

*260 K*

# A Course in **WORKSHOP TECHNOLOGY**

VOL. I

[Suitable for Engg. Diploma, B.E., B.Tech., B.Sc. (Engg.), A.M.I.E. (India),  
A.M.I. Mech. E (I), A.M. Ae, S.I., Indian Engg. Services, U.P.S.C.  
and various other Exams.]

by

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Types of maintenance. **Unplanned maintenance**—Breakdown maintenance, Demerits of Breakdown maintenance. Opportunistic maintenance., Corrective maintenance. **Planned Maintenance**—Routine maintenance, Preventive maintenance - Main objectives, Procedure of Preventive maintenance; Priority in Preventive maintenance, Inspection, Frequency of Inspections, Records of Preventive maintenance—Equipment Data History, Work Order, Evaluation of Preventive maintenance. Storing of Spares. Advantages

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## CHAPTER



# METALS AND ALLOYS

### 4.1 INTRODUCTION

A large number of materials are used in engineering. These can be broadly classified into **Metals** and **Non metals**. In selecting a particular material, an engineer is basically concerned with matching the properties of the material with the service requirements of the product to be made out of that material. Taking into consideration the environment and the conditions under which the desired component has to operate an engineer decides the material from which the component should be made.

As such, in order that a correct choice be made, an engineer should be fully familiar with the properties and limitations an engineering material will possess. Of the above two categories both metals and non-metals exhibit specific properties under specific conditions. *Metals* are solid at room temperature, possess high thermal and electrical conductivities, good lusture, strength, hardness and density, low specific heat, etc. Some of these are fairly ductile while others possess good magnetic properties. Some common metals are iron, aluminium, copper, nickel, titanium, tin, zinc, magnesium and lead. The common metallic alloys are steel, brass, bronze, and their several variations. Most of the metals are found to be *elastic* to a certain limit and they deform plastically at higher stresses. Depending upon the pressure and temperature a metal can exist in solid, liquid or gaseous state.

Against these, the **Non-metallic** materials are found to be weaker, less dense and less ductile than metals. Also, they possess poor thermal and electrical conductivities. The common non-metallic materials used in engineering are rubber, wood, plastics, glass, concrete and bricks.

Although it is true that till recently the *metals* were considered more important for engineering work, but of late the *non-metallic group* has also come up into great prominence due to the development made in this area and the newer nonmetals having been developed. These developments have been so significant that in many cases now the non-metals are tough competitors with metals.

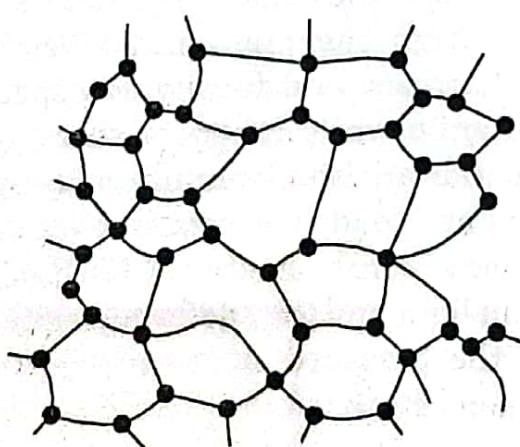
#### 4.2 STRUCTURE OF SOLIDS

Solids can be broadly classified as :

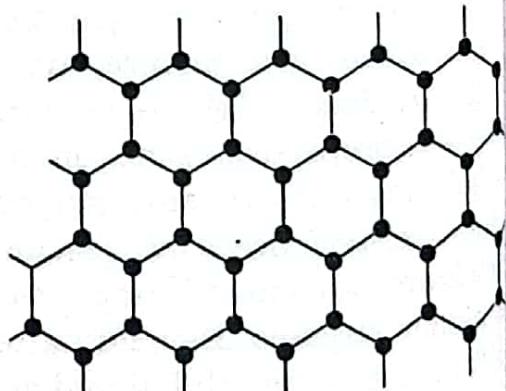
1. **Amorphous.** It means a solid in which the basic structural unit is a *molecule* and whose *atoms* are not arranged in a systematic order, i.e., the positions of their atoms bear no fixed relationship to the positions of other neighbouring atoms. Such solids are generally *non-elastic* but do possess plasticity with some exceptions, of course, like rubber. The common *amorphous* solids, for example, are plastics, glass, rubber, etc.

2. **Crystalline.** A crystal can be defined as a solid in which the constituent molecules or atoms are arranged in a definite and orderly pattern. The solids made up of such crystals are known as ***Crystalline*** solids, and this group includes all metals and some nonmetals as well. The crystals of a solid can be of similar sizes or may vary widely in sizes.

The above two types of solid structures are shown in Fig. 4.1. The diagram is self explanatory.



(a) Amorphous Structure  
(Atoms in disorderly manner)



(b) Crystalline structure  
(Atoms in a perfectly orderly manner)

Fig. 4.1. Structure of solids.

### 4.3 CRYSTAL STRUCTURE OF METALS

All the solids are either *crystalline* or *non-crystalline (amorphous)* as explained in the foregoing article. Now, we will discuss the crystal structure in more detail.

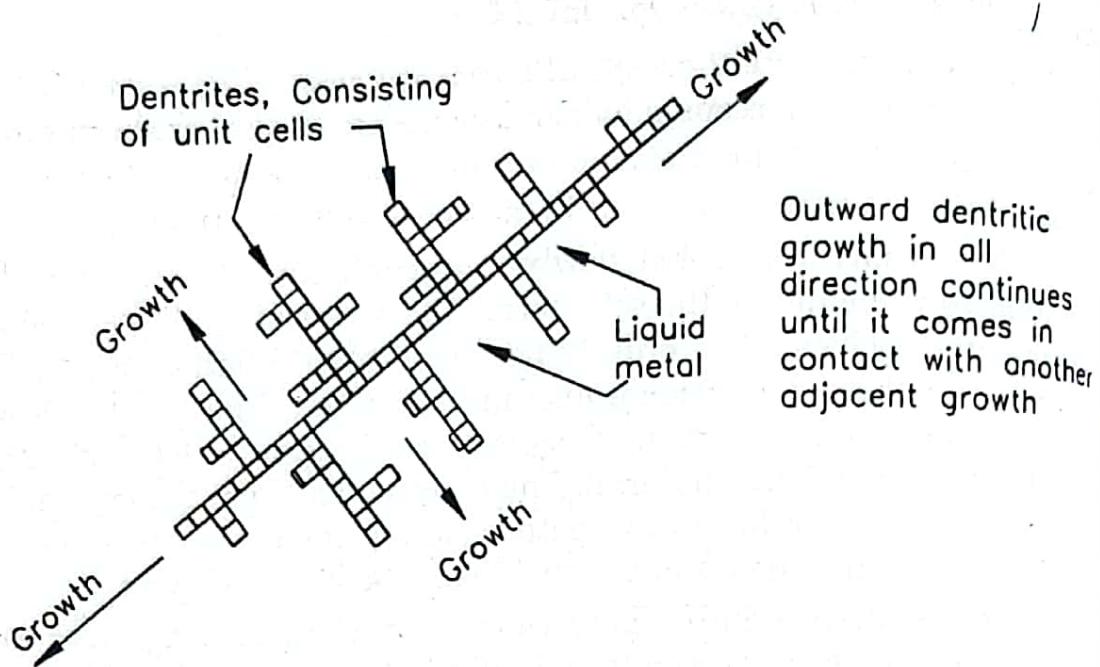
#### Crystal Structure

When a metal is cooled slowly from the liquid (fusion) state it crystallises while taking the solid form. The atoms of the liquid metal arrange themselves in an orderly pattern during solidification. This pattern is a three-dimensional one and repetitive. The repetition of three dimensional pattern in a crystal is on account of the atomic coordination within the material. The external shape of the crystal is also sometimes controlled by this pattern, as is evident when we observe the hexagonal snow flakes or the surfaces of *Gems* and *Quartz*.

A **Crystalline Solid** may consist of a single crystal or an accumulation of several crystals separated by distinct boundaries. Most metals, some ceramics and several ionic and covalent solids fall in the second category, i.e., consisting of an aggregate of several crystals separated by distinct boundaries. These boundaries are called *Grain Boundaries* and are revealed when a metal is etched by a suitable acid. Such a solid is known as a **Poly-crystalline solid**.

#### Crystalline Growth

During solidification, when two or more atoms get attached to one another, *crystallisation* starts. This process may start simultaneously at several locations throughout the liquid mass of the metal and this formation at each location grows outwards till it comes in contact with another adjacent growth. The two adjacent crystalline growths are separated by the '*Grain Boundary*'. The arrangement of atoms, which is in a three-dimensional pattern, is repeated several times in the growth of a *crystal* or *grain*. Each such three-dimensional pattern is called a **Unit Cell**; which is extremely small in size. These *Unit Cells* initially arrange themselves in a straight line. Many small straight-line branches of unit cells are then formed on the initial straight line and follow a geometrical pattern, as shown in Fig. 4.2. These smaller branches of 'unit cells', called **Dendrites**, are surrounded all around by liquid metal. As the liquid metal continues to cool down more and more *Dendrites* are formed on the existing dendrites until the entire liquid metal between them gets solidified. This entire aggregate of the three-dimensional growth of unit cells is surrounded by the '*grain boundary*', which separates it from the similar adjacent formation. Such an aggregate of unit cells, surrounded by the grain boundary, is called a **Crystal** or **Grain**.

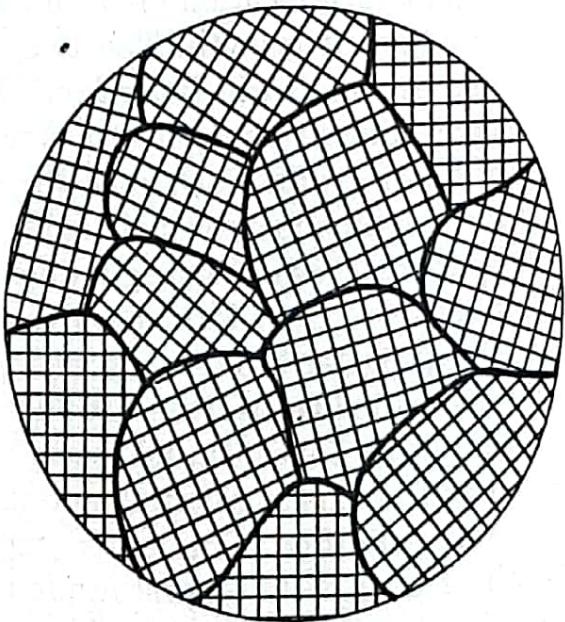


**Fig. 4.2.** A schematic diagram showing dendritic growth of unit cells during solidification of liquid metal to form crystals or grains.

### Polycrystalline solids (materials)

As explained above, most of the crystalline solids are the aggregates of several small *crystals* (*or grains*) surrounded by *grain boundaries*. Each crystal has a proper geometrical form of unit cells inside it but differs in orientation with its neighbouring crystals, as shown in Fig. 4.3. The grain boundaries are usually distorted due to the interference among growing crystals or grains. That is why the *crystals* (*or grains*) in the fracture of a metal are observed to be of irregular shapes. These shapes of grain boundaries, however, have no relationship with the internal symmetry of the grain.

All poly-crystalline materials are usually considered **Isotropic**, i.e., they possess same properties in all directions. Most metals, crystallised polymers and several minerals are *poly-crystalline aggregates*. However, the mechanical properties of crystalline solids may differ when measured in different directions on a specimen. This phenomenon of solids is called **Anisotropy**.



**Fig. 4.3.** Structure of a poly-crystalline metal, showing crystals (*or grains*) having different orientations but geometrical symmetry within them.

#### 4.4 SPACE LATTICES (OR CRYSTAL LATTICES)

Before studying the space lattices it would be advantageous to understand a *unit cell* in more detail. A *unit cell* can be conceived as the smallest component of a **Space Lattice** or **Crystal lattice**. The space lattices of different materials differ from each other in respect of the shapes and sizes of their unit cells. These unit cells, when repeated along the three definite directions in space, show the atomic positions in a crystal. It is because of this repetitive arrangement of unit cells throughout the crystal that if the locations of atoms in a unit cell are known complete information about the structure of the crystal can be known, i.e., to describe one unit cell means describing the complete crystal.

A typical *unit cell* is shown in Fig. 4.4. Its edges ( $a, b, c$ ) are called *primitives* and the three angles ( $\alpha, \beta, \gamma$ ) are known as *interfacial angles*. These six dimensions, i.e., the three lengths  $a, b$  and  $c$  and the three interfacial angles  $\alpha, \beta$ , and  $\gamma$ , of the unit cell are called *lattice parameters* or *geometrical constants* of a *crystal system*, made up of such unit cells.

#### 4.5 CRYSTAL SYSTEMS

**Bravais**, a scientist, developed mathematical models to prove that there are only *fourteen* possible independent ways through which points can be arranged in three dimensional space such that each point carries an identical surrounding, conforming to the conditions of a space lattice. These fourteen space lattices, after their originator, are called **Bravais Lattices**. Each such *space lattice* (or *crystal lattice*) can be described with reference to a unit cell which, if repeated innumerable times in space, will create a *space lattice*. These 14 possible arrangements, called Bravais lattices, are distributed among *seven crystal systems* (or *crystal habits*), each system requiring a different co-ordinate system of reference axes. It can be further understood by conceiving such a unit cell of which the non-parallel *edge vectors* or *primitives* are so chosen that only the lattice points of the cell fall at its corners. Such a unit cell is called **Primitive cell** or **Basic cell**. A total of *seven* such *basic* or *primitive cells* are found among crystals. Each of these is known as a **Crystal system** (or **Crystal habit**). These seven systems are *cubic*, *monoclinic*, *triclinic*, *tetragonal*, *orthogonal*, *rhombohedral* and *hexagonal*.

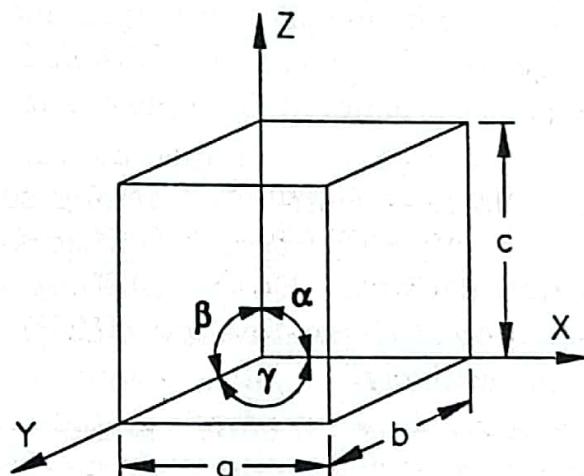


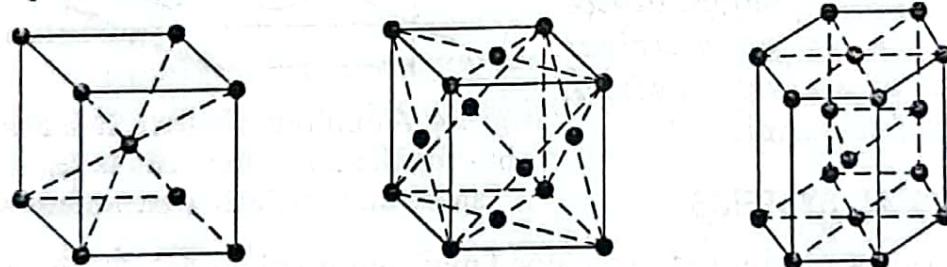
Fig. 4.4. A unit cell, shown schematically, showing the three dimensions ( $x, y, z$ ) in space and the lattice parameters.

From the foregoing discussions it can be easily concluded that the basic unit of space lattice of a solid, in which the atoms are arranged in a definite geometrical order, is a *Unit cell*. These unit cells repeat themselves in all the three dimensions in space to form an aggregate (or larger unit) called *Space lattice* or *Crystal lattice* of a solid.

#### 4.6 SPACE LATTICES IN METALS

As already explained, when a liquid metal solidifies it assumes a crystalline structure. Most of the metals after solidification assume only one lattice form. But, a few of these, depending upon the pressure and temperature, can exist in two or more lattice forms in solid state. Such metals are known as **Allotropic** and the change from one lattice form to another is known as an *Allotropic Change* which is a reversible change. The most prominent example of such a metal is *iron*.

Although, as explained above, there are in all fourteen different space lattices distributed among seven possible crystal systems, in metals only three types of lattices are found. These are (1) **Body Centred Cubic (BCC)**, (2) **Face Centred Cubic (FCC)** and (3) **Hexagonal Close Packed (HCP)**, as shown in Fig. 4.5 (a), (b) and (c) respectively.



(a) Body centred cubic, (b) Face centred cubic, (c) Hexagonal close packed.

Fig. 4.5. Space lattices showing arrangement of atoms in metals.

The atomic arrangement in a **Body Centred Cubic (BCC)** space lattice consists of nine atoms, eight located at the eight corners and one at the centre of the cube. Some prominent metals carrying this type of crystal lattice are iron, chromium, manganese, molybdenum, barium, tantalum, vanadium, tungsten and columbium.

In **Face Centred Cubic (FCC)** crystal lattice there are fourteen atoms in all, eight located at the corners and six at the centres of the six flat faces of the cube. As is evident from the diagram, the atoms in this type of space lattice are found to be more closely packed than those in BCC. Some examples of metals carrying this type of crystal lattices are copper, iron, gold, aluminium, nickel, silver, platinum, lead, calcium, etc.

In Hexagonal Close Packed (HCP) crystal lattice there are seventeen atoms in all, six on the corners of the top hexagonal face, on the six corners of the bottom hexagonal face, one each at the centres of these two faces and three at the centres of alternate vertical flat surfaces, as shown in Fig. 4.5 (c). Evidently, the atomic arrangement in this type of lattice is more compactly packed than any one of the preceding two types. A few examples of the metals carrying this type of crystal lattice are zinc, beryllium, cambium, magnesium, cobalt, titanium, zirconium, etc.

#### 4.7 PACKING FRACTION AND COORDINATION NUMBER

**Packing Fraction** is also known as **Packing Efficiency**, **Packing Density** or **Atomic Packing Factor**. It is the ratio of the volume occupied by the atoms to the total volume of the unit cell containing these atoms, i.e.,

**Packing fraction (p.f.)**

$$= \frac{\text{Volume of total number of atoms in a until cell}}{\text{Total volume of one unit cell}}$$

In every crystal each atom is surrounded by a definite number of equally spaced other atoms. The total number of such equally spaced nearest neighbouring atoms, by which a given atom is surrounded, is called the **Coordination Number (CN)**. This number characterises the packing of all crystal lattices. The higher this number the more closely packed are the atoms in a crystal lattice. For example the *coordination number* of b.c.c. crystal is 8 and that of f.c.c. 12, which means that the f.c.c. crystal is more closely packed than the b.c.c. crystal.

#### 4.8 BONDS IN SOLIDS

Atoms are normally not found as free and independent units. A *chemical bond* holds these atoms together to form molecules and the same bond holds the molecules together to form the entire mass of the material. It is reckoned that atoms and molecules are more closely packed in solid state than in gaseous and liquid states. These atoms and molecules are strongly held together by means of mutually attractive and repulsive forces which are basically *electrostatic* in nature. These forces, which are responsible for holding the atoms, molecules and ions together are known as **Chemical Bonds** and the process of holding is known as **Bonding**. The classification of different types of bonding depends on the electronic structure of the atoms involved and are, therefore, directly linked to the periodic table. The electrical, chemical and physical properties of a material are directly effected by the type of bonding it carries.

## 4.9 TYPES OF BONDS

On the basis of strength, chemical bonds, directionality of bonding forces and the character of a solid material the bonds are classified as *Primary* and *Secondary*. The *primary bonds*, also known as *attractive bonds*, due to their interatomic nature are the strongest. They are further classified as :

1. Ionic or electrostatic bonds.
2. Covalent, atomic or homopolar bonds.
3. Metallic bonds.

### Ionic Bond or Electrostatic Bond

It is also known as **Electrovalent** or **Hetropolar bond**. It is the simplest interatomic bond formed between an electropositive and an electronegative atom. What actually happens is that during chemical reactions the atoms tend to *lose* or *gain* electrons in order to stabilise their outer shell configurations and, in turn, become *electropositive* or *electronegative* ions respectively. This results in the development of an electrostatic attractive force between these positively and negatively charged ions and when they come in close proximity an **Ionic Bond** is formed. It is reckoned that generally metallic ions are electropositive and non-metallic ions are *electronegative*.

### Covalent Bond

It is also known as **Homopolar** or **Atomic Bond**. In this type of bond there is no transfer of electrons as it happens in case of an ionic bond. An atom is supposed to be electronically stable if it carries eight electrons in its outer shell (orbit). But, if it is deficient it makes up the deficiency by sharing the electrons with a neighbouring atom, leading to what is known as **Covalent Bond**. It is, thus, clear that in this type of bond only sharing of electrons takes place and not transfer.

Such, a bond usually takes place between the atoms of those elements in which a very high amount of energy is required to remove the valence electrons, e.g., the elements of **Group IV** of the Periodic Table and, therefore, ionic bonding is not easy.

However, it should be noted that only a few solids carry purely *Covalent bond* because it is not sufficient enough to build a three dimensional solid. That is why most of the solids, apart from having the covalent bond, also carry either *Ionic* or *Vander Waals* bond.

### Metallic Bond

In the earlier two types of bonds we have seen that electron distribution is rearranged either through transfer or sharing so that each *nucleus* carries eight electrons in its outer shell. But, in case of

most metals and alloys the number of valency electrons in each atom is small and, hence, neither of the above two conditions of bonds is fully possible. Also, because the valence electrons in metals and alloys are loosely held by their atoms, they are easily detachable. These electrons are released by their respective atoms and move freely in the solid metal to form what is known as the common *Electron Cloud* or *Electron gas*. These freely moving electrons are temporarily bound to different atoms at different times for a short while.

What actually happens is that after releasing the valence electrons the parent atoms become positively charged ions and the released valence electrons freely travel in all directions within the solid metal or alloy. A metal or alloy can, therefore, be considered as a solid mass consisting of a solid core made from the positively charged ions surrounded by the *electron cloud* or *electron gas*, formed by the freely moving electrons. The *electrostatic force* of attraction between these positively charged ions and the freely moving electrons results in what is known as the *Metallic Bond*.

This bond is a non-directional and unsaturated bond and is weaker than both *Covalent* and *Ionic* bonds.

#### 4.10 SECONDARY BONDS

These bonds are also known as **Intermolecular Bonds** or simply **Molecular Bonds**. These are weak bonds and normally exist in such materials in which very little or no electron transfer takes place between atoms. These bonds are formed either due to *Dipole attractions* or due to weak *Vander Waal's forces* of attraction between atoms. **Dipoles** are nothing but pairs of equal and opposite charges formed on account of unbalanced distribution of electrons in asymmetrical molecules. These equal but opposite charges attract each other and this is what is known as **Dipole Attraction**. The **Van der Walls** forces are the weak *electrostatic* force of attraction between the nucleus of an atom and the electrons of another atom.

These bonds, although weak, play a very important role in determining the structure and properties of a large number of non-metallic materials, liquids, gases, plastics, paraffins, graphite, etc. Most of the compounds carrying secondary bonds are good insulators, transparent to light and have low melting points. Water, of course, is an exception among these. The common types of secondary bonds are :

1. Dispersion bonds
2. Dipole bonds
3. Hydrogen bonds.

## 4.11 MAIN CHARACTERISTICS OF MATERIALS POSSESSING DIFFERENT TYPES OF BONDS

### Ionic Solids (Compounds)

1. Generally crystalline, hard and rigid.
2. Have high melting and boiling points because of the existence of strong electrostatic binding forces.
3. Generally insoluble in organic solvents but highly soluble in water and other polar solvents.
4. Generally non-conductors of electricity, but their melts and solutes do conduct electricity.
5. The ionic bond itself is non-directional because the electrostatic attraction between the oppositely charged ions acts in all directions.

### Covalent Solids (Compounds)

1. These compounds usually exist in gaseous and liquid states, but those of high molecular weight exist in solid state.
2. Except graphite, most of these components are generally electrical insulators.
3. They are generally soft, volatile and easily fusible. However, there are some exceptions like diamond and quartz.
4. They are soluble in non-polar solvents such as alcohol, benzene, paraffins, etc., but insoluble in water.
5. They are directional in nature, possess open structure and have relatively low density.
6. Usually they have low melting and boiling points except, of course, in case of diamond and quartz.
7. They are homopolar and, therefore, their electrons cannot move freely through the material like in metallic compounds.

### Metallic Solids (Compounds)

1. Because of the freely moving electrons within their material these solids are good conductors of heat and electricity.
2. Also, the free electrons absorb light energy and, therefore, the metals are opaque to light.
3. Metals have good lusture and reflectivity due to the radiation of the absorbed light by the free electrons.
4. Metals are quite strong and normally have high melting points, but lower than those of the ionic compounds.
5. They possess crystalline structure.

## 4.12 IMPERFECTIONS (OR DEFECTS) IN METAL CRYSTALS

The *ideal* crystal structures so far considered were perfectly regular in which the atoms were supposed to have been arranged in a very regular manner. In actual practice, however, a lot of *imperfections* or *defects* are found to exist in crystals. The type and nature of these imperfections directly affect the properties of the crystals and, therefore, of the metal carrying these crystals. All the crystal *imperfections* or *defects* can be grouped into the following three main categories, depending upon whether the defect is at a point, along a line or over a surface. Accordingly, they are known as :

1. Point imperfections
2. Line imperfections
3. Plane imperfections.

## 4.13 POINT IMPERFECTIONS

A *point defect* in a crystal lattice is totally localised and is supposed to be zero dimensional. The presence of this defect in a crystal results in an increase in the crystal's internal energy and a decrease in its free energy. The main point defects are :

**Vacancies.** A *Vacancy* means a vacant site i.e., absence of an atom from a normally occupied site within a crystal lattice. It is not necessary that only a single vacancy will always occur. In several cases a condensed group of vacancies, such as *di-vacancies* and *tri-vacancies*, can be found in crystals. This imperfection (defect) usually occurs either due to imperfect packing of atoms during original crystallisation or due to increased thermal energy resulting in thermal vibrations of atoms, causing some atoms to jump out of their positions of lowest energy [Fig. 4.6].

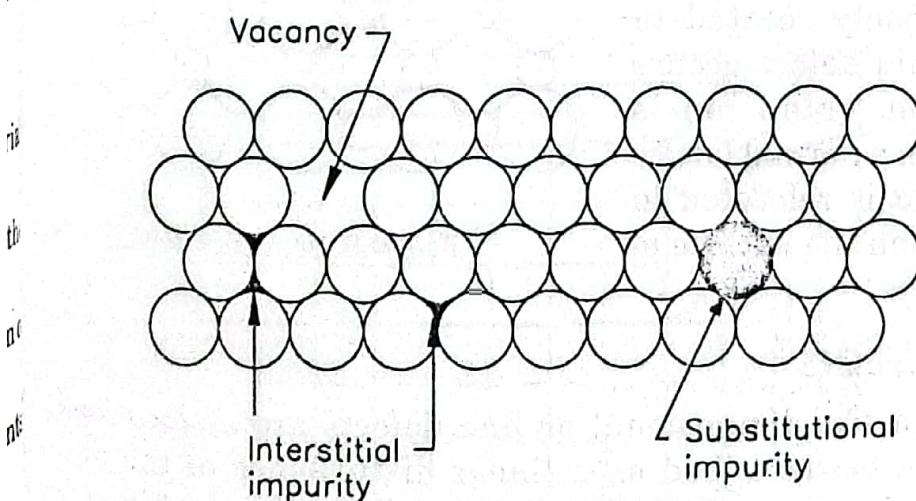


Fig. 4.6. Point Imperfections and impurities.

**Impurities.** Impurities present in the crystals may cause compositional defects in them. If a foreign atom occupies a lattice site, from where a regular atom is missing, it is known as substitutional impurity as shown in Fig. 4.6. Slag inclusion is a common defect in metals.

It results in smaller atoms of slag to occupy spaces between relatively larger and hot atoms of the parent crystal. It is known as *Interstitial impurity*, shown in Fig. 4.6. Such defects lead to phase transformation and atomic diffusion and are responsible for affecting changes in electrical and thermal conductivities of metals and alloys.

**Frankel defect.** It is closely related to *interstices*. In this, an atom in a crystal leaves its site and occupies an interstitial site in the crystal structure. The vacancy so caused and the interstitial atom are known as *Frankel defect*. This defect is more pronounced in open structures than close packed structures.

**Schottky defect.** [Fig. 4.8]. It is closely related to vacancies. This defect occurs when an atom or an ion is dislocated from a normal lattice site inside and is relocated in some position on the surface of the crystal.

#### 4.14 LINE DEFECTS

The main two-dimensional or line defects are *dislocations*. *dislocation* can be described as a linear disturbance of the atomic arrangement of a crystal, wherein a part-plane of atoms is shifted from its stable and symmetrical position in the crystal. It can be conceived as

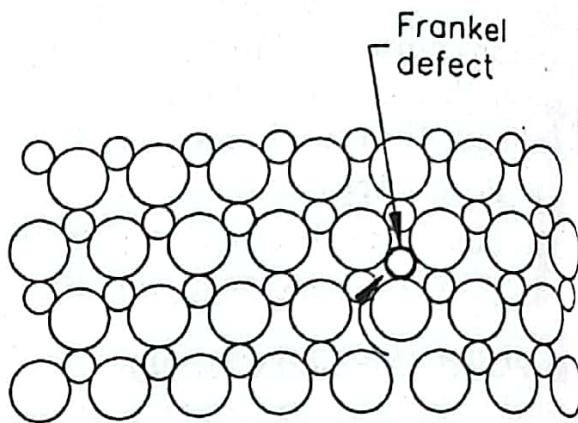


Fig. 4.7. Frankel defect.

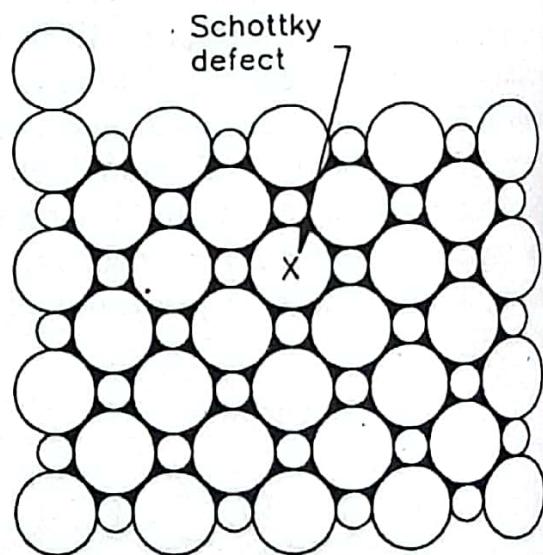


Fig. 4.8. Schottky defect.

a region of localised lattice disturbances which separates the slipped region of the crystal from its unslipped region. The *plastic deformation* of metals due to slip phenomenon is mainly on account of such dislocations only. Dislocations are also connected with several other mechanical phenomena like fatigue, strain hardening, yield point, etc. The two main types of dislocations are :

1. Edge dislocation or Taylor Orwan dislocation.
2. Screw dislocation or Burger's dislocation.

### Edge dislocation

When, within a crystal structure, either a row of atoms is removed or displaced a unit distance an *edge dislocation* occurs at the end of an extra half plane of the atoms, as shown in Fig. 4.9. An edge dislocation is always accompanied by the zones of compression and tension. The atoms just above the slip plane are in tension. A *stress field*, therefore, always surrounds such dislocations.

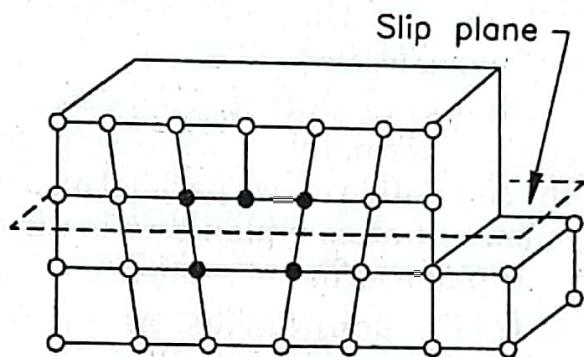
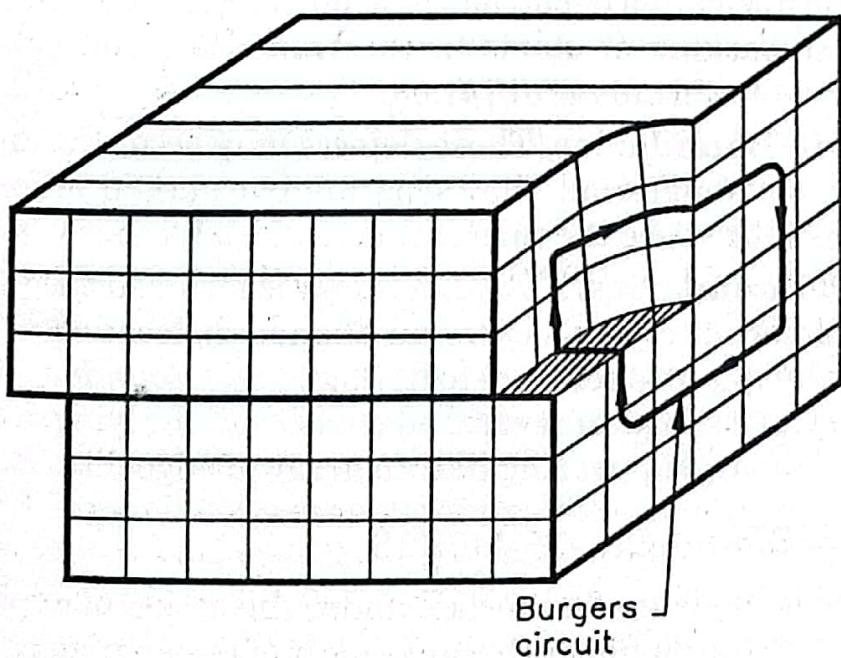


Fig. 4.9. An edge dislocation.

### Screw dislocation [Fig. 4.10]

In this type of dislocation the displacement of atoms occurs in two different places which are mutually at right angles to each other. The lattice points displaced around the dislocation in the lattice follow a helical path, and it is for this reason that it is named as *screw dislocation*.



### Burger Vector

The *burger vector* of a dislocation shows both the magnitude and the direction in which the lattice above the slip plane is shifted with regard to the lattice below the slip plane. Thus, both the above dislocations can be described with the help of their *burger vectors*. In *edge dislocation*, this vector is perpendicular to the direction and in *screw dislocation*, it lies parallel to the direction of dislocation.

### 4.15 PLANE IMPERFECTIONS OR PLANER DEFECTS

These defects are also known as **Surface and Grain Boundaries** or simply **Surface Defects**. They are two dimensional and occur on account of a change in the stacking of atomic planes across a boundary. These defects include *stacking faults*, *grain boundaries*, *twin boundaries*, etc.

**Stacking Defect.** This defect is usually found in HCP and FCC metals. It normally occurs during the growth of a crystal or as a result of the separation of two parallel dislocations. It occurs when the stacking sequence of atomic planes is disturbed because of the stacking of a atomic plane as out of sequence with respect to the adjoining ones.

**Grain Boundaries.** As already explained in Article 4.3 most of the metals are polycrystalline having grains of different orientation. These grains are separate from each other by surface imperfections developed during crystallisation, called *grain boundaries* (Refer Fig. 4.3). The atomic packing in grain boundaries is imperfect and there exists a transition zone between two adjacent grains, which is not in alignment with any of these grains.

Consequently, the atoms at the grain boundaries carry higher energy than the atoms within the grains. This factor plays an important role in the nucleation of polymorphic phase changes. Also, the imperfect and lower packing of atoms in the transition zone along the grain boundary helps in *atomic diffusion*.

**Twin Boundaries.** These defects may occur during growth or deformation of material. They separate two similar orientations which appear as if they are the mirror image of each other.

**Tilt Boundaries.** A *Tilt Boundary* is also a surface defect in which the two adjacent crystals carry an aligned dislocation of less than 10°. That is why it is also referred to as *Low Angle Boundary* or *Small Angle Boundary*. It consists of several edge dislocations lying over one another on the boundary, appearing like an array of edge dislocations.

### 4.16 DEFORMATION OF METALS

The behaviour of materials under the action of applied forces is of basic interest to engineers because most of the engineering components

are supposed to be subjected to applied forces. Materials, when subjected to applied forces, undergo changes in shapes and dimensions. These changes under the action of applied forces are called **Deformations**. These changes are also produced when a material undergoes physical and chemical processes.

These *deformations* can be of two types :

1. *Temporary or Recoverable*, i.e., the one which disappears when the external forces are removed.
2. *Permanent or Non-recoverable*, i.e., the one which remains in the material even after the removal of external forces.

The *temporary or recoverable* deformation is known as **Elastic Deformation** while the *permanent or non-recoverable* deformation is called **Plastic Deformation**.

#### 4.17 ELASTIC DEFORMATION

**Elasticity** is directly related to the interatomic forces between the atoms of a solid. The chemical bonding and the structure of the solid, therefore, have a direct bearing on this property. As such, the phenomenon of **Elastic Behaviour** of a solid can be best explained with respect to its atomic arrangement.

When a metal is subjected to external loading (within elastic limits) its crystal atoms are temporarily displaced from their positions and, thus, the metal crystals are temporarily deformed. As soon as the external loads are removed the atoms revert back to their original stable positions and the crystals regain their original shapes. The direction of deformation depends upon the type and direction of application of the external forces. If tensile loads are applied the interatomic spacing in the crystals is increased, while it decreases when compressive loads are applied. However, the potential energy of atoms within the crystal increases in both the cases. This, in turn, gives rise to the forces of attraction or repulsion among the atoms, depending upon the type of external loads applied. These forces act to bring back the displaced atoms to their original equilibrium positions as soon as the applied external loads are removed. Such a deformation is called **Elastic deformation**.

Most metals, being crystalline, exhibit more plastic deformation than elastic under identical conditions because of the high stress strain ratio. Against this, in *Elastometers*, like rubber, the magnitude of elastic deformation is much larger than metals. If the elastic deformation of a material is found to obey Hooke's law, it is said to be a case of an **Ideal Elastic Deformation**.

#### 4.18 PLASTIC DEFORMATION

If such a heavy load is applied on a metal specimen that the stress in the metal exceeds the elastic limit, the metal is *deformed plastically*, i.e., even after the removal of the applied load the metal specimen does not return to its original shape and size. Every *plastic deformation* follows the *elastic deformation*, i.e., when external loads are applied on a metal piece the latter is first deformed *elastically* so long as the stress remains within the elastic limit and as soon as this limit is crossed the *plastic deformation* starts.

The crystal lattice of the metal undergoes changes during the process and, therefore, the microstructure is distorted. The process is governed by the applied stress, temperature and the strain rate. A metal can be plastically deformed under any type of stress—*tensile*, *compressive* or *torsional*. The internal changes (lattice distortions) and external changes (in shape) of a plastically deformed metal piece are non-reversible. The phenomenon of plastic deformation is widely and effectively used in several forming processes like forging, drawing, rolling, extrusion, pressing, stamping, spinning, etc. An important advantage of this process is that when a metal is plastically deformed through cold working the strength of the metal is increased.

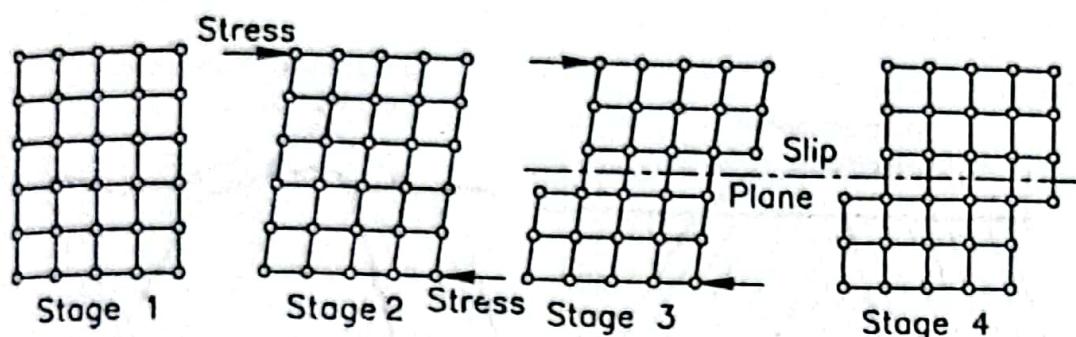
In a crystalline material the **Plastic Deformation** can occur through one of the following two mechanisms :

1. Deformation by slip,
2. Deformation by twinning.

##### Deformation by slip

It is also known as **Shear Deformation**. To explain the phenomenon let us take the example of a single crystal subjected to *shear stress*. The crystal can be considered to be composed of a number of *layers* or *slip blocks* resting over each other. When subjected to stress, these blocks or layers are displaced in relation to each other as if a part of the crystal is made to slide or glide over or along the other, as shown in Fig. 4.11.

The above layers or blocks are considered to be separated by thin layers. These layers are the most dense atomic planes and are called **Slip Planes**. In the process, the slip takes place along these planes. The most closed-packed direction within the slip plane, along which the atomic layers are displaced during slip, is known as the **Direction of slip or Slip direction**.

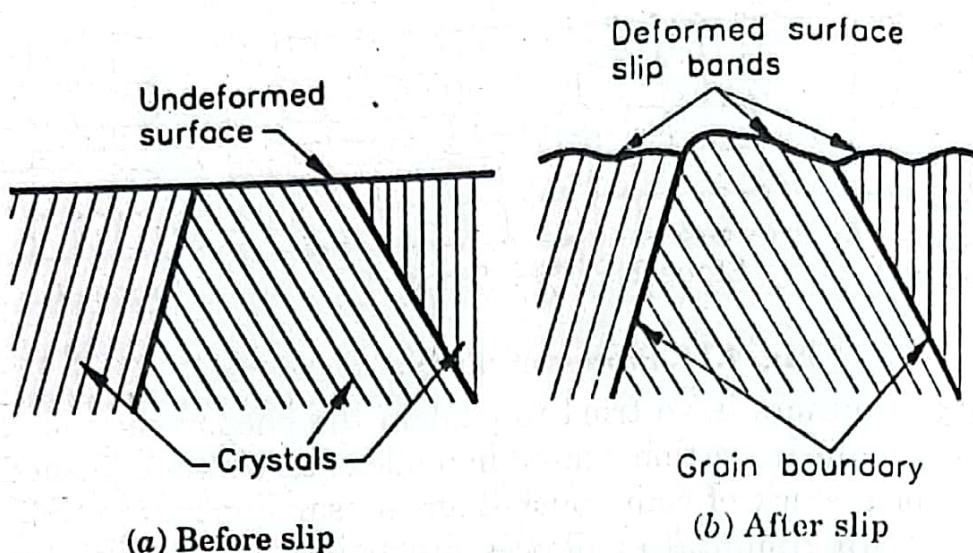


**Fig. 4.11.** Process of slip in a single crystal.

Many authors have tried to explain the phenomenon of *slip* as analogous to the distortion caused in a pile of cards when pushed from one side or a stack of coins pushed in the same manner, and so on. However, experimental evidences prove that the displacements or dislocations in the crystals are actually responsible for the planes of atoms to slip or glide along each other and not the shear stress alone. The shear stress is responsible for causing this movement of dislocations. In order that the movement of dislocations starts, i.e., deformation through slip commences, the applied *shear stress* must reach a *critical value* on the slip plane. It is then known as **Critical shear stress**. An important point to be noted here is that it is not the whole plane that slides instantaneously over the other during the process, but it is a continued series of gliding movements, one following the other. Some important features associated with the slip deformation are:

1. Slip is not confined to the sides of the crystal alone.
2. The displacement of dislocations takes place in such a manner that the displaced atomic blocks do not revert back to their original shapes and locations even after the external force is withdrawn, resulting in a permanent deformation.
3. Slip occurs along certain planes and directions, called *slip plane* and *slip direction* respectively.
4. Slip in all metals of similar crystal structure will occur along the same crystallographic planes and directions.
5. Slip will commence when the shear stress resolved along these planes will reach the critical value.

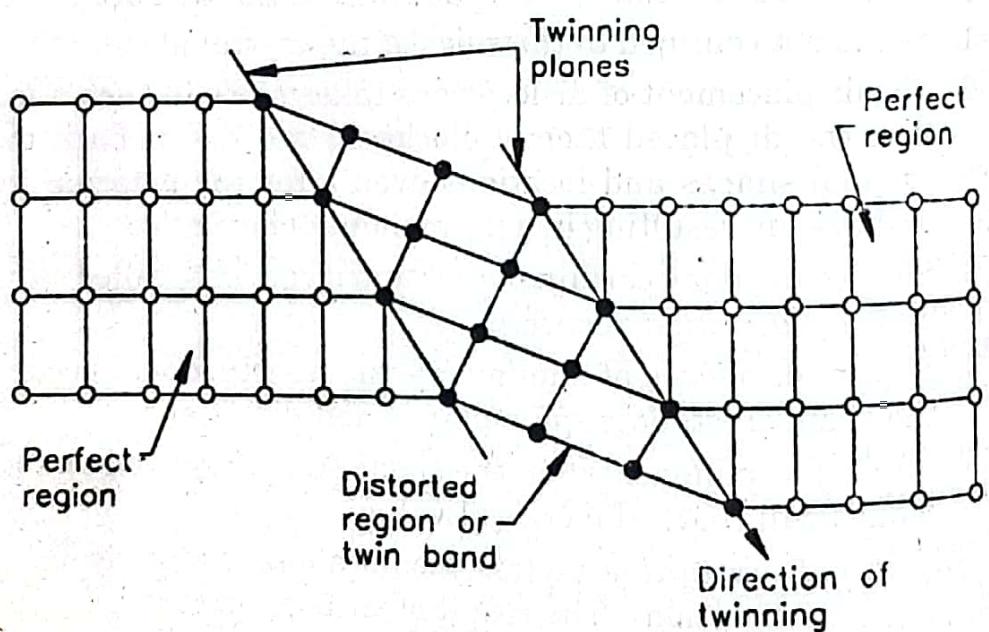
Slip in polycrystalline metals occurs along the *preferred planes* and in *preferred directions*. The result of such deformation can be seen under a microscope. The *slip bands* formed on the surface of the metal piece as a result of deformation will indicate the direction of slip planes. The *slip bands* in a crystal carry a number of parallel slip planes, which are restricted to the grain boundaries, and differ in orientation with those in other crystals, as shown in Fig. 4.12.



**Fig. 4.12.** Effects of deformation by slip and formation of slip bands

### Deformation by twinning

An alternative mechanism of plastic deformation is **Twinning** illustrated in Fig. 4.13. The two regions, called *perfect regions*, show on either side of the disturbed region, carry atoms, of which the positions are not disturbed during the process. The atoms contained between the two parallel *twinning planes* lie in the disturbed area known as *twin band* or *distorted region*. The positions of these atoms are changed as result of *Twinning*.



**Fig. 4.13.** Plastic deformation of metals by twinning.

Under this mechanism the applied stress acts along the twin plane and under the action of this stress the direction in which this plane moves is called the *direction of twinning*. This process makes the region lying between the two twin planes to shear in a homogeneous manner.

as shown in Fig. 4.13, while the two portions of the crystal, lying on either side of the twin planes, remain undistorted.

The process of plastic deformation by twinning does not occur as frequently as slip. A metal will deform by twinning normally when it can not deform by slip. The cubic metals, having **fcc**, **bcc** or **hcp** structures, deform by twinning only under special conditions, such as at low temperatures or during fast forming processes. Iron, for example, will twin when shock load (impact) is applied to it or if the applied stress nears its brittle state. Similarly, in **hcp** crystals twinning may occur when the applied stress is almost normal to the slip plane. Twinning normally occurs :

1. During mechanical deformation, called *mechanical twinning*.
2. During annealing after plastic deformation, called *annealing twinning*.

#### 4.19 DEFORMATION OF POLYCRYSTALLINE METALS

Common commercial metals are all *Poly-crystalline Aggregates* made up of an extremely large number of small (single) crystals or grains having different orientations and surrounded by grain boundaries. Consequently, the deformation in these metals is rather more complex when compared with that of a single crystal described hitherto.

When external stress is applied on these metals only such crystals tend to deform in which the slip planes have a favourable orientation with respect to the applied stress. But, on account of the different orientations of their adjoining crystals the movement of dislocations from these crystals is opposed by the adjoining grains. The main boundaries offer repulsive forces on the deformations sliding down the slip planes. These complexities restrict the transfer of stress throughout the whole mass and, therefore, a much higher amount of applied stress is required to cause a *slip*. For the same reasons, the *polycrystals* are found to be less ductile and normally stronger than single crystals.

The *grain size* of the metal also plays an important role in this regard. It is established that larger the grain boundary the higher is the pile-up of the dislocations and, therefore, more hindrance to their movement, requiring higher applied stress to cause plastic deformation. It is because of this reason that the metals with finer grains exhibit better tensile strength and mechanical properties than those having coarser grains. Some important *characteristics of Polycrystalline materials* are :

1. When loaded, various grains are found to have different orientations for slip with respect to the applied stress.
2. A number of slip planes exist within the same grain.

3. During deformation they undergo considerable structural changes.
4. Their crystals exhibit a lot of yielding and substantial permanent deformation even after elastic deformation.
5. All the crystals behave as perfectly elastic under loading.
6. Unlike single crystals they exhibit elastic after-effects, a property which plays an important role in work hardening.
7. A higher amount of applied stress is required to cause slip and, hence, plastic deformation, than that for a single crystal. Also, its value varies with the orientation of grains.

#### 4.20 CHANGES IN PROPERTIES OF METALS DUE TO DEFORMATION

The mechanical properties of polycrystalline metals undergo a number of changes due to plastic deformation. Some important changes are as follows :

##### Work hardening

It is also known as **Strain Hardening**. We have seen in the previous articles that most of the metals are polycrystalline, having grains with different orientations. Also, because of the surrounding grain boundaries, the movement of the dislocations is considerably restricted during plastic deformation. This increases the resistance of the metal to plastic deformation, *i.e.*, the *shear strain* in the metal increases. Consequently, in order that the slip should continue, *i.e.*, the movement of dislocations should continue, the *shear stress* required to move the dislocations also increases. This increase in the required shear stress is called **strain hardening** or **work hardening** and the metal is said to have been **Strain Hardened** or **Work Hardened**. Ductile materials exhibit a marked increase in their hardness and strength when subjected to plastic deformation at temperatures below the recrystallisation temperature. If plastic deformation is continued beyond the elastic limit of the metal even a small plastic deformation further causes a comparatively larger increase in strain hardening. But, if it is continued further more, the rate of strain hardening decreases and becomes almost constant until fracture takes place.

The phenomenon of strain hardening is advantageously used in several metal forming and fabrication process. It is equally used on both the pure metal as well as alloys for improving their hardness and strength through *cold working*. It also increases the rate of chemical action. However, the ductility, plasticity and electrical conductivity of the metal are reduced as a result of work hardening.

### Season Cracking

It is also known as **Stress Corrosion** or **Stress Cracking**. It is a cumulative effect of corrosive environment and static tensile stresses on the metal. This effect is more predominant in copper alloys, mainly brasses, although pure copper is not susceptible to this effect. However, small additions of elements like zinc, arsenic, silicon, phosphorus, aluminium, antimony, etc., to copper render the latter susceptible to this effect. Out of these, zinc has the most telling effect in increasing the susceptibility of copper alloys, specially brass, to *stress corrosion*. Higher the amount of zinc in brass higher is its sensitivity to stress corrosion.

The effect is clearly seen in cold worked brass components when subjected to corrosive atmosphere, like that of ammonia or sea water. Under such conditions the cold worked brass components may develop cracks and this is called **Season Cracking**. However, this effect can be minimised by annealing the cold worked components at low temperatures of the order of 200°C to 300°C.

### Bauschinger effect

If a metal is plasticity deformed, its yield strength is found to be increasing in the direction of plastic flow during the deformation. When the deforming forces are removed, the metal is left with permanent *residual stresses*. Now, if the deforming stress is applied in the reverse direction, the previously left over residual stresses help the dislocations to move more easily in this reverse direction. With the result the plastic deformation starts at a lower yield stress than that in the previous deformation. This phenomenon of reduction in the yield stress during the plastic deformation in the reverse direction is called **Bauschinger Effect**.

### Strain ageing

If an alloy is overstrained, in order to remove the yield point, and is allowed to *rest* after plastic deformation it is found that the yield point returns with a higher stress when the alloy is reworked. This is called **Strain Ageing** and it has a *hardening* effect on the metal. The hardening is due to the increase in stress value. This effect can be easily noticed in commercial iron and steel. The creep and fatigue behaviour of many metals is greatly affected by this phenomenon. *Strain ageing* is also known as *Strain Age Hardening*.

### Preferred orientation

It has been seen in the foregoing articles that the grains of a polycrystalline material have random orientations. In cold working,

specially in those processes where severe plastic deformation takes place, e.g., in cold rolling or wire drawing, the metal grains tend to orient or align themselves in such a manner that they possess a common axial direction, thereby doing away with their usual random orientation. This condition of non-random or common axial directional alignment or orientation of crystals in polycrystalline materials is known as **Preferred Orientation**.

Under this condition certain crystallographic planes, consequent upon the severe plastic deformation of the metal, are found to align themselves in a preferred number with regard to the direction of maximum strain. The resulting preferred orientation largely depends upon the slip and twinning systems. Metals having grains with preferred orientation will exhibit greater strength and magnetic permeability but will show a negative effect, called **Anisotropy**, in their mechanical properties, i.e., they will show different mechanical properties in different directions. Preferred orientations will also result in reduction of ductility in semifinished products.

#### **4.21 RECOVERY, RECRYSTALLISATION AND GRAIN GROWTH**

In the earlier articles, we have discussed the mechanisms of plastic deformation through slip and twinning and the effects of cold working on the properties of the deformed metal. It has been seen that as a result of cold working the ductility and plasticity of the metal are reduced while its hardness, electrical resistance, ultimate strength and yield strength are increased. Also, it was seen that due to plastic deformation the structure of the crystal lattice breaks up, the number of dislocations increases and many planes in the crystal structure get distorted. This renders the cold worked metals thermodynamically unstable. It is, therefore, necessary to bring back the metal to approximately the same state in which it was before deformation. This is achieved through a heat treatment process, called **Annealing**, through which the deformed metal is reheated to make the metal return back to almost the same equilibrium state as was existing prior to deformation and, thus, restores the original properties changed during deformation. As the temperature of the metal is gradually raised through reheating it passes through the following three stages while restoring the lost equilibrium :

1. Recovery
2. Recrystallisation
3. Grain growth.

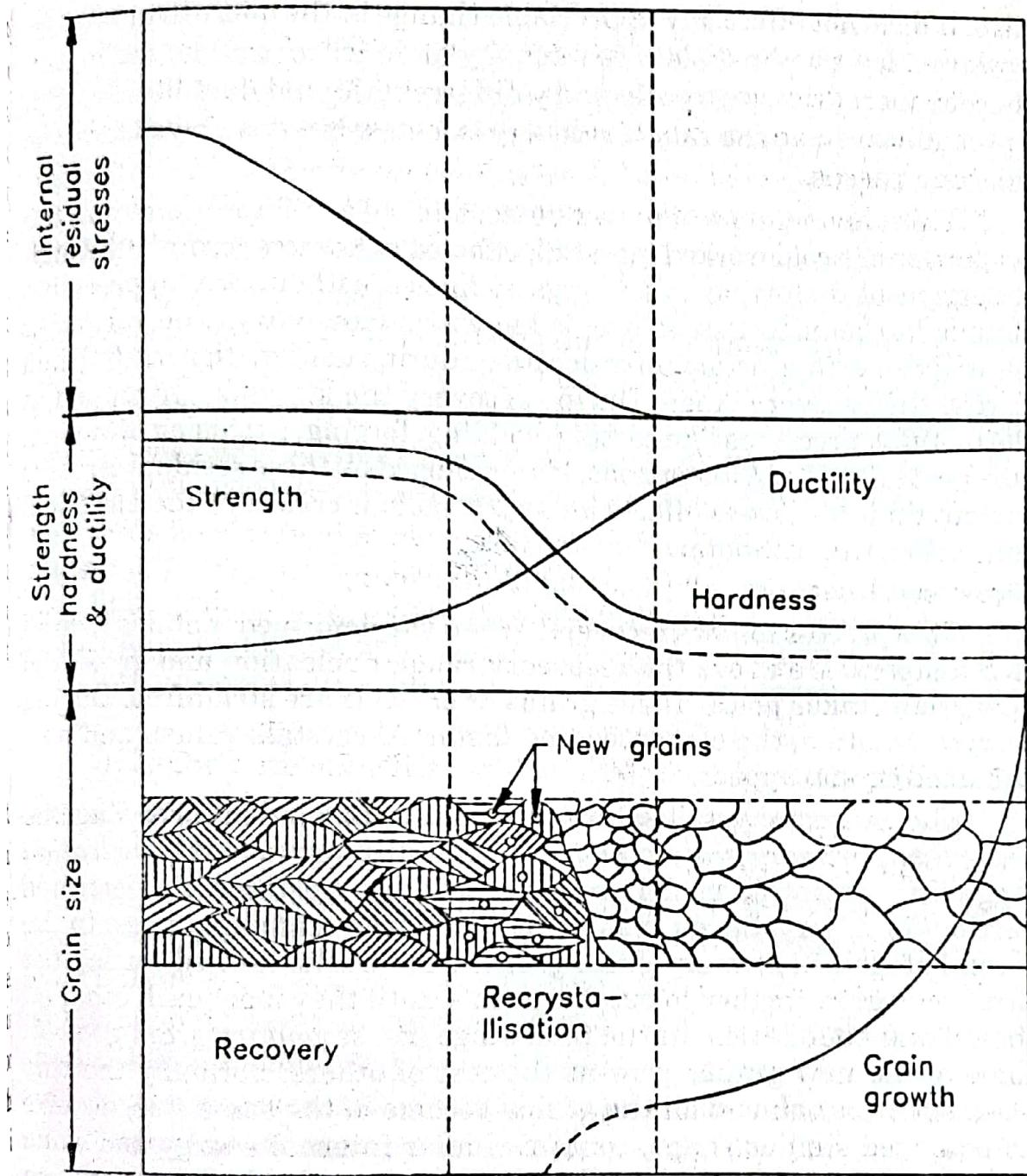


Fig. 4.14. Recovery, recrystallisation and grain growth and the corresponding changes in properties.

These three stages are shown by means of a schematic diagram in Fig. 4.14, which also shows the corresponding effects on the properties of the metal.

#### Recovery

This stage, being the first stage, involving low temperatures, mainly helps in relieving the internal stresses caused in the metal during cold working. Since this change occurs before recrystallisation, the grain growth is not affected by it. Together with stress relieving it does modify some other properties like hardness and strength also, but its effect on these properties is too small when compared to that by recrystallisation.

Also, it does not effect any appreciable change in the microstructure. It, however, lowers the dislocation density and, hence, softens the metal, thereby increasing its tensile and yield strengths and ductility slightly. In the initial stage the rate of recovery is fastest but it is slowed down as the time passes.

This phenomenon of partial restoration of and improvement in the properties of a cold worked material, effected at low temperature through reduction of distortion in the crystal lattice without any appreciable change in the misconstruction, is known as **Recovery**. The vacancies created due to interactions of dislocations during deformation are finished during the recovery stage. During recovery the stresses, entrapped in the metal in processes like casting, welding, forging, extrusion, drawing, etc., are relieved and distortions, if any, caused by these residual stresses are minimised. It also effects an appreciable increase in the electrical conductivity of the metal.

### Recrystallisation

This process follows recovery. When the deformed metal is heated to a temperature above the recovery range nucleation and growth of new grains takes place. These grains or crystals are strainfree. During recrystallisation, the elongated and distorted crystals vanish and new equiaxed crystal appear.

The entire recrystallisation process is completed in three stages—*nucleation, primary grain growth and secondary growth*. In *nucleation* stage tiny strainfree nuclei are formed at the most heavily deformed portions of the crystal, such as grain boundaries and slip planes. In the second stage i.e., *primary grain growth*, the nuclei formed during the first stage grow further to become grains until they meet each other on their grain boundaries. In the final stage, i.e. *secondary grain growth*, some of the new grains grow at the cost of others, normally the tiny ones, such that almost all the grains become of the same size, acquire an equiaxed similar shape, contain similar internal energy and same boundary. It is also found that if heating is prolonged at high temperature abnormal growth of some grains may occur. This, if happens, is called *Secondary Recrystallisation*. This makes the grain size and, hence, the physical properties of metal non-uniform. It is, therefore, considered to be a negative development.

An important point to be noted regarding recrystallisation is that the energy of the metal is reduced during the process and, therefore, the factor responsible for causing recrystallisation is the strain energy of the dislocation. Accordingly, therefore, the heavily cold worked materials recrystallise at higher rates than those which are less severely cold worked. The rate of recrystallisation is also governed by time, temperature and those factors which affect the dislocation movement like impurities and grain size.

### Grain Growth

The last stage in annealing of a work-hardened metal, following recrystallisation, is *grain growth*. As the metal is heated above the recrystallisation temperature range the size of the crystallised grains increases. As the temperature rises, some of the equiaxed grains formed during recrystallisation are absorbed by other neighbouring grains, leading to the increase in sizes of the latter. This is called *grain growth*.

During the process of grain growth the smaller grains become still smaller and are finally absorbed by the larger ones. Thus, the smaller ones disappear and the larger ones become still larger. As a result of grain growth the energy of the metal is lowered because of the surface energy being associated with the grain boundaries. Also, because of the impeding of dislocation slip by grain boundaries some softening of metal also takes place during grain growth. During the process the metal also suffers a loss of strength and hardness, but there is a gain in ductility. The final grain size is more a function of temperature than time. The appearance of the external surface of the metal is affected by the grain size. The process of grain growth is dependent on the following factors :

1. *Annealing time.* There is a rapid growth initially but slows down as the time prolongs.
2. *Annealing temperature.* The grain size increases with the increase in temperature.
3. *Amount of initial deformation.* Heavy deformation will lead to the growth of smaller grains and light deformation to large size grains.
4. *Rate of heating.* Slow heating will promote grain growth and enable formation of coarse grains.
5. *Alloying elements.* Some alloying elements, like nickel, have a marked effect on grain growth.
6. *Insoluble impurities.* The grain size will be directly affected by the amount and distribution of such impurities in the metal. Larger the amount and finer the distribution, finer will be grain size.

### 4.22 FRACTURE

Separation of a solid body under stress into two or more parts is called **Fracture**. It is caused by either physical or chemical forces and new surfaces are generated after fracture. Any type of fracture will consist of two main components, i.e., **Crack Initiation** and **Crack Propagation**. Four types of *fractures* are commonly recognised. They are :

1. Brittle fracture

2. Ductile fracture
3. Fatigue fracture
4. Creep fracture.

The type of fracture occurring in a body depends upon the rate of loading, type of stress applied, nature of material and temperature. Of the above four types the ***Brittle Fracture*** occurs when a small crack in a body grows very rapidly after little or no plastic deformation. The ***Ductile Fracture*** occurs after heavy plastic deformation by slow propagation of the crack. The ***Fatigue Fracture*** occurs on account of the fluctuating stresses whereas the ***Creep Fracture*** occurs under constant stress at high temperature.

### **Brittle fracture**

It occurs when a small crack in a material grows at a very rapid rate with minimum absorption of energy. It may, if at all, be preceded by very negligible or no plastic deformation. In this type of fracture the adjacent parts of an object are separated by the stresses acting at right angles to the fractured surface. Such fractures are commonly found in **bcc** and **hcp** metals but not in **fcc** metals. In crystalline materials this fracture occurs along crystallographic planes, i.e., planes with lesser interatomic bonds. These planes are called **Cleavage Planes** and the corresponding fracture **Cleavage Fracture**. The chances of brittle fracture increase with the increase in stress concentration, increase in strain rate and a decrease in temperature. It, however, always occurs below or at the elastic limit of a material. Since it occurs suddenly it may prove hazardous.

### **Ductile fracture**

Heavy plastic deformation prior to and during the propagation of crack in a material leads to **Ductile Fracture**. It takes place in three successive stages. It can be physically seen while performing a tensile test on a specimen of a ductile material. As the load is applied, the plastic deformation is concentrated around the centre of the specimen and a neck is formed at the centre. This is the *first stage*, in which a *triaxial state of stress* is created by the neck formation and very minute cavities are formed in the necked region. In the *second stage*, due to continued straining of the material, the cavities coalesce to form a tiny crack at the centre of the specimen, which extends in a plane almost perpendicular to the direction of applied stress. In the *final stage* the crack propagates (spreads) outwards, i.e., towards the surface of the material, at an angle of  $45^\circ$  to the tensile axis, till it reaches the surface. Because of this mode of propagation of the crack the fractured ends of the specimen acquire a 'cup and cone' shape. This type of fracture involves the expenditure of a considerable amount of energy but is not very dangerous.

### Fatigue fracture

When a metal part or structure fails under repetitive or fluctuating loading or stress which is much smaller than that required to cause the fracture in a single application the failure is termed as **Fatigue Fracture**. It occurs under the conditions of dynamic loading. Due to repetitive loading there is some dislocation movement at the point of stress concentration in the metal part and a minute crack is developed. With every future cycle of loading this crack grows and propagates, leading ultimately to a *Brittle Fracture*.

However, the nature and rate of propagation of crack will depend on the brittleness of the material. In ductile materials the crack grows slowly till such time as the remaining part of the material is able to support the load. Till that time the failure will not occur, but as soon as that limit is crossed the material fractures abruptly in a brittle manner. In a brittle material the crack rapidly grows to a critical size and then propagates through the entire material quickly to lead to a brittle fracture. Thus, we conclude that in either case the ultimate nature of fatigue failure is that of a brittle fracture.

### Creep fracture

The term **Creep Failure** or **Creep Fracture** refers to the failure of components under high temperatures and stress conditions. In several engineering applications different types of materials are subjected to steady loads for a pretty long time. A few examples of such cases are the pressure vessels used in high temperature chemical processes, telephone cables, turbine blades, furnace parts, etc. In such conditions the material continues to gradually deform till such time as it loses its usefulness. Such deformations in due course of time can grow to a very critical state so as to fail the component even through fracture without any additional loading. Such failures are known as **Creep Fractures**.

## 4.23 METAL ALLOYS

Pure metals are very rarely used in engineering work because of their inherent shortcomings in respect of their physical and mechanical properties. For example, *copper* is a good conductor of electricity but is weak. To make it strong some other metal is required to be added to it. Same is the case with *aluminium*, which is both weak and soft in its purest form. Similarly, *iron* too. So, in order to make these metals suitable for engineering use some other materials are added to them to form an **Alloy**.

An **Alloy** can be described as a substance which carries metallic properties and is made up of two or more elements, of which at least one

is essentially a metal. The metal that is present in the alloy in greatest proportion is termed as **Base Metal**. All other elements present in the alloy, whether metallic or non-metallic, can be considered as *foreign materials*. Those *foreign materials* which are intentionally added to the base metal in order to obtain certain desirable properties, in which the base metal is found lacking, are termed as **Alloying Elements**. Those undesirable elements which are either added accidentally during alloying process or are carried by the base metal due to imperfect smelting or refining operations are known as **Impurities**.

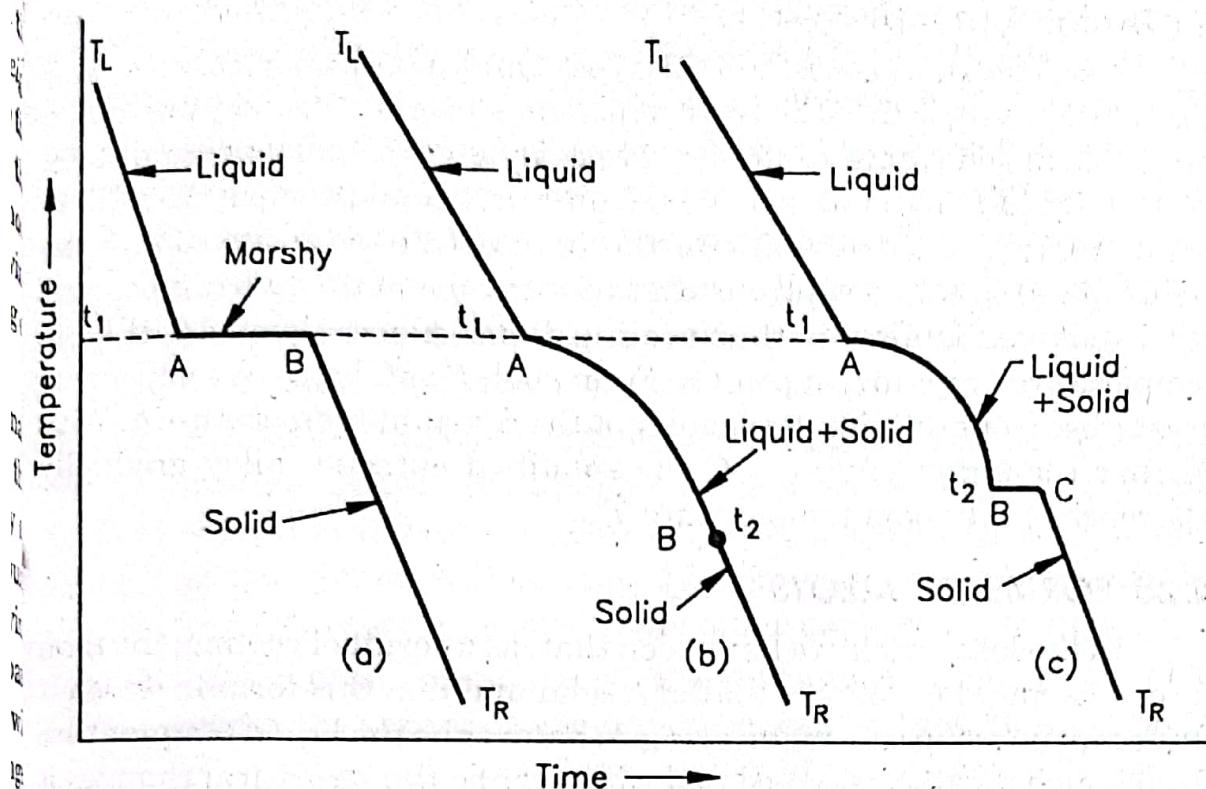
Addition of alloying elements to a base metal, whether in small proportions or high proportions, leads to significant changes in the properties of the base metal. The ultimate properties of the alloy so formed will depend upon the resulting structure of the alloy on account of the addition of alloying elements. The fact as to whether the alloying elements in an alloy are completely soluble or insoluble in the base metal or whether they form a completely new base with the same will determine the change of properties and the extent to which these changes occur.

A *pure metal* is comprised of a single substance whereas an alloy contains more than one constituents. Each of these constituents is known as a *component*. Therefore, a pure metal consists of a *single component* whereas an alloy can be *binary* (two-components) or *ternary* (three-components), etc.

#### 4.24 SOLIDIFICATION OF METALS AND ALLOYS AND COOLING CURVES

A **Cooling Curve** is a graph which shows the variation in temperature with time as a material is cooled down from its liquid phase. It also indicates the temperatures at which the phase changes in a metal or alloy system take place as they are cooled from their liquid phases. It helps in studying the structural changes which occur during solidification of metals and alloys. Equilibrium or phase diagrams are constructed with the help of these cooling curves.

When a metal or alloy is cooled down from its fusion state latent heat is evolved because of the changes taking place in the structure of the metal or alloy during solidification. On account of this, some stages occur during cooling at which it is observed that the uniform rate of fall in temperature is checked for a certain period. This specific point where the check occurs is known as **Critical Point**. To elaborate the above statements further let us consider the three cooling curves shown in Fig. 4.15.



**Fig. 4.15.** Cooling curves for (a) Pure metal or compound, (b) Binary alloy or solid solution, and (c) Binary eutectic system or partially miscible solid solution.

#### (a) Cooling Curve for pure metal

The liquid metal cools down from its liquid state (say, temperature  $T_L$ ), to temperature  $t_1$  (point A). At this point, called the **Critical point**, solidification starts and continues upto point B, where the metal becomes fully solid. From point A to B the temperature remains constant and latent heat is evolved. During this period the metal is in a marshy state, i.e., partly liquid and partly solid. As the metal is further cooled below point B it approaches the room temperature ( $T_R$ ). The specific heats of liquid and solid metal will determine the slopes of the lines  $T_L - A$  and  $B - T_R$  respectively.

#### (b) Binary Solid Solution

The initial portion of the cooling curve ( $T_L - A$ ) for a binary solid solution, i.e., two metals forming a *solid solution*, is exactly similar to that of the pure metal. But, during solidification from point A to B, i.e., as the temperature changes from  $t_1$  to  $t_2$ , there is a continuous fall of temperature, unlike in pure metal where it was constant during this stage. At point B the complete mass becomes solid. As cooling continues below point B (temp.  $t_2$ ) the solidified metal approaches the room temperature ( $T_R$ ).

### (c) Binary Eutectic System

A specific characteristic of this type of multiphase alloy, called *Binary Eutectic System*, is that the two components forming the alloy are totally insoluble in solid state while they are completely soluble in liquid state. As the liquid alloy is cooled down from some liquid temperature  $T_L$  to point A (temp.  $t_1$ ) it remains in the liquid state only. At point A the uniform fall in temperature is checked and one of the two components starts crystallising. Further cooling takes place along AB till the temperature drops to  $t_2$  at point B. From point B or C both the components crystallise (solidify) simultaneously at the constant temperature  $t_2$ . With further cooling below point C the solidified eutectic alloy gradually approaches the room temperature  $T_R$ .

## 4.25 FORMS OF ALLOYS

In the last article we have seen that, as a result of cooling, the final form of a metal or alloy is that of a solid and it is this form in which it finds maximum use in engineering. Whatever be the liquid temperature from which an alloy is cooled and whatever be the structural changes it undergoes during cooling, a solidified alloy may exist in the following forms :

1. **As a Solid Solution.** In which the atoms of the alloying elements have dissolved in the atoms of the base metal to form a homogeneous chemical solution, called the *solid solution*.
2. **As an Intermetallic Compound.** In which the atoms of the alloying elements have formed a chemical compound with the base metal to produce an *intermetallic compound*.
3. **As a Mechanical Mixture.** In which the atoms of the alloying elements could not chemically dissolve in the atoms of the base metal, producing a finely divided *mechanical mixture* of different metals.
4. **As a combination** of two or all of the above forms.

## 4.26 SOME IMPORTANT TERMS

The following important terms will be frequently used in our further studies of alloys and their phases and, therefore, it is necessary to understand these terms at this stage :

1. **System.** A *system* may be conceived as the entire domain of phases of a substance or substances (called *components*), which is unaffected by its surroundings and can undergo changes in composition, pressure, temperature, volume, etc., to the extent it is desired. It may consist of metals and non-metals either in a desired combination or separately. Also, it may be composed of solids, liquids, gases or their combinations.

2. **Component.** A **Component** is a substance whose presence is necessary to build a system. This substance, or substances, may be either a chemical element(s) or a chemical compound (s). If a system is composed of a single substance, as in pure metal, it is called a **One-component system**. If it is composed of two substances it is called a **Binary** or **Two-component System**, three substances then a **Ternary** or **Three-component system**, **Four-components** then a **Quartenary system**, and so on, in case of alloy systems.
3. **Phase.** A **Phase** is a distinct part of a system which is physically and chemically homogeneous. A surface and an interface separates it from the other parts of the system. Each such part of the system will possess different composition and different properties with respect to the other parts of the system.
4. **Structural Constituent.** From the microscopic study of the microstructure of an alloy it will be seen that the different phases of an alloy are not always uniformly distributed through its structure. The distinct fashion in which these phases associate themselves to form the structure is termed as the **Structural Constituent** of the alloy.
5. **Equilibrium.** A system is said to be in *equilibrium* if the changes occurring in a system due to a process that proceeds in one direction are fully offset by the changes which occur when the process is reversed, i.e., a dynamic condition of balancing exists and the resulting change in the process is zero.

#### 4.27 SOLID SOLUTIONS

As already explained in the foregoing articles, pure metals are very rarely used in engineering practice. So, in order to obtain desired properties, other elements are added to the base metal to form an alloy. When the atoms of the base metal and the alloying elements completely dissolve in each other and become an integral part of the solid phase of the alloy, the resulting phase is called a **Solid Solution**.

The different types of atoms of the constituents of an alloy in *solid solution* become chemically homogeneous and physically unseparable and form a common crystal lattice. The constituent, whose lattice is retained, is called **Solvent** and all other constituents as **Solutes**. The solid solutions formed are of two types :

1. Substitutional
2. Interstitial.

#### 4.28 SUBSTITUTIONAL SOLID SOLUTION

In this type of *solid solution* the atoms of the solute metal take up the positions of atoms of the solvent in the lattice structure of the latter, but these positions can be occupied either in an *ordered* or *disordered* manner depending on the size of the atoms of the solute metal. If the sizes of the solute and solvent atoms are same or nearly same the atoms of the solute metal occupy the lattice points in the solvent crystal structure, earlier occupied by the atoms of the solvent metal i.e., they replace the solvent atoms. When this replacement is in an orderly manner the solid solution is called ***Ordered Substitution Solid Solution*** as shown in Fig. 4.16. Copper and zinc and copper and nickel are the examples of metals which form substitution solid solutions readily. Such solutions are commonly formed at lower temperatures rather than higher.

The ***Disordered Substitution Solid Solution*** is formed when the atoms of the solute metal do not replace the atoms of the solvent in the lattice structure of the latter in any specific order, rather they occupy the positions of the solvent atoms in a random or disorderly manner, as shown in Fig. 4.17. Obviously, the distribution and concentration of the solute atoms in the lattice structure will vary considerably.

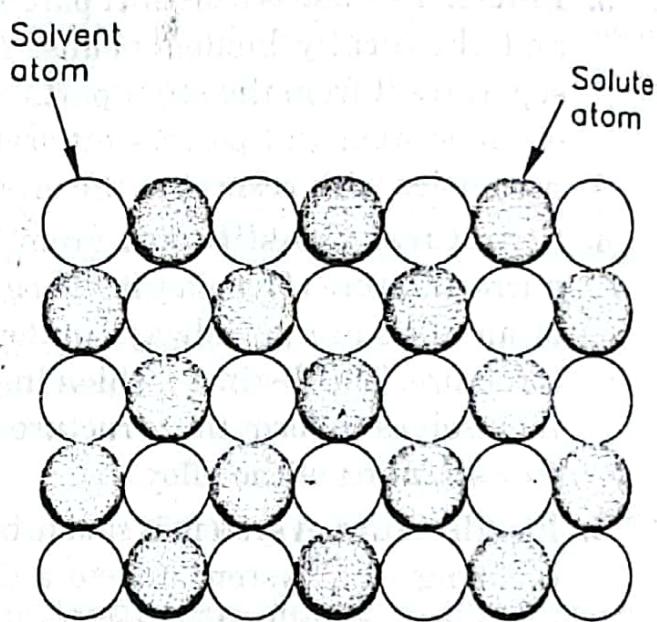


Fig. 4.16. Ordered substitution solid solution.

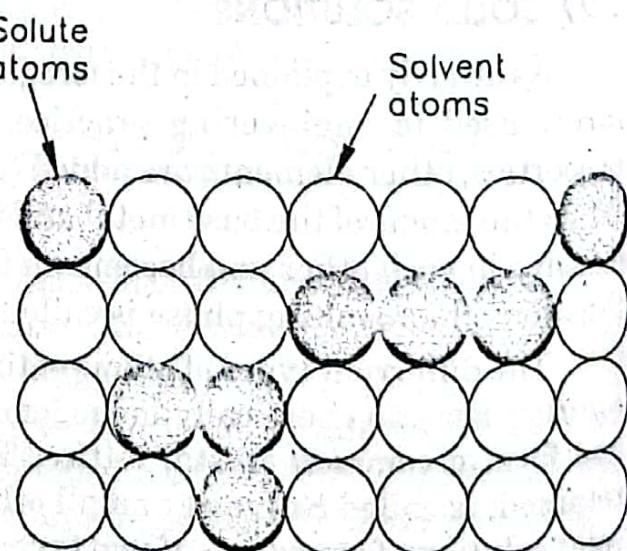


Fig. 4.17. Disordered substitution solid solution.

### 4.29 INTERSTITIAL SOLID SOLUTION

When the atoms of the *solute* metal are much smaller than the atoms of the *solvent*, such that they are incapable of replacing the latter because of the size difference, they enter into and occupy their positions in the empty spaces (called *interstices*) in the crystal lattice of the solvent metal and the resulting solid solution is known as as **Interstitial solid solution**, as shown in Fig. 4.18. The other factor which influences the formation of this type of solid solution is that the small solute atoms dissolve much more quickly in the solvent like iron, nickel, chromium, manganese, etc. An adverse characteristic associated with *interstitial* solid solutions is their limited solubility and that is why these solid-solutions are considered to be of secondary importance.

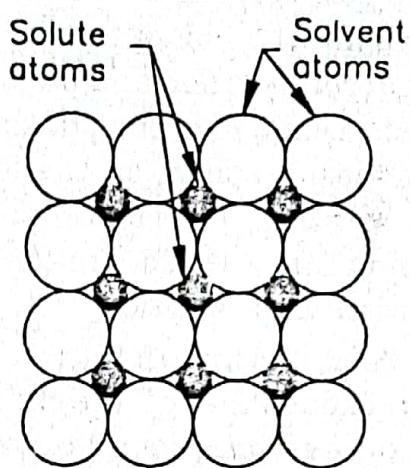


Fig. 4.18. Interstitial solid solution.

### 4.30 INTERMETALLIC COMPOUNDS

**Intermetallic Compounds** can be formed between metals and non-metals. We have seen above that size of the atoms of solute and solvent have a marked effect on the range and solubility of the two metals. But the electron atom ratio of the alloy constituents, which depends on the valencies and electronegativities of the constituents, also effects the range and solubility of the metals considerably. This factor leads to the formation of **Intermetallic Compounds**, which are formed without following the common valency rules.

These compounds are not truly chemical compounds but ordered crystal lattices of the alloy. The crystal structures of these compounds are different than those of the alloy constituents. Also, they possess specific physical and mechanical properties of their own. Their melting points are found to be usually higher than those of the basic constituents. They are generally very hard and brittle.

### 4.31 MECHANICAL MIXTURES

A **Mechanical Mixture** results in the solid state when an alloy consisting of such constituents, which are completely insoluble in each other, is solidified. When the liquid solution of such an alloy is cooled the crystals of its constituents separate themselves from one another and form a finely divided *mechanical mixture*, called the **Eutectic**.

**Mixture.** The mechanical properties and the structural identities of the constituent elements are retained as they were in the mechanical mixtures formed by them.

### 4.32 PHASES OF AN ALLOY

As already described in Art. 4.26, a **Phase** of an alloy is a physically and chemically homogeneous part of an alloy system possessing its own distinct composition and physical and chemical properties. Therefore, if there is a change in the phase there will be corresponding change in the properties. As such, all the forms in which a solid alloy can exist, i.e., solid solution, intermetallic compounds, a mechanical mixture or combination of these, are termed as different *phases*, each carrying its own distinct properties.

Also, it is known that an alloy system may consist of several phases. It is reckoned that all the changes which occur in a system on account of the *external conditions*, i.e., pressure and temperature, are in accordance with the *phase rule*. It establishes the maximum number of phases which can exist in an alloy system under equilibrium in given conditions. Mathematically it is expressed thus :

$$P = C + 2 - F$$

where

$P$  = max. number of phases which can co-exist.

$C$  = the number of components.

$2$  = the no. of external factors (pressure and temperature).

and,

$F$  = the no. of degrees of freedom depending upon the internal and external factors.

When this rule is applied to metals the effect of pressure is considered negligible. Hence, only one external factor (temperature) remains, reducing the above equation to :

$$P = C + 1 - F$$

Under equilibrium conditions the degrees of freedom cannot be less than zero because all the factors will possess definite values. Therefore :

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

or

$$P \leq C + 1$$

*Therefore, we conclude that the maximum number of phases in a system under equilibrium can never exceed the number of components plus one.*

What follows from this is that in a binary system a maximum number of three phases, in a ternary system four phases, and so on, can be in equilibrium.

### 4.33 PHASE DIAGRAMS

They are also known as **Equilibrium Diagrams** or **Constitution Diagrams**. These diagrams represent graphically the changes occurring in the state of an alloy on account of the changes in temperature and concentration. It also enables the determination of the phase content of an alloy at any composition and temperature. They are known as **Constitution Diagrams** because they indicate the constitution and nature of alloys and the composition of phases in a given system. The term **Equilibrium Diagrams** is used for these diagrams because they fully incorporate the phase transformations of an alloy that occur while heating or cooling the latter under equilibrium conditions, i.e., the processes used being reversible.

These diagrams are constructed by using the data from the cooling curves with temperature as *ordinate* and percentage composition of the constituents as *abscissa*. These diagrams indicate the temperatures at which a solid metal or alloy will start and finish melting and the possible changes in the phases which will occur due to variation in the composition and temperature. These diagrams help in controlling and studying the metallurgical processes, such as solidification of metals and alloys, crystallisation and grain growth, separation of phases and the structural changes occurring in different processes like forging, welding, casting, heat treatment, etc. There are three types of phase diagrams :

1. *Uniary*, i.e., having a single component.
2. *Binary*, i.e., having two components.
3. *Ternary*, i.e., having three components.

However, out of the above three, the **Binary Diagrams** are in maximum use because the most commonly used alloys are two-component alloys.

### 4.34 PHASE TRANSFORMATIONS

Through the discussions in the foregoing articles it must have been quite clear that most of the materials, especially metals and alloys, are in molten state at some stage during their processing. When a metal or alloy solidifies, during cooling from the liquid state, grain formation takes place. The rate and manner of cooling for solidification effects the microstructure of the metal or alloy being solidified. By controlling the rate and manner of cooling the process of solidification can be controlled and, hence, the resulting microstructure. Use of this phenomenon is, therefore, taken in various processes like casting, heat treatment, metal forming, etc., for controlling the microstructure and properties of the metal or alloy under process.

Each metal or alloy undergoes change from one phase to another in metallurgical processes. It is known as **Transformation of Phase**. The structure of the metal is controlled by intentionally putting a check on or skipping over a likely transformation of phase. The rate of cooling a metal from its liquid state can be extremely slow, slow, normal, *fast* or *extremely fast*. This rate of cooling, will effect and control the time allowed for a transformation to occur. Slower the rate of cooling more will be the time allowed to a transformation to take place. Faster the rate of cooling lesser will be the time allowed for the change to take place.

#### 4.35 PHASE TRANSFORMATIONS IN IRON-CARBON SYSTEMS

In all modern industries the most excessively used materials are iron and steel. A study of **Iron-Carbon-System** is, therefore, very important to have a good knowledge of ferrous metallurgy. The *Iron-Carbon System* is mainly based on the principles of phase transformations in metals already described. During manufacture of iron, when it is cooled from liquid state to solid state in casting of ingots, phase transformations take place. Such phase transformations again occur when pig iron, along with other constituents, is remelted in cupola and cast in moulds. Similarly, in heat treatment process also phase transformations take place and crystal structure of metal changes, enabling the metal undergoing heat treatment to achieve different mechanical properties. Metal iron is the basic constituent of an iron-carbon system, which forms an alloy with carbon as an alloying element and the main alloys produced as a result of this are the *steels* and *cast irons*. Steels may carry the carbon content to a maximum of 2% and cast irons above 2%.

#### 4.36 PRINCIPAL MICRO-CONSTITUENTS OF AN IRON-CARBON SYSTEM

A study of an **Iron-carbon Equilibrium Diagram**, discussed later in this chapter, will reveal that it is applicable under slow cooling conditions only. However, if an iron alloy is heated to a temperature above the austenitic temperature, *i.e.*, when it attains the liquid phase and then allowed to cool at different rates of cooling, the austenite decomposes to produce different types of constituents of iron and steel. These are called **Micro-constituents** because they can be observed only through a microscope. The main, micro-constituents of this system are :

- 1. Austenite.** The solid solution of ferrite and iron carbide in gamma iron is known as *austenite*. The solid solution is formed in steels carrying carbon to a maximum of 1.8%, at 1130°C. It is a soft and non-magnetic substance and when cooled below 723°C it changes into *Pearlite* and *Ferrite*.
- 2. Ferrite.** It is a BCC phase of iron in which only a very limited amount of carbon can be dissolved. It is the purest form of iron.

and is very soft and ductile but highly magnetic. This type of microstructure is obtained when low carbon steel is cooled slowly below the critical temperature. Even a rapid cooling will not render this constituent hard.

3. **Cementite ( $\text{Fe}_3\text{C}$ )**. It is a very hard and brittle interstitial compound formed between iron and carbon. It has a high compressive strength, low tensile strength and is magnetic below  $200^\circ\text{C}$ . It increases with the increase in carbon percentage and is significantly present in steels carrying above 0.8% carbon.
4. **Ledeburite**. An eutectic mixture of ferrite and cementite is known as *Ledeburite*. It is formed at around  $1130^\circ\text{C}$  and carries 4.3% carbon.
5. **Pearlite**. It is a mechanical mixture of ferrite and cementite, the former being 87% and the latter 13%, and is produced by decomposition of austenite through an eutectic reaction. It carries alternate layers of ferrite and cementite. Steel with 0.8 percent carbon carries a fully pearlitic structure, with below 0.8% carbon it is *Hypoeutectoid* and with more than 0.8% it is *Hypereutectoid*.
6. **Bainite**. It is formed by isothermal decomposition of austenite in alloy steels. When this decomposition takes place at a temperature above that at which martensite is formed the resulting bainite is known as *Upper Bainite* and when it occurs below the temperature at which pearlite is formed the bainite formed is called *Lower Bainite*.
7. **Martensite**. It has a fine needle-like fibrous structure and is very hard and brittle. It results due to the formation of an interstitial solid solution of carbon in  $\alpha$ -iron. The main constituent in a hardened steel, to which it owes its hardness, is martensite. It is a magnetic substance.
8. **Troostite**. Like pearlite, it is also a mixture of radial lamellae of ferrite and cementite, but it differs from the former in respect of the degree of fineness and the amount of carbon content present in it. It will carry the same amount of carbon as contained by the austenite from which it is formed. During heat treatment of steel, if martensite is tempered by heating below  $450^\circ\text{C}$  a microstructure is produced by quenching, called *Troostite*, which consists of ferrite and finely divided cementite. It is softer and less brittle than martensite and is less susceptible to cracking and distortion.
9. **Sorbite**. This microstructure also consists of ferrite and finely divided cementite, but is obtained while tempering the martensite above  $45^\circ\text{C}$ . It very much resembles pearlite and is,

therefore, also-known as *Sorbitic Pearlite*. It is obtained when for tempering the martensite the rate of cooling is faster than that required for obtaining pearlitic structure and slower than that required for producing troostitic structure. Its mechanical properties lie in between those of troostite and pearlite.

#### 4.37 ALLOTROPIC FORMS OF IRON

Iron, which is a soft and ductile metal, has a melting point of  $1539^{\circ}\text{C}$ . It is an allotropic metal i.e., it acquires different lattice structures at different temperatures. Its main allotropic forms are delta ( $\delta$ ), gamma ( $\gamma$ ) and alpha ( $\alpha$ ). **Cooling Curve** of pure molten iron is shown in Fig. 4.19. Above  $1539^{\circ}\text{C}$  iron is in liquid state. As it is cooled down from liquid state freezing starts at  $1539^{\circ}\text{C}$  and heat is evolved. There is no further fall in temperature but heat continues to evolve and also the transformation of phase till such time as the entire liquid iron solidifies and is changed to  $\delta$  form having BCC structure. This *Constant Temperature Transformation* is represented by the horizontal line on the cooling curve at  $1539^{\circ}\text{C}$ .

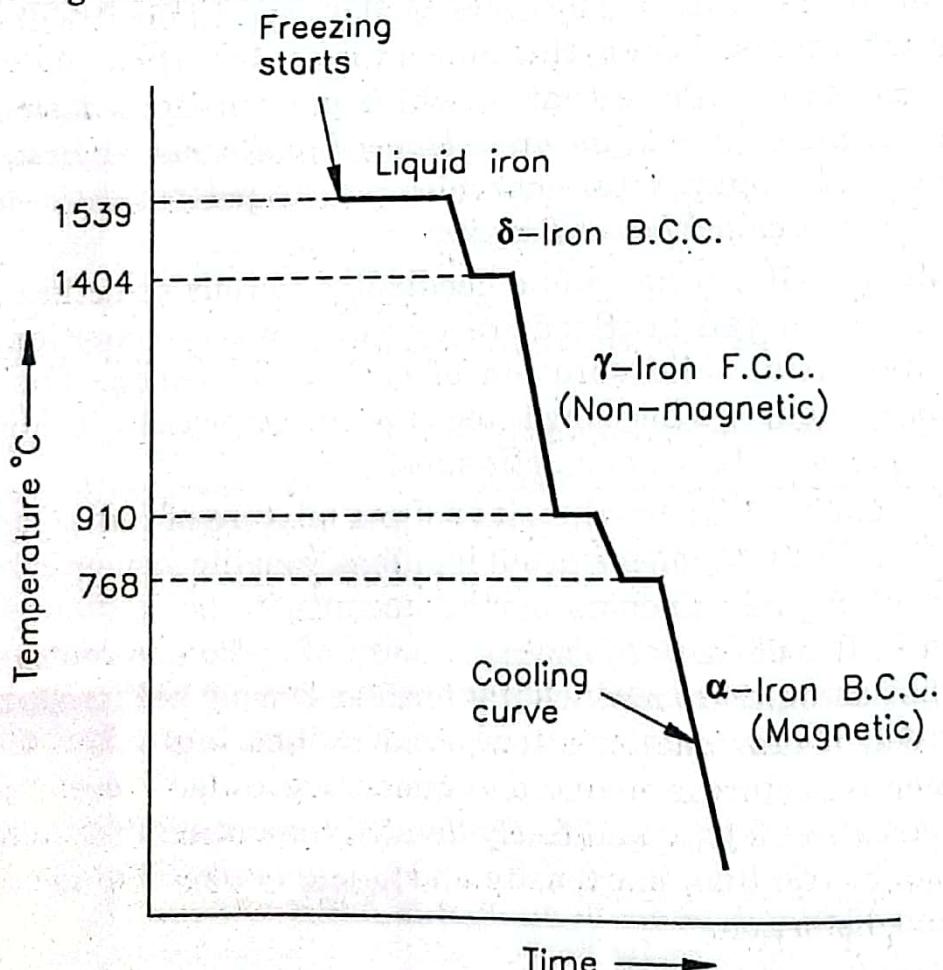


Fig. 4.19. Cooling curve and allotropic transformations in iron.

As this transformation from liquid state to  $\delta$  form is completed, the temperature starts falling again till it reaches  $1404^{\circ}\text{C}$ . At this point the temperature fall is again checked, heat starts evolving and another constant temperature phase transformation starts taking place, which continues till such time as the entire  $\delta$ -iron is changed into ' $\gamma$ ' form carrying FCC structure. The iron in this allotropic form is *non-magnetic*. This transformation is represented by the horizontal line at  $1404^{\circ}\text{C}$  on the cooling curve.

With further cooling, the temperature continues to fall upto  $910^{\circ}\text{C}$  and there is no phase transformation during this period. There is a sudden check in the fall of temperature at  $910^{\circ}\text{C}$  and another phase transformation takes place at constant temperature. It continues till the entire ' $\gamma$ ' iron is transformed into a new allotropic from  $\alpha$ -iron with BCC structure. The iron still continues to be non-magnetic in this new form. This transformation is represented by the horizontal line at  $910^{\circ}\text{C}$  on the curve.

As soon as this transformation is over the temperature starts falling again and continues falling till it reaches  $768^{\circ}\text{C}$ . At this temperature there is a sudden check again and another change takes place at constant temperature. This change is not in the allotropic form or structure, which still remains the same *i.e.*,  $\alpha$ -iron with BCC structure, but in the *magnetic property*. Below  $768^{\circ}\text{C}$  the iron is highly magnetic.

The entire process of allotropic transformations in iron is a reversible one and the same changes in the reverse order are noticed while heating the iron from room temperature to the liquid state.

#### 4.38 IRON-CARBON EQUILIBRIUM DIAGRAM

This diagram graphically represents the effects of temperature and composition on all the phases present in iron-carbon alloys, *i.e.*, plain carbon steels and cast irons. It means that all the transformations taking place in an iron-carbon alloy are represented by this diagram. This diagram is constructed by plotting the temperatures along the ordinate and the carbon percentage along the abscissa. Apart from indicating the temperature ranges and percentage carbon in the alloy it also indicates the boundaries at which the phase changes take place. It also helps in understanding the basis and principles of heat treatment. Such a diagram is given in Fig. 4.20.

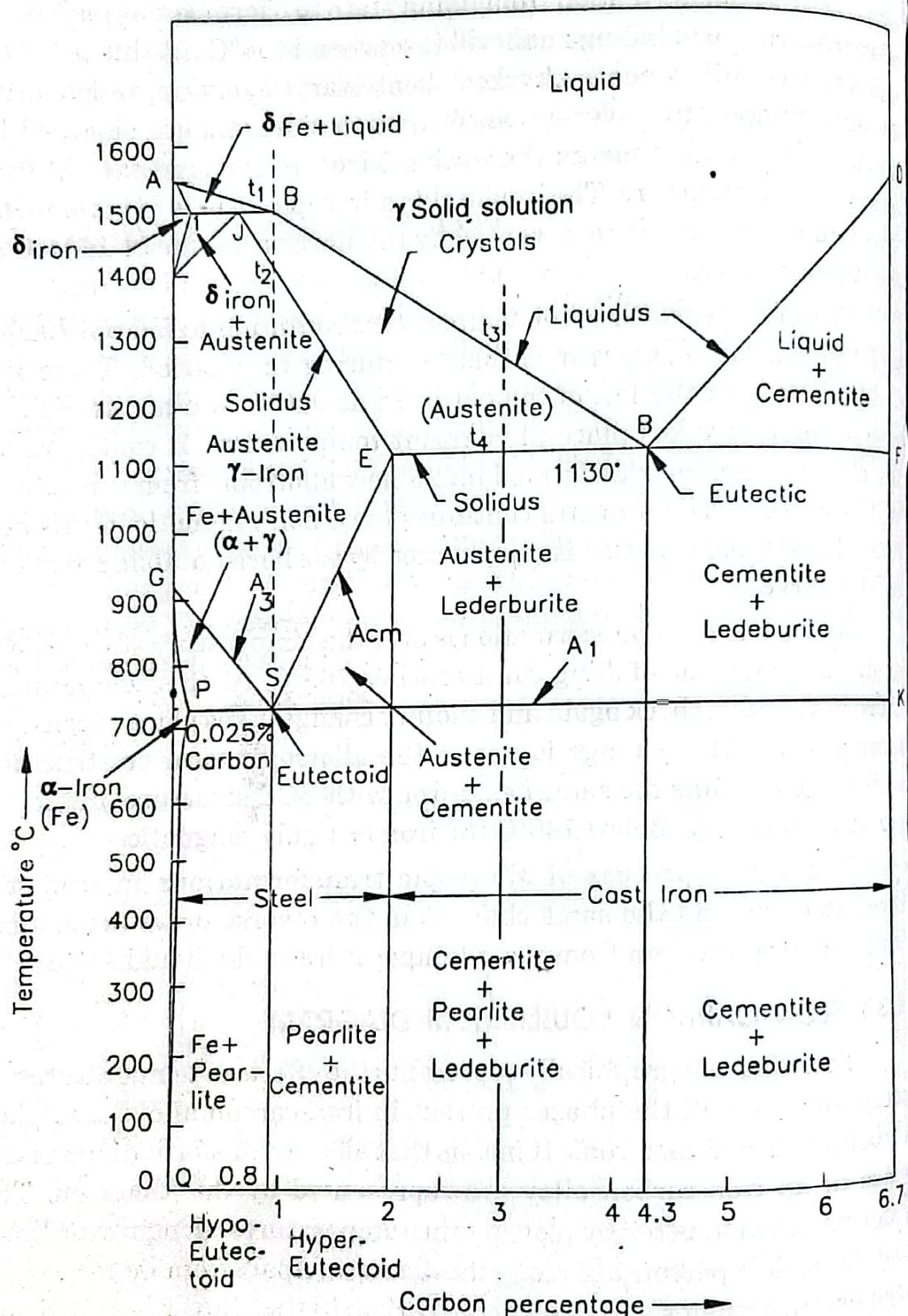


Fig. 4.20. Iron-carbon equilibrium diagram.

All the alloys in the temperature range above the curve ABCD, irrespective of their compositions, are in liquid state. Point A on the curve represents the melting point ( $1539^{\circ}$ ) of pure iron. Point D on the

curve represents the melting point ( $1550^{\circ}\text{C}$ ) of cementite (iron carbide). With the fall in temperature of the liquid along the curve  $ABC$  austenite crystals separate from the liquid metal. Similarly, the crystals of cementite will separate from the liquid with the fall in temperature of the latter along the line  $CD$ . The horizontal line  $HJB$  represents a peritectic reaction in which austenite, *i.e.*, solid solution of carbon in  $\gamma$ -iron, is formed. Crystals of delta ( $\delta$ ) iron separate from the liquid along the line  $AB$ . Delta iron is nothing but a solid solution of carbon in alpha iron at elevated temperatures. The entire configuration  $ABJH$ , etc., at the top left hand corner of the diagram represents high temperature transformations.

The curve  $HJECF$  represents the temperature line along which all iron-carbon alloys will solidify completely irrespective of their compositions. It is known as **Solidus Line**. All the alloys containing 0.18 to 2.0% carbon will, therefore, solidify at temperatures represented by the *solidus line HJE* and all those containing 2.0 to 6.7% carbon at  $1130^{\circ}\text{C}$ , represented by the solidus line  $ECF$ . Point  $C$  corresponds to 4.3% carbon. At this point austenite and cementite are precipitated from the liquid alloy and form an eutectic alloy called **Ledeburite**. Three important points  $J$ ,  $C$  and  $F$  are carried by this diagram at which specific reactions occur leading to important phase changes. These points are respectively known as *Peritectic*, *Eutectic* and *Eutectoid*.

Usually in practice, *i.e.*, in common processes like heat treatment and mechanical working, temperatures above  $1400^{\circ}\text{C}$  are not employed. Therefore, the high temperature transformation region at the top left hand corner of the diagram is normally ignored in practical use of this diagram, which leads to a modified form of equilibrium diagram without showing this region. Two types of transformations are represented by this diagram, called the **Primary Transformations** and **Secondary Transformations**. The primary transformations include the *Primary solidification*, *i.e.*, the change of alloy phase from liquid to solid and the *Secondary transformations* include the phase changes in solid state.

In order to understand the interpretation of this diagram fully let us consider a few concrete examples. Let us consider an alloy carrying 0.8% carbon. As it is cooled from some point in its liquid state it remains liquid till it reaches a temperature  $t_1$  on the liquidus line. At this point *austenite crystals* start precipitating from the liquid. The alloy becomes completely solid at temperature  $t_2$ , when its phase will consist of only *austenite*. Similar behaviour is exhibited by all alloys carrying carbon upto 1.8%, when cooled in the same manner from liquid state down to solidus line and below.

Take the example of another alloy containing 3% carbon. When it is cooled from its liquid state it remains a liquid till it reaches the

temperature  $t_3$  on the liquidus line. At this point austenite begins precipitating from the liquid alloy, which increases with further fall in temperature. At temperature  $t_4$  ( $1130^{\circ}\text{C}$ ) on the solidus line the alloy is completely solidified and the alloy is enriched in carbon content upto 4.3%. At this temperature  $t_4$ , austenite and cementite crystals simultaneously separate themselves from the eutectic mixture. Same behaviour will be exhibited by all alloys containing upto 4.3% carbon, while the alloy containing exactly 4.3% carbon will completely solidify at the constant eutectic temperature of  $1130^{\circ}\text{C}$ .

Alloys carrying above 4.3% carbon start solidifying along the *liquidus line CD*. Below liquidus line *CD* cementite precipitates away from the liquid alloy. Solidification of the alloy will be completed along the *solidus line CF* and the resulting phase will consist of cementite and ledeburite.

We shall extend our discussions further, considering the *Secondary Transformations*, i.e., the transformations occurring in the iron-carbon alloys in solid state. The temperature at which the structural changes occur in steel during heating and cooling are called **Critical Points**. These points are denoted by symbols  $A_c$  for heating and  $A_{ci}$  for cooling. The temperature of  $910^{\circ}\text{C}$  (point *G*) on the diagram represents a reversible transformation from  $\alpha$  to  $\gamma$  and  $\gamma$  to  $\alpha$  iron. Austenite decomposes along the line *GS* and in the process ferrite separates from austenite. Also, the excess carbon resulting from this decomposition forms cementite. Point *S* ( $723^{\circ}\text{C}$ ) corresponds to 0.8% carbon-in solid phase and is known as **Eutectoid Point**. At this point ferrite and cementite separate simultaneously to form a new structure called **Pearlite**.

Along the line *GS* the critical points in heating are designated as  $A_{c3}$  and in cooling as  $A_{r3}$ . All the temperatures on the line *SE*, along which cementite separates due to decomposition of austenite, are designated as  $A_{cm}$  points. All the temperatures along the horizontal line *PSK* are represented by  $A_{c1}$  for heating and  $A_{r1}$  for cooling. These are the temperatures at which pearlite structure is changed into austenite and austenite into pearlite respectively for all iron-carbon alloys.

The area of ferrite formation is represented by the region *GPQ*. Solubility of carbon in alpha iron at  $723^{\circ}\text{C}$  is indicated by point *P*. At this point it is 0.025% carbon and goes on reducing as cooling proceeds. This aspect is represented by the curve *PQ*. Now, if a steel piece containing less than 0.8% carbon is cooled from austenite region, the change in structure occurs along the line *GS* and the alloy is transformed into two piece alloy consisting of  $\gamma$ -iron (austenite) plus  $\alpha$ -iron (ferrite). If the alloy carrying exactly 0.8% carbon is cooled from its austenite region its

complete transformation will occur at a constant temperature of  $723^{\circ}\text{C}$  (eutectoid point  $A_{c1}$ ) and its structure will be changed into *pearlite* and *cementite*.

Steels having less than 0.8% carbon are called **Hypoteutecoid Steels** and those having more than 0.8% carbon **Hypereutectoid Steels**. Those steels which contain exactly 0.8% carbon are known as **Eutectoid Steels**. The *hypoeutectoid* steels below the line *GS* will consist of *ferrite* and *pearlite*. Similarly, *hypereutectoid* steels below the line *ES* will consist of *austenite* and *cementite*. Similarly, cast irons with carbon below 4.3% will have *pearlite* and *ledeburite*, those with exactly 4.3% carbon only *ledeburite* and those having above 4.3% carbon *cementite* and *ledeburite* as their phase structures below the line *EF*.

### TEST QUESTIONS

- Differentiate between metals and non-metals with respect to their properties and uses.
- Explain the difference between amorphous and crystalline structures of solids.
- Write short notes on :
  - Crystalline growth
  - Polycrystalline solids
  - Grain growth
  - Grain boundaries.
- Explain the terms :
  - Unit cell
  - Crystal lattice
  - Lattice parameters and geometrical constants of a crystal system
  - Coordination Number
  - Packing fraction.
- What are 'Bravais Lattices'? Explain the terms 'Primitive Cell' and 'Crystal System'.
- What is an 'Allotropic metal'? Explain the term 'Allotropic change'.
- With the help of suitable diagrams explain the BCC, FCC and HCP space lattices (structures) of metals.
- What do you understand from 'Bonds' as applicable to solids? How many types of bonds you are aware of?
- Explain in brief the different types of bonds in solids, stating their main characteristics and their influence on the properties of solids containing these bonds.
- How do secondary bonds differ from primary bonds?
- Explain the term 'crystal imperfections'. How are the different types of imperfections classified?

12. Write short notes on the following :
  - (a) Point imperfections      (b) Frankel defect
  - (c) Schottky defect      (d) Vacancies.
13. Describe a 'Line defect' in detail explaining the principles of 'Edge dislocation' and 'screw dislocation'. What is a 'Burger Vector'?
14. Explain the different types of planer defects.
15. What do you understand by the term 'deformation' of metals ? How are these deformations classified ? Explain 'Elastic deformation'.
16. What is 'Plastic deformation of metals' ? What are the mechanisms which cause plastic deformation in a metal ?
17. Explain the process of 'Slip deformation' with the help of a neat diagram. How does slip occur in a polycrystalline metal ?
18. Explain the process of plastic deformation of metals by twinning.
19. Write short notes on the following :
  - (a) Twin boundaries      (b) Tilt boundaries
  - (c) Deformation of polycrystalline metals.
20. What are the important characteristics of polycrystalline materials ?
21. What changes in the mechanical properties of polycrystalline metals take place due to plastic deformation ?
22. Write short notes on the following :
  - (a) Work hardening      (b) Season cracking
  - (c) Bauschinger effect      (d) Strain ageing
  - (e) Preferred orientation.
23. Explain the processes of recovery, recrystallisation and grain growth with respect to plastic deformation of metals.
24. Which factors govern the grains during plastic deformation and how?
25. What is 'Fracture' ? How many types of fractures can occur ? Explain each briefly.
26. What is an alloy and how does it differ from pure metal ?
27. Explain the process of solidification in metals and alloys with the help of suitable cooling curves.
28. What are the different forms of alloys ? Describe each form in brief.
29. Explain the terms system, component, phase, structural constituent and equilibrium as applicable to an alloy.
30. What is a solid solution ? How many types of solid solutions are there ? Differentiate between a 'Substitution solid solution' and an 'Interstitial solid solution.'

31. What are 'Intermetallic compounds' and 'Mechanical mixtures'? Explain.
  32. What do you understand by the term 'Phase of an alloy'? Explain.
  33. What is a 'Phase diagram'? How are phase diagrams classified?
  34. What do you understand by 'Phase transformations'? Explain.
  35. What are the principal constituents of an iron-carbon system? Explain.
  36. With the help of a cooling curve explain the different allotropic forms of iron.
  37. Construct a neat iron-carbon equilibrium diagram and explain its interpretations with the help of suitable examples.
  38. What information can be obtained from an iron-carbon equilibrium diagram?
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