curves for - (a) a pure metal (b) a eutectic alloy (c) a hypoeutectic alloy.

Ans. :- See Fig. 2.18. (35), (a), (b) & (c).

Q.2.36. :- Draw the microstructures of - (a) a eutectic alloy (b) a hypoeutectic alloy or hypereutectic alloy.

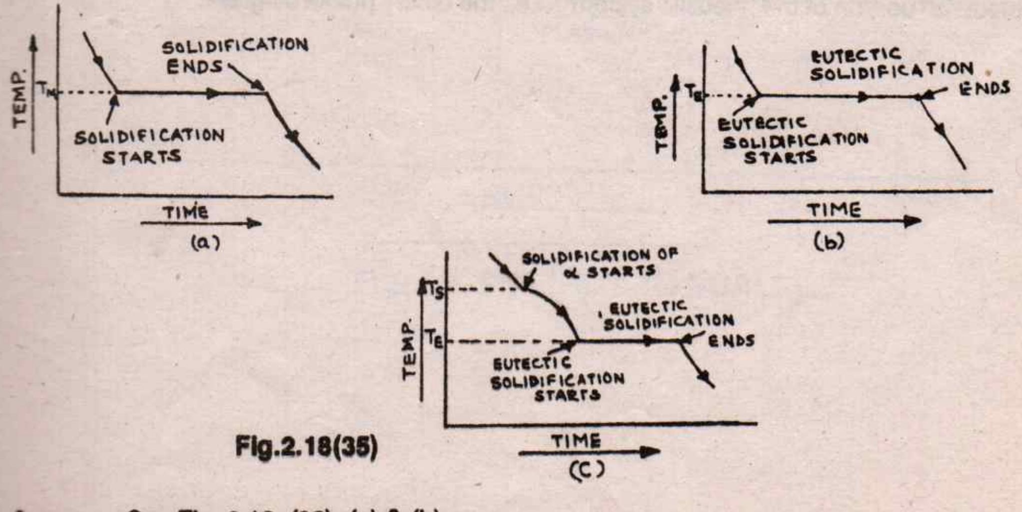


Fig.2.18(35)

Ans. :- See Fig. 2.19. (36), (a) & (b).

Q.2.37. :- What are intermetallic compounds ? When are they formed ?

Ans. :- Intermetallic compounds are nothing but intermediate phases described in Ans. No. 2.32. - viz.,

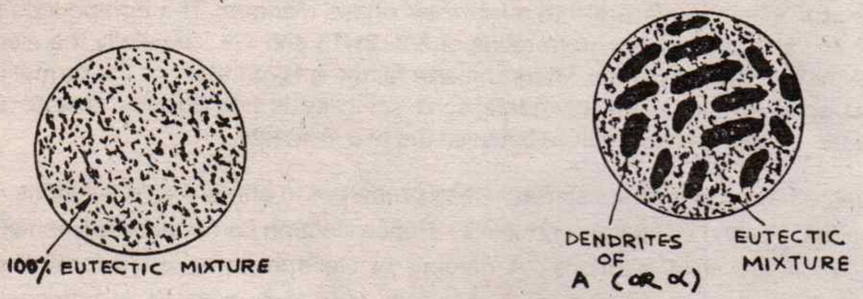


Fig.2.19.(36)

(i) Electrochemical compounds or valency compounds

(ii) Electron compounds

(iii) Size factor compounds.

The word "compound" is loosely used to indicate that they are formed around some specific compositions, although only valence compounds are "compounds" in the sences that they obey the normal rules of valency in their formation, just as the normal chemical compounds do. The adjective "intermetallic" is to indicate that they are found in the "intermediate" portion of the "metallic system" - i.e., the binary phase diagram.

Lesson 3.

IRON-CARBON DIAGRAM, STEELS AND HEAT TREATMENT

Q.3.1. :- Draw iron-iron carbide diagram and label it completely.

Ans. :- See Fig. 3.1.(1).

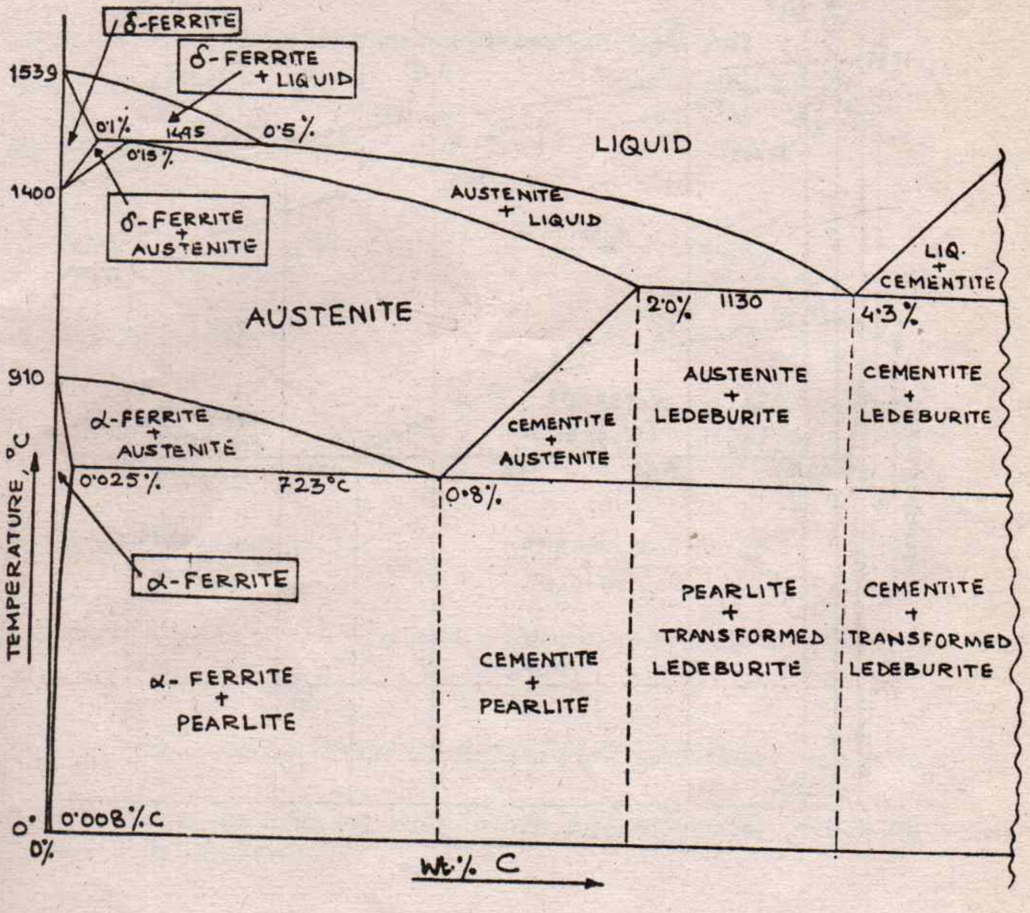


Fig. 3.1. (1). [NOT TO SCALE]

Q.3.2. :- Draw only steel portion of the iron-iron carbide diagram and label it completely.

Ans. :- See Fig. 3.2. (2)

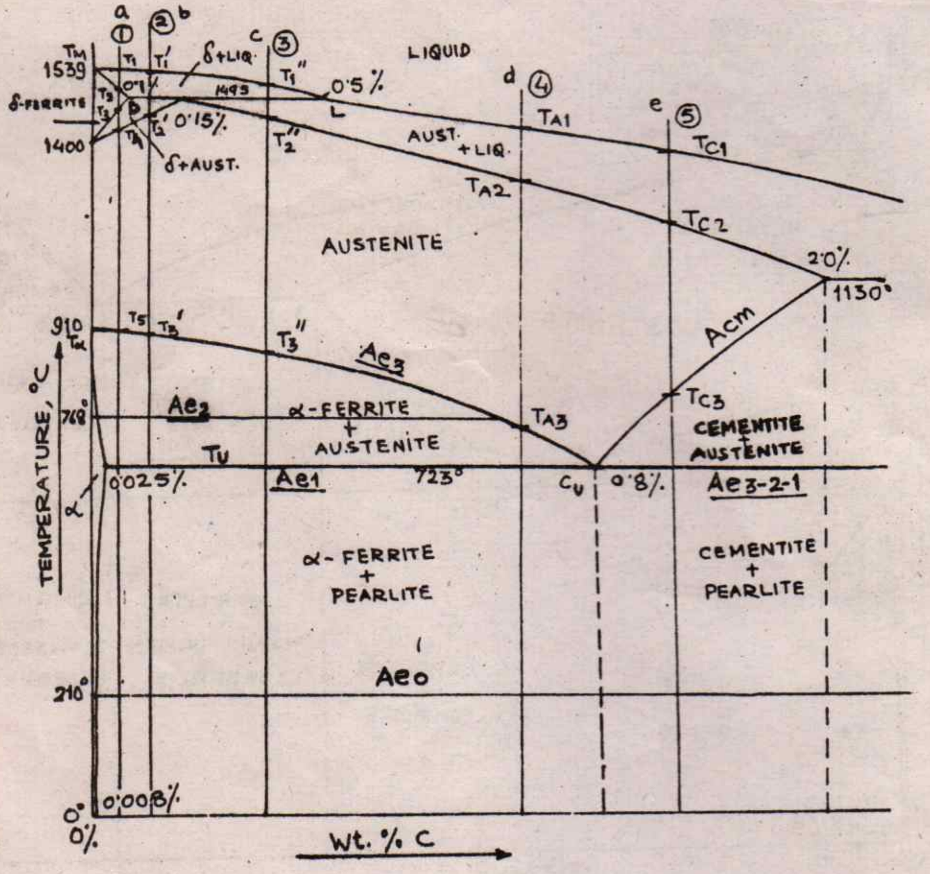


Fig. 3.2.(2)

Q.3.3. :- Explain the three INVARIANT reactions found in iron-carbon (iron-iron carbide) diagram.

Ans. :- we have already seen that in binary systems i.e., two component systems, we get an invariant reaction if three phases are in equilibrium, because under these conditions, applying phase rule, we find that

$$3 + F = 2 + 1$$

Hence $F = 0$

In iron-carbon diagram, three such invariant reactions are found.

They are given below :-

(a) Peritectic reaction :-

$$\delta\text{ - ferrite } (0.1\%\ C) + \text{Liq. } (0.5\%\ C) \xrightleftharpoons[1495^{O}C]{T} \text{Austenite } (0.15\%\ C)$$

(b) Eutectic reaction :-

$$\text{Liq. } (4.35\%C) \xrightleftharpoons[1130^{O}C]{T} \text{Austenite } (2.0\%\ C) + \text{Cementite } (6.67\%C)$$

(c) Eutectoid reaction :-

$$\text{Austenite } (0.8\%\ C) \xrightleftharpoons[723^{O}\ C]{T} \alpha \text{ ferrite } (0.025\%C) + \text{Cementite } (6.67\%C)$$

This mechanical mixture of -ferrite and cementite is known as pearlite.

Q.3.4. :- Define the following :- (a) δ-ferrite (b) Austenite (c) α -ferrite (d) cementite (e) pearlite (f) ledeburite.

Ans. :-

(a) **δ-ferrite :-** δ - ferrite is the interstitial solid solution of carbon in δ - iron. Since δ iron is stable only above 1410^{O} C, ferrite is found only in the high temperature region. It is BCC in crystal structure. The maximum solid solubility of carbon in δ-ferrite is 0.1% at 1495^{O}C.

(b) **Austenite :-** Austenite is the interstitial solid solution of carbon in γ-iron which is stable between 900^{O} C and 1410^{O} C. Hence austenite is found in the intermediate temperature range in the iron-carbon diagram.Its crystal structure is FCC.The maximum solid solubility of carbon in austenite is 2.0% at 1135^{O} C. Austenite of 0.8% C undergoes a eutectoid reaction at 723^{O} C.

(c) α **ferrite:-** α ferrite is the interstitial solid solution of carbon in α -iron which is stable only below 900 C.Hence α - ferrite is found in the lower temperature region of the Fe-C diagram.Its crystal structure is BCC.The maximum solid solubility of carbon in α - ferrite is 0.025% at 723^{O}C and it decreases to .008% at 0^{O} C. Thus α -ferrite is ALMOST pure iron at room temperature because it contains very small amount of carbon in solution.

(d) **Cementite :-** Cementite is the intermetallic compound of iron and carbon. It has a chemical formula Fe_3C,contains 6.67%C and has a fixed composition. Its melting point is quite high,higher than that of iron. Its crystal structure is ORTHORHOMBIC. Being an intermetallic compound, it is extremely hard and brittle because the bond in it has a greater degree of covalent nature. It is the hardest phase found in alloys of iron with carbon.

(e) **Pearlite :-** Pearlite is the product of eutectoid reaction in Fe-C diagram. When austenite containing 0.8% C decomposes eutectoidally at 723^{O} C, it forms pearlite - which is an intimate mechanical mixture of ferrite containing 0.25% C and cementite with 6.67% C. At room temperature, the α -ferrite in this mixture contains approximately 0.008% C because the solid solubility of carbon decreases in α-ferrite with decrease in temperature. Pearlite is lamellar in microstructure - it contains alternate lamellae (plates) of α-ferrite and cementite as illustrated in Fig.3.3.(4). However, this is resolved and clearly seen at higher magnifications only. At low magnifications, it appear dark under the microscope if nital had been used as the etchant.

Fig.3.3(4)

(f) **Ledeburite :-** Ledeburite is the product of the eutectic reaction in Fe-C diagram;

$$\text{Liquid (4.35\%C)} \; \underset{\overleftarrow{1130^{0}C}}{\xrightarrow{T}} \; \text{Austenite (2\%C) + Cementite (6.67\%C)}$$

It is a mechanical mixture of austenite and cementite when it is formed from eutectic liquid. On further cooling, the composition of austenite changes, the eutectoid reaction occurs and austenite changes to pearlite.Hence all the austenite in ledeburite is present as pearlite at room temperature. Therefore, the structure (pearlite + Cementite) which is derivied from the original ledeburite (austenite + Cementite) is known as Trformed Ledeburite.

Q.3.5.:- Explain the "Peritectic Reaction" occuring in the iron-carbon diagram.

Ans. :- In the steel portion of the iron carbon diagram, we find a peritectic reaction which takes place at 1495° C. In this reaction, δ- ferrite containing 0.1% C reacts with liquid containing 0.5% C to produce austenite containing 0.15%C ;

$$\delta \text{ ferrite } (0.1\%C) + \text{Liq. } (0.5\%C) \underset{1495^{\circ} C}{\overset{T}{\rightleftarrows}} \text{Austenite } (0.15\%C)$$

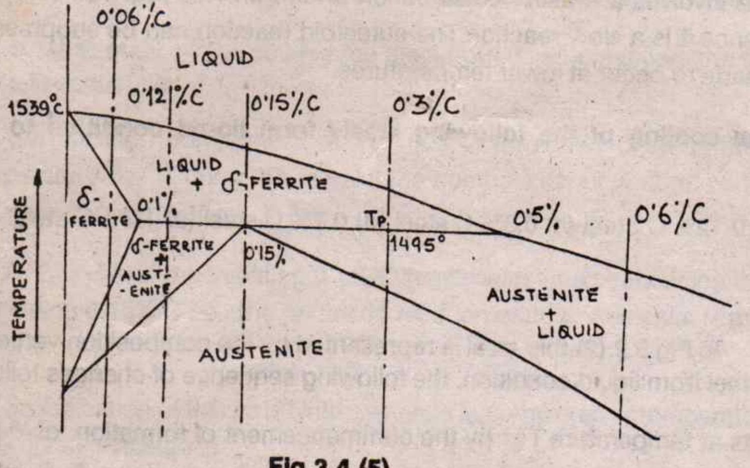


Fig.3.4.(5)

When the composition of solidifying steel is exactly 0.15%C - the peritectic composition,the proportions of δ-ferrite and liquid are just correct to produce 100% austenite without leaving either of the phases in excess. However, if the carbon content of solidifying steel is less than 0.15% C - say 0.12%C, δ -ferrite is more in proportion at T_P and hence some δ-ferrite is left in excess after the peritectic reaction as shown in Fig. 3.4.(5). Similarly for a steel containing greater than 0.15% C - say 0.3% C, the proportion of liquid is more at the peritectic temperature and hence after the reaction,liquid remains in excess as shown in Fig. 3.4.(5).

Since both δ-ferrite and liquid are necessary for the peritectic reaction to occur, steels containing less than 0.1% C or more than 0.5% C do not show peritectic reaction in their solidification because they do not contain both these phases coexisting at the peritectic temperature.

Q.3.6. :- Describe the eutectoid reaction in the Fe-C diagram.

Ans. :- In the iron carbon diagram, a eutectoid reaction occurs at 723 C. In this reaction, austenite containing 0.8% C decomposes isothermally into a mechanical mixture of -ferrite containing 0.025%C and cementite containing 6.67%C. This mechanical mixture is known as pearlite which has a lamellar structure when seen at higher magnification.This structure resembles the surface structure of mother of pearl - hence the name. The eutectoid reaction is written as-

$$\text{Austenite } (0.8\%C) \underset{723^{O}\,C}{\overset{T}{\rightleftarrows}} \alpha\text{ - ferrite } (0.025\%C) + \text{Cementite } (6.67\%C)$$

Hence from the same region of steel,two phases entirely different in composition have to be formed --- one very rich in carbon (Fe_3C) and the other very poor in carbon. Hence the eutectoid reaction involves a drastic redistribution of carbon.This requires diffusion of carbon atoms and hence it is a slow reaction.The eutectoid reaction can be suppressed at 723^{O} C and can be made to occur at lower temperatures.

Q.3.7. :- Explain the cooling of the following steels form liquid condition to room temperature :-

(a) 0.08% C Steel (b) 0.12% C Steel (c) 0.3% C steel (d) 0.7% C steel (e) 1.2% C steel.

Ans. :-

(a) 0.08% C steel :- In Fig.3.2.(2),this steel is represented by the composition vertical No. (1). On cooling this steel from liquid condition, the following sequence of changes follows :-

(i) Solidification starts at temperature T_1 by the commencement of formation of δ-ferrite. On cooling below T_1, the composition of δ- ferrite and liquid change along T_MD and T_ML respectively. The solidification is completed at temperature T_2.

(ii) The structure of the steel remains as δ-ferrite between temperature T_2 and T_3. At T_3, change of δ -ferrite into austenite commences. This change is completed at T_4 temperature.

(iii) The steel remains as austenite between temperatures T_4 and T_5. At T_5, austenite starts changing into α- ferrite. The change gradually takes place first at the grain boundaries and then within the grains.During this separation of α -ferrite, the composition of the austenite changes along $T_\alpha C_u$ till it becomes 0.8% C at 723^{O} C.

(iv) At 723^{O} C this austenite changes into pearlite.There is no change in structure on cooling further to room remperature. At room temperature the structure shows -ferrite grains and a small amount of pearlite at grain boundaries.

(b) 0.12% C steel :- On cooling this steel from liquid condition, the following changes occur in sequence, as shown in Fig.3.2.(2), for composition vertical (2).

(i) Solidification starts at temperature $T_{1'}$. Formation of δ-ferrite starts. Between $T_{1'}$ and TP more δ-ferrite forms. Compositions of δ - ferrite and liquid change along T_MD and T_{ML} respectively. At T_P , peritectic reaction takes place between δ -ferrite and liquid. Austenite is formed and excess δ-ferrite remains.

(ii) At $T_{2'}$ the change of δ -ferrite is completed.

(iii) Between temperatures $T_{2'}$ and T3' the structure remains austenitic. At T 3' austenite starts changing into α-ferrite. Between $T_{3'}$ and TU, the composition of α-ferrite changes along $T_\alpha C_\alpha$ and that of austenite along T_α C_U . At T_U , α -ferrite contains 0.025% C and austenite contains 0.8% C. This austenite decomposes at this temperature following eutectoid reaction and forms pearlite. No further change occurs upto room temperature. The structure of the steel shows grains of α-ferrite with pearlite at the grain boundaries.

(c) 0.3% C steel :- On cooling the steel from liquid condition, the following changes take place in sequence :-

(i) Solidification commences at T_1 " , with formation of δ -ferrite and comtinues upto temperature T_P . During this interval the composition of δ -ferrite and liquid change along T_MD and T_ML respectively.

(ii) At T_P , δ-ferrite containing 0.1% C reacts with liquid containing 0.5%C to give austenite containing 0.15% C i.e., the peritectic reaction occurs. Austenite is the product with excess liquid left over.

(iii) Solidification of this liquid into austenite is completed at temperature T_2" . The structure is completely austenite.

(iv) No change occurs upto $T_{3"}$. At T3" , α-ferrite starts separating out from austenite.

Further changes upto room temperature are similar to those in 0.12% C steel.

The structure at room temperature shows grains of -ferrite and regions of pearlite.

(d) 0.7% C steel :- On cooling this steel from liquid condition, the sequence of changes is as given below :-

(i) Solidification starts at T_{A1} temperature by the formation of austenite.

(ii) Solidification is completed at temperature T_{A2} .

Below this temperature austenite remains without any change till T_{A3} temperature is reached when α -ferrite starts forming from austenite. Further changes are similar to those seen in 0.3% C steel. The structure of the steel, at room temperature, shows regions of pearlite with boundaries of α-ferrite.

(e) **1.2% C steel :-** On cooling this steel from liquid condition, the changes occur as given below :-

(i) Solidification commences at temperature T_{C1} . Austenite forms.

(ii) Solidification ends at T_{C2} . Structure is fully austenite.

(iii) No change occurs between T_{C2} and T_{C3} temperature. At T_{C3} temperature, precipitation of cementite from austenite starts and continues upto T_U temperature. This happens because the solid solubility of carbon in austenite decreases from 2.0% at 1130 C to 0.8% at 723°C. The composition of the austenite changes along T_{C3} T_U till it becomes 0.8% C at 723°C.

(iv) All this austenite under goes eutectoid trformation and forms pearlite.

At room temperature, the structure of steel shows regions of pearlite with boundaries of cementite.

Q.3.8. :- Explain the difference between the microstructures of 0.7%C steel and 1.0%C steel.

Ans. :- When etched with Nital, both these steel samples show black grain-like areas surrounded by white grain boundaries. In both the samples, the black grain-like area is of pearlite. In hypo-eutectoid steel the white grain boundaries are of α -ferrite while in hyper-eutectoid steel the white grain boundaries are of cementite. Hence in general, the microstructures of both these steels look similar.

One can calculate the relative proportions of α-ferrite and cementite, present along with pearlite, and it can be shown that the amount of free α-ferrite in hypoeutectoid steel of 0.7%c is about 12.5% while the amount of free cementite in 1.0%C steel is only about 3%. Hence the white grain boundaries of α - ferrite in hypo-eutectoid steel must be much thicker than the white grain boundaries of cementite in hyper-eutectoid steel. Thus the sample with thinner grain boundaries is hyper-eutectoid steel.

Apart from the thickness or thinness of the grain boundary, there is another point of difference in structure. The α-ferrite grain boundaries in hypo-eutectoid steel are discontinuous and nearly linear while the cementite grain boundaries in hyper-eutectoid steel are extremely fine, continuous, curvaceous or wavy lines.

Q.3.9. :- Is pearlite a phase ? Why or why not ?

Ans. :- Pearlite is not a phase. It is an intimate mechanical mixture of TWO phases; α-ferrite and cementite. A phase is characterized by its crystal structure and at any place within the phase it is same. In pearlite, those regions which are α - ferrite, have a different crystal structure than those regions which are cementite. Pearlite as a whole has no specific crystal structure. Hence it is not a phase but it is a **Phase Mixture**.

Such phase mixtures are termed as MICRO-CONSTITUENTS.

For the purpose of simplicity in describing the microstructure, and for calculation of the proportion, it is treated as a single phase.

Since pearlite is not a single phase, in high carbon steels, the regions of pearlite are not described as "grains of pearlite" because within a grain the orientation of atomic arrangement is same everywhere. Since pearlite contains two phases,the orientation of atomic arrangement **can NOT be same** throughout its volume. That is why we do not say "a pearlite grain " but describe it as a "a region of pearlite".

Q.3.10. :- Calculate the percentage by weight, of -ferrite and cementite in pearlite at room temperature.

Ans. :- Pearlite forms at 0.8% C. At room temperature which can be assumed to be O C, it consists of -ferrite.of 0.008% C and cementite of 6.667% C. For calculating the weight proportions of ferrite and cementite, we apply lever rule -

$$\text{Wt.of ferrite} \times (0.8-0.008) = \text{Wt. of cementite} \times (6.67-0.8)$$

or

$$\text{Wt. of } \alpha\text{-ferrite} \times 0.792 = \text{Wt. of cementite} \times 5.87$$

Hence;

$$\frac{\text{Wt. of } \alpha\text{-ferrite}}{\text{Wt. of cementite}} = \frac{5.87}{0.792}$$

Hence ; $\text{Wt \% of } \alpha\text{-ferrite} = \frac{5.87}{6.662} \times 100 = 88.11\ \%$

and; $\text{Wt. \% of cementite} = \frac{0.792}{6.662} \times 100 = 11.89\%$

Since the α -ferrite contains very little carbon, only 0.008,many books assume that it can be neglected and hence ferrite is assumed to form at 0.0% C, to simpify calculation.

Q.3.11. :- Explain the microstructures of the follwoing steels and calculate the wt. percent of various (i) microconstituents (ii) Phases present in each of them at room temperature (taken as O C) :-

(a) 0.15% C (b) 0.3% C (c) 0.7% C and (d) 1.0% C.

Ans. :- Referring to steel portion of the iron carbon diagram shown in Fig.3.5.(11) and assuming that the solid solubility of carbon in α-ferrite is negligible, i.e., 0%, we can calculate the microconstituents or phases in each case.

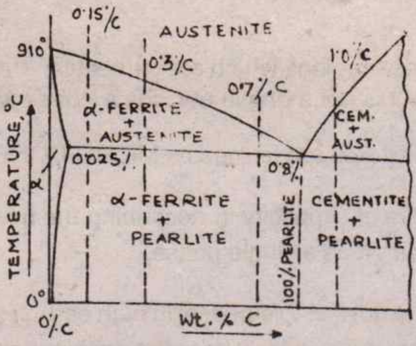


Fig. 3.5. (11)

(a) **0.15% C steel :-** It is evident that at room temperature, this steel contains the microconstituents α -ferrite and pearlite. Since pearlite contains phases α -ferrite and cementite, it me that the phases present in this steel or α-ferrite and cementite.

For the calculation of wt. percentages of microconstituents and phases, we apply lever rule. We know that the composition of - ferrite is 0%C, cementite 6.67% C and pearlite 0.8% C.

Applying lever rule -

Microconstituents' wt. % :-

$$\text{Wt. \% of } \alpha\text{-ferrite} = \frac{0.8-0.15}{0.8-0.00} \times 100 = 81.25\ \%$$

$$\text{Wt. \% of pearlite} = \frac{0.15-0.00}{0.8-0.00} \times 100 = 18.75\%$$

Phases Wt. % :-

$$\text{Wt. \% of } \alpha\text{-ferrite} = \frac{6.67-0.15}{6.67} \times 100 = 97.75\ \%$$

$$\text{Wt. \% of cementite} = \frac{0.15-0.00}{6.67} \times 100 = 2.25\%$$

(b) **0.3% C steel :-** At room temperature, this steel contains -

Microconstituents - α-ferrite and pearlite

Phases - α-ferrite and cementite.

Applying lever rule -

Microconstituents' wt % :-

$$\text{Wt.\% of } \alpha\text{-ferrite} = \frac{0.8-0.3}{0.8-0.00} \times 100 = \frac{0.5}{0.8} \times 100 = 62.5\%$$

Wt.% of pearlite $= \dfrac{0.3-0.00}{0.8-0.00} \times 100 = \dfrac{0.3}{0.8} \times 100 = 37.5\%$

Phases' wt.% :-

Wt. % of α-ferrite $= \dfrac{6.67-0.3}{6.67-0.00} \times 100 = \dfrac{6.37}{6.67} \times 100 = 95.5\%$

Wt.% of cementite $= \dfrac{0.3-0.00}{6.67-0.00} \times 100 = \dfrac{0.3}{6.67} \times 100 = 4.5\%$

(c) 0.7% steel :- At room temperature -

Microconstituents present - α - ferrite and pearlite

Phase - α - ferrite and cementite.

Wt.% of microconstituents :-

wt.% of α - ferrite $= \dfrac{0.8-0.7}{0.8-0.00} \times 100 = \dfrac{0.1}{0.8} \times 100 = 12.5\%$

Wt.% of pearlite $= \dfrac{0.7-0.00}{0.8-0.00} \times 100 = \dfrac{0.7}{0.8} \times 100 = 87.5\%$

Wt.% of phases :-

Wt.% of α -ferrite $= \dfrac{6.67-0.7}{6.67-0.00} \times 100 = \dfrac{5.97}{6.67} \times 100 = 89.5\%$

Wt.% of cementite $= \dfrac{0.7-0.00}{6.67-0.00} \times 100 = \dfrac{0.7}{6.67} \times 100 = 10.5\%$

(d) 1.0% C steel :- At room temperature this steel contains -

Microconstituents - cementite and pearlite

Phases - cementite and ferrite

Wt.% of Microconstituents :-

Wt.% of cementite $= \dfrac{1.0-0.8}{6.67-0.8} \times 100 = \dfrac{0.2}{5.87} \times 100 = 3.4\%$

Wt.% of pearlite $= \dfrac{6.67-1.0}{6.67-0.8} \times 100 = \dfrac{5.67}{5.87} \times 100 = 96.6\%$

Wt.% of phases :-

$$\text{Wt.\% of cementite} = \frac{1.0-0.00}{6.67-0.00} \times 100 = \frac{1.0}{6.67} \times 100 = 15.00\%$$

$$\text{Wt.\% of } \alpha \text{ - ferrite} = \frac{6.67-1.0}{6.67-0.00} \times 100 = \frac{5.67}{6.67} \times 100 = 85.00\%$$

Q.3.12. :- Explain the variation in the mechanical properties of un-heat treated steel with increase in the carbon content.

Ans. :- We can see that as the carbon content increases, the amount of cementite present in steel (either as pearlite or as free cementite along with pearlite) increases. It has already been mentionedthat cementite is the hardest phase in Fe-C alloys. Hence as the amount of cementite in steel increases,its hardness, yield strength and tensile strength must increase and ductility must decrease. It me that as the percentage of carbon in steel increases, its hardness, yield strength and tensile strength increase and its ductility decreases.

Q.3.13. :- Explain how the use of a plain carbon steel is determined by its carbon content :-

Ans. :- We know that as the carbon content in steel increases, it becomes harder and stronger but its ductility is reduced. Hence the use of a steel is determined by its properties.

For those applications where higher deformability is required and lower strength is acceptable, low carbon steel is used. For example for the manufacture of sheet, skelp, reinforcement rods,angles etc., the carbon content is about 0.1 - 0.15 %.

In applications where strength should be a little more, the carbon content is increased. For example for engineering components like shafts etc., the carbon content is between 0.3% and 0.4%.

There are certain applications, where high strength with optimum ductility (or toughness) and wear resistance is required. For example, rails, anvils, forming tools etc., where dynamic loading conditions require a combination of high strength, wear resistance and toughness. Such steels contain 0.55% C.

Applications where wear resistance is more important, hardness alone becomes the criterion - not the toughness or ductility.

For example, wood working tools are made of steel containing 0.7 to 0.8%C while metal working tools like files, blades etc., may contain as high as 1.4%C.

An Interesting thing is that the ordinary razor blade used to be made of 1.4%C steel. This high carbon content is necessary because a very sharp keen cutting edge is necessary for shaving.

Q.3.14. :- What are the various critical temperatures in Fe-C diagram ? How are they represented while heating and while cooling ?

Ans. :- The critical temperatures of a given steel are the temperatures at which a given steel has certain change in structure, i.e., where a trformation starts. In the Fe-C diagram, we find various critical temperatures like Ae_0, Ae_1, and Ae_2. The subscript "e" denotes that the critical temperature refers to equilibrium condition of heating or cooling. These critical temperatures are shown in Fig. 3.2.(2) Their significance is given below :-

Ae_0 :- The curie temperature of cementite. Above this temperature cementite is non-magnetic. It is at 210°C.

Ae_1 :- Eutectoid temperature at 723° C. Above this temperature no pearlite is seen and below this temperature austenite is not found. This is know as LOWER CRITICAL TEMPERATURE.

Ae_2 :- Above this temperature α-ferrite becomes non - magnetic, i.e.,it is the Curie temperature of α-ferrite. Ae_2 is at 768° C.

Ae_3 :- This is known as UPPER CRITICAL TEMPERATURE. Above this structure the steel is completely austenitic. This is the temperature below which α-ferrite is found.

As already mentioned, the above critical temperatures are with respect to equilibrium rate of heating or cooling. However, in practice the cooling rate or heating rate is always faster.Hence during heating the magnitude of a given critical temperature gets raised while it gets suppressed on cooling. For example, eutectoid temperature will be lower than 723° C on cooling, but higher than 723° C while heating. Hence,the critical temperatures while heating and while cooling are represented by different magnitudes and hence different notations. The subscript c (standing for "chaufage" - heating in French) is used for heating and r (standing for "refroidissement" - cooling in French) for cooling. Thus we have Ac_1 temp. and Ar_1 temperature; Ac_3 temp. and Ar_3 temp. etc. It is evident that

$$Ac_1 > Ae_1 > Ar_1$$

and

$$Ac_3 > Ae_3 > Ar_3$$

Q.3.15. :- What are "S" curves or "C" curves or TTT curves ?

Ans. :- The iron-carbon diagram tells us about the condition of steel only for equilibrium conditions or for cooling rates which are very slow. However, in industry the cooling rates are never so slow- and sometimes, deliberately a faster cooling rate is used. A cooling rate is a function of both time and temperature. Hence if we want to study the effect of cooling rate on steel, we must study the eutectoid trformation in steel as a function of both time and temperature. The best method to start is to study the trformation at a "constant" temperature as a function of time,and repeat the experiment at "different constant temperatures". **When the results of such "isothermal" transformation of steel are plotted against time, we get a diagram which is known as TTT diagram (or curves), The abbreviation of Time - Temperature-Trformation diagram. Because of their peculiar shape they are also known as "S-curves" or "C-curves".**

Q.3.16:- How are the S-curve or TTT-curves determined for a given steel ?

Ans. :- The method of determining S-curves for a given steel is as follows. :-

(a) Thin samples of small size are chosen.

(b) About five or six samples are heated to their austenitizaion temperature - ie., $Ac_3 + 50^{O}$ C in case of hypoeutectoid steels and $Ac_1 + 50^{O}$C in case of hyper-eutectoid steels.

(c) The specimens are taken out of the furnace and immediately quenched into a molten salt bath or molten metal bath kept at a constant temperature below Ar_1 temp., say T_1 temperature.

(d) Different specimens are allowed to trform for different times at this constant temperature. After the pre-determined times, a given specimen is taken out and quenched in water to room temperature. In this step, austenite transforms to pearlite up to the time for which the transformation is allowed and then on quenching, the untrformed austenite trforms into martensite. Pearlite and martensite can be distinguished from each other.

(e) With the help of the study of the amount of pearlite formed at different times, the times required for the transformation to start,and to finish are determined. Let these be ts_1 and tf_1

(f) The experiment is repeated at different temperatures T_2, T_3, T_4, etc., and t_s and t_f corresponding to these temperatures are determined.

(g) A plot is made between temperature and time, and t and t values for different temperatures are plotted on it. When all the points indicating "start" of the trformation and "finish" of the trformation are joined together, as shown in Fig.3.6.(16), we get two S-shaped curves.

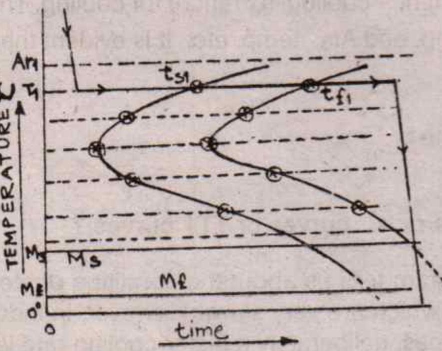


Fig.3.6.(16)

It can be seen that on cooling a steel below a given temperature, martensite starts forming, and below a certain temperature, the trformation to martensite is nearly finished. These two temperatures are also depicted and they are known as Ms temperature and Mf temperature, respectively.

Q.3.17.:- Describe the "S-curve"for a eutectoid steel (0.8%C steel):-

Ans. :- Fig.3.7.(17) shows the S-curve for a eutectoid steel. Since S curves are nothing but isothermal trformation curves, they indicate the product of trformation at any given temperature. The two curves show the (Aust. → pearlite) start and)(Aust. → pearlite) finish times. At any given temperature the time required for the austenite → pearlite trformation to start is known as "incubation period". The incubation period is minimum when the trformation occurs at a temperature corresponding to the nose temperature.

The transformation products obtained at different temperatures are indicated in the figure. All the products--course pearlite, fine pearlite, upper bainite and lower bainite - are mixtures of α ferrite and cementite, but the fineness of dispersion increases as the trformation temperature decreases. Thus fine pearlite is a finer disperson of cementite in α ferrite than coarse pearlite is. Bainites are so fine in structure that the dispersion can be seen only at higher magnification. Since a finer disperson gives greater hardness and strength, bainite is harder than pearlite. Approximate R_C hardness of each constituent is indicated in the figure in brackets.

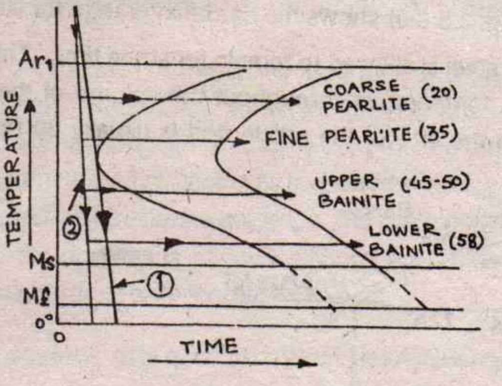


Fig. 3.7.(17)

Q.3.18. :- Define critical cooling rate of a steel with respect to its S-curves.

Ans. :- In Fig.3.7.(17), line 1 shows the critial cooling rate. It can be seen that if the steel sample is cooled from the austenitic condition at a rate faster than the critical cooling rate, austenite to pearlite trformation will not even start. For example, line 2 exhibits a cooling rate faster than the critical cooling rate. It can be seen that this line does not intersect the A-- P start line in the S-curve. Hence if the steel is cooled from the austenitic condition at this rate, the austenite- pearlite trformation is completely avoided and the steel is completely trformed into martensite because this line cuts both Ms and Mf lines.

Hence the critical cooling rate of a steel is that cooling rate which must be exceeded to produce 100% martensite on cooling a steel from the austenitic condition.

Q.3.19. :- What is martensite ? Why is it very hard ?

Ans. :- The maximum solid solubility of carbon in B.C.C. α - ferrite is 0.008% C at room temperature. When austenite is cooled at a rate faster than the critical cooling rate, it trforms to martensite of same composition. Suppose a steel of 0.6% C is used, the martensite produced from it must also contain 0.6% C, Since the crystal sturcture which is stable at room temperature is BCC - of α-iron, all this carbon must remain in solution in α-iron. But the maximum solid solubility of carbon in α-iron is only 0.008% C at $0^{O}C$. Hence martensite is a supersaturated intersititial solid solution of carbon in α-iron. Because of supersaturation, the crystal lattic of α-iron is distorted from BCC to body-centred-tetragonal. Hence martensite is body- centred-tetragonal in structure. This distortion in the lattice causes severe lattice strains and hence the martensite is very hard. Up to 0.6% C, the hardness of martensite is nearly proportional to its carbon content. Martensite containing 0.6% C or more has approximately a hardness of 64 Rc.

Q.3.20. :- What is hardening or quenching of steel ?

Ans. :- Hardening or quenching of steel is carried to produce martensitic structure to harden the steel. In this heat- treatment, the steel is heated to a temperature where it is completely (or nearly) austenitic in structure. For this, hypo- eutectoid steels are heated to $Ac_3 + 50^{\circ}C$ and hyper - eutectoid steels are heated to $Ac_1 + 50^{\circ}C$. This temperature range is known as the hardening range. Fig. 3.8.(20) shows the hardening range for steels.

At this temperature, the steel is allowed to remain for some time. This is known as soaking time. This equalizes the temperature throughout the volume of the article being heated. This time depends upon the size of the article and is usually 30 min per 30 mm thickness of the article.

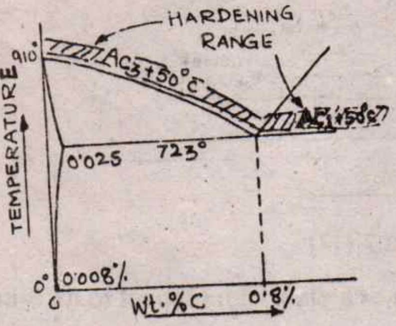


Fig. 3.8.(20)

After soaking at austenitization temperature, the steel article is quenched - cooled fast -inwater or oil depending upon its composition, to produce martensite.

Q.3.21. :- What do you understand by hardenability ?

Ans. :- When a steel component of a given cross-sectional area is quenched in order to harden, the cooling rate across the entire cross section is not same. It varies from surface to centre. Portions nearer to the surface may cool fast enough to produce martensite. However, as we move towards the central portion, the cooling rate decreases and a stage may come after which the cooling rate may be slower than critical cooling rate. In such regions the structure will not be 100% martensite; instead it will be a mixture of martensite and ferrite. To produce fully martensitic structure at these regions also, the cooling rate must be drastically increased. However at such drastic quenching rates, the steel component gets heavily warped or, some times, cracks are produced. Thus the ease with which a steel can be completely hardened will depend upon its ability to avoid austenite-pearlite trformation even at a slower cooling rate. This ability of the steel to harden completely by forming martensite throughout its cross-section, even at lower quenching rates, is known as the hardenability of steel.

It is evident that the hardenability of the steel is directly related to its critical cooling rate. The lower is the value of critical cooling rate, the higher will be the hardenability.

Q.3.22. :- Explain the two factors that affect the hardenability of a steel.

Ans. :- We have seen that the easier it is to avoid the trformation of austenite into pearlite - the higher is the hardenability of steel. The two factors which affect the hardenability are -

(i) **Composition :-** The critical cooling rate of the steel is dependent upon its composition. We have seen that the hardenability depends upon the magnitude of the critical cooling rate. Hence the hardenability of steel is the function of its chemical composition. Addition of alloying elements normally increases the hardenability of steel.

(ii) **Grain size :-** As the size of the austenite grains of the steel being quenched increases, the grain boundary area decreases. Since the grain boundary area facilitates the nucleation of a pearlite nodule, a larger grain boundary area means more nuclei, faster transformation and hence the austenite easily transforms to pearlite. Hence the hardenability is low. On the other hand if the grains of austenite are large, the grain boundary area is decreased and the nucleation of pearlite nodules is difficult. Hence austenite to pearlite trformation is made difficult. Hence the hardenability increases.

Q.3.23. :- Define severity of a quench. What is an ideal quench?

Ans. :- The severity of a quenching medium is mathematicaly defined as -

$$H = \frac{\text{Heat transfer coefficient between steel \& quenching medium}}{\text{Thermal conductivity of the steel}}$$

Physically speaking, the severity of the quench of a medium is its efficiency with which it can bring down the surface temperature of the steel being quenched to the temperature of the medium itself.

An ideal quench is defined as that which brings the surface temperature of the steel INSTANTANEOUSLY (that is, without the loss of ANY time) to the bath temperature. The severity of such a quench is defined to be infinity (∞). H values of some typical media are-

Medium	Severity of quench H	
	bath still	bath agitated
Water	1.0	2 - 4
Oil	0.2	0.4 - 0.8
Brine	2.0	3 - 5

Q.3.24. :- Define critical diameter and distinquish between critical diameter and ideal critical diameter.

Ans. :- Let us take a number of rods of different diamenters (length = 10 dia.), of a given steel, austenitize them and quench them in a bath of a given severity of quench. Let the hardened rods be cut in the middle and the microstructure of the middle cross section of each rod be examined. It will be seen that the smallest rod hardens completely, showing martensite throughout the section, giving a hardness of about 64 Rc through out. It is quite likely that in some rod with a larger diameter, the centre shows 99% martensite and 1% pearlite. In a third rod with still larger diameter, the structure at the centre of the rod may be 50% martensite and 50% pearlite.

The critical diameter is defined either using 99% martensite criterion or 50% martensite criterion. Using the latter criterion, the critical diameter of a steel is that diameter of the rod, which, on hardening, shows 50% martensite at the centre.

It is evident that the critical diameter D_C refers to a given severity of the quench. Hence to make it completely a material property alone, ideal critical diameter D_I is defined.

The ideal critical diameter of a steel is that diameter of a rod, which when quenched in a bath of $H = \infty$, (i.e., an ideal quench) shows 50% martensite at the centre (or 99% martensite at the centre, depending upon the criterion used).

It is evident that $D_I > D_C$.

Q.3.25. :- Describe Jominy end - quench test for determining the hardenability of a steel.

Ans. :- Determining hardenability of a steel in terms of finding its ideal critical diameter is very cumbersome. An easier alternative test is Jominy end-quench test.

This is a standardized test. The specimen is steel rod machined with a collar, with dimensions as shown in Fig. 3.9.(25). The diameter is 25.4 mm. The fixture used is shown in the figure.

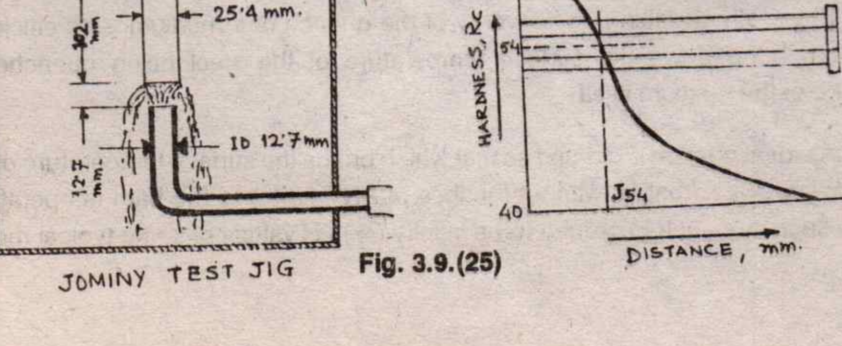


Fig. 3.9.(25)

The test specimen is austenitized at the temperature recommended for the given steel; and is quickly trferred to the test fixture. Immediately the water jet is started. The water-jet pipe should have an internal dia. of 12.7 mm; the distance between the specimen end and the end of the jet-pipe is kept 12.7 mm. The water pressure of jet is so adusted that the free jet achieves a height of 64 mm from the end of the pipe. The temperature of water is kept between 21° C and 27° C.

In the test, the specimen is being quenched from one end. Hence at different distances from this end, the cooling rate would be different. The test is continued till the temperature of the specimen reaches room temperature.

After the test, two flat parallel surfaces are ground on the specimen opposite to each other, along the entire length of the specimen. The hardness along one of these faces is measured at intervals of 1.6 mm from the quenched end. Near this end, the interval may be reduced to 0.8 mm to make the measurements precise. A plot between the hardness and distance from the quenched end is made. We get a plot similar to one shown in the figure. The hardness changes most rapidly at 50% martensite region, with a representiative hardness of 54 Rc. The distance at which this critical hardness is achieved, is called the Jominy distance.

Q.3.26. :- Explain why the hardening range used for hypoeutectoid steel is $Ac_3 + 50\,^{\circ}C$ while for hypereutectoid steel it is $Ac_1 + 50\,^{\circ}C$.

Ans. :- The hypoeutectoid steel must be austenitized above Ac_3 temperature for hardening, because if a lower temperature is used, the structure at that temperature would contain austenite and some α-ferrite. On quenching this, the austenite is converted into martensite, but -ferrite remains as it is. Since α-ferrite is very soft, the hardness of the hardned steel would be lower than it would have been if no α - ferrite were there. Hence for getting optimum hardness, hypoeutectoid steel must be austenitized above Ac_3 temperature.

Hypereutectoid steel is austenitized at $Ac_1 + 50^{\circ}C$ because at this temperature the steel would contain austenite and a small amount of cementite. On quenching, the structure is martensite + cementite. Since cementite is the hardest phase in steel, the hardness is optimal and it is not adversely affected. On the contrary, it is not heated to above Ac_m line to fully austenitize it because -

(i) it is absolutely unnecessary

(ii) grain size of austenite increases and on quenching coarse martensite is produced which is more brittle, and hence, undesirable.

Q.3.27. :- What is tempering ? Why is it employed ?

Ans.:- Tempering is the heat treatment process given to hardened steel. In this process, the hardened steel is heated to a temperature less than 723° C, kept there for about 1/2 hour to 1 hour and then cooled to room temperature in air.

The hardness of hardened steel containing martensite is about 64 Rc. Steel in this condition is brittle. The hardened steel is tempered for the following objectives -

(i) to decrease the brittleness of the hardened steel by relieving the stresses in martensite.

(ii) to decrease the hardness to the desired value i.e., to soften the steel to the required level.

Q.3.28. :- Describe the three stages of tempering.

Ans. :- Martensite is a supersaturated solid solution of carbon in iron. Hence it is metastable in structure and changes into a more stable structure on tempering.

The structual changes that occur on tempering may be considered to take place in three stages.

I Stage :- This stage refers to the first temperature range (upto 200°C). Carbon is rejected from martensite and forms -carbide which is precipitated in a fine coherent form. The composition of carbide is $Fe_{2.4}C$. Because of this precipitation, carbon content of martensite decreases and low carbon martensite is formed. Fig.3.10.(28) shows the variation in the hardness of a high carbon steel on tempering. It is obvious that little change in hardness occurs in the I stage of tempering. The structure produced is black etching martensite.

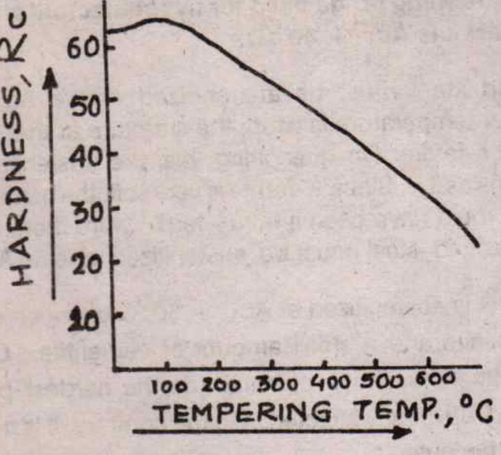


Fig.3.10.(28)

II Stage :- The second stage of tempering refers to the tempering temperatures of 200°C to 300°C. This follows the I stage changes. In the second stage of tempering, two reactions simultaneously occur-

(i) further reduction in the carbon content of martensite

(ii) conversion of any retained austenite to martensite while cooling from the tempering temperature to room temperature.

Hardness continues to fall and is around 55 Rc.

III Stage :- The third stage of tempering refers to the temperature range of 300°C-400°C in which the depletion of carbon from martensite is complete. The carbide is fully converted into Fe_3C - cementite. Hence the structure contains α -ferrite and cementite.

It is customary to refer this temepered structure as secondary troostite. The structure is very fine and can not be resolved under optical microscope. The hardness is about 45-47 Rc.

One can identify a fourth temperature range - above 400°C upto 650°C. Tempering in this range causes "coalescence" of cementite particles. The size of cementite particles increases. This results in a descrease in their number and hence their dispersion becomes coarser and coarser as the tempering temperature is increased. This results in a fall in hardness. The hardness of steel tempered at 450 C is about 40 Rc and it drops to about 20 Rc when tempered at 650°C. The general name given to these ferrite-cementite aggregates is secondary sorbite.

In general, the structure produced on tempering hardened steel is termed as "tempered martensite".

Q.3.29. :- Name the structure produced and give its approximate hardness, when a hardened 0.6% C steel is tempered at -

(i)180°C (ii)300°C (iii)450°C (iv)550°C (v) 650°C

Ans. :-

	Tempering temp.	Structure	Hardness
(i)	180°C	Black etching martensite	65 Rc
(ii)	300°C	Tempered martensite OR Secondary Troostite	55 Rc
(iii)	450°C	Tempered martensite OR Secondary sorbite	45 Rc
(iv)	550°C	-do-	35 Rc
(v)	650°C	-do-	15 Rc

Q.3.30. :- What is retained austenite ? Why is it produced in hardening ?

Ans. :- Ms and Mf temperature of a plain carbon steel are very much dependent on its carbon content. In plain carbon steels containing more than 0.6% C, the Mf temperature is below 0°C. We have already seen that austenite to martensite trformation takes place when the steel from the austentic condition is continuously cooled at a rate faster than critical cooling rate below Ms temperature. The martensite forms while cooling is continued from Ms temperature to Mf temperature. At Mf temperature the martensite formation is nearly complete and little austenite remains untrformed.

Steel is hardened normally by quenching it from austenitization temperature, into a water bath or oil bath kept at room temperature. Normally the room temperature is above 0°C. Hence if a plain carbon steel containing more than 0.6%C is hardened by quenching into a bath at room temperature, all the austenite is not trformed into martensite because the Mf temperature of this steel is below 0°C. This austenite which remains untrformed is known as retained austenite. Thus in high carbon steels, retained austenite is always present after hardening. The alloy steels have still lower Mf temperatures. Hence in alloy steels the proportion of retained austenite is more than in case of plain carbon steels.

Q.3.31. :- How retained austenite can be converted into martensite ?

Ans. :- Retained austenite is very soft and hence its presence in hardened steel is not desirable because it gives lower hardness and non-homogeneous hardness values. Hence it is necessary that the retained austenite be changed into martensite. This can be done by

(i)tempering

(ii) sub-zero treatment.

When the hardened steel is tempered above 300°C, while cooling from the tempering temperature, the retained austenite is converted into martensite. However, this method is useful only when the amount of retained austenite is relatively small. Further more, some retained austenite remains untrformed even after tempering.

In case of those hardened steels in which the amount of retained austenite is large, it is better to convert it into martensite using sub-zero treatment. In this, the hardened steel must be cooled, immediately after hardening, to a temperature lower than its Mf temperature. Since the Mf temperature is below O C,this heat treatment is known as sub-zero treatment. For this, various types of freezing mixtures are used depending upon the temperature to which the steel is to be cooled. Sometimes even liquid nitrogen is used.

Q.3.32. :- Distinguish between jannealing and normalizing.

Ans. :- Both these processes of heat-treatment are based on the Fe-C diagram and eutectoid reaction.

(1) In annealing, the hypoeutectoid steel is heated to $Ac_3 + 50^\circ C$ and hypereutectoid steel is heated to $Ac_1 + 50^\circ C$. The steel is soaked at this temperature for sufficient time depending upon its section size, as in case of austenitization for hardening. Then the steel is allowed to cool slowly to room temperature inside the furnace itself, by putting off the power.

In normalizing, the hypoeutectoid steel is heated to $Ac_3 + 50^\circ C$ and hypereutectoid steel is heated to $Ac_m + 50^\circ C$. The steel is soaked at this temperature as in case of annealing. After soaking, the steel is taken out of the furnace and cooled in still air.

(2) Hence the cooling rate in case of normalizing is faster than in annealing.

As such, the austenite to pearlite trformation in case of annealing occurs at a higher temperature range than in case of normalizing.

(3) Therefor, we obtain coarse pearlite in annealing and fine pearlite in normalizing. Further more the grain size after annealing is larger than that after normalizing.

(4) As such, normalized steel is a little harder and sufficiently stronger than annealed steel.

(5) Hence annealing is an intermediate heat-treatment process used to soften the steel while normalizing is given to the final product.

Q.3.33. :- Distinguish clearly between (a) Full annealing (b) Stress relief anneal (c) Process annealing.

Ans. :- In general, annealing of steel is done to-

(i) reduce its hardness to facilitate machining, or

(ii) relieve internal stresses without affecting its strength, or

(iii) to partly reduce its strength and hardness to increase its ductility for further processing.

Accordingly, full annealing, stress relief anneal and process annealing are used. These processes essentially differ in the temperature used for annealing, the cooling rate is nearly indentical.

(a) In full anealing, hypoeutectoid steel is heated to $Ac_3 + 50^{O}C$ and hypereutectoid steel is heated to $Ac_1 + 50^{O}C$, soaked for sufficient time depending upon the section size and cooled very slowly to room temperature. The changes obtained in properties are-

(i) homogenization of composition.

(ii) reduction of hardness and strength to the minimum level.

(iii) increase in ductility to the maximum level.

The changes in mechanical properties are due to the production of coarse pearlite.

Full annealing is a prolonged high temperature process and hence expensive.

(b) In stress relief anneal, the steel components which become internally stressed during the course of their fabrication, are heated to a temperature, below Ac_1 temperature, usually to about $600^{O}C$, soaked there for sufficiently long time - many hours, and then cooled to room temperature at normal rate. Since the steel is heated to a temperature below Ac_1, no phase change occurs. Hence this is a subcritical anneal and the residual internal stresses are relieved through a process of recovery, without any recrystallization.

(c) Process annealing also is a sub-critical annealing process aimed at increasing the ductility of the material to facilitate further processing. This is done in between the processing operations - hence the name porcess anneal. Usually proces annealing involves partial recrystallization, giving just sufficient ductility to make further processing possible without cracking.

Q.3.34. :- What is spheroidizing ? What is its aim ? How the microstructure obtained after spheroidizing fulfils this aim ?

Ans. :- Spheroidizing is a heat treatment process usually given to high-carbon, hyper-eutectoid tool steels to produce a coarse spheroidal dispersion of cementite particles in the matrix of α - ferrite.

Normally, the process of spheroidizing consists of heating the steel to about 650^{O}-675^{O}C and keep it there for a prolonged time - from 12 hours to 16 hours. The initial structure of steel before spheroidizing contains lamellar pearlite, i.e., cementite and ferrite plates. This prolonged heating at 650^{O}-675^{O}C changes the cementite from its plate like shape to produce spheroids of cementite.

This spheroidal shape of cementite may be achieved also by the following two ALTERNATIVE shperoidizing treatments.

(I) Harden the steel and temper the hardened steel at 650^{O}C for 6 to 8 hours.

(II) Heat the steel to $Ac_1 + 15^{O}$ C, then cool to $Ac_1 - 15^{O}$ C, then again heat it to $Ac_1 + 15^{O}$ C and cool it to $Ac_1 - 15^{O}$ C.

Follow these osillation in temperature for about 8 hours. This is known as pendulum method of spheroidizing.

The aim of the spheroidizing treatment is to get the high carbon tool steels in their softest condition so that their further machining is facilitated.

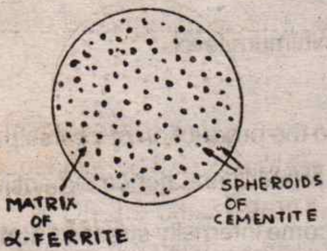


Fig.3.11.(34)

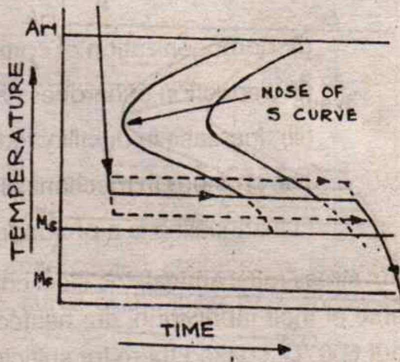


Fig.3.12.(35)

In such high carbon tool steels, even full annealing does not sufficiently reduce the hardness of the steel, and hence in the annealed condition, they are not quite easily machinable. This is because the pearlite after annealing is in lamellar form. The hard lamellar cementite severely disrupts the continuity of the matrix and hence the machinability is poor. Furthermore, its dispersion is not very coarse. Spheroidizing produces a coarse dispersion of spheroids of cementite - decreasing the hardness considerably. Further more a spheroidal dispersion of cementite disrupts the continuity of the matrix less severely and hence the machining is easier. Fig.3.11.(34) shows the microstructure of spheroidized steel.

Q.3.35. :- What is Austempering ?

Ans. :- Austempering is an isothermal heat treatment process. Usually it is used for low alloy steels with higher hardenability. It is relatively difficult to carry out in plain carbon steels with low hardenability.

In this treatment the steel is austenitized and then quenched into a molten salt bath or metal bath kept at a temperature below the nose of the S-curve of the steel, but, above its Ms temperature. At this constant temperature, the austenite is allowed to trform completely. After the trformation is over (say in a couple of hours), the steel is cooled to room temperature, in air.

If the bath temperature is relatively higher, i.e., nearer to the nose temperature, the product is feathery bainite or upper bainite.

The hardness of upper bainite is about 45 Rc. It is not as tough as a steel hardened and tempered to produce this same hardness level.

If the bath temperature is lower, i.e., nearer to Ms temperature, the trformation product is lower bainite or acicular bainite with a hardness of about 55-58 Rc. Lower bainite gives the best combination of optimum toughness with the high hardness of 55-58 Rc. It is much tougher than a hardened and tempered steel with same hardness. Fig.3.12.(35) shows the cooling sequence followed in austempering.

Q.3.36. :- What is martempering and why is it used ?

Ans. :- Martempering is essentially a hardening process of steel in which the cooling of steel is so controlled as to avoid any cracking or warpage, and yet produce almost fully martensitic structure. The cooling cycle employed in martempering is schematically illustrated in Fig, 3.13.(36).

In martempering, the component to be hardened is austenitized at the temperature decided by its chemical composition - above Ac temperature or Ac temperature, as the case may be. Then the component or article is quenched into a bath of molten metal or salt kept at a temperature slightly above the Ms temperature of the given steel.

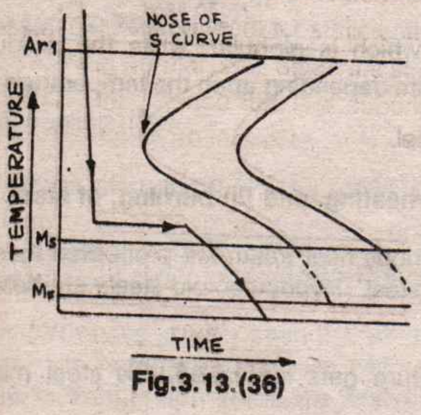


Fig.3.13.(36)

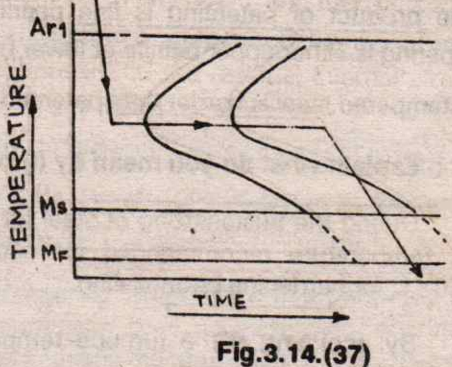


Fig.3.14.(37)

The steel component is then allowed to remain in this bath for sufficient time to equalize the temperature at its surface and in its core. Then the steel is taken out of the bath and cooled in air to room temperature, producing martensite.

Martempering is used to avoid the quenching cracks and warping in steel being hardened. The quenching cracks and warping are due to the nonuniform cooling of surface and core of the steel and the drastic cooling rate during trformation. Both these factors are reduced in martempering and hence the possibility of warping and cracks is completely avoided and a fully martensitic structure is produced. Since martempering involves interrupted quenching by using a high temperature bath, it is more suitable to low alloy steels than plain carbon steels.

Q.3.37. :- What is patenting ?

Ans. :- Patenting also is an isothermal heat treatment process in which the steel is trformed at the nose temperature of its S curve t o give a fine pearlite structure as illustrated in Fig. 3.14.(37). The steel is austenitized at its austenitization temperature ($Ac_3 + 50^{O}$ C or $Ac_1 + 50^{O}$ C as the case may be) and then quenced into a salt bath kept at a temperature corresponding to the nose of the S curve of that steel. The austenite is allowed to trform isothermally at this temperature. The product is very fine pearlite and the cementite in this pearlite is globular in structure. Hence the steel is strong and tough.

Patenting is usually employed for producing high carbon steel wires used for the manufacture of wire ropes employed for haulage.

Q.3.38. :- Distinguish clearly between patenting and austempering.

Ans. :-

(1) In patenting, the supercooled austenite is isothermally trformed at a temperature corresponding to the nose of the S curve of the steel.

On the other hand, in austempering, the supercooled austenite is isothermally trformed at a temperature BELOW the nose of the S curve of the steel BUT above its Ms temperature.

(2) The product of patenting is fine pearlite which is globular, while the product of austempering is either upper bainite or lower bainite depending upon the temperature used.

(3) Austempered steel is harder than patented steel.

Q.3.39. :- Explain what do you mean by (i) overheating, and (ii) burning, of steel.

Ans. :- During the austenitizing of steel for various heat treatment processes there is a specific temperature recommended for each steel. Hypoeutectoid steels are heated to $Ac_3 + 50^{O}$ C for hardening or annealing.

By accident, if the furnace temperature gets increased, the steel may get OVERHEATED, or BURNT.

As the temperature is increased, the size of austenite grains increases. Hence a steel, in which the size of the austenite grains is abnormally large, is definitely heated to a much higher temperature than its Ac_3 temperature. In this case we say that the steel is overheated. Overheating of steel results in abnormally large austenite grain size. This gives inferior toughness. The bad effect of overheating can easily be removed by heating the steel again to the CORRECT $Ac_3 + 50^O$ C temperature. The old large grains disappear and the new grains which are formed are quite fine.

On the other hand, if the temperature of the furnace in which the steel is being heated really shoots up to a high level, higher than in the previous case, selective oxidation along the grain boundaries occurs. When such selective grain boundary oxidation occurs, we say that the steel is BURNT. Burnt steel is useless as it can not be rectified by any me. It is only to be melted as scrap.

Q.3.40. :- What is the usefulness of S curves in heat treatment? What are its limitations ?

Ans. :- The usefulness of S curves in heat-treatment is as follows -

(a) S curves are helpful in determining the bath temperatures to be used for isothermal heat treatment processes like austempering, martempering and patenting.

(b) S curves give us the critical cooling rate of the steel and hence give us an idea about the hardenability of steel.

(c) Although S-curves are isothermal trformation curves, they give us an idea as to what structure, and hence properties, we can expect when the steel is continuously cooled at a given cooling rate.

The limitations of the S-curves are -

(i) the S curves do not predict the exact temperature of start or end of trformation during continuous cooling.

(ii) Like an equilibrium diagram, S-curves can not be used as MAPS giving the structure at different cooling rates

(iii) S- curves can not be used for predicting the structure obtained in tempering.

Q.3.41. :- What is temper-embrittlement ? What are its types ? How can its bad effect be removed ? How can it be completely avoided ?

Ans. :- We have already seen that as the tempering temperature of a hardened steel is increased, its hardness decreases while it toughness goes on increasing, continuously. However, in certain alloy steels, the relationship between the tempering temperature and the toughness (impact strength) is more complicated, and is represented as schematically shown in Fig.3.15.(41)

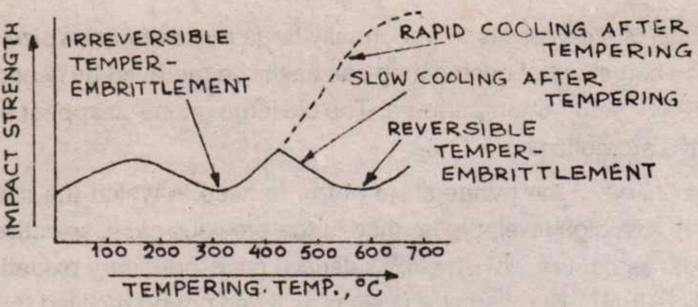


Fig.3.15.(41)

The figure shows that there are two minima. The toughness is lowest at tempering temperatures of about 300° C and about 500°- 550° C.

The first minimum value of impact strength observed at 300° C is called "Irreversible temper-embrittlement". Its reason is not known at present. This embrittlement can not be avoided if the tempering temperature corresponds to about 300° C. Further more, its adverse effect can not be removed (i.e., the impact strength can not be increased) by retempering the temper-embrittled component of steel at a suitable high temperature. Hence the name "irreversible temper-embrittlement".

The second minima corresponding to a tempering temperature of about 500°-550° C, is called "reversible temper-embrittlement". This occurs when the tempered steel component is slowly cooled to room temperature after the tempering treatment. On the contrary, if the tempered steel is cooled faster from the tempering temperature, this embrittlement is not exhibited, as is clear from the figure.

If a steel component has suffered "reversible temper embrittlement", its impact strength can be again increased by simply tempering it again at a slightly higher temperature followed by rapid cooling. Hence this type of embrittlement is called "reversible temper-embrittlement".

In alloy steels prone to such temper-embrittlement, it can be completely avoided by incorporating about 0.25% Mo as an alloying element. Hence low alloy Cr steels always contain about 0.25% Mo., because steels containing chromium are susceptible to this type of temper-embrittlement.

Lesson 4

CAST IRONS

Q. 4.1.:- What are cast irons ? What is the difference between steel and cast irons ?

Ans. :- Cast irons are defined as the alloys of iron and carbon containing more than 2.0% C. Ordinarily, the cast irons contain between 2.5 to 4% C. In addition to iron and carbon, the commercial cast irons contain elements like sulphur, phosphorus, silicon and manganese. The name cast irons indicates that these alloys are mostly used for casting.Some special cast irons may contain some other alloying elements like Al, Cr, Ni etc., which are purposefully added to develop certain properties. Steels contain less than 0.05%P while cast irons may contain as much as o.15 % P.

The essential difference between a plain carbon steel and a cast iron is that steels do not exhibit eutectic reaction during solidification,while cast irons undergo the eutectic reaction during solidification. It means that steels do not exhibit primary cementite (cementite directly formed from the liquid) while cast irons may show either primary cementite or graphite depending upon the chemical composition of the melt and the cooling rate.

With respect to mechanical properties, steels are tougher than cast irons. Steels are ductile and are deformable while cast irons are relatively brittle and undeformable.

Q. 4.2.:- Discuss the factors which affect the mode of solidification of cast irons.

Ans. :- It is known that cementite is metastable. Hence if conditions are favourable, carbon may exist in its stable forrn , i.e., graphite.

In cast irons, carbon may exist in both the forms, either as cementite or as graphite. Hence the eutectic reaction can be :

(i) according to iron-iron carbide system forming a eutectic of austenite and cementite which is known as ledeburite, or

(ii) according to the iron - graphite system, in which the eutectic mixture is of austenite and graphite.

When the cast iron solidifies according to $FeFe_3C$ system, we get white cast iron while if it solidifies according to iron-graphite system, we get Gray cast iron.

Whether the cast iron solidifies as white cast iron or grey cast iron, is determined principally by the following factors :

(a) Carbon and silicon content.

(b) Cooling rate during, and after, solidification.

The solidification of a cast iron melt as white cast iron is favoured by :

(1) a lower silicon content, ≈ 1%

(2) a lower carbon content, ≈ 2.5 - 2.8 %, and

(3) a faster cooling rate.

If all these factors are favourable, we get white cast iron. If not, some of the melt may soldify as grey cast iron, giving a mixed structure known as mottled cast iron. The solidification of a melt as grey cast iron is favoured by :

(1) a higher silicon content, > 1.7%

(2) a higher carbon content, 3.5 4%

(3) a slower cooling rate.

Hence, it is the balance between the chemical composition and cooling rate which controls the mode of solidification of a cast iron melt.

Q.4.3. :- Explain MAURER'S DIAGRAM in brief.

Ans.:- Maurer's diagram is a plot between carbon content and silicon content of a cast iron, to show as to what would be its mode of solidification for a **given cooling rate**. The cooling rate for which the MAURER'S diagram is drawn, is the normal cooling rate encountered in sand moulds. Obviously, if the cooling rate is changed, the diagram would also change.

Fig.4.1.(3) shows the normal Maurer's diagram. From this diagram, it can be concluded that for a normal given cooling rate :

(a) a high carbon content and a high silicon content invariably produces ferritic grey cast iron. For example a carbon content of 2.5% will produce ferritic grey cast iron if silicon % is greater than 4.5%

(b) a low silicon content and a low carbon content always results in the formation of white cast iron.

Hence, it is evident that under the normal conditions of cooling, the cast iron obtained will totally depend upon the (C + Si) content.

Since silicon favours the solidification of the melt according to iron-graphite system, forming graphite in structure, it is known as a graphitizer. It favours graphitization of carbon, both during soldification as well as later cooling to room temperature.

Q.4.4. :- Describe the solidification of white cast iron.

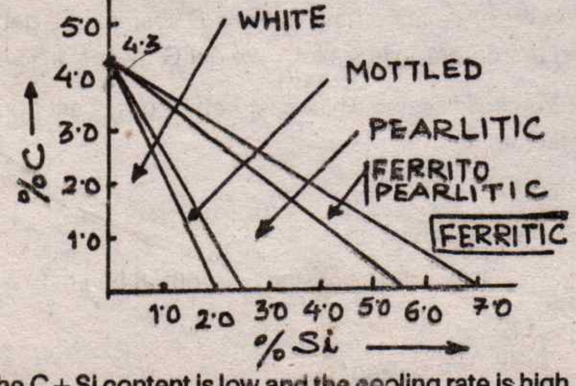


Fig. 4.1.(3)

Ans.: When the C + Si content is low and the cooling rate is high, a cast iron melt solidifies as white cast iron. The solidification takes place according to the FeFe C diagram. This means that the eutectic reaction which occurs during its solidification is

$$\text{Liquid } (4.35\%\ C) \xrightarrow[T\ =\ 1130^{O}C]{} \text{Austenite } (2.0\%\ C) + \text{Cementite } (6.67\%\ C)$$

The eutectic mixture is called "Ledeburite". The solidification of white cast irons can be understood by referring to the cast iron portion of the Fe-Fe C diagram shown in Fig 4.2.(4). A hypoeutectic cast iron containing 3% C starts solidifying at temperatre T_1 with the formation of Austenite of composition C_{A1} . With further cooling, more austenite forms and this continues upto eutectic temperature T_E . During cooling from T_1 to T_E , the composition of austenite changes along T_1- M . At eutectic temperature, the composition of austenite is 2%C and liquid contains 4.35% C. This liquid solidifies according to the eutectic reaction mentioned above, giving Ledeburite.

On further cooling cementite gets precipitated with a change in the composition of austenite, which reaches 0.8%C at 723^{O}C(T). At this temperature austenite forms pearlite. Hence the final structure at room temperature contains pearlite and cementite.

In case of a hypereutectic composition i.e., a melt containing more than 4.35%C, the only difference is that the solidification starts with the formation of primary cementite. Eutectic reaction and other changes upto room temperature are similar to those in case of a hypoeutectic composition. Thus this cast iron also has pearlite and cementite in its microstructure at room temperature.

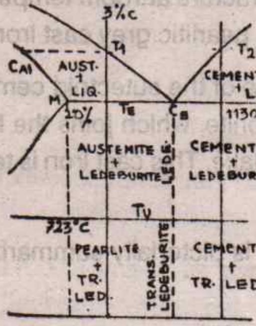


Fig. 4.2. (4)

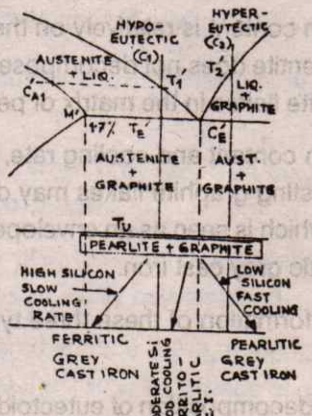


Fig. 4.3. (5)

Q. 4.5. :- Describe the solidification of grey cast iron, and its cooling to room temperature.

Ans. :- Let us consider the soldification of grey cast iron, For a melt to solidify as grey cast iron, the C + Si content must be high and the cooling rate slow.Suppose such a melt is being solidified.The eutectic reaction in solidification of grey cast iron is

$$\text{liquid } (4.3\%\ C) \xrightleftharpoons[T\ =\ 1135^{O}C]{} \text{Austenite } (1.7\%\ C) + \text{Graphite}$$

In a melt containing less than 4.3%C (C_1), the solidification commences with the formation of dendrites of austenite, at temperature T_1' as shown in the Fig. 4.3.(5). Solidification of austenite continues as temperature is decreased. The composition of austenite changes along $C'_{A1}M'$ and the composition of liquid along T1'CE'. At eutectic temperature TE' austenite contains 1.7%C and liquid contains 4.3% C. This liquid undergoes eutectic reaction giving a mixture of austenite and graphite.

A hypereutectic liquid (C_2) starts solidification at $T_{2'}$ with the formation of graphite known as KISCH graphite which floats to the top and is skimmed away. The ectectic reaction occurs similar to that in hypoeutectic alloy.

It is evident that whatever be the composition, the structure of this cast iron **just after its solidifiction** (i.e.just below 1135^{O}C)is austenite of 1.7%C and graphite. Further cooling to 723^{O}C results in rejection of carbon by austenite and this carbon joins the already present graphite which is in the form of FLAKES. At 723^{O}C, the eutectoid reaction occurs and just after the eutectoid reaction, the structure contains pearlite and graphite flakes.

The structure which is finally obtained on cooling from this stage depends greatly on the silicon content of the cast iron and the cooling rate. Three possibilities exist :

(a) If the silicon content is high and cooling rate is slow all the cementite contained in pearlite (called EUTECTOID CEMENTITE) decompses to give α-ferrite and graphite. Hence the final structure contains only these two phases and the cast iron is called ferritic grey cast iron , showing graphite flakes in the matrix of α-ferrite grains.

(b) If the silicon content is relatively on the lower side (2.0%) and the cooling rate is fast, the eutectoid cementite does not decompose and hence the final structure at room temperature remains graphite flakes in the matrix of pearlite.This is known as pearlitic grey cast iron.

(c) If the silicon content and cooling rate, are intermediate, some of the eutectoid cementite around the existing graphite flakes may decompose giving graphite, which joins the flakes, and α-ferrite which is seen as an envelope around the graphite flake. This cast iron is termed as ferritopearlitic grey cast iron.

The formation of these three types of grey cast irons is pictorially summarized in Fig. 4.3.(5).

The decomposition of eutectoid cementite is known as "secondary graphitization." Some books refer to the formation of austenitegraphite eutectic as "primary graphitization."

Q. 4.6.: Compare the properties of ferritic grey cast iron and pearlitic grey cast iron in terms of their structure.

Ans. : Pearlitic gray cast iron contains graphite flakes in the matrix of pearlite while ferritic grey cast iron contains graphite flakes in the matrix of α-ferrite. Since pearlite contains cementite and α-ferrite and since cementite is hard and strong, it is evident that pearlite is harder and stronger than α-ferrite. Hence the hardness and tensile strength of pearlitic cast iron will be more than that of ferritic grey cast iron. For example the tensile strength of ferritic grey cast iron is around 15Kg/mm^2 while the T.S. of pearlitic grey cast iron can be as high as 35 Kg/mm^2 . Hence pearlitic grey cast iron is used for heavy duty purposes where higher tensile strength and wear resistance are important. On the contrary, since ferritic grey cast iron is soft, it is used in making those castings where a lower tensile strength is O.K. but a high machinability is required.

Q. 4.7. : Why white cast iron is extremely hard and brittle ? What are the uses of white cast iron ?

Ans. : When the carbon is present in the form of cementite, it is said to be present in the "combined form". In white cast iron, all the carbon is in the combined form, i.e., in the form of cementite. The amount of this cementite (primary and eutectoid) is about 35 - 40%. This amount is very large. Presence of this large amount of cementite, which itself is very hard and brittle, makes the white cast iron extremely hard and brittle. It is unmachinable.It can be shaped only by grinding.

Because of this high hardness, it has excellent wear resistance. It is generally used for the manufacture of cold rolling rolls and grinding media balls for ball mills.

Q. 4.8. : Examplain why grey cast iron is softer than white cast iron.

Ans. : Grey cast iron contains most of its carbon in the free form. Even the hardest and strongest of the grey cast irons, the pearlitic grey cast iron, contains about 0.8%C in the combined form as pearlite. The rest of the carbon is in the form of graphite. Hence the total amount of cementite present even in the pearlitic grey cast iron is very small as compared to white cast iron in which all the carbon is in the combined form. Hence grey cast irons are relatively much softer than the white cast iron.

Q.4.9.: Distinguish clearly between white cast iron and grey cast iron

Ans. : The points of difference between white cast iron and grey cast iron are given below

(a) White cast iron contains all the carbon in the combined form while in grey cast iron, most of the carbon is in the free form.

(b) White cast iron contains pearlite and cementite while grey cast iron may show α-ferrite and graphite, or pearlite and graphite or a mixture of the two.

(c) White cast iron is very hard and brittle while the grey cast iron is softer and brittle. White cast iron can not be machined while grey cast iron can easily be machined.

(d) If a rod of white cast iron is fractured, the fractured surface is bright metallic. Hence it is given the name "white cast iron". On the other hand the fractured surface of grey cast iron is "Grey" which explains the name given to it.

(e) White cast iron has very poor damping capacity while grey cast iron has an excellent damping capacity.

Q.4.10 : Explain the mechanical characteristics of grey cast iron and give its possible uses.

Ans :

(a) The tensile strength of ferritic grey cast iron is approximately 12 - 15 Kg/mm^2 while the tensile strength of pearlitic grey cast iron is about 30 - 35 kg/mm^2 . The tensile strength of ferritopearlitic grey cast iron is in between these limits and depends upon the amount of pearlite present.

(b) Grey cast irons have excellent compression strength.

(c) Due to the presence of graphite flakes, which act as discontinuities in the metallic structure, the grey cast irons have a high damping capacity.

(d) The hardness of pearlitic grey cast iron is about 230 B.H.N., while that of ferritic grey cast iron is nearly 160 B.H.N.

(e) In tensile tests, grey cast irons show 0% elongation. Thus they have no ductility. They are exterenely brittle.

(f) The impact strength (Izod) is only about 0.5 Kg.m/cm^2

Hence grey cast irons are eminently suitable in those applications where dynamic loading conditions involving bending or torsion are absent. They are excellent in compression and damping capacity . Hence their main engineering use is for making foundation blocks of large diesel engines in ships, machine bodies, various fittings etc. They are the cheapest of all cast irons. Because of their excellent castability, even intricate shapes can be easily cast.

Q. 4.11. :-Explain why grey cast iron is extremely britle.

Ans.:- Graphite flakes are nonmetallic in nature. Hence there is no bond of any significant strength between the graphite flake and the surrounding metallic matrix. Hence they serve as discontinuities in the metallic matrix. Because of their flake like nature, they have large surface areas. Hence along large areas, the metallic surfaces on the two sides of a graphite flake have no bond. In effect, they act like "cracks" and hence as stress raisers. Because of this, when a rod of cast iron is fractured, the fractured surface follows graphite flake surfaces as they act like cracks. That is why the entire fractured surface is full of graphite flake surfaces, and hence, looks grey. Because of the presence of such a large number of nonmetallic graphite flakes, the continuity of the metallic matrix is very severely disrupted. Hence they fail without any plastic deformation in tensile test, thus showing a 0% elongation. This also explains their low impact strength.

Q. 4.12. :-Explain how the graphite flake size and their distribution affect the strength and toughness.

Ans.:- The graphite flakes are nonmetallic in nature and their bond strength with the surrounding metallic matrix is very low. They act like cracks and stress raisers. Hence it is obvious that they disrupt the continuity of the matrix. If the size of the graphite flakes is reduced and their distribution is made uniform naturally the severity with which the continuity of the metallic matrix is disrupted, gets reduced. Hence the tensile strength and toughness (impact strength) of the grey cast iron is improved if the graphite flake size is reduced.This reduction in graphite flake size is obtained by increasing the number of nuclei of graphite during eutectic solidification. This is achieved by adding either calcium silicide and ferrosilicon, and /or nickel. Such a cast iron is known as **MEEHANITE** cast iron, which is a heavy duty cast iron. The graphite flake size in Meehanite cast iron is quite small.

Q. 4.13. :-Explain the two routes through which tough cast iron can be produced.

Ans. :- We know that white cast iron is brittle because of a large amount of cementite present which is brittle. On the other hand grey cast iron is brittle because it contains graphite flakes which act as stress raisers or notches. Hence to have a tough, ductile iron it is necessary that -

(i) its combined carbon content should not be more than 0.8%C. That is, it may contain only that much cementite, which may, at the maximum, give a fully pearlitic matrix.

(ii) the rest of the carbon should **NOT** be present as combined carbon, it should be present as free carbon, i.e., in the form of graphite but it **should not be present as flakes. Instead, it should be present in a nearly spheroidal or nodular form.**

There are two ways in which these conditions can be fulfilled ;

(a) Produce a casting entirely in white cast iron form (that is all the carbon in the form of cementite) and then decompose the cementite into temper carbon (graphite) and α-ferrite by heat treatment. This temper carbon (graphite) is present as roughly spheroidal rosettes. This method is known as "Malleablizing" and the product is known as malleable cast iron.

(b) Treat the molten cast iron with some additives such that, on soldification, it has graphite in a spheroidal form. This method is known as "nodulizing" and the cast iron is known as "Nodular cast iron" or "Spheroidal graphite (SG) iron".

Q.4.14. :- Discuss the steps involved in the production of malleable cast iron.

OR

What is malleablizing ? Discuss it fully.

Ans. :- The heat treatment process, which is given to the white cast iron castings, in order to produce malleable cast iron, is known as MALLEABLIZING. The production of malleable cast iron contains the following steps :

(a) **Production of white cast iron castings :** For the production of malleable cast iron castings, it is necessary that the castings be first produced as white cast iron castings without even a trace of graphite flakes. This is because if graphite flakes are present, the further decomposition of cementite does not produce temper carbon as rosettes. Instead, the already present graphite flakes grow in size. Hence cast iron containing graphite flakes can not be malleablized.

To get fully white structure, C + Si % should be low and cooling rate should be fast.

(b) **Malleablizing treatment :** The white cast iron castings are then packed in sand kept in boxes, and given the malleablizing heattreatment.The boxes are kept in the furnace and heated to achieve a temperature of 1050^{o}C. At this temperature the castings are kept for about 72 to 96 hrs. This stage is known as the primary graphitization. In this step, all the primary cementite decomposes to give austenite and temper carbon.

One can follow two different routes for further cooling to room temperature.

(a) cooling directly from this temperature to room temperature by cooling the boxes in the air, or

(b) cooling slowly from 1050^{o}C to 760^{o}C, then decreasing the cooling rate still further for cooling upto 680^{o}C, and then cooling slowly to room temperature.

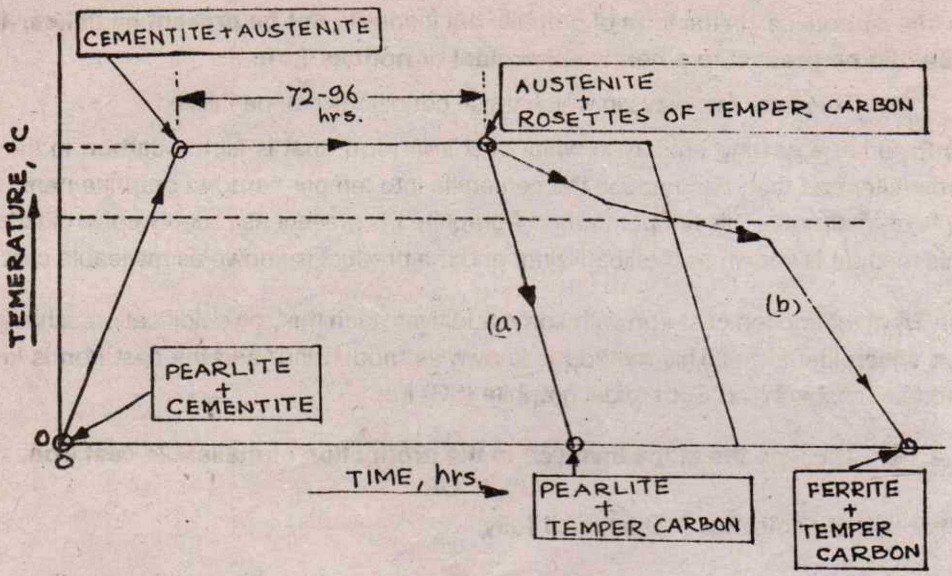


Fig. 4.4. (14)

These two modes of cooling are shown in Fig. 4.4.(14).

In the case of direct faster cooling, (a), the pearlite formed after eutectoid reaction remains as it is upto room temperature. Hence we get "pearlitic malleable" cast iron. If the second route (b), is used, because of slow cooling during and after eutectoid transformation, all the eutectoid cementite (i.e. that contained in pearlite) decomposes to ferrite and temper carbon.

$Fe_3C \longrightarrow$ ferrite + temper carbon

This is known as "**secondary graphitization.**" As such the final product is ferritic malleable cast iron.

Q. 4.15. :-Discuss the mechanical characteristics of malleable cast iron and compare them with that of grey cast iron.

Ans. :- Pearlitic malleable cast iron contains the rosettes of temper carbon in pearlitic matrix while the ferritic malleable cast iron has a ferritic matrix. Since pearlite is stronger than ferrite,it is obvious that pearlitic malleable cast iron would be stronger than ferrtic one. However, its ductility will be inferior to that of ferritic malleable cast iron. These properties are summarized below :

	Tensile Strength	% Elongation	Impact Strength
Pearlitic malleable cast iron	35 - 40 Kg/mm^2	8 - 10	1.5 - 2.5 Kg.m/cm^2
Ferritic malleable cast iron	25 - 30 Kg/mm^2	15 - 20	2 - 4 kg.m/cm^2
Ferritic grey cast iron	12 - 15 Kg/mm^2	nearly 0.00%	0.5 Kg.m/cm^2

It can be seen that as compared to ferritic grey cast iron, ferritic malleable cast iron is superior in all the respects.

Because of the ductility, both the types of malleable cast irons can be used for applications involving dynamic loading conditions. For greater strength with relatively lower requirement of toughness, pearlitic malleable will be chosen while if toughness is of prime importance, ferritic malleable must be used. The advantage of malleable cast iron castings over steel castings is

(I)They are more economical.

(II) Even most intricate shapes can be cast which is not possible with steel because of its poor castability and fluidity.

Q. 4.16.:- What is nodular cast iron ? How is it produced ?

Ans.:- Nodular cast iron is a variety of tough cast iron which is produced by forcing the solidification of the cast iron melt to occur according to iron graphite system but producing graphite in the nodular form. The solidification mode is obtained in this fashion by introducing magnesium as the nodulizer.

Since the melt should give the eutectic reaction according to iron-graphite system, it means that the amount of graphitizer, i.e., Si, must be high enough, along with a higher carbon content. The usual composition of the melt is -

C - 2 to 3.5%
Si - 1.5 to 2.0%
S < 0.02%
P < 0.04%

Sulphur content should be low because it reacts with magnesium and hence, the nodulizing efficiency is reduced. Phosphorus should be low for good toughness.

Magnesium is introduced either as the pure metal, or as a nickel-magnesium alloy. A phosphorizer or some other equipment is used to introduce magnesium into the molten iron, without any burning of magnesium.

Depending upon the exact silicon + carbon content, and the cooling rate after solidification, two types of nodular cast irons are possible -

(i) Pearlitic nodular cast iron containing nodules of graphite in the matrix of pearlite.It means that graphite is formed only due to eutectic solidifiction; that is, only primary graphitization has occured.

(ii) Ferritic nodular cast iron containing nodules of graphite in the matrix of ferrite grains. Since no pearlite is present, it means that all the eutectoid cementite has decomposed giving graphite and ferrite. This means that the secondary graphitization is complete.

Q. 4.17. :-Compare the mechanical properties of malleable cast iron with nodular cast iron.

Ans. :- In order to appreciate the difference in the mechanical properties of malleable cast iron and nodular cast iron, it must be remembered that, malleable cast iron contains only about 1.0% Si while nodular cast iron has a high silicon content of 1.5 to 2.0% This high silicon content makes the nodular cast iron relatively stronger but less ductile. However, the impact strength of both the cast irons is comparable. The following table compares the mechanical properties of pearlitic malleable iron with nodular iron

	T.S. Kg/mm%	**Elongation**
Pearlitic Malleable C.I.	35-40	8 -10%
Pearlitic Nodular C.I.	50-52	2%
Ferritic Nodular C.I.	38-42	10 -12%

Q. 4.18. :-Distinguish clearly between malleable cast iron and nodular iron (or spheroidal graphite iron).

Ans. :- The points of difference between the malleable cast iron and nodular iron are given below :

(a) **Medhod of Production :** Malleable cast iron is produced by the heat treatment of white cast iron castings, while nodular cast iron is produced by the nodulizing treatment of the melt with magnesium. Thus nodular iron is entirely produced by the solidification process alone.

(b) **Chemical composition :** Malleable cast iron contains a lower C + Si content.While nodular iron has a higher C + Si content.

(c) **Microstructure :** Both of these contain carbon in the free form as graphite, and in both the cases the graphite is nearly spheroidal. However, the temper carbon in malleable cast iron is in the form of rosettes. These rosettes have a general spheroidal appearence but the periphery is not smooth, it is irregular. On the contrary, the peripheries of nodules of graphite, in nodular cast iron, are smooth and the shape is exactly spheroidal or slightly ellipsoidal.

(d) **Strength and ductility :** With the matrix structure being same (i.e., either both ferritic or both pearlitic), the nodular cast iron has always a higher tensile strength and lower ductility as compared to malleable cast iron.

Q. 4.19.:- Distinguish between pearlitic malleable iron and pearlitic grey cast iron.

Ans. :- The points of difference between the pearlitic malleable cast iron and pearlitic grey cast iron are as given below :

(a) Pearlitic malleable iron contains irregular spheroidal rosettes of temper carbon in the matrix of pearlite while pearlitic grey cast iron contains graphite flakes in the pearlite matrix.

(b) Pearlitic malleable cast iron is produced by the heat treatment of white cast iron while pearlitic grey cast iron is not given any heat-treatment to change the structure.

(c) Pearlitic malleable cast iron contains less C + Si as compared to pearlitic grey cast iron.

(d) Pearlitic malleable cast iron has a higher tensile strengdth and ductility (810% elongation) than grey cast iron (% elongation nearly zero).

Q. 4.20. :-What is "Bull's eye" malleable cast iron ? How it gets produced ?

Ans. :- Normally one wishes to produce either pearlitic maleable iron or ferritic melleable iron. We know that in the production of pearlitic malleable iron, secondary graphitization must be avoided, so that no eutectoid cementite is decomposed into ferrite and temper carbon. However, if the cooling rate or silicon content of the cast iron is not properly controlled, it may happen that some eutectoid cementite is decomposed. In such cases, the eutectoid cementite in the immediate vicinity of an existing temper carbon rosette, is the one most likely to decompose. Because of the presence of temper carbon rosette, no fresh nucleation is required. Thus the cementite contained in pearlite surrounding the temper carbon rosette preferentially decomposes. The temper carbon produced joins the already present rosette of temper carbon and a ferrite envelope is left. This bright ferrite envelope with the dark rosette of temper carbon in the middle resembles the "Bull's eye" the target used in shooting. Hence such ferritopearlitic malleable cast iron is known as bull's eye malleable cast iron.

Q. 4.21. :-Define " Ledeburite."

Ans.:- When the C + Si content of a cast iron melt is on the lower side, the solidification of the melt takes place according to the Iron-IronCarbide (FeFe C) diagram. In this diagram the eutectic reaction exhibited is as given below :

$$\text{Liquid (4.35\% C)} \xrightleftharpoons[T\,=\,1130^{0}C]{} \text{Austenite (2.0\%C)} + \text{Cementite (6.67\%C)}$$

This mechanical mixture of austenite and cementite produced in the eutectic reaction is called "Ledeburite."

Q. 4.22. :-What is steadite ?

Ans. :- Cast irons contain a larger amount of phosporus than steels. In some cast irons it may be as high as 0.15%. Phosphorus forms an intermetallic compound iron phosphide, Fe P. Presence of phosphorus in cast irons gives rise to the formation of a ternary eutectic comprising of austenite, cementite and iron phosphide (Aust., Fe C, Fe P). Later on the austenite changes in to ferrite and cementite. This ternary eutectic is given the name "STEADITE". If the phosphours content is considerable, steadite is seen at the meeting areas of three or more austenite dendrites, and looks like the skin of a leopard.

Q. 4.23. :-Draw the microstructures of all types of cast irons.

Ans.:-

(i) White cast iron	.. Fig. 4.5.(23)
(ii)Pearlitic grey cast iron	.. Fig. 4.6.(23)
(iii) Ferritopealitic gery cast iron	.. Fig. 4.7.(23)
(iv)Ferritic grey cast iron	.. Fig. 4.8.(23)

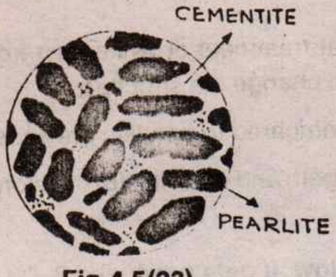


Fig 4.5(23)

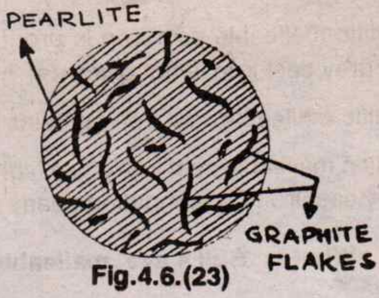


Fig.4.6.(23)

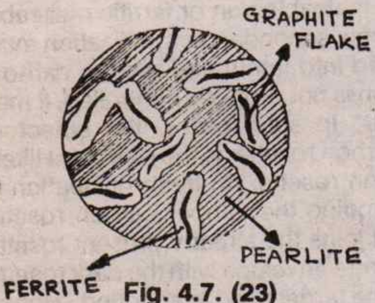


Fig. 4.7. (23)

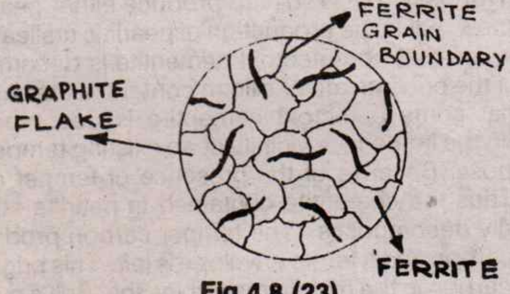


Fig.4.8.(23)

(v) Pearlitic malleable cast iron .. Fig. 4.9.(23)
(vi) Bull's eye malleable cast iron .. Fig. 4.10.(23)
(vii) Ferritic malleable cast iron .. Fig. 4.11.(23)
(viii) Pearlitic nodular cast iron .. Fig. 4.12.(23)
(ix) Bull's eye nodular cast iron .. Fig. 4.13.(23)
(x) Ferritic nodular cast iron .. Fig. 4.14.(23)

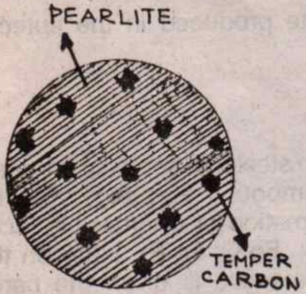


Fig.4.9.(23)

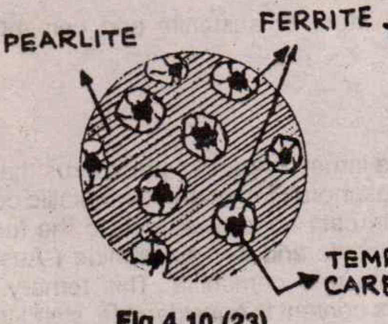


Fig.4.10.(23)

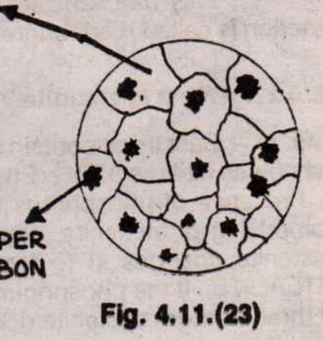


Fig. 4.11.(23)

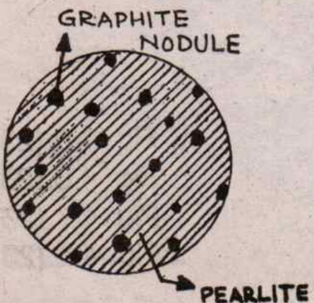


Fig.4.12.(23)

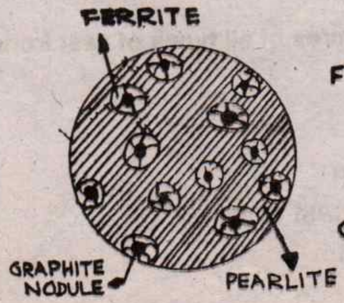


Fig 4.13.(23)

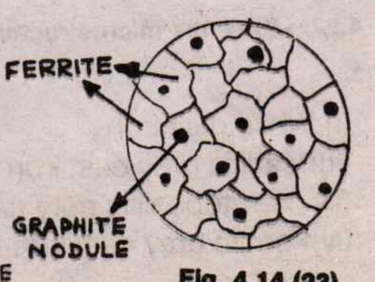


Fig. 4.14 (23)

Lesson 5

ALLOY STEELS.

Q.5.1.:- What are alloy steels ?

Ans.:- A steel is defined to be a plain carbon steel if the amounts of S, P, Mn and Si, which are normally present in steel due to the production process, are :

% S	0.05
% P	0.05
% Si	0.5
% Mn	0.6

A steel is defined to be an alloy steel if the amounts of any or all of the above elements exceed the above limits, or, any other element than the above four is present in significant amount (not as a trace element). This is because in such cases, the element is " intentionally added " to steel and not " incidentally present " due to the method of production.

Alloy steels contain a wide variety of alloying elements like Ni, Cr, Co, Si, Mn, S, P, W, V, Mo, Al etc.

Q.5.2.:- Why alloying elements are added to steel ?

OR

Why at all alloy steels are developed ?

Ans. :- Although plain carbon steels are suitable for a good number of applications, they have only a limited range of physical, mechanical and electrochemical properties. Hence, for a number of more critical applications requiring a higher strength, higher hardness, higher hardenability and specific physical properties and corrosion resistance, plain carbon steels are inadequate. Furthermore, a variety of combinations of physical and mechanical properties may be required for some applications, and it is impossible to get such a combination of properties in plain carbon steels. Hence the alloy steels are developed. For making alloy steels, various alloying elements, individually or together, are added to steel. The aims of adding alloying elements may be to achieve one or more of the following :

(a) to increase the yield strength and tensile strength of the steel.
(b) to increase the hardenability of steel.
(c) to increase the wear resistance of the steel.
(d) to increase the creep resistance of the steel.
(e) to impart red hardness to steel.
(f) to increase the corrosion resistance of the steel.
(g) to increase the oxidation resistance of the steel at elevated temperatures.
(h) to increase the machinability of steel.
(i) to produce special magnetic properties in steel.

Q.5.3.:- What are the various types of alloy steels ?

OR

Classify the alloy steels in brief.

Ans.:- Alloy steels are classified according to one of the following criteria :

(a) **Composition :** Depending upon the total content (in wt.%) of alloying elements present, the alloy steel are defined as low alloy steels or high alloy steels.If the alloy content is less than 10% the steel is known as a low alloy steel,and if more, a high alloy steel.

(b) **Use :** Depending upon the end use of the steel, steels are classified as (i) structural steels (ii) engineering steels (iii) tool steels (iv) high temperature steels (v) stainless steels (vi) soft magnetic steels (vii) hard magnetic steels etc.

(c) **Structure :** Depending upon the microstructure of the steel in its normalized condition, the steels are classified as

- (i) pearlitic steels
- (ii) ferritic steels
- (iii) martensitic steels
- (iv) austenitic steels
- (v) carbidic steels

Q.5.4. :- How are the alloying elements classified ?

OR

Distinguish clearly between austenite stabilizers and ferrite stabilizers.

Ans. :- Depending upon the effect of the addition of an alloying element on the Ae_3 temperature (α iron - γ iron transformation) and Ae_4 temperature (γ iron - δ iron change), the alloying elements added to steel are classified as austenite stabilizers and ferrite stabilizers.

Austenite stabilizers increase the stability field of FCC-γ iron. Hence they RAISE the Ae_4 temperature and LOWER the Ae_3 temperature.

Ferrite stabilizers increase the stability field of BCC δ - ferrite and α- ferrite. Hence they lower the Ae_4 and raise the Ae_3 temperature.

The other points of difference between the austenite stabilizers and ferrite stabilizers are given below :

	Austenite stabilizer	**Ferrite stabilizer**
(i)	more soluble in austenite	more soluble in ferrite
(ii)	do not form carbides (except Mn)	these are strong carbideformers
(iii)	FCC in crystal structure	BCC in crystal structure
(iv)	Lower Ae_1 (eutectoid) temperature	Raise the Ae_1 (eutectoid) temperature.

Q.5.5. :- Discuss in general the effects of alloying elements in steels.

Ans. :- The general effects of alloying elements in steel are given below :

(a) **Effect on eutectoid temperature :** All the austenite stabilizers like Ni, Co, and Mn lower the eutectoid temperature while all the ferrite stabilizers like W, V, Ti, Mo, Cr, Si, etc., raise the eutectoid temperature. This is illustrated in Fig.5.1.(5).

(b) **Effect on eutectoid composition :** All the alloying elements, both autenite as well as ferrite stabilizers, change the eutectoid composition by decreasing the carbon content of eutectoid mixture. This is schematically shown in Fig. 5.2.(5).

(c) **Effect on mechanical properties :** All the alloying elements increase the yield strength and tensile strength of steel. All the alloying elements EXCEPT Nickel, decrease the ductility and toughness of steel. Nickel alone increases the ductility as well as toughness of the steel.

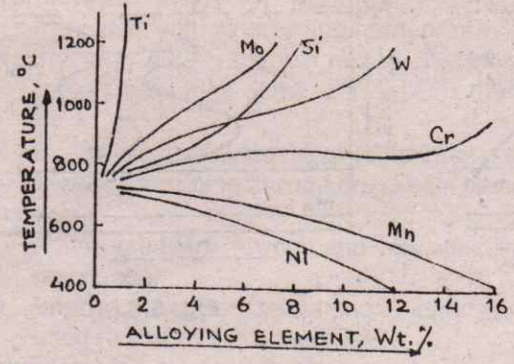


Fig. 5.1.(5)

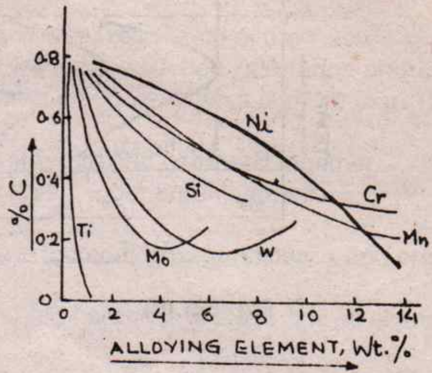


Fig. 5.2. (5)

(d) **Effect on hardenability :** All the alloying elements EXCEPT Cobalt, increase the hardenability of the steel. Cobalt decreases the hardenability of the steel.

(e) **Effect on S curves :** All the alloying elements have a profound effect on the shape and position of the Scurves.

Q.5.6. :- Explain the effect of alloying elements on the position and shape of the S curves.

Ans. :- All the alloying elements have a profound effect on the position and shape of the S curves of the steel. These effects can be summarized as given below :

(a) **Effect on the position of the S curves :** All the alloying elements EXCEPT COBALT shift the S curves towards the right. This means that all the alloying elements except cobalt decrease the critical cooling rate of the steel and hence increase the hardenability of the steel. This effect is schematically shown in Fig. 5.3.(6).

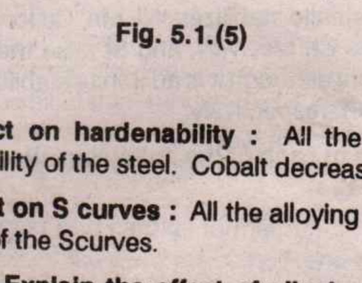


Fig. 5.3. (6)

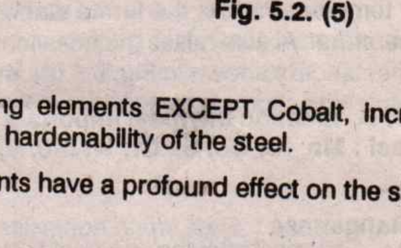


Fig. 5.4.(6)

(b) **Effect on shape of the S curve :** Austenite stabilizers do not change the shape of the S curves. It has only one NOSE. Ferrite stabilizers change the shape of S curves they give two noses. The upper nose is called pearlite nose and the lower nose is called bainite nose. This effect is schematically illustracted in Fig. 5.4.(6).

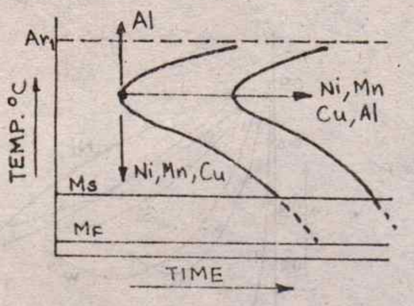


Fig. 5.5.(6)

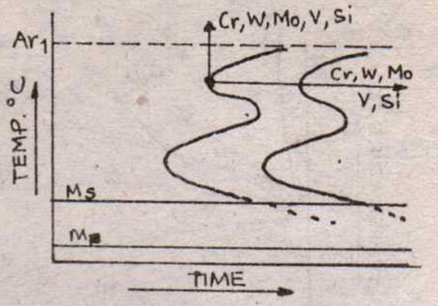


Fig. 5.6.(6)

(c) **Effect on the nose temperature :** The austenite stabilizers Ni, Mn, Cu lower the pearlite nose temperature. All the ferrite stabilizers like Cr, Mo, V,W, and Si raise the pearlite nose temperature. Al also raises the nose temperature although it is austenite stabilizer. This effect is schematically shown in Fig. 5.5.(6) and 5.6.(6). respectively.

Q.5.7. :- Mention the most important effects of each of the following alloying elements in steel : Mn, Ni, Co, Si, Cr, W, Mo, V, Al, S, P.

Ans.:-

(a) **Manganese :**

i) Cheapest alloying element for increasing the strength and hardenability of the steel.
ii) Upto 2.0% it does not decrease the ductility very adversely.
iii) The only austenite stabilizer which forms carbides, but only in the absence of other strong carbide formers.
iv) Beyond 10%,it stabilizes austenite completely in steels, and is used to produce Hadfield's manganese steel.
v) Toughness of the steel is slightly improved.
vi) Removes hot shortness of the steel due to sulphur.

(b) **Nickel :**

i) The only alloying element which increases yield strength and tensile strength of the steel along with incresing its ductility.
ii) Gives low temperature toughness to steel. This is the only element to give low temperature toughness to steel.
iii) Improves corrosion resistance in conjunction with Cr.
iv) Present in magnetic steels.

(C) **Cobalt :**

i) This is the only alloying element which decreases the hardenability of the steel.
ii) Increases the red hardness of high speed steels.
iii) Improves the magnetic properties.
iv) Increases the creep resistance of the steel.

(D) **Silicon :**

i) Very effective in increasing the elastic limit of the steel, without very adversely affecting its toughness, when used upto 1.5% along with Mn.
ii) A carbide former and improves heat resistance of the steel.

iii) Used for improving the acid resistance of the steel.

iv) Used for making soft magnetic steels because it reduces the area of the hysteresis loop.

(E) **Chromium :**

i) Very effecient in increasing hardenability and wear resistance of the steel.

ii) The only element which remarkably increases the oxidation resistance and corrosion resistance of the steel. Makes the steel stainless when it is more than 12% by wt.

iii) Economical alloying element to increase strength and hardness together.

iv) Steels containing chromium exhibit reversible temper embrittlement.

(F) **Tungsten :**

i) A strong carbide former and very effective in increasing wear reistance and creep resistance.

ii) Imparts secondary hardening tendency and red hardness to steel. It is an element used to make high speed steels.

(G) **Molybdenum :**

i) Similar to tungsten in increasing wear resistance and creep resistance.

ii) Imparts red hardness like tungsten. Used for making high speed steels. More economical than tungsten as 1 part by wt. of Mo = 2 parts by wt. of W.

iii) Added in small amounts (0.25%) to remove the tendency of temper brittleness in chromium containing low alloy steels.

(h) **Vanadium :**

i) A very strong carbide former.

ii) Increases the wear resistance and creep resistance of the steel.

iii) Increases the cutting efficiency of high speed steels.

(I) **Aluminium :**

i) Used as a deoxidizing agent to remove oxygen from the steel melt.

ii) It is strong nitride former and is essentially present in Nitriding steels or nitralloys.

(j) **Sulphur :**

i) A nuisance element in steel. It results in "hot shortness" of the steel - that is the tendency of the steel to crack during hot working. This is due to the formation of the low melting Fe-FeS eutectic.

ii) Used upto 0.15% to increase the machinability of mild steel. Due to long chip formation, machining of mild steel is difficult.Presence of sulphur produces short chips and thus improves machinability of the steel.Such steels are called "free cutting steels" and are used for the production of machined steel parts in large numbers by automatic machining.

(k) **Phosphorus :**

i) Another nuisance element.

ii) Highly undersirable because it makes the steel brittle.

iii) Decreases the soft magnetic properties of the steel; hence undesirable in soft magnetic steels.

Q.5.8. :- What is ball race steel or ball bearing steel ? Explain its heat treatment.

Ans. :- This is a typical low alloy steel, designated as En 31 in British Industrial specifications, containing chromium. Its typical composition is carbon 1.0%, Mn 0.5%, Cr 1.31.5%. Because of the presence of chromium, it has excellent hardenability and can be quenched in oil to harden. It is mainly used for the manuacture of steel balls and rollers for ball and roller bearings. Hence the name ball race steel or ball bearing steel.

Its heat treatment consists of :

(i) austenitization at 810°C followed by oil quenching.
(ii) tempering at 150 180°C.

The low temperature of tempering ensures that the hardness does not decrease, but all the internal strains due to martensite be relieved. The hardness after proper heat treatment is about 65 Rc. Because of the presence of chromium carbide in the structure, the heat treated steel has excellent wear resistance.

Q.5.9.: What is O.H.N.S. steel ? Explain its heat treatment and uses.

Ans. : The full form of O.H.N.S. steel is "oil hardening non shrinking" steel. It is a type of tool steel in which the hardening and tempering does not produce any appreciable change in size by proper control of tempering temperature. The most common of this type of steel has a typical composition of C 1.0%, Mn 1.0 - 1.5%, W 0.5% Cr 0.8%, V 0.2%.

The heat treatment of this steel consists of :

(i) austenitization at 770-800°C followed by quenching in oil and
(ii) tempering at 225-250°C. This tempering temperature range involves MINIMUM (or negligible) dimensional change.

This steel is used mainly for producing measuring equipments like vernier calipres, screw gauges, dial guage components etc.

Q.5.10. : What is high carbon high chromium steel (HCHC) ? Explain its heat treatment and uses.

Ans. : High carbon high chromium steel is a tool steel which gives the optimum wear resistance at room temperature, at minimum cost. It means that it is the most economical tool steel having maxiumum room temperature wear resistance.

This steel contains about 10 - 13 % Cr with about 1 - 1.3 % C, maintaining the Cr/C ratio as 10/1. The steel is heat treated by

(i) austenitizing at 950°C and oil quenching,
and, (ii) tempering it at 180°C or 400°C depending upon the hardness required.

This steel is used for making cold drawing dies and thread rolling dies. In this case, the tempering temperature is 180°C. It is also used to make cold punching dies, cold forming tools etc., which are tempered at about 400°C, because relatively higher toughness is desirable. Presently grinding media balls for ball mills are also being made of this steel.

Q.5.11.: What are high speed steels ? What are their types ? Explain.

Ans. : High speed steels constitute the most important class of tool steels. As the name suggests, the steels are used for high speed cutting at such high speeds that the tool tip becomes red hot. Hence they are based on the tungsten or molybdenum addition to steel in substantial amounts because both these elements give red hardness to steel - the cabability of maintaining high hardness and and a keen cutting edge even up to the red hot temperature of 600°C.

The first high speed steels that were developed were tungsten type. Later on molybdenum high speed steels were developed. Presently we have high speed steels of both the types and those in which both the elements are present. One example of each type is given below :

Grade	%C	Cr%	%W	%M0	%V
M1	0.8	4.0	1.5	8.0	1
T1	0.7	4.0	18.0	–	1
M2	0.8	4.0	6.0	5.0	2

Q.5.12. :- What are ultra high speed steels ?

Ans. :- Ultra high speeds steels are those high speed steels which contain larger amounts of vanadium and, in addition, they contain cobalt also. The vanadium content is increased up to about 4.0% while the cobalt content may vary from 5% to 12%.

Cobalt is extremely efficient in increasing the red hardness of the high speed steel and hence a longer tool life is achieved. Also, more severe cutting can be done, thus increasing the productivity.

Vanadium increases the cutting efficiency by maintaining a very fine cutting edge. It also makes the tool capable of cutting even gritty material containing hard particles.

Q.5.13. :- Describe the steps involved in the heat treatment of high speed steel tools.

Ans. :- High speed steels are relatively less ductile and their thermal conductivity is not very good. Hence special care is needed in the heat treatment of high speed steel tools, particularly during austenitization. Heat treatment of high speed steel tools involves the following steps :

(I) **Heating for austenitization :** As already pointed out special care is taken in heating machined high speed steel tools to their austenitization temperature. A slow heating rate is essential otherwise due to uneven heating, the tools may crack during heating. This is known as "clinking". To avoid this, the H.S.S. tools are heated to their austenitization temperature in three steps :

(a) **Preheating stage 1 :** Upto 500^{O}- 650^{O} C. This relieves most of the machining stresses.
(b) **Preheating stage 2 :** Upto 850^{O} C

Both these heating steps are done at very slow rates in salt bath furnaces. In the second stage, the tools are kept at 850^{O} C and soaked for some time, depending upon the section size of the tool, to homogenize the temperature throughout the cross section.

(c) **Final heating for austenitization :** After the second stage of preheating, the tools are quickly transferred to another salt bath furnace, kept at 1175^{O} C to 1290^{O} C depending upon the austenitization temperature recommeded for H.S.S. steels, as given below :

(i) M1 HSS : 1175^{O}- 1220^{O} C
(ii) T1 HSS : 1250^{O} - 1290^{O} C
(iii) M2 HSS : 1190^{O}- 1235^{O} C

The tools are kept only for 1 min to 5 miuntes at this temperature depending on the size of their cross section.

(d) **Quenching :** From this austenitization temperature, HSS tools are quenched to room temperature in one of the following ways:

(i) directly quenched in an oil bath kept at room temperature,till the tools cool fully.

(ii) directly quenched in an oil bath kept at room temperature, till the temperature of the tool is decreased to about 450° C, then taken out and cooled in air.

(iii) quenched into a salt bath kept at 600°-650° C, homogenize the temperature, and then take out to cool in air upto room temperature.

(e) **Tempering :** After quenching, the tools are tempered in a circulating air furnace at about 550°C to 600° C to develop maximum hardness. The tempering treatment is repeated twice or thrice and is known as double or triple tempering.

The final hardness after tempering is about 67 Rc.

Q.5.14.:- Explain the changes that occur on tempering high speed steel. Why double or triple tempering is essential for high speed steels ?

Ans. :- The correctly hardened high speed steel contains about 20-25% retained austenite and the rest is martensite and undissolved alloy carbides. The hardness is around 63 Rc. For obtaining red hardness, it is essential that the martensite be tempered at 550° C to 600° C for 1.5 hrs. The martensite is a metastable phase and hence on tempering it decomposes. During the tempering of high speed steels, the hardness varies with tempering temperature as shown in Fig. 5.7.(14). During tempering, complex alloy carbides of W and Mo are very finely precipitated in the matrix of low carbon martensite. This is called tempered martensite. Due to the fine precipitation of alloy carbides the hardness increases to about 65-66 Rc. During cooling from this tempering temperature some of the retained austenite changes into martensite. Hence the structure after first tempering is "Tempered martensite + martensite + alloy carbides + retained austenite". To temper this newly formed martensite the same tempering cycle is once more repeated. This tempers the newly formed martensite, but during cooling most of the remaining retained austenite transforms into martensite. Hence after the second tempering, the high speed steel contains "tempered martensite + alloy carbides + martensite + very little retained austenite (if any)". Hence to temper this freshly formed martensite, the tempering cycle is repeated a third time, giving nearly 99% tempered martensite + alloy carbides in structure.

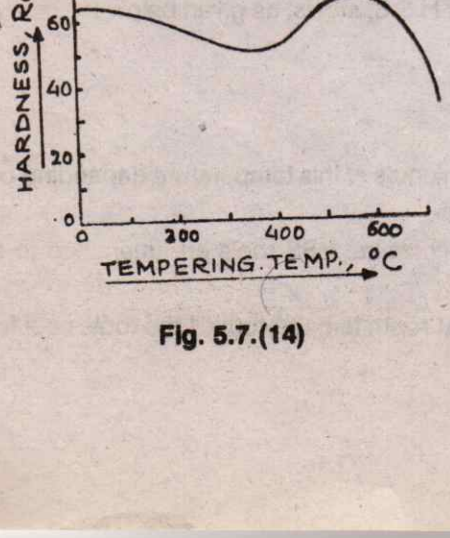


Fig. 5.7.(14)

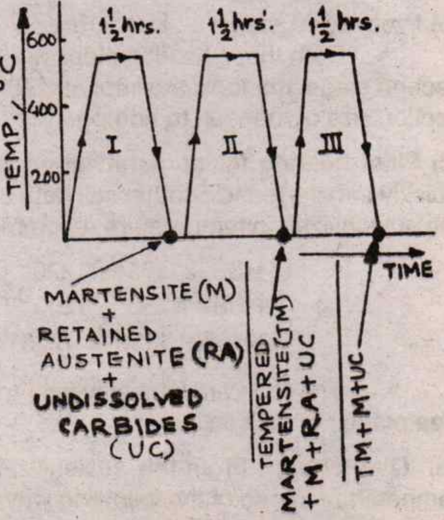


Fig. 5.8. (14)

Complete tempering of all martensite is essential because,for the development of red hardness, the fine precipitation of complex alloy carbides from martensite is ESSENTIAL. Hence the triple tempering treatment.

Fig. 5.8.(14). diagramatically depicts the structural changes in double or triple tempering.

Q.5.15. :- What do you understand by red hardness ? How is it achieved in high speed steels ?

Ans. :- Red hardness is the ability of the high speed steels to maintain their high hardness of Rc 67 even at the red heat temperature of 550^{O} C to 600^{O} C. Red hardness is also called "Hot hardness'. During high speed cutting, the tool tip becomes red hot, but, even then the tool contiues to be hard and goes on cutting. This is due to the red hardness.

Red hardness is obtained due to the fine precipitation of complex alloy carbides of tungsten and molybdenum during the tempering of martensite in high speed steels. This is achieved by tempering hardened high speed steel at 550^{O}C 600^{O}C. The conventional low temperature tempering of martensite will not result in the precipitation of these alloy carbides. Hence if the high speed steel is tempered at say 180^{O}C 200^{O}C, the hardness slightly falls down, and in service, the tool would miserably fail as the red hardness is not achieved. Red hardness is increased by cobalt addition.

Q.5.16. :- What is secondary hardening ?

Ans. :- When certain high alloy steels containing chromium, tungsten, and molybdenum (like high speed steels) are hardened and tempered, the variation in the hardness with tempering temperature is as shown in the tempering curve of high speed steel, illustrated by Fig. 5.7.(14). For lower tempering temperatures, the hardness falls with increase in tempering temperature as is found in the ordinary plain carbon and low alloy steels. However, after a temperature of about 475^{O}C, the hardness after tempering again starts increasing with increase in tempering temperature and attains a maximum in the tempering temperature range of 550^{O}-600^{O}C. This increase in the hardness due to the high temperature tempering is known as "secondary hardening". This increase in hardness i.e., secondary hardening is due to the coherent precipitation of complex alloy carbide particles.This produces elastic strains in the matrix and these elastic strains are responsible for the increase in hardness.

Q.5.17. :- What are hot die steels or hot working steels ? Give their typical composition and heat treatment.

Ans. :- Hot working dies or hot working (forming) tools come in contact with hot steel at a temperature of about 1050^{O}C.Most of these dies or forming tools require good toughness,and good wear resistance at the temperature of working, that means, some red hardness, though not as high as that of high speed steels.

These characteristics are completely fulfilled by using a steel which contains 10-14% W along with 0.4 - 0.6% carbon. The lower carbon variety is used for forging dies where impact loads are severe. Like high speed steels, these steels are also hardened by quenching from about 1250^{O}C, followed by double tempering at 650^{O}C for 1.5 hrs, each time. A hardness of about 50/55 Rc is obtained and is maintained for a long time at the hot working temperature. Hence these steels are also called "semihigh speed steels".

Q.5.18. :- What are stainless steels ? What are the three types of stainless steels and what are their nominal compositions ? Explain their characteristics deciding their end use.

Ans. :- Stainless steels are a class of steels which do not rust in the atmosphere as most other steels do. The term "stainless" means a resistance to staining, rusting or pitting in the air which is moist and polluted. Stainless steels are essentially alloys of iron and chromium with about 12-30% chromium. For the stainless property it is essential that minimum 12% chromium be present "in solution" in steel. Apart from Fe and Cr, other alloying elements like Ni, etc. may also be present.

Depending upon the room temperature microstructure obtained on air cooling from austenitic region, three types of stainless steels are indentified : ferritic, martensitic and austenitic stainless steels.

(a) **Ferritic stainless steels :** As the name suggests, these steels contain ferrite at room temperature. They are magnetic below 768^{O}C.

Ferritic stainless steels contain 1227% Cr, no nickel and 0.08- 0.2%C, such that the chromium-carbon balance satisfies the relation -

$$\%Cr - (17 \times \%C) > 12.5\%$$

These stainless steels are cheapest of all stainless steels, and are preferred when moderate strength and corrosion resistance are required and castings are to be produced. Since ferrite is BCC in structure, its deformability is poorer and hence ferritic stainless steels can not be shaped or processed by various cold working operations like deep drawing, cold extrusion, spinning etc. That is why their use is much more limited.

(b) **Martensitic stainless steels :** These steels contain martensite at room temperature and hence they are called the hardenable stainless steels. The chromium-carbon balance should satisfy the relation

$$12\% < [\%Cr - (17 \times \%C)] < 12.5$$

If the chromium content is such that the factor %Cr – (17 x %C) is more than 12.5%, the steel would be a ferritic stainless steel and if it is less than 12%, the steel is martensitic but it is not stainless, its corrosion resistance is poor. All martensitic stainless steels are magnetic at room temperature.

We have three kinds of martensitic stainless steels:

(i) **Low carbon martensitic stainless steel:** 11.5 - 13% Cr, 0.15% C. These steels may contain some nickel also (1-2%).Designation 403 is termed as the "turbine quality" martensitic stainless steel because it is mostly used for making steam turbine blades. This steel is hardened by quenching from 1000^{O}C, and tempered at 400^{O}- 500^{O}C for optimum toughness with a hardness of about 25 - 30 Rc.

(ii) **Medium carbon martensitic stainless steel :** 15 - 17% Cr, 0.3 - 0.4% C. This stainless steel is called the "cutlery grade" martensitic stainless steel because of its extensive use in making cutlery. On hardening and tempering, it develops a hardness of about 40 Rc, with adequate ductility.

(iii) **High carbon Martensitic stainless steel :** 16 -18% Cr, 0.6 - 0.9%C, 0.75% Mo. These steels are used for making surgical tools, impellers for corrosive chemical fluids and abrasive slurries, corrosion resistant tools etc., because on heat treatment they develop high hardness. These steels are usually hardened by quenching from 1000^{O} - 1050^{O}C,in oil, or by air cooling, followed by tempering at 350^{O}C, to develop a hardness between 50 to 60 Rc. These steels are relatively brittle.

(c) **Austentic stainless steels :** These steels show an austenitic structure at room temperature. Since austenite is FCC in structure, these steels have excellent deformability in cold condition. Hence a variety of products may be made of austentic stainless steel using cold forming operations like cold rolling, deep drawing, pressing, spinning, drawing etc. Hence austentic stainless steels are the most widely used of all the stainless steels. The most typical composition of an austentic stainless steel contains 18% Cr, 8% Ni, and 0.08% C. This is known as 18-8 stainless steel (304 SAE or AISI designation).

Most of the reactors used in mildly to strongly corrosive atmospheres, food processing plants, utensils etc., are made of austentic stainless steel.

Austentic stainless steels are nonmagnetic and have excellent low temperature toughness. Hence for subzero applications, the components are invariably made of austentic stainless steel.

Q.5.19. :- What is sensitization of austentic stainless steel ?

Ans. :- When during processing, welding, or, accidentally,austenitic stainless steel is heated to any temperature between 425^{O} C 825^{O} C and slowly cooled to room temperature, it is found that its corrosion resistance is greatly decreased. It is found that corrosion in such steel preferentially occurs along the grain boundaries. Hence it is called intergranular corrosion. Such a steel which gets heated to the above temperature range and is air cooled is prone to intergranular corrosion and hence called to be "sensitized".

When the austenitic stainless steel gets heated to 425^{O} - 825^{O}C, and is slowly cooled, chromium carbide gets precipitated along the grain boundaries. This chromium carbide precipitation requires a large amount of chromium in a short time. Hence all the chromium for this precipitation is drawn from a localized region near the grain boundary. Hence in regions all along the grain boundaries, the amount of chromium content falls below 12%. We have already seen that for corrosion resistance, minimum 12% Cr is essential. Hence the corrosion resistance of this grainboundary region is markedly decreased. This results in a preferential corrosion all along the grain boundaries causing intergranular corrosion.

Q.5.20. :- How can sensitization of austenitic stainless steel be avoided ?

Ans. :- Since the sensitization of austenitic stainless steel is due to the precipitation of carbon as chromium carbide all along the grain boundary, it can be avoided by : (i) decreasing the carbon content to a very low level (say 0.03%), thus reducing the chromium required for carbide formation, or, (ii) by adding columbium or titanium, in small amounts (0.2%) to austenitic stainless steel. These elements are very strong carbide formers. In preference to chromium, they form the carbides which are precipitated at the grain boundary. The chromium content remains undisturbed and hence no "Sensitization" occurs. Avoiding sensitization by incorporating Cb or Ti, is known as "Stabilization" and the austenitic stainless steel containing Cb or Ti is said to be stabilized.

Q.5.21. :- How can the sensitized austenitic stainless steel be brought back to its normal condition ?

Ans. :- The sensitization of austenitic stainless steel is due to the precipition of chromium carbide along the grain boundaries. This results in a preferential reduction in chromium content in the regions adjacent to the grain boundaries, bringing it below 12%. This makes the steel prone to intergranular corrosion.

This condition may be removed by redissolving all the chromium carbide back into the austenite. This is achieved by heating the sensitized austentic stainless steel to 1000^{O} C - 1050 ^{O}C, soak it there for some time (1hr), and then cool it rapidly in air. This redissolves all the chromium back in to austenite, and the faster cooling prevents carbide precipitation.

Q.5.22. :- What is weld decay ?

Ans. :- During the welding of stainless steel, a region some distance away from the weld gets heated to a temperature range of 450^{O}- 850^{O} C. Hence this region near the weld gets sensitized and becomes prone to intergranular corrosion. During service, corrosion preferentially occurs in this region near the weld and it crumbles due to intergranular corrosion, almost as if the material is "decayed" there. This is known as weld decay.

It is clear that the weld decay is due to the sensitization of austenitic stainless steel. Hence it can be prevented by using either stabilized austenitic stainless steel for making welded parts or, by the heat treatment used to redissolve chromium carbide and thus remove the bad effects of sensitization.

Q.5.23. :- What is Hadfield's manganese steel ? Explain its heat treatment and uses.

Ans. :- Hadfield's manganese steel is a unique austenitic steel possessing excellent strength and toughness with high wear resistance under impact wear conditions encountered in material handling and earth moving equipments. It is an extremely tough nonmagnetic alloy steel. It can be used as castings or hot rolled products like aromour plate.

The nominal composition of Hadfields manganese steel is 1.2-1.4%C and 12-14% Mn, keeping the Mn/C ratio as 10/1. The standard heat treatment used for this steel is given below :

The steel is austenitized by heating it to 1050^{O} - 1100^{O}C with sufficient soaking time depending upon the size of the component. Then the steel is water quenched. Water quenching does not alter the structure. It remains austenitic. The fast cooling is used to avoid the precipitation of manganese carbide along the grain boundaries, because such precipitation of carbide decreases toughness.

Before the component is used, it is customary to plastically deform the component on the surface by blows of a hammer. This forms a layer of martensite on the surface which gives excellent wear resistance.

Q.5.24. :- Hadfield's manganese steel is austenitic in structure and hence it is soft. Even then it has excelent wear resistance in impacta brasion condition. How ? What are its uses ?

Ans. :- It is true that the Hadfield's manganese steel is austenitic in structure and it is also true that austenite is soft. However, as soon as it is used under impacta brasion conditions, a layer of austenite at the surface (where the impact takes place) gets converted into martensite due to plastic deformation by impact. This martensitic layer is extremely hard and gives an excellent wear resistance. Furthermore, this layer of martensite is backed by tough austenite. Hence the unique combination of excellent wear resistance with high toughness is achieved.

The combination of wear resistance and toughness makes the Hadfiled's steel eminently suitable where abrasion occurs under impact loading conditions as in crushers, caterpillars, showels, bullodzoers etc. Hadfield's manganese steel is used for making jaw crusher plates, coal grinding mill rings, showel tubs, railway points etc.

Q.5.25. :- What are soft magnetic steels ? Mention the two types and their nominal compositions.

Ans. :- Soft magnetic steels are a class of alloy steels developed by incorporating silicon as the alloying element. They are economical than other specially developed magnetic alloys and hence are industrially used in a number of applications.

In some magnetic applications, only temporary magnetic properties are required. That means that the component has to be repeatedly magnetized and demagnetized. Obviously, the material used for such an application must have the hysteresis loop with minimum area. This reduces the hysteresis losses and increases the efficiency of operation. Addition of silicon as an alloying element reduces the hystersis losses as well as eddy current losses (due to high resistivity) of steels. These steels are known as soft magnetic steels.

Basically two types of silicon steels are developed for soft mangetic applications.

(i) **Hot rolled silicon steels :** These steels contain from 1% Si to 4.5% Si. The steel is hot rolled. It is used for the manufacture of armatures of motors,generators, low power transformer cores, small transformer cores, pole bricks etc. The silicon content is increased as the capacity is to be increased.

(ii) **Cold rolled grain oriented steel :** This steel contains about 3% silicon, 0.015% C, 0.003% S, 0.006% P and 0.15% Mn. It means that it is an extremely pure steel. It is used in the cold rolled and heat treated condition. Mainly it is used for high power applications.

Q.5.26.:- What is cold rolled grain oriented silicon steel ? Explain its processing and uses.

Ans. :- The cold rolled grain oriented silicon steel is a high purity soft magnetic steel containing about 3% Si, 0.015% C, 0.003% S and 0.006% P. It undergoes a special sequence of processing operations which are given below :

(a) Hot rolling of ingots to produce strip of about 2.5 mm thickness, in variouos steps.
(b) Cold rolling of this strip, in steps, to the desired thickness,0.3 mm or less.
(c) Annealing of cold rolled sheet at 800^{O} C in an atmosphere of pure hydrogen or cracked ammonia.
(d) Cooling the steel sheets from the annealing temperature of 800^{O} C to room temperature, at a controlled rate of 50^{0} C/hr.

The annealing treatment is essential to produce the desired orientation.After the final annealing treatment the < 100 > direction in all the grains in the sheet becomes parallel to the rolling direction, i.e., the length of the sheet. This < 100 > direction is the direction of easiest magnetization and hence the mangnetic permeability is very high, even for a small H value. Hence if the strips are cut in lengths parallel to the length of the sheet, and then they are bolted to form transformer cores, the hysteresis loop would be extremely small. This is schematically illustrated in Fig. 5.9.(26). Such laminated cores are used for large power.

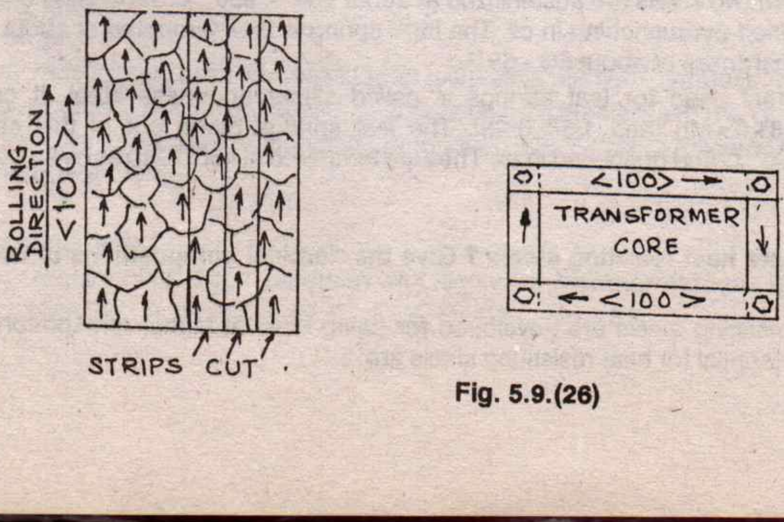


Fig. 5.9.(26)

Q.5.27. :- What are hard magnetic steels ? Give their nominal composition, and heat treatment .

Ans. :- Permanent magnets are those which, once magnetized, should not be easily demagnetized. The materials used for making permanent magnets are called hard magnetic materials. These materials are characterized by a large hysteresis loop, a high magnitude of B remnant and high value of coercive force. Earlier it was believed that magnetic hardness and mechanical hardness go along with each other. This led to the development of hard magnetic steels.

Steel in martensitic condition with a high hardness, has high coercive force. Cheaper hard magnetic steels contain about 0.9% C and 3.5% Cr or 6% W. Costlier varieties contain cobalt also in various amounts from 3% to as high as 35% Co.

The heat treatament of these steels is done by

(i) austenitizing at 850^{O} C and quenching in oil.
(ii) tempering at 180^{O}C.

Apart from these hard magnetic stels, some highly alloyed iron alloys are also developed for permanent magnets. The most important of these are Alnico, Alcomax and Columax. The nominal compositions of these alloys are given below :

	Ni	Al	Cu	Co	Nb	Fe
Alnico	18	10	6	-	-	Bal
Alcomax	13	8	3	24	2.5	Bal
Columax	13	8	3	24	0.7	Bal

Q.5.28. :- Give nominal chemical composition and heat treatment used for any two types of spring steels.

Ans. :- The material used for a spring must have high elastic limit and high resilience along with enough toughness. Steels developed for springs must have both these properties. Hence they are always used in the heat treated condition. Springs are of two types

(i) Coiled springs
(ii) Leaf springs

The steel used for making the coiled springs is usually a CrW steel or CrMo steel. The nominal compositions are

(a) 0.5%C, 1.5%Cr, 2.5%W the usual chisel steel
(b) 0.5%C, 3.25%Cr, 1.4%Mo

The springs are made from the steel either by cold forming (if the spring is made from a wire) or hot coiling. Generally, after coiling, the springs are heat treated. The springs made of the above two steels are austenitized at about 900^{O}- 950^{O} C depending upon their grade and hardened by quenching in oil. The hard spring is then tempered at about 250^{O}C 350^{O} C to get a hardness of about 5O - 55 Rc.

The steel used for leaf springs is called silicomanganese steel. It contains 0.45-0.55%C, 0.81.0%Mn, and 1.5-2.0%Si. The leaf springs made out of this steel are austenitized at 900^{O} C and quenched in oil. They are tempered at 450^{O} C to acieve a hardness of about 50 Rc.

Q.5.29. :- What are heat resisting steels ? Give the nominal compositions of two such steels.

Ans. :- Heat resisting steels are developed for being used at higher temepratures. The characteristics essential for heat resistiung steels are

(i) high resistance to oxidation and scaling.
(ii) high creep resistance to retain good strength at the temperature of application.
(iii) structural stability at high temperature. Structural changes,which reduce the strength should not occur.

Naturally the composition of the steel will be determined by
(i) the temperature of application.
(ii) the strength level required.

In general, all the heat resisting steels contain a high amount of chromium as it is the basic element to improve resistance to oxidation. The chromium content varies from 20% to 33% depending upon the requirement. Besides chromium, they contain W, Mo, V etc., to improve their creep resistance.

Two compositions of the heat resisting sceels are given below
(1) C - 0.4%, Si - 0.8%, Ni - 4%, Mo - 2%.
(2) C - 0.35%, Si - 1.7%, Ni - 7%, Cr - 20%, W - 4%.

Q.5.30. :- Suggest suitable steel with heat treatment to be used for each of the following applications :

Ans.:-

(a) **Wood cutting saw :**

(i) *Property requirement :* Moderate hardness and wear resistance, economy.

(ii) *Steel suggested :* 0.7%C plain carbon steel.

(iii) *Heat treatment :* Oil quenching from 825^{O}C followed by tempering at 180^{O}C because a hardness of 64 Rc is required.

(b) **Cheap hack saw blades :**

(i) *Property requirement :* High hardness and wear resistance, economy.

(ii) *Steel suggested :* 1.0%C, 2.0%W, 1.5%Cr. 1.0%Ni.

(iii) *Heat treatment suggested :* Oil quenching from 775^{O}- 800^{O} C following by tempering at 180^{O} C . Hardness 64 Rc.

(c) **Good hacksaw blades :**

(i) *Steel suggested :* High speed steel 18%W, 4%Cr, 1%V, 0.70.9%C.

(ii) *Heat treatment suggested :* Slow preheaating to 650^{O} C and then to 850^{O} C in salt bath, final austenitization at 1250^{O} C followed by oil quenching, double tempering at 550^{O}- 600^{O}C Hardness 67 Rc.

(d) **Drills and reamers :**

High speed steel,same composition and heat treatment as suggested for good hack saw blades, above.

(e) **Hot forging dies:**

(i) *Property requirement :* red hardness,creep resistance,medium hardness , high toughness.

(ii) *Steel suggested:* Semi high speed steel containing 0.30.4% C, 10.0% W, 3%Cr, 0.5% V.

(iii) *Heat tratment suggested :* Quenching from about 1200^{0} C in oil followed by tempering at 550^{0} C. Hardness 45 Rc.

(f) **Ball bearing balls :**

(i) *Property requirement:* High hardness with high wear resistnce at room temperature.

(ii) *Steel suggested :* Ball race steel C 1.0%, Cr 1.5%, Mn 0.5%

(iii) *Heat treatment suggested :* Oil quenchig from 810^{O}C followed by tempering at 180^O-200^O C. Hardness 64 Rc.

(g) **Cold drawing dies :** Same as balls for ball bearings. Alternatively, high carbon high chromium steel.

(h) **Cold punching dies :**Same as in answer (g) i e., ball race steel

(i) **Cold threading dies :** Same as in answer (h).

(j) **Jaw Crusher plates :**

(i) *Property requirement :* High wear resistance in impact abrasion.

(ii) *Steel suggested :* Hadfield's manganese steel 14 %Mn, 1.4 %C.

(iii) *Heat treatment :* Water quenching from 1050^O-1100^{O}C, followed by impact blows on surface.

Structure : Martensite at surface
Austenite at core

(k) **Bulldozer plates, power showel tubs etc. :** Same as for jaw crusher plates.

(l) **Steam turbine blades :**

(i) *Property requirement :* High strength, corrosion resistance, creep strength and wear resistance upto 350^O - 400^O C.

(ii) *Steel suggested :* Turbine quality stainless steel, i.e.,low carbon martensitic stainless steel:C 0.15%,Cr 11-13%,Mn 1.0%.

(iii) *Heat treatment :* Oil quenching from 1000^{O}C followed by tempering at 425^O- 500^O C. Hardness 35 Rc.

(m) **Impeller and pump bodies for slurries :** Same as for turbine blades.

(n) **Food processing equipment :**

(i) *Property requirement :* Good corrosion resistance, ease of fabrication by cold forming and welding.

(ii) *Steel suggested :* 18-8 stainless steel, 18% Cr, 8% Ni, 0.08% C. No heat treatment required.

(o) **Leaf springs :**

(i) *Property requirement :* Good elastic limit, high resilience and toughness.

(ii) *Steel suggested :* Silicomanganese spring steel, C 0.45%, Si 1.5 - 2.0%, Mn 1.5%.

(iii) *Heat treatment :* Oil quenching from 900^O C followed by tempering at 450^O C to get a hardness of about 45 - 50 Rc.

(p) **Gears :**

(i) *Property requirement :* High hardness at the surface for wear resistance and tough core for power transmission.

(ii) *Steel suggested :* Low alloy Ni - Cr steel, C 0.35%, Ni 1.5%, Cr 1.0%.

(iii) *Heat treatment :* Case carburizing followed by hardening and tempering at 180^O C

(q) **Large crank shafts or engine shafts :**

(i) *Property requirement :* Wear resistance at the surface and a tough core , high fatigue strength.

(ii) *Steel suggested :* Nitriding steel 0.25 - 0.3% C, 1.5 - 2.5% Ni, 1.5% Cr, 1.5% Al.

(iii) *Heat treatment :* Normalizing to give a tough core followed by nitriding.

Lesson 6.

SURFACE HARDENING OF STEEL.

Q.6.1.:- Why surface hardening of steel is done ? Why at all it becomes necessary ?

Ans.:- The rate of wear under many industrially important conditions can be reduced to an acceptable value by the use of high hardness at the wearing surface. Hardening an entire cross- section has the disadvantage of decreasing the overall ductility and toughness. It is therefore common practice to harden just the surface layer, often by means of an extremely hard brittle phase embedded in a more ductile matrix, thus producing a hard case and a tough core. Such surface hardening can be done by various methods, and rather becomes necessary for developing the dual properties of hard surface and tough core in many of the components such as gears, crank pins and cams.

Q.6.2.:- What are the steels which are surface hardened and, for which applications ?

Ans.:- Since toughness in the core is one of the most important characteristics of case hardening steels, usually steels with the carbon contents below 0.2% are selected. However, steels with carbon as high as 0.3% are also selected in some applications where greater support for the case is desired (particularly for heavy loads).

Table-1 : Plain Carbon steel

Carbon %	Mn%	
0.06 - 0.15	0.6	Max. core toughness, thin sections
0.1 - 0.8	0.8	General purpose, gears, shafts.
0.2 - 0.5	0.5	High load carrying capacity, e.g. roller bearings.

Normally it is advisable to use an alloy steel with high strength combined with toughness instead of a plain carbon steel. With alloy steels, the desired properties may be obtained by oil quenching, thus reducing the risk of distortion to which water- quenching steels are susceptible. The following plain carbon steels and alloy steels are selected for various components, as shown in table-1 and table-2.

Table-2 : Alloy steels

Composition%	C	Mn	Ni	Cr	
(1) 1.5 % Mn - steel	0.15	1.5	-	-	For max.surface hardness without severe shock.
(2) 3 % Ni - steel	0.12	0.5	3	-	Shafts & Gears
(3) 3 % Ni-Cr-steel	0.12	0.35	3.3	1	For automobile steering worm and oberhead valve gear.

Q.6.3. :- What are the different methods of surface hardening ?

Ans.:- The following methods are used for the surface hardening:-

(1) Flame hardening

(2) Induction hardening

(3) Carburizing

(i) Solid carburizing
(ii) Liquid carburizing
(iii) Gaseous carburizing

(4) Nitriding
(5) Carbonitriding
(6) Tufftriding

Q.6.4. :- What is pack carburizing ? What are its advantages and limitations ?

Ans.:- Pack carburizing consists of packing the roughly machined parts in some material, rich in carbon, in boxes which are covered with lids and luted (sealed airtight) with fireclay, to exclude air and the escape of gases.

These boxes are then heated at 900-950 C for a period of 6- 15 hrs depending on the depth of case desired.

Any portions of the part which are not required to be hardened, are protected by covering them with a mixture of asbestos and fireclay or copper plating (0.003" thick).

The carburizing material consists of wood or bone charcoal, charred leather or petroleum coke together with an energiser (such as barium carbonate - $BaCO_3$ 10-15%) which promotes rapid action on the steel.

The absorption of nascent carbon take place on the surface of the steel parts. This nascent carbon is obtained due to the decomposition of CO in the presence of iron according to the reversible reaction;

$$2CO \xrightleftharpoons[950^\circ C]{} CO_2 + C\text{(nascent carbon at the hor surface on the steel)}$$

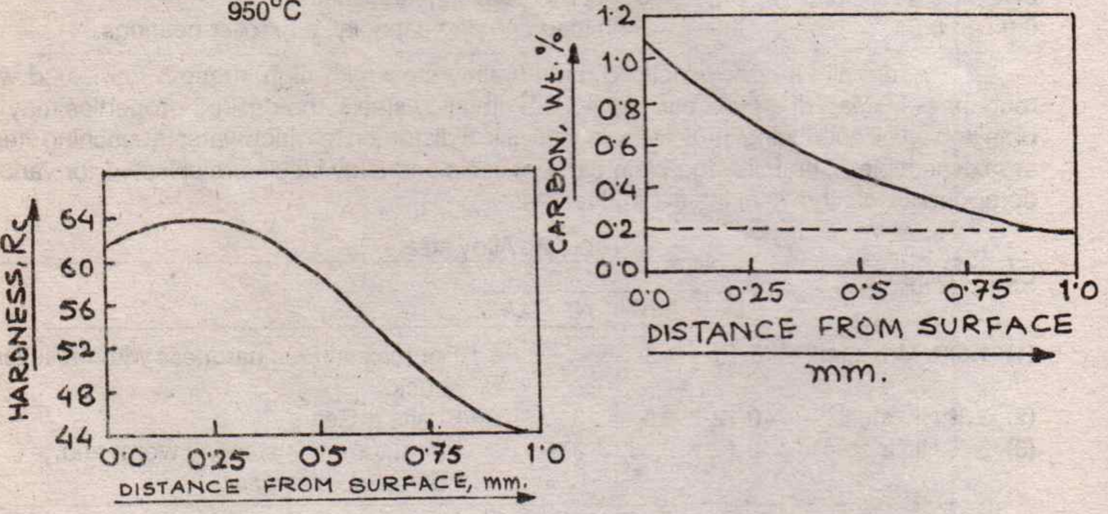


Fig. 6.1. (4)

The carbon is appreciably soluble in austenite, hence the operation must be carried out above the upper critical temperature. Once the 'C' atoms enter the surface of the steel, they tend to diffuse inwards. The diffusion rate depends on the composition of the steel and increases with increase in temperature. This produces a carbon concentration gradient from outside to the inside, as shown in Fig. 6.1. (4).

Advantages :-

(1) Case thickness upto 0.16" is poslible, so more grinding allowance is available.

(2) Negligible dimensional change during carburizing. Distortion my occur during heat-treatment (hardening).
(3) Process is mainly used for gears, camshafts and bearings, and does not require skilled workers.
(4) The process is cheap.
(5) No special equipment is required.

Limitations :-

(i) Process is batch type and dirty.
(ii) Case carburized layer is not uniform.
(iii) Requires very long time cycle.
(iv) Rate of 'C' diffusion depends on CO/CO_2 ratio. If the concentration of CO_2 increases, deposition of soot takes place on the surface which retards the 'C' diffusion rate.
(v) Due to packing in a box, larger parts require very large boxes and furnace.
(vi) Surface finish is poor.
(vii) Corburized parts have a tendency to form grinding cracks, during grinding after hardening.

Q.6.5. :- What is gas carburizing ? What are its advantages ?

Ans :- The gaseous hydrocarbons, town or city gas, cracking gases (propane and butane) and natural gas (methane) are all carbon- bearing gases. They contain carbon-monoxide (town gas) and hydrocarbons that decompose on heating and deposit carbon upon the surface of the articles to be carburised.

The gas carburizing process is carried out in a muffle furnace. Inside the muffle furnace, the special atmosphere consisting of a mixture of carbon-bearing gases is created. In gas carburizing, it is necessary to maintain a continuous fresh stream of carburizing gases to the carburizing furnace.

$$C_2H_4 \longrightarrow 2H_2 + 2C$$
$$CH_4 \longrightarrow 2H_2 + C$$

If the gas mixture is rich hydrocarbons, they tend to break down and form soot carbon which gets deposited on the articles and retards the carburizing process.

The amount of carbon deposited on the surface of the articles depends upon the rate of supply of carburizing gases. Carburizing is conducted at a temperature of 1050°C. To produce a case depth of 0.8 to 1.0 mm it is sufficient to hold the work at the carburizing temperature for 30 to 40 minutes.

Advantages :-

(1) The total time required is drastically reduced than that required in pack carburizing process.
(2) The process is clean, with a good control with the help of various instruments.
(3) The surface finish of the product is superior to that obtained in the pack carburizing process.
(4) Automation of the process is possible for higher production.
(5) Consistency in results is obtained for the largescale production.

Q.6.6. :- Discuss the heat-treatment given after carburizing. Why this heat-treatment is necessary ? Discuss some important types of post-carburizing heat-treatment cycles.

Ans :- Carburizing does increase the carbon content of steel component upto a certain depth. However this in itself does not harden the surface. To increase the hardness at the surface, or in the case, this portion must be suitably hardened to produce martensite.

However this martensitic structure would be too brittle. Hence this hardening must be flowed by tempering.

Furthermore, during carburing, the temperature employed is quite high; about 930°C. Hence the grain size of the steel at the core gets increased. This decreases its toughness. In many cases, it becomes necessary to refine the grain structure of the core. Hence a normalizing treatment is also followed to do so.

Thus we see that heat-treatment after carburizing is necessary to --

(i) Produce high hardness and tolerable toughness in the case.

(ii) to increase the toughness of the core by grain refinement, particularly in havier and costly components.

This step is unnecessary if the components are made of inherently fine grained steel.

Accordingly we can identify basically three types of heat- treaments followed after carburizing --

(a) Direct quenching from carburizing temperature, followed by tempering at 160°C-180°C, as shown in Fig. 6.2.(6).

(b) Cooling the boxes to room temperature in air, heating the carburized components to 760°-780° C, followed by quenching and tempering at 160°-180°C, as shown in Fig.6.3. (6).

(c) Cooling the boxes to room temperature in air, heating the carburized components to 850°-900° C followed by air cooling (normalizing to produce grain refinement in core); then reheating the components to 760°-780° C, followed by quenching and tempering at 160°-180° C, as shown in Fig.6.4.(6).

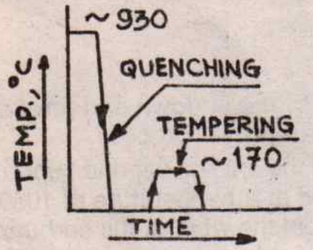


Fig 6.2.(6)

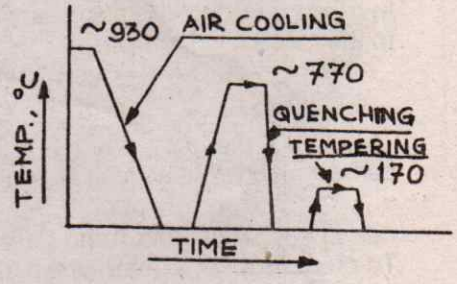


Fig. 6.3. (6)

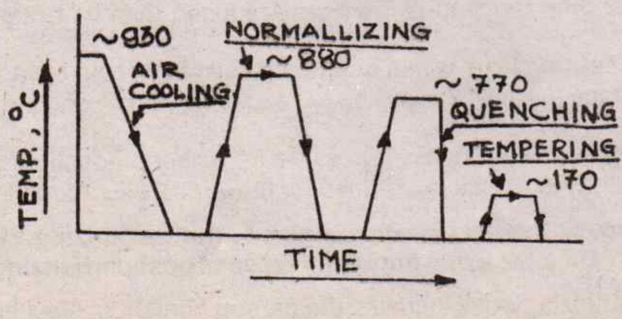


Fig. 6.4. (6)

Q.6.7. :- What is cyaniding ? Discuss liquid cyaniding process.

Ans.:- Cyaniding involves heating steel in an environment that introduces carbon and nitrogen simultaneously in to its surface. cyaniding is used for the same purpose as carburizing and nitriding i.e., for giving steel a high surface hardness and wear resistance.

There are two methods of cyaniding;

(i) Liquid cyaniding

(ii) Gas cyaniding called carbonitriding.

In liquid cyaniding process the plain carbon-steel articles, 0.15-0.2% C are heated in a cyanide bath at a temperature of 820°-870° C for a period of 10 min. to 90 min. depending on the depth of case required.

Case depth mm	Time of cyaniding in minutes
0.1	10
0.15	20
0.20	40
0.25	60
0.30	90

Cyanide bath contains 20 - 30 % NaCN along with a nutral salt Na_2Co_3 or NaCl. At this temperature, first NaCN oxidises and forms Cyanate, NaCNO, which breaks down and produces nascent 'N' and CO. Carbon monooxide then decomposes giving nascent 'C' and CO_2. Nascent 'C' and 'N' produced are absorbed by the hot surface of the steel article, and further diffuse in to the surface layers, producing the desired depth of the case.

After holding the articles in cyanide bath for the predetermined time, they can be directly quenched for hardening. Hard martensitic structure is formed along with iron nitride which is also extremely hard and brittle. Tempering at 150°-170° C for one hour is essential to minimise the quenching stresses and to improve the shock-resistance.

Precautions :-

(1) Cyanides are very poisonous, hence care must be taken in handling them.

(2) The shop should have an effective exhaust and ventilation system.

(3) Eating and smoking are prohibited where cyaniding is being conducted.

(4) Workers should use the mask.

Q.6.8. :- Explain the process of carbonitriding.

Ans :- Gas cyaniding or carbonitriding process is similar to gas carburizing and is performed in a similar furnace. A mixture of gases, cracking gas (propane, butane) 70-80% by vol. and, 30-28% Ammonia gas by vol., is used in a furnace as a the atmosphere, in which the steel articles are palced. A fresh stream of this gas mixture is maintained. Operating temperature range is from 820°C to 850°C.

The time of holding at this cyaniding temperature is calculated on the basis to produce a case depth of 0.1 mm; it is necessary to heat the steel at this temperature for a period of about 1 hr. 'CO' gas is obtained from cracking gases or hydrocarbon gases. While cracking of ammonia gas takes place at this temperature producing nascent 'N', $2NH_3 \longrightarrow 2N + 3H_2$, CO decomposes at the hot surface of steel producing nascent 'C'. The nascent 'C' and nascent 'N' are absorbed by the hot surface of the steel and further diffuse into the surface layers. Low temperature of operation promotes more of nascent 'N' while high temperature promotes more of nascent 'C'. After carbonitriding process the articles can be directly quenched for hardening and then they should be tempered.

Advantages :-

(1) The process is not harmfull as liquid cyaniding.
(2) Time required is less than that required for pack curburizing.
(3) Clean surface is obtained.

Q.6.9. :- Explain the process of nitriding of steel ?

Ans.:- The process by which steel is made to absorb nitrogen alone is called nitriding.

In nitriding, ammonia gas is introduced into a gastight furnace chamber heated up to a temperature of 500° to 600° C. Ammonia decomposes;

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

The nascent nitrogen, which is capable of entering in to the surface layer of the hot steel and duffuses further into it, forms iron nitride Fe_2N and Fe_4N in case of plain carbon steels. In case of alloy steels, the formation of nitrides of the alloying elements, such as chromium, molybdenum and aluminium along with iron nitride takes place. In the outer zone of the steel, complex carbides with nitrides are present (together with cementite) which are called carbonitrides. This layer of carbonitride is very hard and brittle in nature. The hardness value is from 65-70 Rc. After nitriding treatment, hardening treatment is not required as the nitrided layer has a very high hardness. The process is applied to a steel to increase its wear resistance and is a fairly long one. A period of about 10 hrs at 500°-540° C is required to produce a nitrided case of 0.1 mm thickness. Maximum case depth obtained by this process is around 0.5 mm.

The process can be controlled by the degree of dissociation of the ammonia gas, which in turn depends on the rate of flow of ammonia introduced into the furnace. To accelerate the nitriding process it is usually done in two stages.

1st stage :- Holding at 500°-520° C for the period of 8-12 hrs where dissociation of ammonia is around 18-25% .

2nd stage :- Holding at 560°-580° C where dissociation of ammnia is around 50-60% . The time of holding will depend on the case depth required.

The nitriding process is more complex and expensive. The presence of alloying elements like Cr, Mo and Al, is essential for good results.

The process is performed at low temperature and quenching is not required after it. Since quenching is not required, the distortion in the parts is negligible as compared to other proesses of surface hardening.

Nitrided steels are used for the manufacture of parts which require an extremely hard surface combined with minimum distortion, such as spindles for lathes, milling machines and grinding machines which work at speeds more than 2000 rpm.

Nitriding is the last process applied to an article before it is ground. Therefore the stock to be nitrided must be finish- machined and fully heat-treated. Particularly the articles made of alloy steels containing Cr, Mo and Al should be heated to 900°-940° C, quenched in oil and then tempered at 600°-650° C for grain refinement prior to nitriding.

Q.6.10. : Can all steels be nitrided ? If not why ? What are nitriding steels or nitralloys?

Ans.:- No. All the steels can not be nitrided. For nitriding either plain carbon steels with carbon from 0.2-0.3% C or alloy steels containing Cr, Mo, Al and Ni, are selected. With plain carbon steels, iron nitride (Fe_2N and Fe_4N) is formed to a greater depth but the case is less hard and more brittle. When Al is present in the steel, it forms more stable nitrides which do not diffuse readily and produces a shallow but very hard case (Rc 67-72). Chromium helps to increase the hardness, maintain this hardness below the surface layers, and thus reduces the risk of spalling. Molybdenum increases hardenability and prevents embrittlement. Thus when Al, Cr and Mo are presnet with 0.2-0.3% C, we get best properties after nitriding. Such steels are called nitriding steels or nitralloys.

Two composition of such Nitralloys are :-

	C	Al	Cr	Mo	Ni
1.	0.39	1.1	1.6	0.2	-
2.	0.3	-	0.88	1.1	0.8

Q.6.11. : What are the advantages of nitriding over carburizing? What are the limitations?
Ans.:-

Advantages :-

(1) By this process, a higher surface hardness of Rc 65-70 can be obtained and hence it gives a better wear resistance than carburizing.

(2) The process is performed at low temperature and quenching is not required; hence negligible distortion occurs in the parts, as compared to carburizing.

(3) Low C-steel can be nitrided to 0.02 to 0.04 mm case depth for a better corrosion resistance in water or humid air.

(4) Surface finish is extremely good in comparison to that obtained by carburizing process.

Limitations :-

(1) The process is complex and expensive than carburizing.

(2) Process is clean, but only a thin nitrided layer is possible, so only a limited grinding allowance is available in the parts.

(3) Only nitralloys can develop a proper adhesive - carbonitrided layer, and hence only selected grades of steel can be used.

(4) Grain refinement treatment is essential to the steels, before nitriding.

Q.6.12. :- What is flame hardening ? Which type of steels can be flame hardened ?

Ans,:- This method involves rapid heating of the surface of the steel, above its Ac_3, temperature to the desired depth, with the help of oxyacetylence torch or, by a flame obtained from any other gas, followed by cooling as desired.

If steel has 0.2-0.3% C, then the wear resistance can be obtained only by the grain refining at the surface due to rapid cooling and will have a hardness value between 30-35 Rc.

If the steel has 0.5-0.6% C, then by rapid cooling of the surface, a good amount of martensitic structure will form at the surface with a hardness of 55-63 Rc and such steel will have a good wear-resistance. For flame hardeneing of articles of cylindrical shape, the part to be surface hardened is fixed between centres of a lathe; an oxyacetylence torch and a spray nozzle for spraying water against the heated surface of the steel, are held in a carriage. The surface to be hardened is rapidly heated with a multi-flame annular torch-head moving along the rapidly rotating shaft. An annular spraying device is used to cool the heated surface quickly. This process of surface hardening is called as flame hardening process. The arrangement is shown is Fig.6.5.(12).

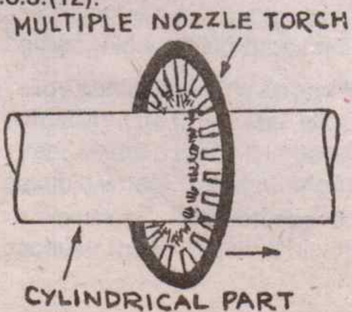


Fig. 6.5.(12)

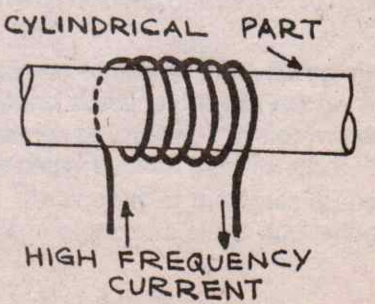


Fig. 6.6. (13)

Q.6.13. :- What is induction hardening ?

Ans.:- Induction hardening is the process in which steel articles are rapidly heated to the desired depth by means of high frequency electrical induction current and subsequently, cooled reapidly.

Cylindrical parts are heated by induction, by being placed within a copper induction coil, through which an alternating current is passed as shown in Fig.6.6.(13). The magnetic field produced around the copper coil penetrates the article and induces eddy currents in it. Due to the resistance of the steel articles to the eddy currents, heat is generated and article get heated. Higher is the frequency of current, lesser is the penetration of eddy current or less is the depth of the heated zone. Such heated surface is immediately quenched for hardening. Hardness of the surface will depend on the carbon content of the steel.

Salient features of the process are :-

(1) the process is very fast and used for higher production.
(2) current frequencies from 10,000 to 250,000 cycles/sec are used in this process, depending on the depth required.
(3) the process is easy to operate.
(4) the process is widely used for the production of small gears, crank-shafts, cams, machine tool guides, hdraulic turbine blades etc.

Lesson. 7

NON-FEROUS ALLOYS

Q.7.1. :- Draw the copper zinc equilibrium diagram upto 50% Zn by weight.

OR

Draw that portion of the copper zinc phase diagram which covers all the brasses of engineering importance.

Ans. :- See Fig 7.1.(1)

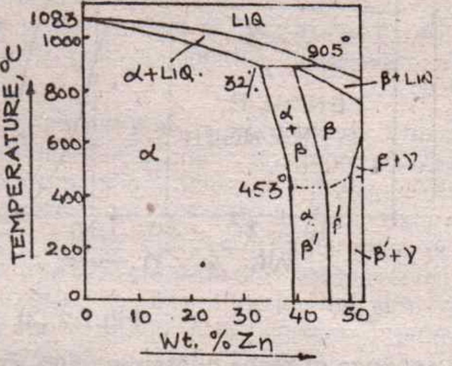


Fig. 7.1. (1)

Q.7.2. :- Why brasses containing 50 wt. % Zn or more can not be used for making engineering components or consumer goods?

Ans. :- From the CuZn equilibrium diagram it is evident that in brasses containing 50% Zn or more, γ phase appears. α phase is the primary solid solution of Zn in copper, and β phase is the electron compound of Zn and Cu based on the valence electron/atom ratio of 3/2. Both these phases possess good ductility to be useful. However, γ phase is an intermetallic compound which is extremely brittle. Brasses which contain γ phase fracture with 0 % elongation. Engineering components and comsumer goods must possess some toughness and should not fail in such a brittle fashion. Hence brass containing 50 % or more zinc can not be used for making engineering component or consumer goods.

Q. 7.3. :- Explain the variation in the mechanical properties of brasses with their zinc content.

Ans. :- Solid solutions are always stronger than pure metals. As the amount of zinc in brass increases, initially both the tensile strength and ductility (% elongation) increase. This variation is exhibited schematically in Fig. 7.2.(3). An alloy containing 30% Zn and 70% Cu has maximum ductility. This brass is known as "cartridge brass" because it is extensively used for making cartridges. It has an excellent combination of tensile strength (35 kg/mm^2) and maximum ductility (55-60%) and hence, it is extremely suitable for forming by deep drawing, cold rolling, spinning and other cold working processes.

An alloy containing 40% Zn and 60% Cu has maximum tensile strength (53 kg/mm^2) and tolerable ductility (10-15%). This alloy is known as Muntz metal and it can not be cold worked to a great extent. Hence it is used for making castings or is formed by hot working. This alloy is suitable where higher strength is required like heavy bushes, sleeves etc.

It can been seen that on approaching 50% Zn, the ductility of the brass drops to 0%. This is because the γ phase which is an intermetallic compound, starts appearing in brasses containing 50% Zn or more. γ phase is extremely brittle and hence brasses containing γ phase fail in a brittle fashion. Hence such brasses can not be used for making engineering products.

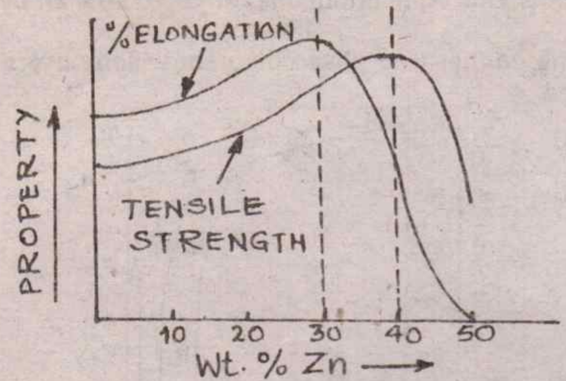


Fig.7.2.(3)

Q. 7.4. : What is the only use of brass containing 50% Zn ?

Ans. : Brass containing 50% Zn is known as the "Brazing brass " because it is extensively used for brazing in production as well as repair. When two steel components are brazed with brazing brass, during the brazing operations, the brass melts but the steel components do not melt. From this molten pool of brass, zinc atoms diffuse into the two steel components in contact with the molten pool. A substantial amount of zinc diffuses into the steel components and because of this, the composition of this pool gets changed to a lower content of zinc, about 41-42%. On solidification, the diffused zinc forms an alloy with the steel components, in continuity with the solidified joint which now contains only 41-42% Zn. Such a composition ensures high strength and tolerable ductility in the brazed joint.

Another recent use is the development of a dental filling alloy based on 50/50 composition.

Q. 7.5. : What is cartridge brass ? What are its special characteristics and uses ?

Ans. : Cartridge brass is single phase α brass which contains 30% Zn by wt. It is extensively used for the production of cartridge cases and hence the name. This brass has maximum ductility (55% elongation) and a good tensile strength (35-38 kg/mm^2). Hence it is extremely suitable for deep drawing.

All cold working processes like spinning, extrusion wire drawing, pressing, cold rolling etc can be used to manufacture various products from this brass.

The cast structure of cartridge brass contains cored dendrites of α solid solution. The effect of coring can be removed by prolonged annealing at 650° C or by cold working and annealing at 600° C in a shorter time.

Cartridge brass is used for making sheets, rods, tubes. deep drawn articles etc.Boiler tubes or condenser tubes are based on this composition with a slight modification.

Q. 7.6. : What is "orange peel" effect ? How can it be avoided ?

Ans. : If the cartridge brass sheet is annealed above 700° - 750° C for a longer time, the grains of α grow to a large size. On subsequent deep drawing, the portion which experiences maximum deformation shows a rough surface like the skin of an orange. This type of undesirable surface appearance on deep drawing is known as "orange peel effect". Evidently this is due to the large grain size in the starting material.

Orange peel effect can be avoided by properly controlling the final grain size of the cartridge brass sheet in its production. It should be ensured that the grain size be fine and hence the final annealing temperature of these brass sheets should never be more than 600°C.

Q. 7.7. : What is "Season Cracking" ? How can it be avoided ?

Ans. : Although this is exhibited by both α brasses as well as brasses $\alpha + \beta$ (i.e. brasses containing less than 39% Zn, or, more than 39% Zn), more often it is encountered in α brasses because they are usually formed by cold working operations, while $\alpha + \beta$ brasses are usually hot worked.

Brass articles like condenser tubes, cartridge cases, pressings etc. may suddenly show cracks during their service life. These cracks are intercrystalline in nature. It has been found that the tendency to season cracking is increased in presence of corrosive environments containing ammonia, mercurous nitrate, sea water etc. It has been shown that season cracking is nothing but "stress corrosion cracking" a corrosive attack which occurs when the material contains internal stresses. Hence season cracking of α brasses is usually due to the fact that they had not been properly annealed to remove the internal stresses due to cold working operations. Usually a recovery anneal at 300° C is sufficient to remove the internal stresses without decreasing the tensile strength.

Hence to avoid season cracking, the cold worked brass articles must be fully stress relieved at 300° C before they are put to use.

Q. 7.8. : What is admiralty brass ?

Ans. : In order to improve the corrosion resistance of single phase α brasses, particularly under marine atmospheric conditions, a small amount of tin is added to α brass. The amount of tin added is about 1-1.5%. Such a brass is known as "admiralty brass". This is used for condenser tubes.

Corrosion resistance of brasses can be improved by the addition of about 2% Al also.

Q. 7.9. : What is Muntz metal ? What are its characteristic properties and uses.

Ans. : Muntz metal is $\alpha + \beta$ brass (two phase brass) containing 40% Zn. This brass has the maximum tensile strength (48 kg/mm^2) coupled with sufficient ductility (15 - 20%) and hence it is useful for many engineering applications like castings of bushes, rods for electrical engineering parts, manufacture of small engineering components etc. It has excellent corrosion resistance in ordinary atmospheric conditions.

The as cast structure of $\alpha + \beta$ brasses consists of "feathers" of α in the matrix of β. The amount of α can be controlled by controlling the cooling rate from hot working temperature. The best form of phase, distribution and best mechanical properties are obtained by hot working the Muntz metal at about 650° C - 700° C. This gives a fine grain size and fine dispersion of α.

Q. 7.10. : What are high tensile brasses ?

Ans. : To increase the tensile strength of Muntz metal, Al, Fe, Mn, Sn or Ni are frequently added to it in small amounts. The ductility of the alloy is not seriously affected. 60/40 brasses containing one or more of the above elements are called "high tensile brasses". A typical composition is 3% Mn, 2.5% Al, 0.52% Fe, 1.5% Sn, 1% Ni, 55% Cu, balance zinc. The high tensile brasses have tensile strengths of 55-65 kg/mm^2 in the cast condition, with 15% elongation.

Most of the high tensile brasses are two phase brasses and hence can be forged extruded or rolled in hot condition. However they are eminently suitable for high strength castings of large size.

Q. 7.11.:-Give the composition and use of red brass, yellow brass, cartridge brass, Muntz metal, admiralty brass, naval brass, gilding metal, leaded brass and delta metal.

Ans. :-

Brass	Composition in Wt. %						
	Zn	Sn	Al	Mn	Fe	Pb	Uses
1. Red brass	5-10	-	-	-	-	-	Coins
2. Yellow brass	25	-	-	-	-	-	General uses
3. Cartridge brass	30	-	-	-	-	-	Cartridges, deep drawing
4. Muntz metal	40	-	-		-	-	Castings, hot worked rods
5. Admiralty brass	30	1	-	-	-	-	Condenser tubes
6. Naval brass	40	1	-	-	-	-	Naval castings
7. Gilding metal	15	-	-	-	-	-	Costume jewellery
8. Leaded brass	35-40	-	-	-	-	2-4	Improved machinability, machined parts
9. Delta metal	40	-	-	-	1.5	-	High tensile castings.

Q. 7.12. : What is manganese bronze ?

Ans. :- This name is a "misnomer" because it is not a bronze It is a high tensile brass containing about 2-4% Mn, added as ferro manganese. Hence some iron is also present. Manganese is a good deoxidizer and hence it deoxidizes the molten bath of brass. Hence the ZnO inclusions in the brass castings are eliminated and a high quality casting is produced with a high tensile strength and sufficient ductility.

Q. 7.13. :-What is "dezincification" of brass ? How can it be controlled or eliminated ?

Ans. :- This is often encountered in condenser tubes or boiler tubes made of cartridge brass. This is nothing but corrosion by pitting. At some places the condenser tubes might get covered with the scale formed due to the salts in the water. The metal beneath these spots is preferentially corroded by cavitation. Both copper and zinc atoms are dissolved, but copper gets reprecipitated at the same place. The net result is the selective removal of zinc, leaving copper in a porous, spongy condition. This selective removal of zinc is known as dezincification.

Dezincification of α brass can be decreased by adding Sn or Al to improve the corrosion resistance and by adding a little arsenic (0.05%) to the brass. Addition of arsenic minimizes the tendency towards dezincification.

Q. 7.14. :-What is "nickelsilver" ? Mention its uses.

Ans. :- "Nickel silver" or "germansilver" is an alloy of Cu, Zn and Ni. It does not contain any silver. However, its appearance is "silvery" and hence the name.

Nickel silvers are single phase brasses containing nickel from 7 to 30% . An alloy containing more than 20% Ni appears silvery white. The zinc content is around 20-27%.

The alloys can be cold formed like other alpha brasses. The components which are to be silver plated are usually made of nickel silver because they accept good silver plating and, in use if the silver plating is worn out, the underneath metal does not look too shabby because of its silvery colour.

Nickel silvers are also used as tapes, wires and springs for electrical instruments and as contactors and springs in telephone and wireless industry.

Q. 7.15. :-Draw the microstructure of annealed cartridge brass or annealed α brass.

Ans. :- See Fig. 7.3. (15). Contains equiaxed grains of α . Colour difference is due the to difference in orientations of the grains.

Q. 7.16. :-Draw the microstructure of coldworked and annealed brass.

Ans. :- See Fig.7.4. (16) . The microstructure shows equiaxed grains of α which contain twins shown by the presence of alternate bright and dark bands (difference in contrast being due to the difference in the orientation between the twinned regions).

Fig. 7.3. (15)

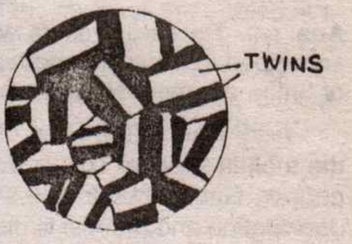


Fig. 7.4. (16)

Q. 7.17. :-Draw the copper rich end of the CuSn phase diagram and explain the main types of industrial bronzes based on it.

Ans. :- The copper rich end of the Cu-Sn equilibrium diagram is shown in Fig. 7.5.(17). In normal terminology, these alloys of copper and tin are known as bronzes. Now the term bronze is used for any alloy of copper with an element other than zinc, like aluminium bronze,silicon bronze etc.

From the equilibrium diagram, we see that a peritectic reaction occurs at 798° C. The product of this reaction is β phase - the electron compound. At 580°C, this β phase undergoes a eutectoid reaction forming the mechanical mixture of α solid solution containing about 16% Sn and γ containing about 25 % Sn. The γ phase undergoes a eutectoid reaction at 520° C, forming a mechanical mixture of α solid solution containing about 16% Sn and δ phase (an intermetallic compound) containing about 32% Sn. δ phase is $Cu_{31}Sn_8$. This phase undergoes a eutectoid transformation at 350° C to give a mechanical mixture of phase α containing 11% Sn and ε phase containing about 38% Sn. However, the reactions below 375° C never occur in industrially cooled alloys and hence in industrial bronzes, the ε phase is never seen. We find that the solid solubility of Sn is about 16% at 520° C and decreases considerably on cooling to room temperature. However since the reactions below 375° C are very sluggish, bronzes containing less than 10 % Sn show single phase α solid solution in their structure. Two phase bronzes used in industry normally contain 12-20% Sn and show α solid solution in the matrix of $\alpha + \delta$ eutectoid mixture.

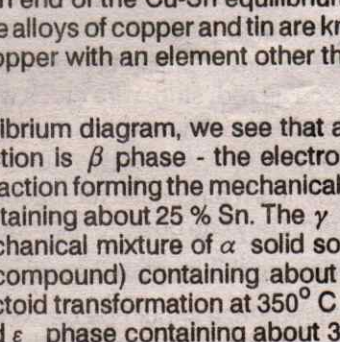


Fig. 7.5. (17)

Single phase α bronzes are used for producing a variety of wrought products like rods, wire, strip, bars, tubes etc. Two phase bronzes are used essentially for strong castings like bearings, sleeves, pump parts, pressure tight castings etc.

Q. 7.18. :-What is phosphor bronze ?

Ans. :- Tin easily reacts with oxygen to form tin oxide which is heavy and gets easily entrapped in the melt, and hence, in the final casting.Bronze castings containing inclusions of SnO_2 are mechanically weak and porous. They show dirty patches on machining.

Hence formation of SnO_2 must be avoided and this can be done by deoxidizing the molten bronze. This is done normally by adding phosphorus to the melt as phosphor copper. Generally 0.3 to 0.5% P is added. A good amount of phosphorus is used up in deoxidation and the rest is dissolved in the bronze.

A true phosphor bronze must contain more than 0.1% P as residual phosphorus after the deoxidation is completed. In some cases, even a larger amount of residual phosphorus is specified because it is dissolved in bronzes and increases its elastic limit and yield strength.

Depending upon the tin content, phosphor bronze can be divided as wrought phosphor bronze and cast phosphor bronze.

Wrought phosphor bronze is a single phase bronze containing 6% Sn, 93.7% Cu and 0.2% residual phosphorus. It is used as rod, strip, wire etc. It was used for turbine blades. It is still in use for springs with good electrical conductivity.

Cast phosphor bronze may or may not be a two phase alloy and contains 5-18% Sn and 0.3 to 0.5% residual phosphorus. It is mainly used for machine parts for carrying heavy loads as bearings, gears, slide valves etc. They can be used to produce pressure tight castings.

Q. 7.19. :-What are gunmetals ? What are the various types of gun metals ?

Ans. :- We have seen that the molten bronze should be deoxidized for producing a clean casting without the inclusions of SnO_2. In phosphor bronzes, the deoxidation is achieved by adding phosphorus as phosphor copper which is costly.

Deoxidation can alternatively be achieved by adding some zinc to the melt. ZnO formed is not trapped in the liquid. Hence we get a clean casting free of any SnO_2 or ZnO.

Bronzes to which zinc is added as deoxidizer, are known as **Gun metals**. In past these alloys were manufactured for making the barrels of guns and mortars because of their excellent strength and corrosion resistance and hence they were called with this name. Now for this purpose steels only are used. Zinc is added in enough amounts to suffice for deoxidation and,a good amount more is sometimes intentionally put in to make the alloy cheaper as zinc is cheaper than tin.

Two gun metals are quite popular one for light duty castings, and the second essentially for heavy duty purposes.

(i) 85/5/5/5 gun metal containing 85% Cu, and 5% each of Sn, Zn and Pb.This is used for making light duty castings with excellent machinability due to the presence of lead, which is especially added to improve the machinability of bronzes.

(ii) 88/10/2 gun metal containing 88% Cu, 10% Sn and 2% Pb, used for strong castings and heavy bearings.

Addition of lead increases the machinability of bronzes but decreases their strength. Hence it is reduced in bronzes for heavy duty.

Q. 7.20. :-Why heavy duty bearings of bronze are never annealed before they are put to use, although they are cored ?

Ans. :- Heavy duty bronze bearings contain about 12-15% Sn depending upon the load which they have to withstand. Hence they are two phase bronzes containing dendrites of α in the matrix of $\alpha + \delta$ in the matrix of eutectoid. Since most of the castings are cooled at a faster rate, the α dendrites are heavily cored. Even then, the bearings, after machining, are never annealed because on annealing, these bronzes revert to their equilibrium structure, showing either only α phase or a little of δ phase with α phase. Thus on annealing, almost all the δ phase disappears. This is detrimental to the wear resistance of the bearing because δ phase is the hard phase. Hence the bearing becomes soft on annealing.

Further more, since the specific volume of δ phase is greater than that of α phase, shrinkage pores are produced, reducing the pressure tightness and over all compression strength.

Hence two phase heavy duty bronzes are never annealed before they are put to use.

Q. 7.21. :-What are "Babbits" or "White metal alloys" ? Mention the two types, give their nominal composition and explain their structure.

Ans. :- "Babbits" or "white metals" are either lead base alloys or tin base alloys containing Pb, Sn, Sb and Cu. They are also called "antifriction alloys" because their coefficient of friction against steel is quite low. In the earlier days it was thought that bearings must have a two phase structure, having hard phase particles embedded in the matrix of a softer phase. White metal alloys were developed to achieve this requirement. They contain the hard phase particles of an intermetallic compound of Sb and Sn - compound SbSn, in the matrix of soft ternary eutectic of Pb, Sn and Sb.

Two main types of babbits are developed (i) lead base babbits and (ii) tin base babbits. The nominal compositions of two babbits of each type are given below :

	% Pb	% Sn	% Sb	% Cu
1. Lead base babbit	80	5	15	-
2. -do-	63.5	20	15	1.5
3. Tin base babbit	-	86	10.5	3.5
4. -do-	4	83	10.5	2.5

Tin base babbits are stronger than lead babbits and have higher load bearing capacity. They are used for making main bearings, with steel backing in Aero, Auto, and large diesel engines etc.

Lead base babbits are relatively softer but cheaper. They are used for general purpose bearings, working under lighter loads and at lower speeds. The structure consists of cuboids of SbSn compound, with streaks (starlike) of compound Cu_6Sn_5 in the matrix of binary or ternary eutectic depending upon the composition.

Q. 7.22. :-What is "inverse segregation" in babbits" ? How can it be prevented ?

OR

What is the function of copper addition to babbits ?

Ans. :- During the solidification of a white metal casting, the first phase to solidify is the compound SbSn. Hence a large number of cuboids of SbSn compound form in the remaining molten liquid. These cuboids have a much lower density than the liquid melt in which they form. Hence instead of being uniformly suspended in the melt, these cuboids float to the top of the casting. Hence after the solidification is completed, we find that all the cuboids of SbSn compound are segregated in the top region of the casting. This type of segregation found in babbits is known as " inverse segregation". This nonuniform distribution of cuboids is harmful for the mechanical properties of the bearing.

About 2 to 3% copper is added to prevent this segregation. When copper is present in the molten white metal alloy, during its solidification, needle shaped particles of a compound Cu_6Sn_5 are the first to form throughout the liquid and they create a web like network in the liquid. A little later at a still lower temperature, the cuboids of SbSn compound form and solidify throughout the volume of the liquid. However, since the web like network of Cu_6Sn_5 compound is present in the volume of the molten metal, the cuboids formed at different places in the molten liquid are not allowed to float to the top. Hence they remain in the region in which they formed. Thus the web like network of $Cu_6 Sn_5$ effectively prevents the inverse segregation and gives a uniform distribution of cuboids in the cast bearings of white metals. This compound Cu_6Sn_5 is seen as bright starry streaks in the microstructure.

Q. 7.23.:- Enumerate the properties desirable in bearing metals.

Ans. :- Although the ball bearings and roller bearings have been developed, the conventional journal bearings are still widely used. The properties required in the metal used for such stationary bearings are :

(a) The coefficient of friction between the bearing metal and the rotating part should be as small as possible.

(b) The bearing metal should not be too hard otherwise, the wear of the rotating part will be too high.

(c) The bearing must have sufficient load bearing capability and should withstand loads that may arise due to misalignment also.

(d) The bearing metal should contain a relatively low melting constituent. In the event of failure of lubrication and resulting heat, the bearing should soften and prevent seizure. Seizure may lead to the fracture of the rotating shaft, causing a major breakdown.

(e) The bearing metal should have good fatigue resistance and corrosion resistance.

(f) It must be capable of retaining a continuous lubricating oil film.

Q. 7.24. :-Draw Al-Si phase diagram and explain it. Why Al-Si alloys are important ? What are their uses?

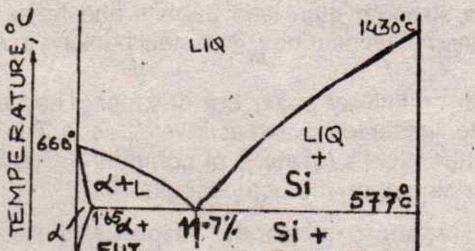


Fig. 7.6. (24)

Ans. :- Fig. 7.6.(24) illustrates the AlSi equilibrium diagram. They exhibit a eutectic type of diagram, with a eutectic composition of 11.7% Si and a eutectic temperature of 577° C. Aluminium appears to be insoluble in silicon, in solid state. The maximum solid solubility of silicon in aluminium is 1.65% at the eutectic temperature and markedly decreases to nearly zero % silicon at room temperature. The solid solution of silicon in aluminium is the α solution.

If an alloy of exactly 11.7% Si is solidified in ordinary conditions, it exhibits a eutectic mixture of silicon and aluminium. In this mixture,the needle like silicon (or-plate like) is present in the matrix of α solid solution called α aluminium (because it contains nearly no silicon).

A **hypoeutectic alloy**, containing less than 11.7 % silicon, shows dendrites of α solid solution in the matrix of eutectic mixture containing silicon needles and α solid solution. A **hypereutectic alloy** shows polyhedral crystals of primary silicon in the matrix of eutectic mixture containing needles of silicon and α solid solution.

Q. 7.25. :-What is "modification" of Al-Si alloys ? Explain the changes in structure of the eutectic on modification.

Ans. :- Modification is the process of treating the molten melt of an Al-Si alloy with about 0.01% sodium. The sodium metal is plunged into the melt with the help of a "phosphoriser" and it is ensured that it dissolves into the molten liquid without rising to the top and getting burnt.

The effect of modification can be understood by considering the structure of modified eutectic alloy and an unmodified eutectic alloy. In the unmodified eutectic alloy, the microstructure of the eutectic shows coarse needles of silicon in the matrix of α solid solution of aluminium. The structure is quite coarse and the needles can be easily seen even at a low magnification of 50X to 100X . On the other hand, a modified Al-Si alloy shows a very fine eutectic mixture of silicon and α aluminium solution. In the modified eutectic fine spheroids or globules or rods of silicon are present in α aluminium solution. The size of the silicon spheroids or globules is so fine that they can not be seen clearly at low magnification and the eutectic looks like a black field. However at magnifications of 400 X, the fine spheroids of silicon can be easily seen.

It must be remembered that modification alters the structure of the eutectic only and makes only the eutectic silicon to have a fine spheroidal form. It does not refine the primary silicon polymorphs in the hypereutectic Al-Si alloys.

Q. 7.26. :-Explain the effect of modification on the Al-Si phase diagram.

Ans. :- Modification of Al-Si alloy not only changes the microstructure of the eutectic but it also changes the equilibrium diagram.

On modification by adding about 0.01% Na, both the eutectic composition and eutectic temperature are altered. For the alloy treated with sodium, the eutectic composition shifts from 11.7% Si to 12.7% Si, and the eutectic temperature is lowered from 577° C to about 568° C as shown in Fig. 7.7.(26). This has a profound effect on the structure of a 12% Si alloy after solidification.

An alloy containing 12% Si is a hypereutectic alloy and on solidification without any modification, this alloy shows the primary silicon crystals in the matrix of **unmodified** Al-Si eutectic containing silicon in the form of coarse needles. This is shown is Fig. 7.8.(26).

On the contrary,if the 12% Si alloy is modified by adding sodium, the alloy behaves like a hypoeutectic alloy because the modification treatment shifts the eutectic composition from 11.7% to 12.7% Si. Hence, on solidification, the alloy shows dendrites of α aluminium solution in the matrix of **modified** Al-Si eutectic which now contains silicon in the fine globular or spheroidal form. The structure of 12% Si alloy in the modified condition is shown in Fig. 7.9.(26).

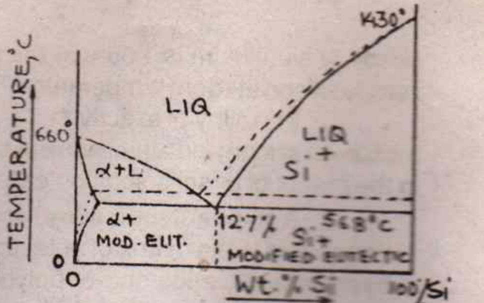


Fig. 7.7. (26)

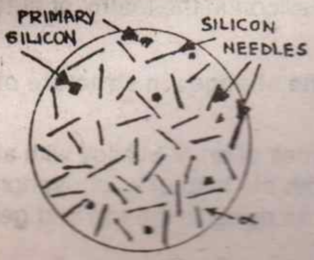


Fig. 7.8. (26)

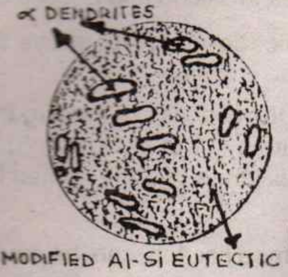


Fig. 7.9. (26)

Q. 7.27. :-What is the effect of modification on the mechanical properties of an Al-Si alloy, and why this effect is produced ?

Ans. :- We know that modification refines the eutectic structure. This refinement of structure enhances the mechanical properties of the Al-Si alloys. Let us compare the mechanical properties of an Al-Si alloy LM 6 containing 10-13% Si :

	Tensile strength Kg/mm^2	% Elongation
Unmodified alloy	12-13	5%
Modified alloy	18-23	7-8%

Apart from this the impact strength of the modified alloy is much higher than that of the unmodified alloy.

We know that modification refines the eutectic structure. In the unmodified alloy, the eutectic mixture contains silicon in the form of coarse needles. Silicon is brittle, and these brittle needles of silicon very severely disrupt the continuity of the soft metallic matrix of α aluminium solution. Hence the alloy containing unmodified eutectic is weaker and less ductile. On modification, the eutectic structure is refined and it contains the silicon in fine globular form. This fine globular dispersion of silicon disrupts the continuity of the α aluminium solution matrix far less severely than in the needle like form. Hence modification increases the tensile strength, ductility and impact strength of the AlSi alloys.

Q. 7.28. :-Draw the microstructures of

(i) Al - 6% Si alloy modified

(ii) Al -16% Si alloy modified.

Ans. :- See Fig. 7.10.(28) and Fig.7.11.(28) respectively.

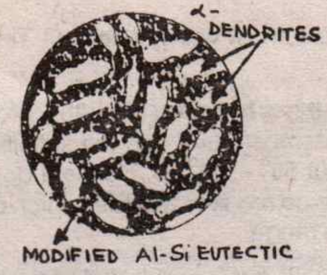


Fig. 7.10. (28)

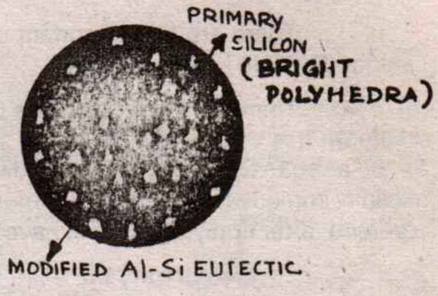


Fig. 7.11. (28)

Q. 7.29. : Draw the microstructure of a two phase bearing bronze.

Ans. : See Fig. 7.12.(29).

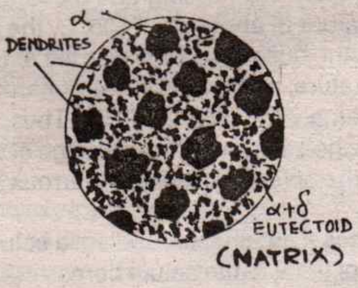


Fig. 7.12. (29)

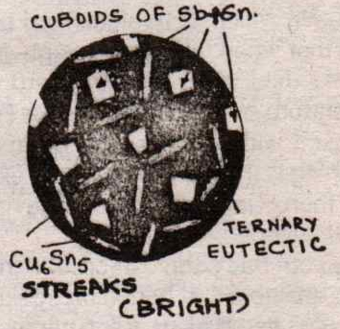


Fig. 7.13. (30)

Q. 7.30. : Draw the microstructure of a babbit containing copper.

Ans. : See Fig. 7.13.(30)

Q. 7.31. : What are solders ? Give nominal compositions of two important solders and explain their uses.

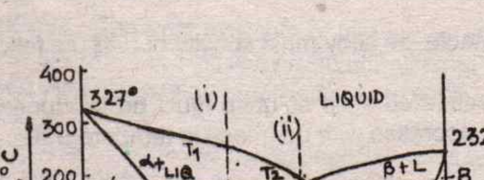


Fig. 7.14. (13)

Ans :- Solders are leadtin alloys. Fig 7.14(31) shows PbSn phase diagram. Both the elements are partially soluble in each other and form a eutectic at 183° C. Because of this low melting point, the alloys based on PbSn diagram are used as solders.

There are two important compositions which are most widely used (i) Tinman's solder (ii) 60/40 solder.

Tinman's solder contains 60% Pb and 40% Sn. It is a hypoeutectic alloy. From the diagram it is evident that this alloy starts soldifying at T temperature, and the solidification ends at 183° C. Thus it has a solidification range of about 55° - 60° C. Hence it does not solidify immediately. As such it is mostly used by tinsmith who requires a solder which can be "spread" after applying. It must have a larger solidification range.

On the contrary there are some applications in which it is required that the solder solidifies quickly. For example soldering electrical and electronic circuits requires such fast solidifying solder. The 60-40 solder containing 60% Sn and 40% Pb satisfies this requirement. This alloy starts solidifying at T_2 temperature and the solidification ends at 183° C. Thus, it has a solidification range of only about 8° - 10° C that is it solidifies quickly.

Q.7.32.:- What do you understand by Age-Hardening?

Ans:- The phenomenon of age hardening was accidently discovered by Wilm in Duralumin which is an aluminium base alloy containing 4.5% Cu, 1.5%Mg and 0.6%Mn. He found that when this alloy was quenched from a temperature of about 490°-500°C, the alloy did not exhibit any increase in hardness. However, when the quenched alloy was left at room temperature or at a slightly higher (120° - 190°C) temperature, it was found that its hardness increased with the passage of time, and hence the name AGE HARDENING. Thus, age hardening is the hardening effect, experienced by a quenched alloy, with the passage of time. Since then, a large number of age hardenable alloys - both nonferrous as well as ferrous have been developed.

It has been established that quenching produces a super-saturated solid solution. This is unstable and hence on ageing (i.e. with passage of time) it the solute comes out and gets precipitated as very fine particles of a second phase in the matrix of the solid solution. It is this fine dispersion of the second phase particles which increases the strength and hardness.Hence age hardening is also known as precipitation hardening.

Q.7.33.:- What are the requirements for an alloy to be age hardenable ?

OR

State the conditions which an alloy must satisfy to be age hardenable.

Ans:- To be age hardenable, an alloy must specify or fulfil the following conditions -

(i) On quenching, a supersaturated solid solution must be produced. This means that the solubility of the solute must decrease with decrease in temperature.

(ii) On ageing, the precipitate that forms must be -

(a) itself a hard phase, thus giving a fine dispersion of hard particles in the soft matrix.

or (b) in the form of coherent particles producing lattice strains in the matrix around them or (c) both.

The structural features described at (a) and (b) are responsible for increase in the hardness and strength of the alloy, because both of these features are efficient obstacles in the path of moving distications and thus make the plastic deformation more and more difficult.

Q.7.34.:- Explain the steps involved in the age-hardening of any age hardenable alloy.

Ans:- The technology of age hardening any given alloy consists of the three essential steps - Solution Heat treatment, Quenching and Ageing.

(a) **Solution Heat Treatment (or Solutionizing or Solution annealing)** : In this step the alloy is annealed at a high enough temperature for sufficient time to dissolve either all the solute or at least as much of solute as is practically possible. This step is necessary to ensure that a good amount of solute goes into solution so that a sufficient volume of precipitate forms during subsequent ageing because smaller the volume of the precipitate, lesser is the hardening effect.

(b) **Quenching** : After the soaking is over at the annealing temperature, the alloy is rapidly cooled to room temperature by quenching it in water or by some other suitable medium. This step is essential to produce a supersaturated solid solution.

(c) **Ageing** : The third and final step is ageing - i.e the passage of time. Two modes of ageing are possible;

(i) **Natural Ageing** : In this process, the quenched alloy is allowed to age at room temperature it self. The rate of hardening is quite slow.

(ii) **Artificial Ageing** : In this ageing process, the quenched alloy is heated to a relatively low temperature, varying from alloy to alloy, and kept there for the required period. Since the temperature of ageing is higher than the room temperature, the rate of ageing is increased and hence the rate of hardening is also increased. Hence for faster production, artificial ageing is used.

In duralumin type alloys, the ageing temperature is between 120° to 150°C depending upon the composition of the alloy.

Q.7.35.:- Give nominal compositions and details of heat treatment for some industrially important age hardenable alloys.

Ans :- (a) **Al-Si-Cu alloys** : The best example of this series of aluminium base alloys is LM4 which contains 5% Si and 3% Cu. This alloy is solutionized at about 510°C for about 10 hours and water quenched. Artificial ageing is carried out at 160°C for 8 to 18 hours. This alloy is basically used for castings.

(b) **Al-Cu-Mn alloys** : These are the wrought aluminium base alloys marketed in various forms like sheets, semifinished pressed products, bars, extrusions etc. They contain 4.5-5.3% Cu, 0.6 - 1.0 % Mn with or without some titanium. These alloys are solutionized at about 500°C. After quanching, artificial ageing is done at temperatures from 120° to 190° C for times varying from 4 hours to 24 hours, to develop the required level of strength.

(c) **Al-Zn-Mg alloys** : These aluminium alloys develop maximum stregth amongst the aluminium alloys. One alloy of theis series, DTD 5024 contains 5.5% Zn, 2.8% Mg, 0.45% Cu and 0.5% Mn. These alloys are solutionized at about 460° - 470°C. Artificial ageing is carried out at 110°- 135°C for 24 hours to 48 hours.

(d) Cu-Be alloys : These copper base alloys are known as beryllium bronzes. They contain about 1.5-2.25% Be. These alloys are solutionized at 800°C and water quenched. Ageing is done between 300°-320°C for 2-4 hours. On ageing, they can develop a tensile strength as high as 1400 MPa and a hardness as high as 400 BHN. These alloys are used in many electrical applications, springs, and also for making NON SPARKING TOOLS to be used in gassy mines.

(e) Precipitation Hardenable Martensitic Stainless Steels : These steels are essentially martensitic in constitution with the addition of some alloying elements for obtaining precipitation hardening. One such steel contains 0.09% C, 16.0 - 18.0% Cr, 6.5-7.75% Ni and 0.75-1.5% Al. This steel is water quenched from 950°C, cooled to -70°C and then aged at 500° - 600°C for 1 hour. Such steels are used for elevated temperature service, and are popular for making steam turbine blades.

Lesson 8.

MECHANICAL WORKING AND PROCESSING OF METALS.

Q.8.1. :- What is plastic deformation ? How does it occur ?

Ans.:- We know that there can be two types of deformations :

(i) Elastic deformation or temporary deformation, and
(ii) Plastic deformation or permanent deformation

Plastic deformation of a metal produces a permanent change in the shape of the metal. It can take place by two different modes of movement of atoms in the crystal :
(a) Slip (b) Twinning

Both the processes of deformation have been studied with respect to single crystals because the single crytals do not contain grain boundaries which greatly influence the process of plastic deformation.

Q.8.2. :- What is slip ? How does it occur ? Define "slip plane" and "slip direction".

Ans.:- In experiments with single srystals, it has been found that whatever be the nature of stress applied, e.g., compressive, tensile, torsional or shear, the deformation which occurs is shear type.

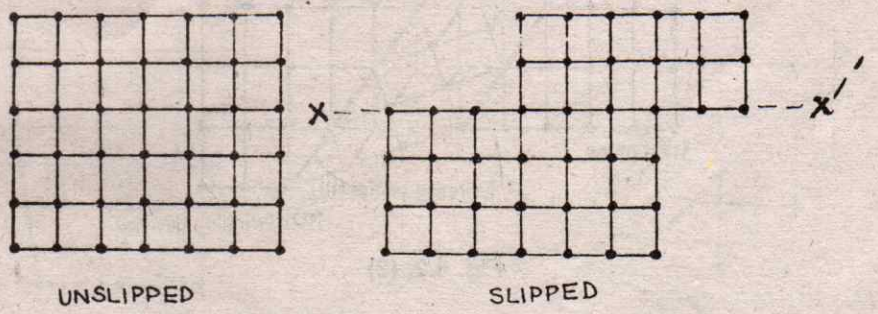


Fig. 8.1.(2)

In the process of deformation by SLIP it appears that individual "blocks" or "parts" of a single crystal "slip" past one another, like playing cards in a deck of cards, and produce deformation by shear. The process of slip is schematically shown in Fig.8.1.(2). It can be seen that block A of the single crystal slipped past block B, along the slip plane XX. It can be seen that, even after slip, the atomic arrangement or ORIENTATION of the slipped region remains the same as it was before it slipped. Furthermore, it can be seen that the atoms of the "slipped" region do not move relative to each other. Their movement is only relative to atoms of another block or region of the single crystal, with respect to which they slipped.

Experiments have shown that the slip occurs only along some specific crystallorgaphic planes, and in some specific crystallographic directions in these planes. These crystallographic planes of slip are known as "slip planes" and the crystilographic directions of slip are known as "slip directions".

It has been found that slip planes are the most closely packed planes and slip directions are the most closely packed directions. The slip planes and slip directions for HCP, FCC and BCC crystals are given below :-

Crystal structure	Slip planes	Slip direction
HCP	(0001)	$[2\bar{1}\bar{1}0]$
FCC	(111)	[110]
BCC	(110),(112)	[111]

Q.8.3. :- What is twinning ?

Ans.:- Twinning is the second mode in which the plastic deformation may occur the first being slip. The twinned region (i.e. the deformed region) and the udeformed region of a crystal are separated by a crystallographic plane which is known as the "twinning plane".

In twinning, ALL the atoms of the twinned region move in the twinning direction, parallel to twinning plane. However the atoms contained in different successive parallel planes move through different distances. The atoms in the **FARTHEST** plane from the twinning plane move through **LONGEST** distance, and vice- versa. Such well controlled movement of atoms is called "homogeneous deformation". The atomic arrangement i.e., the orientation of the region being deformed is changed in twinning and a completly new orientation is obtained in the twinned region. The new orientation of the twinned region is the **MIRROR IMAGE** of the undeformed region across the twinning plane. That is why the name "TWIN" is given to the deformed region. Fig. 8.2.(3) depicts twinning.

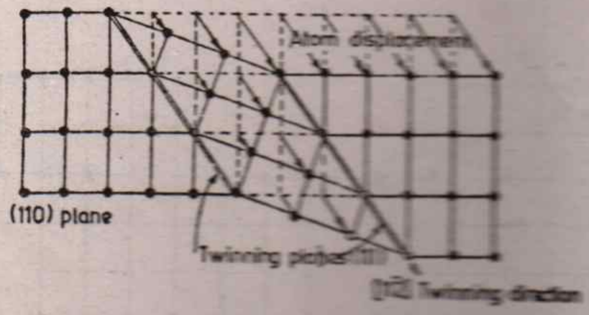


Fig. 8.2. (3)

Twinning is relatively less frequent than slip. However, in some metals like tin, bismuth, antimony and zinc, it may occur to a considerable extent.

Q.8.4. :- Distinguish clearly between SLIP and TWINNING.

'Ans.:- Both slip and twinning are nothing but two modes of atom movements which result in plastic deformation. However the exact mechanisms substantially differ. The points of difference between slip and twinning are given below

(i) In slip, all the atoms in all the planes in the slipped region move through the **SAME** distance. On the other hand, the atoms in different planes in the twinned region move through **DIFFERENT** distances. These are integral multiples of a least distance of atom movements in the plane next to the twinning plane.

(ii) Slip does not produce any change in the orientation of the slipped region. On the other hand, twinning results in an entirely **NEW** orientation of the region which is twinned. The orientation of the twinned region is a **MIRROR IMAGE** of the orientation of the undeformed region, the twinning plane acting as the **MIRROR**.

(iii) Plastic deformation by slip is **EXTENSIVE** and most common in almost all metals. Deformation by twinning is **LIMITED** and occurs more frequently in some metals with complex crystal structures, like tin, antimony and bismuth.

Q.8.5.:- What do you understand by "dislocations"? Explain the two basic types of dislocations.

Ans.:- We have already seen that real crystals are never perfect and contain a veriety of imperfections or defects in their lattice structure. Dislocations are the line defects as they exist over a length of the crystal lattice.

Geometrically, depending upon the atomic arrangement around the dislocation line, two types of dislocations are identified ; **EDGE DESLOCATION** and **SCREW DISLOCATION**. These defects are schematically shown in Fig. 8.3. (5), (a) & (b)

An edge dislocation is a line defect in which there is an extra helf plane of atoms above a plane which is the slip plane ; as shown in (a) of the above mentioned figure. Note that this extra half plane may be "**BELOW**" the slip plane as well. In the first case it is called a positive edge dislocation and in the second case, a nagative edge dislocation.

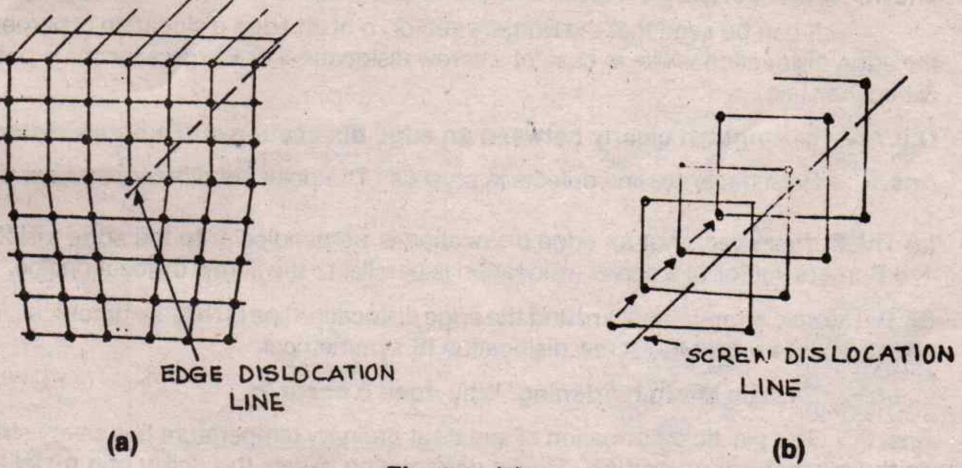


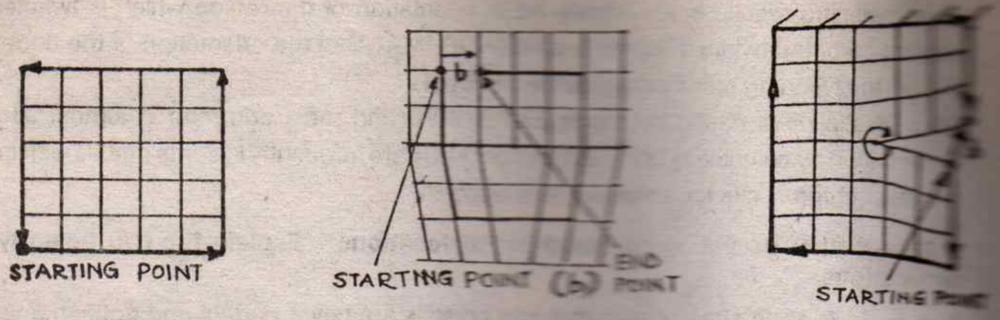
Fig. 8.3. (5)

A screw deslocation is a line defect formed due to a type of shear and the defect contains the atoms in the form of a helical screw around its line of orientation, as shown in (b) of the above figure.

Both the types of dislocations move in the plane in which their lines lie. These planes are the slip planes.

Q.8.6.:- Define Burgers vector of a dislocation.

Ans.:- The dislocations are line defects and hence along their length, the atomic arrangement is not perfect as elsewhere in the perfect portion of the lattice.



(a) (b) (c)

Fig. 8.4. (6)

In a perfect portion of the lattice, starting from a given atom, if we move through equal number of atoms (or lattice points) in X direction, Y direction, then -X direction and -Y direction, as shown in Fig. 8.4.(6) (a), we close the circuit and reach back to the starting point. On the contrary, if an edge dislocation or a screw dislocation is present, and we try to make such a circuit around it, it remains incomplete, as shown in Fig 8.4.(6((b) and (c). We do not reach back to the starting point. In order to complete the circuit, an additional distance is to be moved. This distance to be moved **from the starting point to complete the circuit is known as the BURGERS vector and the circuit itself is known as Burgers circuit.**

It can be seen that the Burgers vector, b of an edge dislocation is perpendicular to the edge dislocation while, in case of a screw dislocation, its Burgers vector is parallel to the dislocation line.

Q.8.7.:- Distinguish clearly between an edge dislocation and a screw dislocation.

Ans.:- Both these are line defects in crystals. The points of difference are given below.

(a) The Burgers vector of an edge dislocation is perpendicular to the edge dislocation line. The Burgers vector of a screw dislocation is parallel to the screw dislocation line.

(b) The atomic arrangement **around** the edge dislocation line is NOT symmetrical. The atomic arrangement **around** the screw dislocation IS symmetrical.

Q.8.8.:- Explain strain hardening. Why does it occur ?

Ans.:- The plastic deformation of metals at ordinary temperature has a very striking effect on the mechanical properties. Plastic deformation lowers the ability of a metal to undergo further deformations and increases the ability of the metal to resist further deformation. This is due to the fact that the cold work causes the metal to lose its plasticity. In general the strength properties, such as tensile strength, yield strength, proportional limit, elastic limit, proof strees and hardness are increased by cold working. On the other hand plastic properties such as ductility (elongation), formability, malleability and toughness decrease. These general effects of cold working are referred to as work hardening or strain hardening. Plastic deformation of polycrystalline metal takes place as a stress is applied in a particular direction. Then all the slip planes of the crystals will try to rotate simultaneously to align in the direction of applied stress. During this, there shall be a movement of atomic blocks along the slip planes. Dislocations which are present in the slip planes will also move along with the propagation of

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slip. Since there are a number of such slip planes and enormous number of dislocations moving along, there may be interaction of dislocations with each other. Hence a larger stress will be required for further plastic defomation.

Q.8.9.:- What happens when a cold worked metal is annealed ?

Ans.:- Since work hardened metals are in a state of high internal energy, they will revert to the stable state if the dislocated atoms in the distorted lattice are given sufficient mobility to find stable positions. This happens when cold worked metals are heated. This process of heating and cooling operation that is usually applied to induce softening is termed as annealing. This type of annealing is accompanied by three stage, as shown in Fig. 8.5.(90.

1st stage : Recovery or stress relife : In this annealing process the internal stresses are relieved as lattice recovers its normal shape. The stress recovery of cold worked metal increases with time and temperature.

2nd stage : recrystallization : If the annealing tempperature is gradually raised, a point is reached at which work hardened metals begin to soften and weaken rapidly. At the same time metals regain their plasticity. The microstructure also changes at this stage of annealing. The distorted elongated grains produced during cold working are gradually replaced by a number of tiny well-fomed grains that continue to grow at the expense of the strained grains until the latter disappear and the structure consists entirely of the newly formed grains. See Fig. 8.6.(9).

3rd stage : Grain Growth : The recrystallization of a cold worked metal is said to be complete when the distorted grains are entirely replaced by newly formed grains. However, the metals continue to become softer and ductile, if the annealing temperature is raised further. This is due to grain growth, which always occurs after recrystallization, provided that the recrystallized grain size is reasonably small. During the grain growth, the grain size attained depends principally upon temperature and time of annealing. See Fig. 8.7.(8).

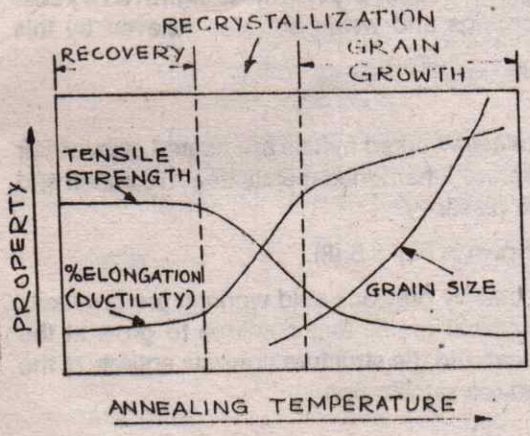

Fig. 8.5. (9)

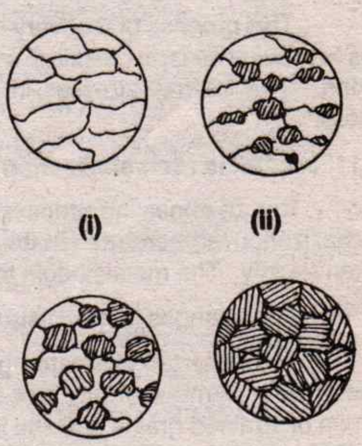
(i) (ii)
(iii) (iv)

Fig 8.6. (9)

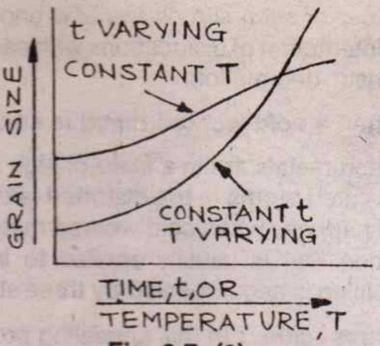

Fig. 8.7. (9)

Q.8.10 :- What is recovery ?

Ans.:- It is an annealing process used for the cold worked metals and performed below the recrystallization temperature of the metal. In this process, the internal stresses are relieved as the lattice revcovers its normal shape and hence such an annealing process is also called as **stress relieving**.

(1) Recovery begins before any observable change in microstructure and it decreases electrical resistance.

(2) During recovery process, mechanical properties remain unchanged, though, there is a tendency to slightly reduce the tensile properties in lightly cold worked metals and to increase the tensile properties a little, if the metals were severely cold worked.

This process of recovery is adopted for cold drawn cartridge cases and condenser tubes to prevent season cracking, without losing the strength and hardness improved by cold working. The internal stresses in castings, forgings and welds are also relieved by this process.

Q.8.11. :- What is recrystallization ?

Ans.:- It is an annealing process in which the cold worked metals are heated above their recrystallization temperature. At this temperature, work hardened metals begin to soften and weaken rapidly. The metals begin to regain their plasticity.

The changes in micro-structure are shown in Fig. 8.6.(8).

The distorted elongated grains produced by previous cold working are gradually replaced by a number of tiny well-formed (equiaxed) grains that continue to grow at the expense of strained grains until the latter disappear and the structure consists entirely of the newly formed grains. This phenomenon is called recrystallization.

Recrystallization is accompanied by

(1) A rapid change in physical properties.
(2) Disappearance of elongated distorted grains.
(3) Disappearance of etch bands.
(4) Relief of internal stresses.
(5) Grain refinement.

The higher the degree of cold work, the lower will be the temperature necessary to produce complete recrystallization in a given annealing period as schematically shown in Fig.8.8.(11), and smaller will be the final grain size.

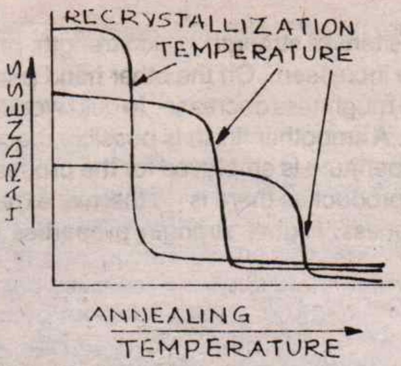

Fig. 8.8.(11)

In commercial fabrication of metal parts such as wire drawing, cupping and rolling, the degree of deformation is sufficient to result in a very fine grain size after recrystallization. Therefore many times, the recrystallization process is termed as grain refinement operation.

Q.8.12. :- What do you mean by recrystallization temperature ?

Ans.:- Within limits the temperature at which a cold worked metal begins to recrystallize is lowered by increasing the time of annealing. Increasing the amount of cold work also lowers the recrystallization temperature. Recrystallization starts in the most severely deformed regions and, as newly formed (nuclei) crystallites grow, other recrystallization centres spring up in the less distorted regions. **Thus recrystallization normally may take place over a range of temperature and, at any given temperature in this range, recrystallization takes place over a period of time, determined by the temperature used.**

The recrystallization temperature depends upon several factors as

(1) The severity of plastic deformation.
(2) The grain size prior to plastic deformation.
(3) The temperature at which plastic deformation occurs.
(4) The time for which the plastically defomed metal is heated to attain recrystallization.
(5) Presence of dissloved or undissolved elements.

The recrystallization temperatures of the common metals after drastic deformations is given in the following table with their melting points.

	Metals	Melting point °C	Approximate recrystallization temperature °C
1.	Tin	232	Below room temperature
2.	Lead	327	-do-
3.	Zinc	419	Room temperature
4.	Aluminium	660	150
5.	Copper	1083	200
6.	Iron	1539	450
7.	Tungsten	3400	1200

Q.8.13. :- Distinguish clearly between cold working and hot working.

Ans.:- Cold working is defined as plastic deformation at temperatures below the recrystallization temperature. Due to cold working, the internal energy increases, distortion and elongation of grains takes place as shown in fig.8.9.(13), (a), with loss in plasticity. In general, strength properties such as tensile strength, yield strength, proportional limit, elastic limit, proof stress and hardness are increased. On the other hand plastic properties such as ductility formability, malleability and toughness decrease. In cold working, plastic deformation is restricted by the work hardening. A smoother finish is possible, because surface oxidation or scaling is absent, as a lower temperature is employed for the process. Closer dimensional tolerances are obtained inthe final product as there is no thermal expansion and contraction due to low temperature of the process. Higher strength properties with uniform structure develop in cold working.

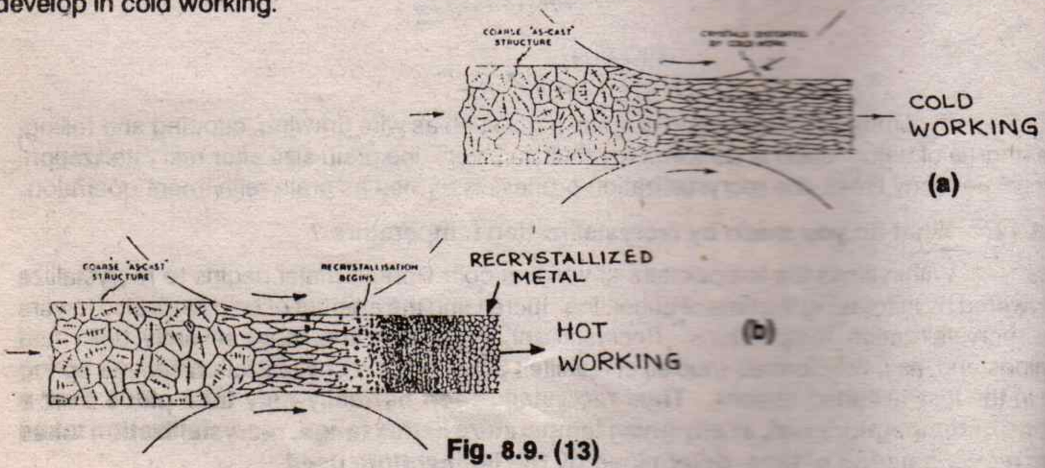

Fig. 8.9. (13)

If required, an intermittent annealing is given in cold working operation.

Hot working :- Hot working is defined as plastic deformation at temperatures above the recrystallization temperature. In hot working the ease of plastic flow at temperatures above the recrystallization temperature is associated with the large number of available slip systems, the decrease of interatomic strength and the continuous self annealing and recrystallization that occurs. With increased rates of deformation, time may not permit the complete recrystallization of the strained lattice, and the process may resemble cold working in this respect. If not working is done at temperatures close to the melting point, a coarse-grained structure may be produced and there may be a strong tendency towards surface oxidation. A fine grained structure will be produced in a metal by continuing the hot working process while metal cools to a temperature nearer to the recrystallization temperature, as shown in Fig.8.9.(13),(b).

Hot working of metals causes the segregated regions and impurities to be elongated in the direction of plastic flow and thus form flow lines, fibres or banded structure. The elongation of such non metallic impurities is responsible for permanent directional properties. Such directional properties may be used advantageously.

Effect of hot working :

(1) Various types of surface defects are formed in hot working and surface finish is poor.

(2) Dimensional tolerance is poor due to the themal expansion and contraction.

(3) Oxidation and scaling take place

(4) There is no change in mechanical properties like tensile strength, hardness, elastic limit, ductility, malleability etc.

(5) Additional annealing process is eliminated.

(6) Higher reduction in cross-section by plastic deformation is possible.

(7) Fibrous structure with directional properties can be obtained.

Q.8.14. :- Draw a figure to explain the changes in properties during recovery and recrystallization.

Ans.:- Ref.Fig. No. 8.5.(9).

Q.8.15. :- What is grain growth ?

Ans.:- When a plastically deformed metal is heated above recrystallization temperature, the small recrystallised grains grow larger.

This increase in size occurs by the process of coalescence. As the grain size increases, the strength and hardness continue to decrease. If the metal has been uniformly plastically deformed prior to recrystallization, all grains become uniformly larger. If however the metal has not been uniformly plastically deformed or if composition is not uniform through-out the structure, an abnormally large and non-uniform grain size may result. The formation of abnormally large and non-uniform grains is called germination.

The formation of coarse grains by growth after recrystallization is not desirable. Germination resulting from heating after plastic deformation is extremely detrimental. In general, grain growth is undesirable in many operations such as heat treatment and welding of metals.

Q.8.16. :- Give the principle of rolling process.

Ans.:- When the section of a metal is changed and reduced by passing it between metal rollers revolving in opposite directions as shown in Fig 8.10.(16-17), the process is called rolling. Compressive forces are involved and an increase in length is obtained as a result of the reduction in section, the metal leaving the rolls faster than it enters. If flat sheet is to be produced, plain rolls are used; if sections are required, the rolls are grooved accordingly. Rolling is a hot or a cold working process for steels and non-ferrous metals. It is the most usual method for breaking down ingots, as well as being a finishing process for producing sheets, various sections like rounds, hexagons, angles, rails and girders.

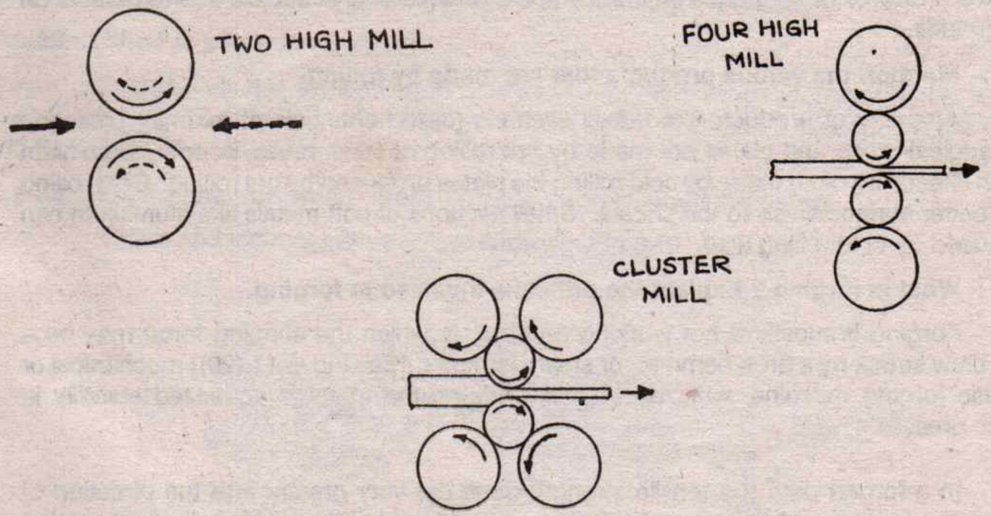

Fig. 8.10. (16. 17)

Q.8.17. :- Give brief description of two high and four high rolling mills .

Ans.:- Two high mill is the simplest form of mill, in which two rolls are revolving in opposite directions as shown in Fig 8.10. (16-17). For the return of work to be given another pass, the metal must be lifted back over the top, or carried round to the front again for further reduction. Alternatively, the work passes to another mill, as in continuous rolling. An improvement is the reversing two-high mill, in which the rolls are made to revolve in reverse direction; then the work can be passed backwards and forwards. For rolling of sheet and strip in comparatively long lengths, the use of small working rolls reduces the power required; however, these small rolls are not strong enough and hence must be supported by backing up rolls which are quite large in size. Such types of rolling mills are called **four high rolling mills.** In addition there are six high or cluster mills, which are used in cold rolling of sheets and strips. These mills have higher rigidity and produce the products with a close dimensional accuracy.

Q.8.18. :- What are the rolling defects ?

Ans,:- There are various types of defects that develop during the hot and cold rolling of metals which are called as rolling defects. Some of these defects are (1) Scabs (2) Tears (3) Slivers (4) Seams (5) Laps (6) Blisters (7) Rolled in scalse and (8) Scores.

(1) **Scabs** :- Scabs are caused by elongation of metal splashes that have chilled and adhered to the wall of ingot mould.

(2) **Tears** :- Tears are transverse surface cracks caused by rupture of skin of improperly heated metal which may develop into slivers : (3)

(4) **Seams** :- These my be caused by sub-surface blow holes or longitudinal surface craks that close but are not welded in hot working operation.

(5) **Laps** :- These are seams caused by fins that fold over without welding during rolling.

(6) **Blisters** :- These may be caused by dissolved gases that expand to raise the surface during rolling or heating.

(7) **Rolled in scale** :- This results from improper descaling of ingots or semifinished products before further rolling. Such scalse gets embedded during rolling.

(8) Scores :- Scores or scratches on the surface of the rolled product are due to defects on rolls or guides.

Q.8.19 :- Mention the vaious products that are made by rolling.

Ans,:- A variety of products like rails, I sections (called channels or beams), L-section (called angles) strips and plates are made by hot rolling of steel, brass, copper, aluminium etc. Thin sheets are often made by cold rolling the plates produced by hot rolling. Cold rolling gives a better surface finish to the sheets. Small sections of soft metals like aluminium can be produced by cold rolling also.

Q.8.20. :- What is forging ? Explain the principle involved in forging.

Ans,:- Forging is mostly a hot working process, in which the shaping force may be a sudden blow struck by a drop hammer, or steam hammer, [See Fig. 8.11 (20)] mechanical or pneumatic forging machine, whereas in press forging the metal is squeezed steadily in hydraulic presses.

In a forged part, the tensile strength does not vary greatly with the direction of working. The impact and fatigue resistance are considerably higher in longitudinal section than in transverse section due to the fibre flow. This fibre flow gives the directional properties. These directional porperties are quite advantages in many products e.g., the gear blanks produced by upsetting, in which original fibre pattern present due to rolling changes and (due to upsetting) provides directional properties.

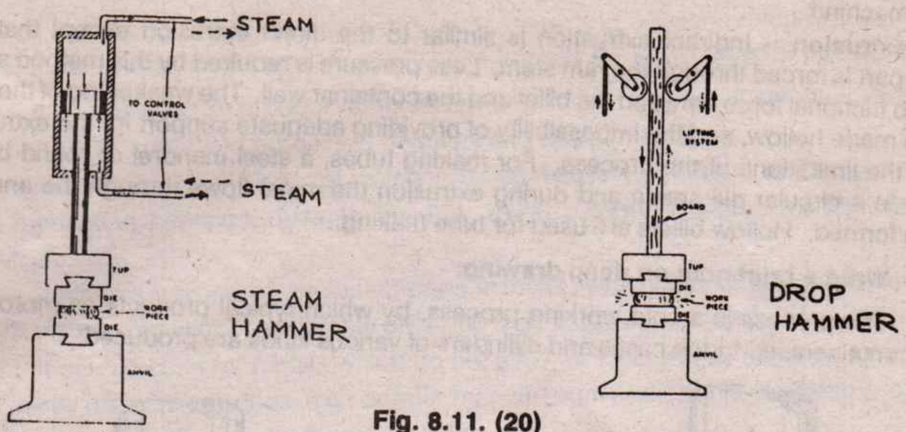

Fig. 8.11. (20)

Q.8.21. :- Describe some important forging defects.

Ans.:- The following defects in forging may develop in parts produced by forging;

(1) **Mis-match :-** Relative shifting of dies will cause mis-match.

(2) **Cold shuts :-** In drop forging two surfaces fold together to cause cold shuts.

(3) **Under fill :-** Insufficient metal to fill the die impression will cause **underfill.**

(4) **The flash :-** This is the excess metal after filling the die impression in the form of thin layer which cools at a very fast rate than the main forging. Due to this, a good amount of stress develops at the base of the flash. During trimming, the flash- crack may initiate at the base of flash and the surface of the forging. These are called as forging cracks.

(5) **Scores :-** Scores on the forging may from due to defects in the dies.

Q.8.22. :- What is extrusion ?

Ans.:- Extrusion is the hot-working process used for the plastic deformation of metals in various shapes or sections in one stage. A heated cylindrical billet is placed in a container and forced out of it die opeining in cross section.

Q.8.23. :- Distinguish between direct extrusion and indirect extrusion.

Ans.:- Direct and indirect extrusion are shown in Fig.8.12. (23).

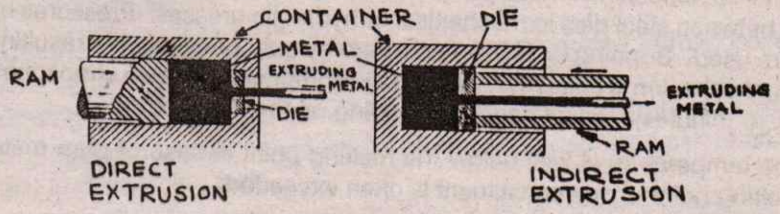

Fig. 8.12. (23)

Direct extrusion :- A heated round billet is placed in to the die chamber and the dummy block. Pressure is aplied with the ram, the metal gets extruded through die opening in a shape having the cross section of the die. This is then cut off next to the die and the butt end is removed from the machine.

Indirect extrusion :- Indirect extrustion is similar to the direct extrusion except that the extruded part is forced through the ram stem. Less pressure is required by this method since there is no frictional force between the billet and the container wall. The weakening of the ram when it is made hollow, and the impossibility of providing adequate support for the extruded part, are the limitations of the process. For making tubes, a steel mandrel or round bar is arranged in a circular die space and during extrusion the metal flows through the annular space so formed. Hollow billets are used for tube making.

Q.8.24.:- Write a brief note on deep drawing.

Ans.:- The process is a cold working process, by which typical products as motor car bodies, containers, cartridge cases and cylinders of various kinds are produced.

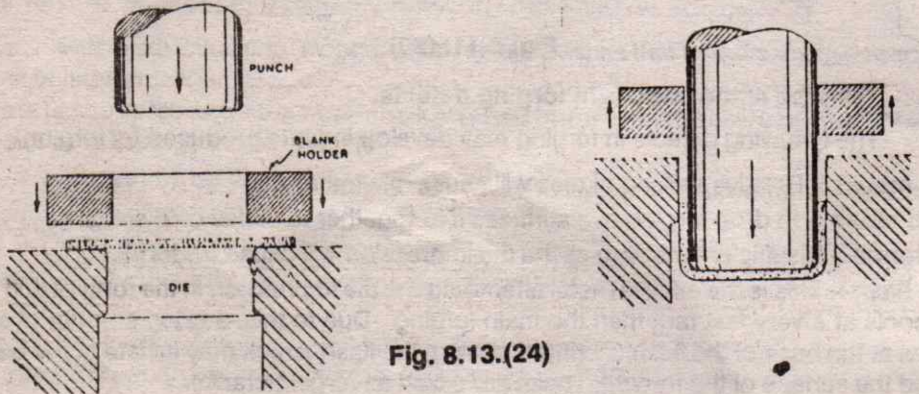

Fig. 8.13.(24)

The operations range from making suitable impression in one stage to cupping as shown in Fig. 8.13.(24), followed by number of redrawing operations. Working is carried out in hydraulic, pheumatic or mechanical presses. Deep drawing of mild steels, stainless steels, brasses, copper and its alloys, aluminium and its alloys, nickel and magnesium alloys is possible.

Q.8.25. :- Explain the principle involved in the production of components by powder metallurgy techinque.

Ans.:- In this process fine metal powder is agglomerated to form stock, or usually, shaped parts. The main process consists of cold pressing followed by heating called sintering. Shaping and initial adhesion of metal particles are obtained by pressing the powders at room temperature between steel dies in mechanical or hydraulic presses. Pressures up to 30 tons per sq. in. are used. Bonding is definitely attained by cold pressing, but resulting compacts are weak. Final cohesion is caused by heating the compact in suitable atmospheres for times varying from 10 minutes to a few hours, depending on the material.

The temperature is well below the melting point in case of pure metals, but with alloys the melting point of one constituent is often exceeded.

Considerable contraction in volume and increase in density with increase in mechanical properties result from heating. After heating they are again compacted in the same die to get the accurate size - this process is called coining. A second heating is done to produce a sounder powder metallurgical part.

Q.8.26 :- What are the advantages of powder metallurgy technique ?

Ans.:- Many products are now being made better and more economically with the use of powder metallurgy techniques. Following are some of the advantages of powder metallurgy.

(1) It is possible to produce articles having unique properties unobtainable by other methods e.g., controlled porosity in bearings and filters (metallic)

(2) It is suitable for mixtures of metals and non metals e.g., copper and graphite (Fluon) in self lubricating bearings, dynamo brushes, metal ceramic mixtures for high temperature services.

(3) It offers a method of producing parts in metals which cannot be melted commercially or which are cast with considerable difficulty, e.g., tungesten, molydbdnum and tantalum.

(4) It can be used for metals which do not alloy, or have widely separated melting points or greatly different densities, e.g., copper molydbenum and copper-tungsten products used for switch constacts, conductive brake lining, etc.

(5) It offers a mass production method of producing large quantities of identical parts. Complex shapes can be produced which may avoid further operations or machining, e.g., automobile oil pumps, gears, very small magnets and oil-less bush bearings.

Q.8.27. :- What are the limitations of the powder metallurgy technique.

Ans,:- Following are the limitations of the powder metallurgy technique :

(1) Restriction on the size of parts that can be produced. This depends on the capacity of the presses available.

(2) The restriction on the design of parts that lend themselves to pressing.

(3) Large quantites are required to justify the cost of dies and tooling.

(4) High cost of metal powder

(5) The volume of the uncompressed powder is 2-3 times that of finished piece and creates problems in storing.

(6) Some powders in finely divided state present explosion and fire hazards. Such metals include Aluminium, Magnesium, Zirconium and Titanium.

Q.8.28. :- Discuss the steps involved in the production of a compact by powder metallurgy technique and explain the changes occuring at each step.

Ans,:- The following steps are involved in the production of a compact by powder metallurgy technique.

(1) **Producing metal powder :-** Metal powders are produced, either from their solid state or liquid state by one of the methods given below.

(i) **Machining :-** A coarse grained metal powder is produced from solid stock.

(ii) **Milling process :-** Metal powders are produced by various types of crushers, rotary mills (ball mills) and stamping mills.

(iii) **Shotting :-** Pouring liquid metal through a sieve, or orifice (vibrating) and cooling by dropping into water produces coarse powder.

(iv) **Atomization :-** Metal spraying - liquid metal is sprayed to produce metal powder.

(v) By electrolytic deposition, and

(vi) By reduction Method.

(2) **Compaction** :- Metal powders are than compacted to shape in steel dies under pressures of 20 to 30 tons/sq. in. with the help of mechanical or hydraulic presses as shown in Fig. 8.14. (28). In pressing, oxide film ruptures and this increases the metal to metal contact. Joining of particles takes place due to plastic deformation and produces the desired shape.

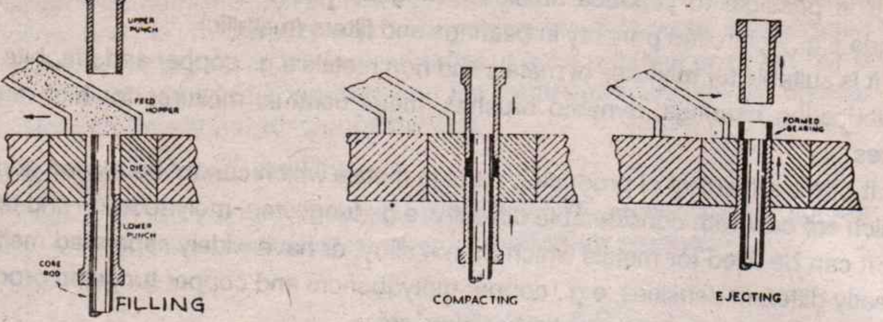

Fig. 8.14. (28)

(3) **Sintering** :- Metal compacts are heated in the controlled atmosphere furnaces, where these compacts develope appreciable strength due to joining of the particles. The enhanced bonding is brought about by recrystallization and crystal growth across the coldworked interfaces; with the formation of new crystals.

(4) **Sizing and coining** :- During sintering the deformation of shape takes place due to contraction and the density of the product is increased. TO achieve close tolerances, the products are repressed in the same die to give the correct shape. This process is called sizing and coining.

(5) **Heat Treatment** :- The metal parts are then heat treated to develop the desired mechanical properties.

(6) **Machining** :- The powder metallurgy parts are then machined if required, to a given tolerance limit.

Q.8.29. :- Enumerate various methods of making powders.

Ans,:- Refer the answer in part one (1) of the Q. No. 8.28.

Q.8.30. :- Describe the process of atomizing for making powder of a metal.

Ans,:- This process of production of metal powder is used for metals having lower melting points and is also called as spraying. Atomizing consists in forcing a thin stream of molten metal through a small orifice and then bombarding it with a stream of compressed gas, which causes metal to disintegrate and solidify into finely divided particles. Usually gas stream is directed through a nozzle which is partly submerbged in molten metal, in such a way as to draw metal upto nozzle and to the tip. Degree of fineness and particle size distribution of the atomised product can be varied over a considerable range -

(1) by proper design of the orifice, nozzle and the tip.
(2) by controlling the temperature, viscosity and flow of liquid metal through the orifice
(3) by adjusting the pressure and temperature of the gas.

This process is useful for a large scale production of metal powders of aluminium, lead, tin and cadmium.

Q.8.31. :- Explain the principle involved in producing metal powder by (a) Electolytic method (b) Reduction process.

Ans. :-

(a) Electrolytic Method :- Metla powders can be produced by an electro-deposition from solutions or from fused salts, e.g., iron, copper, nickel, zinc, cadmium, antimony, silver, lead etc. Metal powders can be produced with a good size control by this method.

The process can be controlled by :

(i) Regulation of current dinsity
(ii) Temperature of the electrolyte
(iii) Bath composition or concentration
(iv) Size of the electodes
(v) Agitation of the bath

Three types of electro-depositions are in practice :

(1) Deposition as a hard, brittle mass, which is subsequently ground in hammer mill, e.g., nickel and iron.

(2) Deposition as a soft mass, only loosely adherent to the electrode and easily disintegrated into powder.

(3) Direct deposition as a powder.

Low acidity and low metal ion concentraion increases brittleness of Ni deposits while low acidity and high current density increases brittlenessof iron powder. (2) and (3) method are used ofr copper powders. Formation of loosely adherent spongy deposit is favoured by low metal ion concentraion and high current density.

(b) Reduction :- Production of metal powders by the reduction method is very common. In this process the oxides of the metals are reduced with various gaseous reduing agents or the gas forming solids. Lower operating temperatures are employed (well below melting point of metal oxide). Treatment of pulverized oxides at elevated temperatures in reducing atmosphere is the method most commonly used.

By varying raw materials and conditions of reduction, a considerable control over the properties of the final product is obtained. Temperature and rate of reduction are very important conditions. Finest powders are produced at lowest reduction temperatures while high temperature increases the tendency of the powder to form a sintered mass.

Selection of suitable reducing agent is made on the basis of composition, impurities and economy of the operation. Hydrogen, carbon monoxide, natural gas, hydrocarbons and dissociated ammonia gas are the common reducing agents. Molybdenum, tungsten and iron powders are produced by this process from their respective oxides.

Q.8.32. :- Write about any two products made by powder metallurgy technique :

Ans :- (1) Porous Bronze Bearings :

(a) Powders :- The powder mixtures used for the production of porous bronze bearings contain 6 to 12% tim (electrolytic or atomised), 0-6% graphite, the balance copper (elctrolytic or reduced) powders of -325 mesh.

(b) Processing :- Powders are mixed in a ball mill with the addition of lubricants like zircon silicate or boron nitrate. Then this mixture is fed to press for compaction in suitable shape at a pressure of 15-30 tons per sq. inch. Sintering is then performed in a reduing atmosphere, at a temperature of 400°C. This temperature melts tin, starts diffusion, and alloying takes place.

(c) **Sizing :-** Shrinkage during sintering is non-uniform and the faces are not smooth. Hence a sizing operation is performed in the same die by repressing. With some bearings having very fine pores, sizing may result in a closing of the pores. In this case, sizing is replaced by machining.

(d) **Impregnation :-** Imprengaion is usually performed by heating finished bearings in oil at 110°C. A treatment of a few minutes is generally sufficient. In some instances, vacuum is applied for the removal of air from the pores prior to the impregnation. Such types of bearings are called as oil-less porous bearings, which do not need any lubrication in service.

(2) **Production of tungsten carbide tools :-**

Ans :- Tungsten carbide and cobalt powders are milled in a ball mill either dry (in air or hydrogen) or wet (in presence of water or organic liquids like benzol) until cobalt powder forms a continuous coating upon the carbide particles. The time required for coating is from several hours to several days, and the resulting mixtures differ widely in particle sizes.

Then this mixture is subjected to a reducing treatment with dry hydrogen at 600o-700°C. A cold or hot pressing is employed for the compaction from this powder mixture, at a pressure of 15-30 T/sq. in. Thise parts are thn presintered at 900°-1000$_{o}$C. Such presintered parts are machined to the desired shapes. These machined compact are again sintered at 1350°-1500°C for a period of 1 to 2 hours. Shrinkage during sintering is around 12-25%. Sintered parts are sent for coining and sizing. The sintered carbides are used for producing various types of cutting tools.
