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Basics of Material Science and Engineering

New Pattern
for
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PREFACE

Materials are the spinal chord of technology. An Engineer, regardless of which discipline he/she belongs to, must have sound understanding of the basic concepts of material science.

This understanding of materials enables the engineers to select the most appropriate materials and use them with greatest efficiency whilst causing minimum pollution in their extraction, refinement and manufacturing.

On account of the above UPSE has introduced basics of material science in its syllabus of Engineering Services Examination.

We at IES Master have tried to present the subject matter in simple, lucid and exam oriented manner. At the end of each chapter exercises have been given, so that students could practice the questions and check their understanding of the topic.

Hope this will suffice the need of students who are preparing for Engineering Services Examination.

Mr. Kanchan Kumar Thakur
Director Ex-IES

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Atomic Structure and Interatomic Bonding

1.1 ATOMIC STRUCTURE

Atomic Structure

Fundamental Components of Atoms

Thomson's Atomic Model

Rutherford's Atomic Model

Bohr's Atom Model

Atomic Bonding in Solids

Ionic Bonding

Covalent Bonding

Metallic Bonding

Fluctuating Induced Dipole Bonds

Polar Molecule-Induced Dipole Bonds

- Atoms are made of electrons, protons, and neutrons. Electrons and protons are negative and positive charged particles respectively. The magnitude of each charged particle in an atom is 1.6×10^{-19} Coulombs.
- The mass of the electron is negligible with respect to the proton and the neutron (constitute the nucleus of the atom). The unit of mass is an atomic mass unit (amu) = 1.66×10^{-27} kg, and equal 1/12 the mass of a carbon atom. The Carbon nucleus has $Z = 6$, and $A = 6$, where Z is the number of protons, and A the number of neutrons.
- Neutrons and protons have very similar masses, equal to 1 amu each. A electrically neutral atom has the same number of electrons and protons, Z .
- A mole is the amount of matter that has a mass in grams equal to the atomic mass in amu of the atoms. Thus, a mole of oxygen has a mass of 32 grams.
- The number of atoms in a mole is called the Avogadro number, $N_{av} = 6.023 \times 10^{23}$.
- $N_{av} = 1$ gram/1 amu.
- Most solids have atomic densities around 6×10^{22} atoms/cm³.
- The mean distance between atoms is 0.25 nm. This gives the scale of atomic structures in solids.

1.2 FUNDAMENTAL COMPONENTS OF ATOMS

Matter is composed of tiny particles called atoms. These particles can be divided in three groups :

1. Stable particles – electron, proton and neutron
2. Unstable particles – Positron, neutrino, anti-neutrino and meson
3. Composite particles – Deuteron and α -particles

➤ **Electron** : It carries a very small negative electrical charge. It has negligible mass i.e., its mass is $1/1836$ th of the mass of hydrogen atom. Electrons are present in all the atoms, they revolve around the nucleus in orbitals of definite energy levels.

➤ **Proton** : It carries small positive electrical charge. Mass of each proton is same as that of hydrogen atom. Protons are also present in all the atoms. It is identical with hydrogen atom from which single electron has been removed.

➤ **Neutron** : It does not carry any electrical charge. Its mass is equivalent to that of proton.

➤ **Positron or positive electron** : During studies on the effects of magnetic field upon the particles ejected from atomic nucleus by absorption of cosmic rays, Anderson found fog tracks exactly like those given electrons but deflected in opposite directions. Those particles which are responsible for such tracks are called positron. Thus, they are the positive counterpart of the electrons.

➤ **Neutrino and anti-neutrino** : They have no electrical charge and have small mass. During the radioactive emission of electrons and positrons, a change in energy is observed. The neutrino the radioactive emission of electrons and positrons, a change in energy is observed.

The neutrino shares the energy of electron while the antineutrino occupies the same position with respect to positron.

➤ **Meson** : The mass of meson particles is in-between the mass of electron and proton. Mesons were discovered during cosmic ray studies. They are of two types : (i) π -meson which is heavier, (ii) μ -meson which is light. Both types of mesons may be either negatively or positively charged.

➤ **Deuteron** : It is positively charged. It is heavy hydrogen nucleus. Deuteron bears same relation with heavy hydrogen as proton bears with ordinary hydrogen. It does not play any role in ultimate composition of matter. It is useful as bombarding particle.

➤ **Alpha particles** : They are double charged helium nucleus. They appear as product of radioactive decay.

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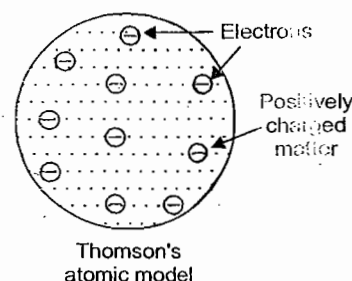
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1.3 THOMSON'S ATOMIC MODEL

- Atom is a sphere filled with positively charged matter. The positive charge is distributed uniformly, with sufficient electrons embedded in it to balance positive charge.
- The radius of the sphere of an atom is about 10^{-10} m.
- An atom is electrically neutral, so that total positive charge on it is equal to the total negative charge on it
- The electrons possess vibratory motion about their equilibrium position and cause emission of light.



1.3.1 Drawbacks of the Model

Thomson's model did not explain,

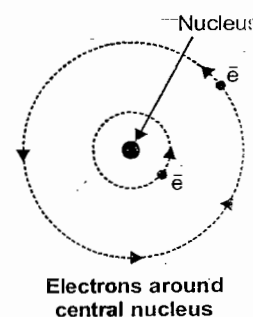
- The scattering of α -particles incident on metal foil
- The emission of spectral lines by the atoms

This model of atom had, therefore, to be superseded.

1.4 RUTHERFORD'S ATOMIC MODEL

On the basis of α -particles scattering through large angle, Rutherford proposed the following structure of atom :

- An atom has a small central part called the nucleus, in which the whole mass and positive charge are concentrated. The nucleus size is about 10^{-15} m.
- As the atom is electrically neutral, so an equal number of electrons (negatively charged particles) are distributed in the space around nucleus to balance the positive charge of nucleus. (shown in figure)
- Electrons are not stationary. They revolve around the nucleus in circular path in the same way as planets go around the sun. By this way Rutherford explained the stability of atom. He assumed that the electrons are revolving at a high speed around the nucleus in close circular orbits. The force of attraction between nucleus and electrons are balanced by the centrifugal force acting on the electron.

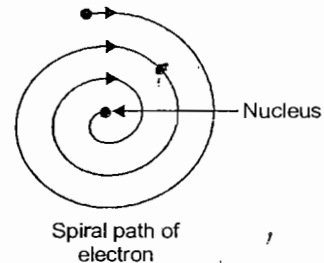


1.4.1 Drawbacks of Rutherford's Atomic Model

- A revolving electron around the nucleus must be continuously accelerating due to the change in direction of motion at every point. According to electromagnetic theory, an

accelerating charge particle (a revolving around the nucleus possesses centripetal acceleration and there would be continuous loss in energy of the revolving electron. Thus, the electron must move along a spiral path of decreasing radius and ultimately falls into the nucleus (Shown in Figure) when its whole rotational energy is exhausted. This would result in annihilation of atom.

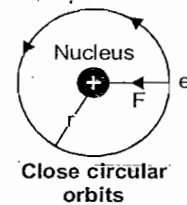
- According to electromagnetic theory the revolving electron must radiate continuous radiations of all increasing frequencies. But it is observed that elements emit spectral lines of fixed frequencies and not all the frequencies.
- In Rutherford model, there is no discussion of distribution of electrons.



1.5 BOHR'S ATOMIC MODEL

Bohr's extended the above model further by applying Planck's quantum theory. He made the following assumptions in his theory :

- An atom consists of a small heavy central part called nucleus in which whole of the mass and positive charge of the atom are concentrated. The negatively charged electrons revolve around the nucleus in close circular orbits (Shown in Figure). The centripetal force required for rotation is provided by electrostatic force of attraction between positively charged nucleus and the negatively charged electrons.



Let m = mass of electron revolving around the nucleus

Z = atomic number

e = charge on electron

v = orbital velocity of electron

r = radius of the orbit

Ze = charge on the nucleus

ϵ_0 = permittivity of free space = 8.854×10^{-12} F/m

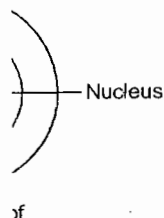
The electrostatic force of attraction between nucleus and the electron,

$$= \frac{1}{4\pi\epsilon_0} \cdot \frac{Ze^2}{r^2} \left[\frac{1}{4\pi\epsilon_0} = \text{constant} \right]$$

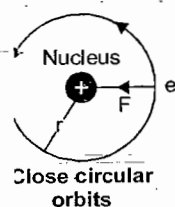
The necessary centripetal force = $\frac{mv^2}{r}$

Hence, according to Bohr's theory

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$$\frac{mv^2}{r} = \frac{1}{4\pi\epsilon_0} \frac{Ze^2}{r^2}$$

- The electrons revolve only in certain specific non-radiating orbits defined as stationary orbits. When the electrons revolve in these orbits there is no loss of energy. Bohr found that electron can only occupy an orbit for which the angular momentum of moving electron is an integral multiple of $h/2\pi$, where h is Planck's constant. Thus, for any given orbit,

Momentum of electron = mv

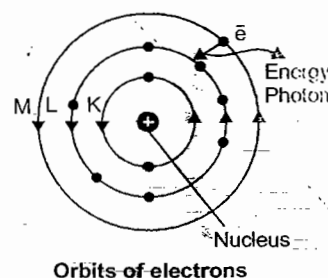
Angular momentum of electron = $mv r$

According to the above postulate of Bohr's theory, we have

$$mvr = n \cdot \frac{h}{2\pi}$$

where n is any positive integer having values ($n = 1, 2, 3, \dots$ etc.) and is called principal quantum number. $n = 1$, for innermost orbit.

- When an atom jumps from one orbit of higher energy to another orbit of lower energy, the energy is released in the form of radiations. The amount of energy released is the difference of energies of electron in the two orbits (Shown in figure). Thus, an atom may emit or absorb energy photons only when one electron of atom jumps from higher to lower orbit or from lower to higher orbit respectively.



Let, E_1 = energy of electron in inner or lower orbit

E_2 = energy of electron in outer or higher orbit

ν = frequency of radiation emitted, when electron jumps from higher orbit to lower orbit.

Now, according to this postulate of Bohr's theory, we have

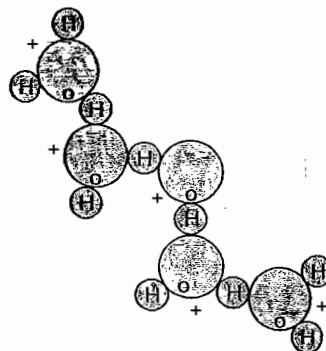
$$h\nu = E_2 - E_1$$

1.5.1 Drawback of Bohr's Theory

- It gives no information regarding the arrangement of distribution of electrons in the atom.
- This theory does not explain wave nature of electrons.
- The theory does not explain why only circular orbits have been considered where as elliptical orbits are also possible.
- This theory does not explain the fine structural lines even for hydrogen.
- It does not give any information about the relative intensities of spectral lines.
- This theory explains the atomic spectra only for simple atoms like hydrogen, etc.

1.6 ATOMIC BONDING IN SOLIDS

- **Ionic Bonding** : This bond exists between two atoms when one of the atoms is negative (has an extra electron) and another is positive (has lost an electron). Then there exist a strong, direct Coulomb attraction. Ionic bonds are non-directional in nature. CaCl_2 in this, there are more electrons around Cl, forming Cl^- and fewer electrons around Ca, forming Ca^{++} . Ionic bonds are the strongest bonds.
- **Covalent Bonding** : In covalent bonding, electrons are shared between the atoms, to saturate the valency. The simplest example is the H_2 molecule. Each bond is between a specific pair of atoms, which share a pair of electrons (of opposite magnetic spins). Typically, covalent bonds are very strong, and directional in nature.
- **Metallic Bonding** : Metals are characterized by high thermal and electrical conductivities. Thus, neither covalent nor ionic bondings are realized because both types of bonding localize the valence electrons and stop conduction. However, strong bonding does occur in metals. The valence electrons of metals also are delocalized. Thus surrounded by a sea of delocalized electrons. It is non-directional.
- **Fluctuating Induced Dipole Bonds** : As the electrons may be on one side of the atom or the other, a dipole is formed : the positive nucleus at the center, and the electron outside. Since the electron moves, the dipole fluctuates.
This fluctuation in atom A produces a fluctuating electric field that is felt by the electrons of an adjacent atom, B. Atom B then polarizes so that its outer electrons are on the side of atom closest to the positive side (or opposite to the negative side) of the dipole in A.
- **Polar Molecule-Induced Dipole Bonds** : Another type of secondary bond exists with asymmetric molecules, also termed as polar molecules because of positively and negatively charged regions. A permanent dipole moment arises from net positive and negative charges that are respectively associated with the hydrogen and chlorine ends of the HCL molecule, formed the bonding. The magnitude of this bond will be greater than for fluctuating induced dipoles.
- This two kinds of bonds are also called van der Waals bonds. Third type of secondary bond is the hydrogen bond. It produces the strongest forces of attraction in this categories.
- **Permanent Dipole Bonds/Hydrogen Bonding** : It occurs between molecules as covalently bonded hydrogen atoms - for example C-H, F-H - share single electrons with other atom essentially resulting in positively charged proton that is not shielded any electrons. This highly positively charged end of the molecule is capable of strong attractive force with the negative end of an adjacent molecule.



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QUESTIONS

- According to Thomson's plum pudding model, an atom consists of
 - A nucleus of negative charge with protons around
 - A sphere of negative charge seasoned with enough number of proton plums.
 - A heavy sphere of positive charge seasoned with enough number of electron plums to make it electrically neutral
 - None of these
- Rutherford's experiment of Bombardment of α -particles by striking on a thin gold foil showed that
 - All the α -particles passed straight through the foil
 - All the α -particles were deflected back
 - Some particles passed through the foil and some were deflected back.
 - Most of the α -particles went straight through the foil while very few were deflected the foil while very few were deflected back by various angles
- The energy (E) of an electron in an atom is equal to

(a) $\frac{mZ^2e^2}{8\epsilon_0n^2h^2}$	(a) $\frac{mZ^2e^2}{4\epsilon_0n^2h^2}$
(c) $\frac{m^2Z^2e^2}{2\epsilon_0n^2h^2}$	(d) $\frac{m^2Ze^2}{\epsilon_0n^2h^2}$
- Mesone carries a charged
 - Negatively
 - Positively
 - Either negatively or positively
 - None of the above
- Neutron carries a charged
 - Positive electrical
 - Negative electrical
 - Either negative or positive
 - None of the above
- The weight of an electron is of the weight of a proton or neutron

(a) $\frac{1}{1850}$	(b) $\frac{1}{2000}$
(c) $\frac{1}{1836}$	(d) $\frac{1}{3050}$
- Hydrogen bonds are stronger than
 - Van der Waals bonds
 - Metallic bonds
 - Ionic bonds
 - Covalent
- The atomic number of a certain element is 83. An atom of this element must contain
 - 42 protons and 41 electrons
 - 83 neutrons
 - 1 neutron, 41 electrons and 41 protons
 - 83 electrons
- Avogadro number, N
 - 6.023×10^{23}
 - 6.02×10^{21}
 - 6.023×10^{-26}
 - 6.023×10^{-29}

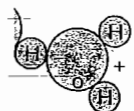
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10. What is the atomic or ionic characteristic that determines the elements of the which the atom or ion is representative?
- The number of protons
 - The number of neutrons
 - The number of electrons
 - The mass
11. Particles that most effects material propertis
- Nueutrons
 - Protons
 - Electrons
 - Valence electrons--
12. Mean distance between atoms in the range of
- 25 nm
 - 2.5 nm
 - 0.25 nm
 - 0.025 nm
13. Which one of the following is not a strong bond?
- Van der Waals bond
 - Covalent bond
 - Metallic bond
 - Ionic bond
14. Bond strength of seconedary bonds is in the range of
- 1 kJ/mol
 - 10 kJ/mol
 - 100 kJ/mol
 - 1000 kJ/mol
15. Electron sea exists in
- Polar bonds
 - Ionic bond
 - Covalent bond
 - Metallic bond

□ □ □

ANSWERS

1. (c)	4. (c)	7. (a)	10. (a)	13. (a)
2. (d)	5. (d)	8. (d)	11. (d)	14. (b)
3. (a)	6. (c)	9. (a)	12. (c)	15. (d)

2.1 INIntroducUnit CelFCC CryCut

Coordina

Atoms P

Atomic F

BCC StrHexagorPolymoiLatticeFigGeCryCrystallCrystallAnisotrImperfe

Point D

Linear L

InterfaciMeasurPlasticMe

Bausch

RecoveRecrysGrain

2

Crystal Structures

2.1 INTRODUCTION

Introduction

Unit Cells

FCC Crystal Structure (Face Centred Cubic)

Coordination Number

Atoms Per unit Cell

Atomic Packing Factor (APF)

BCC Structure (Body Centred Cubic)

Hexagonal Closed Packing (HCP)

Polymorphism

Lattice Parameter Relationships and Figures Showing Unit Cell Geometries for the Seven Crystal Systems

Crystallographic Directions

Crystallographic Planes

Anisotropy

Imperfections in Solids

Point Defects

Linear Defects

Interfacial Defects

Measurement of Grain Size

Plastic Deformation of Polycrystalline Materials

Bauschinger Effect

Recovery

Recrystallization

Grain Growth

- A crystalline material is one in which atoms are arranged in a regular pattern over large atomic distances. Thus, a long range order exists and upon solidification, atoms will position themselves in a regular 3-D pattern.
- Atoms are considered to be as solid spheres having well defined diameters
- Lattice is a 3-D array of atoms arranged in space.
- Basic crystal structure governs the fracture strength of material.

2.2 UNIT CELLS

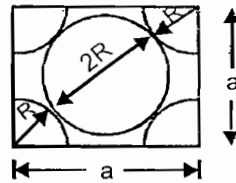
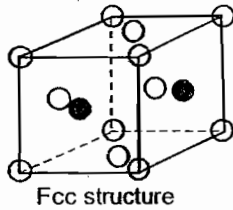
These are the smallest unit of a structure which when repeated in all 3 dimensions produces the crystal structure.

- Unit cells for most crystals are parallelepiped as parallelepiped having 3 sets of parallel planes.
- It represents the symmetry of crystal structure.
- It is the basic structural unit or building block of the crystal structure and defines the crystal structure by virtue of its geometry and the atoms position within.
- Space lattice + Basis = Unit cell
- Way of filling up of points in space lattice in atom is known as basis.

- Space lattice : Infinite array of points in 3-D space in which each point located with respect to other.

2.3 FCC CRYSTAL STRUCTURE (FACE CENTRED CUBIC)

- The unit cell has a cubic geometry, with atom located at the corners and centers of all the cubic faces.

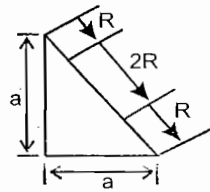


So, from figure :

$$a^2 + a^2 = (4R)^2$$

$$\text{or } a^2 = 8R^2$$

$$\text{or } a = 2\sqrt{2}R$$



2.3.1 Coordination Number

It is equal to the number of nearest neighbour to an atom and number of atom touching it. For FCC the coordination number is 12.

2.3.2 Atoms Perunit Cell

As each corner atom is shared by eight unit cells thus, its contribution is $1/8^{\text{th}}$, while each face atom is shared by two unit cells and its contribution is $1/2$.

Thus, total no. of atoms per unit cell are :

$$= 1/8 \times 8 + 1/2 \times 6 = 4.$$

2.3.3 Atomic Packing Factor (APP)

- It is the ratio of volume of atoms per unit cell to total unit cell volume.

$$\begin{aligned} (\text{ADF})_{\text{FCC}} &= \frac{4 \times \frac{4}{3} \times \pi \times R^3}{a^3} \\ &= \frac{16 \pi R^3}{3 (2\sqrt{2}R)^3} \\ &= \frac{\pi}{3\sqrt{2}} = 0.7404 \end{aligned}$$

- FCC
- All sp
- sheilc
- Exarr

- A
- N

Note : A
a

2.4 BC

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- FCC structure has the maximum packing possible for spheres.
- All spheres having the same diameter. Metals typically have large APF to maximize shielding provided by free electron cloud.
- Examples of Metals having FCC structure

> Aluminum	> Copper	> Gold	> Lead
> Nickel	> Platinum	> Silver	

Note : Atomic packing factor of simple cubic is 0.523. Co-ordination number is 6 and effective number per unit cell is 1.

2.4 BCC STRUCTURE (BODY CENTRED CUBIC)

- Atoms are located at eight corners and a single atom at the centre of cube.
- There are two atoms per unit cell of a BCC structure.
- Coordination number of BCC crystal structure is 8, and its atomic packing factor is 0.68.

8 atoms at the corner $\times 1/8 = 1$ atom

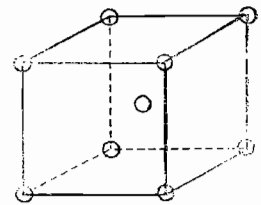
1 centre atom = 1 atom

Total = 2 atoms per unit cell.

Here, $a^2 + a^2 + a^2 = (\text{diagonal of cube})^2 = (4R)^2$

or $3a^2 = 16R^2$

or $a = \frac{4R}{\sqrt{3}}$



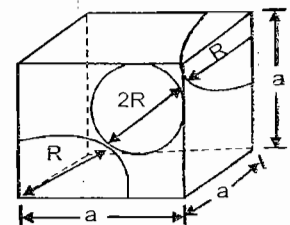
BCC structure
(a)

$$\text{APF} = \frac{\text{Volume of atoms per unit cell}}{\text{Volume of unit cell}}$$

$$= \frac{2 \times \frac{4}{3}\pi R^3}{a^3}$$

$$= \frac{8\pi}{3} \times \frac{R^3}{\left(\frac{4R}{\sqrt{3}}\right)^3} = \frac{8}{3} \times \frac{2^3 \times 3\sqrt{3}}{64R^3}$$

$$= \frac{\sqrt{3}}{8} \pi = 0.6801$$



(b)

- Example of BCC structure are—

- > Chromium > Iron (α) > Molybdenum
- > Tantalum > Tungstun > Potassium (k)

2.5 HEXAGONAL CLOSED PACKING (HCP)

- The third type of crystal is HCP. Here one dimension is greater than other two.
- The coordination number of HCP crystal is 12 and APF 0.74 same as FCC structure.
- Density computations:

$$\text{Density} = \frac{nA}{VN}$$

where, n = no. of atoms per unit cell.

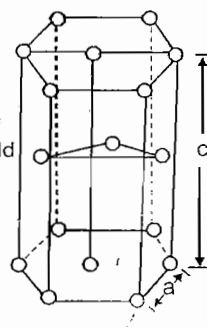
A = At weight

V = Volume of unit cell

N = Avogadro's number (6.023×10^{23} atoms/mol).

e.g. : graphite, Cd, Zn, Mg, Be, Ti, Mg, Zr

c/a ratio of
HCP should
be 1.633



2.6 POLYMORPHISM

Some metals as well as non metals have more than one crystal structure, this phenomenon is called polymorphism and when found in elemental solids the condition is termed as allotropy.

e.g., graphite and diamond, α -iron, δ -iron, γ -iron.

These material have different structure at different temperature.

Crystal Systems

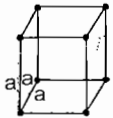
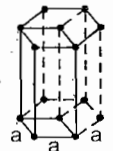
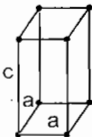
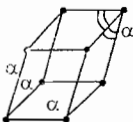
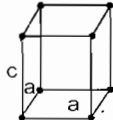
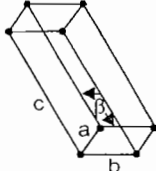
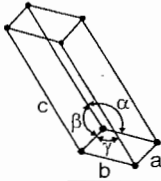
The unit cell geometry is completely defined in terms of the

- (i) Three edges are a , b and c .
- (ii) Three inter axial angle α , β and γ .

Based on different possible combinations of (a , b & c) and (α , β and γ).

There are seven diff. possible crystal structures called crystal system.

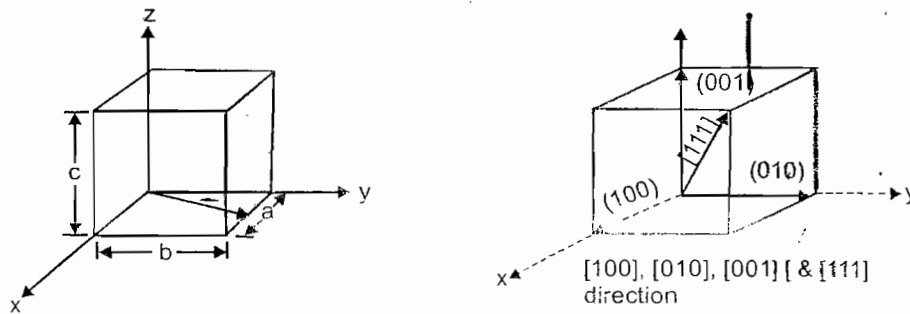
2.7 LATTICE PARAMETER RELATIONSHIPS AND FIGURES SHOWING UNIT CELL GEOMETRIES FOR THE SEVEN CRYSTAL SYSTEMS

Crystal system	Axial	Interaxi Angles Relationship	Unit cell Geometry
Cubic	$a = b = c$ e.g. Au, Po, Li, Na, Ag, Al etc.	$\alpha = \beta = \gamma = 90^\circ$	
Hexagonal	$a = b \neq c$ e.g. La, Pr, Nd, Am, Se, Te, AgCl	$\alpha = \beta = 90^\circ, \gamma = 120^\circ$	
Tetragonal	$a = b \neq c$ e.g. Pa, In, white Sn, KH_2PO_4 , U(668°C to 774°C)	$\alpha = \beta = \gamma = 90^\circ$	
Rhombohedral	$a = b = c$ e.g. B, SiO_2 , CaCO_3 , LiNbO_3 , LiTaO_3	$\alpha = \beta = \gamma \neq 90^\circ$	
Orthorhombic	$a \neq b \neq c$ e.g. As, Sb, Bi, BaSO_4 , KNO_3 , MgSO_4	$\alpha = \beta = \gamma = 90^\circ$	
Monoclinic	$a \neq b \neq c$ e.g. Na_2SO_4 , Li_2SO_4 , CaSO_4 , Rochelle salt, FeSO_4 , S	$\alpha = \gamma = 90^\circ \neq \beta$	
Triclinic	$a \neq b \neq c$ e.g. $\text{K}_2\text{Cr}_2\text{O}_7$, CuSO_4	$\alpha \neq \beta \neq \gamma \neq 90^\circ$	

2.8 CRYSTALLOGRAPHIC DIRECTIONS

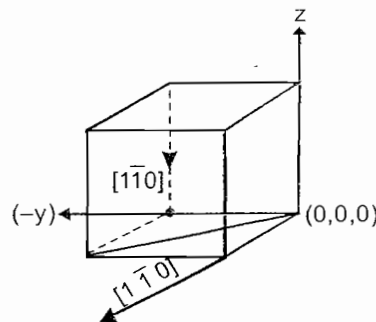
1. A vector of convenient length is positioned such that it passes through the origin of the coordinate systems.
2. The length of this vector projections on each of 3 axis is determined in term of unit cell dimensions a , b , c
3. The three number obtained are multiplied or divided by a common factor to reduce them to smallest integer values.
4. The direction are represented as $[uvw]$. i.e. not separated by commas.

Q.1: Determines the indices for direction shown in the figure :



- The coordinates in terms of a , b , c are $\left(\frac{a}{2}, b, 0z\right)$.
- Direction indices $\left[\frac{1}{2} 10\right]$
- Multiplying all the co-ordinate by 2.
Hence the direction indices is $[120]$

Q.2: Draw $[\bar{1}\bar{1}0]$ direction within a cubic unit cell.



Sol. When several number of 'n' parallel directions with different indices are equivalent they are called family of indices.

Example : In crystal all direction represented by an indices $[100]$, $[010]$, $[001]$, $[001]$ constitute a family. For hexagonal crystal instead of z axes we have four axes.

2.9 CRYSTALLOGRAPHIC PLANES

- The layers of atoms or the planes along which atoms are arranged are known as crystallographic planes. The relation of a set of planes to the axes of the unit cell is designated by Miller indices. One corner of the unit cell is assumed to be the origin of the space coordinates and any set of planes is identified by the reciprocals of its intersections with these coordinates.

- The unit of the coordinates is the lattice parameter of the crystal.

- If a plane is parallel to an axis, it intersects it at infinity.

- In figure (b), or the cubic system, the crosshatched plane BCHG intersects the Y axis at one unit from the origin and is parallel to the X and Z axes or intersects them at infinity. Therefore,

	X	Y	Z
Inter section	∞	1	∞
Reciprocal	$\frac{1}{\infty}$	$\frac{1}{1}$	$\frac{1}{\infty}$
Miller indices	0	1	0

- The shown plane has Miller indices of (010).

- If a plane cuts any axis on the negative side of the origin.

- The index will be negative and is indicated by placing a minus sign above the index, as $(h \bar{k} l)$.

- For example, the Miller indices of the plane ADEF which goes through the origin (point A) cannot be determined without changing the location of the origin.

- Any point in the cube may be selected as the origin.

- For convenience, take point B. The plane ADEF is parallel to the X-axis (BC) and the Z-axis (BG) but intersects the Y-axis at -1 .

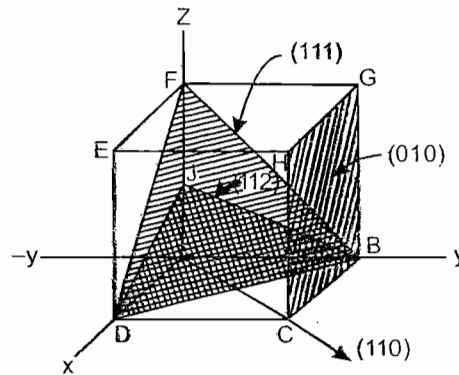
- The plane has Miller indices of $(0 \bar{1} 0)$.

- As another example, the Miller indices of the plane BDJ (figure) may be determined as follows:

- Hence this plane has Miller indices of (112).

- If the Miller indices of a plane result in fractions, these fractions must be cleared.

	X	Y	Z
Inter section	1	1	$\frac{1}{2}$
Reciprocal	$\frac{1}{1}$	$\frac{1}{1}$	$\frac{1}{1/2}$
Miller indices	1	1	2



Determination of Miller indices : the (010) plane, the (111) plane, and the (112) plane.

Figure (b)

Example : Consider a plane that intersects the x-axis at 1, the y-axis at 3, and the z-axis at 1.

- Taking reciprocals gives indices of 1, 1/3, and 1.
- Multiplying through by 3 to clear fractions results in Miller indices of (313) for the plane.
- All parallel planes have the same indices.
- Parentheses (hkl) around Miller indices signify a specific plane or set of parallel planes.
- Braces signify a family of planes of the same "form" (which are equivalent in the crystal), such as the cube faces of a cubic crystal: $\{100\} = (100) + (010) + (001) + (\bar{1}00) + (0\bar{1}0) + (00\bar{1})$.
- Reciprocals are not used to determine the indices of a direction.
- In order to arrive at a point on a given direction, consider that starting at the origin.
- It is necessary to move a distance u times the unit distance along the x-axis, v times the unit distance b along the y-axis, and w times the unit distance c along the z-axis.
- If u, v and w are the smallest integers to meet the desired motion, they are the indices of the direction and are enclosed in square brackets (uvw).
- A group of similar directions are enclosed in an angular brackets <uvw>

Example : In figure to determine the direction AC starting at the origin (point A), it is necessary to move one unit along x-axis to point D and one unit in the direction of y-axis to reach the point C. The direction AC would have indices of [110].

- In a cubic crystal the direction has the same indices as the plane to which it is perpendicular.
- An approximate idea of the packing of atoms on a particular plane may be obtained by visualizing a single unit cell of the b.c.c. and f.c.c. structure. Considering the atoms as the lattice points, the number of atoms on a particular plane would be :

Plane	b.c.c.	f.c.c.
(100)	4	5
(110)	5	6
(111)	3	6
(120)	2	3
(221)	1	1

Linear and Planer Densities

For a particular material, equivalent directions have equal linear density.

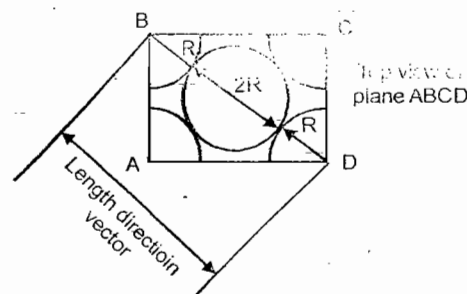
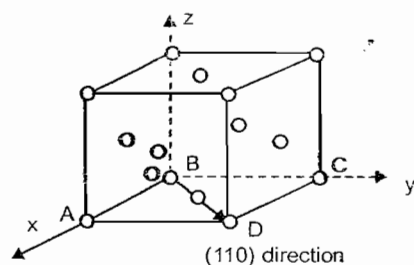
$$\text{Linear density (LD)} = \frac{\text{No. of atoms centered on unit length of direction vector}}{\text{Length of the direction vector}}$$

Consider an eg. of FCC unit cell and the [110] direction, therein.

No of atoms centered on direction vector are $1/2 + 1 + 1/2 = 2$ atoms

Length of Direction vectors $R + 2R + R = 4R$

$$LD_z = \frac{2}{4R} = \frac{1}{2R}$$



(ii) Planer density: Equivalent crystallographic planer have equal planer density.

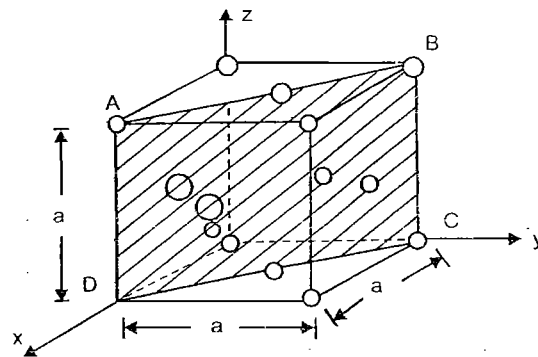
$$PD = \frac{\text{No. of atoms centered on a plane}}{\text{Area of the plane}}$$

for the same case of (110) plane with an FCC unit cell.

No. of atoms centered on plane ABCD = $1/2 + 1/2 + 1/2 + 1/2 = 2$

Area of plane ABCD = $4R \times a = 4R \times 2\sqrt{2} R = 8\sqrt{2} R^2$.

$$PD = \frac{2}{8\sqrt{2}R^2} = \frac{1}{4\sqrt{2}R^2}$$



L.D and P.D are important considerations as slip takes place on most dense packed crystallographic planes, and in those planes, along directions having greatest atomic packing.

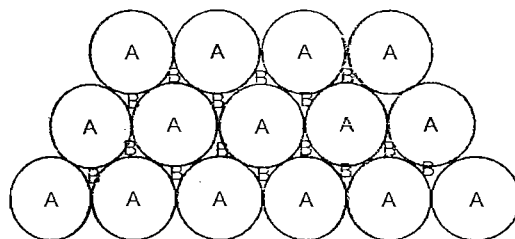
Close-Packed Crystal Structures

HCP – AB AB AB AB...

FCC – ABC ABC ABC...

For HCP let A be first plane of closed packed atoms. The second plane atoms (B plane) are placed in the voids made by atoms of first plane, while atoms of next A plane are directly above the (A) atoms of first plane. Thus forming AB AB AB... structure.

For FCC structure B plane atoms also rest in triangular voids of A plane atoms while C plane atoms rest in triangular voids of B plane atoms. This sequence is repeated.



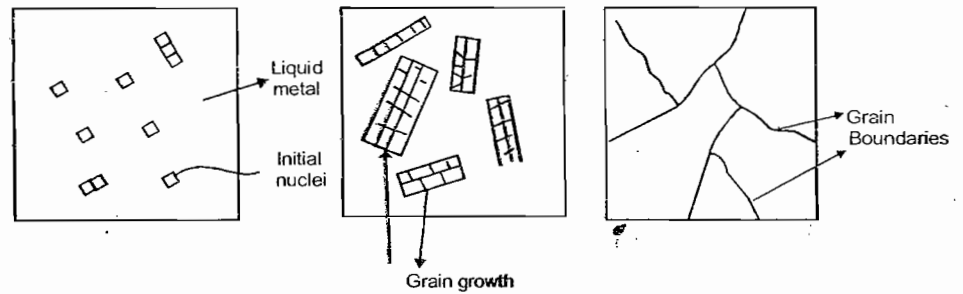
Single crystals

When the periodic and repeated arrangement of atoms is perfect and extends throughout the entire specimen without interruption, the result is a single crystal. All unit cells have the same orientation. Single crystals exist as nuclei grow at the expense of surrounding liquid. Grains formed have different orientations and boundaries separating these different orientations are called grain boundaries.

2.10 AN

The physical properties in which materials differ and refractive index of properties of ionic space.

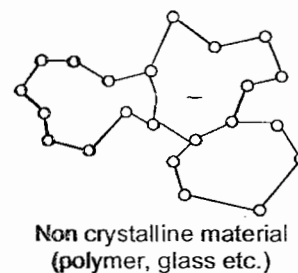
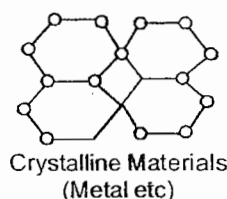
- Substitutional alloys are isotropic.
- "The effect of grain size on properties is i.e. decrease in grain size leads to increase in strength."
- Thus, grain size is an important factor in determining the mechanical properties of polycrystalline materials.
- For materials with grain boundaries, the grain boundaries act as barriers to dislocation motion, which increases the strength of the material.
- Some materials have grain boundaries that are more resistant to dislocation motion than others, depending on the material and the grain boundary structure.



2.10 ANISOTROPY

The physical properties of some substances depend upon the crystallographic direction in which measurements are taken for eg: The elastic modulus, the electrical conductivity and refraction index may have different values in $[100]$ & $[111]$ directions. This directionality of properties is termed as 'Anisotropy' and it is associated with variance of atomic and ionic spacing with crystallographic direction.

- Substances for which physical properties are independent of direction of measurement are isotropic materials.
- "The extent of anisotropic effects is a function of symmetry of the crystal structure i.e. degree of anisotropy increases with decreasing structure symmetry.
- Thus monoclinic, triclinic structure are highly anisotropic.
- For many polycrystalline materials, the crystallographic orientations of individual grains are random. Each grain is anisotropic in nature but the specimen composed of aggregates of grains behaves isotropically. Also the magnitude of measured value represents some average of the directional values.
- Sometimes the grain in polycrystalline materials have preferential direction of orientation or growth, in which case the material is said to have a "Texture".



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2.11 IMPERFECTIONS IN SOLIDS

2.11.1 Point Defects

Those associated with one or two atomic positions. They are :

- (i) Vacancies.
- (ii) Self-interstitials
- (iii) Substitutional impurity
- (iv) Interstitial impurity

Equilibrium, no. of vacancies are given as –

$$N_v = N \exp \left(\frac{-Q_v}{kT} \right), \quad Q_v = \text{energy required for vacancy formation,}$$

T = temperature

Thus, as temperature increases vacancies increases exponentially.

where
$$N = \frac{\text{Avogadro's No.} \times X_p}{\text{Atomic weight of vacancy atoms.}}$$

Note : Crystal imperfection causes change in yield point, semiconductivity and ductility.

Frankel Defect

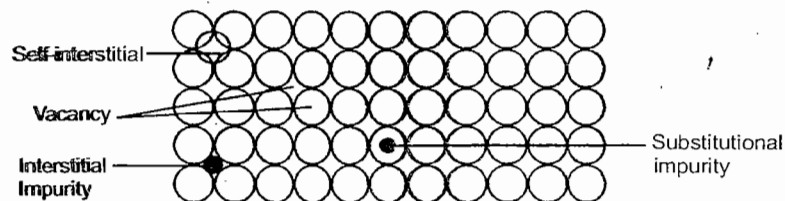
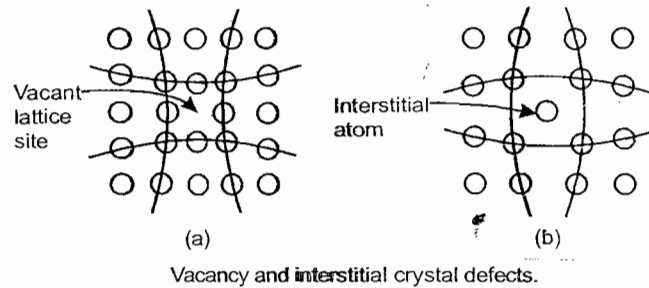
When the atom in the lattice point goes and occupies the interstitial void of other atom then it is called Frenkel defect.

Schottky Defect

In the combination of cation and anion if there is a vacancy defect it is called schottky defect.

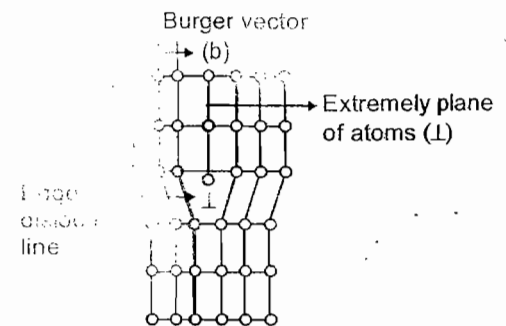
Mechanical & electrical properties of metals such as yield, fracture strength electrical conductivity are adversely affected by these defects, they are known as "structure sensitive properties".

Where properties such as melting point, specific heat, coefficient of thermal expansion are structure insensitive properties.



2.11.2 Linear Defects

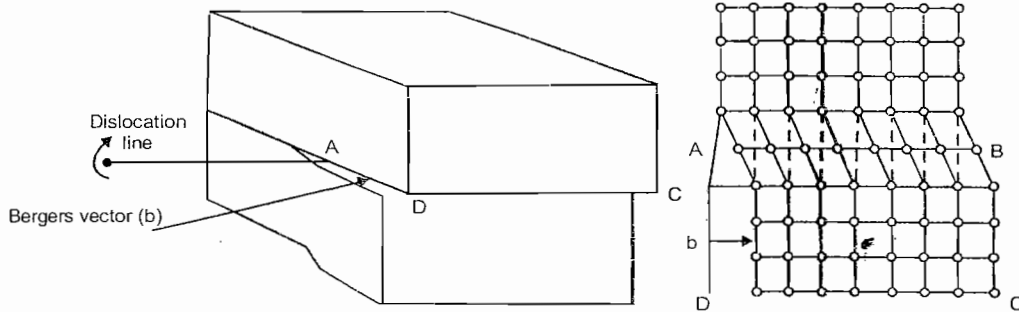
1. **Edge Dislocation** : This defect occurs when an extra half plane of atoms is introduced into the crystal structure. This defect centers around the dislocation line that is defined along the end of the extra half plane of atoms. Edge dislocation is perpendicular to the plane of the page. Around edge dislocation there is some lattice distortion.



Atoms above the dislocation lines are squeezed together and these below are pulled apart. Magnitude of this distortion decreases at distances away from the dislocation line. For extra half plane of atoms included on bottom portion of the crystal, the symbol is (T).

2. **Screw Dislocation** : This Dislocation is formed by shear stress, the upper front region of the crystal is shifted one atomic distances to the right relative to the bottom portion.

The screw dislocation derives its name from the spiral or helical path traced by the atomic planes around the dislocation line.



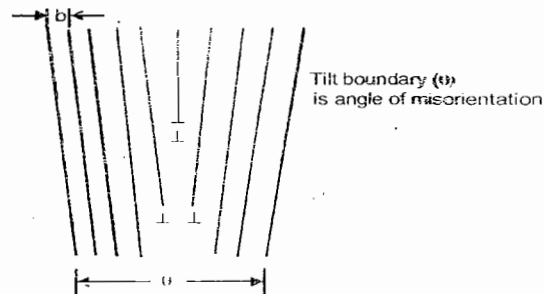
The magnitude and direction of the distortion associated with a dislocation is expressed in terms of "Burgers Vectors". (b) For an edge dislocation Burgers vector are perpendicular to dislocation line and are parallel to dislocation line for screw dislocation. They are neither perpendicular nor parallel to mixed location. For mettalic materials, the burgers vector for a dislocation will point in a close packed crystallographic direction, and its magnitude equal to interatomic setting.

2.11.3 Interfacial Defects

These are following types :

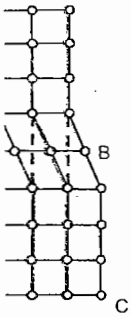
External surfaces : It is the boundary at which the crystal structure terminates. Atoms at the surface are not bonded to maximum. Number of nearest neighbours and therefore are in a higher energy state. To reduces this energy they tend to minimize the surface area e.g., liquid droplet become spherical.

Grain Boundaries : Grains boundaries are boundaries separating two crystals, have different crystallographic orientation within a polycrystalline material. When the match in orientation between adjacent boundaries is small then they are called low angle grain boundary or tilt boundary.



- When the angle of misorientation parallel to the boundary (grain) it is called a 'Twist Boundary'.

The atoms are bonded less regularly along a grain boundary and thus boundaries are in a high energy state. The magnitude of this energy is a function of degrees of misorientation (being larger for high angle boundaries).



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- Grain boundaries are chemically more reactive than the grain themselves. Further more, the impurity atoms preferentially segregate along these boundaries because of their high energy state.
- The total interfacial energy is lower for coarse grain material as compared to fine grained ones because of less total boundary area.

(iii) Twin Boundaries :

- It is a special type of grain boundary such that atoms on one side of the boundary are mirror images of atoms on the other side of the boundary. The region of material between these boundaries is called 'twin'.
 - Twins are produced by atomic displacements by mechanical shear force (mechanical twins) and also during annealing heat treatment following deformation (Annealing twin).
 - Annealing twins are typically found in FCC crystal structure, while mechanical twins are found in BCC and HCP metals.
- (iv) **Stacking faults** : These are found in FCC metals when there is interruption in the ABC ABC—stacking sequences of closed packed atoms.
- (v) **Phase Boundaries** : Boundaries separating two different phases having different mechanical properties and chemical characteristics.
- (vi) **Ferromagnetic Domain walls** : Boundary that separates region having different directions of magnetization is termed as domain wall.

Bulk or Volume Defects

Pores, cracks foreign inclusion. they are normally introduced during processing and fabrication steps.

2.12 MEASUREMENT OF GRAIN SIZE

- (i) Straight lines of same length are drawn on microphotograph that show the grain structures. The grain intersected by each line segment are counted, and the length of line is divided by an average of the number of grains intersected over all the line segments. The average grain is then found by divided this result by linear magnification of the photomicrographs.
- (ii) Another way is through ASTM size number charts. Which has grain size number from 1-10 (Higher number indicates fines grain).

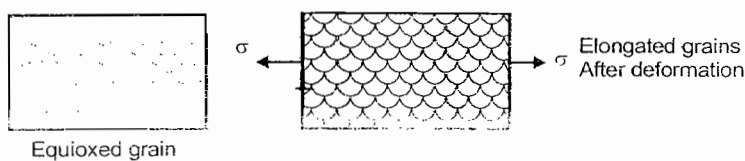
Grain structure is photographed at a magnification of 100. The grain size is expressed as grain size number of the chart that most nearly matches the grain in the micrograph.

Average number of grains per inch at magnification of 100, $[N = 2^{n-1}]$

where n = given size number.

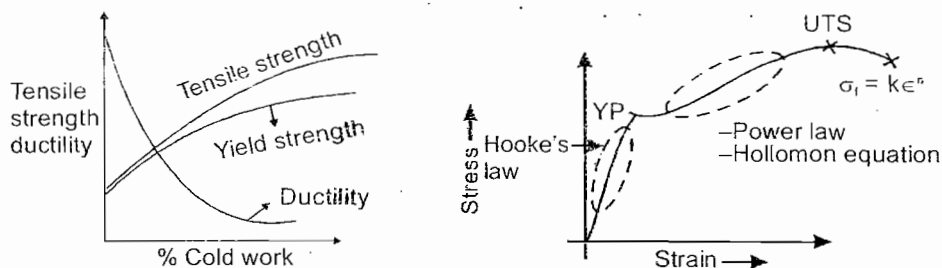
2.13 PLASTIC DEFORMATION OF POLYCRYSTALLINE MATERIALS

- In polycrystalline material there are many preferred planes and direction for different grains due to their random orientation.
- Thus, in case of poly-crystalline materials "gross plastic deformation" take place, where in individual grains undergo comparable distortion and the grain boundaries do not come apart or open up.
- Before deformation the grains are equiaxed but after deformation they get elongated in the direction of applied forces.
- Polycrystalline materials are stronger than single crystal material because they require more stresses to initiate slip and yielding.
- These higher stresses are consequences of constraints that are imposed on the grains during deformation.



2.13.1 Bauschinger Effect

When the specimen unloads the strength of material got increase due to work hardening and if reloading it in opposite direction then back stress now support the movement of dislocation. As a result of that yield points in opposite direction appears prematurely. This phenomenon called Bauschinger effect.



- At temperature = 0.4 melting temperature, upon cold working the number of dislocation in the material increases.
- The amount of dislocation multiplication takes place, is the property of material and it is expressed by work hardening exponent (n) in the flow curve equations $\sigma_f = K\epsilon^n$ where, k = strength coefficient, σ_f = true stress and ϵ = true strain.

Higher the value of ' n ', creation of dislocation is increased by cold working. Finally, these dislocation gather at the grain boundary and created dislocation forest.

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- This

2.14 R

- During
- There

2.15 R

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EXPERIMENTALS

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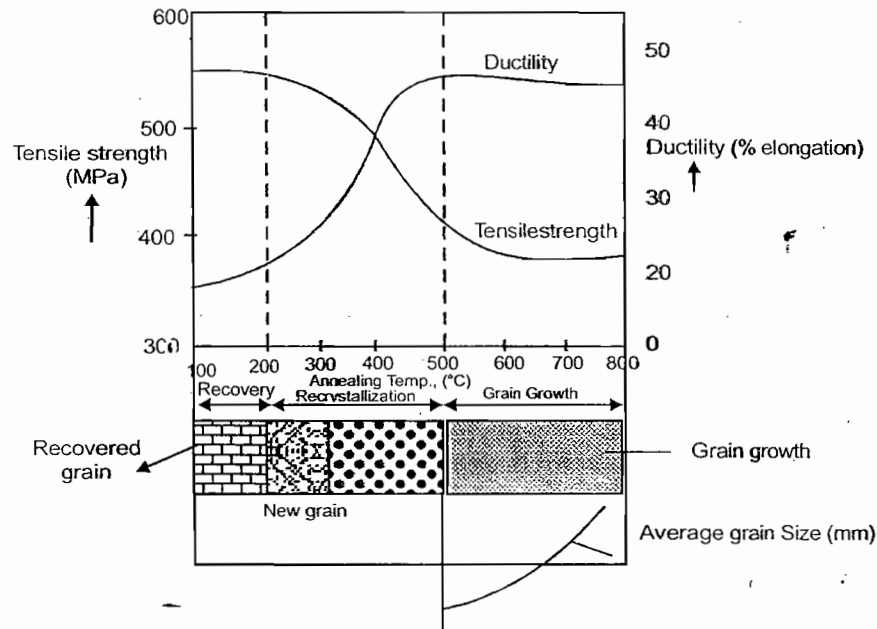
- These dislocation are repulsive in nature, which results in creation of back stress in the movement of dislocation.
- This is finally results in increase in strength of material upon unloading the specimen from the region of work hardening and reloading in opposite direction.

2.14 RECOVERY

- During recovery, some of the stored internal strain energy is relieved by virtue of dislocation motion in the absence of an externally applied stress, as a result of enhanced atomic diffusion at an elevated temperature.
- There is some reduction in the number of dislocation also. Physical properties such as electrical and thermal conductivities are recovered to their pre cold worked states.

2.15 RECRYSTALLIZATION

- Even after recovery the grains are still in a high strain energy state. Recrystallization is the formation of new set of strain free grains that are required. Dislocation densities are reduced and properties are restored to pre cold work conditions. "The driving force is the difference in the internal energy of strained and unstrained material.
- The new grains forms initially as a small nuclei and grow at the expense of parent material.
- It also refines the grain structure.
- Extent of recrystallization depends upon both time and temperature. The degree of recrystallization increases with time.
- Recrystallization temperature is the temperature at which recrystallization just reaches completion in 1 hour. It typically ranges between $0.3T_m - 0.5T_m$ for most materials and alloy, where T_m = melting point temperature.
- As the amount of cold work increases, the degree of recrystallization is enhanced and thus the recrystallization temperature is lowered and approaches a constant value at high deformation. There is some critical degree of cold work below which recrystallization will not take place.
- The recrystallization rate increases exponentially with temperature.
- A larger the initial grain size, the greater degree of deformation is required to produce an equivalent recrystallization temperature.
- A minimum amount of deformation is needed to cause recrystallization temperature.
- Smaller the degree of deformation, higher will be recrystallization temperature.
- Greater the degree of deformation and lower the annealing temperature, the smaller will be the recrystallization grain size.
- Alloying raises the recrystallization upto $0.7 T_m$.



2.16 GRAIN GROWTH

- After recrystallization is complete, the grains will continue to grow if the metal specimen is left at elevated temperature, this phenomenon is called grain growth.
- Grains boundaries are associated with higher energies, and as the grain size increases the total grain boundary area decrease resulting in reduction of total energy. This is the driving force for grain growth.
- Here large grains grown at the expense of smaller grains which further shrink in size. Average grain size increases.
- This is done by short range diffusion of atoms from one side of boundary to the other. The direction of boundary movement and atomic motion are opposite to each other.

Time dependences of grain growth is

$$d^n - d_0^n = kt$$

where k, n are constants and ' d_0 ' is initial grain size.

Grain growth proceeds more rapidly at higher temperature as diffusion rate increases with temperature.

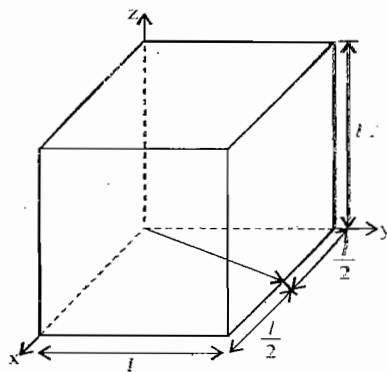
QUESTIONS

1. In metals subjected to cold working, strain hardening effect is due to
- Slip mechanism
 - Twining mechanism
 - Dislocation mechanism
 - Fracture mechanism
2. Which of the following properties of a solid are dependent on crystal imperfections?
- Yield stress
 - Melting point
 - Semiconductivity
 - Ductility

Select the correct answer using the codes given below:

- (a) 1 and 3 (b) 1, 3 and 4
(c) 2, 3 and 4 (d) 2 and 4

4. A unit cell of a crystal is shown in given figure. The miller indices of the direction (arrow) shown in the figure is



- (a) $[0\ 1\ 2]$ (b) $[0\ 2\ 1]$
(c) $[2\ 1\ 0]$ (d) $[2\ 0\ 1]$
(e) $[1\ 2\ 0]$

5. Match List-I (Material) with List-II (Structure) and select the correct answer using the codes given below the lists:

List-I	List-II
A. Charcoal	1. F.C.C.
B. Graphite	2. H.C.P.
C. Chromium	3. Amorphous
D. Copper	4. B.C.C.

Codes:

	A	B	C	D
(a)	3	2	1	4
(b)	3	2	4	1
(c)	2	3	4	1
(d)	2	3	1	4

DIRECTIONS:

The following items consists of two statements; one labelled as 'Assertion (A)' and the other as 'Reason (R)'. You are to examine these two statements carefully and select the answers to these items using the codes given below:

Codes:

- (a) Both A and R are true and R is the correct explanation of A
(b) Both A and R are true but R is not a correct explanation of A
(c) A is true but R is false
(d) A is false but R is true

7. **Assertion (A):** Carbon would form an interstitial solid solution with iron.

Reason (R): The atomic radius of iron is smaller than that of carbon.

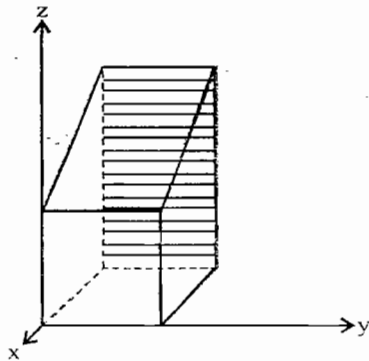
8. Match List-I (Crystal structure) with List-II (Atomic packing factor) and select the correct answer using the codes given below the lists:

List-I	List-II
A. Simple cubic	1. 74%
B. Body-Centred cubic	2. 74%
C. Face-Centred cubic	3. 52%
D. Hexagonal close packed	4. 68%

Codes:

	A	B	C	D
(a)	3	4	2	1
(b)	4	3	2	1
(c)	3	4	1	2
(d)	4	3	1	2

9. The set of Miller indices of the plane shown in the given figure is



- (a) (1 0 0) (b) $(\bar{1}00)$
 (c) (1 0 1) (d) (1 1 0)
10. Atomic packing factor (APF) in the case of copper crystal is
 (a) 0.52 (b) 0.68
 (c) 0.74 (d) 1.633
11. Which one of the following pairs of axis lengths (a, b, c) and interaxial angles

(α, β, γ) represents the tetragonal crystal system?

- (a) $a = b = c$; $\alpha = \beta = \gamma = 90^\circ$
 (b) $a = b \neq c$; $\alpha = \beta = \gamma = 90^\circ$
 (c) $a \neq b \neq c$; $\alpha = \beta = \gamma = 90^\circ$
 (d) $a = b = c$; $\alpha = \beta = \gamma \neq 90^\circ$
12. In the grain-size determination using standard charts, the relation between the given size number n and the average number of grains 'N' per square inch at a magnification of 100 X is

- (a) $N = 2^n$ (b) $N = 2^{n-1}$
 (c) $N = 2^{n+1}$ (d) $N = 2^{n+1}$

13. Chemicals attack atoms within grain boundaries preferentially because they have

- (a) lower energy than those in the grains
 (b) higher energy than those in the grains
 (c) higher number of atoms than in the grains
 (d) lower number of atoms than in the grains

14. The coordination number for FCC crystal structure is

- (a) 4 (b) 8
 (c) 12 (d) 16

15. Match List-I (Crystal Structure) with List-II (Example) and select the correct answer using the codes given below the lists:

List-I

- A. Simple Cubic
 B. Body-centred Cubic

16.

17.

- C. Face-centred Cubic
D. Hexagonal Close Packed

List-II

1. Zinc
2. Copper
3. Alpha iron at room-temperature
4. Manganese

Codes:

	A	B	C	D
(a)	4	3	1	2
(b)	4	3	2	1
(c)	3	4	2	1
(d)	3	4	1	2

16. Which one of the following pairs is not correctly matched?

- (a) Point defect in crystal lattice : Self interstitial
- (b) Linear defect in crystal lattice : Grain boundary
- (c) Planar defect in crystal lattice : External surface
- (d) Volume defect in crystal lattice : Other phases

17. A screw dislocation

1. Lies parallel to its Burger's vector
2. Lies perpendicular to its Burger's vector
3. Moves in a perpendicular direction to the Burger's vector
4. Moves in an inclined direction to the Burger's vector

Select the correct answer using the codes given below:

- | | |
|-------------|-------------|
| (a) 1 and 4 | (b) 1 and 3 |
| (c) 2 and 3 | (d) 2 and 4 |

18. Consider the following statements about FCC and HCP crystal structure:

1. Both have same coordination number and atomic packing fraction.
2. Both represent closely packed crystal structures.
3. Both structures are generated by stacking of close packed planes on top of one another, but only the stacking sequence is different.

Which of these statements are correct?

- | | |
|----------------|-------------|
| (a) 1 and 2 | (b) 2 and 3 |
| (c) 1, 2 and 3 | (d) 1 and 3 |

19. In Zinc Blende structure each atom is surrounded by four atoms of the opposite kind which are located at the corners of which one of the following?

- | | |
|-----------------|------------------|
| (a) Tetrahedron | (b) Hexahedron |
| (c) Cube | (d) Orthorhombic |

20. Which one of the following pairs is not correctly matched?

Space Lattice Relation between Atomic Radius r and Edge Element a

- | | |
|----------------------------------|------------------|
| (a) Simple cubic structure | : $a_2 = 4r_2$ |
| (b) Body-centred cubic structure | : $3a_2 = 16r_2$ |
| (c) Triclinic | : $2a_2 = 3r_2$ |
| (d) Face-centred cubic structure | : $a_2 = 8r_2$ |

21. What is the planar density of (100) plane in FCC (face-centred cubic) crystal with unit cell side a equal to?

- | | |
|-------------------------|----------------------------|
| (a) $\frac{1.484}{a^2}$ | (b) $\frac{2}{a^2}$ |
| (c) $\frac{1}{a^2}$ | (d) $\frac{\sqrt{2}}{a^2}$ |

22. Match List-I (Element) with List-II (Crystal Structure) and select the correct answer using the codes given below the lists:

List-I	List-II
A. Alpha Iron	1. Hexagonal closed packed
B. Copper	2. Body-centred cubic
C. Zinc	3. Amorphous
D. Glass	4. Face-centred cubic

Codes:

	A	B	C	D
(a)	2	3	1	4
(b)	1	4	2	3
(c)	2	4	1	3
	1	3	2	4

23. What is the movement of block of atoms along certain crystallo-graphic plane and directions, termed as?
- (a) Glide (b) Twinning
(c) Slip (d) Jog
24. Which one among the following is the most effective strengthening mechanism of nonferrous metal?
- (a) Solid solution hardening
(b) Strain hardening
(c) Grain size refinement
(d) Precipitation hardening
25. Which one of the following is the correct ascending order of packing density for the given crystal structures of metals?
- (a) Simple cubic – Face central cubic – Body centrad cubic
(b) Body centred cubic – Simple cubic – Face centred cubic
(c) Simple cubic – Body centred cubic – Face centred cubic
(d) Body centred cubic – Face centred cubic – Simple cubic
26. For a Rhombohedral space lattice, which one of the following is correct?
- (a) $\alpha = \beta = \gamma = 90^\circ$
(b) $\alpha = \beta = \gamma = 90^\circ$
(c) $\alpha = \beta = 90^\circ = \gamma$
(d) $\alpha = \beta = \gamma \neq 90^\circ$
27. In the atomic hard-sphere model of the crystal structure of Copper, what is the edge length of unit cell?
- (a) $2 \times$ Atomic radius
(b) $(4/\sqrt{3}) \times$ Atomic radius
(c) $(2/\sqrt{2}) \times$ Atomic radius
(d) $\sqrt{2} \times$ Atomic radius
28. What is a surface imperfection, which separates crystals of different orientations a poly-crystalline aggregate, called?
- (a) Edge dislocation
(b) Stacking fault
(c) Grain boundary
(d) Screw dislocation
29. Which one of the following statements is correct in the case of screw dislocations?
- ($\vec{b}$ = Burger's Vector; $\vec{t}$ = Imaginary Vector)
- (a) $\vec{b}$ is perpendicular to $\vec{t}$
(b) $\vec{b}$ is parallel to $\vec{t}$
(c) $\vec{b}$ is inclined to $\vec{t}$
(d) $\vec{b}$ and $\vec{t}$ are non-coplaner and non-intersecting

30.

31.

32.

33.

34.

35.

30. **Assertion (A):** Elements are classified into metals and nonmetals on the basis of their atomic weights.

Reason (R): The valence electron structures contribute to the primary bonding between the atoms to form aggregates.

31. Which one of the following crystal systems is valid for gold?

(a) Orthogonal (b) Cubic
(c) Hexagonal (d) Triclinic

32. Which one of the following is correct for 'Climb'?

(a) Dislocation moves parallel to the slip plane
(b) Dislocation moves perpendicular to the slip plane
(c) Sliding of one plane of atoms over the other plane
(d) Dislocation moves from a slip plane to another slip plane

33. Which one of the following is correct for "Burger's vector" in screw dislocation?

(a) Perpendicular to the dislocation line
(b) Inclined to the dislocation line
(c) Parallel to the dislocation line
(d) Opposite to the dislocation line

34. Which one of the following defects is 'Schottky defect'?

(a) Vacancy defect
(b) Compositional defect
(c) Interstitial defect
(d) Surface defect

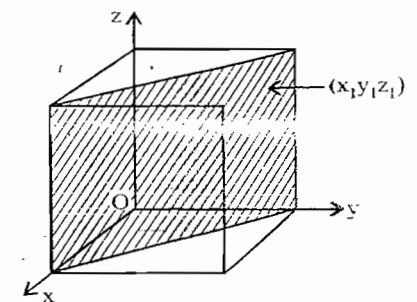
35. Surface imperfections which separate two orientations that are mirror image of one another is called

(a) Stacking fault
(b) Grain boundary
(c) Tilt boundary
(d) Twinned boundary

36. An allotropic material has

(a) Fixed structure at all temperatures
(b) Atoms distributed in random pattern
(c) Different crystal structures at different temperature
(d) Fixed structure but random atom distribution

37. Miller Indices (x, y, z) for the hatched plane in the below unit cell are represented as



(a) (1 0 0) (b) (1 1 0)
(c) (1 1 1) (d) (1 0 1)

DIRECTIONS:

The following items consists of two statements; one labelled as 'Assertion (A)' and the other as 'Reason (R)'. You are to examine these two statements carefully and select the answers to these items using the codes given below:

Codes:

(a) Both A and R are true and R is the correct explanation of A
(b) Both A and R are true but R is not a correct explanation of A
(c) A is true but R is false
(d) A is false but R is true

38. **Assertion (A):** Most of the materials exist in single crystal.

Reason (R): Sugar is a single crystal material.

39. **Assertion (A):** Poly-crystalline material is stronger than ordinary one.

Reason (R): Crystals in Poly-crystalline material have different orientations with respect to each other.

40. **Assertion (A):** Natural crystals always contain defects.

Reason (R): The defects may affect colour and can make a crystal a valuable gem.

41. The effective number of lattice points in the unit cell of simple cubic, body centered cubic, and face centered cubic space lattices, respectively, are

(a) 1, 2, 2 (b) 1, 2, 4

(c) 2, 3, 4 (d) 2, 4, 4

42. The material property which depends only on the basic crystal structure is

(a) fatigue strength

(b) work hardening

(c) fracture strength

(d) elastic constant



ANSWERS

1. (c)	11. (b)	19. (c)	27. (c)	35. (d)
2. (b)	12. (b)	20. (c)	28. (c)	36. (c)
4. (e)	13. (c)	21. (c)	29. (b)	37. (b)
5. (b)	14. (c)	22. (c)	30. (d)	38. (d)
7. (c)	15. (b)	23. (c)	31. (b)	39. (b)
8. (a,b)	16. (b)	24. (d)	32. (b)	40. (c)
9. (b)	17. (b)	25. (c)	33. (c)	41. (b)
10. (c)	18. (c)	26. (b)	34. (a)	42. (c)

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which depends
structure is

3

Phase Diagrams

3.1 SOLID SOLUTION

Solid Solution

Substitutional Solid Solution

Interstitial Solid Solutions

Intermediate Alloy Phase of Compound

Solubility Unit

Phase

Gibb's Phase Rule

Phase Equilibrium

Phase Diagram

Terminology Used in Phase Diagram

Type of Phase Diagram

Various Type of Phase Diagram Reaction

Congruent Phase Transformations

Relationship between the Phase Diagram and Properties of Material

Allotropy of Iron

Iron-Iron Carbide Phase Diagram

Transformation Rate Effects and TTT Diagrams, Microstructure and Property Changes in Fe-C Alloys

Limitations of TTT Diagram

Effect of Alloying Elements on TTT Curve

Influence of Alloying Elements on Phase Diagram

Effect of Alloying Element on Fe

- Solute is the minor element that is added to the solvent, and solvent is the major element of solution.
- When a particular crystal structure of the solvent is maintained during alloying the alloy is called a solid solution.
- The amount of solute that may be dissolved by the solvent is generally a function of temperature (with pressure constant) and usually increase with temperature.

There are three possible condition for solution :

- Unsaturated
- Saturated
- Supersaturated.

There are two types of solid solutions :

3.1.1 Substitutional Solid Solution

If the size of the solute atom is similar to that of the solvent atom, the solute atoms can replace solvent atoms to form a substitutional solid solution.

Example : Brass, in which zinc (solute atom) is introduced into the lattice of copper (Solvent).

Two conditions are generally required to form complete substitutional solid solution.

- Two elements must have similar crystal structure.
- The difference in their atomic radii should be less than 15%.

(d)

(c)

(b)

(d)

(b)

(c)

(b)

(c)

Example : In the Aluminium nickel alloy system, both metal are FCC. The relative size factor is 14%. However, nickel is lower in valence than Al and as per relative valence factor solid nickel dissolve 5% Al but higher valence Al, dissolve only 0.04 % Ni.

3.1.2 Interstitial Solid Solutions

- If the size of the solute atom is much smaller than that of the solvent atom the solute atom can occupy an interstitial position forming interstitial solid solution.
- Since the space of the lattice structure are restricted in size, only atoms with atomic radii less than 1 angstrom are generally form interstitial solid solution.
These are hydrogen (0.46), boron (0.97), Carbon (0.77), Nitrogen (0.71) and Oxygen (0.60).
- More solute atoms may be dissolved interstitially until the solution become saturated at that temperature.
- Interstitial solid solutions normally have limited solubility and generally are of a little importance.
- Carbon in iron is a notable exception and forms the basis for hardening steel.
- Carbon dissolves in iron interstitially. The maximum solubility of Carbon in iron (F.C.C.) is 2% at 1150°F while maximum solubility of carbon in α iron (B.C.C.) is only 0.025% at 727°C.

Two necessary conditions for forming ISS are :

- (i) The solvent atom must have more than one valence.
- (ii) The atomic radius of solute atom must be less than 59% of the atomic radii of solvent atom.

Example : Steel, where carbon atoms are present in interstitial positions between iron atoms with maximum percentage of 2. Atomic radius of carbon is 0.071 nm which is less than 59% of 0.125 nm radius of iron atom.

3.1.3 Intermediate Alloy Phase of Compound

The intermediate alloy phase are compound whose chemical composition are intermediate between the two pure metals and generally have crystal structures different from those of pure metals.

These are of three types

- (i) **Intermetallic compound or valency compound :** These are generally formed between chemical dissimilar metals and are combined by following the results of chemical valence. They have strong bonding their properties are essentially non metallic. These are formed where metals are far away in periodic table.
i.e., poor ductility, poor electrical conductivity.
e.g., MgPb_2 , Mg_2Sn , Cu_2Se , Ti_3Al , Ni_3Al etc.

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(ii) **Interstitial compound** : These compounds formed between the transition metal such as Scandium (SC), titanium (Ti), Ta, W, Fe etc with hydrogen, oxygen, carbon, boron & nitrogen.

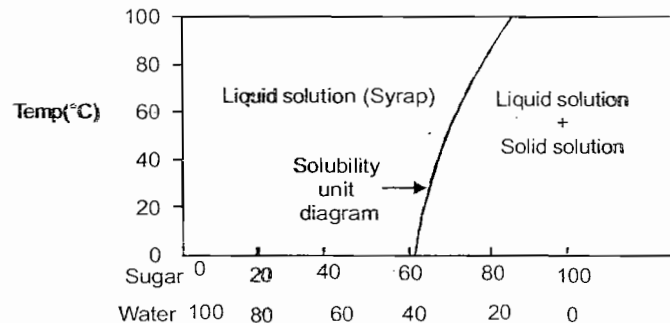
These compound are metallic having high melting point and are extremely hard.
e.g. TiC, TaC, Fe₄N, W₂C, CrN, TiH etc.

(iii) **Electron compound** : These are formed by Copper, gold, silver, iron, nickel with the metal like cadmium, magnesium, tin, zinc and aluminium.

These compound have definite ratio of valence electrons to atom and therefore called electron compound. Many electron compounds have properties resembling to solid solution.

3.2 SOLUBILITY UNIT

- Maximum concentration of solute atoms that may dissolve in the solvent to form a solid solution is called solubility limit.
- When this limit is exceeded it results in the formation of another solid solution that has distinctively different composition e.g., Sugar solution in water.



3.3 PHASE

- A phase is a **physically distinct, chemically homogeneous** and **mechanically seperable region** in a system in equilibrium.
- If more than one phase is present in a given system, each phase will have its own distinct properties and a boundary separating it from other phases will be there, across which there will be abrupt change in physical and chemical characteristics.
- If two phases are present in a system it may not be necessary that they differ in both physical and chemical properties.
- Gases are always single phase. Liquids can be single phase (salt solution) or two phase (oil and water). Solids can be multiphase or single phase (Pure metal).

- **Property** : It governs the state of system or we may say it as characteristic of system known as properties.
- **Compound** : It constitute the system :
- **Phase** :
- **Equilibrium** :
- **Degree of Freedom** : It is the number of independent variables required to describe the state of a system.

3.3.5 Type of Phase Diagram

1. **Unary phase diagram (single component)**: It is used mainly for carbon and pure metal.

There is very limited practical utilities of such diagram plotted between temperature and pressure axis.

Example : Water, graphite, mettalic carbon, diamond.

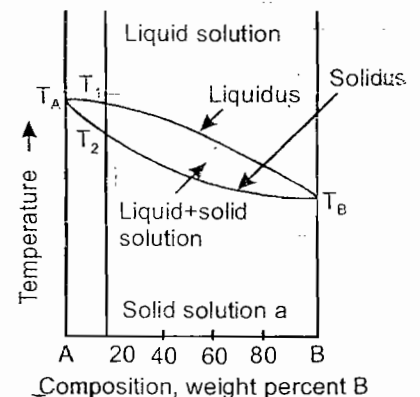
2. **Binary phase diagram (two components)** :

These are of following type :

3.3.5.1 Type 1 (Binary Isomorphous Systems)

The material which are completely soluble in liquid as well as solid state.

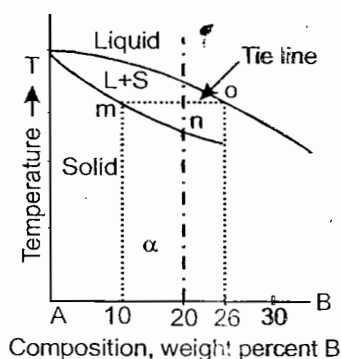
- Since, the two metals are completely soluble in solid state, the only type of solid phase formed will be a substitution solid state.
- The two metals will generally have the same type of crystal structure and differ in atomic radii by less than 8%. The corresponding such diagram shown below :
- This phase diagram consist of two points and three areas. The two points of the two pure metals A & B.
- The upper line, obtained by connecting the points showing the beginning of solidification is called liquidus line, and the lower line, determined by connecting the points showing the end of solidification is called the solidus line.
- Area above the liquidus line is single phase region and any alloy in that region will consist of homogeneous liquid solution. Similarly, lower region is homogeneous in nature.
- In between the solidus and liquidus line there exist a two phase region. It is the mixture of both solid and liquid, it is mushy in type.



There is two rule to find the actual composition and relative amounts of the two phases that are present :-

(i) **Rule 1. (Chemical composition of phases) :** To determine the actual chemical composition of the phase of an alloy, in equilibrium at any specified temperature in a two-phase region, draw a **horizontal temperature line** (called a **tie line**) to the boundaries of the field.

- These points of intersection are dropped to the base line, and the composition is read directly. e.g., In the below figure 'mo' tie line to the boundaries of the field.
- Point 'm', the intersection of the tie line with the solidus line, when dropped to the base line, gives the composition of the phase that exists at that boundary.
- In this case, the phase is a solid solution α of composition 90A-10B. Similarly, point O, when dropped to the base line, will give the composition of the other phase constituting the mixture in the liquid solution of composition



Rule 2. (Relative amount of each phase) : To determine the relative amount of the phases in equilibrium at any specified temperature in a two phase region, draw a horizontal line representing the alloy and a horizontal temperature line to the boundaries of the field. The vertical line will divide the horizontal line into two parts whose lengths are inversely proportional to the amount of phase present. This is known as lever rule.

- The point where the vertical line intersects the horizontal line may be considered as the fulcrum of a lever system. The relative length of the lever arms multiplied by the amounts of the phase present must balance. In the previous figure, the vertical line representing the alloy 20B, divides the horizontal tie line into two parts 'mn' and 'no'.
- If the entire length of the tie line mo is taken to represent 100% or the total weight of the two phases present at temperature T, the lever rule may be expressed mathematically as:

$$\text{Liquid (\%)} = \frac{mn}{mo} \times 100$$

$$\alpha(\%) = \frac{no}{mo} \times 100$$

For numeral value

Note :

The ab

- This stru

$$\text{Liquid (\%)} = \frac{10}{16} \times 100 = 62.5\%$$

$$\alpha(\%) = \frac{6}{16} \times 100 = 37.5\%$$

- For such phase diagram, there is one degree of freedom.

So, in this case Gibb's rule converts into

$$F - 1 + P = C + 2 - 1$$

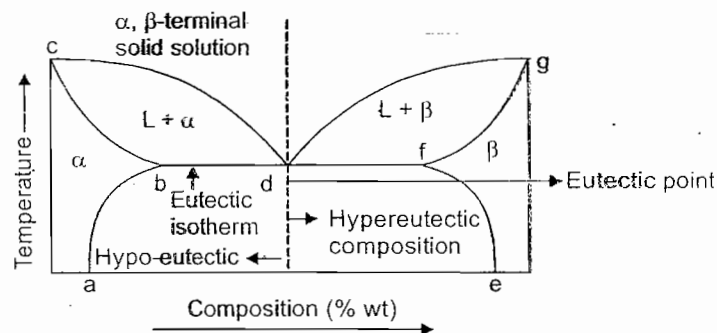
$$F + P = C + 1 \quad \text{e.g., Cu \& Ni solution.}$$

Basically, when the material transform from one phase to another phase two type of process occur :

$$V_{\text{Liquid}} = \frac{V_{\alpha}}{V_{\alpha} + V_{\text{Liquid}}}; \quad V_{\alpha} = \frac{V_{\text{Liquid}}}{V_{\alpha} + V_{\text{Liquid}}}$$

$$\text{or} \quad V_{\text{Liquid}} = \frac{\frac{\text{Weight of } \alpha}{\text{density of } \alpha}}{\frac{\text{Weight of } \alpha}{\text{density of } \alpha} + \frac{\text{Weight of liquid}}{\text{density of liquid}}}$$

$$\text{Similarly,} \quad V_{\alpha} = \frac{\frac{\text{Weight of liquid}}{\text{density of liquid}}}{\frac{\text{Weight of } \alpha}{\text{density of } \alpha} + \frac{\text{Weight of liquid}}{\text{density of liquid}}}$$



Note : When process is carried out below the recrystallization temperature ($0.3T_m$ to $0.5T_m$) these are known as cold working and above of it is termed as hot working. Here T_m = Melting temperature.

The above figure shows the following :

- This phase is a substitutional solid solution of Cu and Ni atoms and having FCC structures.

- At temperature below 1085°C Cu and Ni are mutually soluble in each other in solid state for all composition as both have same FCC crystal structure and nearly identical atomic radii and electronegativity.
- Liquid (L): It is a homogenous liquid solution composed of both Cu and Ni.
- ($\alpha + L$): Phase between liquidus line and solidus line. This is a mushy zone where both Cu and Ni are present in varying compositions.
- Solidus and liquidus lines intersect at two extremities (composition) point of intersection represents the melting point of pure metal (Cu and Ni).
- Melting or freezing occurs over a range of temperatures between solids and liquidus lines.

Phase diagrams gives there kinds of informations.

(i) Phases present

(ii) Composition of phases present

(iii) Percentages of the phase

3.3.5.2 Binary Phase Diagram of Type-II

- The material which are completely soluble in liquid state but partially soluble in solid state (eutectic phase diagram) :

Binary Eutectic system consists of three phase

(i) α

(ii) β {Solid solutions}

(iii) Liquid phase (L)

- Here a eutectic point is defiend, where degree of fredoms are zero.

Example 1 :

Cu-Ag eutectic Phase Diagram

- Eutectic means in latin word Eu means : nice & tectic means : melting.

Here number of phase equal to 3.

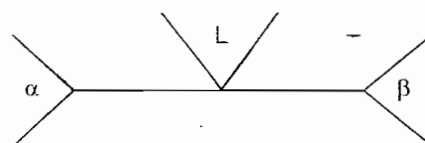
- As per Gibb's law $F + P = C + 1$

- At eutectic point

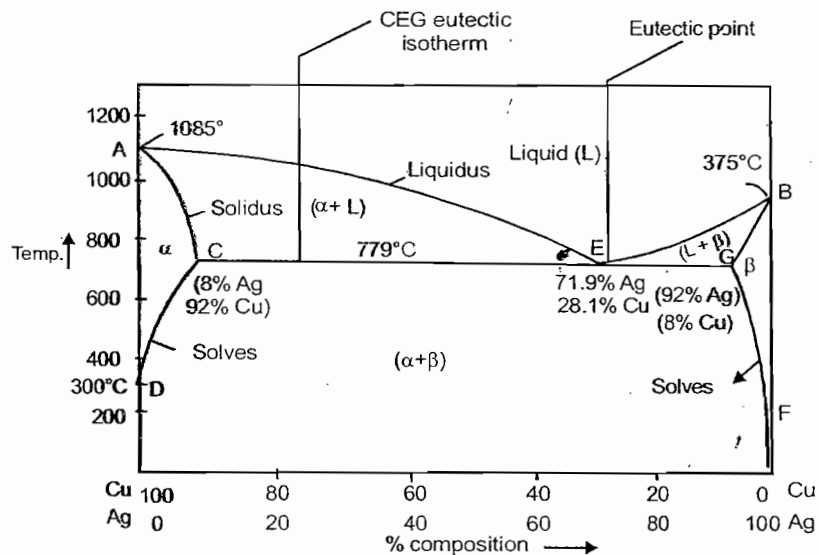
$F = 0$, So by Gibb's law

$O + P = 2 + 1$; $P = 3$.

So three phase α , β , L will be there at eutectic point.



Schematic of eutectic invariant reaction



α phase: It is rich in copper and Ag is present as solute and has FCC structure.

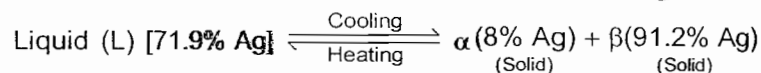
β phase: It is rich in Ag and Cu is present as solute and again has FCC structure.

$(\alpha + \beta)$ phase constitutes of pure copper and pure silver.

- Below line CEG (779°C), there is only partial solubility of Ag in Cu (α phase) and Cu in Ag (β -phase). Maximum solubility of Ag in Cu occurs at 779°C and is 8%. Likewise, maximum solubility of Cu is 8.8% in Ag again at 779°C.
- Solvus line demarcates between α and $(\alpha + \beta)$ phases and β and $(\alpha + \beta)$ phases.

Salient Features

- In liquid regions as silver is added to copper, we see that on the liquidus line AE, the melting point of copper decreases with silver addition. Same is true for copper addition to silver.
- Point E on the phase diagram it is called invariant point at this point an important reaction takes place at constant temperature Called Eutectic reaction where liquid (L) is directly converted to (α) and β phase.



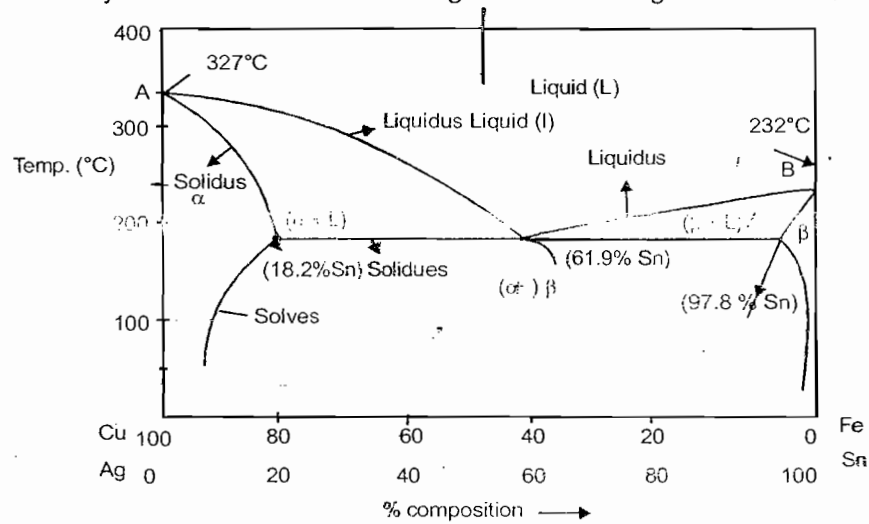
- Line CEG is called eutectic isotherm.
- It is also seen that single phase region (α or β) are separated from each other by a two phase region.

- Invariant point is also termed as eutectic point.
- Invariant reaction: The eutectic reaction, in which a liquid transforms into two solid phases, is just one of the possible three-phase invariant reaction that can occur in binary system those are not isomorphous.

Example 2 :

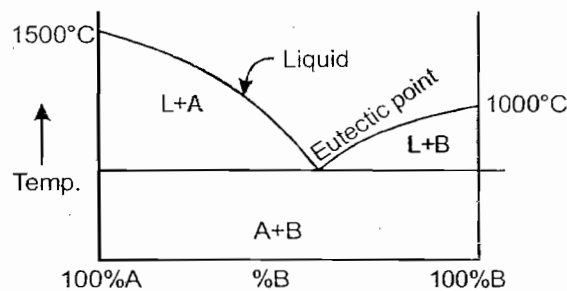
Sn-Pb Eutectic System

- For a 40% Sn – 60% Cu alloy at 150°C. Calculate composition of phase present.
- Amount of each phase present in terms of mass fractions and volume fractions. Given density of Pb and Sn are 11.23 kg/cm³ and 7.24 g/cm³.



3.3.5.3 Binary Phase Diagram of Type-III

The material which are completely soluble in liquid state and completely insoluble in solid state.

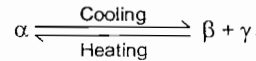


Example : Alloy of Bi.

3.4 VARIOUS TYPE OF PHASE DIAGRAM REACTION

Eutectoid Reaction

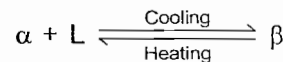
- Here a solid phase (α) directly transforms to two other solid phase (β) and (γ). Eutectoid means eutectic like.



- It is also an invariant reaction. It is denoted by point E.

Peritectic Reaction

- It involved three phases at equilibrium. In this reaction upon cooling a solid and a liquid, phase transform isothermally to a solid phase (β).



- The new solid formed is usually an intermediate phase but in some case it is terminal solid solution.
- Peritectic reaction occurs in alloys having large difference in melting point.

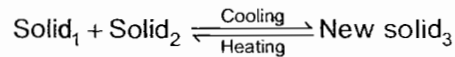
Peritectoid Reaction

- It involves reaction between two solid and final product will be solid.
- The peritectoid reaction has the same relationship to the peritectic reaction as the eutectoid has to the eutectic. The new product is intermediate alloy.

Note : Eutectic temperature is lower to melting point of all other composition. Eutectic means nice melting.

Summary of invariant reaction in binary system

Reaction	Symbolic equation	Schematic presentation	Example
Eutectic	$L \leftrightarrow \alpha + \beta$		Fe-C, 4.27C%, 1147°C
Eutectoid	$\alpha \leftrightarrow \beta + \gamma$		Fe-C, 0.80C%, 723°C
Peritectic	$L + \alpha \leftrightarrow \beta$		Fe-C, 0.16%C, 1495°C
Peritectoid	$\alpha + \beta \leftrightarrow \gamma$		
Monotectic	$L_1 \leftrightarrow L_2 + \alpha$		Fe-C, 0.51%C, 1495°C



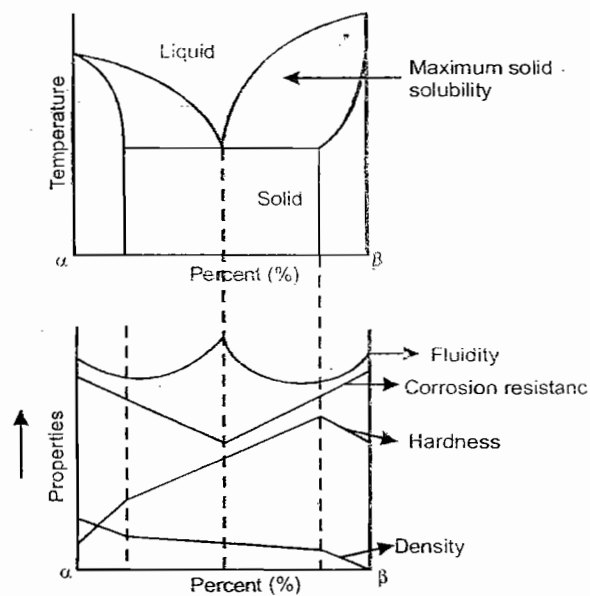
Monotectic Reaction : $\text{Liquid}_1 \xrightleftharpoons[\text{Heating}]{\text{Cooling}} \text{Liquid}_2 + \text{Solid}$

Syntetic Reaction: In this two liquid phases react to form a solid phase.

3.5 CONGRUENT PHASE TRANSFORMATIONS

- These are phase transformation for which there are no alteration in composition of phases.
e.g. Allotropic transformations and melting of pure metals.
- **Incongruent transformations**, at least one of the phase will experience change in composition.
e.g. Eutectic and Peritectic reactions.
- These are carried out isothermally.

3.6 RELATIONSHIP BETWEEN THE PHASE DIAGRAM AND PROPERTIES OF MATERIAL



(Properties of material in eutectic system)

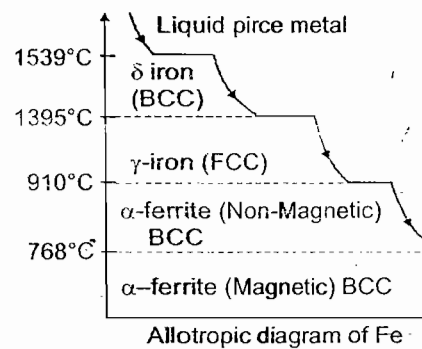
- Fluidity is maximum for pure material at eutectic. It is directly proportional to the area of mushy zone. Larger the area of mushy zone. Lower will be the fluidity.

- Corrosion resistance : Poor for eutectic composition. It increase both side of eutectic point.
- Generally density is higher for low melting point materials.
- Hardness of pure material is very poor and maximum strength will be at the point of maximum solid solubility.

3.7 ALLOTROPY OF IRON

1. **α -ferrite** : It is a solid solution of BCC iron and carbon with maximum solubility of carbon is 0.022% at 727°C.

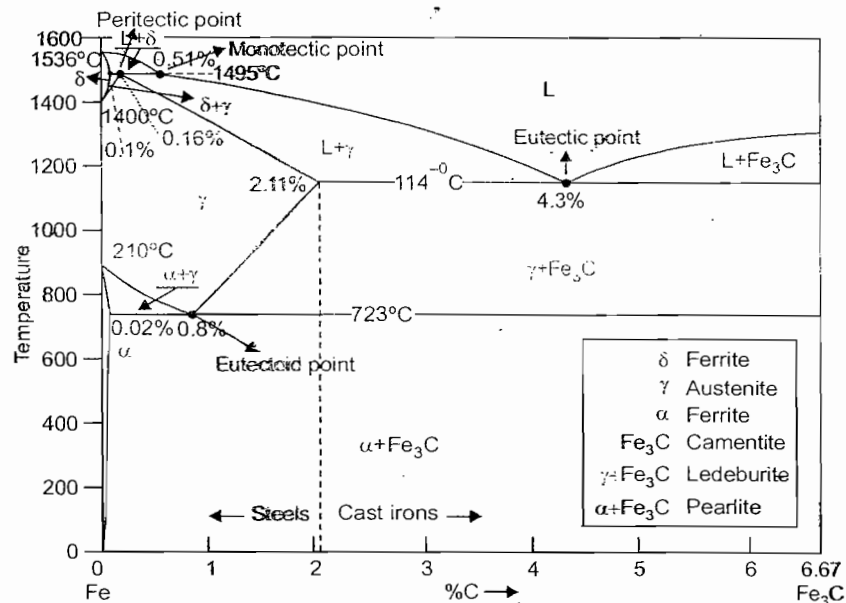
- At room temperature it has **only** 0.002% C.
- δ -ferrite is stable at very high temperature.
- α -ferrite is soft and ductile and magnetic from room temperature to 768°C (curie pt), above which upto 910°C it is non-magnetic.



2. **γ -iron or austenite** : It is a solid solution of FCC iron and carbon with maximum solubility of 2.11% C at 1148°C.
 - It is present between temperature limits from (910°C to 1395°C).
 - It is because of FCC structure it has more interstitial positions, thus solid solubility of carbon increases in austenite phases.
 - It is denser than ferrite and ductile at elevated temperature.
 - It is non-magnetic.
3. **Cementite or Fe_3C** : It is 100% iron carbide having maximum solid solubility of 6.67% C.
 - It is **very hard and brittle** intermetallic compound and has significant influence on the properties of steel.
 - The **martensitic transformation** starts at a temperature designated M_s , which is generally below the equilibrium temperature, T_e .

3.8 IRON-IRON CARBIDE PHASE DIAGRAM

- The Fe-Fe₃C is defined by five individual phases and four invariant reactions. Five phases are: α -ferrite (BCC) Fe-C solid solution, γ -austenite (FCC) Fe-C solid solution, δ -ferrite (BCC) Fe-C solid solution, Fe₃C (iron carbide) or cementite - an inter-metallic compound and liquid Fe-C solution. Four invariant reactions are eutectoid, eutectic, monotectic and peritectic.
- As shown in figure by left axes, pure iron upon heating exhibits two allotropic changes. One involves α -ferrite of BCC crystal structure transforming to FCC austenite, γ -iron, at 910°C. At 1400°C, austenite changes to BCC phase known as δ -ferrite, which finally melts at 1536°C.
- Carbon present in solid iron as interstitial impurity, and forms solid solution with ferrites/austenite as depicted by three single fields represented by α , γ and δ . Carbon dissolves least in α -ferrite in which maximum amount of carbon soluble is 0.02% at 723°C.
- This limited solubility give the shape and size of interstitial position in BCC α -ferrite. However, carbon present greatly influences the mechanical properties of α -ferrite. α -ferrite can be used as magnetic material below 768°C. Solubility of carbon in γ -iron reaches its maximum, 2.11%, at a temperature of 1147°C.



- Higher solubility of carbon in austenite is property of FCC structure and corresponding interstitial sites. Phase transformations involving austenite plays very significant role

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in heat treatment of different steels. Austenite itself is non-magnetic. Carbon solubility in δ -ferrite is maximum (0.1%) at 1495°C.

- As this ferrite exists only at elevated temperature, it is of no commercial importance.
- Out of these four solid phases, cementite is hardest and brittle that is used in different forms to increase the strength of steels. α -ferrite, on the other hand is softest and act as matrix of a composite material.
- Based on %C dissolved in it, a Fe-C solution is classified as: commercial pure irons with less than 0.008%C; steels having %C between 0.008-2.11; while cast irons have carbon in the range of 2.11%-6.67%.
- Thus commercial pure iron is composed of exclusively α -ferrite, at room temperature.
- The presence of Si promotes the formation of graphite instead of cementite.
- Fe-C system constitutes four invariant reactions:
 - peritectic reaction at 1495°C and 0.16%C, $\delta\text{-ferrite} + L \leftrightarrow \gamma\text{-iron (austenite)}$
 - monotectic reaction 1495°C and 0.51%C, $L \leftrightarrow L + \gamma\text{-iron (austenite)}$
 - Eutectic reaction at 1147°C and 4.3%C, $L \leftrightarrow \gamma\text{-iron} + \text{Fe}_3\text{C (cementite)}$
[ledeburite]
 - eutectoid reaction at 723°C and 0.8%C, $\gamma\text{-iron} \leftrightarrow \alpha\text{-ferrite} + \text{Fe}_3\text{C (cementite)}$
[pearlite]
- Product phase of eutectic reaction is called ledeburite, while product from eutectoid reaction is called pearlite. During cooling to room temperature, ledeburite transforms into pearlite and cementite.
- Pearlite is in reality not a single phase, but a micro-constituent having alternate thin layers of α -ferrite (~88%) and Fe_3C cementite (~12%). Steels with less than 0.8%C (mild steels upto 0.3%C, medium carbon steels with C between 0.3%-0.8% i.e. hypo-eutectoid Fe-C alloys) i.e. consists pro-eutectoid α -ferrite in addition to pearlite, while steels with carbon higher than 0.8% (high-carbon steels i.e. hyper-eutectoid Fe-C alloys) consists of pearlite and pro-eutectoid cementite.
- Phase transformations involving austenite i.e. processes those involve eutectoid reaction are of great importance in heat treatment of steels.
- Generally, steels are almost always cooled from the austenitic region to room temperature. During the cooling upon crossing the boundary of the single phase γ -iron, first-pro-eutectoid phase (either α -ferrite or cementite) forms up to eutectoid temperature.
- With further cooling below the eutectoid temperature, remaining austenite decomposes to eutectoid product called pearlite, mixture of thin layers of α -ferrite and cementite.

- Though pearlite is not a phase, and also not a constituent.
- The decomposition of austenite to form pearlite occurs by nucleation and growth. Nucleation, usually, occurs heterogeneously and rarely homogeneously at grain boundaries.
- When austenite forms pearlite at a constant temperature, the spacing between adjacent lamellae of cementite is nearly constant. For a given colony of pearlite, all cementite plates have a common orientation in space, and it is also Applicable for the ferrite plates.
- Growth of pearlite colonies occurs not only by the nucleation of additional lamellae but also through an advance at the ends of the lamellae.
- The thickness ratio of the ferrite and cementite layers in pearlite is approximately 8 to 1. However, the actual layer thickness depends on the temperature at which the isothermal transformation is allowed to occur.
- The spacing of the pearlite lamellae has a practical significance because the hardness of the resulting structure depends upon it; the smaller the spacing, the harder the metal.
- The growth rate of pearlite is also a strong function of temperature. At temperatures just below the eutectoid, the growth rate increases rapidly with decreasing temperature, reaching a maximum at 600°C, and then decreases again at lower temperatures.
- Additions of alloying elements to Fe-C system bring changes (alternations to positions of phase boundaries and shapes of fields) depends on that particular element and its concentration.
- Generally all alloying elements causes the eutectoid concentration to decrease, and most of the alloying elements (e.g. : Ti, Mo, Si, W, Cr) causes the eutectoid temperature to increase while some other (e.g.: Ni, Mn) reduces the eutectoid temperature. Thus, alloying additions alters the relative amount of pearlite and pro-eutectoid phase that form.
- Fe-C alloys with more than 2.11%C are called cast irons. Phase transformations in cast irons involve formation of pro-eutectic phase on crossing the liquidus. During the further cooling, liquid of eutectic composition decomposes in to mixture of austenite and cementite, known as ledeburite. On further cooling through eutectoid temperature, austenite converted to pearlite.
- The room temperature microstructure of cast irons thus consists of pearlite and cementite. Because of presence of cementite (which is hard, brittle and white in color) product is called white cast iron. However, depending on cooling rate and other alloying elements, carbon in cast iron may be present as graphite or cementite. Gray cast iron contains graphite in form of flakes.

- These flakes are sharp and act as stress risers. Brittleness arising because of flake shape can be avoided by producing graphite in spherical modules, as in malleable cast iron and SG (spheroidal graphite) cast iron. Malleable cast iron is produced by heat treating white cast iron ($\text{Si} < 1\%$) for prolonged periods at about 900°C and then cooling it very slowly.

3.9 TRANSFORMATION RATE EFFECTS AND TTT DIAGRAMS, MICROSTRUCTURE AND PROPERTY CHANGES IN IRON-CARBON ALLOYS

- Solid state transformations, which are very important in steels, are known to be dependent on time at a particular temperature, as shown in figure.
- Isothermal transformation diagram, also called as TTT diagram, measures the rate of transformation at a constant temperature i.e. it shows time relationships for the phases during isothermal transformation. Information regarding the time to start the transformation and the time required to complete the transformation can be obtained from set of TTT diagrams.
- One such set of diagram for reaction of austenite to pearlite in steel is shown in below figure. The diagram is not complete in the sense that the transformations of austenite that occur at temperatures below about 550°C are not shown.
- This curve also termed as S-curve or Ben-curve.

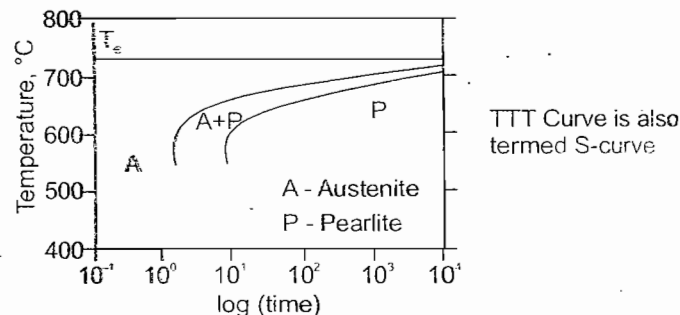


FIGURE : Partial TTT diagram for a eutectoid Fe-C alloy.

- As thickness of layers in pearlite depends on the temperature at which the transformation occurred.
- If the transformation took place at a temperature that is just below the eutectoid temperature, relatively thick layers of α -ferrite and cementite are produced and is termed as coarse pearlite.

- This is because of high diffusion rates of carbon atoms. Thus with decreasing transformation temperature, very slow movement of carbon results in thinner layers α -ferrite and cementite i.e. fine pearlite is obtained.
- At transformation temperatures below 550°C , austenite results in different product known as bainite. Bainite consists of α -ferrite and cementite phases.
- Bainite forms needles or plates, depending on the temperature of the transformation; the microstructural details of bainite are so fine that they can be seen only through electron microscope.
- It differs from pearlite in the sense that different mechanism is involved in formation of bainite which does not have alternating layers of α -ferrite and cementite.
- In addition, because of equal growth rates in all directions pearlite try to form spherical colonies, whereas bainite grows as plates and has a acicular (needlelike) appearance.
- Upper bainite, formed at the upper end of the temperature range (550°C - 350°C), is perceived by relatively coarse, irregular shaped cementite particles in α -ferrite plates.
- If the transformation is taking place at lower temperatures (350°C - 250°C), the α -ferrite plates turned out to be a more regular needlelike shape, and the obtained product is called lower bainite.
- At the same time carbide particles become smaller in size and appear as cross-stratifications making an angle of about 55° to the axis of the α -ferrite plate.
- Upper bainite has large rod-like cementite regions, whereas lower bainite has much finer cementite particles as a due to very slow diffusion of carbon atoms at lower temperatures. Lower bainite is considerably harder than upper bainite.
- Another characteristic of bainite is that as it has crystallographic orientation that is similar to that of ferrite nucleating from austenite, it is thought that bainite is nucleated by the formation of ferrite.
- This is opposite to pearlite which is thought to be nucleated by formation of cementite.
- Bainite is a transformation product that is not as close to equilibrium as pearlite. The most confusing feature of the bainite reaction is its dual nature.
- In terms of numbers, it reveals properties that are typical of a nucleation and growth type of transformation such as occurs in the formation pearlite and also a mixture of α -ferrite and cementite despite the quite different morphology (no alternate layers), but at the same time it differs from the Martensite as bainite formation is athermal and diffusion controlled though its microstructure is founded by acicular (needlelike) appearance.
- The time-temperature dependence of the bainite transformation can also be presented using TTT diagram. It occurs at temperatures below those at which pearlite forms i.e.

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it does not form until the transformation temperature falls below a definite temperature, designated as B_s .

- Above this temperature austenite does not form bainite except under action of external stresses. Below B_s , austenite does not transform completely to bainite. The amount of bainite formed increases as the isothermal reaction temperature is lowered.
- By reaching a lower limiting temperature, B_f , it is possible to transform austenite completely to bainite. The B_s and B_f temperatures are equivalent to the M_s and M_f temperatures for Martensite.
- In simple eutectoid steels, pearlite and bainite transformations overlap, thus transition from the pearlite to bainite is smooth and continuous i.e. knees of individual pearlite and bainite curves are merged together. However each of the transformations has a characteristic C-curve, which can be distinguishable in presence of alloying elements.
- As shown in complete TTT diagram for eutectoid steel in figure above approximately 550°C-600°C, austenite transforms completely to pearlite. Below this range up to 450°C, both pearlite and bainite are formed. Finally, between 450°C and 210°C, the reaction product is bainite only.
- Thus bainite transformation happened at a high degree of supercooling, and the pearlite transformation at a low degree of supercooling. In middle region, pearlitic and bainitic transformations are competitive with each other.

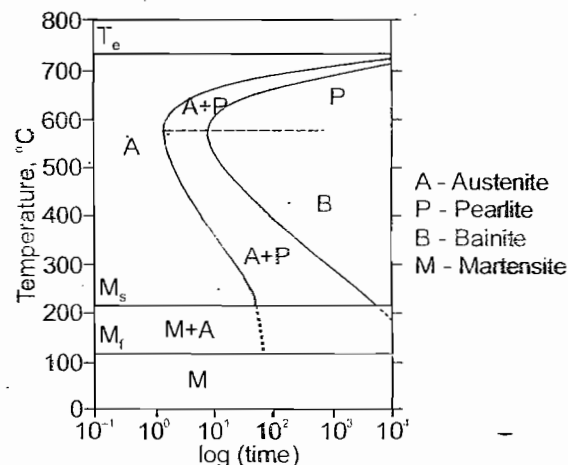


FIGURE : Complete TTT (isothermal transformation) diagram for eutectoid steel.

- Martensitic transformation can dominate the proceedings if steel is cooled rapid enough so that diffusion of carbon can be seized. Transformation of austenite to Martensite is diffusion-less, time independent and the extent of transformation depends on the transformation temperature.

- Martensite is a meta-stable phase and decomposes into ferrite and pearlite but this is extremely slow (and not noticeable) at room temperature.
- Alloying retard the formation rate of pearlite and bainite. Start of the transformation is designated by M_s , while the completion is designated by M_f in a transformation diagram.
- Martensite forms in steels possesses a body centred tetragonal crystal structure with carbon atoms occupying one of the three interstitial sites available.
- Tetragonal distortion caused by carbon atoms increases with increasing carbon content and so is the hardness of Martensite.
- Mechanically, Martensite is extremely hard, thus its applicability is limited by brittleness associated with it.
- However, structure and the properties can be altered by tempering, heat treatment observed below eutectoid temperature to permit diffusion of carbon atoms for a reasonable period of time.
- During tempering, carbide particles attain spherical shape and are bifurcated in ferrite phase – structure called spheroidite. Spheroidite is the softest yet toughest structure of the steel.
- At lower tempering temperature (250° to 650°), a structure called tempered Martensite with similar microstructure as like spheroidite except that cementite particles are very, much smaller. The tempering heat treatment is also applicable to pearlitic and bainitic structures.
- At higher temperatures of with increasing tempering times, precipitation of cementite begins and is finished by dissolution of the unstable carbide. Furthermore, the Martensite loses its tetragonality and becomes BCC ferrite, the cementite coalesces into sphered. A schematic of possible transformations involving austenite decomposition are shown in below figure.

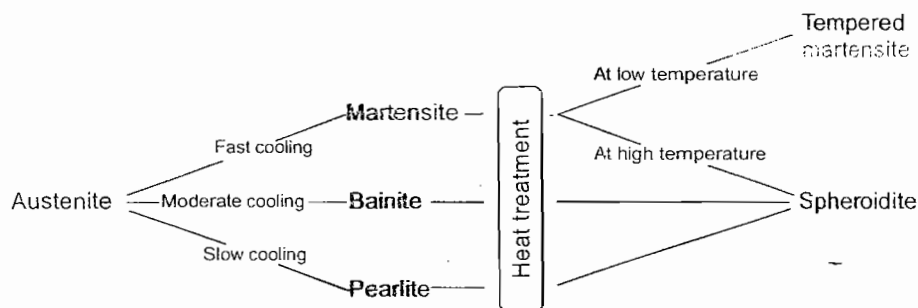


FIGURE : Possible transformation involving austenite decomposition.

- Tempering of some steels may result in a reduction of toughness called as temper embrittlement. This may be avoided by (1) compositional control, and/or (2) tempering above 575 or below 375, followed by quenching to room temperature.

- Impurities responsible for temper brittleness are: P, Sn, Sb and As. Si reduces the risk of embrittlement by carbide formation. Mo has a stabilizing effect on carbides and is also used to minimize the risk of temper brittleness in low alloy steels.
- TTT diagrams have less of practical importance since an alloy has to be cooled rapidly and then kept at a temperature to allow for respective transformation to take place. However, most industrial heat treatments involve continuous cooling of a specimen to room temperature.
- Hence, Continuous Cooling Transformation (CCT) diagrams are generally more appropriate for engineering applications.
- CCT diagrams measure the extent of transformation as a function of time for a continuously decreasing temperature.
- Both TTT and CCT diagrams are, in a sense, phase diagrams with added parameter in form of time. Each is experimentally determined for an alloy of specified composition.
- Thus, as shown in below figure, region representing austenite-pearlite transformation terminates just below the nose.

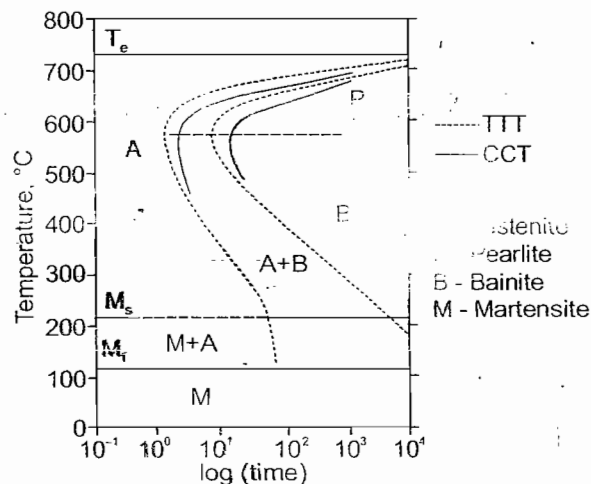


FIGURE : Superimposition of TTT and CCT diagrams for a eutectoid steel.

Note : Temper embrittlement phenomenon occurs when steel is tempered to a temperature above about 575°C or (between 375°C to 575°C).

3.9.1 Limitations of TTT Diagram

- Only applicable for iron-carbon alloy of eutectoid composition thus for other composition, curves will have different configurations.
- These plots are accurate only for transformations in which the temperature of alloy is held constant throughout the duration.

3.9.2 Effect of Alloying Elements on TTT Curve

Alloying elements like Cr, Ni, Mo and W can have two effects :

- To shift the nose of Austenite to pearlite transformation diagram to longer times.
- Formation of a separate Bainite Nose.

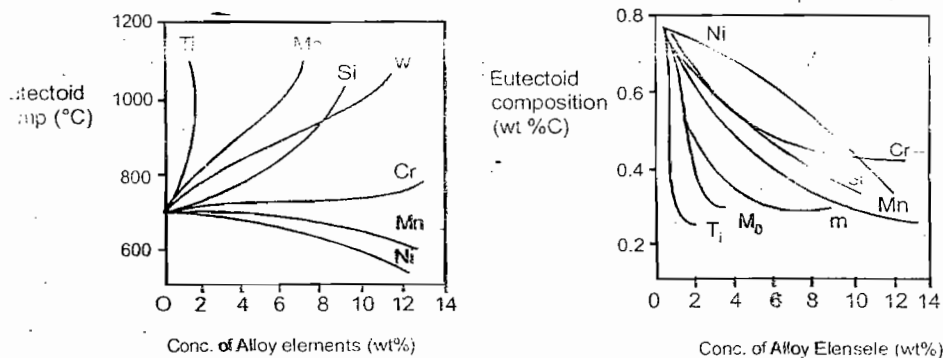
Note : 1. Annealing : When rate of cooling is very slow 10°C/S or less.

2. Normalizing : Rate of cooling is slow as 50°C/S or less.

3. Hardening: Rate of cooling is faster than critical cooling 350°C/S or marks.

3.10 INFLUENCE OF ALLOYING ELEMENTS ON PHASE DIAGRAM

Alloys elements addition always reduces eutectoid composition i.e. % of C while they may increase or decrease the eutectoid temperature. (Ni) specially is an austenite stabilizer.



3.11 EFFECT OF ALLOYING ELEMENT ON Fe

1. **Carbon** : By increase in percentage of carbon in iron, ductility decreases and brittleness increases and when carbon % increase from more than 2.1 % in iron, iron convert into cast iron.
2. **Sulfur** : Sulfur in commercial steel is generally kept below 0.05%. Sulfur formed iron sulfide with iron, Iron sulfide forms a low melting point eutectic alloy with iron which tends to concentrate at the grain boundaries. When the steel is forged or rolled at elevated temperatures, the steel becomes brittle or hot-short due to the melting of the iron sulfide eutectic which destroys the Cohesion between the grains allowing cracks to develop, and material got failed due to brittle fracture.

- To overcome from this problem Manganese is added with which Sulfur formed manganese sulfide rather than FeS. Manganese sulfide improve the machinability as due to presence of more number of sulfide inclusions which breakup the chips, thus reducing tool wear.

- It is noted that Mn has low shear strength.

3. **Manganese** : It promotes the soundness of steel casting through its deoxidizing action on liquid steel.

- Large quantity of manganese in steel formed MnS as well as Mn_3C which is formed associated with cementite.
- Hadfield steel have 12% Mn and to make Bull-dozer rolls.

4. **Phosphorus** : Phosphorus generally kept below 0.4%.

- This small quantity tends to dissolve in ferrite, increasing the strength and hardness slightly. Large quantity of phosphorus tend to crack the steel when cold worked making steel cold-short.

5. **Silicon** : It's amount generally varies in between 0.05% to 0.3%.

- It dissolves in ferrite, increasing the strength of steel without gradually decreasing the ductility.
- By addition of Silicon, eutectic point shift towards left and graphite formation takes place at much lower percentage of Carbon.
- If act as deoxidizer.

□□□

QUESTIONS

1. Eutectoid reaction occurs at
(a) 600°C (b) 723°C
(c) 114°C (d) 1493°C
2. Match List-I (Name of material) with List II (% Carbon range) and select the correct answer using the codes give below the lists:
 A. Hypo-eutectoid steel
 B. Hyper-eutectoid steel
 C. Hypo-eutectic cast iron
 D. Hyper-eutectic cast iron
 List-II
 1. 4.3 – 6.67
 2. 2.0 – 4.3
 3. 0.8 – 2.0
 4. 0.008–0.8
 Codes:

	A	B	C	D
(a)	4	3	2	1
(b)	1	3	4	2
(c)	4	1	2	3
(d)	1	2	3	4
3. Which one of the following sets of constituents is expected in equilibrium cooling of a hypereutectoid steel from austenitic state?
(a) Ferrite and pearlite
(b) Cementite and pearlite
(c) Ferrite and bainite
(d) Cementite and martensite
5. In a eutectic system, two elements are completely
(a) Insoluble in solid and liquid state
(b) Soluble liquid state
(c) Soluble in solid state
(d) Insoluble in liquid state
6. During peritectic solidification, one liquid
(a) combines with one solid to form a second new solid
(b) Solidifies into two different solids
(c) forms one solid
(d) forms one solid and another liquid
7. Martensite is a supersaturated solution of carbon in
(a) alpha iron (b) beta iron
(c) gamma iron (d) delta iron
9. Match List-I (Phase diagram) with List-II (Characteristic) and select the correct answer using the codes given below the lists:
 List-I
 A. Isomorphous system
 B. Eutectic system
 C. Peritectic system
 D. Monotectic system
 List-II
 1. One liquid decomposes into another liquid and solid
 2. One liquid and another solid combine to form a new solid

3. Two metals are completely soluble in liquid state and completely insoluble in solid state

4. Two metals, soluble in solid and liquid state

Codes:

	A	B	C	D
(a)	2	3	4	1
(b)	4	1	2	3
(c)	2	1	4	3
(d)	4	3	2	1

10. I.T.T. diagram indicates time and temperature transformation of

- (a) Cementite (b) Pearlite
(c) Ferrite (d) Austenite

11. A 60 C-plain carbon steel has, approximately,

- (a) 75% of pearlite and 25% of ferrite
(b) 25% of pearlite and 75% of ferrite
(c) 75% of cementite and 25% of ferrite
(d) 75% of pearlite and 25% of cementite

12. Increase of ferrite phase in steel increases

- (a) Strength (b) Hardness
(c) Ductility (d) Brittleness

13. The eutectoid of carbon in iron, above lower critical temperature, when cooled, results in

- (a) Ferrite and austenite
(b) Ferrite and cementite
(c) Cementite and austenite
(d) Ferrite, cementite and austenite

14. Match List-I (Fe-Fe₃C Phase Diagram Characteristic) with List-II (Phase) and select the correct answer using the codes given below the lists:

List-I

- A. Alpha (α) iron
B. Iron carbide having crystal lattice
C. BCC pure allotrope of iron is stable between 1388°C & its melting point at 1535°C

List-II

1. δ iron
2. Eutectic with 3 iron and 1 carbon atom
3. Ferrite stable between 1388°C
4. Cementite

Codes:

	A	B	C
(a)	4	2	3
(b)	3	4	1
(c)	4	2	1
(d)	3	1	2

15. Match List-I (Effect of Cooling) with List-II (Cooling Medium) and select the correct answer using the codes given below the lists:

List-I

- A. Martensite
B. Very fine pearlite
C. Fine pearlite
D. Coarse pearlite

List-II

1. Water quenched
2. Air cooled
3. Furnace cooled
4. Oil quenched

Codes:

	A	B	C	D
(a)	1	4	2	3
(b)	2	3	1	4
(c)	2	3	4	1
(d)	1	2	3	4

16. Which one of the following is the correct statement?

Pearlite in iron-carbon system is a

- (a) phase consisting of ferrite and cementite at room temperature
- (b) mechanical mixture of ferrite and cementite at room temperature
- (c) eutectic mixture of ferrite and cementite at room temperature
- (d) all the above the three are correct

17. Which one of the following elements is an austenitic stabilizer?

- (a) Chromium
- (b) Tungsten
- (c) Nickel
- (d) Molybdenum

18. Which one of the following elements is a ferritic stabilizer?

- (a) Nickel
- (b) Manganese
- (c) Copper
- (d) Chromium

19. The correct statement is

- (a) Characteristic of any series of alloys cannot be found by phase diagram.
- (b) Phase diagram does not give amount of phases which are a function of composition, temperature and pressure.
- (c) The phase may be liquid or vapour with ordered crystal structure

(d) Phase diagram provides the information on how rapidly equilibrium is reached

20. Pearlite phase in an iron-carbide phase diagram is

- (a) Eutectic phase
- (b) Hypo-eutectic mixture
- (c) Eutectoidal mixture
- (d) Hyper-eutectic phase

21. Iron-carbon equilibrium diagram,

- (a) correlates the microstructure and properties of steel and cast iron
- (b) indicates the phase changes occurring during heating and cooling
- (c) is made by plotting carbon percentage along x-axis and temperature along y axis
- (d) all of the above

22. If a particular Fe-C alloy contains less than 0.83% carbon, it is called

- (a) High speed steel
- (b) hypoeutectoid steel
- (c) hypereutectoid steel
- (d) cast iron

23. Gibb's phase rule is given by

(F = number of degree of freedom

C = number of components

P = number of phases)

- (a) $F = C + P$
- (b) $F = C + P - 2$
- (c) $F = C - P - 2$
- (d) $F = C - P + 2$

24. Which one of the following is true?

- (a) Structure of metallic consists of atoms having valence of 5, 6 or 7

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$C - P + 2$

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of 5, 6 or 7

(b) Ceramic materials have long range
electron matrix bond

(c) Polymers are composed of long
chain of repeating molecules

(d) Ceramics are weaker than metals
because of weak electrostatic
bond

25. According to Gibbs' phase rule, the
number of degrees of freedom of an
eutectic point in a binary system is

- (a) 1 (b) 2
(c) 0 (d) 3

26. Which one of the following factors is
more relevant to represent complete
solubility of two metals in each other?

- (a) Chemical affinity
(b) Valency factor
(c) Crystal structure factor
(d) Relative size factor

DIRECTIONS:

The following items consists of two
statements; one labelled as '**Assertion (A)**'
and the other as '**Reason (R)**'. You are to
examine these two statements carefully and
select the answers to these items using the
codes given below:

Codes:

- (a) Both A and R are true and R is
the correct explanation of A
(b) Both A and R are true but R is not
a correct explanation of A
(c) A is true but R is false
(d) A is false but R is true

27. **Assertion (A):** Lever Rule can be
applied to determine relative amounts
of phases present at any temperature.

Reason (R): Lever Rule is restricted
to estimate relative phases, only if they
are solid phases.

28. Consider the following:

1. Crystal structure
2. Relative size
3. Chemical affinity
4. Valency

Which of these factors govern relative
solubility of two metals in each other
in the solid state?

- (a) 1, 2 and 3 only
(b) 2, 3 and 4 only
(c) 1, 2 and 4 only
(d) 1, 2, 3 and 4

29. When the temperature of a solid metal
increases,

- (a) strength of the metal decreases
but ductility increases
(b) both strength and ductility of the
metal decrease
(c) both strength and ductility of the
metal increase
(d) strength of the metal increases but
ductility decreases



ANSWERS

1. (b)	9. (d)	15. (a)	21. (c)	27. (c)
2. (a)	10. (d)	16. (b)	22. (b)	28. (d)
3. (b)	11. (a)	17. (c)	23. (d)	29. (a)
5. (b)	12. (c)	18. (d)	24. (c)	
6. (a)	13. (b)	19. (a)	25. (c)	
7. (a)	14. (b)	20. (c)	26. (c)	

4.1 F

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4

Physical, Mechanical Properties and Testing of Material

4.1 PHYSICAL PROPERTIES OF MATERIALS

Physical Properties of Materials

Density

Electrical Conductivity

Melting Temperature of Material

Semiconductors

Thermal Conductivity

Fusibility

Reluctance (as magnetic properties)

Temperature stability

Mechanical Properties of Materials

Tensile strength

Toughness

Malleability

Hardness

Ductility

Stiffness

Brittleness

Elasticity

Plasticity

Creep

Fatigue

Fracture

Meaning of Fracture and its Types

Types of Fractured Ends in Ductile Failure

These properties concerned with such properties as melting, temperature, electrical conductivity, thermal conductivity, density, corrosion resistance, magnetic properties, etc. and the more important of these properties will be considered as follows :

4.1.1 Density

Density is defined as mass per unit volume for a material. The derived unit usually used by engineers is the kg/m³. Relative density is the density of the material compared with the density of the water at 4°C. The formulae of density and relative density are:

$$\text{Density } (\rho) = \frac{\text{Mass (m)}}{\text{Volume (V)}}$$

$$\text{Relative density (d)} = \frac{\text{Density of the material}}{\text{Density of pure water at 4°C}}$$

4.1.2 Electrical Conductivity

- Figure shows a piece of electrical cable. In this example copper wire has been chosen for the conductor or core of the cable because copper has the property of very good electrical conductivity.

Creep Fracture

Improving the Fatigue Life

Methods of Protection Against Fracture

Ductile-Brittle Transition

Material Testing

Tensile Test

Compression Test

Ductility Testing

Impact Testing (Toughness Testing)

The Effect of Temperature on the
Materials Mechanical Properties

Creep Test

Hardness Testing

Non-Destructive Testing (NDT)

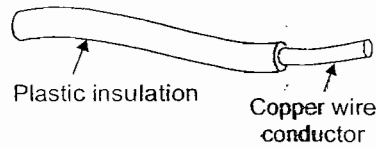


FIGURE : Electrical conductivity.

- That is, it offers very little resistance to the flow of electrons (electric current) through the wire. A plastic materials such as polymerized has been chosen for the insulating sheathing surrounding the wire conductor.
- This material has been chosen because it is such a bad conductor, where very few electrons can pass through it.; Because they are **very bad conductors** they are called as **insulators**. There is no such thing as a perfect insulator, only very bad conductors.
- Pure metal shows this effect more strongly than alloys. However, pure metals generally have a better conductivity than alloys at room temperature. The conductivity of metals and metal alloys improves as the temperature falls.
- Conversely, non-metallic materials used for insulators tend to offer a lower resistance to the passage of electrons, and so become poorer insulators, as their temperatures rise. Glass, for example, is an excellent insulator at room temperature, but becomes a conductor if raised to red heat.

4.1.3 Melting Temperature of Material

The melting temperatures and the recrystallisation temperatures have a great effect on the materials and the alloys of the materials properties and as a result on its applications.

4.1.4 Semiconductors

- In between conductors and insulators lies a range of materials known as semiconductors. These can be good or bad conductors depending upon their temperatures.

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4.1.5 The

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4.1.6 Fus

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FIGUR

- The conductivity of semiconductor materials increases rapidly for relatively small temperature increases. This enable them to be used as temperature sensors in electronic thermometers.
- Semiconductor materials are capable of having their conductors properties changed during manufacture. Examples of semiconductor materials are silicon and germanium.
- They are used extensively in the electronics industry in the manufacture of solid-state devices such as diodes, thermistors, transistors and integrated circuits.

4.1.5 Thermal conductivity

- This is the ability of the material to transmit heat energy by conduction. Figure shows a soldering iron. The bit is made from copper which is a good conductor of heat and so will allow the heat energy stored in it to travel easily down to the tip and into the work being soldered.

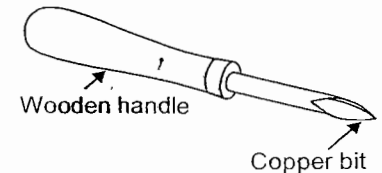


FIGURE : Thermal conductivity.

- The wooden handle remains cool as it has a low thermal conductivity and resists the flow of heat energy.

4.1.6 Fusibility

- This is the ease with which materials will melt. It can be seen from figure that solder melts easily and so has the property of high fusibility. On the other hand, fire bricks used for furnace linings only melt at very high temperatures and so have the properties of low fusibility.
- Such materials which only melt a very high temperatures are called refractory materials.
- These must not be confused with materials which have a low thermal conductivity and used as thermal insulators.
- Although expanded polystyrene is an excellent thermal insulator, it has a very low melting point (high fusibility) and in no way can it be considered a refractory material.

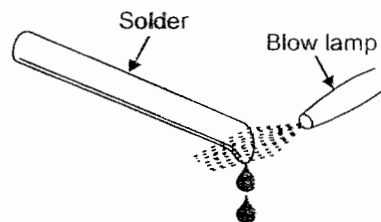


FIGURE : Solder melts at a low temperature and therefore it has a high fusibility.

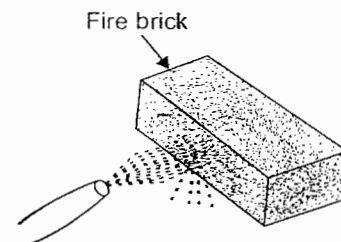


FIGURE : Fire brick only melts at very high temperatures and therefore it has a low fusibility and is called a refractory.

4.1.7 Reluctance (as Magnetic Properties)

- Just as some materials are good or bad conductors of electricity, some materials can be good or bad conductors of magnetism. The resistance of *magnetic circuit* is referred to as *reluctance*.
- The good magnetic conductors have low reluctance and examples are the ferromagnetic materials which get their name from the fact that they are made from iron, steel and associated alloying elements such as cobalt and nickel.
- All other materials are non-magnetic and offer a high reluctance to the magnetic flux field.

4.1.8 Temperature Stability

- Any changes in temperature can have very significant effects on the structure and properties of materials. However, there are several effects can appear with changes in temperature such as creep.
- For example gas-turbine blades. The creep rate increases if the temperature is raised, but becomes less if the temperature is lowered.

4.2 MECHANICAL PROPERTIES OF MATERIALS

These properties are concerned with the following properties :

4.2.1 Tensile Strength

- It is the ability of a material to withstand tensile (stretching) loads without breaking.
- As the force of gravity acting on the load is trying to stretch the rod, the rod is said to be in tension. Therefore, the material from which the rod is made needs to have sufficient tensile strength to resist the pull of the load.
- **Strength** : is the ability of a material to resist applied forces without fracturing.

4.2.2 Toughness

- It is the ability of the materials to withstand bending or it is the application of shear stresses without fracture, so the rubbers and most plastic materials do not shatter, therefore they are tough.
- For example, if a rod is made of high-carbon steel then it will be bend without breaking under the impact of the hammer, while if a rod is made of glass then it will be broken by impact loading.

4.2.3 Malleability

- It is the ability of a material to be deformed or the ability of a material to be deformed by plastic loading.
- Such as a material that is soft and such as a material that is hard and heading.

4.2.4 Hardness

- It is the ability of a material to withstand wear or indentation by a hard body, i.e. a material that is hard and a material that is soft.
- As seen in a material that is hard and a material that is soft.

4.2.5 Ductility

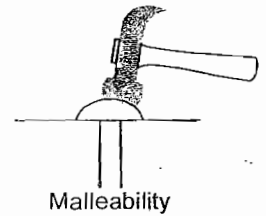
- It refers to the ability of a material to be deformed by plastic deformation without fracture.
- For example, a material that is ductile and a material that is brittle.

4.2.6 Stiffness

- It is the ability of a material to resist deformation.
- For example, a material that is stiff and a material that is flexible.

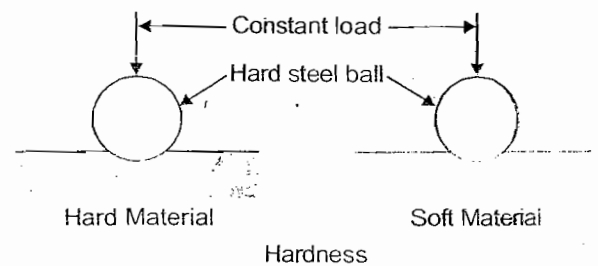
4.2.3 Malleability

- It is the capacity of substance to withstand deformation under compression without rupture or the malleable material allows a useful amount of plastic deformation to occur under compressive loading before fracture occurs.
- Such a material is required for manipulation by such processes as forging, rolling and rivet heading.



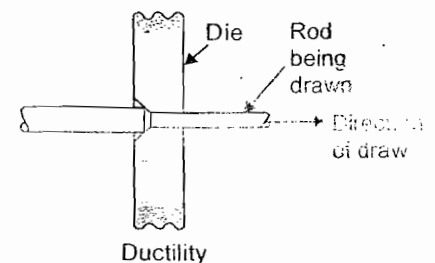
4.2.4 Hardness

- It is the ability of a material to withstand scratching (abrasion) or indentation by another hard body, it is an indication of the wear resistance of the material.
- As seen that the ball only makes a small indentation in the hard material but it makes a very much deeper impression in the softer material.



4.2.5 Ductility

- It refers to the capacity of substance to undergo deformation under tension without rupture as in wire drawing (as shown in figure), tube drawing operation.
- For more ductile material $\epsilon_p > 15\%$, for less ductile material $\epsilon_p < 5\%$.



4.2.6 Stiffness

- It is the measure of a material's ability not to deflect under an applied load.
- For example, steel is very much stronger than cast iron, then the cast iron is preferred for machine beds and frames because it is more rigid and less likely to deflect with consequent loss of alignment and accuracy.

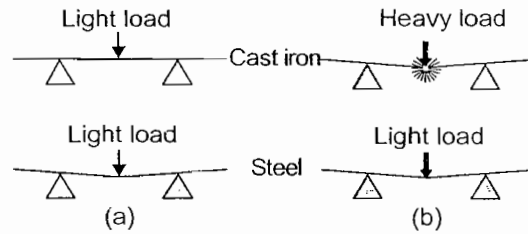


FIGURE : Stiffness (rigidity) :

(a) The tested materials deflect under a light load

(b) The tested materials deflect under a heavy load.

2.4.7 Brittleness

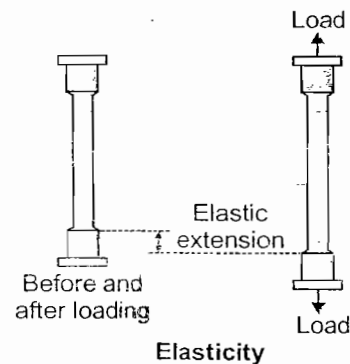
It is the property of a material that shows little or no plastic deformation before fracture when a force is applied. Also it is usually said as the opposite of ductility and malleability.

For brittle material $\epsilon_p < 5\%$.

$$\epsilon = \frac{\Delta l}{l} = \frac{\text{Change in length}}{\text{Original length}}$$

4.2.8 Elasticity

- It is the ability of a material to deform under load and return to its original size and shape when the load is removed.
- If it is made from an elastic material it will be the same length before and after the load is applied, despite the fact that it will be longer whilst the load is being applied.
- All materials possess elasticity to some degree and each has its own **elastic limits**.



4.2.9 Plasticity

- This property is opposite to elasticity, while the ductility and malleability are particular cases of the property of the plasticity.
- It is the state of a material which has been loaded beyond its elastic limit so as to cause the material to deform permanently.
- Under such conditions the material takes a permanent set and will not return to its original size and shape when the load is removed.

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- The time
- Length
- Temperature
- Creep (an increase in length with time at a constant temperature)

4.2.11

- The term
- Fatigue is fatigue plasticity

Main Effects

- Loss of strength
- Loss of stiffness
- Enhancement of fatigue life

Salient features of fluctuating stress

- When a piece of mild steel is bent at right angles into the shape of a bracket, it shows the property of **plasticity** since it does not spring back strength again.

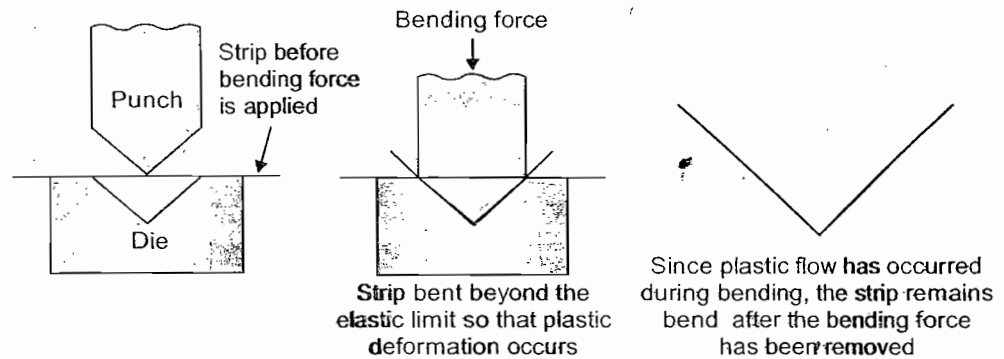


FIGURE : Plasticity.

4.2.10 Creep

- The permanent deformation (strain) of a material under steady load as a function of time is called *creep*.
- Length of our waist belt increases after some duration, is due to creep effect.
- Thermally actuated process, and hence is influenced by temperature. Appreciable at temperature above $0.4 T_m$ where T_m is melting point of material in degree kelvin.
- Creep occurs at room temperature in many materials such as lead, zinc, solder wire (an alloy of Pb and Sn), white metals, rubber, plastics and leather etc. e.g. consider zinc where melting point is 420°C (693 K). Its creep rate is considerable above a temperature of $(0.4 \times 693\text{ K} = 277\text{ K})$ is a at about 4°C only.

4.2.11 Fatigue

- The behavior of materials under fluctuating and reversing loads (or stresses) is termed as *fatigue*. This behaviour is different from that under the steady load.
- Fatigue is, however, not a **dynamic effect**. The rate of loading is usually not a factor in fatigue behavior. Fatigue behavior is experienced by all materials whether metals, plastics, concretes, or composites.

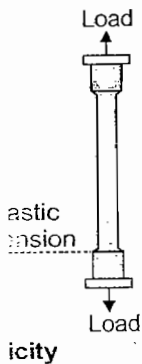
Main Effects of Fatigue

- Loss of ductility,
- Loss of strength, and
- Enhanced uncertainty in strength and the service life of materials.

Salient features: Fatigue occurs at stresses well within the elastic range. Various types of fluctuating and reversing stresses are shown in figure (a-d) in a simplified manner.

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In practical situations the stress variations may be drastic, unpredictable and complex. One such example, Figure (d), is that of an aeroplane during its take-off, flight and landing.

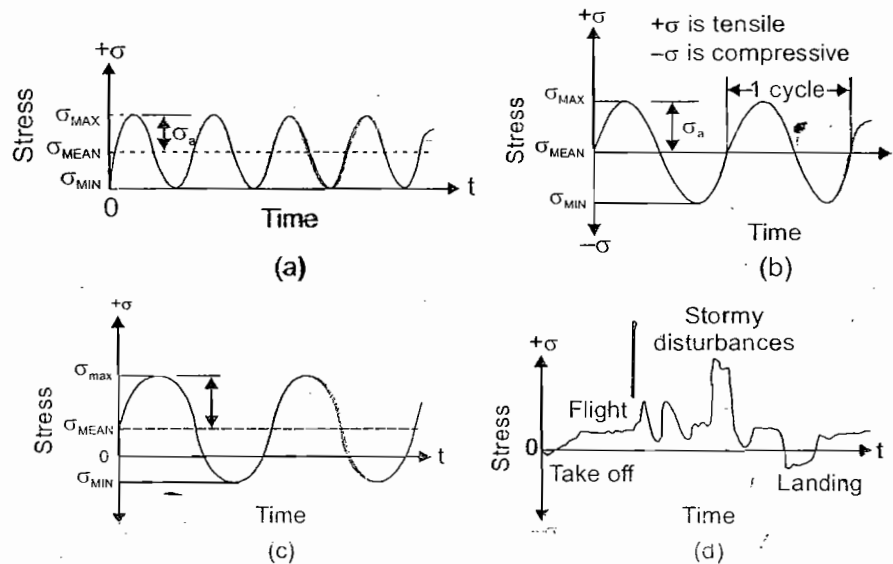


FIGURE : Variations of stresses (a) fluctuation, and (c) reversal, and (d) in aeroplane operation.

Fatigue Limit (or Endurance Stress) and S-N Diagram

- Total number of cycles N required to bring about fracture in a material (or its specimen) under an applied stress defines its basic fatigue life.
- Fatigue life of a material is expressed in percent survival out of large number of specimens. Generally median fatigue life is estimated at 50% survival.
- It is evaluated from the data of stress (S or σ) and number of cycles of failure N by conducting fatigue test. The plot is referred to as S-N diagram.
- The curve of mild steel is asymptotic beyond B. It implies that the material can withstand a stress equal to σ_c for any number of cycles without fatigue fracture. This stress is called as **endurance stress**. It is also known as **fatigue limit**.
- This stress is generally 0.3 to 0.5 times the ultimate strength of materials.

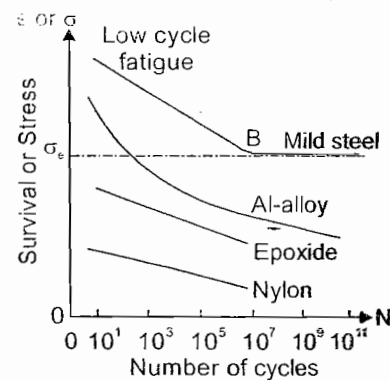
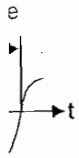


FIGURE : S-N curve of some materials to determine fatigue limit.

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- Ferrous metals usually have a fatigue limit but non-ferrous metals and non-metals often do not.
- Fatigue response of these materials is specified for a number of stress cycle normally 10^7 and known as fatigue strength.

Critical Applications of Fatigue Behaviour

- Wings of aeroplanes and other aircrafts.
- Leaf springs used on automobiles and railways rolling stocks.
- Connecting rods of internal combustion engines.
- Rotating shafts and machine parts.

4.3 FRACTURE

4.3.1 Meaning of Fracture and its Types

- Separation of a solid into two or more parts under application of load or stress is called fracture.
- Depending on the type of load, fracture may be defined by tensile fracture, compressive fracture, shear fracture, fatigue fracture, creep fracture and cleavage fracture etc. However, these fractures are mainly characterized by either a
 1. Ductile fracture, or
 2. Brittle fracture
- The process of fracture basically involves the following phenomenon.
 - (a) Crack initiation, and
 - (b) Crack propagation
- Ductile fracture occurs after prolonged plastic deformation.
- The crack initiates from formation of voids and propagates slowly. Ductile materials fail showing the character of ductile fracture under normal conditions.
- However, they may fail as brittle fracture at lower temperatures and at higher rates of straining.
- Propagation of crack given by Griffith theory.

4.3.2 Types of Fractured ends in Ductile Failure

- Various configuration of fractured ends are found when materials fail in ductile fracture. These fractured ends are of the following types, and are shown in below figure.

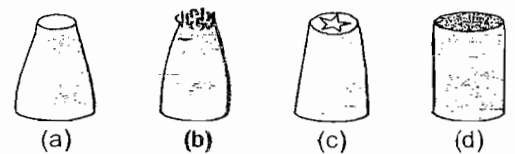


FIGURE : Typical tensile fractures of metals
(a) cup and cone (b) fibrous (c) star, and (d) granular.

- Cup and cone fracture, crack spread in direction 45° to the tensile axis

- Fibrous fracture
- Star fracture, and
- Granular fracture
- **Cup and Cone fracture:** The cup and cone fracture is common in plain carbon steels. Percentage of carbon in steel has an impact on the profile of cup and cone, Figure.
- Mild steel develops deeper cup and cone
- With increasing percentage of carbon it becomes shallower.
- It disappears finally in high carbon steel
- Wrought iron shows fibrous fracture ends.
- Brittle cast iron fails with a plane surface having granular appearance.

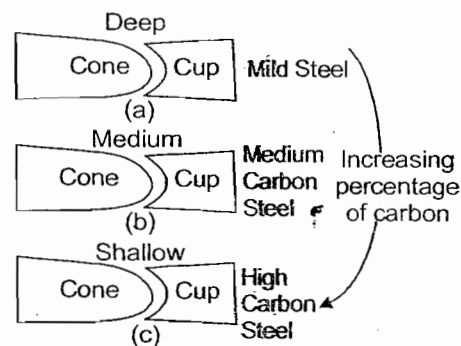


FIGURE : Effect of carbon percentage on shape of cup and cone fracture of plain carbon steel.

Note :

- Surface cracks in nature are twice as effective as the internal cracks. Hence surfaces of machine components should be finely finished.
- A material fractures at a certain value of applied stress. One of its broken pieces will require more applied stress than the previously applied stress to fracture. It is because the most effective cracks are eliminated in the first fracture.
- When folding a piece of paper, we fold it and press. Folding and pressing creates a scratch that induces higher stress concentration. The paper is then torn apart very easily along the scratch.
- A window glass panel is scratched by a mechanical nail to introduce stress concentration. Then the glass breaks very easily in two pieces along the scratch.
- Fracture resistance of a material increases by making blunt cracks, fillets or notches of some radius.

Griffith Theory

- Griffith has furnished a criterion for the propagation of preexisting crack in brittle material (glass) according to which brittle fracture occurred when the energy release rate during crack growth exceeded the rate than the rate at which energy was required.

- All materials deform
- If the change in deformation is small, the crack is not visible
- Irwin's theory of crack growth

Limitations

- It can only be used for brittle materials
- It is not applicable for ductile materials
- It does not consider the effect of temperature

4.3.3 Crack Growth

- Crack growth is the process by which a crack in a material grows larger over time
- Crack growth can be caused by a variety of factors, including stress, corrosion, and fatigue
- Crack growth can be measured by a variety of methods, including optical microscopy, ultrasonic testing, and X-ray diffraction
- Crack growth can be prevented by a variety of methods, including stress reduction, corrosion resistance, and crack repair

Types of Crack Growth

- Intergranular crack growth
- Transgranular crack growth

In intergranular crack growth, the crack propagates along the grain boundaries of the material. In transgranular crack growth, the crack propagates through the grains of the material.

4.3.4 Crack Initiation

- Crack initiation is the process by which a crack first forms in a material
- Crack initiation can be caused by a variety of factors, including stress, corrosion, and fatigue
- Crack initiation can be prevented by a variety of methods, including stress reduction, corrosion resistance, and crack repair

- All metals are not ideally brittle and normally fails with certain amount of plastic deformation.
- If the material in which crack is propagating can deform plastically, the crack tip form changes because of plastic strain. A sharp crack tip will be blunted. Also plastic deformation requires time so the amount of plastic deformation that can occur at the crack tip will depend on rate of advancement of the crack.
- Irwin and Orowan suggested that Griffith criterion can be applied to brittle material undergone plastic deformation before fracture.

Limitations of Griffith Theory

- It cannot explain well the fracture mechanism if the crack in the material is spheroidal.
- It is justified for completely brittle materials only.
- It does not consider the plastic deformation in the vicinity of the crack.

4.3.3 Cleavage Fracture

- Cleavage is a crystallographic mode of fracture catalysed by shear stresses. In a single crystal showing brittle behaviour, fracture occurs along definite crystallographic planes called cleavage planes. These planes generally have low Miller indices and large interplanar spacings. The critical stress required to produce cleavage is a function of crystal orientation relative to the stress direction.
- Cleavage is easily found in **BCC and HCP** metals at low temperatures.
- Such metals possess an enhanced ductile behaviour at elevated temperatures.
- Zinc crystals cleave at room temperature

Types of Cleavage Fracture

- Intergranular cleavage fracture, and
- Transgranular cleavage fracture

In intergranular fracture, crack propagates through the grain boundaries while in transgranular case, it propagates along the cleavage planes. Transgranular cleavage is more often observed in those polycrystalline materials that fail in a brittle manner.

4.3.4 Creep Fracture

- Consider a bar, below figure (a-e), subjected to a steady axial load P at certain temperature T . If this arrangement is kept undisturbed, we shall find the progressive stages of deformation as shown.

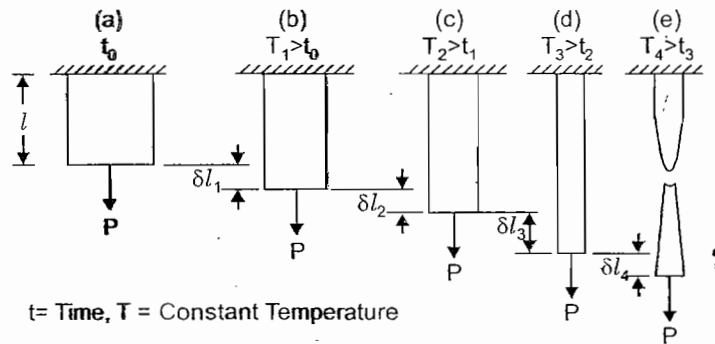
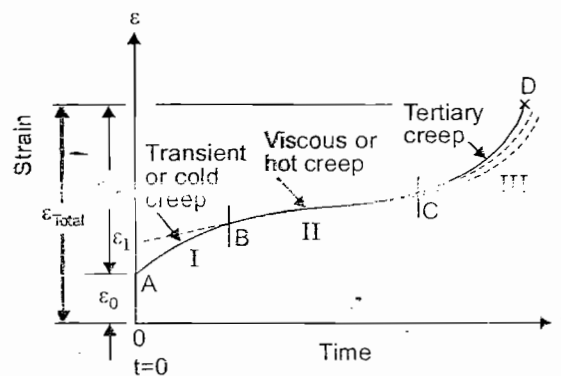


FIGURE : Elongation of material with corresponding reduction in its cross-section under steady load as a function of time.

Creep Curve



Different Stages of Creep Curves

- Transient or cold creep extends from A to B. It is nonlinear. The rate of creep is initially fast but slows down later-on. This occurs even at very low temperatures, hence it is called cold creep. This is also known as I stage or primary creep.
- Viscous or hot creep is from B to C, and is almost linear. This part of curve occurs at high temperatures, so is also known as hot creep. This is also known as II stage or secondary creep.
- Tertiary creep is the last stage before creep fracture. The curve CD rises upward as rate of straining is too fast due to neck formation in the material. This is also known as III stage.

Note :

- The effect of increasing stress and temperature is to speed-up the rate of creep.
- At higher stress or at higher temperature, the total strain is large and creep fracture occurs in lesser time.
- The duration of three creep stages also vary.

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4.3.5 Improving the Fatigue life

- Stress raisers such as sharp corners are avoided so that the stress concentration vanish or diminish considerably.
- Materials with finer grain sizes are utilized.
- Surface irregularities and cracks are removed by polishing the surfaces.
- Compressive stresses are introduced at the surfaces by processes such as shot peening, shot or sand blasting etc.
- Nitriding and carburizing operations are performed to create strong surface layers.

4.3.6 Methods of Protection Against Fracture

- By surface treatment e.g., etching and sizing etc. Etching of glass in hydrofluoric acid removes the surface cracks and thus improves the strength of glass.
- Introduction of compressive stress on the surface of a material makes the surface cracks ineffective. Plexiglass windscreen of autovehicles and tempered glasses require a higher tensile stress to initiate crack propagation as the tensile stress has to overcome the introduced compressive stress.
- Tempering process of heat treatment produce compressive stress in the interior part of the silicate glass, and thus the fracture strength increased by many times.
- Chemical strengthening involves ion exchange method through which sodium cations are replaced by potassium anions on the surface of sodium silicate glass.
- Fine grain control is developed to obtain finer grain sizes in glass and ceramics. The surface cracks are minimized due to fine grains and hence the fracture strength improves.

4.3.7 Ductile-Brittle Transition

- Ductile-brittle transition is a limiting state between ductile and brittle behaviour of a material. This transition between ductile and brittle behaviour is defined by a temperature, called ductile-brittle transition temperature t_{db} .
- A ductile material shows brittle nature below this temperature whereas a brittle material posses ductile nature above this temperature.

Conditions Responsible for Brittle Fracture of Ductile Metals

- A low or decreasing temperature,
- High rate of straining,
- Large grain size of material,
- High stress concentration,
- Rough surface conditions, and
- Triaxial stress conditions.

Factors Affecting the Transition Temperature

- Fine grained materials possess lower transition temperature than the coarse grained materials.
- Transition temperature is raised due to stress concentration such as on sharp notches.
- Effect of higher straining rate is to cause increased transition temperature.
- Most of the ductile BCC metals behave as brittle materials at low temperatures and at a very high rate of straining, whereas many FCC metals behave as ductile materials at very low temperatures.
- It is because a higher yield stress σ_y is required to move dislocations in BCC metals than FCC metals.
- This σ_y increases rapidly when temperature lowers down but this is not the case with the stress required to propagate a crack σ_f .
- Steel structures such as oil rigs, ships and bridges are generally fail in winter than in summer due to ductile-brittle transition effect.
- Ductile to brittle transition temperature for metals is around $0.1-0.2 T_m$ while for ceramics is $0.5-0.7 T_m$.

T_m = Melting temperature

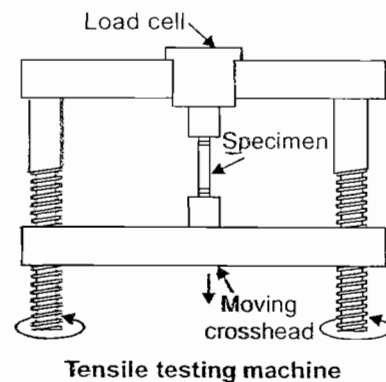
4.4 MATERIAL TESTING

Testing of materials are necessary for many reasons, and the subject of materials testing is very broad one. Some of the purpose for the testing of materials are :

- To determine the quality of a material. This may be one aspect of process control in production plant.
- To determine such properties as strength, hardness, and ductility.
- To check for flaws within a material or in a finished component
- To assess the likely performance of the material in a particular service condition.

4.4.1 Tensile Test

- The main principle of the tensile test is denotes the resistance of a material to a tensile load applied axially to a specimen.
- It is very important to the tensile test to be considered is the standard dimensions and profiles are adhered to. The typical progress of tensile test can be seen in figure.



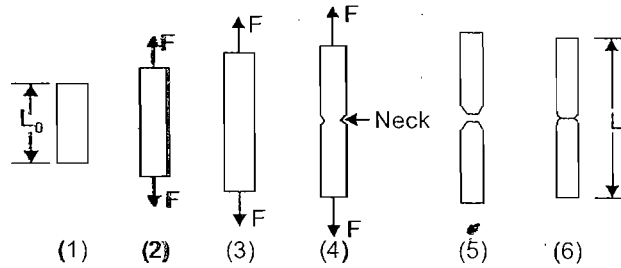


FIGURE : Typical progress of a tensile test : (1) beginning of test, no load; (2) uniform elongation and reduction of cross-sectional area; (3) continued elongation, maximum load reached; (4) necking begins, load begins to decrease; and (5) fracture. If pieces are put back together as in (6), final length can be measured.

Let's now look at another figure. In this figure, the gauge length (L_0) is the length over which the elongation of the specimen is measured. The minimum parallel length (L_c) is the minimum length over which the specimen must maintain a constant cross-sectional area before the test load is applied. The lengths L_0 , L_c , L_f and the cross-sectional area (A) are all specified in BS 18.

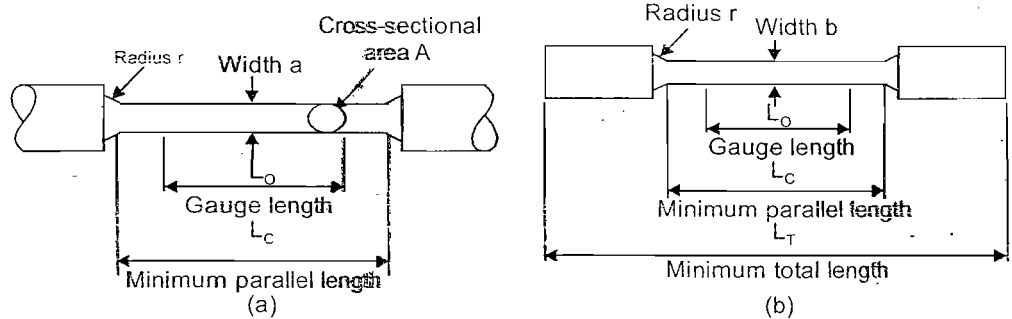


FIGURE : Properties of tensile test specimens : (a) cylindrical (b) flat.

- The elongation obtained for a given force depends upon the length and area of the cross-section of the specimen or component, since:

$$\text{Elongation} = \frac{\text{Applied Force} \times L}{E \times A}$$

where, L = Length, A = Cross-sectional area E = Elastic modulus.

- Therefore if the ratio $[L/A]$ is kept constant (as it is in a proportional test piece), and E remains constant for a given material, then comparisons can be made between elongation and applied force for specimens of different sizes.

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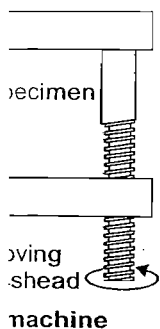
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Tensile Test Results

The load applied to the specimen and the corresponding extension can be plotted in the form of a graph, as shown in figure.

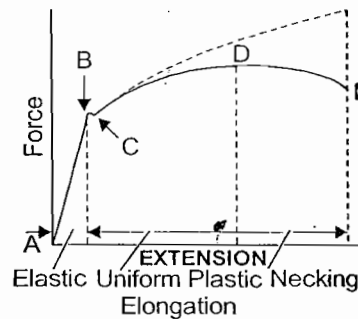


FIGURE : Load-extension curve for a low-carbon steel.

- From A to B the extension is proportional to the applied load. Also, if the load is removed the specimen returns to its original length. Under these relatively lightly loaded conditions the material is showing elastic properties.
- From B to C it can be seen from the graph that the metal suddenly extends with no increase in load. If the load is removed at this point the metal will not spring back to its original length and it is said to have taken a permanent set. Therefore, B is called "limit of proportionality", and if the force is increased beyond this point a stage is reached where a sudden extension takes place with no increase in force. This is known as the "yield point" C.
- The yield stress is the stress at the yield point: that is, the load at B divided by the original cross-section area of the specimen. Usually, a performer works at 50 percent of this figure to allow for a 'factor of safety'.
- From C to D extension is no longer proportional to the load, and if the load is removed little or no spring back will occur. Due to this relatively greater loads the material is showing plastic properties.
- The point D is referred to as the 'ultimate tensile strength' when referred extension graphs or the 'ultimate tensile stress' (UTS) when referred to stress-strain graphs. The ultimate tensile stress is calculated by dividing the load at D by the original cross-sectional area of the specimen. Although a useful figure for comparing the relative strengths of materials, it has little practical value since engineering equipment is not usually operated so near to the breaking point.
- From D to E the specimen appears to be stretching under reduced load conditions. In fact the specimen is thinning out (necking) so that the 'load per unit area' or stress is actually increasing. The specimen finally work hardens to such an extent that it breaks at E.
- In general, values of load and extension are of limited use since they apply to one particular size of specimen and it is more usual to plot the stress-strain curve.
- Stress and strain are calculated as follows:

$$\text{Stress}(\sigma) = \frac{\text{Load}}{\text{Area of cross-section}}$$

$$\text{Strain}(\epsilon) = \frac{\text{Extension}}{\text{Original Length}}$$

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Note : All ductile materials are malleable, but not all malleable materials are ductile since they may lack the strength to withstand tensile loading.

- Therefore ductility is usually expressed, for practical purposes, as the percentage; Elongation in gauge length of a standard test piece at the point of fracture when subjected to a tensile test to destruction.

$$\text{Elongation (\%)} = \frac{\text{Increase in length}}{\text{Original length}} \times 100$$

- The increase in length is determined by fitting the pieces of the fractured specimen together carefully and measuring the length at failure.

$$\text{Increase in length (elongation)} = \text{Length at failure} - \text{Original length}$$

4.4.2 Compression Test

- Because of the presence of submicroscopic cracks, brittle materials are often weak in tension, as tensile stress tends to propagate those cracks which are oriented perpendicular to the axis of tension. The tensile strengths they exhibit are low and usually vary from sample to sample.
- These same materials can never be quite strong in compression. Brittle materials are chiefly used in compression, where their strength is much higher. A schematic diagram of a typical compression test is shown in figure.
- Figure shows a comparison of the tensile strengths of gray cast iron and concrete, both of which are brittle materials.

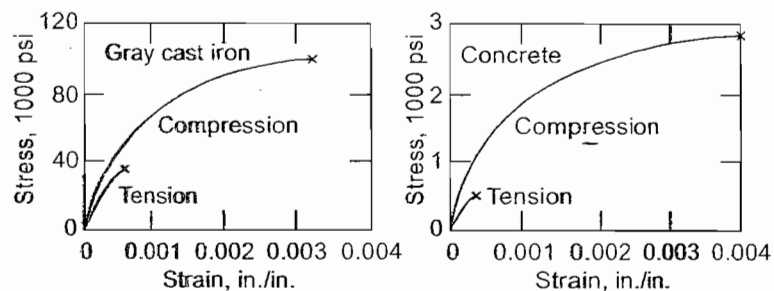
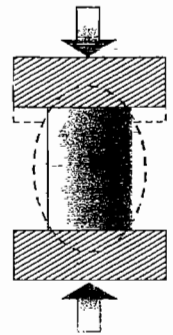


FIGURE : Tensile and compressive engineering stress-strain curves for gray cast iron and concrete.

- Because the compression, it increase the cross-sectional area of the sample, necking never occurs. Extremely ductile materials are seldom tested in compression because the sample is constrained by friction at the points of contact with the plants of the apparatus. This constraint gives rise to a complicated stress distribution which can only be analyzed in an approximate fashion.

4.4.3 Ductility Testing

- The percentage elongation, as determined by the tensile test is a measure of ductility test can also be performed by is a simple bend test.
- There are several ways in which this test can be done, as shown in figure. The test chosen will depend upon the ductility of the material and the severity of the test required.
- **Close bend test :** The specimen is bent on itself and flattened. No allowance made for spring back, and the material satisfactory if the test can be completed out the metal tearing or fracturing. This also applies to the following tests:
- **Angle bend test :** The material is bent over a former and the nose radius of the former and the angle of bend (θ°) are fixed by specification. Again no allowance is made for spring back.
- **180° bend test :** This is a development of the angle bend test using a flat former as shown. Only the nose radius of the former is specified.

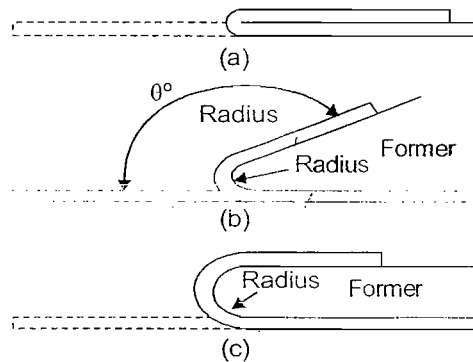


FIGURE : Bend tests : (a) close bend; (b) angle bend and (c) 180° bend.

4.4.4 Impact Testing (Toughness Testing)

- Impact tests consist of striking a suitable specimen with a controlled blow and measuring the energy absorbed in bending or breaking the specimen. The energy value indicates the toughness of the material under test.
- Below figure shows how a piece of high carbon steel rod will bend when in the annealed condition, after hardening and tempering, the same piece of steel will fracture when hit with a different hammer.

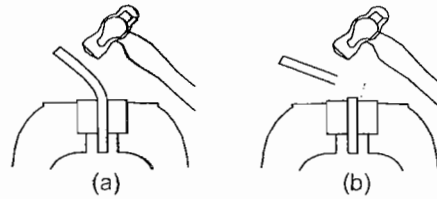


FIGURE : Impact loading : (a) a rod of high-carbon (1.0%) steel in the annealed (soft) condition will bend struck with a hammer (UTS 925 MPa).

Note : After **hardening** and **small** amount of **tempering**, the same piece steel will **fracture** when hit with a hammer despite its UTS having increased to 1285 MPa.

- There are **several** types of the **impact** tests and the mostly famous type is the **Izod test**.
- In the **Izod test**, a 10mm square, notched specimen is used, it is preferred to use a specimen **that have** a more than one or two and even three notched in the same specimen. **The striker** of the **pendulum** hits the specimen with a kinetic energy of 162.72 J at a velocity of 3.8 m/s. Figure shows details of the specimen and the manner in which it is supported.

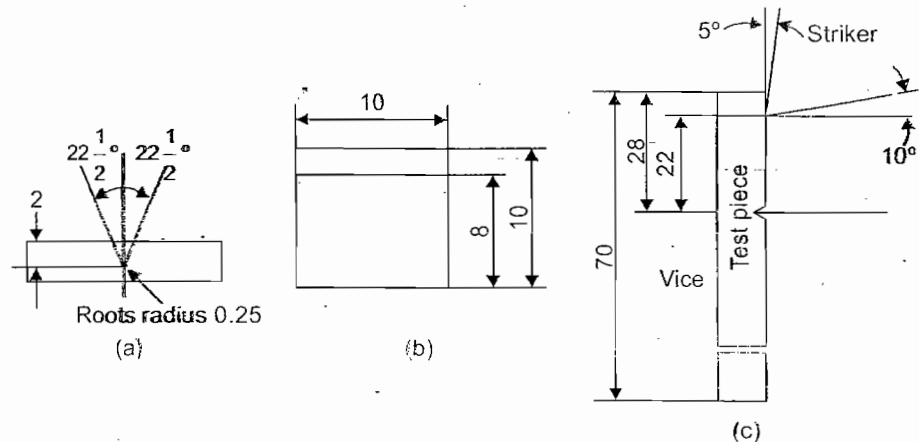


FIGURE : **Dept of Notch** ; $t/5$ to $t/3$, t = thickness of specimen Izod test (all dimensions in millimeters); (a) detail of notch; (b) section of test piece (at notch); (c) position of strike.

- Since test **use** a **notched** specimen, useful information can be obtained regarding the resistance **of the** material to the **spread** of a crack which can **originate** from a point of stress **concentration** such as **sharp** corners, **undercuts**, **sudden** changes in section, and **machining** marks in stressed components. Such points of stress **concentration** should be **eliminated** during **design** and **manufacture**.

- Izod test suitable for room and high temp.
- Angle of (α) : $\alpha < 90^\circ$, normally 90° .
- Needs adjustment in location of specimen.
- A second type of impact test is the Charpy test. While in the Izod test the specimen is supported as a cantilever, but in the Charpy test it is supported as a beam. It is struck with a kinetic energy of 298.3 J at a velocity of 5m/s. The Charpy impact test is use for testing the toughness of polymers. Figure shows details of the Charpy test : manner in which it is supported.
- Charpy test is better for low temperature test (-29°C strike to -186°) $\alpha < 90^\circ$, normally 160° , α = angle of strike.

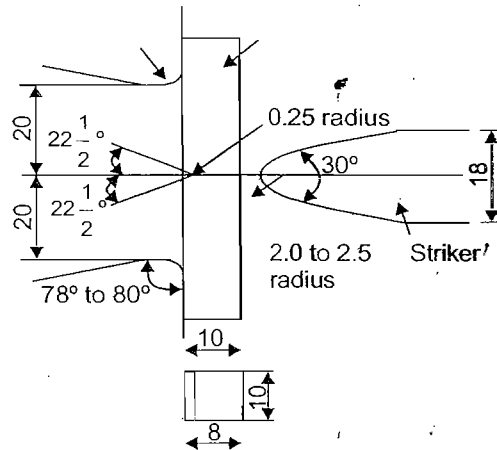


FIGURE : Charpy test (dimensions shown in millimeters)

4.4.5 The Effect of Temperature on the Materials Mechanical Properties

- The embrittlement of low-carbon steels at refrigerated temperatures, and hence they are unsuitable for use in refrigeration plant and space vehicles.
- The nature of ductile material to behave as brittle material is called notch sensitivity. It cause due to stress concentration, and lowers the properties of material.
- The impact test is also useful as a production tool in comparing manufactured materials with others which have shown satisfactory in service.
- Steels, like most other BCC metals and alloys, absorb more energy when they fracture in a ductile fashion rather than in a brittle fashion.
- Due to this the impact test is often used to assess the temperature of the transition from the ductile to brittle state which occurs as the temperature is lowered.
- The transition temperature is also dependent on the shape of the notch in the specimen. For identical materials, the sharper the notch, the higher the transition temperature.

4.4.6 Creep Test

- Creep testing is done in the tensile mode, and the type of test-piece used is similar to the normal tensile test-piece. Generally, creep testing is carried out under constant-load conditions and utilizes dead weights acting through a simple lever system.

- In the creep testing an extensometer readings are noted at regular time intervals until the required amount of data has been obtained, or until the test-piece fractured, depending on whether the object of the test is to determine the creep rate or to determine the total creep strain.
- One of the difficulties in creep testing is that a single test take a very long time to complete (10000 hours is 417 days), and there are serious difficulties in attempting to extrapolate from the results of comparatively short-term tests to evaluate the probable behavior of a material over a 10 or 20 year period of service.
- Creep is sensitive to both the applied load and the testing temperature, as shown in figure : increasing stress raises the level of the creep curve, and increasing temperature, which accelerates recovery processes, increase the creep rate.

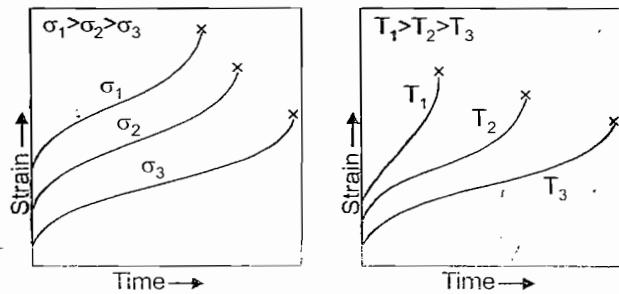
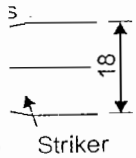


FIGURE : The effect of stress and temperature on creep behavior.

- **Creep deformation strength:** highest stress that a material can bear for a specific duration at a certain temperature without excessive deformation which is predecided.
- **Creep rupture strength:** Highest stress that a material can bear for a specific duration at a certain temp. without rupture.

4.4.7 Hardness Testing

- It is done by indentation. A hard indenter is pressed into the specimen by a standard load, and the magnitude of the indentation (either area or depth) is taken as a measure of hardness.
- Hardness tests are in practice used for assessing material properties because they are quick and convenient. The most well known hardness tests are Brinell and Rockwell.

Brinell Hardness Test

- In this test, hardness is measured by pressing a hard steel ball into the surface of the test piece, using a known load.
- It is important to choose the combination of load and ball size carefully so that the indentation is free from distortion and suitable for measurement.

- The relationship of the Brinell hardness [H_B] which is between load P (kg), the diameter D (mm) of the hardened ball indenter and the diameter d (mm) of the indentation on the surface is given by the expression :

$$H_B = \frac{\text{Load(Kg)}}{\text{Area of curved surface of indentation}} = \text{kgf/mm}^2 \text{ or N/mm}^2$$

$$H_B = \frac{P(\text{Kg})}{\frac{1}{2}\pi \times D [D - \sqrt{D^2 - d^2}] (\text{mm}^2)}$$

- For different materials, the ratio P/D^2 has been standardized in order to obtain accurate and comparative results such as :

$$K = \frac{P}{D^2}$$

where K is a constant; typical values of K are:

Ferrous metals $K = 30$

Copper and copper alloys $K = 10$

Aluminum and aluminum alloys $K = 5$

Lead, tin and white-bearing metals $K = 1$

Figure shows how the Brinell hardness value is determined. The diameter of the indentation is measured in two directions at right angles and the average taken. The diameter is measured either by using a microscope scale, or by a projection screen with micrometer adjustment.

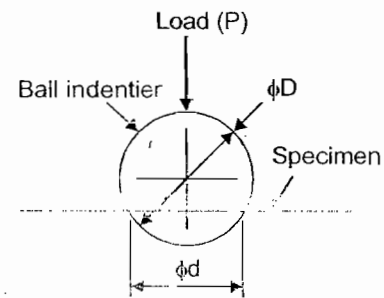


FIGURE : Principle of the Brinell hardness test.

To ensure consistent results, the following precautions should be made:

- To thickness of the specimen should be at least seven times the depth of the indentation to allow unrestricted plastic flow below the indenter.
- The edge of the indentation should be at least three times the diameter of the indentation from the edge of the test piece.
- The test is unsuitable for materials whose hardness exceeds 500 H_B , as the ball indenter tends to flatten.
- There are a definite relationship between strength and hardness so it is possible to measure the tensile strength **from the hardness test**.

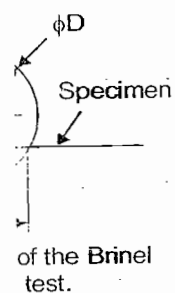
Drawback

- Sinking effect found in manganism steel and austenitic steel.
- Piling-up effect : in lead, Sn, Mg

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Vickers Hardness Test

- This test is preferable to the Brinell test where hard materials are concerned, as it uses a diamond indenter. (Diamond is the hardest material known-approximately 6000 H_B).
- The diamond indenter is in the form of a square-based pyramid with an angle of 136° between opposite faces.
- Since only one type of indenter is used the load has to be varied for different hardness ranges. Standard loads are 5, 10, 20, 30, 50 and 100 kg.
- It is necessary to state the load when specifying a Vickers hardness number. For example, if the hardness number is found to be 200 when using a 50 kg load, then the hardness number is written as $H_V(50) = 200$.
- Hardness number (HD). Calculated by dividing the load by the projected area of the indentation:

$$H_V = \frac{\text{Load(Kg)}}{\text{Surface area of indentation (mm}^2\text{)}}$$

$$H_V = \frac{P(\text{Kg})}{\left[\frac{d^2}{2 \sin \frac{1}{2}(136^\circ)} \right] (\text{mm}^2)}$$

$$= \frac{2P \sin 68^\circ}{d^2} = 1.854 \frac{P}{d^2}$$

Here $\alpha = 136^\circ$

where P is the load in Kg and d (mm) is the diagonal of the impression made by the indenter made by the diamond.

Rockwell Hardness Test

- The Rockwell test is used in industry as it is quick, simple and direct reading.
- Universal electronic hardness testing machines are now used at large scale which, at the turn of a switch, can provide either Brinell, Vickers Or Rockwell tests and show the hardness number as a digital readout automatically.
- They also give a "hard copy" printout of the test result together with the test conditions and date.
- In principle the Rockwell hardness test compares the differences in depth of penetration of the indenter when using forces of two different values.
- That is, a minor force is first applied (to take up the backlash and pierce the skin of the component) and the scale are set to read zero.

- Then a major force is applied over and above the minor force and the increased depth of penetration is shown on the scales of the machine as a direct reading of hardness without the need for calculation or conversion tables.
- The standard Rockwell test can not be used for very thin sheet and foils and for these the Rockwell superficial hardness test is used.

Shore Scleroscope

- The scleroscope is an instrument that measures the rebound height of a hammer dropped from a certain distance above the surface of the material to be tested. The hammer consist of a weight with diamond indenter attached to it.
- The scleroscope therefore measures the mechanical energy absorbed by the material when the indenter strikes the surface. The energy absorbed gives an indication of resistance to penetration, which matches out defination of hardness.
- The primary use of the sclerscope seems to be in measureing the hardness of large parts of steel, large, rolls, casting and gears. Since the sedroscope can be carried to the work piece, it is useful for testing large surfaces and other components which can not easily be placed on the testing tables of any other testing machines.

4.4.8 Non-Destructive Testing (NDT)

- NDT is the method of detection and measurement of properties or condition of materials, structures, machines without damaging or destroying their operational capabilities.
- Examples of NDT are: magnetic dust method, penetrating liquid method, ultrasonic test and radiography. All NDTs are used to detect various types of flaws on the surface of material or internal inclusions of impurities and these techniques are also very useful during preventive maintenance and repair.
- There are few techniques which do not require any special apparatus and are quite simple to-handle and only a moderate skill being required. Some of the applications of NDTs are detecting : (i) surface cracks (ii) material composition (iii) internal inclusions (iv) internal voids and discontinuities and (v) condition of internal stresses.

Ultrasonic Test

- High frequency ultrasonic (sound) waves are applied to the test piece by a Piezoelectric crystal. If the test piece is free from cracks, or flawless, then it reflects ultrasonic waves without distortion.
- If there are any flaws in the specimen, the time taken by the ultrasonic waves will be less as the reflection of these waves will be from flaw points and not from the bottom of the specimen.

- Cathode ray oscilloscope (CRO) is used to receive the sound signals, whose time base circuit is connected to it.
- This test is a very fast method used to test aerospace components and automobiles. This test is generally used to detect internal cracks like shrinkage cavities, hot tears, zones of corrosion and non-metallic inclusions.

Liquid-Penetration Test

- This test is used for detection of small defects which are very small to detect with the naked eye. This test is used to detect surface cracks or flaws in non-ferrous metals.
- This test employs a **visible** colour contrast dye penetrant technique for the detection of open surface flaws in metallic and non-metallic objects.
- The penetrants are applied by spraying over the surface of material to be inspected. The excess penetrant is then washed or cleaned. Absorbent powder is then applied to absorb the penetrants in the cracks, voids which reveals the flaws.
- This test reveals flaws such as shrinkage cracks, porosity, fatigue cracks, grinding cracks, forging cracks, seams, heat treatment cracks and leakage etc., on castings, weldings, machined parts, cutting tools, pipes etc.
- If the fluorescent penetrant is used, the developed surface must be examined under ultra violet light to see the presence of defects.
- This technique is used for non-porous and non-absorbent materials.

Radiography

- Done in/on radiographic film by x-rays to know about crack or flaws in welding etc. to have better results.
- Radiography technique is based upon exposing the components to short wavelength radiations in the form of X-rays (wave length less than 10^{-11} cm to about 40×10^{-8} cm) or gamma (γ) rays (wavelength about 0.005×10^{-8} to 3×10^{-8} cm) from a suitable source such as an X-ray tube or cobalt 60.
- These tests are used to detect defects such as blow holes, cracks, shrinkage cavities and slag inclusions.
- These defects are of special importance in components designed to withstand high temperatures and pressure employed in power plant atomic reactors, chemical and pressure vessels and oil refining equipments, because then (i.e., defects) cause stress concentration which may frequently lead to part failure.

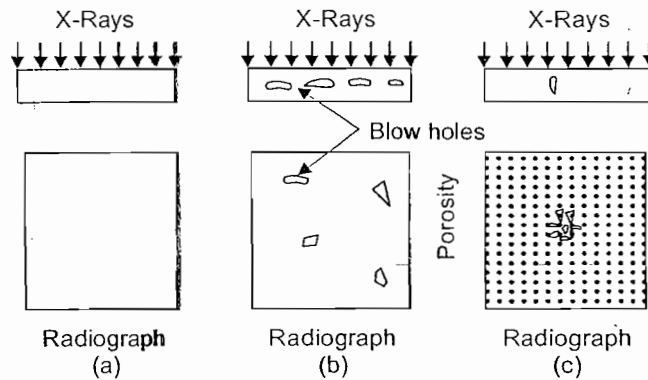


Figure : Radiographs (Expographs).

- In X-ray radiography, the portion of the casting where defects are suspected is exposed to X-rays emitted from the X-ray tube.
- A cassette containing X-ray film is placed behind and in contact with the casting perpendicular to the rays. During exposure, X-rays penetrate the casting and thus affect the X-ray film. –

Since most defects (such as Blow holes, porosity, cracks, etc.) possess low density than the sound metal of the casting, they transmit X-rays better than the sound metal; therefore film appears to be more dark where defects are in line of X-ray beam.

The exposed and developed X-ray film showing light and dark areas is termed as radiograph (or Exograph).

Gamma Radiography

- The principle of detecting defects is same as X-ray radiography. Gamma rays are emitted during the disintegration of radio-active material and like X-rays are electromagnetic radiations.
- Gamma rays are shorter in wavelength and consequently are most penetrating
- Apparatus necessary for gamma-ray radiography is very simple and less costly than X-ray units.
- Gamma rays are used for detecting defects in castings thicker than those inspected by X-rays.
- Owing to less scatter, gamma rays are most satisfactory than X-rays for examining objects varying thickness, whereas X-rays provide better result for casting of uniform thickness.
- X-rays are better than gamma rays for detecting small defects in casting sections less than about 50 mm.
- X-rays method is much more rapid than gamma-ray method, because unlike gamma-ray method, it requires seconds or minutes instead of hours.

QUESTIONS

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| <p>1. Failure due to excessive deformation is controlled by</p> <p>(a) Material properties</p> <p>(b) Design and Dimensions</p> <p>(c) Both</p> <p>(d) None</p> | <p>(c) No need for extra stress during crack propagation</p> <p>(d) All</p> |
| <p>2. Failure due to excessive deformation is controlled by</p> <p>(a) Yield strength</p> <p>(b) Tensile strength</p> <p>(c) Young's modulus</p> <p>(d) All</p> | <p>7. Fracture voids usually form at</p> <p>(a) Inclusions</p> <p>(b) Second phase particles</p> <p>(c) Grain boundary triple points</p> <p>(d) All</p> |
| <p>3. Time dependent yield is known as</p> <p>(a) Fracture (b) Fatigue</p> <p>(c) Buckling (d) Creep</p> | <p>8. Fracture toughness is measured in terms of</p> <p>(a) Strain energy release rate</p> <p>(b) Stress concentration factor</p> <p>(c) Both</p> <p>(d) None</p> |
| <p>4. Cleavage fracture appears</p> <p>(a) Bright</p> <p>(b) Dull</p> <p>(c) Difficult to identify</p> <p>(d) None</p> | <p>9. Fracture toughness decreases with</p> <p>(a) Increasing temperature</p> <p>(b) Increasing strain rate</p> <p>(c) Increase in yield strength</p> <p>(d) Increase in grain size</p> |
| <p>5. Usually materials with following crystal structure fail in ductile mode</p> <p>(a) FCC (b) BCC</p> <p>(c) HCP (d) None</p> | <p>10. Ductile to Brittle Transition Temperature (DBTT) for ceramics is in the range of $X T_m$.</p> <p>(a) 0.1-0.2 (b) 0.2-0.3</p> <p>(c) 0.3-0.5 (d) 0.5-0.7</p> |
| <p>6. Brittle fracture is more dangerous than ductile fracture because</p> <p>(a) No warning sign</p> <p>(b) Crack propagates at very high speeds</p> | <p>11. Following impurity decreases DBTT for steels</p> <p>(a) Mn (b) P</p> <p>(c) Si (d) Mo</p> |

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| <p>12. Fatigue strength for non-ferrous materials is defined at stress cycles</p> <p>(a) 10^3 (b) 10^5
(c) 10^7 (d) 10^9</p> <p>13. Creep rate in tertiary stage</p> <p>(a) Decreases— (b) Constant
(c) Increases (d) None</p> <p>14. Most often machine components fail by</p> <p>(a) Buckling (b) Creep
(c) Fatigue (d) All</p> <p>15. Among the following types of materials which one has the highest modulus of elasticity?</p> <p>(a) Metals
(b) Ceramics
(c) Polymers
(d) Semiconductors</p> <p>16. Yield strength of the materials is the stress at which the material</p> <p>(a) Fractures
(b) Develops cracks
(c) becomes plastic
(d) ruptures</p> <p>17. Materials that normally undergo creep are</p> <p>(a) Metals at room temperature
(b) Metals at high temperature
(c) Low melting point materials
(d) High melting point materials</p> | <p>18. Creep curve is a plot of</p> <p>(a) Strain versus time
(b) Strain versus temperature
(c) Stress versus strain
(d) Elastic modulus versus temperature</p> <p>19. Among the following materials, which one has the highest hardness?</p> <p>(a) Steel
(b) Copper
(c) Cast iron
(d) Silicon Carbide</p> <p>20. Brittle fracture occurs in materials due to</p> <p>(a) The presence of impurities
(b) Presence of cracks
(c) Rise in temperature
(d) Low bond strength</p> <p>21. Time dependent deformation in which the material does not recover its original dimension is called</p> <p>(a) Elasticity (b) Plasticity
(c) Viscoelasticity (d) Anelasticity</p> <p>22. For a good fatigue resistance material, the slope of the S-N curve is _____ (low/high).</p> <p>23. A material is said to be elastic if stress-strain curve is _____ (linear/non-linear).</p> <p>24. The failure of a material due to creep is normally called _____.</p> <p>25. The area under the stress-strain curve gives _____ of the material (hardness/toughness/strength).</p> <p>26. The hardness of steel primarily depends on</p> |
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| <p>(a) Method of manufacture</p> <p>(b) Heat treatment employed</p> <p>(c) Shape of carbides and their distribution in iron</p> <p>(d) Percentage of carbon</p> | <p>32. Vicker's hardness number for diamond could be of the order of</p> <p>(a) 15000 (b) 12000</p> <p>(c) 8000 (d) 4000</p> <p>(e) 800</p> |
| <p>27. Malleability is the property of metals known as</p> <p>(a) Magnetic property</p> <p>(b) Mechanical property</p> <p>(c) Technological property</p> <p>(d) Thermal property</p> | <p>33. Approximate Brinell hardness number for talc is:</p> <p>(a) 1 (b) 2</p> <p>(c) 5-10 (d) 20-30</p> <p>(e) 50-80</p> |
| <p>28. Compressive strength is highest in case of</p> <p>(a) Cast iron</p> <p>(b) Wrought iron</p> <p>(c) Mild steel</p> <p>(d) Low carbon steel</p> <p>(e) High carbon steel</p> | <p>34. The property which enables metals to be drawn into wire is known as</p> <p>(a) Malleability</p> <p>(b) Ductility</p> <p>(c) Straining</p> <p>(d) Plastic deformation</p> <p>(e) Elastic deformation</p> |
| <p>29. The fatigue strength of materials increases</p> <p>(a) with temperature</p> <p>(b) by providing scratches on the surface</p> <p>(c) by providing notches</p> <p>(d) by understressing the material</p> | <p>35. In Brinell hardness testing the minimum thickness of the specimen should be</p> <p>(a) less than 5 times the depth of impression</p> <p>(b) less than 10 times the depth of impression</p> <p>(c) thickness of specimen has no relevance to the depth of impression</p> <p>(d) more than 10 times the depth of impression</p> |
| <p>30. Hardness is</p> <p>(a) Resistance to sliding</p> <p>(b) Resistance to deformation</p> <p>(c) Resistance to scratching</p> <p>(d) Resistance to machining</p> | <p>36. In Brinell hardness testing the time of loading is</p> <p>(a) 1 second</p> <p>(b) 15 to 30 seconds</p> <p>(c) 5 seconds</p> <p>(d) 15 seconds</p> <p>(e) 1 minute</p> |
| <p>31. Which of the following is the hardest?</p> <p>(a) Talc (b) Fluorite</p> <p>(c) Quartz (d) Topaz</p> <p>(e) Corundum</p> | |

37. Which of the following is a non-destructive test?
- (a) Charpy test
 - (b) Izod impact test
 - (c) Tensile test
 - (d) Cupping test
 - (e) X-ray test
38. Slow plastic deformation of metals under a constant stress is known as
- (a) Fatigue
 - (b) Proof deformation
 - (c) Gradual deformation
 - (d) Creep
 - (e) Endurance failure
39. The maximum hardenability of any steel depends on
- (a) Carbon content
 - (b) Chemical composition
 - (c) Grain size
 - (d) Presence of alloying elements
40. Increasing order of hardness
- (a) Talc, quartz, topaz, diamond
 - (b) Talc, quartz, diamond, topaz
 - (c) Talc, diamond, quartz, topaz
 - (d) Talc, diamond, topaz, quartz
41. Which of the following metals has the lowest specific gravity?
- (a) Monel metal
 - (b) Copper
 - (c) Magnesium
 - (d) Bronze
 - (e) Cast iron
42. The capacity of a material to undergo deformation under tension without rupture is known as
- (a) Mechanical strength
 - (b) Stiffness
 - (c) Toughness
 - (d) Ductility
43. Which of the following metals has highest specific gravity?
- (a) Iron
 - (b) Magnesium
 - (c) Copper
 - (d) Aluminium
 - (e) Brass

ANSWERS

1. (c)	12. (c)	23. (Linear)	34. (b)
2. (c)	13. (c)	24. (Rupture)	35. (d)
3. (d)	14. (c)	25. (Toughness)	36. (b)
4. (a)	15. (b)	26. (c)	37. (e)
5. (a)	16. (c)	27. (c)	38. (d)
6. (d)	17. (b & c)	28. (e)	39. (a)
7. (d)	18. (a)	29. (d)	40. (a)
8. (c)	19. (d)	30. (c)	41. (c)
9. (b)	20. (b)	31. (c)	42. (c)
10. (a)	21. (c)	32. (c)	43. (a)
11. (a)	22. (Low)	33. (d)	

5

Alloys and its Various Types

5.1 INTRODUCTION

Introduction

Classification of Alloy

Purpose of Alloying

Ferrous Alloys

Carbon Steel

Alloy Steels

Alloys (or Corrosion Resistant)

Copper

Alloys of Copper

Aluminium and its Alloys

Alloys of Aluminum

Nickel

Nickel Alloys

K-Monel Metal

Super Alloys

Tin Alloys

Refractory Metals

Zinc

An alloy is a substance that has metallic properties and is composed of two or more chemical elements, of which, at least one is a metal. Basically, alloying is done to give strength to metal as the alloying element occupies interstitial space, which create compressive and tensile strength depending on the position of alloying element leads to strengthen the metal.

5.1.1 Classification of Alloy

- Alloy may be homogeneous or mixture. Alloy having single phase is called homogeneous alloy.
- If it is mixture, it will have combinations of several phases and it is termed as heterogeneous alloy.

5.1.2 Purpose of Alloying

- (i) Increase in hardenability.
- (ii) Improve strength at ordinary temperature.
- (iii) Improve mechanical properties at high or low temperature.
- (iv) Improves toughness, wear resistance, corrosion resistance and magnetic properties.

5.2 FERROUS ALLOYS

5.2.1 Carbon Steel

- Iron-carbon alloy that may contain appreciable amount of alloying elements.
- Carbon content is normally less than 1%.

- Plain carbon steels are alloys of iron and carbon where carbon does not exceed 1%, Manganese does not exceed 1.65% and copper and silicon does not exceed 0.60%.

They are classified as :-

Low Carbon Steels

- Carbon content is generally less than 0.25%, and these are unresponsive to heat treatment intended to form martensite and strengthening is accomplished by cold working.
- Microstructure consists of ferrite and pearlite constituents. These are soft, weak but ductile and tough and are least expensive to produce.
- They have weldability better than all steel due to low Carbon Percentage.

Usages :

- Automobile body structural shape such as I-beams, channels and angle irons etc.
- Tin cans

Medium Carbon Steels

- Carbon content between 0.25%C-0.65%C. These alloys can be heat treated by quenching and then tempering to improve mechanical properties.
- Microstructure is generally tempered martensite.
- These have low hardenabilities and can be heat treated in only very thin section with very rapid quenching rate.
- These are stronger than low carbon steel but less ductile and tough.

Usages :

- Railways wheels and trucks
- Gears
- Machine point
- Crankshaft

Designation

Plain carbon steels initial digits start with (1 and 0). Last two digits gives carbon percentage.

- For alloy steels initial digits are other than (1 and 0)
- Unified Numbering system (UNS) is used for indexing both ferrous and Non ferrous alloys.

- It consists of a letter prefix followed by a 5 digit. Letter indicates family of metals to which alloy belongs. For medium carbon steels it is (G), for tool steel it is (T).

High Carbon Steel

- Carbon content between (0.6%C–1.5%C). These are hardest and strongest, but ductility and toughness is lowest than plain carbon steel.
- Most suitable for hardening.
- These are wear resistant and capable of holding sharp cutting edge tool.
- Die steels are high carbon steels.

5.2.2 Low Alloy Steels

Steels containing total alloy content upto 5% are called low alloy steels. Categories of various low alloysteels are :

- These are almost always used in a hardened and tempered condition
- The tools and dies steel are high carbon alloys usually containing chromic vanadium, tungston and molebdenum.

5.2.3 Stainless Steels (or Corrosion Resistant Steels)

- These are highly resistant to corrosion in variety of environments. Predominant alloying element is chromium, whose content of minimum 11% is required.
- These steels have good ductility and toughness at low temperature and high strength upto elevated temperature.
- Chromium gives high corrosion resistance and because of this property, it is called stainless steel.

EFFECTS OF A ALLOYING ELEMENTS ON STEEL

Alloying Elements Effects

1. **Boron:** Improves hardenability without loss of machinability and formability.
2. **Calcium:** Deoxidiser, improves toughness.
3. **Carbon:** Improves hardenability, strength, hardness, wear resistances, reduced ductility toughness and weldability.

4. Chrc incre
5. Cob
6. Cop
7. Man
8. Mo : is "c
9. Nick
10. Pho Toug
13. Niob
14. Tita
15. Van
16. Volu

17. Anti

18. Tin:

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5.2.4 C

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4. **Chromium:** Corrosion resistances, improves toughness, promotes carburization thus increasing depth of hardness penetration.
5. **Cobalt:** Strength and hardness at elevated temperatures.
6. **Copper:** Adversely affects hot working characteristics and surface quality.
7. **Manganese:** Hardenability, strength, and Machinability, reduces hot shortness.
8. **Mo :** Hardenability, wear resistance, elevated temperature strength and most important is "creep resistance", minimizes temper embrittlement.
9. **Nickel:** Hardenability, strength and corrosion resistances.
10. **Phosphores:** Increases strength and hardness but evenly reduces ductility and Toughness and weld ability.
13. **Niobium:** "Imparts fineness of grain size" and decreases hardenability"
14. **Titanium:** Improves hardneability and deoxidizes steel.
15. **Tungsten:** Improves strength and Hardness at elevated temperatures.
16. **Vanadium:** "Inhibits grain growth during heat treatment", improves strength, abrasion resistance and toughness.
17. **Antimony and Arsenic:** Causes temper embrittlement. (TE)
18. **Tin:** Hot shortness and TE.

Note : Rate of crystal growth is accelerated particularly at high temperature by the presence of chromium.

Fortunately grain growth retarded by presence of nickel and vanadium whose presence thus produce a steel which is less sensitive to the temperature condition of heat treatment.

5.2.4 Cast Iron

- Alloys of iron and carbon having carbon content more than 2.11%.
- Generally all cast iron have carbon content between 3 to 4% when Fe-Fe₃C diagram is extended to 100% C.
- Graphite is a more stable phase as compared to cementite.
- Slow cooling rate and silicon content of more than 1% promote graphatization.

EFFECTS OF ELEMENTS ON CAST IRON

Element	Percentage	Effect
Vanadium	0.01-0.5%	Increases hardness strength and machinability.
Copper	0.02-2.5%	Promotes formation of graphites
Molybdenum	0.15-0.9%	To improve tensile strength, hardness to casting and also improves toughness, fatigue strength machinability, hardenability.
Chromium	0.15-0.9%	Acts as a carbide stabilizer, increases strength, hardness and wear-resistant.
Nickel	0.25-2.0%	Aids fusibility and fluidity but induces brittleness.
Phosphorus	1.0%	Aids fusibility and fluidity but induces brittleness.
Manganese	0.75%	Harden the cast iron by encouraging the formation of carbide.
Sulphur	0.1%	Makes hard and brittle
Silicon	2.5%	Promotes the formation of free graphite > 4% which makes the iron soft and causes brittleness machinable.
Carbon		~6.67% Graphite (formed by slow cooling of carbon) tough iron, easy to machine cementite (rapidly cool) high tensile strength, difficult to machine element.

Gray Cast Iron

- Carbon content (2.5–4% wt C).
- Silicon content (1–3% wt).
- It exists in the form of flakes which are surrounded by α -ferrite or pearlite matrix. Because of graphite flakes, the fractured surface take grey appearances.

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- It is weak in tension as tips of graphite flakes are pointed and serve as points of stress concentration.
- Strength and ductility are higher in compression, thus high compressive strength.
- It has excellent vibration damping characteristic, high wear resistance, high fluidity, at casting temperature shrinkage is very low.
- Low ductility and impact strength compared with steel.
- It possesses lowest melting point of the ferrous alloy.
- It possesses high fluidity and hence cast into complex shapes on thin section.
- Due to graphite lubrication quality grey cast iron easily mechanical.

Applications : Castings M/c Bases, cylinder lines, cylinder blocks, clutch plates, pistons, sanitary works, tunnel segment underground pipes.

Mottled Cast Iron (Composition)

Iron = 93.5%, Graphite = 1.75%, Combined carbon = 1.75%, the remaining is impurities.

Properties

- Mixture of the two states, grey cast iron and white cast iron
- Strength and hardness vary according to the ratio of free carbon to combined carbon
- Less tendency to rust than grey iron
- Fluidity is good
- Hard and brittle

Uses :

- Used for manhole covers and pipes

Ductile (Nodular) Cast Iron

- When a small amount of magnesium or cerium is added to gray iron before casting a different microstructure and set of mechanical properties are produced in this microstructure.
- Graphite exist in the form of nodules or sphere like particles instead of flakes.
- This is called nodular CI.
- The matrix phase surrounding is generally pearlite. This CI has more strength and ductility as compared to gray CI (380 - 480 MPa strength) and ductilities (as elongation) form 10% to 20%.

Composition : (3.5 - 4%) C + (2 - 2.8%) Si + (0.05%) Mg + (< 20%) Ni.

Application : Valve pump bodies, high strength gears, Pinion rollers, slides, cranks shafts, machine components etc.

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White Cast Iron

- When the cooling rates of cast iron are high and silicon content is below 1%, most of the carbon exists as cementite instead of graphite.
- This alloy is called white CI. Fractured surface of this alloy is white in appearance.
- It is also called chilled CI as cooling rates are very high.
- It is extremely hard and brittle and almost impossible to machine.
- It has a very limited application where wear resistance is required without ductility e.g. Rollers of rolling mills.

Malleable Cast Iron

- When white CI is heated to a temperature of 800 - 900° C for a prolonged time period and in neutral atmosphere (to prevent oxidation), it causes decomposition of cementite to graphite in the form of clusters or rosetts surrounded by a ferrite or pearlite matrix.
- Strength and ductility increases.
- **Composition :** (2.3 - 2.7% C) + (1 - 1.5% Si) + (<0.55% Mn)
- **Applications :** connecting Rods, Transmission gears, differential cases, flanges marine and heavy duty services.

Properties

- It possesses high yield strength.
- It can be hammered and rolled to different shapes
- It has high Young's modulus and low coefficient of thermal expansion
- It possesses good wear resistance and vibration damping capacity
- It has shrinkage of 1.5mm/100mm
- It is soft, tough and easily machined

Uses :

- Brake pedals, (ii) Tractor springs, (iii) Hangers, (iv) Washing machine parts
- Agriculture implements, (vi) Universal joint yoke, (vii) Automotive crankshafts, (viii) Rail road, etc.

Wrought Iron

- Extremely low carbon content (0.02%). It has a fibrous structure. It is ductile and has good forming qualities & has very high resistance to corrosion.
- It produce in less quantity because of high cost.

Applications : Pipe making, engine bolts and rivets, chains and crane hooks, forging applications etc.

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5.3 COPPER

- Copper has many applications, both as pure metal and an alloy base metal.
- It is malleable and ductile metal and can be easily rolled, drawn or forged.
- The tensile strength and hardness of copper can be improved by cold working although the ductility is reduced.
- Conversely, the annealing can improve the ductility at the expense of the tensile strength and hardness.
- The importance of copper is due mainly to its very high coefficient of electrical conductivity.
- Has very good thermal conductivity and corrosion resistance. The impurities present in copper can have serious effects upon the properties of the metal.
- The electrical conductivity is reduced by 25% due to the presence of 0.04% phosphorus.
- Addition of 0.5% lead or tellurium imparts free-cutting properties to copper.
- Hydrogen is soluble in solid copper.
- Addition of 1% Cd improves the strength when used in telephone wire with minimal effect on the electrical conductivity.
- Copper is rapidly attacked by sulphuric acid, hydrochloric acid, nitric acid, ammonia, sodium hydroxide, potassium hydroxide and amines. Copper can be safely used with sulphurous acid (in paper industry), neutral salts, e.g., sodium chloride, hydrocarbons, alcohols, acetic acid aldehydes, ketones, ethers, lactic and tannic acid.
- Upto 0.5% arsenic added to copper to used in locomotive.

5.3.1 Alloys of Copper

BRASS

Alloy of Cu & Zn having high corrosion resistance and good machinability.

- It acts, as good bearing material.
- Brass may joined by soft soldering using tin based solders with an antimony content below 5% with decrease in Zn-content, risk of cracking drawing timing and soldering reduced.

Example of Brass :

Brass	Composition	Applications
Muntz Metal	60% Cu + 40% Zn	It has high tensile strength, suitable for hot working by rolling, stamping, extruding • Used in pump parts, marine fittings, valves.
Cartridge Brass	70% Cu + 30% Zn	Useful for cold working. • Used for tubes sheets and cold press work.
Admiralty Brass	70% Cu + 29% Zn + 1% Sn	High corrosion and abrasion resistance. Used in condenser tubes and marine work.
Red Brass	5% to 20% Zn alloys	Freedom from seasonal cracking. Used in rivets, pipe end connections etc.
Delta Metal	55% Cu + 41% Zn + 2% Pb + 2% Fe	Used in marine engines, screw propeller, chemical, hydraulic and mining plants.

- Brass also used in manufacturing of evaporators in sugar industries due to corrosion resistance and heat conductivity.
- Conductivity of brass is lesser than Cu.

Bronze

It is a Cu - Sn alloy. Tin varies from 2 - 12%. These are "harder" than brass.

Bronze is formed by "casting", brass is formed by "working".

Phosphor Bronze	(94.8% Cu + 5% Sn + 0.2% P)	• Used in springs, welding Rods, diaphragms, fuse clips, Bellows, clutch disks.
Gun Metal	83% Cu + 10% Sn + 2% Zn	High corrosion resistance. • Used in marine work, valves, water fittings.
Engineers Bronze	88% Cu + 10% + 2% Zn	Steam fittings, Engine parts and hydraulic machinery.
Aluminium Bronze	85% Cu + 4% Fe + 11% Al	• Used in Bearings, gears, worms, busings, valve seats, pickling hooks.

Leaded yellow Brass	67% Cu + 29% Zn + 3% Pb + 1% Sn	Used in Furniture hardware, radiator fittings, light fixture, Battery clamps.
Berelium Bronze	1.9% Be + 0.2% Co + Rest Cu	Used in Valves, Bushings, firing pins.

Note : Unlike steel, bronze struck against a hard surface will not generate spark so it (along with seryllium copper) is used to make hammer, mallet, wrenches.

5.4 ALUMINIUM AND ITS ALLOYS

- Aluminum cannot be purified by blowing air through it, as in the case of iron. This treatment would oxidise the aluminum and leave behind the impurities.
- Therefore the ore must be purified before being electrolysed and this involves an expensive chemical process.
- Aluminum has a great affinity for oxygen. its corrosion-resistance is relatively high.
- This is due to the dense impervious film of oxide which forms on the surface of the metal and protects it from further oxidation.
- The high affinity of aluminum for oxygen also makes it useful as a deoxidant in steels and also in the thermite process of welding.
- Aluminum use as a metallurgical material are its low relative density and its high affinity for oxygen.
- Since its relative density is only about one-third that of steel, or of a copper-base alloy, it is used, when alloyed with small amounts of other elements, for castings in aero, automobile and constructional engineering.
- Alloying and heat-treatment can produce alloys of aluminum which are stronger than steel, so that the use of aluminum alloys is further extended to stress-bearing members in both aero-engine and airframe.
- Pure aluminum is relatively soft and weak (it has a tensile strength of about 90 N/mm² in the annealed condition), so that for most other engineering purposes it is used in the alloyed condition.

5.4.1 Alloys of Aluminum

- One of the chief defects to which aluminum alloys are prone to porosity due to gases dissolved during the melting process.

- Molten aluminum will dissolve considerable amounts of hydrogen if, for any reason, this is present in the furnace atmosphere.
- When the metal is cast and starts to solidify the solubility of hydrogen diminishes almost to zero, so that tiny bubbles of gas are formed in the partly solid metal. These cannot escape and give rise to "pinhole" porosity.
- The defect is eliminated by treating the molten metal before casting with a suitable "flux, or by bubbling nitrogen or chlorine through the melt.
- As a substitute for chlorine, which is a poisonous gas, tablets of the organic compound hexachlorethane can be used.
- Aluminum alloys are used in both the cast and wrought conditions.
- Mechanical properties of them, both cast and wrought, can be improved by the process known as "precipitation-hardening".

Duraluminium

Composition (%) :

Cu	Mn	Mg	Fu & Su	Al
(3.5 - 4.5)%	(0.4 - 0.7)%	(0.4 - 0.7)%	(< 0.7)%	Rest.

- It has high machinability.
- It is strong as steel, but has 1/5th of its weight.
- So it is used to fabricate parts of aircrafts and automobiles.
- It can be heat treated to increase its strength upto 4300 Kg/cm².
- New generation Al - Li alloys are used in aircraft and aerospace industries in cryogenic tank structures.
- These materials have relatively low density, high specific modulus and excellent fatigue and low temperature toughness.

5.5 NICKEL

- It is crystalline, non-ferrous, ferromagnetic metal of silvery-white colour.
- Its hardness matches and compared with the hardness of soft-steel but ductility is less than that. The thermal conductivity and electrical conductivity are poor as compared to copper.
- It possesses excellent corrosion resistant against many alkalies and acids. Nickel can be easily joined and hot or cold worked.
- It can be used for both anode and cathodes.
- Nickel is often used as a cladding on mild steel (niclad), providing both strength and corrosion resistance.

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- It is capable of high quality polishing, thereby provides lustre to the products on which it is polished.
- It is reasonably malleable and can also be rolled provided the carbon content is in small amount (upto 0.5% or less)
- It is resistant to acidic attacks, but dissolves readily in nitric acid.
- Its melting point and specific gravity are 1453°C and 8.9 respectively.

5.5.1 Nickel Alloys

Hastelloy

- These are Nickel and Molybdenum alloys with Fe, Cr, Cu, Al present in certain proportion.
- These are high strength and high temperature alloys with a very high creep resistance.

Monel Metal

Composition (63% Ni + 30% Cu + Fe + Mn + Si + C). It is not affected by sea water or atmosphere.

- It is highly resistant to the corroding affect of alkalies and acids.
- It is used in evaporators (chemical plants), pump impellers for corrosive liquids, pickling plants and drying plants.
- Monel metal filter cloth is used extensively, paints and varnishes are made of Monel metal.

K-Monel Metal

- When (Al) is added to monel metal.
- The utility of K - monel is that it can be made hard by heat treatment retaining corrosive resisting properties of monel metal.
- It can be either hot rolled or cold worked.
- It used in valves and seats in pumps, valves and seats of air bottles used for diesel engines.
- Blades, used in paper making industry, impulse blades for steam turbines, radio instruments due to its non-magnetic nature.

German Silver

(65% Cu + 25% Zn + 10% Ni). It is very resistant to corrosion used in rivets, screws, fasteners, nameplates, hollow wares etc.

Nickel-Fe Alloys

As nickel content increases in iron, magnetic properties decrease and reduce to almost negligible at Ni (28 - 30%). The coefficient of expansion of alloys is practically zero at Ni (25 - 35%), this property is used for making precision instruments.

Invar

Very low coefficient of thermal expansion or may be zero, so it is used in precision equipment. Thus used in clock pendulums, measuring tapes and thermostats.

Nichrome

- (Ni + Cr) alloy (80% Ni + 20% Cr) : Resistance to oxidation increases by the addition of chromium.
- Also as the Cr content increases electrical resistance of the alloy increases. At 20% Cr the alloy has electrical resistance 11 times that of ordinary nickel.
- It is used in making heating element, coils for furnaces sheet and cast plates for furnace bottom, thermocouple sheets.

Monel

- (80% Ni + 14% Cr + 6% Fe) : High mechanical properties coupled with corrosion and heat resisting properties. It is highly resistant to oxidation up to 900° C.
- It can be welded, brazed, soldered, pressed etc. tensile strength may reach up to 1400 MPa.
- It is used in manufacturing of machinery for food processing industries, especially milk and milk products, electronic parts, gas turbine parts, heat treating equipment etc.

5.6 SUPER ALLOYS

- Also known as heat resistant or high temperature alloys.
- Major applications are gas turbines and jet engines, rocket engines, nuclear, petrochemical industries. For such an application mechanical integrity is critical.
- In this regard density is important. Consideration because the centrifugal stresses are diminished in rotating member when density is reduced.
- These materials are classified on the basis of dominant metal in alloy.
- These alloys are resistant to creep and thermal corrosion.
- Most superalloys have maximum service temperature of about 1000° C. There are 3 types of superalloys.

- (a) **Iron Base Superalloys** : contain (32% - 67% Fe + 15% - 22% Cr + 9 - 38% Ni)
- (b) **Cobalt Base Superalloys** : (35 - 65% Co) + (upto 35% Ni) + (19 - 30% Cr).
These alloy specially retain their strength at high temperature due to cobalt.
- (c) **Nickel Base Superalloys** : Most common type proportion of Nickel varies from (38 - 76%) + (< 27% Cr) + (< 20% Co).

5.7 TIN ALLOYS

1. **Solder** : These are three types :

	Sn (%)	Pb (%)
(i)	50	50
(ii)	40	60
(iii)	67	33

2. **Bearing Materials - Babbit Metals** :

Tin Based Babbits : 90% Sn + 4.5% Cr + 5% Antimony + 0.5% Pb

Lead Based Babbit : 84% Pb + 6% Sn + 0.5% Cu + 9.5% Antimony.

- These babbit metals are bearing materials that are used as cast liners with bronze or steel backing. Babbit is preferred to bronze for high speeds and fluctuating loads.
- These have excellent conformability and embedability.
- Tin based babbits have better corrosion resistance as compared to lead based babbits.
- For low speed operations under high pressures bronzes are preferred upto 20% tin lead is added to bronze where lubrication is poor.
- Aluminium bronze is another good material for bearing (Ni-Cd) compound acts as a hardening agent.
- Latest is the metal flouro-plastic material where a thin porous bronze layer (0.3mm) is filled with a mixture of flouro plastic and molybdenum disulphide. This is an anti friction material.

5.8 REFRACTORY METALS

- Metals with extremely high melting point. They are Niobium, Mo, W, Ta. Melting point rang from (2500 - 3400°). (W) has highest m.p of 3410° C.
- These have high strength and hardness at very high temperature.
- Used as alloying elements to steel for improving various properties.

- Mo-alloy are used in extrusion dies, space vehicals, **incandescent** light filaments, x-ray tubes. W-alloys are in making welding electrodes. Tantalum alloys are immune to chemical attack in all enviornments below 150° C.

5.9 ZINC

- Pure zinc is relatively **soft** and weak and is brittle **at room** temperature. It is therefore difficult to cold work, but can be easily rolled into sheets at temperatures between 100°C and 150°C.
- In this form, it is used for battery cases and roofing **and** provides corrosion resistance due to the formation of a dense protective **surface layer**. Zinc is **also** used for sacrificial anodes **to protect** ship's hulls and buried **pipes**.
- A major use of zinc is in providing a coating, **known** as galvanising, for corrosion protection on ferrous materials.

Zinc Alloys

- The low melting point of zinc-based alloys makes **them** an excellent material for die-casting purposes, **and** so they can be cast in relatively inexpensive **dies**.
- A small amount of aluminium or diffusing into solid solution with Zn has a low melting temperature. Alloys used for die casting usually contain 4% Al, 1% to 2% Cu and the balance is zinc, producing a reasonably strong material.



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QUESTIONS

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|--|--|---|---|---|---|---|-----|---|---|---|---|-----|---|---|---|---|-----|---|---|---|---|-----|---|---|---|---|
| <p>1. In low carbon steels, presence of small quantities sulphur improves
 (a) weldability (b) formability
 (c) mechanability (d) hardenability</p> <p>2. Consider the following statements:
 Addition of silicon to cast iron</p> <ol style="list-style-type: none"> 1. Promotes graphite module formation 2. Promotes graphite flake formation 3. Increases the fluidity of the molten metal 4. Improves the ductility of cast iron <p>Of these statements:</p> <ol style="list-style-type: none"> (a) 1 and 4 are correct (b) 2 and 3 are correct (c) 1 and 3 are correct (d) 3 and 4 are correct <p>3. Match List-I (Alloy) with List-II (Use) and select the correct answer using the codes give below the lists:</p> <div style="margin-left: 20px;"> <p>List-I</p> <p>A. Low carbon steel</p> <p>B. Hadfield manganese steel</p> <p>C. Constantan</p> <p>D. Babbitt alloy</p> <p>List-II</p> <ol style="list-style-type: none"> 1. Bearing 2. Thermocouple 3. Wire nails 4. Bulldozer blades </div> | <p>Codes:</p> <table border="0" style="margin-left: 40px;"> <tr> <td></td> <td style="text-align: center;">A</td> <td style="text-align: center;">B</td> <td style="text-align: center;">C</td> <td style="text-align: center;">D</td> </tr> <tr> <td>(a)</td> <td style="text-align: center;">1</td> <td style="text-align: center;">2</td> <td style="text-align: center;">3</td> <td style="text-align: center;">4</td> </tr> <tr> <td>(b)</td> <td style="text-align: center;">3</td> <td style="text-align: center;">4</td> <td style="text-align: center;">1</td> <td style="text-align: center;">2</td> </tr> <tr> <td>(c)</td> <td style="text-align: center;">3</td> <td style="text-align: center;">2</td> <td style="text-align: center;">1</td> <td style="text-align: center;">4</td> </tr> <tr> <td>(d)</td> <td style="text-align: center;">3</td> <td style="text-align: center;">4</td> <td style="text-align: center;">2</td> <td style="text-align: center;">1</td> </tr> </table> <p>4. Addition of magnesium to cast iron increases its
 (a) hardness
 (b) ductility and strength in tension
 (c) corrosion resistance
 (d) creep strength</p> <p>5. 18/8 stainless steel contains
 (a) 18% stainless, 8% chromium
 (b) 18% chromium, 8% nickel
 (c) 18% tungsten, 8% nickel
 (d) 18% tungsten, 8% chromium</p> <p>6. Tin base white metals are used where the bearings are subjected to
 (a) large surface wear
 (b) elevated temperature
 (c) light load and pressure
 (d) high pressure and load,</p> <p>7. Alloy steel which is work hardenable and which is used to make the blades of bulldozers, bucket wheel excavators and other earth moving equipment contain iron, carbon and
 (a) Chromium (b) Silicon
 (c) Manganese (d) Magnesium</p> | | A | B | C | D | (a) | 1 | 2 | 3 | 4 | (b) | 3 | 4 | 1 | 2 | (c) | 3 | 2 | 1 | 4 | (d) | 3 | 4 | 2 | 1 |
| | A | B | C | D | | | | | | | | | | | | | | | | | | | | | | |
| (a) | 1 | 2 | 3 | 4 | | | | | | | | | | | | | | | | | | | | | | |
| (b) | 3 | 4 | 1 | 2 | | | | | | | | | | | | | | | | | | | | | | |
| (c) | 3 | 2 | 1 | 4 | | | | | | | | | | | | | | | | | | | | | | |
| (d) | 3 | 4 | 2 | 1 | | | | | | | | | | | | | | | | | | | | | | |

8. Which of the following pairs regarding the effect of alloying elements in steel are correctly matched?

1. Molybdenum : Forms abrasion resisting particles
2. Phosphorous : Improves mechanability in free cutting steels
3. Cobalt : Contributes to red hardness by hardening ferrite
4. Silicon Reduces oxidation resistance

Which of these statements are correct?

- (a) 2, 3 and 4 (b) 1, 3 and 4
(c) 1, 2 and 3 (d) 1, 2 and 4

9. **Assertion (A)** : Austenitic stainless steel contains 18% chromium and 8% nickel. Since it retains its austenitic structure at room temperature, it is called austenitic stainless steel.

Reason (R) : Chromium present in the steel improves its corrosion resistance by forming a thin film of chromium oxide on the surface.

10. Match List-I (Alloying element in steel) with List-II (Property conferred on steel by the element) and select the correct answer using the codes given below the lists:

List-I

- A. Nickel
- B. Chromium
- C. Tungsten
- D. Silicon

List-II

1. Corrosion resistance
2. Magnetic permeability
3. Heat resistance
4. Hardenability

Codes:

	A	B	C	D
(a)	4	1	3	2
(b)	4	1	2	3
(c)	1	4	3	2
(d)	1	4	2	3

11. Match List-I (Alloys) with List-II (Applications) and select the correct answer using the codes given below the lists:

List-I

- A. Chromel
- B. Babbitt alloy
- C. Nimonic alloy
- D. High speed steel

List-II

1. Journal bearing
2. Milling cutter
3. Thermocouple wire
4. Gas turbine blades

Codes:

	A	B	C	D
(a)	3	1	4	2
(b)	3	4	1	2
(c)	2	4	1	3
(d)	2	1	4	3

12. **Assertion (A)** : Carbon forms interstitial solid solution when added to iron.

Reason (R) : The atomic radius of carbon atom is much smaller than that of iron.

13. Percentages of various alloying elements present in different steel materials are given below:

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1. 18% W; 4% Cr; 1% V; 5% Co; 0.7% C
2. 8% Mo; 4% Cr; 2% V; 6% W; 0.7% C
3. 27% Cr; 3% Ni; 5% Mo; 0.25% C
4. 18% Cr; 8% Ni; 0.15 C

Which of these relate to that of high speed steel?

- (a) 1 and 3 (b) 1 and 2
(c) 2 and 3 (d) 2 and 4

14. Addition of vanadium to steel results in improvement of

- (a) heat-treatability by quenching
(b) hardenability
(c) fatigue strength
(d) resistance to oxidation at elevated temperature

15. The alloy steel designated as 40 Cr 18 Ni 2 by Bureau of Indian Standards contains

- (a) 0.4% C, 18% Cr and 2% Ni
(b) 4.0% C, 1.8% Cr and 0.2% Ni
(c) 0.4% C, 1.8% Cr and 2% Ni
(d) 0.4% C, 1.8% Cr and 0.2% Ni

16. Which of the following factors govern solubility of two nonferrous metals both in liquid state as well as in solid state?

1. Crystal structure
2. Relative size factor
3. Chemical-affinity factor
4. Relative valence factor

Select the correct answer using the codes given below:

- (a) 1, 2 and 3 (b) 2, 3 and 4
(c) 1 and 4 (d) 1, 2, 3 and 4

17. The correct composition of austenitic stainless steel used for domestic utensils is

- (a) 0.08% C, 18% Cr, 8% Ni, 2% Mn, 1% Si
(b) 0.08% C, 24% Cr, 12% Ni, 2% Mn, 1% Si
(c) 0.15% C, 12% Cr, 0.5% Ni, 1% Mn, 1% Si
(d) 0.30% C, 12% Cr, 0.4% Ni, 1% Mn, 1% Si

18. Monel metal is an alloy of

- (a) Iron and carbon
(b) Copper and zinc
(c) Aluminium and copper
(d) Copper and nickel

19. Gunmetal, which is used in journal bearings, contains

- (a) 88% Cu, 10% Sn, 2% Zn
(b) 80% Cu, 10% Zn, 10% Al
(c) 85% Cu, 5% Mg, 10% Al
(d) 85% Cu, 5% Sn, 10% Pb

20. The correct sequence of elements of 18-4-1 HSS tool is

- (a) W, Cr, V (b) Mo, Cr, V
(c) Cr, Ni, C (d) Cu, Zn, Sn

21. **Assertion (A)** : The machinability of steels improves by adding sulphur to obtain so called 'Free Machining Steels'.

Reason (R) : Sulphur in steel forms manganese sulphide inclusion which helps to produce thin ribbon like continuous chip.

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Codes:

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- (a) $\begin{pmatrix} 1 & 2 & 3 & 4 \\ 4 & 3 & 2 & 1 \\ 4 & 2 & 3 & 1 \\ -1 & -3 & 2 & 4 \end{pmatrix}$

24. Match List-I (Alloying Element) with List-II (Effect on Steel) and select the correct answer using the codes given below the lists:

- List-I**

A. Vanadium
B. Molybdenum
C. Silicon
D. Chromium

11-11

1. Increases endurance strength
2. Improves creep properties
3. Increases hardness
4. Increases resistance to high temperature oxidation

Codes:

A B C D

- (a) 2 1 3 4
(b) 1 3 2 4
(c) 2 1 4 3
(d) 1 2 4 3

25. Match **List-I** (Steel) with **List-II** (Application) and select the correct answer using the codes given below the lists:

1. Marine bearings
2. Cutting tools
3. Springs
4. Transformer laminations

List-I

- A. Mild Steel
- B. Tool Steel
- C. High Carbon Steel
- D. Medium Carbon Steel

List-II

- 1. Ball bearing
- 2. Cold chisels
- 3. Shaft and axles
- 4. Rolled steel sections

Codes:

- | | A | B | C | D |
|-----|---|---|---|---|
| (a) | 2 | 1 | 4 | 3 |
| (b) | 4 | 3 | 2 | 1 |
| (c) | 2 | 3 | 4 | 1 |
| (d) | 4 | 1 | 2 | 3 |

26. Match List-I (Alloy) with List-II (major Constituent) and select the correct answer using the codes given below the lists:

- | List-I | List-II |
|---------------|-----------------|
| A. Babbitt | 1. Nickel |
| B. Invar | 2. Tin and lead |
| C. Gun Metal | 3. Aluminium |
| D. Duralumin | 4. Copper |

Codes:

- | | A | B | C | D |
|-----|---|---|---|---|
| (a) | 2 | 4 | 1 | 3 |
| (b) | 3 | 1 | 4 | 2 |
| (c) | 2 | 1 | 4 | 3 |
| (d) | 3 | 4 | 1 | 2 |

27. Which of the following materials is used in the manufacture of extrusion nozzles?

- (a) Grey cast iron
- (b) Malleable cast iron
- (c) White cast iron
- (d) Nodular cast iron

28. Consider the following statements:

- 1. Cast Iron has poor ability to damp vibrations.
- 2. Cast Iron has higher compressive strength compared to that of steel.
- 3. Cast Iron parts are suitable where permanent deformation is preferred over fracture.

Which of these statements is/are correct?

- (a) 1, 2 and 3
- (b) 1 and 3
- (c) 3 only
- (d) 2 only

29. Match List-I (Composition) with List-II (Application) and select the correct answer using the codes given below the lists:

List-I

- A. Commercial bronze (10% Zn)
- B. Red brass (15% Zn)
- C. Aluminium brass (22% Zn 2% Al)
- D. P-bronze (11% tin, small amount of P)

List-II

- 1. Radiator
- 2. Spring metal
- 3. Forging and stamping
- 4. Power plant and chemical equipment

Codes:

	A	B	C	D
(a)	2	4	1	3
(b)	3	1	4	2
(c)	2	1	4	3
(d)	3	4	1	2

30. In case of power screws, what is the combination of materials used for the screw and the nut?
- (a) Cast iron screw and mild steel nut
(b) Carbon steel screw and phosphor bronze nut
(c) Cast iron screw and cast iron nut
(d) Aluminium screw and alloy steel nut
31. Which one of the following elements/alloys exhibits season cracking?
- (a) Iron (b) Brass
(c) Aluminium (d) Steel
32. Vibration damping in machinery is best achieved by means of base structures made of which one of the following material?
- (a) Low carbon steel
(b) Nodular iron
(c) Grey cast iron
(d) White cast iron
33. Which of the following elements given below determine(s) the maximum attainable, hardness in steel?
1. Chromium 2. Manganese
3. Carbon 4. Molybdenum
- Select the correct answer using the code given below:
- (a) 1 only (b) 1 and 2
(c) 3 only (d) 2 and 4
34. Coefficient of Expansion is practically nil in a particular alloy. What is this alloy?
- (a) Had field Manganese Steel
(b) Invar
(c) Vitallium
(d) Stellite
35. Consider the following statements in respect of austenitic stainless steels:
1. Austenitic stainless steels are hardened and strengthened by cold working.
2. Austenitic stainless steels cannot be quenched and tempered.
- Which of these statements is/are correct?
- (a) 1 only (b) 2 only
(c) Both 1 and 2 (d) Neither
36. Which one of the following is correct? Babbitts are used for
- (a) gears (b) bearings
(c) bolts (d) clutch liners
37. Which material is used for bushes in the bushed-pin type of flexible coupling?
- (a) Gun metal (b) Plastic
(c) Rubber (d) Aluminium
38. The elements which, added to steel, help in chip formation during machining are
- (a) sulphur, lead and phosphorous
(b) sulphur, lead and cobalt
(c) aluminium, lead and copper
(d) aluminium, titanium and copper

39. Which one of the following cast irons consists of carbon in rosette form?

- (a) White cast iron
- (b) Gray cast iron
- (c) Malleable cast iron
- (d) Nodular cast iron

40. Which one of the following possesses the property of non-sparking character?

- (a) Hadfield's manganese steel
- (b) Spring steel
- (c) Stellite
- (d) Invar

41. Why are Babbitt alloys used for bearing material?

- (a) They have excellent embeddability
- (b) They are relatively stronger than other bearing materials
- (c) They do not lose strength with increase in temperature
- (d) They have high fatigue strength

42. Consider the following statements:

Alloying elements are added to

- 1. Improve hardness and toughness.
- 2. Corrosion and oxidation resistance improvement.
- 3. Improve machinability and hardenability.

4. Increase weight and volume.

Which of these statements are correct?

- (a) 1, 2 and 3 only
- (b) 2, 3 and 4 only
- (c) 1, 2 and 4 only
- (d) 1, 2, 3 and 4

43. Match List-I (Component) with List-II (Required Property) and select the correct answer using the code given below the lists:

List-I

- A. Blades of bulldozer
- B. Gas turbine blades
- C. Drill bit
- D. Spring of automobiles

List-II

- 1. High wear resistance and high toughness
- 2. Low Young's modulus and high fatigue strength
- 3. High wear and abrasion resistance
- 4. High creep strength and good corrosion resistance

Codes:

	A	B	C	D
(a)	3	2	1	4
(b)	1	4	3	2
(c)	3	4	1	2
(d)	1	2	3	4



ANSWERS

1. (c)	10. (a)	19. (a)	28. (d)	37. (c)
2. (b)	11. (a)	20. (a)	29. (b)	38. (a)
3. (d)	12. (a)	21. (a)	30. (b)	39. (d)
4. (b)	13. (b)	22. (d)	31. (b)	40. (b)
5. (b)	14. (b)	23. (c)	32. (c)	41. (a)
6. (a)	15. (a)	24. (d)	33. (d)	42. (a)
7. (c)	16. (d)	25. (d)	34. (b)	43. (c)
8. (c)	17. (a)	26. (c)	35. (c)	
9. (b)	18. (d)	27. (c)	36. (b)	

6.1 INTRODUCTIONIntroductionAnnealingNormalizingHardeningWater QuenchingTemperingHigh Tempering
(500-650°C)Medium Tempering
(350-500°C)Low Tempering
(150°C-350°C)Case HardeningType of CaseInduction HardeningFlame Hardening

6

Heat Treatment

6.1 INTRODUCTION

Introduction

Annealing

Normalizing

Hardening

Water Quenching

Tempering

High Temperature Tempering
(500-650°C)

Medium Temperature Tempering
(350-500°C)

Low Temperature Tempering
(150°C-350°C)

Case Hardening

Type of Case Hardening

Induction Hardening

Flame Hardening

- Heat treatment is a combination of heating and cooling operation and applied to a metal or alloy in the solid state in a way that will produce desired properties.
- All basic heat treating processes for steel involve the transformation or decomposition of austenite.
- The nature and appearance of these transformation products determine the physical and mechanical properties of any given steel.
- The first step in heat treatment of steel is to heat the material to some temperature in or above the critical range in order to form austenite.
- In most cases, the rate of heating to the desired temperature is less important than other factors in heat-treating cycle.
- Highly stressed materials produced by cold work should be heated more slowly than stress free materials to avoid distortion.
- The difference in temperature rise within thick and thin section of articles of variable cross-section should be considered and whenever possible, provision should be made for slowing the heating of the thinner section to minimize thermal stress and distortion.

6.2 ANNEALING

Annealing is a heat treatment process generally used to :

- (i) Relieve internal stresses
- (ii) Increase, softness, ductility and toughness
- (iii) Produce a specific microstructure.

It consists of three stages :

- (i) Heating to a desired temperature
 - (ii) Holding or 'Soaking' at that temperature
 - (iii) Cooling usually to room temperature.
- It is employed for low and medium carbon steels that will be experiencing plastic deformation during forming operation.
 - It refines the structure.
 - It is carried out a 15° C to 40° C above upper critical temperature for hypo-eutectoid steels and above lower critical temperature for hyper-eutectoid steels.
 - Holding time is generally 3-4 min. per mm thickness of the largest sections.
 - After heating furnace is turned off and both alloy and furnace cool together to room temperature at the same rate.
 - The microstructure product of full annealing is "coarse pearlite" in addition to any proeutectoid phase (α or Fe_3C).
 - Grains are small and uniform.

6.3 NORMALIZING

- Steels that have plastically deformed for eg : a rolling operation, consists of grains of pearlite and a proeutectoid phase, which are irregularly shaped and relatively large and vary in size.
- Normalizing is used to refine these grains (i.e. to decrease average grain size) and produce more uniform and desirable size distribution.
- The microstructure formed is fine grained pearlite with a proeutectoid phase.
- It is accomplished by heating alloy (55° C to 85° C) above the upper critical temperature. After sufficient time has been given to alloy to completely transform to austenite (Austenizing), the treatment is terminated by cooling in air. It raises hardness and strength of alloy, but decreases ductility of steels.
- Normalizing is done to increase the strength of medium carbon steel.
- Improve machinability of low carbon steel.
- Improve structure of weld.
- Mechanical properties is better than annealing and process is of short duration because of cooling in air.
- The selection process of annealing, normalising and spheroidizing normalizing and spheroidizing depend on carbon content.
- Steel produced in Normalizing is less ductile than annealed steel having the same composition.
- It helps in achieving desired result in mechanical and electrical properties.

6.4 HARDENING

"Hardenability" is the ability of alloy to get hardened by the formation of martensite microstructure after suitable heat treatment.

- **Hardening of steels involves 3 process :**

- (i) Heating the object to a temperature above the critical point.
- (ii) Holding the object at this temperature for a definite period.
- (iii) Quenching in a suitable medium.

- Hypoeutectoid steels are heated 30 - 50° C above the Upper critical temperature while hypercutectoid steels are heated above Lower Critical Temperature (L.C.T).

- Upon heat transformation to austenite takes place (Austenizing), Steels are then cooled at a rate faster than critical cooling rate that enables austenite to transform directly to martensite. Hardening must be followed by tempering to improve mechanical properties of steel.

Hardening Depends Upon

1. Adequate carbon content

- In order to produce structures like martensite at least 0.5% C is required.
- Carbon increases hardness upto 1%.

2. Heating Rate and time

- Heating rate depends upon the composition of steel, its structure, residual stresses, form & size of the part to be hardened.
- If heating rate is too high there will be temp-gradient between surface & core of the part.
- Best way is to heat the part & hold it there for a sufficient time so that entire volume attain the same temperature. Heating time of tool & high steels is 50% more than carbon steels.

3. Quenching Medium

- It has to provide cooling rates greater than Critical Cooling rate to avoid decomposition of austenite to pearlite or bainite.
- Most widely used quenching media are water, brine, oil, air, molten salt etc.

6.4.1 Water Quenching

- Water & aqueous solution are most widely used as quenching media for hardening carbon & low alloy steels.

- But water quenching tends to form a vapour blanket which reduces the cooling rate and there is a sharp reduction in cooling capacity at higher temperature.
- It also leads to high stresses leading to distortion and even quenching cracks.
- Adding NaCl , H_2SO_4 , soda to water substantially increases its cooling capacity and provides more uniform cooling. Maximum cooling rate is obtained when 10-15% salt is added.

Mineral oil Quenching

Suitable for quenching alloy steels in which austenite is highly stable and critical cooling rate is therefore low.

Advantages

- Due to its high boiling point the cooling rate in the martensite range is comparatively low. This prevents quenching defects.
- Compared to water, oil cools steel more uniformly over the entire temperature range which reduces quenching stresses.

Disadvantages

- Low cooling rates as compared to water.
- High inflammability of oil.
- It has a tendency to thicken in the furnace.

Quenching Rate

It depends upon quenching medium. The higher the quenching rate the more is the temperature gradient between the core and the surface.

Size and Shape

Long articles of cylindrical & other cross-section should be quenched with their axis perpendicular to both surface.

- Long articles should be immersed at one end and the direction of movement during cooling should coincide with direction of immersion.
- Heavy article should be held stationary and the liquid should be agitated.

Martempering (or Stepped Quenching)

Martempering is performed in two steps, first the steel is quenched in water to a temperature 300-400° C and then quickly transferred to a higher temperature medium like oil where it is held until it is completely cooled.

As this is done in two steps so it is called as stepped quenching, after heating steel to hardening temperature. It is quenched in a medium to a temperature slightly above M_s (240° C). The Holding time must be enough so that the temperature of cooling medium.

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The holding time must be sufficient to bring entire volume to a uniform temp, but should not be long enough to cause decomposition by austenite to Bainite. This treatment gives a micro structure of martensite & retained austenite.

Advantages

1. Less volume change due to presence of retained Austenite
2. Less distortion since transformation occurs simultaneously in the entire volume.
3. Less chance of quenching cracks.

Disadvantages

It can be applied to sections of 5-8 mm thickness only.

Austempering

Longer holding times as compared to martempering in hot bath. Austenite transforms to Bainite. Here molten salts & alkalies are used as quenching media. Temperature is maintained between 150°C-450°C.

Here, sample has quenched below the nose of TTT diagram but above the martensite start line then it hold for longer period.

Advantages

1. No martensite formation thus no brittleness.
2. No quenching cracks, distortion.
3. Improved ductility.
4. Impact strength & toughness are increased.

Disadvantages

It can be applied to small sections only as big sections cannot be cooled rapidly enough to avoid pearlite formation.

6.5 TEMPERING

It is done (i) To relieve residual stress (ii) To improve ductility (iii) Toughness is increased.

- Tempering is carried out in the temperature Range of 150°C-650°C.
- It is heating of steel below lower critical temperature (hardened steel), holding it for sometime and then slowly cooling.
- It is the final operation in the heat treatment.
- It is done to improve the mechanical properties of martensite which become very brittle during quenching.
- Thus hardening should be followed by tempering.
- High temperature tempering causes reduction in hardness and increase in toughness and by slow cooling residual stress generated during hardening will be decreased.

6.5.1 High Temperature Tempering (500-650°C)

Resulting structure is sorbite, residual stress completely vanished.

6.5.2 Medium Temperature Tempering (350-500°C)

Resulting in Troostite formation. This process increases endurance limit. This process is used for making "spring steels and die steels". After tempering work is cooled to water, leads to enhanced endurance strength.

6.5.3 Low Temperature Tempering (150°C-350°C)

Holding time is 1-3 hrs. This apart from above properties of tempering, provides additional "wear resistance". Used for measuring & cutting tools bending & true tensile strength, in case hardness change small extent.

Note : Tempering can be judge by temper color which appear on the bright red surface and experienced eye can view them.

Color	Tempering Temperature
Very pale yellow	about 220°C
Straw yellow	about 238°C
Brown yellow	about 260°C
Bright purple	about 177°C
Dark purple	about 288°C
Pale yellow	about 321°C

6.6 CASE HARDENING

Here hard surfaces are produced with relatively soft core. Hard surface has good wear resistance while soft core has good toughness. Hard surface is called case.

6.6.1 Type of Case Hardening

Carburizing

It is applied to low carbon steels having upto 0.18%C (Temp range is between (870-950°C) and result in formation of Austenite phase, which has maximum solubility of carbon.

Methods are as follow

6.6.2 Pack Carburizing

Piece is surrounded by a carburizing mixture and packed in a steel box. It is heated to around (870-950°C)

Carburizin

- BaCO₃
- Heatir
- Fe + C
- Fe₃C

Advant

High labor

See in fig

This atom

Advantage

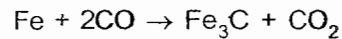
High quality
flexibility

Liquid Car

Workpiece
which pro

Carburizing mixture : 50% charcoal + 20% BaCO_3 + 5% CaCO_3 + 5-12% Na_2CO_3

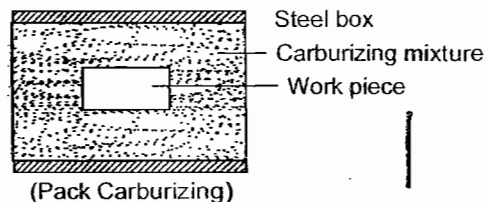
- BaCO_3 acts as an energizer and increases action of carbon on low carbon steel.
- Heating time is 6-8 hours and carbon diffuses into layer of part.



- Fe_3C is austenite which dissolves carbon.

Disadvantages

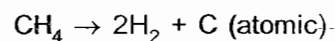
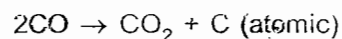
High labour cost, time consuming, difficult to quench directly from carburizing temperature.



Gas Carburizing

Here workpart is treated in a atmosphere of gases containing carbon and hydrocarbon gases such as CH_4 , butane etc.

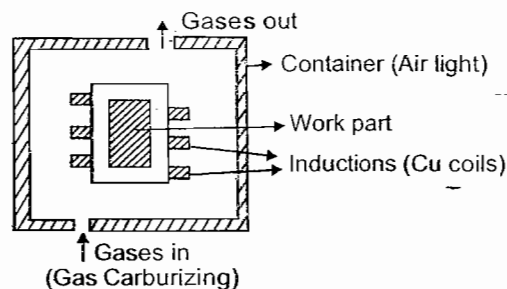
Part is heated to temperature of 950°C for 3-12 hrs (holding time).



This atomic carbon diffuses into austenite and produced hard surfaces.

Advantages

High quality, quick process, low labour cost, process is clear, production cost is low, more flexibility of operation



Liquid Carburizing

Workpiece is heated to 950°C and dipped in a molten salt bath containing 20% NaCN , which provides Carbon & Nitrogen. At this temperature Carbon and small amount of

Nitrogen diffuses into surface. The only disadvantage is that cost of carburizing salt is very high.

In carburizing operations carbon can be penetrated upto the depth of 0.3mm with hardness obtained around (55-65 HRC).

Applications

Gears, cams, shafts, bearings, piston pins, sprockets.

Nitriding

- Here nitrogen content of the surface is increased.
- It is done by heating steel in the atmosphere of NH_3 gas.
- Piece to be nitrided are placed in an air tight container. workpiece is heated to a temperature in range (500-600°C), at which NH_3 dissociates into $2\text{NH}_3 \rightarrow 2\text{N} + 3\text{H}_2$
- This atomic nitrogen diffuses to the surface making case hardened.
- This process make the hardest case on steels.
- Maximum thickness of case is around (0 – 0.5mm).
- After nitriding the work is cooled in the furnace in the presence of ammonia.
- Holding time is 30-40 hrs

Advantages (Hardest Case Obtained)

- High wear resistance endurance limit and resistance to corrosion.
- No heat treatment is required after nitriding.

Applications

Gears, shaft, valves, boring bars, fuel injection pump parts Generally alloy steels, HSS, stainless steels are heat treated.

Disadvantages

- Case produced is brittle
- Costly compared to carburizing

Cyaniding

- Here work part is immersed in molten salt bath containing sodium cyanide (NaCN), which is heated to 820-860°C.
- This is usually followed by water quenching.
- The cyanide bath consists of :
20-30% NaCN + 25-50% NaCl + 25-50% Na_2CO_3

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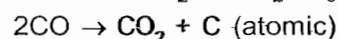
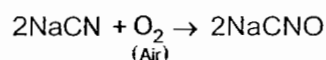
s heated to a

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/ steels, HSS,

anide (NaCN),

- Time required is 30-90 minutes depending upon depth of case required. which is in the range 0.15-0.5mm. The following reaction takes place:



- The atomic C & N diffuse into steel surface,
- The work can be directly quenched as soon as it is taken from molten bath.
- Cases obtained by cyaniding are more wear resistance and have high endurance compared to carburizing.

Applications

Small shafts, worms, gears, nuts, springs etc.

Carbonitriding (Gas Cyaniding)

- A mixture of NH_3 and a hydro carbon gas is used.
- The work is heated to 850°C for 2-10hrs.
- This is followed by quenching and low temperature tempering.
- Carbon diffuses at a rate higher than nitrogen.
- Troosite is the product of tempering here.
- It is better process compared to carburizing and cyaniding.
- In this process carbide and nitride lower the stability of austenite leads to formation of troosite which reduce the endurance limit ductility and toughness of steel.
- This is used for steel having percentage of carbon in the range of medium carbon steel.
 - This process involves lower temperature
 - Higher corrosion and wear resistances.
 - Clean operation
 - Toxic salts are not required
 - Less time consume
 - Work can be machined
 - Nitrogen and Carbon contents can be controlled

6.7 INDUCTION HARDENING

- Workpieces heated in an induction furnace surrounded by copper coils which are water cooled. High frequency AC current is passed through Cu coils and thus alternate magnetic field set up which induce eddy currents on the surfaces.

- Heat is generated on the surface by eddy currents.
- The surface of work piece is heated in austenitic range then quenched immediately to form martensite.
- The structure of core remain unchanged because it is not affected by heat.
- The composition should contain 0.4-0.5% C or sufficient alloying element as Cr, Ni or Mo approximately 90% of the heat generated in the work layer of thickness X.

$$\text{where } X = 5000 \sqrt{\frac{\rho}{\mu f}}$$

where f = frequency, μ = magnetic permeability, ρ = electrical resistivity.

- Heating rate is 300°/sec for hypoeutectoid steel and subsequently heating time is very small (2-50 sec.) quenching temperature depend upon rate of heating if the rate is 500°C/sec, it is 1000°C & if it is 250°C then 900°C.

Induction hardening is done in three ways

- Whole workpieces is heated at one go and quenched. This process is used for hardening small shafts and tools.
- Sections of work are heated and quenched consequently. Used for hardening crank shaft journals, gear teeths and cams of camshaft.
- Work is made to travel w.r.t stationary inductor and spray quenching is done. Used for hardening long shafts and axles.

Advantages

Process is very quick and highly productive

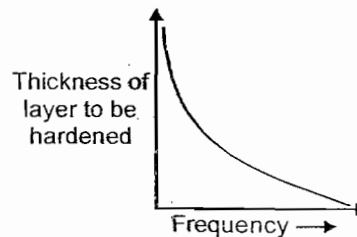
- Scale is not formed.
- Process can be automated and depth of hardness can be controlled easily.
- Distortion is reduced.
- Both internal and external surfaces can be hardened.
- Maximum production method.

Disadvantages

Special fixtures are required for holding workpieces.

Application

Used in hardening surfaces of camshaft, crank shaft, gears, automobile components, splines, spindles, brake drum etc.



6.8 FLAME

- Process gas flame
- Heat is that the
- The thick

Advantages

- Practical heated.
- Due to
- Easy Air
- It is more
- Very efficient

Disadvantages

- This is
- High heat

6.8 FLAME HARDENING

- Process consists of heating the surface of high carbon steels by a high temperature gas flame at 2400-3500°C, followed by immediate cooling in air or water.
- Heat is supplied by oxy-acetylene torch. The heat is supplied so quickly to the surface that the core remains unaffected.
- The thickness of hardened layer is 2-4mm and its structure is martensite.

Advantages

- Practically no distortion of workpiece because only small sections of workpiece is heated.
- Due to high heating rate workpiece surface remains clean.
- Easy Automation.
- It is more efficient for large works as compared to induction hardening.
- Very economical for large works.

Disadvantages

- These sections may get distorted extensively.
- High heat may cause cracks.



QUESTIONS

1. Match **List-I** (Heat treatment) with **List-II** (Effect on the properties) and select the correct answer using the codes given below the lists:

List-I

- A. Annealing
- B. Nitriding
- C. Martempering
- D. Normalising

List-II

- 1. Refined grain structure
- 2. Improves the hardness of the whole mass
- 3. Increases surface hardness
- 4. Improves ductility

Codes:

	A	B	C	D
(a)	4	3	2	1
(b)	1	3	4	2
(c)	4	2	1	3
(d)	2	1	3	4

2. Machines tool guideways are usually hardened by
- (a) vacuum hardening
 - (b) martempering
 - (c) induction hardening
 - (d) flame hardening
3. Guideways of lathe beds are hardened by

- (a) carburizing
- (b) cyaniding
- (c) nitriding
- (d) flame hardening

4. A given steel test specimen is studied under metallurgical microscope. Magnification used is 100 X. In that different phases are observed. One of them is Fe_3C .

The observed phase Fe_3C is also known as

- (a) ferrite
- (b) cementite
- (c) austenite
- (d) martensite

5. Assertion (A): Refining the grain size of polycrystal line material renders it harder and stronger.

Reason (R): Grain boundaries provide easy paths to dislocation motion.

- (a) Both A and R are true and R is the correct explanation of A
- (b) Both A and R are true but R is not a correct explanation of A
- (c) A is true but R is false
- (d) A is false but R is true

6. Heating the hypoeutectoid steels to $30^\circ C$ above the upper critical temperature line, soaking at the temperature and then cooling slowly to room temperature to form a pearlite and ferrite structure, is known as
- (a) Hardening
 - (b) Normalising
 - (c) Tempering
 - (d) Annealing

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7. **Assertion (A)** : Normalized steel will have lower hardness than annealed steel.

Reason (R) : The pearlite of normalized steel is finer and has lower intermolecular space.

- (a) Both A and R are true and R is the correct explanation of A
 (b) Both A and R are true but R is not a correct explanation of A
 (c) A is true but R is false
 (d) A is false but R is true

8. Consider the following quenching media:

1. Oil 2. Water
 3. Water + NaOH 4. Brine

The correct sequence of these media in order of increasing hardness of steel undergoing heat treatment is

- (a) 1, 3, 2, 4 (b) 2, 1, 3, 4
 (c) 1, 2, 3, 4 (d) 4, 3, 2, 1

9. 'Tempering' of quenched martensitic steel is necessary to improve the

- (a) hardness of the metal
 (b) surface texture of the metal
 (c) corrosion resistance of the metal
 (d) ductility of the metal

10. Primary object of full annealing is to

- (a) Increase toughness and yield point
 (b) Reduce ductility and resilience
 (c) Remove foreign impurities and improve surface finish
 (d) Increase ductility and machinability

11. Globular form of cementite in the structure of steel is obtained through

- (a) Normalising (b) Malleabilising
 (c) Spheroidising (d) Carbonizing

12. Match List-I (Name of treatment) with List-II (Media used) and select the correct answer using the codes given below the lists:

List-I

- A. Pack carburizing
 B. Gas carburizing
 C. Cyaniding
 D. Nitriding

List-II

1. Ammonia gas
 2. Sodium cyanide
 3. Carburising compound
 4. Ethane

Codes:

- | | A | B | C | D |
|-----|---|---|---|---|
| (a) | 3 | 4 | 2 | 1 |
| (b) | 2 | 1 | 3 | 4 |
| (c) | 3 | 1 | 2 | 4 |
| (d) | 2 | 4 | 3 | 1 |

13. Consider the following pairs:

Heat treatment	Effects on medium carbon steel
1. Normalising	: Grain refinement
2. Full annealing	: Uniform grain structure
3. Martempering	: Decreased ductility
4. Spheroidizing	: Maximum softness

Which of the pairs given above are correctly matched?

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- (a) 1 and 2 (b) 2 and 3
(c) 3 and 4 (d) 1, 2, 3 and 4
14. Austempering is employed to obtain
(a) 100% martensitic structure
(b) 100% bainitic structure
(c) 50% martensitic and 50% bainitic structure
(d) 100% pearlitic structure
15. Consider the following statements about medium carbon steel:
(1) It can be quench-hardened but not case-hardened
(2) It cannot be quench-hardened but case-hardening can be done
(3) It exhibits distinct yield point under tension test
Which of these statements are correct?
(a) 1 and 2 (b) 2 and 3
(c) 1 and 3 (d) 1, 2 and 3
16. Consider the following statements:
Assertion (A) : Carburizing is done on nonferrous alloys to increase the surface hardness.
Reason (R) : Precipitation hardening of nonferrous alloys involves solution heat treatment followed by precipitation heat treatment.
Of these statements
(a) Both A and R are true and R is the correct explanation of A
(b) Both A and R are true but R is not a correct explanation of A
(c) A is true but R is false
(d) A is false but R is true
17. The pattern known as Widmanstatten structure is encountered in
(a) tempering (b) normalizing
(c) spheroidizing (d) annealing
18. Which one of the following is the process to refine the grains of metal after it has been distorted by hammering or cold working?
(a) Annealing (b) Softening
(c) Recrystallizing (d) Normalizing
19. Tempering is a process of annealing
(a) martensite at low temperatures
(b) martensite at higher temperatures
(c) bainite at low temperatures
(d) bainite at higher temperatures
20. Which of the following factors influence hardness in a plain carbon steel?
1. Percentage carbon
2. Quenching media
3. Work size
Select the correct answer using the code given below :
(a) 1 and 2 only (b) 2 and 3 only
(c) 1 and 3 only (d) 1, 2 and 3
21. Which one of the following mediums is used for the fastest cooling rate of steel quenching ?
(a) Air (b) Oil
(c) Water (d) Brine
22. Which one of the following materials can be subjected to an age hardening process?

23.

24.

25.

- (a) HSS (b) Aluminium
(c) Pure iron (d) Stellite
23. Isothermal annealing is mainly used in alloy steels to improve.
- (a) Malleability (b) Toughness
(c) Ductility (d) Weldability
24. Match List-I (Quenching media) with List-II (Structure produced) and select the correct answer using the code given below the lists:

List-I

- A. Water
B. Oil
C. Air
D. Furnace cool

List-II

1. Coarse pearlite
2. Martensite
3. Very fine pearlite
4. Fine pearlite

Codes:

- | | A | B | C | D |
|-----|---|---|---|---|
| (a) | 1 | 3 | 4 | 2 |
| (b) | 2 | 3 | 4 | 1 |
| (c) | 1 | 4 | 3 | 2 |
| (d) | 2 | 4 | 3 | 1 |

25. Consider the following:

1. Water 2. Ice
3. Brine solution 4. Oil

Which of these is/are used as quenching media in case of Alloy steels?

- (a) 1, 2 and 3 only
(b) 2, 3 and 4 only
(c) 1 and 4 only
(d) 4 only

26. Consider the following statements regarding annealing process:

1. All structural imperfections are removed.
 2. The hypo-eutectoid steel is heated to about 50 – 70°C below upper critical temperature.
 3. Cooling can be done in heat treating furnace, by heating it, keeping the metal in it and turning off furnace till it, cools to room temperature.
 4. Uniform grain structure is resulted.
- Which of these statements are correct?

- (a) 1, 2 and 3 only
(b) 2, 3 and 4 only
(c) 1, 3 and 4 only
(d) 1, 2, 3 and 4

27. During heat treatment of steel, the hardness of various structures in increasing order is

- (a) martensite, fine pearlite, coarse pearlite, spherodite
(b) fine pearlite, martensite, spherodite, coarse pearlite
(c) martensite, coarse pearlite, fine pearlite, spherodite
(d) spherodite, coarse pearlite, fine pearlite, martensite

28. Hardness of steel greatly improves with

- (a) annealing (b) cyaniding
(c) normalising (d) tempering

29. From the lists given below, choose the most appropriate set of heat treatment process and the corresponding process characteristics

Process	Characteristics
P. Tempering.	1. Austenite is converted into bainite
Q. austempering	2. Austenite is converted into martensite
R. Martempering	3. Cementite is converted into globular structure

4. Both hardness and brittleness are reduced

5. Carbon is absorbed into the metal

- (a) P-3, Q-1, R-5 (b) P-4, Q-3, R-2
(c) P-4, Q-1, R-2 (d) P-1, Q-5, R-4

30. The main purpose of spheroidizing treatment is to improve

- (a) hardenability of low carbon steels
(b) machinability of low carbon steels
(c) hardenability of high carbon steels
(d) machinability of high carbon steels

ANSWERS

1. (a)	7. (d)	13. (d)	19. (a)	25. (f)
2. (d)	8. (c)	14. (b)	20. (d)	26. (e)
3. (d)	9. (d)	15. (b)	21. (d)	27. (e)
4. (b)	10. (d)	16. (d)	22. (e)	28. (e)
5. (c)	11. (c)	17. (a)	23. (e)	29. (e)
6. (d)	12. (a)	18. (c)	24. (b)	30. (d)

7

Magnetic Properties of Materials

7.1 PROPERTIES OF MAGNETIC MATERIAL

Properties of Magnetic Material

Permeability

Magnetic Dipole Moment

Bohr Magneton

Magnetization (M)

Origin of Permanent Magnetic Dipole

Classification of Magnetic Materials

Diamagnetic Material

Paramagnetic Material

Ferromagnetic Material

Antiferromagnetic Materials

Ferrimagnetic Materials

Curie Temperature

Curie Law

Magnetization Curve

Magnetic Hysteresis Loop (or Cycle Magnetization)

Cold Working

Magnetic Annealing

Magnetic Quenching

Magnetostriction

Salient Features of Magnetostriction

Magnetostrictive Materials

Soft Magnetic Materials

Hard Magnetic Materials (Permanent Magnet Materials)

High Energy (Product) Hard Magnetic Materials (HEHMMs)

7.1.1 Permeability

- Permeability is defined as the ratio of magnetic flux density and magnetic field intensity.

$$\mu = \frac{B}{H}$$

where,

B = Magnetic flux density (Wb/m²),

H = Magnetic field intensity (A/m)

- And, $\mu = \mu_0 \mu_r$

μ_0 = Permeability of free space

$$= 4\pi \times 10^{-7} = 1.257 \times 10^{-6} \text{ H/m or wb/Am}$$

μ_r = Relative permeability, dimensionless

$$= 1 \text{ for vacuum}$$

7.1.2 Magnetic Dipole Moment

- A current loop constitutes a magnetic dipole.
- Magnetic dipole moment is defined as the product of the area of loop and current through the loop.
- It is the vector quantity and its direction is normal to the plane containing current loop.

Magnetic dipole moment (μ_m) associated with the current loop

$$\mu_m = I \times A \hat{n} \quad \dots(1)$$

$\hat{n}$ = Normal unit vector

- Unit of magnetic dipole moment is A-m².

- The torque on a magnetic dipole produced by a flux density

$$T = \mu_m \times B \quad \dots(2)$$

- Magnetic dipole moment μ_m is also defined as the dipole moment due to the orbital angular momentum of electron owing to quantum numbers and expressed $\mu_m = \frac{eP}{dm}$

where e = electron charge

m = mass number

$P = \omega r^2 =$ angular momentum

ω = angular velocity

r = radius of electron motion

7.2 BOHR MAGNETRON

- Atomic unit of magnetic moment is called Bohr Magnetron.
- Let us consider an electron revolving around a nucleus in a circular orbit. The current through the loop is

$$I = \frac{Q}{t} = \frac{e}{\left(\frac{2\pi}{\omega}\right)} = \frac{e\omega}{2\pi}$$

Magnetic dipole moment,

$$m_m = IA = \frac{e\omega}{2\pi} \times \pi r^2$$

$$m_m = \frac{e\omega r^2}{2} \quad \dots(i)$$

By bohr's hypothesis

$$\text{Angular momentum, } mvr = \frac{nh}{2\pi}$$

where, h = Plank's constant = 6.623×10^{-34} J-sec.

$$m(\omega r)r = \frac{nh}{2\pi}$$

$$\omega = \frac{nh}{2\pi m r^2}$$

From equation ... (i)

$$m_m = \frac{er^2}{2} \cdot \left(\frac{nh}{2\pi m r^2} \right)$$

... (2)

to the orbital

$$\text{sed } \mu_m = \frac{eP}{dm}$$

$$m_m = \frac{neh}{4\pi m}$$

$$1 \text{ Bohr magnetron} = \frac{eh}{4\pi m}$$

$$= \frac{1.6 \times 10^{-9} \times 6.626 \times 10^{-34}}{4 \times \pi \times 9.1 \times 10^{-31}}$$

$$= 9.27 \times 10^{-24} \text{ A-m}^2$$

Larmor's angular frequency :

$$\text{When } B = 0, \omega = \omega_0 = \frac{nh}{2\pi m r^2}$$

$$B \neq 0 \quad \omega = \omega_0 + \omega_L$$

$$\text{where, } \omega_L = \text{Larmor's angular frequency, } \omega_L = \frac{eB}{2m}$$

- Therefore, Larmor's angular frequency is defined as the change in angular frequency of orbital electron when an external magnetic field is applied.

7.3 MAGNETIZATION (M)

- It is defined as magnetic moment per unit volume.

$$M = \frac{\mu_m}{\text{Volume}} = N \times \mu_m$$

where,

N = Number of dipoles per unit volume.

Unit = A/m = unit of H

... (i)

- The magnetic flux density inside a magnetic material under the influence of external field has two components –
 - One component because of magnetisation
 - Other one because of external field.

$$\Rightarrow B = \mu_0 H + \mu_0 M \quad [\text{Similar to } D = \epsilon_0 E + P; \text{ in electric field}]$$

$$B = \mu_0 (H + M)$$

$$\mu_0 \mu_r H = \mu_0 (H + M)$$

$$M = (\mu_r - 1) H \quad [\text{Similar to } P = \epsilon_0 (\epsilon_r - 1) E]$$

$$M = \chi_m H \quad [\text{Similar to } P = \epsilon_0 \chi_e E]$$

where, χ_m = Magnetic Susceptibility = $\mu_r - 1$

7.4 ORIGIN OF PERMANENT MAGNETIC DIPOLE

- Whenever a charged particle has an angular momentum, the particle will contribute to permanent dipole moment. In general there are three contribution to the angular momentum of an atom:
 - Orbital angular momentum** : It is due to orbital motion of electron.
 - Electron spin angular momentum** : It is due to self spin of electron. Since electron has a charge so its spin produces a magnetic dipole moment.
- Magnetic properties of material are only effected by electron spin dipole moment (angular momentum).
- The atoms having completely filled inner shells have zero resultant electron spin dipole moment.
- Nuclear spin angular momentum** : It is due to nucleus spin.
- Suscaptibility : (χ) : $M \propto H$

$$M = \chi H$$

$$\text{Or, } \chi = \frac{M}{H}$$

= Suscability (Parameter to access magnetic ability of material)

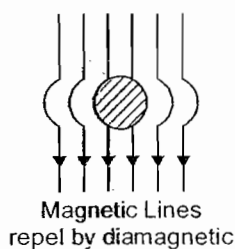
- Value means be positive or negative
- Higher positive value, better is the magnetic quality of material

Note : Electron spin dipole moment > Orbital dipole moment > Nuclear dipole moment.

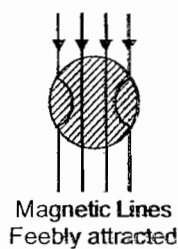
7.5 CLASSIFICATION OF MAGNETIC MATERIALS

Magnetic materials can be classified as:

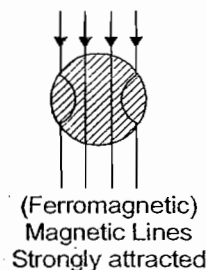
1. Diamagnetic



2. Paramagnetic



3. Ferromagnetic



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4. Antiferromagnetic or
5. Ferrimagnetic

7.5.1 Diamagnetic Material

- Materials which lack permanent magnetic dipoles are called diamagnetic.
- These material have small and negative magnetic susceptibility.
- These material repel the applied magnetic field.
- The magnetic flux inside diamagnetic material is zero. i.e. $B = 0$.

$$\mu_0[H + M] = 0$$

$$M = -H$$

As we know, $M = \chi_m H$

So, $\chi_m = -1 = \mu_r - 1$

$\therefore \mu_r = 0$

- Hence, $\mu_r = 0$; this relation is for perfect diamagnetism, which is also a necessary condition for a material to be a Super Conductor.
- Magnetic susceptibility of these material is independent of temperature.
- **Example :** Si, Ge, diamond, NaCl, Al_2O_3 , Cu, Au (Gold) graphite.
- The susceptibility of some diamagnetic material (At room temperature) :

Material	$\chi = (\mu_r - 1)$	Material	$\chi = (\mu_r - 1)$
Al_2O_3	-0.5×10^{-5}	Cu	-0.0×10^{-5}
$BaCl_2$	-2.0×10^{-5}	Au	-3.6×10^{-5}
NaCl	-1.2×10^{-5}	Ge	-0.8×10^{-5}
Diamond	-2.1×10^{-5}	Si	-0.3×10^{-5}
Graphite	-12×10^{-5}	Se	-1.7×10^{-5}

- Note that induced dipole moments occur in all materials and also a dipole moment induced by a magnetic field in a particular atomic model, is independent of the magnetic dipole moment present in the absence of the field. In this regard, all materials are diamagnetic.

7.5.2 Paramagnetic Material

- There are permanent magnetic dipoles associated with the atoms in a paramagnetic material. But the interaction between the atomic permanent dipole moments is zero or negligible.

- When these material are placed in an external magnetic field acquires a weak magnetisation in the same direction of magnetic field.
- These materials have small positive value of magnetic susceptibility.
- In paramagnetic material permanent dipole moment of the atoms and ions has no mutual interaction. However in the presence of field the magnetic moment have a tendency to turn towards the direction of applied field.
- If no opposing force act, complete alignment of the dipole will be produced and the specimen would acquire a very large magnetisation. But thermal agitation of atoms opposes this tendency and tends to keep the dipole moment at random.
- This result only into a partial alignment in the field direction. Therefore a weak magnetisation and small positive value of susceptibility occurs. The effect of increase in temperature is to increase the thermal agitation and therefore there is decrease in the susceptibility.
- Some paramagnetic materials follow curie law.

7.5.3 Ferromagnetic Material

- In ferromagnetic material, the dipoles interact in such a manner that they tend to line up in parallel.
- These are the material which get magnetised in the direction of external field and remain magnetised even after the removal of magnetic field. This property of ferromagnetic material is called Spontaneous Magnetization.

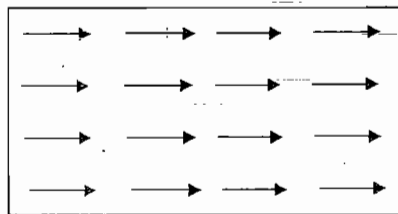


FIGURE : Ferro Magnetic Material.

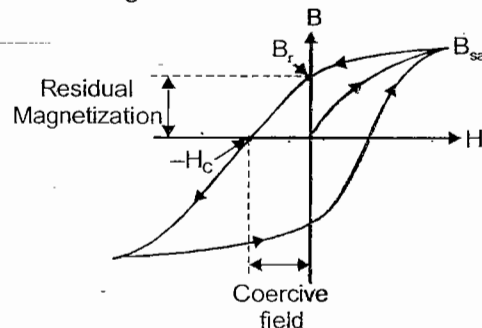


FIGURE : Hysteresis loop for a ferromagnetic material.

- Direction of magnetization can be reversed by reversing the direction of external magnetic field.
- The ferromagnetic materials are characterised by parallel alignment of magnetic dipole.
- **Example :** Fe, Co, Ni, Gd (Gadolinium), Dy (Dysprosium) etc.
- The ferromagnetic material remains ferromagnetic upto a critical temperature

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called Curie Temperature. These materials start behaving like Paramagnetic Material above Curie Temperature (θ_f).

- Gadolinium possesses this property at low temperature (below 290K)
- Europium oxide (EuO) is an example of ferromagnetism.
- Its susceptibility is positive of order 10^2 to 10^5 .
- Above Curie-temperature hysteresis loop merges to a straight line.

(i) $T > \theta_f$

- In the region above the θ_f , the behavior of ferromagnetic material is somewhat similar to that of a paramagnetic material

∴ Curie-weiss law :

$$\chi = \mu_r - 1 = \frac{C}{T - \theta} \text{ for } T > \theta_f$$

where,

C = Curie Constant

θ = paramagnetic curie temperature

- The paramagnetic curie temperature θ is usually somewhat higher than the ferromagnetic curie temperature.

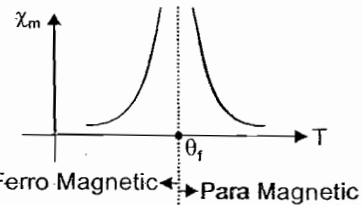


FIGURE : Variation of χ_m with temperature for ferromagnetic and paramagnetic material.

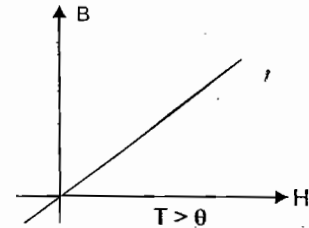


FIGURE : B-H curve for ferromagnetic material above Curie temperature.

Material	Curie Temperature ($^{\circ}\text{K}$)	Material	Curie Temperature ($^{\circ}\text{K}$)
Co	1404	Ni	631
Fe	1043	Gd	289

(ii) $T < \theta_f$:-

- Below the θ_f , ferromagnetic materials exhibit the well-known hysteresis in the B Vs H curve.

Metal	M_{sat} (A/m)	Curie Temperature ($^{\circ}\text{K}$)
Fe	1.75×10^6	1043
Co	1.45×10^6	1393
Ni	0.51×10^6	631

7.5.4 Antiferromagnetic Materials

- In the atomic configuration, if neighbouring dipoles tend to line up so that they are antiparallel, the material is antiferromagnetic or ferrimagnetic, depending on the magnitudes of the dipoles on the two "sub lattices".
- In the ferromagnetic case, there is large resultant magnetization, whereas in an antiferromagnetic configuration the magnetization vanishes. In the case of ferrimagnetic materials, there may be a relatively large net magnetization resulting from the tendency of antiparallel alignment of neighbouring dipole moments of unequal magnitude.
- In ferromagnetic materials, the tendency for parallel alignment of the electron spins was due to quantum mechanical exchange forces. In certain materials, for example when the distance between the interacting atoms is small, the exchange force produce a tendency for antiparallel alignment of electron spins of neighbouring atoms. This kind of interaction is encountered in antiferromagnetic and in ferrimagnetic materials.
- In antiferromagnetic materials, net magnetization is zero when no external field is applied but when material is subjected to an external field, the dipole moment starts aligning in the direction of field.
- These materials have small positive values of susceptibility.
- These materials are antiferromagnetic upto a critical temperature called the Neel temperature and above this temperature these materials start behaving like paramagnetic.
- The most characteristics feature of an antiferro-magnetic material is the occurrence of a rather sharp maximum in the susceptibility-vs-temperature curve.
- The temperature for which this maximum susceptibility occurs is called the Neel temperature T_N .
- Above the Neel temperature, the susceptibility is observed to follow the equation

$$\chi = \frac{C}{T + \theta} \text{ for } T > T_N$$

where, C = the curie constant, θ = paramagnetic curie temperature.

Note : Para $\rightarrow \chi = \frac{C}{T}$

Ferro $\rightarrow \chi = \frac{C}{T - \theta} \text{ for } T > \theta_f$

Antiferro $\rightarrow \chi = \frac{C}{T + \theta} \text{ for } T > T_N$

FIGURE :
function.

Table : Neel temperature (T_N) and Paramagnetic Curie temperature (θ) for some antiferromagnetic material.

Material	$T_N(^{\circ}\text{K})$	$\theta(^{\circ}\text{K})$
MnF_2	72	113
MnO_2	84	316
MnO	122	610
MnS	165	528
FeO	198	570
NiF_2	73	116
CoO	292	280

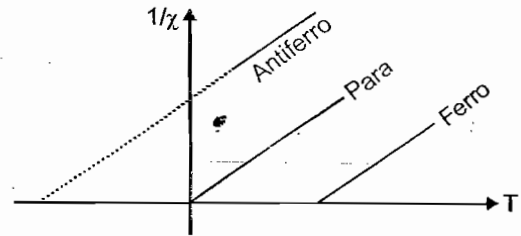


FIGURE : $1/\chi$ Vs T for para, ferro and Antiferro magnetic materials.

7.5.5 Ferrimagnetic Materials

- In ferrimagnetic material dipole moments of adjacent atom are also aligned in opposite direction but they are of unequal magnitude.
- Ferrimagnetic materials are similar to ferromagnetic ones in the sense that both kinds may exhibit a large magnetization. On the other hand, ferrimagnetic materials resembles antiferromagnetic materials with respect to the tendency for antiparallel alignment of neighbouring dipole moments.
- They are also called Ferrites. They behave as ferromagnetic materials in as much as they show spontaneous magnetization below a certain temperature. As far as their conductivity is concerned, they behave as semiconductors.
- The dc-resistivity of ferrites is many orders of ten higher than that of iron ; consequently the eddy current problem preventing penetration of magnetic flux into the material is much less severe in ferrites than of iron. Ferrites can therefore be used for frequencies upto microwaves in transformer cores and are of great technical importance in this respect.
- Electrical and Magnetic characteristics of Ferrite :
 - High d.c. resistivity
 - Low eddy current losses.
 - High permeability.
 - High dielectric constant.
 - High curie temperature.
- The Chemical formula of simple ferrites is $\text{Me}^{2+}\text{Fe}_2^{3+}\text{O}_4^{2-}$ where, Me^{2+} may represent a variety of divalent metallic, such as Fe^{2+} , Co^{2+} , Mn^{2+} , Zn^{2+} , Cd^{2+} , Mg^{2+} etc.

Note : It is observed that if in Fe_3O_4 , some of the magnetic Fe^{2+} ions are replaced by non-magnetic ions such as Zn^{2+} or Cd^{2+} , the magnetisation increases.

Reason : Zinc ions go preferably into tetrahedral positions, thereby forcing some of the Fe^{3+} ions from tetrahedral to octahedral sites. Since the Zn^{2+} ions have no magnetic dipole moment, the net magnetisation increases.

Applications of Ferrimagnetic Materials

- Ferrites are compound of two mettalic oxides out of which one is invariably an iron oxide. Other mettalic oxide may be bivalent element. Such as Ni, Mn, Zn, Cu, Fe, Symbolically ferrite may be designated as $(\text{Me}^{+}\text{O} \cdot \text{Fe}_2\text{O}_3)$. Where Me^{+} stands for mettalic oxide.

- Soft Ferrites :** These are used for construction of core of inductors and transformer. These materials have high permeability, low coercive force and low eddy current loss.

Example : Mn-Zn Ferrites, Ni-Zn Ferrites.

- Ni-Zn ferrites are used in audio and TV transformer.
- Hard Ferrites :** These are used for construction of permanent magnet. These materials have high permeability, high coercive force and high resistivity.

Example : Ba & Sr-Ferrites.

- Rectangular Ferrites :** These are used as the core of magnetic memories. These ferrites are having rectangular shape of hysteresis curve.

Example : Mn-Mg Ferrites, Mn-Cu Ferrites, Ni-Li Ferrites.

- Microwave ferrites :**
- These ferrites are used at microwave frequency.
- At this frequency the electromagnetic wave interact with the spin magnetic moment of electron. Because of this, the plane of polarization of electromagnetic field gets rotated by some angle when the wave passes through the material. This phenomenon is called as faraday rotation.
- These ferrites are used in microwave devices, Example : Gytrators, Circulators and Isolators etc.

Example : Mn-ferrites, Co-ferrites, Ni-ferrites, Garnets (used in magnetic bubble memory).

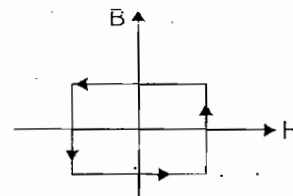


FIGURE : Hysteresis curve for rectangular ferrites.

Note : (i)

(ii)

(iii)

(iv)

(v)

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Ferrir

Note : (i) Barium ferrite ($\text{BaO} \cdot 6\text{Fe}_2\text{O}_3$) is used in permanent magnet.

(ii) Hard ferrite such as barium, strontium & lead ferrites show semiconductor behaviour.

(iii) Lithium ferrites are soft ferrites. They possess square hysteresis loop, low dielectric losses. These are low mobility semiconductor, due to their high curie temperature they are used for application at microwave frequencies.

(iv) Ferrite have three different types of crystal.

- **Spinel** : Cubic structure, MFe_2O_4 , example : $\text{M} = \text{Zn, Mg, Co, Cd, Cu, Mn, Ni}$
- **Garnet** : Cubic structure, example : $\text{MFe}_2\text{O}_{12}$, $\text{M} = \text{Sm, Tb, Ho, Er, Lu, Tm, Gd, O}_4$.
- **Magnet plumbite** : Hexagonal, example : $\text{MFe}_2\text{O}_{19}$, $\text{M} = \text{Ba}$

(v) The spinel ferrite unit cell contains $8 \times \text{MFe}_2\text{O}_4$ unit where M = divalent metal ion. Similar to MgAl_2O_4 . Iron and metal ion occupy octahedral and tetrahedral site of the spinel lattice. This distribution give intrinsic property in terms of magnetic and electric.

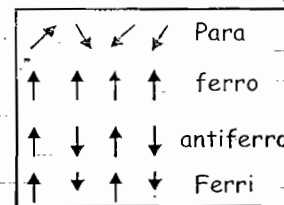


FIGURE : Schematic illustration of a paramagnetic, ferromagnetic, antiferromagnetic and ferrimagnetic arrangements of spins.

Table : Classification of magnetic materials on the basis of permanent atomic magnetic dipoles, and the interaction between them.

Classification	Permanent dipoles	Interaction between neighbouring dipole
Diamagnetic	No	-----
Paramagnetic	Yes	Negligible
Ferromagnetic	Yes	Parallel orientation
Antiferromagnetic	Yes	Antiparallel orientation of equal moments
Ferrimagnetic	Yes	Antiparallel orientation of unequal moments

Table : Susceptibility of different magnetic materials.

Type	Susceptibility (χ)
1. Diamagnetic	$\sim -10^{-5}$ (Negative)
2. Paramagnetic	$\sim 10^{-3}$ (Positive)
3. Ferromagnetic	very large & positive
4. Antiferromagnetic	Small and Positive
5. Ferrimagnetic	Large and Positive

7.6 CURIE TEMPERATURE

- Ferromagnetic solids behave as paramagnetic solids at high temperatures. A critical temperature at which the alignment of magnetic moments vanish is called Curie point or Curie temperature.
- The susceptibility of a ferromagnetic material decreases with an increase in the curie temperature.
- Magnitude of exchange energy has an effect on the value of curie temperature.
- Higher the energy, higher will be the curie temperature
- Curie temperature is different for ferromagnetic and paramagnetic materials. It is, therefore, referred to as ferromagnetic curie temperature T_{fc} and paramagnetic curie temperature T_{pc} .
- To maintain magnetic properties in transformers, motors, alternators, relays and permanent magnets; materials used must have curie temperature higher than their maximum operating temperatures.
- A lower curie temperature than the lowest operating temperature is required in the spectrometers, cathode-ray tubes, and in compass housings.
- Non-magnetic quality is desired in these cases. Therefore, curie temperature of a material needs to be varied to get the desired results. It is varied by suitable alloying.

7.6.1 Curie-law

We know,

$$M = \frac{N\mu_m^2}{KT} \cdot H$$

$$M = \frac{C}{T} H$$

$$M = \chi_m H$$

where, $\chi_m = \frac{C}{T}$ and $C = \frac{N\mu_m^2}{K}$

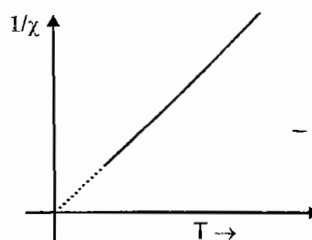


FIGURE : $1/\chi$ Vs T , for paramagnetic materials illustrating curie law.

- Some paramagnetic material follow curie-weiss law

$$M = \frac{N\mu_m^2}{KT} H_i \quad \dots(i)$$

$$H_i = H + \gamma M \quad \dots(ii)$$

Now from (i) and (ii), we get $M = \frac{N\mu_m^2}{KT} [H + \gamma M]$

$$M = \frac{\frac{N\mu_m^2}{KT}}{1 - \frac{N\mu_m^2}{KT} \gamma} \cdot H$$

$$M = \frac{N\mu_m^2 / K}{T - \frac{N\mu_m^2}{K} \gamma} \cdot H$$

$$M = \frac{C}{T - \theta} H, \quad [\text{Similar to } P = \frac{C\epsilon_0}{T - \theta} \cdot E]$$

where, $C = \frac{N\mu_m^2}{K}$ Curie Constant

$$\theta = \text{Curie-temperature} = \frac{N\mu_m^2}{K} \gamma$$

$$\gamma = \text{internal field constant} = \frac{\theta}{C}$$

- In general, susceptibility χ is of the order of 10^{-3} at room temperature for paramagnetic material.

Table : Susceptibility of some material (paramagnetic) at room temperature.

Substance	$\chi = (\mu_r - 1)$	Substance	$\chi = (\mu_r - 1)$
CrCl ₃	1.5×10^{-3}	Fe ₂ O ₃	1.4×10^{-3}
Cr ₂ O ₃	1.7×10^{-3}	Fe ₂ (SO ₄) ₃	2.2×10^{-3}
CaO	5.8×10^{-3}	FeCl ₂	3.7×10^{-3}
CoSO ₄ ·H ₂ O	2.0×10^{-3}	FeSO ₄	2.8×10^{-3}
MnSO ₄	3.6×10^{-3}	NiSO ₄	1.2×10^{-3}

- $C_{\text{dia}} \ll C_{\text{para}}$
- It is a good approximation to take the μ_r of paramagnetic substances equal to unity.

- **Example :** EuS, Gd_5Si , ErNi_2 , FeSO_4 , MnSO_4 , NiSO_4 , Fe_2O_3 , DAG ($\text{Dy}_3\text{Al}_5\text{O}_{12}$) GGG* (Gd_3 , Ga_5O_{12})

Here EuS, Gd_5Si , ErNi_2 , DAG, GGG* are salt.

Applications of the Paramagnetic Material

1. Paramagnetic salts are the working material used in obtaining very low temperature ($<1^\circ\text{K}$) by adiabatic demagnetization.
2. Paramagnetic salts are essential material used in the solid state MASER [Microwave Amplification through Stimulated emission of Radiation].

7.7 MAGNETIZATION CURVE

- Magnetization curve is the relationship between changing magnetic field H and its influence on the magnetic flux density B . This curve has three regions.
- In the first region OA, the curve rises up. The second region AC has almost a constant slope which starts bending near C.
- The third region CD has a decreasing slope, and becomes almost horizontal at D. At this part the material has reached to a saturation flux density B_s . If H is enhanced further, there will be no useful increase in the value of flux density.
- The slopes of the first and second regions are known as initial permeability and maximum permeability respectively.

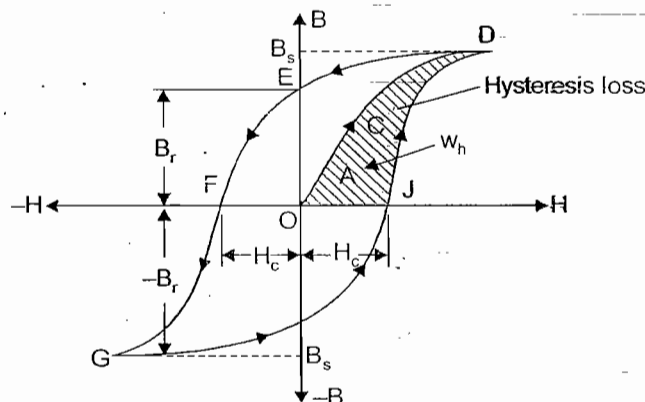


FIGURE : Magnetization curve OACD, and magnetic hysteresis loop ODEFGHJD showing variation of magnetic induction and the magnetic field.

7.8 MAGNETIC HYSTERESIS LOOP (OR CYCLE MAGNETIZATION)

- **Remanence :** The changes in magnetization in a ferromagnetic material lag behind the variations of the magnetic field applied on it.

- In figure curve as $OE = B_r$
- This is n of ferro material.
- Coerciv of indic
- It means down its of $-H_c$.
- On furth saturat
- Now the B-H curv curve D $OE = O$
- The end Compar
- Eddy cu loss is c
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7.9 COLD

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- It is pro method

- In figure, When the magnetic field is decreased and brought back to zero, the curve assumes DE path. Even at $H = 0$, the magnitude of magnetic flux is equal to $OE = B_r$.
- This is residual magnetic flux density, and is also known as retentivity or remanence of ferromagnetic material. Higher this value, better is the quality of ferromagnetic material.
- **Coercive force** : When direction of the field H is reversed, the curve follows EF path. OF indicates demagnetization force or coercive force.
- It means that a ferromagnetic material requires magnetic field of $H = -H_c$ to bring down its flux density to zero. A strong ferromagnetic material will need a higher value of $-H_c$.
- On further increasing the magnetic field, the curve follows FG path, and reaches to saturation flux density $-B_s$ in the opposite direction. Thus one cycle is complete.
- Now the magnetic field is applied again on the ferromagnetic material. This time the B-H curve follows HJD path. The curve does not take on the original OACD path. The curve DEFGHJD is called magnetic hysteresis loop. $OB_s = -OB_s$, $OF = OJ$, and $OE = OH = B_r$.
- The enclosed area OACDJO is called hysteresis loss.

Comparison of properties of eddy current and hysteresis losses. These are

- Eddy current loss is proportional to the square of the frequency, while the hysteresis loss is directly proportional to the frequency.
- Eddy current loss is proportional to the square of the peak flux density, while the hysteresis loss is usually proportional to the 1.6th power of the peak flux density.
- Eddy current loss is proportional to the square of the thickness of the laminations, while the hysteresis loss does not depend on thickness of laminations.
- Eddy current loss is dependent on the resistivity of the material, while the hysteresis loss is dependent on the Steinmetz constant of the material.

7.9 COLD WORKING

In this method, material is cooled down using cold rollers. This method induces magnetic anisotropic in direction of rolling.

7.10 MAGNETIC ANNEALING

It is process of heating and slow cooling in the presence of magnetic field.

7.11 MAGNETIC QUENCHING

- It is process of heating and fast cooling in the presence of magnetic field. In this method material is cooled down to curie temperature in order to induce Anisotropy.

- This method induces magnetic anisotropy either in the direction of applied field or in a direction perpendicular to the applied field.

7.12 MAGNETOSTRICTION

- When a ferromagnetic material is magnetized, changes in physical dimensions in general occur. This phenomenon is known as magnetostriction.
- There are three type of magnetostriction:
 1. **Longitudnal** : When change in the dimension is in the direction of applied field.
 2. **Transverse** : When change in the dimension is perpendicular to applied field.
 3. **Volume** : When change in the dimension is perpendicular as well as parallel to applied field.
- It has been observed experimentally that Ni and Co crystals contract when magnetised in either of three directions of crystal and an iron crystal expands when magnetised in the easy direction of magnetisation and contracts when magnetised in the hard direction. So Ni and Co crystals posses negative magnetostriction

$$Y = \frac{\text{Stress}}{\text{Strain}}$$

Normal and Inverse Spinel

The spinel can be of two types, (i) Normal spinel and (ii) Inverse spinel. Magnetite (Fe_3O_4) is an inverse spinel. The range of spinel-ferrites ranges between 700 K to 860 K. Their conductivity ranges between 10^2 ohm-m to 10^{-11} ohm-cm.

Garnets

- This is the name for a class of compounds crystallizing in a certain crystal structure. Example is yttrium-iron garnet ($\text{Y}_3\text{Fe}_5\text{O}_{12}$), which is ferromagnetic for a curious reason.
- The spin of the yttrium atoms is opposite to the spin of the iron atoms so the magnetic moments line up alternately, if the orbital magnetic moments are small.
- But for yttrium the orbital magnetic moment is larger than the spin, and is in the opposite direction.
- Hence the total magnetic moment of yttrium atom is in the same direction as that of iron, making the compound ferromagnetic.

Ferrites in Memory Devices :

- For a typical ferrite the properties are as follows :
- Coefficient of linear thermal expansion $\approx 10^{-5}/^\circ\text{C}$
- Thermal conductivity $\approx 5 \times 10^2 \text{ W/m}^\circ\text{C}$

- Thermal conductivity $\approx 0.17 \text{ kcal/kg}^\circ\text{C}$
- Density $\approx 3000 \text{ to } 5000 \text{ kg/m}^3$
- Ferrites are suitable for use in those devices which require
 - (i) high speed response, (ii) very low power loss, and (iii) high frequency

7.12.1 Salient Features of Magnetostriction

- This effect is analogous to electrostriction that occurs in polarized dielectrics.
- It has an inverse effect also, if the physical dimensions of magnetostrictive materials are changed by application of external force, a change in magnetization also occurs.
- Also a very small change in volume occurs at ordinary temperatures, if a very strong magnetic field is applied on the magnetic material.
- The change in dimension takes place in the direction of magnetization.

7.12.2 Magnetostrictive Materials

- The property magnetostriction is found in iron, nickel, cobalt, and gadolinium. It is also observed in alloys of iron with chromium, cobalt and aluminium.
- Pure nickel and nickel-iron alloys.
- Pure iron shows either a positive or negative magnetostriction on magnetization, which on adding nickel possesses only positive magnetostriction for all the field intensities.
- Longitudinal magnetostriction diminishes to zero on adding 30% Ni in iron.
- Volume magnetostriction becomes zero by adding 36% Ni in iron. (A 36% Ni-iron alloy is called INVAR and possesses almost zero value of coefficient of thermal expansion).
- It is due to the volume contraction because of loss of magnetization on heating upto curie temperature, compensates for very small value of thermal expansion.
- Metglass, an amorphous alloy, having a composition of $\text{Fe}_{81}\text{B}_{13.5}\text{Si}_{3.5}\text{C}_2$. It is available in the form of thin ribbon of around $25\mu\text{m}$ thickness.
- Terfenol, an alloy of terbium and dysprosium with steel, having a composition of $\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_{2-}$

Application

- Audio-frequency oscillators at sonic and ultrasonic frequencies.
- Magnetostrictive transducers.

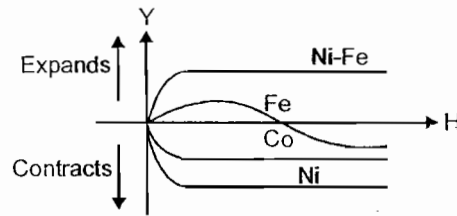


FIGURE : Variation of Joule magnetostriction as a function of field.

7.13 SOFT MAGNETIC MATERIALS

- These materials are easy to magnetise and demagnetise.
- In these materials, the direction of magnetization can be altered easily by an applied field.
- Soft magnetic materials should have following characteristics :
 1. These materials have low retentivity.
 2. Low coercivity
 3. High permeability
 4. High magnetic saturation
 5. Hysteresis curve should be tall and thin.
 6. Low hysteresis losses (because of lesser area of hysteresis loop)

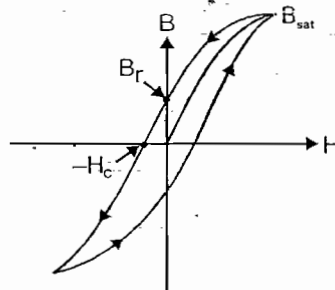


FIGURE : Hysteresis curve for soft magnetic materials.

- These materials are used for transformer and inductor core to minimize energy dissipation (reduction in hysteresis loss).
- Soft magnetic materials are desirable for electromagnets.

Examples and Applications

1. Silicon-steel/Soft-iron/Fe-Si Alloy

- They are used in power transformer.
- They are used up to power frequency (50 to 60 Hz).
- Silicon is added to increase dc resistivity and to reduce the area of hysteresis loop, i.e. for low eddy current loss and low hysteresis loss.

2. Fe

(a)

(b)

(c)

(d)

(e)

(f)

Note

7.14

• H

m

w

m

• T

tu

• M

1

2

3

4

5

• T

• F

1

2

3

4

5

2. Fe-Ni Alloy

- (a) 36% Ni → used for high frequency applications such as high speed relay and transformer.
- (b) 50% Ni → used for magnetic memory.
- (c) 77% Ni → used for precision voltage and current transformers.
- (d) 45% Ni → Permalloy
- (e) 79% Ni → Superalloy
- (f) 75% Ni → Mu-metal

Note : Alloys (d), (e) and (f) have high permeability and less area of hysteresis loop.

7.14 HARD MAGNETIC MATERIALS (PERMANENT MAGNET MATERIALS)

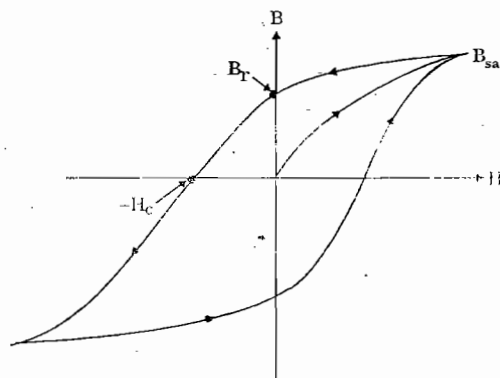
- Hard magnetic materials are those which retain a considerable amount of their magnetic energy after the magnetizing force has been removed, i.e., the materials which are difficult to demagnetize. These materials are also called permanent magnet materials.
- The important applications of permanent magnets are in meters, transducers, electron tubes, motors, focusing magnets in TV tubes.
- Materials for use as permanent magnets should have the following characteristics :-
 1. high permeability ensured by a large content of magnetic atoms or ions.
 2. high coercive force, generally, above 10^4 A/m.
 3. appreciable remanent flux density
 4. High curie temperature, to minimize easy demagnetization.
 5. Low cost.
- They have high hysteresis losses (because of large area of B-H curve)
- Hard Magnetic Materials are :
 1. Hardened Steels and Iron
 2. Carbon Steel – 98% Fe, 1% Mn, 0.9%C, used as magnet for latching relays or compass needle.
 3. Tungsten Steel – Fe, W, C, Cr-used as magnets in dc motors.
 4. Alnico – Al, Ni, Co- Their magnetic properties are very stable with time and temperature. (retain 70% magnetization at 600°C)
 5. Platinum Cobalt – 77% Pt, 23% Co

6. Cunitite (Cu, Ni, Fe)
7. Remalloy
8. Ba – ferrite
9. $\text{Na}_2\text{Fe}_{14}\text{B}$
10. Powder ceramic permanent magnetic material such as COOFe_2O_3 & $\text{PbO} \cdot 6\text{Fe}_2\text{O}_3$
11. MnBi

For metallic magnet $B_r > 2H_c$ & $BH_{\max} = \frac{1}{2}B_rH_r$.

For Ceramic magnets $B_r \leq H_c$ & $BH_{\max} = \frac{B_r^2}{4}$.

Aelomax (55% Fe, 11% Ni, 22% Co, 8% Al, 4% Cu) & Hycomax (50% Fe, 21% Ni, 20% Co, 9% Al) are found as hard magnetic material



Hysteresis curve for hard magnetic materials

7.15 HIGH ENERGY (PRODUCT) HARD MAGNETIC MATERIALS (HEHMMs)

- Hard magnetic materials whose energy products $(B_r H_{c,\max})$ are in excess of about 80 kJ/m^3 are called high energy HMMs.
- Conventional HMMs generally possess an energy product of about 3 to 80 kJ/m^3 . The high energy HMMs are recently developed materials having the structure of intermetallic compounds. These are available in different compositions. Example :
Samarium-cobalt rare earth (SmCo_5), and
Neodymium-Iron-Boron alloy ($\text{Nd}_2\text{Fe}_{14}\text{B}$)

Samarium-Cobalt Rare Earth

It belongs to the family of alloys which are formed by combining iron or cobalt with a rare earth element. These are produced by sintering method of powder metallurgy technique.

Magnetic Properties of High Energy HMMs and Their Comparison with a Conventional (Non-High Energy) Hard Magnetic Material

- **Composition/formula :**

Samarium-cobalt rare earth : SmCo_5

Neodymium-iron-boron alloy : $\text{Nd}_2\text{Fe}_{14}\text{B}$

Alnico 8 : 7% Al, 15% Ni, 35% Co, 4% Cu, 5% Ti, rest Fe

- **Maximum energy product (kJ/m^3)**

Samarium-cobalt rare earth : 170

Neodymium-iron-boron alloy : 255-400 (maximum)

Alnico 8 : 36 (minimum)

- **Remanence (tesla)**

Samarium-cobalt rare earth : 0.92-1.0

Neodymium-iron-boron alloy : 1.16 (maximum)

Alnico 8 : 0.76 (minimum)

- **Coercivity (kA/m)**

Samarium-cobalt rare earth : 200

Neodymium-iron-boron alloy : 220-345 (maximum)

Alnico 8 : 125 (minimum)

- **Resistivity (ohm m)**

Samarium-cobalt rare earth : 5×10^{-7}

Neodymium-iron-boron alloy : 16×10^{-7}

- **Curie temperature ($^{\circ}\text{C}$)**

Samarium-cobalt rare earth : 725

Neodymium-iron-boron alloy : 310 (minimum)

Alnico 8 : 860 (maximum)

- **Fabrication technique**

Samarium-cobalt rare earth and Alnico 8 : Sintering

Neodymium-iron-boron alloy : Sintering, or rapid solidification

- **Cost**

Samarium-cobalt rare earth : Costlier

Neodymium-iron-boron alloy : Cheaper

Alnico 8 : Cheaper

- **Uses:**

Samarium-cobalt rare earth : As magnets for fractional horse power motors

Neodymium-iron-boron alloy : As magnets for fractional horse power motors

Alnico 8 : As magnets for large horse power motors

$\text{PbO} \cdot 6\text{Fe}_2\text{O}_3$

Fe, 21% Ni,

HEHMMs)

is of about 80

10kJ/m^3 . The structure of . Example :

of cobalt with or metallurgy

QUESTIONS

- | | |
|---|--|
| <p>1. Diamagnetism is exhibited by</p> <p>(a) Only those materials which do not possess permanent magnetic moments.</p> <p>(b) All materials</p> <p>(c) Only those materials which possess permanent magnetic moments</p> <p>(d) Only those materials which have strong internal fields.</p> <p>2. Paramagnetic materials when placed in a magnetic field, get</p> <p>(a) Feebly attracted</p> <p>(b) Feebly repelled</p> <p>(c) Strongly repelled</p> <p>(d) Strongly attracted</p> <p>3. The net spin magnetic moment of Fe^{3+} ion is</p> <p>(a) $5\mu_B$ (b) $4\mu_B$</p> <p>(c) $3\mu_B$ (d) $2\mu_B$</p> <p>4. The susceptibility of diamagnetic material</p> <p>(a) Varies directly with temperature</p> <p>(b) Varies as $1/(T - \theta)$</p> <p>(c) Varies as $1/T$</p> <p>(d) Is independent of temperature</p> <p>5. The condition for an atom to possess orbital magnetic moment is that the atom must have</p> <p>(a) Completely filled s-shells</p> <p>(b) Partially filled s-shells</p> | <p>(c) Partially filled p, d or f shells</p> <p>(d) Completely filled p, d or f shells</p> <p>6. In transition metals, the contribution to magnetic moment is due to</p> <p>(a) Only spin magnetic moment of 3d electrons</p> <p>(b) Only spin magnetic moment of 4s electrons</p> <p>(c) Both spin and orbital moments of 3d electrons</p> <p>(d) Both spin and orbital moments of 4s electrons</p> <p>7. In high frequency applications a ferrite is preferred to a ferromagnetic material because, the ferrite has</p> <p>(a) High permeability</p> <p>(b) High resistivity</p> <p>(c) High saturation magnetization</p> <p>(d) Square saturation magnetization</p> <p>8. In the ceramic material MnO</p> <p>(a) There is a net magnetic moment due to the Mn^{2+} ion</p> <p>(b) There is a net magnetic moment due to the O^{2-} ion</p> <p>(c) There is a net magnetic moment due to both Mn^{2+} and O^{2-} ions</p> <p>(d) There is no net magnetic moment</p> <p>9. Curie-Weiss Law is obeyed by</p> <p>(a) Paramagnetic materials</p> <p>(b) Antiferromagnetic materials</p> |
|---|--|

10.

11.

12.

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14.

15.

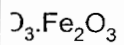
- (c) Ferromagnetic materials above Curie temperature
(d) Ferromagnetic material below Curie temperature
10. The magnetic effect which is analogous to converse piezoelectric effect
(a) Exchange interaction
(b) Magnetostriction
(c) Magnetic Hysteresis
(d) Antiferromagnetism
11. The units of magnetic permeability are
(a) A m^{-1} (b) Wb m^{-2}
(c) H m^{-1} (d) $\text{Wb A}^{-1} \text{m}^{-1}$
12. In base SI units, tesla is expressed as
(a) $\text{N A}^{-1} \text{m}^{-1}$ (b) $\text{N A}^{-1} \text{m}^{-3}$
(c) $\text{kg m}^{-2} \text{s}^{-2} \text{A}^{-1}$ (d) $\text{kg s}^{-2} \text{A}^{-1}$
13. In a paramagnetic material of susceptibility equal to 10^{-3} , the induction in Wb m^{-2} at an applied field of 100 kA m^{-1} is ($\mu_0 = 1.257 \times 10^{-6} \text{ H m}^{-1}$)
(a) 0.1257 (b) 0.1258
(c) $4\pi \times 10^{-7}$ (d) none of these
14. The net magnetic moment of Fe atom in BCC crystal ($a = 2.857 \text{ \AA}$) is $2.2\mu_B$ ($\mu_B = 9.273 \times 10^{-24} \text{ A m}^2$). The saturation magnetization of Fe at 0 K is
(a) 0 (b) 1750 kA m^{-1}
(c) 1750 A m^{-1} (d) 1750 A m^{-1}
15. Gadolinium has a higher saturation magnetization than Co at
(a) -273°C (b) 25°C
(c) 290°C (d) 769°C
16. The Curie temperature of cobalt is
(a) 2000K (b) 1400K
(c) 1040K (d) 650K
17. The total iron loss in a transformer core at 25 Hz and 50 Hz is 250 W and 800W, respectively. The eddy current loss at 25 Hz is
(a) 100W (b) 150W
(c) 200W (d) 600W
18. Using a permalloy core ($\mu_r = 2700$), a 19m long 300 turn coil of a conductor giving an induction of 7.5 T is to be made. The current in the coil should be
(a) 0 A (b) 52 mA
(c) 7.4 A (d) 140 A
19. The ratio of the atomic radius to the radius of Mn, which shows antiferromagnetic behavior, is
(a) 1.47 (b) 1.5
(c) 1.82 (d) 1.88
20. The temperature of the antiferromagnetic-to-paramagnetic transition is called
(a) Antiferromagnetic Curie temp.
(b) Curie-Weiss temp.
(c) Neel temp.
(d) Debye temp.
21. The factors that obstruct domain wall motion in Fe are
(a) dislocation tangles
(b) impurity atoms
(c) voids
(d) nonmagnetic inclusions

22. The transition from the ferromagnetic to the paramagnetic state is named after
 (a) Curie (b) Curie-Weiss
 (c) Neel (d) Debye
23. The magnetic moment of a ferric ion in nickel-zinc ferrite is
 (a) 5
 (b) 0
 (c) depends on Zn%
 (d) 2.2
24. The saturation magnetization of magnetite with 16 ferric ions and 8 ferrous ions in the cubic unit cell ($a = 8.37 \text{ \AA}$) is ($\mu_B = 9.273 \times 10^{-24} \text{ A m}^2$)
 (a) 1770 kA m^{-1} (b) 638 kA m^{-1}
 (c) 506 A m^{-1} (d) 506 kA m^{-1}
25. If the saturation magnetization of magnetite is 510 kA m^{-1} , that of nickel ferrite in the same units is (Given: atomic number of Fe = 26; Ni = 28)
 (a) 255 (b) 510
 (c) 1020 (d) 340
26. To make the Mn atom ferromagnetic by alloying, the ratio of its atomic radius-to-3d radius should be
 (a) constant (b) increased
 (c) decreased (d) zero
27. In nickel-zinc ferrite with Zn/Ni atom ratio equal to 3/5, the number of unpaired electron spins present per $\text{Ni}_{0.625}\text{Zn}_{0.375}\text{Fe}_2\text{O}_4$ is (assume that zinc ions push the ferric ions from tetrahedral sites to octahedral sites and change their spins)
 (a) 5 (b) 3.75
 (c) 1.25 (d) 4.5
28. The garnet crystal used in a microprocessor has the formula
 (a) $\text{YO.Fe}_2\text{O}_3$ (b) $\text{Y}_3\text{Fe}_5\text{O}_{12}$
 (c) $\text{YO.6Fe}_2\text{O}_3$ (d) $\text{Y}_2\text{O}_3\text{-Fe}_2\text{O}_3$
29. The highest measured energy product a permanent magnet is about
 (a) 10^3 J m^{-3} (b) 80 kJ m^{-3}
30. The factor of
 (a) 1.1 (b) 5
 (c) 100 (d) 1000
31. A suitable material for audio and TV transformers is
 (a) ferrite (b) Fe-4% Si
 (c) Fe-30% Ni (d) very pure Fe

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ANSWERS

1. (b)	9. (c)	17. (b)	25. (a)
2. (a)	10. (b)	18. (d)	26. (b)
3. (a)	11. (c,d)	19. (a)	27. (a)
4. (d)	12. (d)	20. (c)	28. (b)
5. (c)	13. (b)	21. (a,b,c,d)	29. (c)
6. (a)	14. (b)	22. (a)	30. (c)
7. (b)	15. (a)	23. (a)	31. (a)
8. (d)	16. (b)	24. (d)	

8

The Conductivity of Metals

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8.1 OHM'S LAW (POINT FORM)

Ohm's Law (Point Form)

Mean Free Path (L)

Relaxation Time

Factors Affecting Resistivity of Metals

Superconductivity

Silsbee Rule

Meissner Effect

Types of Super-Conductor

Type-I Super-Conductor

Type-II Super Conductor

Low Resistivity Conducting Material

High Resistivity Conducting Material

Insulating Materials

Application of Conductors

Types of Conducting Materials

Modern Ceramic Superconductors

Superconducting Magnet

- When a electric field is applied to a conductor, the current density developed (J) in the conductor is related to electric field applied (E) as follows:

$$J = \sigma E$$

This relation is a well known ohm's law.

Note : $\tau \propto \frac{1}{\sqrt{T}}$

$$J = \sigma E$$

- The current density is a general property of the material and does not depend upon the size of the conductor. It is proportional to the electric field

E and a constant $\frac{ne^2\tau}{m}$, called the conductivity of the material σ ;

$$\sigma = \frac{ne^2\tau}{m}$$

Mobility

- The average drift velocity varies in direct proportion to the electric field, through a proportionality factor $\frac{e\tau}{m}$, called the mobility of the electrons, μ_e .

$$\mu_e = \frac{e\tau}{m}$$

- Mobility is defined as the magnitude of the average drift velocity per unit electric field. i.e. $\mu_e = \frac{v_d}{E}$. Mobility and conductivity have the relation, $\sigma = ne\mu_e$.

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$$\text{Unit of } \mu_e = \text{m}^2 \text{ volt}^{-1} \text{s}^{-1} \text{ or } \frac{\text{m}^2}{\text{Volt} \cdot \text{sec}}$$

Effect of Temperature on Conductivity

1. **Conductor** : We know that,

$$s = \frac{ne^2\tau}{m} \quad \left(\because \tau \propto \frac{1}{\sqrt{T}} \right)$$

$$\sigma \propto \frac{n}{\sqrt{T}}$$

With increase in temperature there is no appreciable increase in number of electrons as conductor have already large number of electrons in their conduction band. So overall conductivity decreases with increase in temperature.

2. **Semiconductor** : We know that,

$$\sigma \propto \frac{n}{\sqrt{T}}, \text{ and}$$

$$n_i^2 = A_0 T^3 e^{-E_{g0}/KT}$$

where,

n_i = Intrinsic concentration

E_{g0} = Energy gap with 0°K

A_0 = is constant that depends on the semiconducting material (9.64×10^{15}).

K = is Boltzmann's constant

$$n_i = n = A_0^{1/2} T^{3/2} e^{-E_{g0}/2KT}$$

$$\frac{n}{\sqrt{T}} = A_0^{1/2} T e^{-E_{g0}/2KT}$$

Since

$$\sigma \propto \frac{n}{\sqrt{T}}$$

$$\sigma \propto T e^{-E_{g0}/2KT}$$

$$\sigma \propto \frac{T}{e^{E_{g0}/2KT}}$$

- Therefore, conductivity of semiconductor increases with the rise in temperature. In other words semiconductors have negative temperature coefficients.

Note : These materials do not follow Ohm's law. Band gap of these materials is nearly 1 eV. The semiconducting material is a perfect insulator at 0 K.

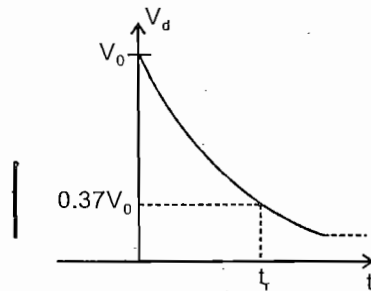
8.2 MEAN FREE PATH (L)

It is defined as the average distance travelled by electron before collision takes place.

$$\lambda = V_d \cdot \tau$$

where, τ = average collision time, V_d = drift velocity.

8.3 RELAXATION TIME



It is defined as the time required at which the drift velocity of electron reduces to 37% of its value after the removal of electric field. For isotropic material the relaxation time and the average collision time are equal.

8.4 FACTORS AFFECTING RESISTIVITY OF METALS

- In pure metals and dilute alloys, the total resistivity is the sum of two terms.

$$\rho = \rho_T + \rho_r \quad \dots(i)$$
- The thermal component ρ_T ; which arises from the lattice vibrations, and the residual resistivity ρ_r , caused by impurities and structural imperfections. The residual resistivity is independent of temperature.
- Equation (i) is Matthiessen's rule. This rule becomes less accurate at high temperature or at high impurity levels.
- The electrical resistance of most metals increases with increase of temperature. At temperatures above the so called **Debye temperature**, the thermal component of resistivity of conductors is approximately linear.
- Many conducting materials have vanishing resistivity near absolute zero temperature. This phenomenon is known as **superconductivity**.

Note : Debye temperature for Cu is 315 K, while for Al it is 398 K.

8.5 SUPERCONDUCTIVITY

- It was discovered in 1911 by Kamerlingh Onnes in Leiden when he observed that the electrical resistivity of mercury disappeared completely at temperature below approximate 4.2°K.

- A state of material in which it has zero resistivity is called super conductivity.
- These elements compounds and alloys of metal exhibit extraordinary magnetic and electrical behaviour at extremely low temperature.

Transition Temperature

The temperature at which the **transition** from the 'normal' state to the super **conducting** state occurs is called transition temperature (T_c).

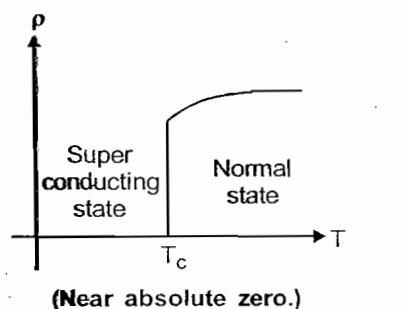


FIGURE : Relationship between resistivity and temperature of superconductive materials.

- Note :**
1. The material having number of valance electron (Z) from 2 to 10 generally show super conductivity.
 2. It is noted that the transition temperature all lie below 10°K .
 3. The elements which at room temperature are good conductors (Cu, Ag, Au and the alkali-metal) are **absent** from the list of super conducting materials. In fact, the superconducting elements are relatively poor conductors at room temperature.
 4. Fe, Ni, Co, are also **not** superconducting materials.
 5. The super conducting compounds and alloys do not necessarily **have** super conducting components such as : Pb_2Au , Pb_2Ti_2 , SnSb , CuS , NbN , MoN , NbB , ZrC .

Condition for Super Conductivity

1. Resistivity should be zero.
2. Perfect dia-magnetism ($\mu_r = 0$).
3. Applied magnetic field **should** be less than critical magnetic field.
4. Power loss (copper) $I^2R = 0$.
5. Specific resistance, $P = 0$.
6. Magnetic susuptibility $\chi = -1$.

Critical Magnetic Field

- It is a minimum amount of magnetic field required at a given temperature to destroy super conductivity. Its value is given by :

$$H_C = H_0 \left(1 - \frac{T^2}{T_C^2} \right)$$

where,

H_0 = Critical field at 0°K

H_C = Critical field at $T^\circ\text{K}$

T_C = Transition or critical temperature

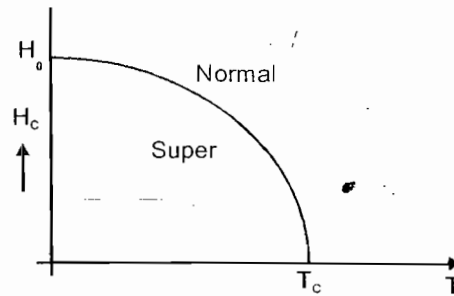


FIGURE : Schematic diagram or representation of the critical magnetic field H_C as a function of temperature.

Note : The transition temperature (T_C) of a super conductor can be reduced by the application of a magnetic field.

8.6 SILSBEE RULE

- The magnetic field which causes a super-conductor to become normal is not necessarily an externally applied field; it may also arise as a result of electric current flow in the conductor.
- Thus superconductivity in a long circular wire of radius R may be destroyed when the current exceeds the value I_C which at the surface of the wire would produce the critical magnetic field H_C .
- If a current I is flowing in long wire of super conducting materials, according to ampere's law :

$$\oint H \cdot dl = i$$

$$H = \frac{i}{2\pi R}$$

$$H_C = \frac{I_C}{2\pi R}$$

So, the critical current,

$$I_C = 2\pi R \cdot H_C$$

and the critical current density, $J_c = \frac{I_C}{A} = \frac{H_C \times 2\pi R}{\pi R^2}$

$$J_c = \frac{2H_C}{R}$$

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- This rule prevents the use of super conductors as coils for the production of strong magnetic fields.
- The disappearance of super conductivity for fields above the critical field is the principle on which a cryotron operates.

Note : For a superconductor the relative permeability is zero; this is referred to as perfect diamagnetism.

- As we know that in super conductor resistivity is zero and also the magnetic flux density in a super conductor also vanishes i.e., $B = 0$.

- Also we know that

$$B = \mu_0 (H + M)$$

but

$$B = 0 \Rightarrow M = -H$$

Therefore,

$$M = (\mu_r - 1)H \Rightarrow -H = (\mu_r - 1)H$$

$$-1 = \mu_r - 1$$

$$\mu_r = 0$$

- Relationship between Transition Temperature T_C and Isotopic Mass M :

$$M^{1/2} T_C = \text{constant}$$

Table : Superconducting elements and their T_C .

Element:	Al	V	Zn	Ga	Cd	Sn	Hg	Pb	Th	U
T_C (K):	1.14	5.1	0.79	1.07	0.54	3.69	4.12	7.26	1.32	0.6

8.7 MEISSNER EFFECT

- The repulsion of magnetic flux from the interior of a piece of superconducting material, as the material undergoes to the transition to the super conducting phase is known as meissner's effect.
- It has been observed that when a long super conductor is cooled in a longitudinal magnetic field from above transition temperature, the line of induction are pushed out. Then inside the specimen, $B = 0$

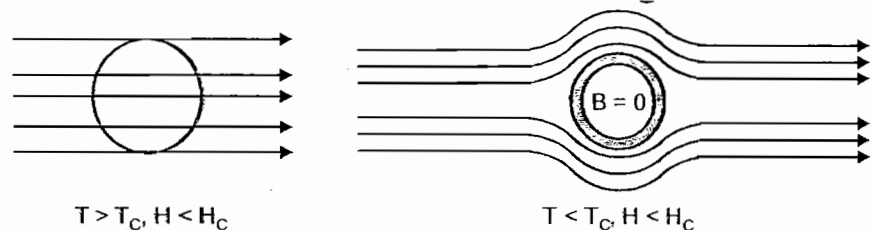


FIGURE : Flux lines in sphere under different conditions of temperature and field.

- Also $B = \mu_0 (H + M)$, for $B = 0$, $H = -M$, consequently since $X_m = -\frac{M}{H} = -1$, we may state that magnetic susceptibility in a superconductor is negative. This referred to as perfect diamagnetism. This phenomenon is called Meissner Effect.

Factors Affecting Super Conductivity and Transition Temperature

- Frequency** : Super conductivity decreases with increase in frequency and it is observed upto radio frequency (10 MHz). Above 10 MHz resistivity increases. At infrared frequency (10^{13} Hz) the resistivity of material is same as normal state.
- Entropy** : Entropy increases on going from super conducting state to normal state.
- Thermal Conductivity** : It decreases on going from normal state to super conducting state.
- Isotope Mass (M)** : $T_C \propto \frac{1}{\sqrt{M}}$.

8.8 TYPES OF SUPER-CONDUCTOR

8.8.1 Type - I Super-conductor

- Low temperature superconductor : Critical Temp. less than 30K. These are metallic e.g. Nb-Ti, Nb-Zr, Nb₃Sn, Nb₃Al, V₃Ga etc.
- High temperature super conductor (HTS) : Critical Temp. more than 30K. These are ceramics type e.g. : Perovskite oxide.
- Certain materials, particularly those, that have low melting points and are mechanically soft and easily obtained in pure, strain free condition display similarities in their super-conductive behavior. They are distinguished as Ideal or soft super-conductors.
- Their critical field and transition temperature are low.
- They exhibit complete meissner's effect and silsbee rule.
- The change of state from normal to super-conducting and vice versa is sharp.
- These are unsuitable as magnets because of their low critical field.

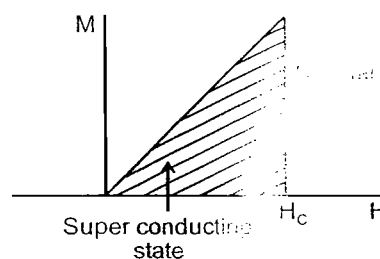


FIGURE : Relationship between M and H of type-I superconductor.

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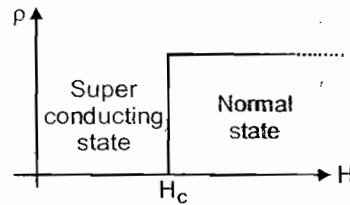


FIGURE : Relationship between ρ and H of type-I superconductor.

Note : $H_c < 10^5$ A/m corresponding to about 0.10 tesla.

- **Example :** Zn, Pb, Hg, Al, In etc.

8.8.2 Type-II Super-conductor

- They are also called hard super-conductor or non-ideal super-conductor.
- They exhibit incomplete meissner's effect and break down of silsbee rule.
- Their critical field and transition temperature are high.
- The change of state from normal to super-conductor and vice versa is gradual.

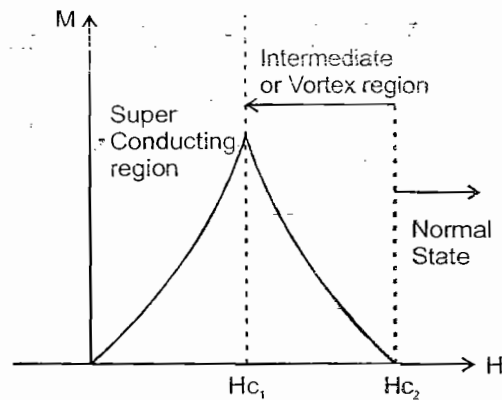


FIGURE : Relationship between M and H of type-II superconductor.

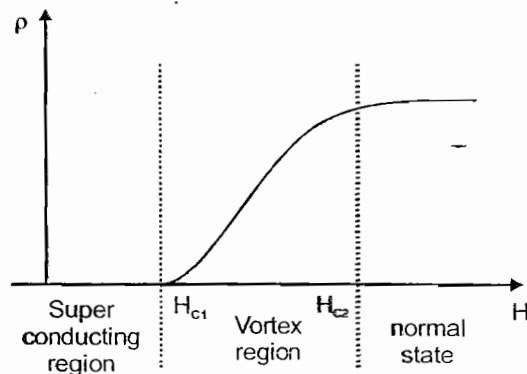


FIGURE : Relationship between ρ and H of type-II superconductor.

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- These super conductor exhibit incomplete meissner's effect in vortex region.

Example : Nb_3Al , NbTi , Nb_3Sn , (BiPbSrCaCuO) bismuth lead strontium calcium copper oxide.

Application of Super-conductors

- Magnetic Resonance Imaging (MRI)
- Generators and Motors
- Switching elements like "Cryotrons"
- Magnets for Nuclear Fission.

Note : Thermo Electric Effects :

(a) Seeback Effect (b) Peltier Effect

(a) **Seeback Effect :** When two dissimilar metals are jointed at their ends and junction ends are maintained at **different temperature** then an emf exist across the junction, this is called seeback effect.

(b) **Peltier Effect :** An electric current which flows though a rod consisting of two dissimilar metal causes a decrease in temperature of one end and increase in temperature of the other end. It is converse of seeback effect.

8.9 LOW RESISTIVITY CONDUCTING MATERIAL

- Silver has low resistivity than Cu, but it is very costly, which restrict its use for commercial purpose.
- Aluminium is cheaper than Cu, so it is often used as a Cu substitute in electrical power system.
- Brass is a alloy of Zinc and Copper. It has high tensile strength but lower conductivity than Copper.
- Brass is used in rheostats, lamp holders and plug points. It has good corrosion resistance.
- Bronze is a alloy of Cu, Tin, Al, Ni and Si. It has superior mechanical property and corrosion resistance than brass.
- Phosphor-Bronze is used in current carrying springs and brush holders.
- Silicon Bronze is used in wires and telephone parts.
- Alloy of Tin, Lead, Cu-Zn are used in solder material.
- Tungsten is a metal which is used upto 3300°C as heating filament in bulbs, CRTs.

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8.10 HIGH RESISTIVITY CONDUCTING MATERIAL

- Pure carbon is a semi-conductor with negative temperature coefficient of resistivity. It is used in brushes for electrical machine.
- Lead has high anti-corrosion properties, because of this it is used for covering of underground and under water cables for power and communication lines.
- Platinum is used for contact fabrication in low power rating contactors.
- Nickel is used for making electrodes.

Table : Comparison between high resistivity conducting materials.

Material	Composition	Operating Temperature	Applications
Nichrome	Ni + Cr + Mn + Fe	Upto 1100°C	Heating element in soldering, iron furnaces.
Constantan	Cu + Ni	Upto 500°C	Wire wound resistors, rheostats, strain gauge
Manganin	Mn + Ni + Cu	~ 60°C	Precision instruments, for bridge potentiometer
Tungsten	Metal	3300°C	Heating filaments such as bulbs, CRTs etc.

8.11 INSULATING MATERIALS

1. Ceramics

- These materials are hard, strong and brittle.
- They have high temperature stability.
- Ceramics are generally inorganic material (absence of carbon).
- These are generally crystalline in nature (except amorphous glass).
- These are non metallic oxide, nitrides and carbides.

Examples : Garnets, BaTiO_3 , Ferrites, TiO_2 (Rutile) (Ti dioxide), Porcelains, Quartz, ZnS, MgO, SiC, CdS etc.

- Ceramics can be broadly described as :
 - Porcelains ($\epsilon_r < 12$)
 - Alumina ceramics ($\epsilon_r < 12$)
 - Steatite ($\epsilon_r < 12$)
 - Titanate ($\epsilon_r > 12$)

- Porcelain is used in insulation of transmission and distribution of power system. It is used in low and high voltage application.
- Steatites are used in high frequency applications.
- Alumina ceramics are used for high temperature applications as circuit breakers and resistance cores.
- Titanate is used in capacitor dielectrics.

Another classification of ceramics :

Ceramics can also be divided into two groups depending whether the permittivity is lesser or greater than 12.

- (i) $\epsilon_r < 12$: Ceramics having permittivity less than 12 are used as insulators, as they have high dielectric strength and low loss tangent.

Example : Porcelain, Steatite, Alumina Ceramic.

- (ii) $\epsilon_r > 12$: Ceramics with high permittivity ($\epsilon_r > 12$) are used in capacitor applications.

Example : Titanates, Rutile.

2. Transformer Oil

- Transformer cores are dipped in mineral oil known as transformer oil. It acts as an insulator and cooling medium.
- Break down voltage of transformer oil decreases with contamination, example : moisture. To absorb moisture, absorbents added are Silica gel and Alumina.

3. Askarels

- They are fire resistance insulating material.
- Two types of Askarels
 - (a) Chlorinated benzene
 - (b) Chlorinated biphenyl
- Now a days they are not used in transformer and capacitor because on decomposition they produce toxic and poisonous gases.

8.12 APPLICATION OF CONDUCTORS

- Electricity transmission and distribution lines,
- Electrical contacts viz. relays, brushes, switches etc.,
- Resistors and
- Heating elements

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Gold is the best conductor electricity followed by silver, copper and aluminium. Keeping in view the cost factor, copper and aluminium are the natural choices although silver is used for contacts in aircrafts.

- Aluminium conductor reinforced with steel (ACSR) is an improved material for transmission lines.
- Oxygen-free-high conductivity (OFHC) copper conductor is very suitable for low temperature applications. It has high purity whose resistivity is 1×10^{-10} ohm m at 4.2K and zero electric field.

8.13 TYPES OF CONDUCTING MATERIALS

I. On the Basis of quality of resistivity

1. Low resistivity (or high conductivity) materials such as Au, Ag, Cu, Al, brass, bronze etc.
2. High resistivity (or low conductivity) materials such as W, Pt, C, Ni, Ta, nichrome, etc.

II. On the Basis of nature of materials

1. Metals such as Cu, steel, Al, Pt, Ir, Pd, Rh etc.
2. Non-metals such as conducting polymer
3. Alloys such as brass, bronze, rose metal, constantan etc.
4. Reinforced composites such as ACSR.

III. On the Basis Applications

1. Cable purpose materials such as Cu, Al, ACSR, OFHC
2. Filament purpose materials such as W, carbon (graphite)
3. Contact purpose materials such as Au, Pt, Ag, Mo, Ir, W etc.
4. Soldering purpose materials such as Cu, Zn, Sn, Ag, Cd
5. Fusible (or fuse) purpose materials such as Pb, Sn, Ag etc.
6. Sheathing purpose materials such as Pb, p.v.c., Pb-Cd alloy
7. Sealing purpose materials such as Fe with Si, Mn, Mo.

IV. On the Basis Temperature Requirements

1. High temperature conducting materials such as ACSR
2. Low temperature conducting materials such as OFHC copper

3. Very low (or cryogenic) temperature conducting materials such as Ni-based steel alloy.

V. On the Basis of State of Material

1. Solid conducting materials such as metals, alloys
2. Liquid conducting materials such as Hg
3. Gaseous conducting materials such as N_2 in gas-filled pressure cables.

Copper

- High Conductivity and reasonable cost.
- It is a crystalline, non-ferrous, non-magnetic (diamagnetic), reddish coloured metal.
- It is a ductile metal having a ductility of more than 15%. Because of this property, it can be easily drawn into thin bars and wires. Hence, it is very useful for making cables, strands, and conductors.
- Its ultimate tensile strength is high enough (300-350 MPa) which makes it substantially strong to sustain mechanical loads.
- Its melting point is sufficiently high (1083°C) so it is use at high temperatures also.
- When exposed to atmospheric environment, it forms a protective layer of copper oxide (CuO). Thus, it is highly resistant to corrosion which is require property for bare/open overhead conductors.
- It can be easily brazed (a kind of welding) which is a necessary requirement in wiring and other connections.

Aluminium

- Conductivity is lower to that of copper, but it is cheaper than copper.
- It is a crystalline, non-ferrous, weak magnetic (paramagnetic) metal of white colour.
- It is a lightweight metal having a specific gravity of 2.7 only.
- It is a ductile metal because of which it can be easily drawn into thin bars and wires. Therefore, aluminium is very useful for making cables and conductors.
- Its ultimate tensile strength is sufficiently high (about 50-70 MPa).
- It can be easily soldered which is an essential requirement in wiring. However, due to insulating nature of aluminium oxide layer, the soldered joint may not be so strong
- Its electrical contacts faces the possibility of loss connections due to its softness.

Comparison of different conducting metals with steel

Description	Copper	Aluminium	Steel
• Resistance to corrosion	More	More	Less
• Tensile Strength	More	Less	Maximum
• Ductility (about)	55%	50%	18-25%
• Density (kg/m^3)	8960	2700	7800
• Melting point ($^{\circ}\text{C}$)	1083	660	1539
• Thermal conductivity at 25°C (W/m-K)	425	300	65
• Salient feature	Can be drawn into thin wires	Can be drawn into wires upto 0.1 mm diameter	Can be drawn into thick wires
• Comparative cost	12	8	1
• Working efficiency	Best	Better	Good
• Life	Highest	Higher	High
• Resistivity (ohm-m)	17×10^{-9}	28×10^{-9}	—
• Coefficient of linear expansion ($/\text{K}$)	17.7×10^{-6}	17.7×10^{-6}	15.2×10^{-6}
• Coefficient of temperature resistance at 20°C	0.0039	0.0035	0.004-0.005

8.14 MODERN CERAMIC SUPERCONDUCTORS

1. La Ba CuO superconductor, superconducting at 70K.
2. The Yttrium barium copper oxide i.e. YBCO ($\text{Y Ba}_2 \text{Cu}_3 \text{O}_{7-x}$) behave as superconductors at 90 K. Critical current densities in excess of 10^8 A/cm^2 was achieved in it.
3. Bismuth and thallium superconducting compounds has characteristics same order line with yttrium compounds.
4. BSCCO (Bi Sr Ca CuO) showing $T_c = 106 \text{ K}$. and Zero resistance at 85 K.
5. Thallium barium calcium copper oxide i.e. TBCCO (Th Ba Ca CuO) superconducting at 125 K, but practical application is doubtful due to highly poisonous nature of thallium.
6. In 2005, the value of $T_c = 115 \text{ K}$ has been reported in $\text{Sn}_2 \text{Ba}_2 (\text{Ca}_{0.5} \text{Tm}_{0.5}) \text{Cu}_3 \text{O}_x$.
7. The value of $T_c = 127\text{-}128 \text{ K}$ has been found with material system $\text{Tl}_2 \text{Ba}_2 \text{Ca}_2 \text{Cu}_3 \text{O}_{10}$.
8. The highest value of critical temperature $T_c = 138 \text{ K}$ reported so far is in $\text{Hg}_{0.8} \text{Tl}_{0.2} \text{Ba}_2 \text{Ca}_2 \text{Cu}_3 \text{O}_{8.33}$.

- **Josephson Junction** is a device having two superconducting plates separated by an oxide layer. These junctions are used in SQUID, (superconducting quantum interference device) computer memories and other microelectronic devices. It works on the principle of Josephson effect. This quantum effect is characterized by the tunnelling of superelectrons through the insulator of Josephson junction, and it is found that flow of current without any driving potential.
- **Maglev or Magnetic Levitation.** This is a levitation phenomenon caused by the opposing magnetic fluxes. The use of this is in wheel-less high speed trains that are equipped with superconducting magnets. The Nb_3Sn and Nb-Ti are used as magnet grade superconductors.
- **Magnetohydrodynamics (MHD) :** MHD deals with the motion of an electrically conducting fluid under the influence of magnetic field. This principle is employed in
 - MHD power generation
 - MHD ship propulsion, and
 - MHD magnets
- In MHD power generation, the thermal energy of hot ionized gas is converted into d.c. electric power. In MHD ship propulsion, the sea water is accelerated by magnetic field. In both these applications, the superconducting magnets are required. The Japanese experimental ship Yamato sailed in 1992 utilized MHD principle.
- **Magnetic resonance imaging (MRI) :** Here, the visual images of the brain and other body parts can be created. Superconducting magnets above 2T are suitable for this purpose.
- **Suspension systems and motors.** Frictionless suspension systems may be found by the interaction between a magnetic flux produced externally and the currents flowing in a superconductor. If the superconductor is pressed downwards it tries to oppose and come out of the magnetic field, hence the magnetic flux on which it rests is compressed and the repelling force is increased. Since it is possible to allow high speed rotation to a suspended superconducting body, and that all the conductors in the motor are free of resistance, it is obvious that the ideal of a 100% efficient motor can be closely approximated.

Radiation detectors

The operation of these is based on the heat provided by the incident radiation. The superconductor is kept just above its critical temperature, where the resistance is a rapidly varying as a function of temperature. The change in resistance is then calibrated as a function of the incident radiation.

8.15 SUPERCONDUCTING MAGNET

Superconducting magnet which can generate magnetic flux densities upto $B = 15$ tesla ($H = 12 \times 10^6 \text{ Am}^{-1}$ in free space). The wires used to make the coils of the superconducting solenoid can carry much higher current densities than conventional conductors.

A cryotron is a coil of a superconductor. The cryotrons 'β' are superconducting cryotrons in working order.

(i)

(ii)

Superconducting

Superconducting tesla or magnetic density p

Note : 1

A cryotron is an assembly of a superconducting wire (core material) ' α ' surrounded by a coil of another superconducting material β . When temperature of a system in which the cryotron is used, is below the transition temperature of two materials, both ' α ' and ' β ' are superconducting; otherwise they attain a normal state. Based on this fact, a cryotron is used as an element in control devices such as flip-flop in a computer. Its working may be understood as follows:

- (i) The current I_α in the wire is controlled by the current I_β in the coil. It is due to magnetic field produced by the coil normally exceeds the critical field of the wire (core material) at operating temperature. The intensity of controlling current I_β required to make the core in normal state, depends upon d.c. current flowing through the core. Hence, the core current also produces a magnetic field.
- (ii) Tantalum is a suitable material for making wire (or core), if the operating temperature is extremely low (≈ 4.2 K which is liquefaction temperature of helium). Since the coil has to be superconducting even if the control current flows, hence niobium or lead are suitable coil materials.

Supercooled Coils

Supercooled coils are such electrical systems which can produce a flux density of 10 tesla or more in superconducting state. This flux density is 'ten' times more than the flux density produced by normal-coils at room temperature.

Note : 115.5 K (-157.5°C) is known as cryogenic temperature. Those industries in which the operations are performed below this temperature are called cryogenic industries. Industries involved fertilizer industry (at -190°C) etc. are such examples. Engines using liquid fuels at so low temperatures are called cryogenic engines.

□□□

$B = 15$ tesla
superconducting
actors.

QUESTIONS

1. Consider the following properties pertaining to an alloy used as a precision resistor :

1. Uniform resistance
2. Stable resistance
3. Zero or low temperature coefficient of resistivity

Which of these properties are desirable?

- (a) 1, 2 and 3 (b) 1 and 2
(c) 1 and 3 (d) 2 and 3

2. When temperature of a conductor is approaching zero Kelvin, the mean free path of the free electrons in the conductor is proportional to

- (a) T (b) T^3
(c) $(1/T)^{1/3}$ (d) $1/T^3$

3. In a conductor of size 20 mm × 10 mm × 10 mm, the wavelength of the slowest moving free electron is

- (a) 5 mm (b) 10 mm
(c) 20 mm (d) 40 mm

4. The conductivity of a super conducting material on being subject to critical magnetic field changes to

- (a) normal state
(b) unstable state
(c) temperature-independent state
(d) temperature-dependent state

5. Which of the following has the greatest mobility?

- (a) Positive ion (b) Negative ion
(c) Electron (d) Hole

6. Which of the following insulating materials has the least affinity to moisture?

- (a) Cotton (b) Paper
(c) Asbestos (d) Mica

7. Which of the following statements is NOT true?

- (a) Superconductors show perfect diamagnetism
(b) Superconductors have not zero resistivity
(c) The external magnetic field has no effect on superconductors
(d) Entropy increases on going from superconducting state to normal state

8. The transition temperature of Mercury at which it becomes superconductive is

- (a) 4.12°F (b) 4.12°C
(c) 4.12 K (d) 41.2 K

9. De Broglie wavelength associated with a material particle is

- (a) inversely proportional to its energy
(b) directly proportional to its momentum
(c) directly proportional to its energy
(d) inversely proportional to its momentum

10. Which of the following is correct?

- (a) ...
(b) ...
(c) ...
(d) ...

11. According to the theory of superconductivity, the resistance of a superconductor is

- (a) ...
(b) ...
(c) ...
(d) ...

12. Which of the following is correct?

- (a) ...
(b) ...
(c) ...
(d) ...

13. The conductivity of a superconductor is

- (a) ...
(b) ...
(c) ...
(d) ...

10. Which one of the following is NOT true for Sulphur hexafluoride gas?
- It is electronegative in nature
 - It has high dielectric strength
 - It is non-toxic
 - It is highly inflammable
11. According to Wiedemann-Franz law the ratio of thermal conductivity to electrical conductivity of a conductor is
- Independent of temperature
 - Directly proportional to temperature
 - Inversely proportional to temperature
 - Inversely proportional to square of temperature
12. Which one of the following statements is correct for four-point probe method of determining resistivity?
- The sample must be extrinsic
 - The current source is connected to the two inner probes
 - One probe point must inject minority carriers
 - Current flow only in a small area of the sample
13. The average drift velocity V_d of electrons in a metal is related to electric field E and collision time T as
- $V_d = Q_e ET/m_e$
 - $V_d = m_e Q_e T$
 - $V_d = m_e Q_e T/2E$
 - $V_d = Q_e ET/2m_e$
14. On which of the following factors does the value of critical current density in a superconductor depend?
- Temperature
 - Applied magnetic field
 - Temperature and applied magnetic field
 - Silsbee's rule
15. The magnetic field at which a superconductor remains in its superconducting state at a temperature less than the transition temperature is
- Zero
 - Greater than the critical field corresponding to the given temperature
 - Less than the critical field corresponding to the given temperature (or) equal to the critical field corresponding to the transition temperature
16. Match List-I (Insulator) with List-II (Application) and select the correct answer using the codes given below:
- | List -I | List -II |
|-------------------|------------------------------|
| A. Mica | 1. Bushings |
| B. Polystyrene | 2. Electric wires and cables |
| C. Porcelain | 3. Low voltage capacitors |
| D. Silicon rubber | 4. Iron |
| | 5. Radio Cabinets |

Codes:

	A	B	C	D
(a)	4	5	1	2
(b)	2	1	3	4
(c)	4	1	3	2
(d)	2	5	1	4

17. Metallic copper is a

- (a) Paramagnetic substance
- (b) Diamagnetic substance
- (c) Ferromagnetic substance
- (d) Ferrimagnetic substance

18. Superconductivity is destroyed

- (a) At high temperature
- (b) At high magnetic field
- (c) In presence of magnetic impurities
- (d) In all the above cases

19. In metals, resistivity is composed of two parts: one part is characteristic of the particular substance. The other part is due to

- (a) Applied voltage
- (b) Crystal imperfections
- (c) Applied magnetic field
- (d) Supplied thermal energy

20. Consider the following :

Applications of low permittivity ceramics include which of the following?

- 1. Suspension insulators for high voltage lines.
- 2. Superconductors
- 3. Pin insulators for low voltage lines.

Select the correct answer using the code given below :

- (a) 1 and 2
- (b) 1 and 3
- (c) 2 and 3
- (d) 1, 2 and 3

21. Consider the following statements in connection with superconductors :

- 1. Transition temperature of a super conductor can be reduced by the application of a magnetic field
- 2. Transition from the superconducting to normal state under the influence of a magnetic field is irreversible.

Which of these statements is/are correct?

- (a) 1 only
- (b) 2 only
- (c) Both 1 and 2
- (d) Neither 1 nor 2

22. Which one of the following is the correct statement?

(a) Superconductivity is a property of metal in super-cooled state.

23. The temperature coefficient of resistance of a wire is $0.0008/^{\circ}\text{C}$. If the resistance of the wire is 8 Ohm at 0°C . What is the resistance at 100°C ?

- (a) 8.64 Ohm
- (b) 8.08 Ohm
- (c) 7.92 Ohm
- (d) 7.20 Ohm

24. Two materials having temperature coefficient of 0.004 and 0.0004 respectively are joined in series. The overall temperature coefficient is approximately

- (a) 0.08
- (b) 0.04
- (c) 0.001
- (d) 0.0001

25. Match List-I with List-II and select the correct answer using the code given below the list:

A.
B.
C.
D.

1.
2.
3.
4.

Cc

(a)

(b)

(c)

(d)

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(a)

(c)

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.08 Ohm

.20 Ohm

temperature
and 0.0004
in series. The
coefficient is

b) 0.04

d) 0.0001

II and select
ing the code

List -I

- A. Enamel covering
- B. Insulation
- C. Fibrous Materials
- D. Empire cloth

List -II

- 1. Laminations
- 2. Wires
- 3. Machines
- 4. Transformers

Codes:

	A	B	C	D
(a)	2	4	1	3
(b)	3	4	1	2
(c)	2	1	4	3
(d)	3	1	4	2

26. Consider the following statements :
Characteristics of a good insulating material are

- 1. Should give uniform electric and thermal properties.
- 2. High permittivity.
- 3. Low dissipation factor.
- 4. Low insulating resistance.

Which of the above statements are correct?

- (a) 1 and 4 only (b) 2 and 4 only
- (c) 1 and 3 only (d) 1, 2, 3 and 4

27. Consider the following statements about superconductors :

- 1. The temperature at which the conductor becomes a super conductor is called transition temperature.

- 2. Superconductors repel magnetic flux lines.

- 3. All superconductors are paramagnetic materials.

- 4. Superconductors become normal when placed in a magnetic field of certain critical value.

Which of the above statements are correct?

- (a) 1 and 2 only (b) 2 and 4 only
- (c) 1, 2 and 4 only (d) 1, 2, 3 and 4

28. Match List-I with List-II and select the correct answer using the code given below the list:

List -I	List -II
---------	----------

- A. Precision Work 1. Graphite
- B. Rheostat 2. Nichrome
- C. Heating devices 3. Constantan
- D. Brushes 4. Magnesium

Codes:

	A	B	C	D
(a)	4	3	2	1
(b)	1	3	2	4
(c)	4	2	3	1
(d)	1	2	3	4

29. Match List-I with List-II and select the correct answer using the code given below the lists:

List -I

- A. High conductivity materials
- B. High resistivity materials
- C. Metal for lightly loaded contacts
- D. Materials for bimetallic strip

List -II

1. Tungsten, Carbon
2. Platinum, Molybdenum
3. Aluminium, Copper
4. Iron, Nickel Constantan

Codes:

	A	B	C	D
(a)	3	1	2	4
(b)	4	1	2	3
(c)	3	2	1	4
(d)	4	2	1	3

30. Consider the following statements with regard to manufacture of a standard resistor :

1. The material should be of high resistivity and low temperature coefficient.
2. Resistors are shielded against magnetic field.
3. Nickel-chromium is best suited for resistance of high value.

Which of the these statements is/are correct?

- (a) 1 and 2 only (b) 1 only
(c) 1 and 3 only (d) 3 only

31. Materials in superconducting state have the property of

- (a) Absorbing magnetic field
- (b) Repelling magnetic field
- (c) Absorbing electric field
- (d) Repelling electric field

32. A superconductor may be used for generating

- (a) Voltage (b) Pressure
(c) Temperature (d) Magnetic field

33. As temperature falls below the transition temperature, the value of critical magnetic field of a superconductor

- (a) Remains unchanged
- (b) Increases
- (c) Decreases
- (d) First increases, reaches a peak and then decreases

34. The energy gap of a superconductor

- (a) Is independent of temperature
- (b) Increases with temperature
- (c) Is maximum at a critical temperature
- (d) Is minimum at a critical temperature

35. Which of the following properties is NOT correct for a superconductor in its superconducting state?

- (a) Its resistivity is zero
- (b) Magnetic flux density inside the conductor is zero
- (c) Its relative permeability is unity
- (d) Its magnetic susceptibility is negative

36. Lead

1. Is not used to form cable sheaths.
2. Is least affected by sea water.
3. Has good malleable and ductile properties
4. Will not alloy with many other metals

- (a) 1 and 2 are correct
(b) 2 and 3 are correct
(c) 3 and 4 are correct
(d) 1 and 4 are correct

37. Match List-I with List-II and select the correct answer using the code given below the list:

List-I

- A. Po
- B. St
- C. M
- D. R

List-II

1. U
- ap
2. U
- at
3. U
4. R

Code

- (a)
- (b)
- (c)
- (d)

38. It is p
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- (b) a
- tra
- (c) a
- (d) a
- at

39. Consic
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List -I

- A. Porcelain
- B. Steatite
- C. Mica
- D. Rutile

List -II

- 1. Used for high frequency applications
- 2. Used in capacitors to be operated at high frequencies
- 3. Used for insulators
- 4. Releases water when heated

Codes:

	A	B	C	D
(a)	3	1	4	2
(b)	1	2	4	3
(c)	3	4	2	1
(d)	1	4	2	3

38. It is possible to destroy the superconductivity of a material by applying
- (a) a strong magnetic field
 - (b) a temperature much below the transition temperature
 - (c) a strong electric field
 - (d) a pressure below that of the atmosphere
39. Consider the following properties of insulators:
- 1. Insulation resistance
 - 2. Dielectric breakdown strength
 - 3. Dielectric losses
 - 4. Permittivity

Some of these properties are for DC use and some are for AC use.

The correct combination is

DC use	AC use
(a) 1, 2 and 3	1, 2 and 4
(b) 1 and 3	1, 2 and 3
(c) 2 and 4	1 and 2
(d) 1 and 2	1, 2, 3 and 4

Directions:

The following items consist of two statements, one labelled as 'Assertion A' and the other labelled as 'Reason R'. You are to examine these two statements carefully and select the answer to these two statements carefully and select the answer to these items using the codes given below:

- (a) Both A and R are individually true and R is the correct explanation of A
- (b) Both A and R are individually true but R is not the correct explanation of A
- (c) A is true but R is false
- (d) A is false but R is true.

40. **Assertion (A):** Lepidolite type mica is unsuitable for electric insulation.

Reason (R): Lepidolite is hard and brittle.

41. **Assertion (A):** Glazing is done on ceramic insulators to make the surface smooth and non-absorbent.

Reason (R): Moisture from the atmosphere can collect on the surface discontinuities on a ceramic and result in electric breakdown.

42. **Assertion (A):** An electric or mechanical input makes the flux jump from one superconductor to another, generating large direct currents.

Reason (R): The electric resistivity of superconductors depends upon the magnetic field.

43. **Assertion (A):** Cryotron is a switch constructed out of superconducting materials.

Reason (R): Switching action is characteristic of superconductors only.

44. **Assertion (A):** An insulator has a high value of resistivity, and with increasing temperature the value of its resistivity decreases exponentially.

Reason (R): With increasing temperature, the value of the energy band gap decreases.

45. **Assertion (A):** Superconductivity of a superconducting material can be destroyed by application of an external magnetic field.

Reason (R): If the applied magnetic field is greater than the critical

magnetic field at a given temperature which is more than the transition temperature, super-conductivity can be destroyed.

46. **Assertion (A):** At absolute zero degree Kelvin temperature the semiconductor materials behave as insulators.

Reason (R): At absolute zero degree Kelvin temperature, there is no energy available to generate the current carriers in the semiconductor.

47. **Assertion (A):** Superconductors cannot be used as coils for production of strong magnetic fields.

Reason (R): Superconductivity in a wire may be destroyed if the current in the wire exceeds a critical value.

□□□

ANSWERS

1. (d)	11. (b)	21. (c)	31. (b)	41. (a)
2. (d)	12. (b)	22. (c)	32. (d)	42. (d)
3. (c)	13. (a)	23. (a)	33. (b)	43. (c)
4. (a)	14. (d)	24. (c)	34. (d)	44. (d)
5. (c)	15. (c)	25. (b)	35. (c)	45. (a)
6. (c)	16. (d)	26. (c)	36. (b)	46. (a)
7. (c)	17. (b)	27. (c)	37. (c)	47. (a)
8. (c)	18. (d)	28. (a)	38. (a)	
9. (d)	19. (b)	29. (a)	39. (d)	
10. (d)	20. (b)	30. (c)	40. (a)	

2. (d)

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SOLUTIONS

2. (d)

As we know, mean free path, $\lambda = v_d \tau$

$$\text{and } \lambda \propto \frac{1}{T^3}$$

4. (a)

Critical magnetic field is the required magnetic field to bring conductivity of super conducting material to normal state.

5. (c)

Mobility of electron is more than hole

7. (c)

External magnetic field equal to critical magnetic field can destroy super conductivity. Also by the application of external magnetic field, the value of transition temperature decreases.

10. (d)

 SF_6 is an inert gas.

13. (a)

$$V_d = \frac{Q_e E T}{m_e}$$

15. (c)

At critical field the superconductor will come to normal state.

19. (b)

Resistivity is composed of two components:-

(i) **Thermal Resistivity** : It is due to lattice vibration and is characteristic of the particular substance

(ii) **Residual Component** : This component arises due to impurity and defect present in the material. This is independent of temperature.

22. (c)

For super-conducting metals,

$$\chi_m = -1$$

$$\text{and } \chi_m = \mu_r - 1$$

$$\text{So } \mu_r = 0$$

23. (a)

$$R_{\text{new}} = R_0 [1 + (\alpha \Delta t)]$$

$$\Delta t = T_2 - T_1 = 100^\circ\text{C}$$

$$\alpha = 0.0008, R_0 = 8 \text{ ohm}$$

$$R_{\text{new}} = 8(1 + 0.08)$$

$$R_{\text{new}} = 8.64 \text{ ohm}$$

31. (b)

Superconductors are essentially diamagnetic, so they repel the magnetic field

33. (b)

$$H_C = H_0 \left[1 - \left(\frac{T}{T_c} \right)^2 \right]$$

where, H_C = critical magnetic field.
Hence as temperature T decreases below the transition temperature (T_c), the value of critical magnetic field increases.

36. (b)

Lead has good corrosion resistance, so it is least affected by sea water.

37. (c)

Porcelain : is a ceramic material and used for insulator.

Mica : used in capacitors to be operated at high frequencies.

38. (a)

If the applied field is greater than the critical magnetic field at any temperature, super conductivity will be destroyed.

9.1 INTRODUCTION

Introduction

Classification of Materials in Terms of Energy Bands

Type of Semiconducting Materials

Classification of Elemental Semiconductors

Position of Fermi Level in Extrinsic Semiconductors

Conductivity of Semiconductor

Hall Effect in Semiconductors

Merits of Semiconductor Materials

Applications of Semiconductor Materials

Formulated (Compound and Alloyed) Semiconducting Materials

Applications of Semiconductor Devices

Microelectronics

Fabrication of Thin Film Microelectronic Circuit

Semiconductor Devices

Semiconductor Lasers

- A semiconductor is defined as a material whose conductivity falls intermediate between that of metals, 10^6 to $10^8 \text{ ohm}^{-1}\text{m}^{-1}$, and that of dielectrics (insulators); 10^{-20} to $10^{-8} \text{ ohm}^{-1}\text{m}^{-1}$.
- Semiconductors are materials which have resistivity between 10^{-5} to about 10^7 ohm-m (at ordinary temperature).
- The resistivity of semiconductors depends greatly on :
 1. **The temperature** : resistivity decreases as the temperature increases. Hence, the temperature coefficient for the resistivity of a semiconductor is usually negative.
 2. **The illumination** : resistivity decreases in brighter surroundings.
 3. **The magnitude of electric field in semiconductors** : Current in semiconductors does not obey Ohm's law and will increase rapidly than voltage, i.e. semiconductors are non-linear resistors.
 4. **External impurities** : A minute amounts of certain other substances change resistivity of semiconductor considerably; certain impurities even change the mechanism of conduction in semiconductors.

9.2 CLASSIFICATION OF MATERIALS IN TERMS OF ENERGY BANDS

- The band theory provides a clear-cut classification of the materials according to which there are three categories normally, metals, insulators and semiconductors.
- If the energy levels of the filled band and the conduction (empty) band overlap, a slight excitation will cause electrons to pass from a filled to a conduction band. A material consisting of such atoms will therefore exhibit high conductivity, and be a conductor.
- In cases, where the atoms of the material concerned have an energy gap lying between filled and conduction band, the material will not be able to act as a conductor. If the difference between the energy levels of filled and conduction band is small, the electrons will only require a small amount of energy (e.g. thermal energy) to become excited and pass into the conduction band. Materials of such a class are semiconductors. In semiconductors the forbidden region (empty band, E_g) has a width of 0.12 to 5.3 eV (normally 1 eV at room temperature).
- The materials, in which the energy gap is still higher ($E_g \cong 15$ eV), the electrons do not leave the filled band even by thermal excitation, such materials are dielectrics (insulators 6 eV).

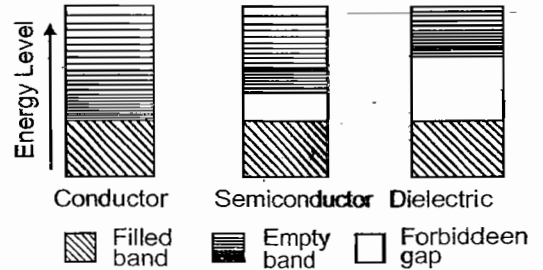


FIGURE : Energy levels in conductors, semiconductors and dielectrics.

9.3 TYPE OF SEMICONDUCTING MATERIALS

Types of semiconductor	Examples														
- Elemental form <table border="0"> <tr> <td>Column II</td><td>Zn, Cd</td></tr> <tr> <td>III</td><td>B, Al, Ga, In</td></tr> <tr> <td>IV</td><td>C, Si, Ge</td></tr> <tr> <td>V</td><td>N, P, As, Sb</td></tr> <tr> <td>VI</td><td>S, Se, Te</td></tr> </table> - Binary compounds <table border="0"> <tr> <td>II-VI compounds</td><td>ZnS, ZnSe, ZnTe, CdS, CdSe, CdTe</td></tr> <tr> <td>III-V compounds</td><td>AlP, AlAs, AlSb, GaN, GaP, GaAs, GaSb, InP, InAs, InSb</td></tr> </table>	Column II	Zn, Cd	III	B, Al, Ga, In	IV	C, Si, Ge	V	N, P, As, Sb	VI	S, Se, Te	II-VI compounds	ZnS, ZnSe, ZnTe, CdS, CdSe, CdTe	III-V compounds	AlP, AlAs, AlSb, GaN, GaP, GaAs, GaSb, InP, InAs, InSb	
Column II	Zn, Cd														
III	B, Al, Ga, In														
IV	C, Si, Ge														
V	N, P, As, Sb														
VI	S, Se, Te														
II-VI compounds	ZnS, ZnSe, ZnTe, CdS, CdSe, CdTe														
III-V compounds	AlP, AlAs, AlSb, GaN, GaP, GaAs, GaSb, InP, InAs, InSb														

- | | |
|-------------------------|--|
| IV-IV compounds | SiC, SiGe |
| • Ternary compounds | GaAsP, HgCdTe, AlGaAs |
| • Quarternary compounds | InGaAsP |
| • Ternary alloys | $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ (30% is Al and 70% is Ga);
$\text{In}_{0.53}\text{Ga}_{0.53}\text{As}$, $\text{In}_{0.11}\text{Ga}_{0.8}\text{As}$,
$\text{GaAs}_{0.88}\text{Sb}_{0.12}$ |
| • Quarternary alloys | $\text{In}_x\text{Ga}_{1-x}\text{As}_y\text{P}_{1-y}$ |

A. Elemental semiconductors (Group IV element)

- (a) Intrinsic semiconductor
- (b) Extrinsic semiconductor

B. Compound semiconductors

- (a) II – VI compound semiconductors
- (b) III – V compound semiconductors
- (c) IV – IV compound semiconductors
- (d) IV – VI compound semiconductors

- As conductivity and band gap of
hence their usefulness is limited. Si
is used to provide better properties

A. Elemental Semiconductor Material

Example : Ge, Si, C, B, Al, Ga, In, Sb, Bi etc.

- It is pentavalent semiconductor material
- It is used as donor N-type semiconductor material
- When it is alloyed with Gallium, it is used in fabrication of LED.
- Se (Selenium) :** It is used in photovoltaic cell.

B. Compound Semiconductor Material

(i) III-V semiconductor materials :

- They provide wider range of band gap and extended temperature range.
- Structure is diamond cubic.

Example : GaAs, AlP etc.

GaAs

- This is large band gap material.
- It has large electron mobility which helps in high speed switching.
- It is 10 times costlier than Si

- It is 2.5 times faster than Si based devices
- In GaAs crystal, Ga takes place corner and face atom where as As takes place of four inside atoms:

70% is Ga);

Application

- LED
- Laser
- Satellite Amplifier.

(ii) Group II-VI Semiconductor Materials :

Example : Cds, CdSe, CdTe, ZnS, ZnSe etc.

- They are used in photo conductors.
- Band gap is larger than group III-V semiconductor material.

(iii) Group IV - IV Semiconductor materials :

Example : SiC

- Its band gap is 3eV.
- α -SiC can be used for high temperature devices.
- Its drawback is that it is expensive and not easy to manufacture.

(iv) Group IV - VI semiconductor materials :

Example : PbS, PbSe, PbTe

- In these semiconductors excess Pb give rise to N-type semiconductors and less Pb give rise to p-type semi-conductors.

9.4 CLASSIFICATION OF ELEMENTAL SEMICONDUCTORS

A. Intrinsic semiconductor

- The semiconducting material in its pure (no impurity added) form is generally known as intrinsic semiconductor.
- In such materials there are no charge carriers at 0°K as the valence band is completely full of electrons and the conduction band is empty.
- At higher temperatures, electron - hole pairs are generated as the electron of valence band can cross the energy gap by incident thermal energy.

B. Extrinsic semiconductor

- The real power of semiconductor materials is realised when these are doped. Even a very little impurity addition (nearly $1 : 10^{12}$ atom) leads to a drastic change in the electrical properties of these materials.
- The drastic influence of an impurity on the conductivity of a semiconductor is a result of change in the energy band spectrum.

- Extrinsic semiconductor can be obtained by doping the pure semiconductor by IIIrd or Vth group elements of the periodic table.
- The most frequently used elements from the third column are boron, gallium, indium and aluminium, and from fifth : phosphorus, antimony, or arsenic.

(a) n-type semiconductor

- n-type semiconductors are those in which Ge or Si is doped with an element from the fifth column, for example, Ge or Si doped with phosphorus, antimony or arsenic. These impurities from the fifth column have five electrons in its outer shell available for interaction with other atoms.
- The four nearest silicon atoms then form covalent bonds with four of the five valance electrons of the arsenic atom. In the energy band diagram, the energy level of this electron will be close to the conduction band as indicated in figure.

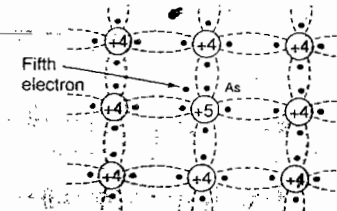


FIGURE : n-type semiconductor.

Note : n-p junction diode

n-p-n used for transistor

- Impurity atoms like arsenic, that contribute free electrons as described above, are called donors, because they donate electrons.
- Introducing a group-V element in a pure semiconductor create a level close to the conduction band. The impurity levels created by group-V impurity atoms is known as donor level.
- This addition of group-V element leads to increase in the number of electrons. The majority carriers in n-type semiconductor are "electrons".

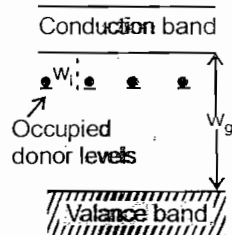


FIGURE : Energy band diagram for donor impurity.

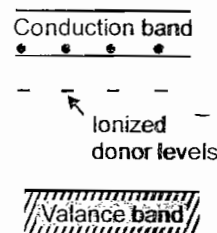


FIGURE : Donor atoms are ionized by thermal excitation, leading to conduction by electrons.

(b) p-type semiconductor

- p-type semiconductors are those semiconductors in which Ge or Si is doped with an element from the third column, for example, Ge or Si doped with boron, gallium, or aluminium.
- Three of the neighbouring silicon atoms form covalent bonds with the three valance electrons of the aluminium atom (trivalent impurity).
- Impurity atoms, that contribute holes in this manner are termed acceptors, because they accept electrons from Si or Ge atoms.
- Introducing a group-III element in pure semiconductor creates a level near to the valance band. The impurity levels created by group-III elements is known as acceptor level.
- Thus addition of group-III impurity leads to increase in number of holes. Majority carriers in p-type semiconductor are "holes".

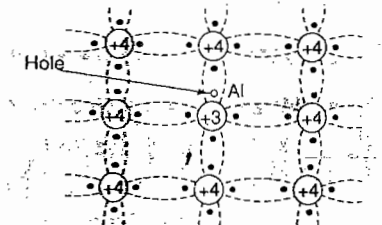


FIGURE : p-type semiconductor.

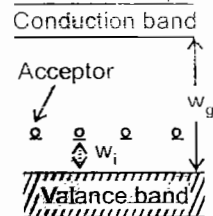


FIGURE : Energy band diagram for acceptor impurity.

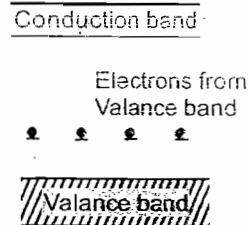
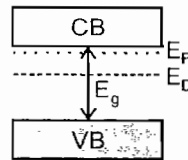


FIGURE : Acceptors have accepted electrons from valance band at the expense of energy W_i .

9.5 POSITION OF FERMI LEVEL IN EXTRINSIC SEMICONDUCTORS

A. n-type extrinsic semiconductor

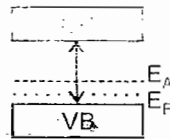
- In intrinsic semiconductor, fermi level lies very close to the middle of forbidden energy gap (E_g) indicating equal concentrations of free electrons and holes.
- When donor type impurity is added to the crystal (if we assume that all the donor atoms are ionised). The donor electron will occupy the states near the bottom of the conduction band.
- Hence it will be more difficult for the electrons from the valance band to cross energy gap by thermal agitations. Consequently, the number of holes in the valance band is decreased. Hence E_F for n-type semiconductor must move closer to the conduction band

FIGURE : Position of Fermi level in **N-type** semiconductors.

$E_D \rightarrow$ Energy levels corresponding to the **Donor** impurities

B. **p-type extrinsic semiconductor**

- When a group III impurity is added, it creates new energy levels, that are near to the top of the valence band.
- The energies for holes are highest near the **valence** band and decrease vertically upward in energy level diagram.
- When an intrinsic semiconductor is doped with acceptor type impurity. The concentration of holes in the valence band is more than the concentration of electrons in the conduction band; Fermi level shifts towards the valence band.

FIGURE : Position of Fermi level in **p-type** semiconductors.

$E_A \rightarrow$ Energy levels corresponding to the **acceptor** impurities

9.6 CONDUCTIVITY OF SEMICONDUCTOR

- Since both types of charge carriers (electrons and holes) are available in a semiconductor and both are influenced by external applied electric field, therefore the net conductivity of a semiconductor will be a sum of conductivity of holes and electrons.
- If n be the no. of electrons and p be the no. of holes.

The current density due to electrons $J_e = n.e.v_e$

The current density due to holes $J_h = p.e.v_h$

The net current density of a semiconductor

$$\begin{aligned}
 J &= J_e + J_h = n.e.v_e + p.e.v_h \\
 &= eE \left[n \frac{v_e}{E} + p \frac{v_h}{E} \right] \\
 J &= eE [n.\mu_e + p.\mu_h]
 \end{aligned}$$

where

$m_e \rightarrow$ mobility of electron

$m_h \rightarrow$ mobility of hole

$$m = \frac{V_d}{E} = \frac{\text{Average drift velocity}}{\text{Applied electric field}}$$

- And conductivity due to drift motion of charge carriers

$$s = \frac{J}{E} = e [n \mu_e + p \mu_h]$$

For an intrinsic semiconductor;

$$n = p = n_i$$

The conductivity will; therefore be

$$\sigma = n_i e (\mu_e + \mu_h)$$

- The reciprocal of conductivity is resistivity

$$r = \frac{1}{\sigma} = \frac{1}{\sigma} = \frac{1}{e(n \mu_e + p \mu_h)}$$

- The intrinsic concentration (n_i) is very sensitive to temperature. It is a function of temperature on the rate of production of electron-hole pairs. Theory shows that for any intrinsic semiconductor, the intrinsic concentration n_i , and hence the conductivity, follows the relation

$$n_i = AT^{3/2} e^{-eV/2kT}$$

Here V = The energy in volts required to break the covalent bond and is called ionization energy,

T = The absolute temperature,

k = Boltzman's constant,

e = The charge of an electron,

and A = A constant that depends on the semiconducting material.

- In pure germanium $V = 0.75$ volt and $A = 9.64 \times 10^{15}$, so that at room temperature of $T = 300$ K, $n_i = 2.5 \times 10^{10}$ electrons per m^3 .
- The mobilities of holes and free electrons in germanium are 0.17 and 0.36 $m^2 \text{ volt}^{-1} \text{ sec}^{-1}$, respectively.

9.7 HALL EFFECT IN SEMICONDUCTORS

- The Hall effect occurs when a transverse magnetic field is applied to a specimen (metal or semiconductor) carrying current. Under these conditions, a transverse electric

field is produced (perpendicular to both the direction of electric current and the applied magnetic field). The effect thus produces a measurable transverse voltage across the specimen.

- The conductivity of a semiconductor does not determine the mobility and the density of charge carriers separately (determine the product of the two). However, in case there is only one type of charge carriers (either electron or holes); the density of charge carriers can be found from a measurement of the, so called, Hall coefficient, R_H of the material.

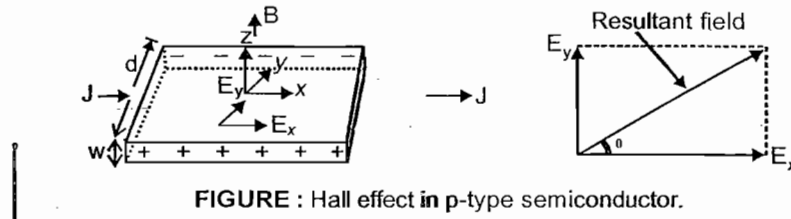


FIGURE : Hall effect in p-type semiconductor.

- Let us discuss the Hall effect for a p-type material, assuming the carriers are positive holes then by applying electric field they will drift with an average velocity v_x in the x-direction.

When a magnetic field of flux density B_z (Wb/m²) is applied along the z-direction, the carriers will experience a Lorentz force perpendicular to v_x & B_z , resulting in an excess of holes near the front face and deficiency of holes near the back face. These charges will in turn create an electric field along the negative y-axis i.e. E_y

$$eE_y = e.v_x.B_z \quad \dots(1)$$

$$v_x = \frac{E_y}{B_z} \quad \dots(2)$$

also, the current density

$$J_x = n_h e.v_x \quad \dots(3)$$

where,

J_x – is the current density in the x-direction.

n_h – is the density of holes. (only positive charges).

Then "Hall coefficient" R_H is defined as.

$$R_H = \frac{E_y}{B_z J_x} = \frac{1}{en_h} \quad \dots(4)$$

- If instead of holes the carriers were electrons, then the voltage measured across the Hall probes would be reversed. Hence, for electrons,

$$R_H = \frac{E_y}{B_z J_x} = -\frac{1}{en_e} \quad \dots(5)$$

where n_e is the density of conduction electrons.

Note :

$$R_H = \begin{cases} \frac{1}{\rho}, & \text{when electron is moving with drift velocity} \\ \frac{3\pi}{8\rho}, & \text{when electron motion is random} \end{cases}$$

$$\text{where, } r = \text{charge density} = \frac{1}{ne}$$

$$R_H = \begin{cases} \text{negative} & \text{for n-type semiconductors} \\ \text{positive} & \text{for p-type semiconductors} \end{cases}$$

- Measurement of the hall coefficient in a semiconductor gives us the information about the density of the carriers and their sign (whether electron or holes).
- Due to the presence of the hall field E_y , the resultant field in the material no longer remains longitudinal but makes an angle θ with the x axis (previous field direction). The angle θ is called "Hall angle".
- Calculation of Hall voltage :

From equation (2)

$$\begin{aligned} E_y &= E_H = v_d B \\ \frac{V_H}{d} &= v_d B \\ V_H &= v_d \cdot d \cdot B \end{aligned} \quad \dots(6)$$

where d is the width of the specimen

We know that,

$$v_d = \frac{J}{ne} = \frac{J}{\rho} \quad (r = \text{charge density})$$

∴ From equation (6)

$$\begin{aligned} V_H &= \frac{J}{\rho} \times d \times B \\ V_H &= \frac{I}{A \cdot \rho} \times d \times B \\ V_H &= \frac{I}{w \cdot d \cdot \rho} \times d \times B \quad (w = \text{thickness of the specimen}) \\ V_H &= \frac{BI}{\rho \cdot w} \\ V_H &= R_H \times \left(\frac{BI}{w} \right) \end{aligned}$$

- For comparable electron and hole concentration

$$R_H = \frac{1}{\rho} \frac{(n_h \mu_h^2 - n_e \mu_e^2)}{(n_h \mu_h + n_e \mu_e)^2}$$

- For intrinsic semiconductor

$$n_e = n_h = n_i$$

$$R_H = \frac{1}{-n_i e} \frac{n_i (\mu_h^2 - \mu_e^2)}{n_i^2 (\mu_h + \mu_e)^2}$$

$$R_H = \frac{1}{n_i^2 e} \frac{(\mu_h^2 - \mu_e^2)}{(\mu_h + \mu_e)^2}$$

$$R_H = \frac{1}{n_i^2 e} \frac{(\mu_h - \mu_e)}{(\mu_h + \mu_e)}$$

But for intrinsic semiconductor $\mu_e > \mu_h$

$\therefore R_H$ is negative for intrinsic semi-conductor

Note : Value of R_H for Si = -10^{-9}

Value of R_H for Ge = -10^{-6}

Application of Hall Effect

- To determine the type of semiconductor.
- To determine the carrier concentration,
- To calculate mobility of carriers.

9.8 MERITS OF SEMICONDUCTOR MATERIALS

- Smaller in size
- Very light in weight
- They consume negligible power
- Their operating voltage is low
- Do not show ageing effect

T.S. Applications of semiconductor materials

1. Thermistors, 2. Varistor, 3. Photo electric device, 4. Photo cells, 5. Refrigerators

9.9 FOR MA

Gallium /

- Gallium is a soft, silvery metal.
- Its melting point is 29.76°C and boiling point is 2400°C.
- Uses:
 - Semiconductor
 - Superconducting
 - Sealing

Indium A

- This is a soft, silvery metal.
- Its melting point is 15.66°C and boiling point is 2072°C.
- Uses:
 - Semiconductor
 - Superconducting
 - Sealing

Oxides, S

- These are the oxides of semiconductors.
- Sulphur dioxide (SO₂)
- Tellurium dioxide (TeO₂)
- Uses:
 - Ba
 - Co
 - Sw

of TV camera

- Metal-semiconductor field-effect transistor (MESFET)
- Metal-insulator-semiconductor field effect transistor (MISFET)

Optoelectronic devices e.g.

- Photodiodes
- Photocells
- Light emitting diodes (LEDs)
- Optical fibres
- Photodetectors
- Solarcells
- Semiconductor lasers

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gap is 2.4 eV.

Negative conductance microwave devices e.g.

- Tunnel diodes
- The Gunn diode
- Impatt diode

Power devices e.g.

- p-n-p-n diode
- Silicon controlled rectifiers (SCRs)

9.10.1 Semiconductor Devices

- **Junction** : Boundary between p and n semiconductors is known as junction. The region of small thickness at the junction is called depletion layer. The rectifying action takes place in this region.
- **Transistor** : Two junction (n-p and p-n) system shows amplifying action of electrical signals. Miniature, cheap, reliable, instant acting and less power consuming solid state transistors. Metal oxide semiconductor field-effect transistor (MOSFET) is a modern transistor used in street lights and as burglar alarm. CdS, CdSe and CdTe are commonly used photoconducting semiconductors.
- **Photodiodes** : A photodiode is a two terminal device, which responds to photon absorption.
- **Photoconductors** (or photo detectors) used to detect and measure the quanta of light such as in automatic door opener, in switching the street lights and as burglar alarm. CdS, CdSe and CdTe are commonly used photoconducting semiconductors.
- **Photocells** convert the light energy into electrical energy. Made from CdS, Se and PbSO₄. Photocells are used in cinematography, firealarms and television cameras etc.
- **Solar cells** from semiconducting materials are of immense utility in satellites and space-going vehicles. They are also used in calculators, solar power generation and solar automobiles.
- **Light-emitting** diode is an incoherent light source, that is used as a light source in fiber optic systems and other devices.

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- **Laser** is the source of a highly directional, monochromatic coherent light which is used as a light source for various optical and electronic devices.
- **Optical fiber** is a means of transmitting optical signals from a source to a detector. Thermistors are used to determine the temperature of systems in process industries, ovens and furnaces etc. They are manufactured from sintered manganese oxide that contains dissolved germanium or lithium.
- **Integrated circuits** are made on a single chip that contains diodes, transistors, resistors and capacitors etc. These are generally monolithically constructed using either unipolar or bipolar techniques.
- **Thermistors** : These work on temperature dependency effect of semiconductors.
- **Varistors** : These work on voltage dependency effect of semiconductors.
- **Rectifiers** : These work on impurity dependency effect of semiconductors.
- **Strain gauges** : These work on change in resistance effect of semiconductors.
- **Zener diodes** : These work on electrical field effect of semiconductors.
- **Transistors** : These work on amplification effects of semiconductors.
- **Photoconductive cells** : These work on the light illumination effect of semiconductors.
- **Photovoltaic cells** : These work on the optical characteristics of semiconductors.
- **Hall effect generators** : These work on the carrier drift effect in semiconductors.

9.10.2 Semiconductor Lasers

- Laser (light amplification by stimulated emission of radiation) is a quantum electronic device that generates intense electromagnetic radiation.
- Now a days solid ruby laser (chromium ions in alumina), liquid lasers (having rare-earth ions), and gaseous laser (such as carbon dioxide laser) are used in successful applications but semiconductor lasers are more efficient than these lasers.
- GaP, GaAs and GaSb are the most significant compounds for this purpose.
- In semiconductor lasers, light emission is obtained through a pn junction as a result of recombination of electrons and holes.

Materials for Semiconductor Lasers

- It must be efficient light emitter.
- It ease in formation of p-n junctions.
- It and heterojunction barriers.
- II-VI compounds efficiency high for light emission, but formation of their junction is difficult. However using nitrogen (N) as acceptor, the junction can be grown easily in the following materials by crystal growth techniques like MBE (molecular beam epitaxy) and MOVPE (metal-organic vapour-phase epitaxy).

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- ZnS
- ZnSe
- ZnTe

Lasers made of these materials emit in the region of green and blue-green light spectrum.

Large bandgap semiconductors : Semiconductor of large band gaps (about 2 to 5 eV) offer good candidature as semiconductor lasers materials. e.g.

- InN ($E_g = 2 \text{ eV}$)
- GaN ($E_g = 3.4 \text{ eV}$)
- AlN ($E_g = 5 \text{ eV}$)

- This covers a wide range of light emission from blue to UV spectrum.
- **Ternary alloy system** : These are used in the lasers used in fibre-optic communication systems.

- AlGaAs
- PbSnTe
- InGaSb

- The PbSnTe is able to provide laser output in the wavelength range from $7\mu\text{m}$ to above $30\mu\text{m}$ at low temperatures. The InGaSb is suitable for use at intermediate wavelengths.

- **Quaternary alloy system** : These are versatile in fabricating, by allowing flexibility in lattice matching. e.g. InGaAsP

- Short wavelength emitters : Blue/UV semiconductor lasers are very suitable for storage purposes such as compact discs (CDs), digital versatile discs (DVDs) etc.

- By reducing the laser wavelength i.e. by using short wavelength emitters, the storage density of these devices can be increased many times. e.g. InGaN

This laser has multi-quantum-well heterostructures.

9.11 MICROELECTRONICS

- In microelectronics single piece of semiconductor can connect more than 1000 transistors on an area of about 1 square centimetre.
- Processes of microelectronics may be classified as :
 - Semiconductor microelectronics, and
 - Thin film microelectronics
- Diodes, pnpn switches, transistors and resistors belong to semiconductor microelectronics group while the interconnections of various electronic circuits and capacitors are the products of thin film microelectronics.

9.12 FABRICATION OF THIN FILM MICROELECTRONIC CIRCUIT

- In fabricating of these circuits, glazed ceramics and glass substrates are used.
- Substrate is a polished surface on which many hundred I.Cs may be located.

- Deposition of I.Cs on thin films can be done by one or more of the following processes.
 - (i) Vacuum deposition
 - (ii) Silk screening
 - (iii) Vapour plating
 - (iv) Electron beam decomposition
 - (v) Plasma decomposition
 - (vi) Sputtering, and
 - (vii) Anodization
- Thin film resistors employ metallic film while the conductors employ film of gold or aluminium; and capacitors use a dielectric film.
- Ion implantation is a most modern method of doping microelectronic devices such as in MOSFET.



1.

2.

3.

QUESTIONS

1. For a semiconductor, which one of the following statements is NOT correct?

- (a) When an electron and a hole recombine, energy must be liberated
- (b) Electrons in the conduction band can acquire a net acceleration from a field because there are empty energy levels available
- (c) An electron in the valence band cannot be accelerated by the field unless there are empty energy levels available
- (d) Holes cannot be accelerated by the field unless there are empty energy levels available

2. Consider the following statement:

Extrinsic semiconductors show high electrical conductivity because the impurities are

- 1. Of high conductivity
- 2. Highly mobile
- 3. Highly charged

Which of these statements are NOT correct?

- (a) 1 and 2 (b) 2 and 3
- (c) 1 and 3 (d) 1, 2 and 3

3. Match List-I with List-II and select the correct answer :

List -I

List -II

- | | |
|-------------|-----------------------|
| A. Ga-As | 1. Integrated circuit |
| B. Nichrome | 2. Laser |
| C. Quartz | 3. Busbar |
| D. Si | 4. Heating element |
| | 5. Oscillator |

Codes:

- | | A | B | C | D |
|-----|---|---|---|---|
| (a) | 2 | 4 | 5 | 1 |
| (b) | 1 | 5 | 3 | 2 |
| (c) | 2 | 5 | 3 | 1 |
| (d) | 1 | 4 | 5 | 2 |

4. Assuming the Fermi level E_f is independent of temperature, E_f may be defined as the level with an occupancy probability of

- (a) 0% (b) 50%
- (c) 75% (d) 100%

5. The forbidden energy gap in silicon at 300 K is

- (a) 1.41 eV (b) 1.1 eV
- (c) 0.785 eV (d) 0.72 eV

6. With an increase in temperature, the Fermi level in an intrinsic semiconductor

- (a) Moves closer the conduction band edge

- (b) Moves closer to the valence band edge
(c) Moves into the conduction band
(d) Remains at the centre of the forbidden gap
7. On which of the following factors does the electrical conductivity of a semiconductor depend?
- Carrier concentration
 - Carrier mobility
 - Sign of the carrier
- Select the correct answer using the codes given below :
- (a) 1 and 2 (b) 1 and 3
(c) 2 and 3 (d) 1, 2 and 3
8. An intrinsic semiconductor at a temperature of absolute zero behaves like an insulator because of
- Non-availability of free electron
 - Non-recombination of electron with holes
 - Low drift velocity of free electrons
 - Low (almost zero) electron energy
9. In which one of the following ways can the Hall voltage across an impurity semiconductor crystal be increased?
- By increasing the thickness of the crystal
 - By increasing the concentration of impurity atoms in the crystal
 - By increasing the width of the crystal
 - By increasing the current flowing through the crystal
10. Which one of the following statements is correct? The Hall coefficient of an intrinsic semiconductor is
- positive
 - negative
 - zero
 - infinite
11. The electrical conductivity of a semiconductor increases with increase in temperature because
- The mobility of the carriers increases
 - The carrier concentration increases
 - Both carrier concentration and mobility increases
 - Thermal energy of electron increases
12. Fermi level in a p-type semiconductor lies close to
- The top of the valence band
 - The bottom of the valence band
 - The top of the conduction band
 - The bottom of the conduction band
13. To find the type of semiconductor (whether p or n type)
- To find carrier concentration
 - To measure conductivity
 - All of the above
14. Width of energy bands depends on which of the following?
- Temperature
 - Pressure
 - Relative freedom of electrons in the crystal
 - Mass of atom in the material
15. Which one of the following statements is not true for a p-type semiconductor?
- Conduction is due to the movement of holes in the valence band
 - Electrons are the majority carriers
 - It is an extrinsic semiconductor
 - It is a semiconductor

16.

17.

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- (b) Holes constitute the majority charge carriers
(c) Fermi level lies closer to the conduction band
(d) It is formed by adding an acceptor impurity to germanium
16. Principle of Hall effect is used in the construction of which one of the following?
(a) Ammeter (b) Voltmeter
(c) Galvanometer (d) Gaussmeter
17. For which one of the following materials, is the Hall coefficient zero?
(a) Metal
(b) Insulator
(c) Intrinsic semiconductor
(d) Alloy
18. In an intrinsic semiconductor, the number of electrons is equal to the number of holes at which temperature?
(a) 0 K
(b) 0°C
(c) High-temperature
(d) All temperatures
19. Elements can reach a stable atomic structure by
(a) losing electrons only
(b) gaining electrons only
(c) losing or gaining of sharing electrons
(d) collisions between atoms
20. III-V alloy semiconductor crystallizes in what form?
(a) Simple cubic structure
(b) Body-centered cubic structure
(c) Zinc blende structure
(d) Wurtzite structure
21. Which one of the following is the Fermi function $f(E)$?
(a) $\frac{1}{1+e^{(E-E_F)/(kT)}}$ (b) $\frac{1}{1-e^{(E-E_F)/(kT)}}$
(c) $\frac{1}{1+e^{(E_F-E)/(kT)}}$ (d) $\frac{1}{1-e^{(E_F-E)/(kT)}}$
22. What is the output voltage produced across the crystal by Hall effect, due to?
(a) Drop across the crystal due to current passing through it
(b) Movement of charge carriers towards one end
(c) Induced voltage by the applied magnetic field
(d) Induced voltage by the applied electric field
23. The measurement of which one of the following will reveal the sign of the charge carriers?
(a) Conductivity
(b) Mobility
(c) Hall coefficient
(d) Diffusion constant
24. Consider the following statements about semiconductors?
1. The forbidden energy gap in semiconductors lies between the valence band and conduction band.
2. The forbidden energy gap in germanium at 0 K is about 0.72 eV.
3. Semiconductors have negative temperature coefficient of resistivity.
Which of these statements are correct?
(a) 1, 2 and 3 (b) 1 and 2
(c) 2 and 3 (d) 1 and 3

25. Consider the following statements :
In a Hall effect experiment, the sign of Hall voltage will change if

1. Direction of applied field is changed.
2. Direction of applied magnetic field is changed.
3. Direction of both applied electric and magnetic fields are changed.
4. Direction of current is changed.

Which of these statements is/are correct?

- (a) 1, 2 and 3 (b) 3 only
(c) 1, 2 and 4 (d) 3 and 4

26. For intrinsic Ga As, the room-temperature electrical conductivity is $10^{-6} \text{ (ohm-m)}^{-1}$, the electron and hole mobilities are, respectively, 0.5 and $0.04 \text{ m}^2/\text{V-s}$. What is the intrinsic carrier concentration n at the room temperature?

- (a) 10^{21} m^{-3}
(b) 10^{-20} m^{-3}
(c) $7.0 \times 10^{12} \text{ m}^{-3}$
(d) $7.0 \times 10^{-20} \text{ m}^{-3}$

27. Consider the following statements :

1. Fermi level lies below the donor level at room temperature (T).
2. Fermi level lies above the donor level as $T \rightarrow 0$.
3. Fermi level lies in valence band.
4. Fermi level remains invariant with temperature.

- (a) 1 only (b) 1 and 2 only
(c) 2, 3 and 4 (d) 1, 2 and 3

28. A semiconductor has a band gap of 2 eV. The wavelength of radiation emitted from the semiconductor when electrons and holes recombine is

- (a) 625 nm (b) 625 μm
(c) 625 mm (d) 625 cm

29. The Fermi function for an electron is $f(E)$, where E is energy. Then, the Fermi function for a hole is

- (a) $f(E)$ (b) $1 - f(E)$
(c) $1/f(E)$ (d) $1 + f(E)$

30. According to free electron theory, electron in a metal are subjected to

- (a) Constant potential
(b) Sinusoidal potential
(c) Square wave potential
(d) Non-periodic potential

31. Controlled addition of group III element to an elemental semiconductor results in the formation of

- (a) Intrinsic semiconductor
(b) n-type semiconductor
(c) p-type semiconductor
(d) Degenerate semiconductor

32. The Fermi energy E_F of a metal is proportional to (n is the number of free electrons per unit volume of the metal) as

- (a) n^2 (b) $n^{1/2}$
(c) $n^{2/3}$ (d) $n^{3/2}$

33. The temperature coefficient of a resistance of a doped semiconductors is

- (a) A
(b) A
(c) Z
(d) P
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(a) Always positive

(b) Always negative

(c) Zero

(d) Positive or negative depending on
the level of doping

34. The current flow in a semiconductor is
due to

1. Drift current

2. Displacement current

3. Diffusion current

(a) 1, 2 and 3 (b) 1 and 2 only

(c) 1 and 3 only (d) 2 and 3 only

35. Consider a metallic conductor of length
L m and a constant cross-sectional
area of Am^2 . A steady potential
difference of V volts is applied between
the ends of the conductor. The drift
velocity of the free electrons is γ m/s.
The mobility of the electrons is defined

as $u = \frac{\gamma}{V/L}$. If the number of free
electrons per m^3 is N and each carries
a charge of e Coulomb, the resistance
R of the conductor is

(a) $\frac{L}{NAue}$ ohm (b) $\frac{LN}{Aue}$ ohm

(c) $\frac{Lu}{NAe}$ ohm (d) $\frac{Lue}{NA}$ ohm

36. Match List-I with List-II and select the
correct answer using the code given
below the list:

List -I

List -II

A. Carbon (Diamond) 1. Conducting

B. Silicon 2. Semi-
conducting

C. Tin (Grey) 3. Insulating

D. Lead

Codes:

	A	B	C	D
(a)	3	2	1	1
(b)	1	2	1	3
(c)	3	1	2	1
(d)	1	1	2	3

DIRECTIONS :

The following items consist of two
statements, one labelled as 'Assertion A'
and the other labelled as 'Reason R'. You
are to examine these two statements
carefully and select the answer to these
two statements carefully and select the
answer to these items using the codes given
below:

- (a) Both A and R are individually true and
R is the correct explanation of A
- (b) Both A and R are individually true but
R is not the correct explanation of A
- (c) A is true but R is false
- (d) A is false but R is true.

37. **Assertion (A):** A doped semiconductor
will behave as a perfect insulator at
zero Kelvin but its electrical
conductivity will rise if the temperature
is slowly increased above zero Kelvin.

Reason (R): The rise in electrical conductivity is mainly due to increased ionization as the temperature is raised above zero Kelvin.

38. **Assertion (A):** Energy released when an electron jumps from a higher to a lower level is usually in the form of photons.

Reason (R): Energy released when an electron jumps from a higher to a lower level is absorbed by the nucleus.

39. **Assertion (A):** An intrinsic semiconductor has low electrical conductivity. Hence, it is normally not used in the device fabrication without doping.

Reason (R): Its electrical resistivity can be increased by raising its temperature.

40. **Assertion (A):** Intrinsic semiconductors show negative Hall coefficient.

Reason (R): The number of electrons and holes are equal in an intrinsic semiconductor.

□□□

ANSWERS

1. (d)	9. (d)	17. (a)	25. (c)	33. (d)
2. (a)	10. (b)	18. (d)	26. (c)	34. (c)
3. (a)	11. (b)	19. (c)	27. (b)	35. (a)
4. (b)	12. (a)	20. (c)	28. (a)	36. (a)
5. (b)	13. (d)	21. (a)	29. (b)	37. (d)
6. (d)	14. (a)	22. (b)	30. (a)	38. (a)
7. (a)	15. (c)	23. (c)	31. (c)	39. (c)
8. (a)	16. (d)	24. (d)	32. (c)	40. (b)

4. (b)

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6. (d)

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9. (d)

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11. (b)

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12. (a)

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4. (b)

The Fermi level represents the energy state with 50% probability of being filled, if no forbidden band exists.

6. (d)

Fermi level in an intrinsic semiconductor does not depend on temperature. It moves up or down only if some impurity is added in semiconductor.

7. (a)

Conductivity of semiconductor = $ne(\mu_e + \mu_n)$

9. (d)

Hall Voltage, $V_H = \frac{B.i}{\rho w}$

So $V_H \propto i$

10. (b)

For intrinsic semiconductor,

$$n = p = n_i$$

$$\text{and } R_H = \frac{1}{n_i^2 q} \left(\frac{\mu_p - \mu_n}{\mu_p + \mu_n} \right)$$

and as μ_n (mobility of e^-) $> \mu_p$

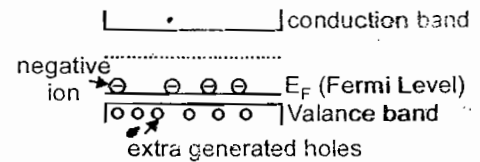
$R_H \Rightarrow$ negative, for intrinsic semiconductors.

11. (b)

At high temperature more covalent bonds will break, and so more charge carriers will be available.

12. (a)

Energy band diagram for p-type semiconductor :-



15. (c)

In p-type semiconductors, Fermi level is slightly above the valance band.

17. (a)

$$R_H = \frac{1}{ne}$$

where, n = carrier concentration as for metals $n \rightarrow \infty$ so, $R_H \rightarrow 0$

18. (d)

For intrinsic semiconductor, $n_i = n = p$

23. (c)

Due to the presence of charge carriers moving in the crystal, an output voltage is produced across the crystal by hall effect.

26. (c)

As for intrinsic GaAs, $n_i = n = p$

$$\sigma = ne(\mu_n + \mu_p)$$

$$\eta_i = \frac{\sigma}{e(\mu_n + \mu_p)}$$

$$= \frac{10^{-6}}{1.6 \times 10^{-9} (.5 + .04)}$$

$$\eta_i = 7 \times 10^{12} \text{ m}^{-3}$$

27. (b)

Fermi level in an n-type semiconductor at zero degree kelvin will be below donor level and above the half way between the conduction band and the valance level.

28. (a)

Given, $E_g = 2\text{eV}$ Wavelength of radiation, $\lambda(\mu\text{m}) = \frac{1.24}{E_g}$

$$\lambda = \frac{1.24}{2} \times 10^{-6} \text{m}$$

$$\lambda = 625 \text{nm}$$

29. (b)

Fermi Function determines the probability of electron or hole and

$$f(E)_{\text{electron}} + f(E)_{\text{hole}} = 1$$

32. (c)

$$E_f = \left(\frac{(hc)^2}{8mc^2} \right) \left(\frac{3}{\pi} \right)^{2/3} n^{2/3}$$

$$\text{So, } E_f \propto n^{2/3}$$

33. (d)

The temperature coefficient of intrinsic semiconductor is negative, but temperature coefficient of a doped semiconductor may be positive or negative depending on the level of doping.

34. (c)

Current flow in semi-conductor is due to –

(i) Drift Current – which is due to applied voltage

(ii) Diffusion Current – which is due to difference in concentration of charge carriers in semiconductor

35. (a)

As we know current density,

$$J = p v_d$$

$$\text{given, } p = ne, v_d = \gamma$$

$$\text{so } i = neA\gamma \quad \dots(i)$$

$$\text{and given } u = \frac{\gamma}{V/L}$$

$$\text{so } \gamma = \frac{Vu}{L} \quad \dots(ii)$$

$$\text{so } R = \frac{V}{i} = \frac{L}{nAue}$$

37. (d)

Due to doping the semiconductor have some charge carriers at room temperature, so it will behave as insulator but not perfect insulator.

39. (c)

As semiconductors have negative temperature coefficient, there electrical resistivity decreases by raising temperature.

10

10.1 INTRODUCTIONIntroductionRefractionReflectionAbsorptionRayleigh ScatteringTransmissionElectro-opticsPhotoelectric EffectPhotoemissivityBrightnessOptical PropertiesOptical PropertiesOptical PropertiesOptical PropertiesSemiconductorVisibility RangeOptical PropertiesOptical AbsorptionLuminescencePhoto-LuminescenceElectro-Luminescence

10

Optical and Thermal Properties of Materials

10.1 INTRODUCTION

Introduction

Refraction

Reflection

Absorption

Rayleigh Scattering

Transmission

Thermal Emission

Electro-Optic Effect

Photoelectric Effect

Photoemissivity

Brightness

Optical Properties of Non-Metals

Optical Properties of Metals

Optical Properties of Semiconductors

Visibility Range of Light Spectrum

Optical Properties of Insulators

Optical Absorption in Ionic Crystals

Luminescence

Photo-Luminescence

Electro-Luminescence

Optical property deals with the response of a material against exposure to electromagnetic radiations, specially to visible light. When light falls on a material, several processes such as reflection, refraction, absorption, scattering etc.

10.2 REFRACTION

When light photons are transmitted through a material, they causes polarization of the electron in the material and by interacting with the positive ion nuclei, photons lose some of their energy. As a result of this, the speed of light is reduced and the beam of light changes direction.

Example :

	Material	Refractive index
(i)	Germanium	4
(ii)	Air	1
(iii)	Water	1.33
(iv)	Ice	1.309
(v)	Dimond	2.41
(vi)	Silica glass	1.458
(vii)	Sapphire Al_2O_3	1.76
(viii)	NaCl	1.54
(ix)	Rutile, TiO_2	2.68

Opto-Electronic DevicesSolar CellsLight Emitting DiodesLight Emitting MaterialsOptical FibresTypes of Optical FibresThermal PropertiesHeat CapacityThermal ExpansionThermal ConductivityRelation between Coefficient of Thermal Expansion and Melting PointThermal StressSpalling (or Thermal) CrackingThermal Fatigue and Thermal ShockThermal Temperature Effect**10.3 REFLECTION**

When a beam of photons strikes a material, some of the light is scattered at the interface between the two media even if both are transparent. Reflectivity, R , is a measure of fraction of incident light which is reflected at the interface.

10.4 ABSORPTION

When a light beam is struck on a material surface, portion of the incident beam that is not reflected by the material is either absorbed or transmitted through the material. The fraction of beam that is absorbed is related to the thickness of the materials and the manner in which the photons interact with the material's structure.

10.5 RAYLEIGH SCATTERING

Here photon interacts with the electron orbiting around an atom and is deflected without any change in photon energy. This is more vital for high atomic number atoms and low photon energies. Ex. Blue colour in the sunlight gets scattered more than other colors in the visible spectrum and thus making sky look blue.

- **Tyndall effect** : Here scattering occurs from particles much larger than the wavelength of light. Ex. cloud look white
- **Compton scattering** : In this incident photon knocks out an electron from the atom losing some of its energy during the process.

10.6 TRANSMISSION

The fraction of beam that is not reflected or absorbed is transmitted through the material. Thus the fraction of light that is transmitted through a transparent material depends on the losses incurred by absorption and reflection. Thus, $R + A + T = 1$

where R = reflectivity, A = absorptivity, and

T = transmittivity

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10.7 THERMAL EMISSION

- When a material is heated electrons are excited to higher energy levels generally in the outer energy levels where the electrons are less strongly bound to the nucleus. These excited electrons, upon returning back to the ground state, release photons in process termed as thermal emission.
- By measuring the intensity of a narrow band of the emitted wavelengths with a pyrometer, material's temperature can be estimated.

Note : Lasers are useful in welding, metal cutting, heat treatment, surgery, mapping, reading compact disc etc. Ex. Ruby, single crystal of Al_2O_3 doped with little amount of Cr_2O_3 ; yttrium aluminium garnet ($\text{Y}_3\text{Al}_5\text{O}_{12}$) - YAG doped with neodymium, Nd; CO_2 gas; He-Ne gas; some semi-conductors like GaAs and InGaAsP. Gas lasers produce lower intensities and powers, but are useful in continuous operation since solid-state lasers generate appreciable amounts of heat.

10.8 ELECTRO-OPTIC EFFECT

The behaviour of a material in which its optical isotropic nature changes to anisotropic nature on application of an electric field. This effect is seen in LiNbO_3 , LiTiO_3 etc.

10.9 PHOTOELECTRIC EFFECT

Phenomenon in which the ejection of electrons from a metal surface takes place, when the metal surface is illuminated by light or any other radiation of suitable frequency (or wavelength). Several devices such as phototube, solar cell, fire alarm etc. work on this effect (principle).

10.10 PHOTOEMISSIVITY

Phenomenon of emission of electrons from a metal cathode, when exposed to light or any other radiations.

10.11 BRIGHTNESS

- Power emitted by a source per unit area per unit solid angle.
- **Photo conductivity :** Phenomenon of increase in conductivity of a semi-conductor due to excess carriers arisen from optical luminescence.

10.12 OPTICAL PROPERTIES OF NON-METALS

- These materials may be transparent, translucent, or opaque. Therefore, they exhibit different optical properties such as reflection, refraction, absorption and transmission. The phenomenon of refraction is more dominant in them.

- The non-metals which are transparent, are generally coloured due to light absorption and remission in the visible region by them. Absorption of light occurs due to : Electronic polarization.
- Excitation of electrons from filled valence band to empty state within conduction band, and Wide band gaps in dielectric materials.
- The non-metallic transparent materials transmit light due to net energy formed by absorption and reflection processes.

10.13 OPTICAL PROPERTIES OF METALS

- In metals, the valence band is partially filled and so there are large number of quasi continuous vacant energy levels available within the valence band. When light is incident on metals the valence electrons absorb all frequencies of visible light and get excited to vacant states inside the valence band (intra-band transitions). This result in the opacity of metals.
- The total absorption of light by the metal surface is within a very thin outer layer of less than 0.1 μm . The excited electrons return to lower energy states thus causing emission of radiation. The sun's radiation on metal in the form of visible light of the same wavelength. This emitted light which appears as the reflected light is cause of the lustrous appearance of metals.
- In copper, inter-band transitions occur for energies greater than 2.2 eV i.e. all photons of energy greater than 2.2 eV are strongly absorbed. This energy corresponds to wavelength below 5625 Å. This means that the radiation in the blue-violet range is absorbed. This is reason for the reddish-orange colour of copper.
- In silver and aluminium, there is no absorption in the full range of visible radiation. So, the re-emission occurs over the entire wavelength range of the visible spectrum due to which the white colour of these metals-exist.
- Gold appears yellow because there is absorption in green portion and reflection in yellow and red region.

10.14 OPTICAL PROPERTIES OF SEMICONDUCTORS

- Intrinsic semiconductors at low temperatures have a completely filled valence band and an empty conduction band. So no intra-band transitions can occur in semiconductors.
- Radiation of low frequencies, i.e. infrared radiation are not absorbed and that's why semiconductors are transparent to infra-red radiation.

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- The energy gaps in semiconductors are in the range of 0.5 – 3eV. So inter-band absorption occurs for radiation in this range which corresponds to near infra-red and visible range, this is responsible for the opacity of semiconductors.

10.15 VISIBILITY RANGE OF LIGHT SPECTRUM

- Semiconductors infrared region: InSb, Ge, Si, GaAs.
- Semiconductors lying in visible region: CdSe (red visibility) GaP (yellow visibility).
- Semiconductors lying in ultraviolet region: CdS (green visibility), SiC (blue visibility) ZnS.

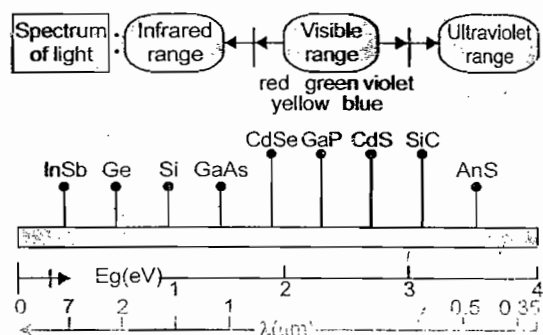


FIGURE : Some semiconductors under different visibility range.

10.16 OPTICAL PROPERTIES OF INSULATORS

- Insulators have completely filled valence band and so like as in semiconductors, no intra-band transitions can occur.
- The energy gap in insulators are greater than 5 eV and so no inter-band transition can occur in the visible range of radiation.
- Absorption occurs only for the ultraviolet radiation. Insulators are transparent from infra-red up to the ultra-violet radiation.

Examples :

- Perfect diamond crystal
- Fused quartz
- Window glass

Non transparent insulator

- Enamels,
- Porcelains,
- Opal glass etc.

- Above materials are opaque because the incident radiation gets scattered in all direction by the small particles present in these materials.
- Due to this, there cannot be perfect transmission. Part of the radiation is diffusely transmitted and part is diffusely reflected. This makes the materials appear opaque.

- If the particle size is of the order of the wavelength of visible radiation, there will be maximum scattering.
- For some applications, such particles are deliberately introduced in dielectrics to make them opaque.

10.17 OPTICAL ABSORPTION IN IONIC CRYSTALS

- Ionic crystals are insulators. The energy gap in these crystal are in the range of 5-8 eV. The electrons cannot absorb photons in the visible radiation and get excited to the conduction band. So the complete range of visible radiation is transmitted by ionic crystals and they are transparent.
- The absorption properties of ionic crystals change drastically if point defects such as lattice vacancy or Schottky defects are present in them. Because of this defect materials are found to be colored.
- Another method by which the optical absorption in ionic crystals can be changed is by adding impurities.

10.18 LUMINESCENCE

Luminescence is the property by which a material emits the light. In non-conducting materials, the light is emitted under certain conditions which are as below.

- When electron-hole pairs (EHP) are generated, or
- When the carriers fall to their equilibrium state after being excited to higher impurity levels.

Different Types of Luminescence

Photo-luminescence	in which the carriers are excited by photon absorption
Cathode-luminescence	in which the carriers are created by high-energy bombardment of electrons on the material.
Electro-luminescence	in which the carriers are excited by introducing current in the material.
Chemi-luminescence	in which the luminescence is created by chemical action.

10.18.1 Photo-Luminescence

- It is the phenomenon of emission of light from a semiconductor on account of recombination of excited electron-hole pair (EHP).

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- Here one photon is emitted from each photon absorbed. Recombination in semiconductors takes place at varying rates; fast and slow. Accordingly, the photoluminescence may be of following two types.
- **Fluorescence** : It is a fast process property of material in which the emission of photon stops in about 10^{-8} s after the excitation is removed. Example :
 - (i) Glass surface coated with tungstates or silicates such as in fluorescent lamps.
 - (ii) Television screen coated with sulphides, oxides, tungstates etc.
- **Phosphorescence** : Slow process property of material in which the emission of photon continues for a longer duration, lasting for seconds and minutes after removal of excitation. Materials falling in this category are termed as phosphors, example :
 - ZnS coated with Cu as impurity
 - CdS coated with Ag as impurity
 - KCl coated with Tl as impurity
 - NaI coated with Tl as impurity

Example : 'fluorescent lamp'. It is a glass tube filled with a gas, which is generally the mixture of mercury vapours and argon. The inside of the tube has a fluorescent coating. When an electric discharge is induced between electrodes of the tube, the atoms of the gas are excited and emit photons.

10.16.2 Electro-Luminescence

- This effect can be created by introducing the electric current into a semiconductor. The electrical current can be used in different ways to produce light in semiconductors. One such way is 'injection'.
- The name of the process is injection electro-luminescence which is used in making light-emitting diodes (LEDs).
- In them the minority carriers are injected by electric current, into the regions of a crystal where they can recombine with majority carriers. It results in emission of recombination radiation.
- The effect of electro-luminescence can be found in devices incorporating the phosphor powder (such as of ZnS) in a plastic binder.
- This phosphor gives-off the light when an alternating current (a.c.) field is applied on it. Such device is known as 'electro-luminescence cell', which is used as lighting panel.
- **Destriau effect** : The emission of photons in certain phosphors occurs when they are subjected to alternating electric field, was observed for the first time by Destriau. Hence this phenomenon is known as 'Destriau effect'.

10.19 OPTO-ELECTRONIC DEVICES

- Optoelectronic devices are those devices whose function involve the interaction of photons with semiconductors. Some of the optoelectronic devices detect photons, while some others emit photons.

- Devices that convert optical energy into electrical energy, such as
 - Photodiodes
 - Solar cells
- Devices that emit photons, such as
 - Incoherent sources like light-emitting diodes (LEDs).
 - Coherent sources such as lasers.

10.20 SOLAR CELLS

- A solar cell is found in application to convert solar energy into electrical energy. It is a direct energy conversion system, based on photovoltaic action.
- A solar cell is a self-generating arrangement which employs semiconductor contacts against metals. The current generated depends on the extent of illuminated area.
- As an illustration, the current generated is about 10–100 mA from a junction of about 1-cm² area.
- Usually the amount of current generated from a single solar cell is too less, so many solar cells are used together to form a 'solar battery'.
- The power produced by a solar battery is measurable. The arrays of p-n junction solar cells are widely used to supply electrical power to space satellites.

10.21 LIGHT EMITTING DIODES

- Light-emitting diodes are the devices that behave as the generator of light. They are the light source for fibre optic systems.
- Their working is based on the effect defined as 'injection electroluminescence'. According to this effect, the semiconductors characterized by direct recombination give-off light from their junctions under forward-bias.
- It is opposite to with the semiconductors having indirect band gaps (e.g. Si or Ge), in which only heat is released on recombination and not the light.

10.21.1 Light Emitting Materials

A large variety of light emitting semiconductors are known to exist. They include n-type, p-type, III-V and II-VI group materials, ternary and quaternary compounds and alloys.

n-type binary compounds

- ZnSe
- ZnS
- CdSe
- CdS

p-type binary compounds

- ZnSe
- ZnTe

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Infrared emitter compounds and alloys

- GaAs
- InP
- GaN ($E_g = 3.4\text{eV}$) for blue wavelength
- InSb ($E_g = 0.18\text{ eV}$) • Maxed alloys of GaAs and InP

Ternary compounds

- AlGaAs
- AlGaP system for yellow and green wavelengths
- Gallium arsenide-phosphide ($\text{GaAs}_{1-x}\text{P}_x$) alloy

Quaternary compounds

- InGaAsP system
- AlGaAsSb system

Multiplayer heterojunction systems

- (Zn, Cd) system
- (S, Se)

For a good light-emitting material its band gap energy should be high.

10.22 OPTICAL FIBRES

- Optical fibres are extremely fine and flexible rods of glass. They are used as a transmitting medium used for the purpose of communication (the fibre).
- These fibres function as an optical waveguide with a transmitter and a detector. Light propagates through it by total internal reflection and refraction.
- During operation, they are placed between a light source and detector for transmission of signals.
- The operation of optical fibers is based on the principle of 'total internal reflection and refraction' at the interface between high refractive index core and lower refractive index cladding of pure glass.

10.22.1 Types of Optical Fibres

On the basis of construction and operation, the optical fibres can be categorized into following two types.

1. **Monomode fibres** in which the diameter of inner core is comparable with the wavelength of light. Hence, *only one mode* of light propagates through it.
2. **Multimode fibres** in which the diameter of core is sufficiently larger than the wavelength of light. Hence, the light propagation takes place in a *large number of modes*. The multimode fibres, on the basis of refractive index μ of the core, may be further divided into following two types.
 - (i) step-index type, and
 - (ii) graded-index type

Optical Fibres Material should have

- (i) High purity, having impurities to the level of less than 1 ppm.
- (ii) Low loss.
- (iii) Low-dispersion.
- (iv) High refractive index for core materials.
- (v) Low refractive index for cladding material.

Materials used in :

- Fiber of highly pure glass.
- Core made of vitreous high-silica glass doped with germanium oxide (Ge_2O_3), i.e. germania.
- Jacket of plastic, glass of rubber.

Advantages

- They are of miniature size.
- They are immune to cross talk.
- They are least subjected to electromagnetic interference.
- They are capable of carrying much more information for a given cross-section of fibre, than can be transmitted via the conventional coaxial cable.
- They can guide the optical signals over long distances (Many kilometres) without the necessity of perfect alignment between source and detector.

Note : 1. Blue LED are short wavelength emitters. GaN is prominent material for it, as it gives a very high efficiency. Blue LEDs are used in outdoor displays and TV screens. They can be combined with LEDs of other colours also to form very intense white light sources. Luminous efficiency of such light source exceeds over the conventional light bulbs.

2. An optoelectronic pair means a pair of a light emitter and a photodiode. It provides electrical isolation between input and output. In an optoelectronic isolator, both these devices are mounted on a ceramic substrate and packed together to form a compact unit. This unit, while maintaining isolation, passes the information.

- **Dark resistance of a photoconductor :** It is the resistance of a photoconducting cell when it is un-illuminated. Dark resistance is always higher than the bright resistance (i.e. the resistance of the cell when illuminated).

10.23 THERMAL PROPERTIES

- The responses of solids against the thermal effects are termed as thermal properties of materials. Proper selection of materials for favourable low and high temperature applications requires knowledge of their thermal properties.

e.g. Liquid ammonia (NH_3) and liquid oxygen (O_2) require thermal protection at very low (cryogenic temperatures) for storage purpose.

- Electric bulb needs to be protected from thermal fatigue at high temperatures.
- Information about thermal conductivity, thermal expansion, melting point and heat dissipation are very essential in the design and operation of power plants (gas and steam).

10.23.1 Heat Capacity

- Many engineering solids when exposed to heat experiences an increase in temperature i.e. it absorbs heat energy. This property of a material i.e. material's ability to absorb heat energy is called its heat capacity, C . It is defined as the energy required to change a material's temperature by one degree.

$$C = \frac{dQ}{dT}, \text{ J/mol-K or Cal/mol-K}$$

- Where dQ is the energy required to produce a temperature change dT .
- Heat capacity is not an intrinsic property i.e. total heat a material. A material property parameter called specific heat c , it defined unit mass (J/kg-K, Cal/kg-K)
- With increase of internal energy, geometrical changes may occur parallelly heat capacity is measured either at constant volume, C_v , or constant external pressure, C_p . The magnitude of C_p is always greater than C_v
- Heat energy absorption of a (solid, liquid or gaseous) material exists in mode thermal energy vibration of constituent atoms or molecules apart from the other mechanical heat absorption such as electronic contribution. With increase of energy atoms vibrate at higher frequencies. However, the vibrations of adjacent atoms are coupled through atomic bonding, which may lead to movement of lattices. This may be represented as waves (**phonon**) or sound waves, Vibrational contribution of heat capacity is varies with temperature.
- C_v equal to zero at 0 K, but increase rapidly with temperature.

10.23.2 Thermal Expansion

- After heat absorption, atoms started vibrating and having larger atomic radius, leads to increase in materials dimensions. The phenomenon is called thermal expansion. Thermal expansion (α) defined as the change in the dimensions length, and is expressed as :

Ge_2O) i.e.

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$$\alpha = \frac{l_f - l_0}{l_0(T_f - T_0)} = \frac{\Delta l}{l_0 \Delta T} = \frac{\epsilon}{\Delta T}$$

- Where T_0 and T_f are the initial and final temperature (in K), l_0 and l_f are the initial and final dimensions of the material and ϵ is the strain. α has units as $(^\circ\text{C})^{-1}$. For range of $5 - 25 \times 10^{-6}$, for ceramics $0.5 - 15 \times 10^{-6}$.
- A volume coefficient of thermal expansion, $\alpha_v (= 3\alpha)$ is used to change with temperature.

$$\alpha_v = \frac{\Delta v}{v_0 \Delta T}$$

- An instrument known as dilatometer is used to measure the thermal expansion.

10.23.3 Thermal Conductivity

- The ability of a material to transport heat energy from high temperature region to low temperature region is defined as thermal conductivity.
- Similar to diffusion coefficient, thermal conductivity is a microstructure sensitive property.
- The heat energy transported across $Q = kA \frac{\Delta T}{\Delta l}$.
- Where k is the thermal conductivity material. It has units as W/m.K. Metals in the range 20–400, ceramics 2–50, while polymers have in order of 0.3.
- Heat energy in solids is transported by two mechanisms: Lattice vibrations (photons) and electrons.
- The amounts of energy transported depends electrons, their concentration and type of material, lattice temperature. The thermal energy associated with electrons is much higher than that of lattice vibrations.
- In ceramic phonon are responsible for thermal conductivity. One reason for experimentally observed low conductivity of ceramics is their ionic nature, as phonons are effectively scattered by imperfections. The scattering of phonons becomes more pronounced with rising temperature. Hence, the thermal conductivity of ceramic materials normally diminishes with increasing temperature. Advanced ceramic materials like AlN, SiC are good thermal conductors, they are also electrical insulators. So, these materials are useful as electronic packaging substrates where heat dissipation is needed.
- Thermal conductivity of polymers is even low, compared with ceramic materials. Vibration and movement/rotation of molecular chains transfer heat energy. In these materials thermal conductivity depends on degree of crystallinity; a polymer with highly crystalline and ordered structure will have higher conductivity than amorphous polymer.

Thermal Properties of Some Materials

Material	Linear coefficient of expansion α ($10^{-6}/K$)	Thermal conductivity K_t (W/m·K) at 25°C	Melting point T_m (K)
Aluminium (pure)	23.7	300	930
Al alloy with 5% Cu	23.2	170	780
Copper (pure)	17.7	425	1355
Brass	18.8	200	1280
Mild steel	15.2	65	1785
18-8 stainless steel	10.5	25	1765
Teflon	140.5	0.20	600
Nylon	107.0	0.40	500
Alumina	6.9	65.00	2320

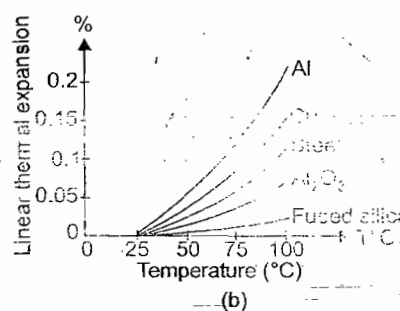
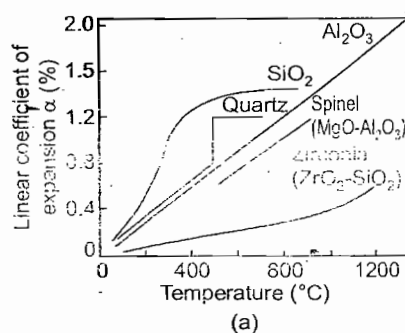


FIGURE : Variation in the coefficient of linear thermal expansion of (a) ceramics, and (b) metals at different temperature.

Note : The thermal conductivity of polycrystalline metals is much lower than that of single crystals due to scattering of electrons along grain boundaries. Thermal conductivity of metals decreases due to strong magnetic field and high temperatures. The thermal conductivity of metals is higher than their alloys due to scattering of electrons and phonons in the presence of alloying (foreign) atoms. In semiconductors, the thermal conductivity increases with increasing temperature due to flow of more number of excited electrons. Thermal conductivity of amorphous solids such as plastics and glasses increases with a rise in temperature.

- Thermal conductivity of metals, alloys, semiconductors and dielectrics are in the decreasing order.

10.23.4 Relation between Coefficient of Thermal Expansion and Melting Point

The coefficient of linear thermal expansion α and the melting point T_m of the solids are related as

$$\alpha T_m = \text{constant} = \lambda$$

The values of λ for different solids are as follows.

- (i) $\lambda = 0.02$ for ionic compounds and metals,
- (ii) $\lambda = 0.03$ for some salts, and
- (iii) $\lambda = 0.007$ for covalent bonded oxides and glasses.

10.23.5 Thermal Stress

- Thermal stresses are caused in a material due to temperature variation (thermal gradient) when thermal expansion is restrained. Example :
- Welded construction of structures and the pressure vessels,
- Joints of two railroad rails,
- Jacketed thick cylinders that are shrink fitted,
- Bimetallic strips in thermostatic controls,
- Refractory bricks in metallic furnaces and ovens,
- Components of I.C. engines, and
- Huge concrete structures such as dams.

Warpage

The distribution of residual stresses is not always symmetrical within the material. Uneven cooling is a cause of such unbalanced stresses. It happens because when one surface of a material is cooled more rapidly than the other, the rapidly cooled surface generates compression whereas tension is developed on other surface. Such asymmetry produces 'warpage' and the material develops convexity towards rapidly cooled surface.

10.23.6 Spalling (or Thermal) Cracking

The residual stresses produced within plastic materials may be relieved partially by warpage, but this is not so in case of non-plastic materials. In them, the dimensional changes cannot relieve the stresses, and the stresses in excess of elastic limit produce thermal cracking. This is called spalling. This is a very common phenomenon in glassware.

10.23.7 Thermal Fatigue and Thermal Shock

- **Thermal fatigue** : Behaviour of a material under repeated heating and cooling is known as thermal fatigue. Due to thermal fatigue, thermal stresses of fluctuating nature are produced in the material which may eventually cause its thermal fatigue failure. The ability of a material to withstand such failure is called thermal fatigue resistance.

- **Thermal shock** : A situation in the material, when there is a severe and sudden temperature change, is known as thermal shock. The capability of a material to withstand this effects of such drastic change is called thermal shock resistance.

Thermal shocks may be minimized in structural and machine systems by using the following devices.

1. Bellows,
2. Expansion loops,
3. Corrugated parts, and
4. Flexible joints

High Thermal Shock Resistivity Material

- Graphite
- Cermets
- Glass-ceramics
- Lithium-ceramics
- Fused silica
- Pyrex glass

Technique of Reflective Insulation

- The technique of reflective insulation is found in tankers transporting liquid oxygen, liquid hydrogen and liquid nitrogen.
- In this technique, highly reflective surfaces are separated by large width of air space.
- Conduction and convection is minimum at about 20 mm width of air.
- Aluminium foils on paper, reflective aluminum surfaces, separated by glass fibre lamina, and Mylar (aluminized plastic films) under high vacuum are used for this purpose.
- Air is not suitable for thermal insulation at cryogenic temperatures as it solidifies at 81.3 K. Hence the insulating layers are kept free from air and are sealed.

Note : High temperature effects are those observed above room temperature and low temperature effects are those observed below of it.

High Temperature Effect

The effects of high temperatures on materials is to cause the following effects :

- Loss of strength,
- Gain in ductility,
- Reduced stiffness,
- Lower yield strength,
- Polymorphic transformations
- Decrease in hardness etc.



QUESTIONS

1. Find the wrong statement : Specific heat of a material
 - (a) Constant for a material
 - (b) Heat capacity per unit mass
 - (c) Extrinsic property
 - (d) Has units as J/kg-K
2. Heat capacity has units as
 - (a) J/kg.k
 - (b) J/mol.K
 - (c) J.ohm/sec.K²
 - (d) W/m.K
3. Units for thermal conductivity
 - (a) J/kg.K
 - (b) J/mol.K
 - (c) J.ohm/sec.K²
 - (d) W/m.K
4. Lorentz constant has units as
 - (a) J/kg.K
 - (b) J/mol.K
 - (c) J.ohm/sec.K²
 - (d) W/m.K
5. Thermal expansion of a material has units as
 - (a) J/kg.K
 - (b) J/mol.K
 - (c) J.ohm/sec.K²
 - (d) 1/°C
6. Polymers have thermal conductivities in the range of
 - (a) < 1
 - (b) 1-10
 - (c) 10-100
 - (d) > 100
7. Polymers have thermal expansion coefficient in the range of x10⁻⁶
 - (a) 0.5 - 15
 - (b) 5 - 25
 - (c) 25 - 50
 - (d) 50 - 400
8. Coefficient of thermal expansion for ceramics is the range of x10⁻⁶
 - (a) 0.5 - 15
 - (b) 5 - 25
 - (c) 25 - 50
 - (d) 50 - 400
9. Metals have thermal conductivities in the range of
 - (a) < 1
 - (b) 1 - 5
 - (c) 5 - 25
 - (d) 20 - 400
10. Heat capacity of most materials is approximately equal to
 - (a) R
 - (b) 2R
 - (c) 3R
 - (d) 1/2 R
11. With increase in temperature, thermal conductivity of a metal
 - (a) Increases
 - (b) Decreases
 - (c) Either
 - (d) All, depending on metal
12. Thermal conductivity in polymers increases with
 - (a) Increase in crystallinity
 - (b) Decreases in crystallinity
 - (c) Either
 - (d) None
13. Visible light's wavelength range
 - (a) 0.39 - 0.77 mm
 - (b) 0.39 - 0.77 μm
 - (c) 0.39 - 0.77 nm
 - (d) 0.39 - 0.77 cm

14. Plane
 - (a) 6
 - (b) 6
 - (c) 6
 - (d) 6
15. Sum
 - (a) F
 - (b) F
 - (c) F
 - (d) F
16. Meta
 - (a) F
 - (c) T
17. Meta
 - (a) T
 - (c) T
18. Meta
 - (a) F
 - (c) M
19. Refle
 - (a) C
 - (c) C
20. Refr
 - (a) E
 - (b) M
 - (c) E
 - (d) M
21. Snel
 - (a) L
 - (b) L
 - (c) L
 - (d) L

14. Planck's constant is
 (a) 6.62×10^{-34} J.sec
 (b) 6.62×10^{-34} J.min
 (c) 6.62×10^{-34} Cal. sec
 (d) 6.62×10^{-34} Cal min
15. Sum of these is unity
 (a) Reflectivity
 (b) Reflectivity + Refractivity
 (c) Reflectivity + Refractivity + Transmittivity
 (d) Any
16. Metals can the light beams
 (a) Reflect (b) Refract
 (c) Transmit (d) Any
17. Metals are
 (a) Transparent (b) Opaque
 (c) Translucent (d) None
18. Metals can transmit these
 (a) Radio ways (b) Visible light
 (c) Microwaves (d) X-rays
19. Reflectivity of metals
 (a) 0.05 (b) 0.50
 (c) 0.95 (d) None
20. Refractive index of materials is approximately equal to square root of
 (a) Electrical permittivity
 (b) Magnetic permeability
 (c) Electrical permittivity x magnetic permeability
 (d) None
21. Snell's law relates
 (a) Light reflection
 (b) Light refraction
 (c) Light transmission
 (d) Light Absorption
22. Bouguer's law relates
 (a) Light reflection
 (b) Light refraction
 (c) Light transmission
 (d) Light absorption
23. Sky looks blue because the sun light is subjected to
 (a) Rayleigh scattering
 (b) Compton scattering
 (c) Both
 (d) None
24. Luminescence is because of
 (a) Photons emitted while excited electrons drops down
 (b) Knocking of electrons by photons
 (c) Photons stimulated by photons
 (d) All
25. Fluorescence occurs within
 (a) 10^{-5} s (b) 10^{-5} ms
 (c) 10^{-5} μs (d) 10^{-5} ns
26. Electro-luminescence occurs in
 (a) Electrical conductors
 (b) Electrical insulators
 (c) p-n junctions
 (d) All
27. Pyrometer works based on
 (a) Laser technology
 (b) Photo-conduction
 (c) Thermal emission
 (d) Tyndall effect

28. Solar cell works based on
 (a) Laser technology
 (b) Photon-conduction
 (c) Thermal emission
 (d) Tyndall effect
29. Optical fibre operators on the principle of
 (a) Total internal reflectance
 (b) Tyndall effect
 (c) Photon-electric effect
 (d) Laser technology
30. The ranges of electromagnetic radiation in which metals exhibit maximum reflectivity is
 (a) Visible
 (b) Beyond ultraviolet
 (c) Ultraviolet
 (d) Infrared
31. In indirect inter-band transition the electron undergoes
 (a) Change in both energy and momentum
 (b) Change in momentum but no change in energy
 (c) No change in both energy and momentum
 (d) Change in energy but no change in momentum
32. Which of the following are examples of direct band gap semiconductors?
 (a) GaAs (b) Si
 (c) Ge (d) Se
33. Among the following lasers which one emits the largest wavelength radiation?
 (a) Ruby laser
 (b) CO₂ laser
 (c) Semiconductor laser
 (d) He-Ne laser
34. Which of the following relations, between the velocity of light in the material v and its dielectric constant are true?
 (a) $v^2 = c^2 / \epsilon_r$ (b) $v^2 = c^2 / \epsilon_r^2$
 (c) $c = v\sqrt{\epsilon_r}$ (d) $c = \sqrt{v\epsilon_r}$
35. Dielectric materials like enamels, porcelain, etc. are opaque (in the visible range) because
 (a) They have band gap greater than 3 eV
 (b) They have band gap less than 3 eV
 (c) They scatter light
 (d) They have low refractive index
36. Which of the following materials does not absorb visible radiation?
 (a) Sapphire (b) Ruby
 (c) Diamond (d) Silicon
37. Cadmium sulphide has a band gap of 2.4 eV. Which of the following wavelength radiation will it absorb?
 (a) 4000 Å (b) 5500 Å
 (c) 6500 Å (d) 7000 Å
38. In day laser, the laser wavelength is tuned by
 (a) Changing the rise time of the pumping source
 (b) Changing the orientation of the grating the cavity
 (c) Changing the solvents
 (d) Changing the intensity of pumping source

1. (b)
 2. (b)
 3. (d)
 4. (c)
 5. (d)
 6. (a)
 7. (c)
 8. (a)

ANSWERS

1. (b)	9. (d)	17. (b)	25. (b)	33. (b)
2. (b)	10. (c)	18. (d)	26. (c)	34. (a) & (c)
3. (d)	11. (d)	19. (c)	27. (c)	35. (c)
4. (c)	12. (a)	20. (a)	28. (b)	36. (c)
5. (d)	13. (b)	21. (b)	29. (a)	37. (a)
6. (a)	14. (a)	22. (d)	30. (a) & (b)	38. (b)
7. (d)	15. (c)	23. (a)	31. (a)	
8. (a)	16. (a)	24. (a)	32. (a)	

relations,
light in the
refractive constant

$$= c^2 / \epsilon_r^2$$

$$= \sqrt{\nu \epsilon_r}$$

in enamels,
aqueous (in the

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than

refractive index
materials does
depend on?

usually

refractive index

band gap of
the following
it absorb?

400 Å

400 Å

the wavelength is

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the of the

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Polymers

11.1 INTRODUCTION

Introduction

Chemistry of Polymer Molecules

Molecular Weight

Molecular Shape

Molecular Structure

Copolymers

Polymer Crystallinity

Characteristics and Typical Applications of Few Plastic Materials

Thermo Plastics

Thermo Setting Polymers

Expanding Plastics

Conducting Polymers

Behaviour of Polymers Under Different Situations

Thermal Behaviour of Polymers

Fibres

Polymeric Fibres

General Applications of Polymersⁱ

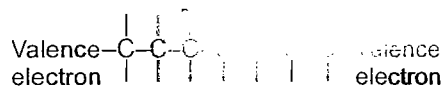
Addition Polymerization

Polymer Additions

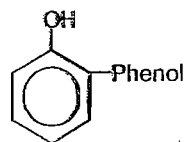
Thermoplastic Elastomers

Vulcaization

- They are **gigantic molecules** and are often referred as **macromolecules**.
- Within each **molecule** the atoms are bound together by **covalent bonds**.
- For most **molecules** are in the form of long flexible chains.
- The backbone of each polymer is a string of atoms.



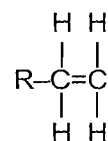
- Remaining **two valence electrons** of **each carbon atom** may be **involved in side bonding** with atom or radical.
- These long **molecules** are composed of structural entities called "**Mer**" units, which are repeated in a chain. The **term polymer** is composed of many mers. e.g.
- Alcohols **R—OH**
- Ether **R—O—R'**
- Acids **R—COOH**
- Aldehydes **R—CHO**



11.2 CHEM

- When the homopol
- While the
Almost a
between

Initiator



- During the 1990s, the average size of the U.S. firm increased. This result is consistent with the prediction for a policy of increasing the number of firms.
- The average size of the U.S. firm increased. This result is consistent with the prediction for a policy of increasing the number of firms.

$$\bar{M}_n =$$

where M is a particular

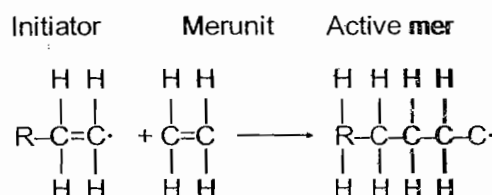
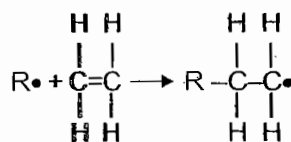
Weight ,

when: 05
... 00

Average
(DOP)

11.2 CHEMISTRY OF POLYMER MOLECULES

- When the repeating units along a chain are of same type, the resulting polymer is homopolymer.
- While those composed of two or **more** different Mer units are termed as copolymers. Almost all polymers are formed when an active 'mer' is formed by the reaction between an initiator or catalyst species.



- Thus the active sets, or unpaired electron is transferred to each successive monomer as it is linked to the chain.

11.3 MOLECULAR WEIGHT

- During the polymerization process **not** all polymers chains grow to the same length. This results in a distribution of molecular weights. Thus an average weight is specified for a polymer.
- The average molecular weight (M_n) is obtained by dividing the chains into a series of size range.

$$\bar{M}_n = \sum x_L M_i$$

where M_i is the mean of size range and x_L in fraction of total no. of chains of a particular size range.

Weight Average molecular weight $\bar{M}_w$ is

$$= \sum w_i M_i$$

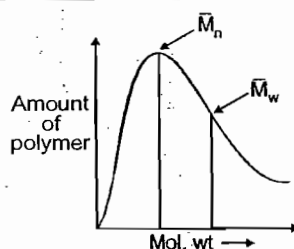
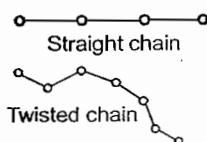
where M_i is again mean molecular weight of a size range and w_i is the weight fraction of molecules within same size interval.

- Average chain size of a polymer is also expressed by degree of polymerization (DOP)

$$DOP = \frac{\bar{M}_n}{\bar{m}} \text{ or } \frac{\bar{M}_w}{\bar{m}}$$

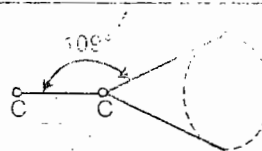
where $\bar{m}$ is the molecular weight of a mer unit

Mol. wt.	State of polymer
> 100 g/mol	Liquids or gases
1000 g/mol	Waxy Solids or soft resins.
<10,000 g/mol	Solid



11.4 MOLECULAR SHAPE

Single chain bonds are capable of rotating and bending in three dimensions. In the shown figure the third carbon atom can take any position on the cone of revolution and still maintain an included angle of 109° .



- As chain atoms are rotated, the chain gets twisted and bended. A single chain molecule composed of many chain atoms might have a large number of links, twists and bends as shown in figure where (r) represents the end to end distance.
- In a polymer this bending, linking and coiling of many chains leads to extensive inter twining and entanglement of neighbouring chain molecules. These random entanglement are responsible for number of important characteristics of polymer such as large elastic extensions, their abilities to experience rotation in response to applied stresses or thermal vibrations.
- Double and triple bonds are rotationally rigid as compared to single bonds. Also, introduction of a bulky or large side group of atoms restricts rotational movement. For e.g. Polystyrene molecules which have a phenyl side group are more resistant to rotation than polyethylene chains.



11.5

Physical
but also

(a) Li

- In v
are
- For
the
- Co

(b) Br

- He
- The
pol
pol

(c) Cr

- He
bor
- The
che
by
vul

(d) Ne

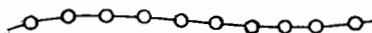
- A M
pol

11.5 MOLECULAR STRUCTURE

Physical characteristics of polymer depend not only on its molecular weight and shape but also on difference in the structure of the molecular chains.

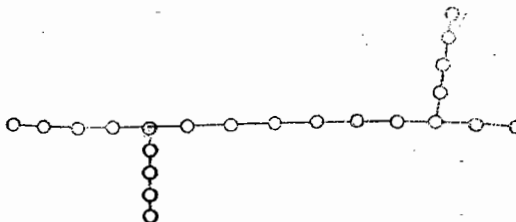
(a) Linear Polymers

- In which mer units are joined together end to end in single chains. These long chains are flexible.
- For linear polymer these are extensive vanderwals and hydrogen bonding between the chains.
- Common example are polyethylene, PVC, polystyrenes, PMMA, Nylon.



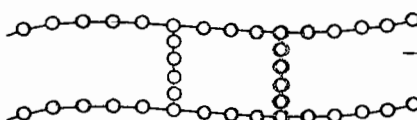
(b) Branched Polymers

- Here side branches are connected to the main branch.
- These branches occur as a result of side reaction that occur during synthesis of the polymer. The **Chain packing efficiency is reduced** which results in lowering of polymer density.



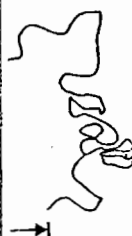
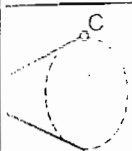
(c) Cross Linked Polymers

- Here adjacent chains are joined to one another at various positions by covalent bonds.
- The cross linking process is either achieved during synthesis or by a non reversible chemical reaction that is carried out at elevated temperature often this is accomplished by additive atoms or molecules that are covalently bonded to the chains. e.g. is vulcanization of rubber.



(d) Network Polymers

- A Mer unit having three active covalent bonds forms a 3-D network called network polymers.



bonds. Also,
movement. For
resistant to

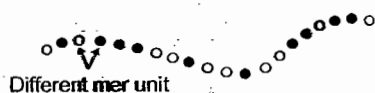
- A polymer that is highly cross linked may be called network polymers. These materials have distinctive mechanical and thermal properties.

Examples are epoxy and phenol formaldehyde.

11.6 COPOLYMERS

Synthesised for obtaining better properties compared to homopolymers. Various sequencing arrangements along the polymer chains are possible. They are.

- Random



- Alternating



- Block

Identicalmers are illustrated in blocks along the chain



- Grafted

When homopolymer side branches of one mer chain is grafted to the main chain of the second homopolymer.

11.7 POLYMER CRYSTALLINITY

- The unit cell of polythelene molecules has an orthorhombic geometry. As a result to their large size and complexity, polymer molecules are only partially crystalline, having crystalline regions dispersed within the remaining amorphous material. Any chain disorder will result in an amorphous region since twisting and bending prevent strict ordering of chains.
- Also crystallization is highly favoured i.e. polymers having simple Mer structures as compared to polymer with complex Mer units. Linear polymer are easily crystallined as compared to branched polymers, as branches interfere in crystallization with regard to stereo-isomerism. Atactic polymers are difficult to crystallize because of random configuration.
- For copolymers, as a general rule, the more irregular and random the mer arrangements, the greater is non crystallinity.

- Alternating and block polymer are somewhat similar to crystallization on the other hand graft and random copolymers are amorphous.

11.8 CHARACTERISTICS AND TYPICAL APPLICATIONS OF FEW PLASTIC MATERIALS

11.8.1 Thermoplastics

1. Acrylonitrile-butadiene-styrene (ABS)

- **Characteristics** : Outstanding strength and toughness, resistance to heat distortion; good electrical properties; flammable and soluble in some organic solvents.
- **Application** : Refrigerator lining, lawn and garden equipment, toys, highway safety devices.

2. Acrylics (poly-methyl-methacrylate)

- **Characteristics** : Outstanding light transmission and resistance to weathering; fair mechanical properties.
- **Application** : Lenses transparent aircraft enclosures, drafting equipment, outdoor signals.

3. Fluorocarbons (PTFE or TFE) i.e. Teflon

- **Characteristics** : Chemically inert in almost all environments, excellent electrical properties; low coefficient of friction; may be used to 260° C; relatively weak and poor cold-flow properties.
- **Application** : Anticorrosive seals, chemical pipes and valves, bearings, anti adhesive coatings, high temperature electronic parts.

4. Polyamides (nylons)

- **Characteristics** : Good mechanical strength, abrasion resistance, and toughness; low coefficient of friction; absorbs water and some other liquids.
- **Application** : Bearings gears cams bushings, handles, and jacketing for wires and cables.

5. Polycarbonates

- **Characteristics** : Dimensionally stable : low water absorption; transparent, very good impact resistance and ductility.
- **Application** : Safety helmets, lenses light globes, base for photographic film

6. Polyethylene

- **Characteristics** : Chemically resistant and electrically insulating; tough and relatively low coefficient of friction; low strength and poor resistance to weathering.
- **Application** : Flexible bottles, toys, tumblers, battery parts, ice trays, film wrapping materials.
- PVC used in electrical insulation, piping gramophone records.
- Polyhexamethylene adipamide (Nylon 66) used in ropes
- Polyhexamethylene sebacamide (Nylon 610)
- Polycaprolactam (Nylon 6) : Synthetic fibre

7. Polypropylene

- **Characteristics** : Resistant to heat distortion; excellent electrical properties and fatigue strength; chemically inert; relatively inexpensive; poor resistance to UV light.
- **Application** : Sterilizable bottles, packaging film, TV cabinets, luggage

8. Polystyrene

- **Characteristics** : Excellent electrical properties and optical clarity; good thermal and dimensional stability; relatively inexpensive; poor resistance to UV light
- **Application** : Wall tile, battery cases, toys, indoor lighting panels, appliance housings.

9. Polyester (PET or PETE)

- **Characteristics** : One of the toughest of plastic films; excellent fatigue and tear strength, and resistance to humidity acids, greases, oils and solvents
- **Application** : Magnetic recording tapes, clothing, automotive tire cords, beverage containers

11.8.2 Thermo Setting Polymers**1. Epoxies** (Specific gravity : 1.2, usable temp. 90-120, excellent electrical properties)

- **Characteristics** : Excellent combination of mechanical properties and corrosion resistance; dimensionally stable; good adhesion; relatively inexpensive; burns slowly.
- **Application** : Electrical moldings, sinks, adhesives, protective coatings, used with fiberglass laminates.

2. Phenol

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- Application : wit...
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- Uses : Pc...
- Advantages : ve...
- Disadvantages : go...
- Materials : sy...
- Examples : Me...
- Applications : ex...
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- Conclusion : ex...
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11.8.3 E

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- Properties : with...
- Uses : Thes...
- Advantages : mon...
- Disadvantages : elect...

2. **Phenolics** (Specific gravity 1.2, usable temp. 250-300°C, electrical properties good)

- **Characteristics** : Excellent thermal stability to over 150°C; may be compounded with a large number of resins, fillers, etc.; inexpensive, self extinguishing
- **Application** : Motor housing, telephones, auto distributors electrical fixtures
- **Polyster** : Specific gravity 1.2, usable temp. 80-120°C, mechanical properties very good, electrical properties excellent water resistant very good, heat resistant good, price low, large care shrinkage fluid before care. burns slowly used as synthetic fibres.
- **Melamine** : Specific gravity 1.4, arc resistance, mechanical properties very good, excellent electrical properties self extinguishing used in crockeries.
- **Silicone** : Specific gravity : 1.5s usable temp. 250-300 mechanical properties fair, excellent electrical properties heat resistance, costly used in high temperature resisting components.

Comprison between Thermosets and Thermoplasts

Description	Thermoplast	Thermoset
• Bonding network	Chain molecules are secondary bonded	3-dimensional, primary bonded
• Effect of heat	Bond breaks and becomes soft	Becomes hard and cannot be soften again
• Consequence of curing	No chemical change occurs	A chemical change occurs during permanent hardening
• Mouldability to any shape	Requires cooling for setting	Both: heat and pressure are required
• Effect of intense heating	They are soften	They breakdown by degradation
• Melting point	115°C-330°C	They do not melt
• Normal usable temperature	60°C-200°C	80°C-300°C

11.8.3 Expanding plastics

- Common plastics shrink when cured. Expanding monomers (EMs) experience zero shrinkage during polymerization. the polycyclic ring opening monomers are combined with conventional monomers and oligomers to produce expanding plastics.
- These plastics have enhanced resistance to corrosion and abrasion. Expanding monomers find use in coatings, adhesives, electro-optics, dentistry, medical prostheses, electronics and other industries.

- Eliminate internal stresses by expanding into microcracks in advanced composites.
- Copolymerize with epoxies, acrylics, and urethanes to generate unprecedented properties in aviation and aerospace plastics applications.
- Deliver bio-degradable polymerized vesicles in Pharmaceutics.
- Produce advanced microchip sealants, and conductive links in electronics.
- Combine with GMA for superior fillings, dentures, and crowns in dentistry.

11.8.4 Conducting polymers

- The conductivity of PAC (Polyacetylene) is enhanced by more than ten times when iodine is doped into it. The doped PAC possesses conductivity much higher, and almost equal to metallic range.

- It, however, loses conductivity rapidly when exposed to atmospheric conditions. Another limitation is the migration and loss of dopant from the surface.

Uses : Conducting polymers can generate electric signals by ion-exchange mechanism. Conducting electroactive polymers belong to the class of smart materials and are used as chemical sensors.

- Several polymers show excellent opto-electronic properties used for Integrated insulation and cross overs for microwave.
- Aviation radome, anti-radar paints, and heat shields are some novel applications of special polymers.

11.9 BEHAVIOUR OF POLYMERS UNDER DIFFERENT SITUATIONS

- Thermosets have low shelf (or pot) life which necessitates that they should be consumed within this time. Therefore, they are unsuitable for high volume (i.e. huge quantity) production. Thermoplasts are suitable for high volume production that helps in lowering their costs.
- Polymers in mixture and alloys forms are suitable for high performance applications because of improved toughness in them. Important amongst these are poly ether ketone (PEEK), poly phenylene sulfide (PPS), Poly ether sulfone (PES), Acrylonitrile butadiene styrene (ABS), Poly ethylene teraphthalate (PET), Poly phenyloxide (PPO), Poly carbonate, Poly ether imide (PEI), Polytetrafluoroethylene (PTEE), Poly phthalamide.

11.9.1 Thermal Behaviour of Polymers

- In the glassy region (up to 80°C), a polymer is hard and brittle. In this region, strain occurs by stretching of bonds **within** and between molecular chains. Behaviour of polymers in this region resembles like the deformation of a spring.
- Leathery region : The modulus drops rapidly with increasing temperature. Reversible sliding becomes possible in the chain as the small sections move causing neighboring sections to move.
- Rubbery region : Viscoelastic behaviour of polymer dominates deformation. As the temperature increases above the glass-transition temperature T_g , the molecular segments slide reversibly past one another and tend to strengthen out.
- Rubbery flow and liquid regions : Permanent sliding molecules dominates the deformation process. As temperature increases, the viscosity decreases and at high temperatures the polymer is essentially a liquid.
- **Glass Transition Temperature (T_g)** : The temperature at which the polymer experiences the transition from rubbery to rigid state is called as glass transition temperature. Normally T_g lies between 0.5 to 0.8 times of melting temperature.

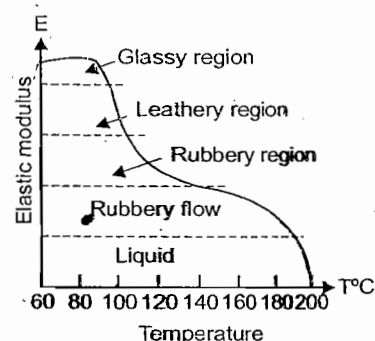


FIGURE : Different regions (states) of polymer as a function of temperature.

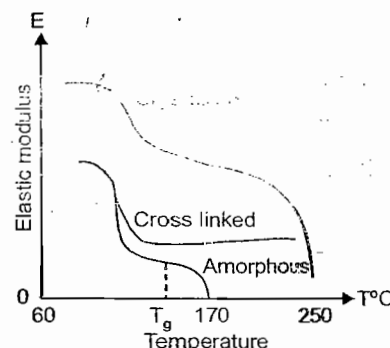


FIGURE : Elastic modulus versus temperature plot for crystalline, cross-linked, and non-crystalline polymer.

Note : Rubbery region : Not found in a crystalline polymer. The elastic modulus in such a material decreases gradually with increasing temperature until the melting point is reached. Most polymers contain both crystalline and amorphous regions. Elastic modulus versus temperature curve of crystalline, cross-linked and non-crystalline polymers is shown in figure. It is highest in crystalline polymer at all temperatures.

11.10 FIBRES

- Fiber polymers are capable of being drawn into long filaments having at least a 100 : 1 length to diameter ratio.

- They have applications in textile industries, being woven or knit into cloth or fabric, during application fibers may be subjected to stretching, twisting, shearing and abrasion. So, they must have high tensile strength and high modules of elasticity and have high abrasion resistance.
- Molecular weight and degree of crystallinity of the fiber material should be high as tensile strength increases with effect of these two parameters.
- Furthermore, they must exhibit chemical stability in variety of environments including acids, bases, bleaches etc. They should be non flammable.

11.10.1 Polymeric Fibers

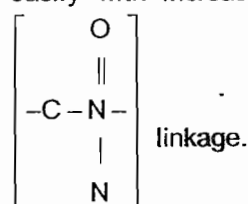
- Polymeric fibres are long chains of molecules aligned in longitudinal direction. This furnish directional properties to the fibre.
- The elastic modulus and strength are much higher in the longitudinal direction than in the other transverse directions. These fibres may be further sub-grouped as follows.
- Natural fibres such as wool, cellulose, cotton, silk etc.
- Synthetic fibres such as nylon, terylene (dacron), rayon, orlon, kevlar etc.
- Cellulose fibres are flexible and strong in tension. Cotton clothes shrink due to the presence of wrinkled molecules. Sanforized cotton clothes are non-shrinking as long chains are made to align in such clothes.

- **Polyester fibres** : Dimensional-synthetic polymeric fibres belong to the family of both, the thermosets and the thermoplastics. Polyester fibres (a thermoset)-such as

terylene, is defined by $\left[\begin{array}{c} \text{O} \\ || \\ -\text{O}-\text{C}- \end{array} \right]$ linkage. Oxygen provides flexibility to polyester.

Becomes soft more easily with increasing temperature these are durable, uniform dimension.

- **Nylon fibres** : Nylon 66 (a thermoplast) which is a polyamide-fibre does not soften easily with increasing temperatures. The polyamide fibres are characterized by



- Nylon 6 is polyamide, SP, gravity 1.14, tensile strength 820 MPa and used for tyre cords.

Different Ty

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- Packing
- Cyclised solid all
- Synthetic are mar gas, alc
- Polychlor ageing,
- Butyl tyres, ti
- Butadiene shoes,
- Nitrile (
- Polyure alkaline
- Silicone Used a

11.11 GE

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Different Types of Processed Natural Rubber

- Chlorinated rubber is used in the production of adhesives and protective coatings.
- Packing of delicate equipment is done by rubber hydrochloride.
- Cyclised rubber is used in manufacturing of papers with the use of paraffin wax (i.e. solid alkanes).
- Synthetic rubbers are superior to natural rubbers in many respects. Synthetic rubber are manufactured from raw materials like coal tar, petroleum, coke, limestone, natural gas, alcohol, ammonia, salt and sulphur etc. These are superior to natural rubber.
- Polychloroprenes (Neoprenes) are highly resistance to temperature, oil, grease and ageing, used as oil seals, gaskets, adhesives, tank lining, low voltage insulation.
- Butyl are highly resistant to oxidizing agents, and impermeable to gases. Used as tyres, tubes insulations for cables and wires.
- Butadiene are highly abrasion and weather used resistant. Used as belts, soles of shoes, flooring.
- Nitrile (Buna-N) are excellent resistant to solvent, grease and oily situations. Used as conveyor belts, tank lining.
- Polyurethane are high strength and highly abrasion resistant, poor to acid and alkaline attacks. These are used as expanded foams, tyres, conveyor belts.
- Silicone are Mechanically weak, costlier, temperature stability upto about 600 K. Used as coatings, packaging tube, gaskets, cable insulation.

11.11 GENERAL APPLICATIONS OF POLYMERS

(i) Coatings

- To protect the item from environmental damage such as corrosion.
- To improve items appearance
- To provide electrical insulation. The coating fall into many categories: Paint, enamel, shellac etc.

(ii) Adhesive

- Used to join surfaces of two solid materials to produce a joint with a high shear strength.
- The bonding forces between adhesive and solid material are electrostatic in nature.
- A strong joint is produced by adhesive layer.

- If a good joint is formed, the adhesive material may fracture before the adhesive.
- The primary drawback is the service temperature. Its adhesive strength decreases rapidly as service temperature increases. e.g. cyanoacrylate araldite.

(iii) Films

- Films have thickness between 0.025 – 0.125 mm. Used for packaging foods, beverages etc.
- Important characteristics of materials used for film production are low density, high degree of flexibility, high tensile and tearing strengths, resistance to attack by moisture and other chemicals. Examples are polyethene, cellophane, polypropylene and cellulose Acetate.

(iv) Foams

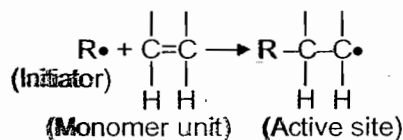
- These are plastic materials that contain high percentage of volume of small pores.
- Both thermoplast and thermoset are used as foams.
- These includes polyethane, rubber, polystyrene and PVC.
- Common use of foams are as automobile cushions and furniture as well as in packaging and thermal insulation.
- Foaming process is carried out by incorporating into the batch of material a blowing agent that upon heating decomposes with the liberation of a gas.
- These gas bubbles remain as pores upon cooling and give rise to a spongy structure.
- Some effect can also be produced by bubbling an inert gas through a material while it is in molten state.
- e.g. polymethane, formed polymethane is insulator used.

11.12 ADDITION POLYMERIZATION

- Addition polymerization also called chain reaction polymerization, there bifunctional monomer units are attached one at a time in chain like fashion to form a linear macromolecule.
- Thus the resultant product is an exact multiple of the original reactant monomer.

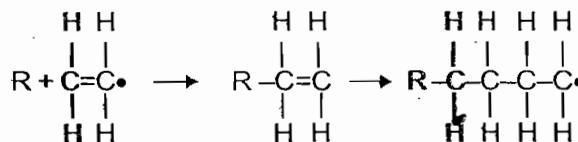
(i) Initiation

Here an active center is formed by a reaction between initiator and monomer unit.



(ii) Propagation

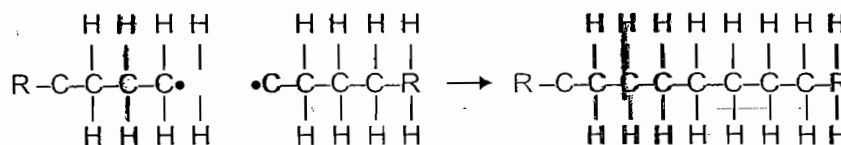
It involves linear **growth** of the molecules as monomer unit attach are at a time to produce a chain **structure**



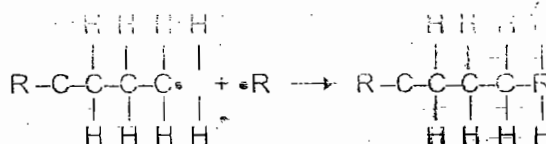
This a very rapid **process** as 1000 mer units **add up** in 10^{-2} to 10^{-3} s.

(iii) Termination

It can be **done** in **two** ways to form a non reactive **molecules**.

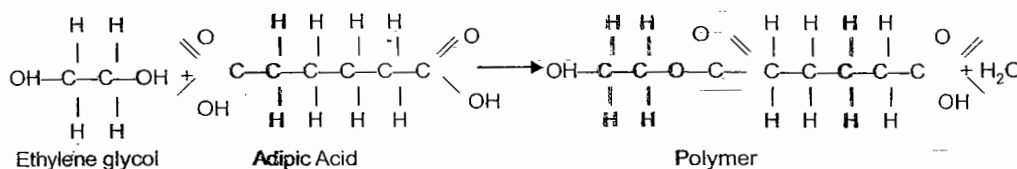


OR



(iv) Condensation Polymerization

- It is also called **step** reaction polymerization. It is a process whereby one or more than one monomer units combine stepwise and as a result of reaction by products are condensed **out**.



- These stepwise **process** is repeated to produce a **linear** molecule. Reaction times of condensation **are** generally longer than for **addition** polymerization.
- Condensation **polymerization** often produce **monomer** capable of forming crosslinked or **network** polymers. All thermosets **nylon** and **polycarbonates** are produced by **condensation** polymerization.

11.13 POLYMER ADDITIONS

(i) Filler Materials

- These are added to polymers to improve tensile and compressive strength, abrasion resistance, toughness, dimensional stability etc.
- Materials used as fillers are wood flour (saw dust), silica flour and sand, glass, clay, talc, limestone.
- Partical sizes range all the way to macroscopic dimensions.
- Because these are inexpensive materials replace some volume of the more expensive polymer, the cost of final product is reduced.

(ii) Plasticizers

- Here the flexibility, ductility and toughness of polymers are improved by addition of plasticizers.
- But hardness and stiffness are also reduced. Plasticizers are generally liquids having low vapour pressure and low molecular weight.
- Small plasticizer molecules occupy positions between the large polymer chains effecievely increasing the interchain distance and reduction in secondary intermolecular bonding forces.
- There applications include thin sheets or films, raincoat, tubing and curtains.

(iii) Stabilizers

- Some polymers even under a normal environmental conditions are rapidly deteriorated in terms of mechanical integrity of polymers.
- UV causes severance of covalent bonds along the molecular chain.
- Common stabalizers are carbon black (soot) as it is a good absorber of UV rays.
- Oxidation also has deterimental effect on polymers and antioxidant coatings are used to prevent oxidation of polymers.

(iv) Colorants

- They impart colour to a polymer.
- They are dyes or pigments. The molecules of dye dissolve and become part of the molecular structure of polymer.
- On the other hand pigments do not dissolve and remain as a seperate phase inside the polymers.

(v) Flame

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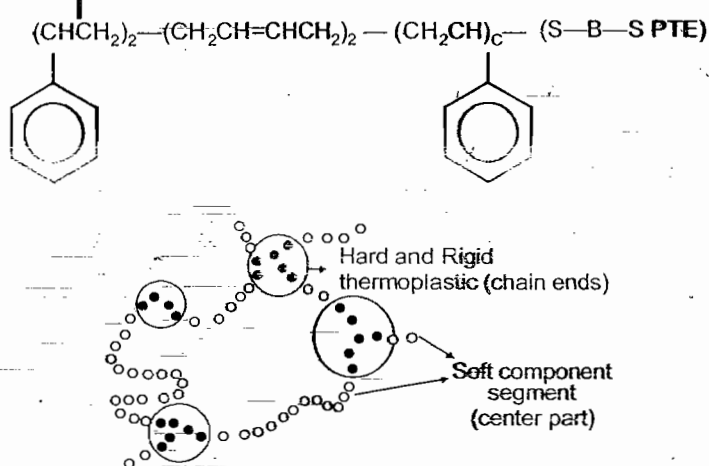
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(v) Flame Retardants

- Most polymers are flammable in their pure form.
- Exceptions are PVC and PTFE. These compounds retard flammability of polymers.
- These retardants either interfere in the combustion process through the gas phase or initiate a chemical reaction that cools the combustion region.

11.14 THERMOPLASTIC ELASTOMERS

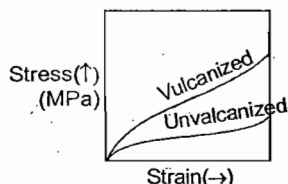
- Polymeric materials that exhibit elastomeric (rubbery) behavior at room temperature. Most of the elastomers are thermoplastic as they are crosslinked by vulcanization.
- Most common example of TPE is styrenebutadiene. Where hard and rigid thermoplastic mer occupies the molecular chain ends, while soft butadiene mers occupy center positions.



- At ambient temperature, the soft, amorphous central segments imparts the rubbery behaviours to the material. Whereas at temperature below T_m , hard component forms the rigid domain regions. These hard ends act as anchor points so as to restrict soft chain segment motions.
- The useful temperature range lies between T_g of soft components and T_m of the hard component.
- The main advantage of TPEs over thermoset elastomers is that upon heating above T_m of the hard component, they melt and therefore, may be processed by conventional thermoplastic forming technique.
- Typical application are automotive bumpers, gaskets, shoe soles and heels, sporting goods, protective coating etc.

11.15 VULCANIZATION

- Cross linking process in elastomers is called vulcanization, which is achieved by non reversible chemical reaction, carried out at elevated temperature. In this process sulphur compounds are added to the elastomer.
- Sulphur atoms bond with adjacent polymer backbone chains and cross link them.



- Main reaction sites are C—C double bond. Modulus of elasticity, tensile strength and resistance to degradation by oxidation are all enhanced by vulcanization. Vulcanized elastomeric materials are thermosetting in nature.

Polymer	Vulcanizing agent
Neoprene rubber	SiMgO, ZnO
Hypalon	PbO
Silicone and viton	Peroxide
Urethane rubber	Di-isocyanate

Note : Scooter repairing has less degree of vulcanization.

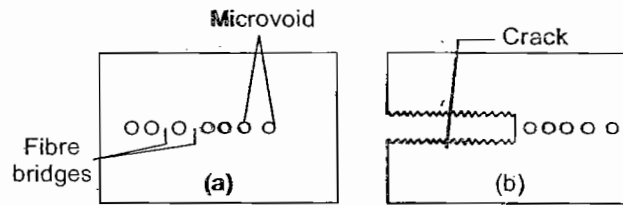
POINT TO BE REMEMBERED

- Fracture of polymers is dependent on morphology of a polymer. As a thumb rule, thermosets fracture in brittle mode. It involves formation of cracks at regions where there is a localized stress concentration. Covalent bonds are break during the fracture.
- However, both ductile and brittle modes are possible mode of fracture for thermoplasts. Many of thermoplasts can exhibit ductile-to-brittle transition assisted by reduction in temperature, increase in strain rate, presence of notch, increased specimen thickness and a modification of the polymer structure.
- Unique to polymer fracture is crazing - presence of regions of very localized yielding, which lead to formation of small and interconnected microvoids. Crazes form at highly stressed regions associated with scratches, flaws and molecular inhomogeneties; and they propagate perpendicular to the applied tensile stress and typically are 5µm or less thick. A craze is different from a crack as it can support a load across its face.

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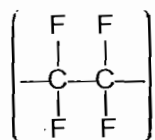
(a) Craze showing microvoids and fibre bridge
(b) Craze followed by crack

- The deformation of plastic materials can be primarily elastic, plastic, or a combination of both types.
- The following factors influence the strength of a thermoplastic; average molecular mass, degree of crystallization, presence of side groups, presence of polar and other specific atoms, presence of phenyl rings in main chains and addition of reinforcements.
- Thermosets are, however, strengthened by reinforcement methods.
- Strength of a thermoplastic is directly dependent on its average molecular mass since polymerization up to a certain molecular-mass range is necessary to produce a stable solid.
- E-glass (lime-aluminium-borosilicate glass with zero or low sodium and potassium levels) is often used for continuous fibers. S-glass (65% SiO₂, 25% Al₂O₃ and 10% MgO) has higher strength-to-weight ratio and is more expensive. Its primary applications include military and aerospace applications. Carbon fiber reinforced plastics are also often used in aerospace applications. However they are very expensive.
- The other classes of reinforcements include aramid (aromatic polyamide) fibers. They are popularly known as Kevlar. Presently two commercial variants of Kevlar are available-Kevlar29 and Kevlar49. Kevlar09 is low-density, high strength aramid fiber designed for applications such as ballistic protection, ropes and cables.
- Kevlar49 is characterized by a low density and high strength/modulus; is used in aerospace, marine, automotive and other industrial application.

□□□

QUESTIONS

1. The structure of a polymer is shown in the given figure. This polymer finds special application in



- (a) packaging (b) adhesives
(c) bearings (d) fertilizer

2. Consider the following statements:

Thermosetting plastic are

1. Formed by addition polymerization
2. Formed by condensation polymerization
3. Softened on heating and hardened on cooling for any number of times
4. modulated by heating and cooling

Which of these statements are correct?

- (a) 1 and 3 (b) 2 and 4
(c) 1 and 4 (d) 2 and 4

3. Match List-I and List-II and select the correct answer using the codes given below the lists:

List-I	List-II
A. Polyethylene	1. Adhesive
B. Polyurethane	2. Film
C. Cyanoacrylate	3. Wire
D. Nylon	4. Foam

Codes:

	A	B	C	D
(a)	2	4	3	1
(b)	4	2	3	1
(c)	2	4	1	3
(d)	4	2	1	3

4. Consider the following statements:

Fibre Reinforced plastic are:

1. Made of thermosetting resins and glass fibre
2. Made of thermoplastic resins and glass fibre.
3. Anisotropic
4. Isotropic

Which of these statements are correct?

- (a) 1 and 4 (b) 1 and 3
(c) 2 and 3 (d) 2 and 4

5. Match List-I with List-II and select the correct answer using the codes given below the lists:

List-I

- A. Neoprene
B. Bakelite
C. Foamed poly-urethane
D. Araldite

List-II

1. Electric switches
2. Adhesive
3. Thermal insulator
4. Oil seal

C

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

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Codes:

	A	B	C	D
(a)	4	1	2	3
(b)	1	4	2	3
(c)	4	1	3	2
(d)	1	4	3	2

6. Which one of the following materials is used for car tyres as a standard material?

(a) Styrene-butadiene Rubber (SBR)
 (b) Butyl rubber
 (c) Nitrile rubber
 (d) Any one of the above depending upon the need

7. Consider the following pairs of plastics and their distinct characteristics:

1. Acrylics...Very good transparency to light
2. Polycarbonate...Poor impact resistance
3. PTFE...Low coefficient of friction
4. Polypropylene...Excellent fatigue strength

Which of these statements are correct?

(a) 2 and 3 (b) 1 and 3
 (c) 1 and 4 (d) 2 and 4

8. **Assertion (A)** : Addition polymerization is a primary summation of individual molecules into long chains.

Reason (R) : In addition polymerization, the reaction produces a small molecule as by-product.

9. The molecular weight of vinyl chloride is 62.5. Thus the molecular weight of

a polyvinyl chloride with a degree of polymerization of 20000 is

(a) $\frac{20000}{62.5}$ (b) $\frac{62.5}{20000}$
 (c) 62.5×20000 (d) 20000

10. Which of the following are fabricated using engineering plastics?

1. Surface plate
 2. Gears
 3. Guide ways for machine tools
 4. Foundry patterns

Select the correct answer using the codes given below:

(a) 1, 2 and 3 (b) 1
 (c) 2, 3 and 4 (d) 1, 2, 3 and 4

11. Consider the following statements:

Poly-tetra-fluoro-ethene is

1. a thermoplastic material.
2. having high friction coefficient.
3. a thermosetting material.
4. having high friction coefficient.
5. an electric insulator.
6. non sticking to surfaces.

Which of these statements are correct?

(a) 1, 2 and 5 (b) 2, 3 and 6
 (c) 3, 4 and 5 (d) 3, 2 and 5

12. Teflon is a

(a) Thermosetting fluorocarbon polymer
 (b) Thermoplastic fluorocarbon polymer
 (c) Inorganic compound of fluorine and carbon
 (d) Laminated phenolic material

13. In the case of rubber, vulcanization refers to the process of producing a

- (a) Linear polymer
(b) Branched polymer
(c) Cross-linked polymer
(d) Network polymer

14. Polyesters can be defined as the condensation products of

- (a) Dicarboxylic acids with dihydroxy alcohols
(b) Biphenol-A and epichlorohydrin
(c) Phenol and formaldehyde
(d) Benzene and toluene

15. Match List-I (Material) with List-II (Typical use) and select the correct answer using the codes given below the lists:

List-I	List-II
A. Branched polyethylene	1. Bottles
B. Polyester	2. Textile fibres
C. Polyvinyl chloride	3. Films for packaging
D. Linear polyethylene	4. Transparent film.

Codes:

	A	B	C	D
(a)	3	2	1	4
(b)	2	3	4	1
(c)	2	3	1	4
(d)	3	2	4	1

16. Phenol formaldehyde is a/an

- (a) thermoplastic polymer
(b) thermoset polymer
(c) elastomer
(d) rubber

17. Consider the following statements:

Assertion (A) : In Addition Polymerization method, polymer is produced by adding a second monomer to the first, then a third monomer to this dimer and so on.

Reason (R) : There must exist at least one double bond in the monomer for Addition Polymerization reaction.

Of these statements

- (a) Both A and R are true and R is the correct explanation of A
(b) Both A and R are true but R is not a correct explanation of A
(c) A is true but R is false
(d) A is false but R is true

18. Match List-I (Material) with List-II (Application) and select the correct answer using the code given below the lists:

List-I

- A. Fibre reinforced plastics
B. Acrylics
C. Phenolics
D. Butadiene rubber

List-II

1. Automobile tyres
2. Aircraft
3. Lenses
4. Electric switch cover

Codes:

	A	B	C	D
(a)	1	4	3	2
(b)	2	3	4	1
(c)	1	3	4	2
(d)	2	4	3	1

19. Stru

- (a)
(b)
(c)
(d)

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- (a)
(b)
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(d)

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19. Structure of a polymer is:

- (a) Long chain
- (b) Rhombic
- (c) Cubic
- (d) Closed pack hexagonal

20. What is the process by which two or more chemically different monomers are polymerized to form a cross link polymer together with a by-product such as water or ammonia, known as?

- (a) Addition polymerization
- (b) Co-polymerization
- (c) Linear polymerization
- (d) Condensation polymerization

21. Consider the following properties for plastics:

- 1. Become hard on heating.
- 2. Increasing plasticity.

3. Ability to deform with rise in temperature.

4. Long chain structure.

Which of these properties for plastics are correct?

- (a) 1, 2, 3 and 4 (b) 3 and 4 only
- (c) 1 and 4 only (d) 2, 3 and 4 only

22. Plastic material is used for the component which requires characteristics os

- (a) Low density, mechanability and high strength
- (b) Mechanability, high strength and large plastic defamtion
- (c) High strength, large plastic deformation and low density
- (d) Low density, mechanability and large plastic deformation

ANSWERS

1. (c)	6. (a)	11. (a)	16. (b)	21. (d)
2. (b)	7. (b, c)	12. (b)	17. (a)	22. (d)
3. (c)	8. (c)	13. (c)	18. (b)	
4. (b)	9. (c)	14. (a)	19. (a)	
5. (c)	10. (c)	15. (a)	20. (d)	

12.1 INTRODUCTION

Introduction

Structure of Ceramics

Mechanical Properties

Brittle Fracture of Ceramics

Hardness

Creep

Electrical behaviour of Ceramics

Dielectric Materials

Lead Zirconate Titanate (PZT) : A

Piezoelectric Ceramic

Lead Lanthanum Zirconate Titanate

(PLZT)

Barium Titanate : A Ferroelectric

Ceramic

Fabrication and Processing of Ceramics

General Example of Ceramics

Schematic Diagram of Pressing and

Blowing Processes

Glasses and Glass Ceramics

Glass Fabrication and Properties

Glass Forming

Clay Products

Fabrication and Processing of Clay Products

Reinforced Cement Concrete (RCC)

Ingredients of RCC

Grades and Strength of RCC

Refractories

Classification

Recent Advances in Ceramics

Ceramics can not be defined under metal, non metal, or organic polymer. Ceramics are non-metallic, inorganic, amorphous solid and are mostly metal oxide. Atomic bonding in them from purely ionic to totally co-valent. These are formed under earth in pressure extensive heat. These ceramics are extremely brittle, having high thermal stability, high chemical stability i.e. corrosion resistance, having high hardness.

e.g., Silica (SiO_2) & Al_2O_3

(a) **Traditional Ceramics** : Such as whiteware, tiles, brick, Sewer pipe, Pottery and abrasive wheel.

(b) **Industrial Ceramics** : It also called engineering, high-tech or fine ceramics such as turbine, automotive and aerospace components. e.g. Al_2O_3 , Si_2 , Si_3N_4 etc.

12.2 STRUCTURE OF CERAMICS

The structure of ceramics is among the most complex of all materials. It contains various atoms of different size. The bonding between these atoms is generally covalent or ionic. These bonds are much stronger than metallic bonds. Ceramics are available as single crystal or in polycrystalline form. These have finer grain which leads to more strength and toughness.

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3. Lithi
4. Lithi

12.3 MECHANICAL PROPERTIES

Ceramic materials are somewhat limited in applicability by their mechanical properties, which in many respects are inferior to those of metals.

12.3.1 Brittle Fracture of Ceramics

- The brittle fracture process consists of the formation and propagation of cracks through the cross section of material in a direction perpendicular to the applied load.
- Crack growth in crystalline ceramics may be either transgranular (i.e. through the grains) or intergranular (i.e., along grain boundaries); for transgranular fracture, cracks propagate along specific crystallographic (or cleavage) planes, planes of high atomic density. Griffith theory brittle fracture holds good for ceramics.

12.3.2 Hardness

One beneficial mechanical property of ceramics is their hardness, which is often utilized when an abrasive or grinding action is required; in fact, the hardest known materials are ceramics. Their hardness normally lies in between 500BHN to 2000BHN.

12.3.3 Creep

- Often ceramic materials experience creep deformation as a result of exposure to stresses (usually compressive) at elevated temperatures.
- In general, the time deformation creep behavior of ceramics is similar to that of metals; however, creep occurs at higher temperatures in ceramics.
- High-temperature compressive creep tests are conducted on ceramic materials to ascertain creep deformation as a function of temperature and stress level.
- Sialon (Si_3N_4 & Al_2O_3) used for gas turbine at 1300°C due to this property.

12.4 ELECTRICAL BEHAVIOUR OF CERAMICS

These are used for insulation purpose in electric power & transmission, electrical m/c etc. Mica, Porcelain, Micanite, Glass bonded mica, glass tape etc. are example.

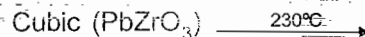
12.4.1 Piezoelectric Materials

1. Quartz, SiO_2 have piezoelectric coefficient.
2. Ammonium dihydrogen phosphate (ADP) ($\text{NH}_4\text{H}_2\text{PO}_4$)
3. Lithium tantalate, LiTaO_3
4. Lithium niobate, LiNbO_3

5. Potassium dihydrogen phosphate (KDP), KH_2PO_4
6. Polyvinylidene fluoride (PVDF), $(\text{CH}_2\text{-CF}_2)_n$
7. Lead zirconate titanate (PZR), $\text{PbTi}_{0.48}\text{Zr}_{0.52}\text{O}_3$
8. Rochelle salt, $\text{NaKC}_4\text{H}_4\text{O}_6 \cdot 4\text{H}_2\text{O}$

12.4.2 Lead Zirconate Titanate (PZT) : A Piezoelectric Ceramic

- It is a solid solution of lead zirconate (PbZrO_3) and lead titanate (PbTiO_3). Both can be mixed in different proportions to yield the properties of aspirated choices.
- It has wide range of dielectric constants.
- Have high curie temperature that allows high temperature operations.
- It has electromechanical coupling coefficients better than the BaTiO_3 .
- They can be produced easily by sintering.
- PbZrO_3 is an antiferroelectric material. At room temperature, its structure is cubic which converts into orthorhombic above curie temperature 230°C .



- PbTiO_3 is a ferroelectric material. Below curie temperature its structure is cubic but it converts to tetragonal structure above 490°C .



- PZT is prepared by mixing the zirconate and titanate in a ball mill and then calcinising above 1000°C .

Applications : Mains applications of PZT in modern uses are the following.

- Ultrasound • Sonar • Buzzers • Spark generators
- Sensors • Transducers • Actuators • Filters

12.4.3 Lead Lanthanum Zirconate Titanate (PLZT)

It is a composition of lanthanum (La) with PZT. Lanthanum is added to modify the properties of PZT. It results in

1. Decreased curie temperature
2. Increased dielectric constant
3. Increased squareness of hysteresis loop
4. Higher electromechanical coupling coefficients

5. Decreased coercive field
 6. Better optical transparency
- The proportion of La in PZT plays a vital role in deciding the property of PLZT.
 - It is added in different proportions. If the piezoelectric properties of PLZT is to be enhanced, La should be added less than 5%.
 - But for PLZT in electro-optical applications, a proportion of more than 5% is required.
 - PLZT is generally designated by La/PbZrO₃/PbTiO₃ combination e.g. 7/55/45, 2/65/35, 12/40/60 etc. Various properties of some PLZT compositions are give below in Table 20.5 for a ready reference.

Various Properties of Some PLZT

Composition	Dielectric constant	Loss tangent tan δ (%)	Curie temperature T_c (°C)	Coercivity H_c (kV/cm)	Specific gravity
2/65/35	650	2.5	320	13.7	7.98
6/65/35	1210	1.6	240	8.7	7.86
10/65/35	5100	5.4	-25		
14/65/35	1450	2.3	—	0.5	7.45

12.4.4 Barium Titanate - A Ferroelectric Ceramic

Barium titanate (BaTiO₃) is most important ceramic. It is a mixed oxide having perovskite structure as shown in figure. It is an artificial ferroelectric material. Its $\epsilon_r > 2000$. The curie temperature of BaTiO₃ is 130°C.

Structure : Its structure is 'cubical' above 130°C and 'tetragonal' below it. When BaTiO₃ crystal is cooled below 130°C, the Ti⁴⁺ ion shifts on one side of the body centre and O²⁻ ions in opposite side as shown in figure. Hence, the centres of positive and negative charges do not coincide, and local dipoles are created in entire crystal. Since the dipoles of neighbouring unit cells are all aligned, they induce a large polarization is solid.

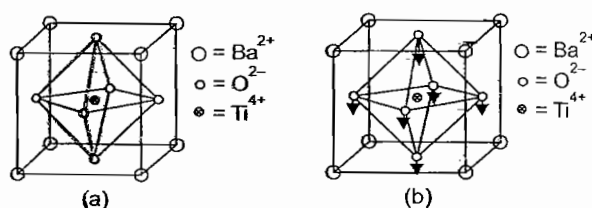
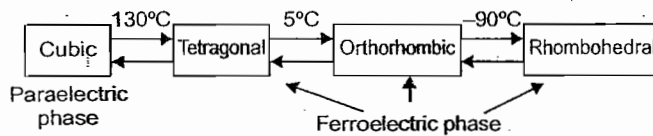


FIGURE : Structure of BaTiO₃ is (a) Cubic above 130°C, and (b) Tetragonal below 130°C.

Effect of temperature on structure of BaTiO_3 

Dielectric constant as a function of temperature. The dielectric constant of BaTiO_3 is affected considerably by temperature as shown in fig. It shows a rise with increasing temperature. There are abrupt and sharp rises at critical temperature viz. -90°C , 5°C and 130°C .

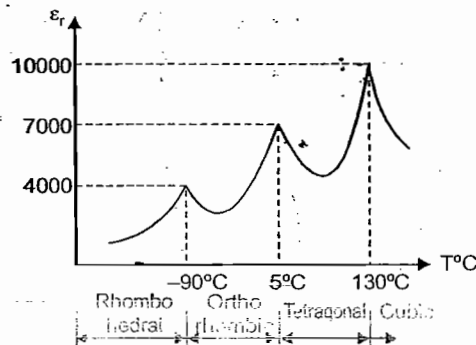


FIGURE : Variation in dielectric constant ϵ_r as a function of temperature T .

Modified Barium Titanate

It is modified by adding curie point shifter. Besides changing the curie point to different operating temperature range, it also smoothens the profile of abrupt change in dielectric constant. The shifting in curie point is accomplished by using some substitutions. Main among them are given below.

$\text{BaTiO}_3 + \text{PbTiO}_3$: This substitution results in formation of $(\text{Ba}_{1-x}\text{Pb}_x)\text{TiO}_3$ when $0 < x < 1$. On mixing them, the curie temperature rises at a rate of 3.7°C i.e. $dT_c/dx = 3.7^\circ\text{C}$. The value of T_c for BaTiO_3 is 130°C and that for PbTiO_3 is 490°C .

$\text{BaTiO}_3 + \text{SrTiO}_3$: At room temperature, it is not a ferroelectric. Its structure is cubic perovskite. On mixing them, the curie temperature lowers down by 3.7°C i.e. $dT_c/dx = -3.7^\circ\text{C}$.

$\text{BaTiO}_3 + \text{CaTiO}_3$: This mixture has no effect on curie temperature, but it lowers the tetragonal orthorhombic transition temperature.

12.5 FABRICATION AND PROCESSING OF CERAMICS

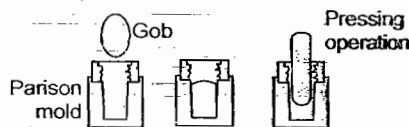
- Ceramic melt at high temperatures and they exhibit a brittle behavior under tension.
- As a result, the conventional melting, casting and thermo-mechanical processing routes are not suitable to process the polycrystalline ceramics.

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- Inorganic glasses, though, make use of lower melting temperatures due to formation of eutectics.
- Hence, most ceramic products are made from ceramic powders through powder processing starting with ceramic powders.
- The powder processing of ceramics is very close to that of metals, powder metallurgy. However there is an important consideration in ceramic-forming that is more prominent than in metal forming: it is dimensional tolerance.
- Post forming shrinkage is much higher in ceramics processing because of the large differential between the final density and the as-formed density.
- Glasses, however, are produced by heating the raw materials to an elevated temperature above which melting occurs.
- Most commercial glasses are of the silica-soda-lime variety, where silica is supplied in form of common quartz sand, soda (Na_2O) in form of soda ash (Na_2CO_3) while the lime (CaO) is supplied in form of limestone (CaCO_3).
- Different forming - are widely in practice to fabricate glass products. Thick glass objects such as plates and dishes are produced by pressing, while the blowing is used to produce objects like jars, bottles and light bulbs.
- Drawing is used to form long objects like tubes, rods, fibers, etc. The pressing and blowing process is shown in below figure.
- Pressing :



- Blowing :

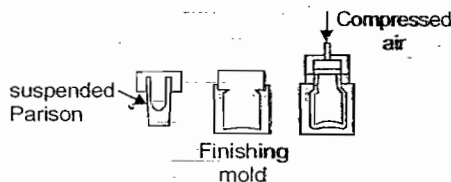
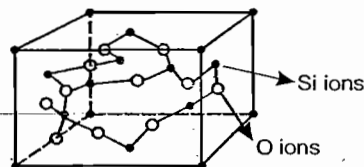


FIGURE : General example of ceramics schematic diagram of pressing and blowing processes.

- SiO_2 : It is the most simple silicate material. It is a 3D network that is generated when each corner oxygen atom of tetrahedra is shared by adjacent tetrahedra. Thus the material is electrically neutral.
- Ratio of Si to O atoms is 1:2. If this array is extended in all directions a crystalline structure is obtained.

- There are three polymorphic forms of silica; "quartz, cristobalite and tridymite."
- These structures are open structures i.e they are not closed packed together.
- As a consequences these crystalline silicon have low densities.



- **Silica Glasses :** Silica can also be made to exist as non crystalline solid or glass having high degrees of randomness. Such structure is called "fused Silica or vitreous Silica". Common glasses used for windows etc are silica glasses.

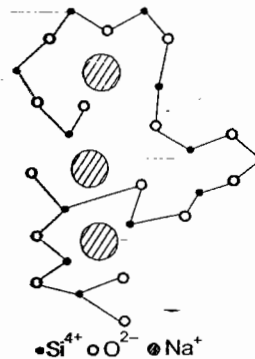
- **Networking Modifiers :** Certain oxides such as Na_2O and CaO are added to silica glass. These oxides donot form polyhedral networks rather their cations are incorporated within and modify the SiO_4^{4-} network. For this reason, these oxide additives are called network modifiers.

Intermediate oxides : Such as TiO_2 and Al_2O_3 which are not network modifiers, substitute for silicon and become part of and stabilize the network. The addition of these modifiers and intermediates lowers the melting-point and viscosity of glass and makes it easier to form at lower temperature.

- **The Silicates (Simple silicates) :** Structurally simple and involves isolated tetrahedra eg. $(\text{Mg}_2\text{SiO}_4)$ for sterite where two Mg^{2+} ion associated with each tetrahedra such that Mg^{2+} ion has six oxygen nearest neighbours.

- **Layered silicates :** These are two dimension sheet or layered structures and can be produced by sharing of three oxygen ions in each of the tetrahedra.

- For these structures the repeating unit is $(\text{Si}_2\text{O}_5)^-$ the net negative charge is associated with unbounded oxygen atoms projecting out of the plane of the page. Electro neutrality is established by a second plane sheet containing excess of cations, which bond with excess unbonded oxygen atoms from the Si_2O_5 sheet.



- Such materials are called the sheet or layered silicates, and their basic structure is characteristics of clays.
- **Silicon Carbide :** Melting point 2400°C used in high temperature transistors. Its energy gap is large, about 3ev.

- One of the properties of diamond is that it is transparent to visible light which is why it is used in high refractive index applications.

Diamond

- Here each carbon atom is tetrahedrally bonded to four other carbon atoms, giving diamond its characteristic high refractive index and transparency.
- It has a very high melting point and is transparent to visible light.
- Industrially, diamond is used as a cutting material in phase change devices.
- These properties make diamond a very valuable material for surface coatings to increase precision.

Graphite

- It is made of layers of carbon atoms, each layer consisting of a hexagonal network of carbon atoms.
- The layers are held together by weak van der Waals forces, giving graphite its characteristic layered structure and properties.
- Graphite has a high thermal conductivity and is used in high-temperature applications.
- Graphite is used in casting, hoppers, brushes, and purification processes.

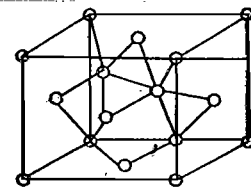
12.6 GLASS

- Glasses are non-crystalline solids and are made from various materials, including silica and Al_2O_3 .

- One of the most common clay minerals kaolinite, has a formula $\text{Al}_2(\text{Si}_2\text{O}_5)(\text{OH})_4$ in which the silica tetrahedral layer represented by $(\text{Si}_2\text{O}_5)^{2-}$ is made electrically neutral by an adjacent $\text{Al}_2(\text{OH})_4^{2+}$ layer.

Diamond

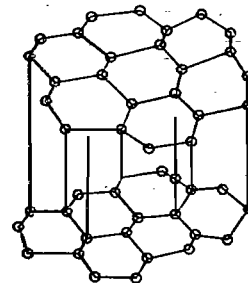
- Here each carbon atom bonds to four other carbon atoms by covalent bonds. Diamond is extremely hard and has a very low electrical conductivity, these characteristics are due to its crystal structure and strong interatomic covalent bonds.
- It has high thermal conductivity and is optically transparent in visible and infrared regions and has high refractive index.
- Industrially, diamonds are used to cut and grind soft materials. Diamond films are produced by vapour phase chemical reactions followed by film deposition.
- These films do not have long range crystalline regularity of natural diamond.
- Surface of drills, dies bearing. Knives and other tools are coated with diamond films to increase surface hardness. It is also applied on loudspeaker tweeter and high precision work.



Diamond

Graphite

- It is more stable than diamond at room temperature and pressure. Its structure consists of layer of hexagonally arranged carbon atoms, within the layers, each carbon atom is bonded to three coplanar neighbour atoms by strong covalent bonds.
- The further bonding electron participates in a weak vanderwaal type of bond between the layers. Thus center plane is fragile, which gives rise to excellent lubricative properties of graphite. Electrical conductivity is also high along hexagonal sheets.
- Graphite has high strength and chemical stability at elevated temperature, high thermal conductivity, low coefficient of thermal expansion and high resistance to thermal shock and good machinability.
- Graphite is commonly used as electrodes in welding, casting molds, refractories and insulations, rocket nozzles, chemical reactor vessels, electrical contacts, brushes and resistors, battery electrodes and in purification devices.

Layered Structure
Graphite

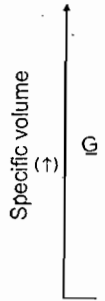
12.6 GLASSES AND GLASS CERAMICS

- Glasses are non crystalline silicates containing other oxides e.g. CaO , Na_2O , K_2O and Al_2O_3 . A typical soda lime glass consists of approx 70% SiO_2 + $[\text{Na}_2\text{O} + \text{CaO}](\text{Rest})$.

- Glass is an amorphous solid with the structure of liquid or we can say it is a supercooled liquid that is cooled at a rate too high to allow crystal to form.
- It doesnot have distinct melting and freezing point. All glass contain atleast 50% silicate defined as glass former and their strength can be modified by adding the oxide of aluminium, Ca, Ba, B, Mg and these oxide defined as intermediate or modifiers. e.g. — soda lime glass, borosilicate glass etc.
- Normally more than 500 type of glasses which are available today.
- Type of glass depends on input means if we modify the input we can make different type of glass.
- Final properties of glass would be depend upon the constituent and processing techniques.
- Most inorganic glasses can be transformed to crystalline state by a proper high temperature heat treatment called "Devitrification".
- The product is a fine grained polycrystalline material called glass ceramic devitrification process.
- Glass ceramics have low coefficient of thermal expansion, high thermal shock resistance and relatively high mechanical strengths and thermal conductivities. Also, conventional glass forming technique may be used in the maximum production of glass ceramics.

12.7.1 Glass Fabrication and Properties

- **Glass fibres :** Continuous glass fibre produced by drawing molten glass through multiple orifices. Fibre of small diameter ($2\mu\text{m}$) can be produced.
- **Short glass fibre or glass wool process :** In this molten glass ejected from a rotating head by centrifugal spraying process. Rotating head contains more than 2000 holes. In this process fiber diameter can be achieved from $20.30\mu\text{m}$ air is supplied from the top to direct the fiber down ward and reduce the temperature. As the fiber descend, the binder is mixed to achieve required wool criteria the amount of binder decide mechanical properties.
- For glassy materials specific volume decreases continuously with temperature reduction. At glass transition temperature, there is a slight decrease in the slope of cooling curve. Below this temperature the material is considered to be glass and above it first a supercooled liquid, and finally a liquid
- **Melting point:** At viscosity of 10^3 Pa-S glass is fluid enough to be considered a liquid.
- **Working point :** corresponding to viscosity of 10^3 Pa-S, the glass is easily deformed at this viscosity.



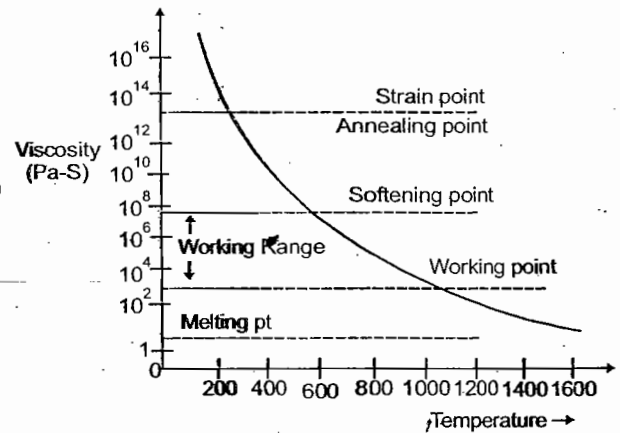
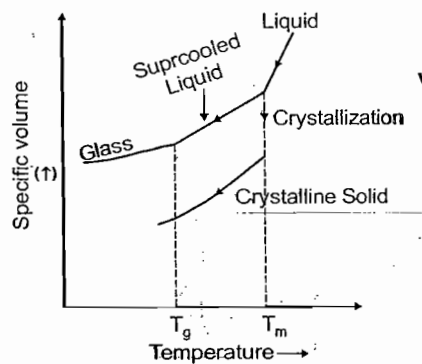
- Softening point of glass is the temperature at which the glass becomes soft and can be deformed.
- Annealing point is the temperature at which the glass becomes sufficiently soft to be deformed.
- Strain point is the temperature at which the glass becomes so soft that it can be deformed by the weight of its own part.

12.7.2 Glass Manufacturing

Various glass manufacturing processes

Glass Manufacturing Processes

- (i) Pressing process :** In this process, the molten glass is pressed into the desired shape by the use of a die. This method is used for the production of glass bottles, jars, etc.
- (ii) Blowing process :** In this process, the molten glass is blown into a desired shape by the use of air. This method is used for the production of glass bottles, jars, etc.
- (iii) Drawing process :** In this process, the molten glass is drawn into a desired shape by the use of a die. This method is used for the production of glass bottles, jars, etc.



- **Softening point** : At viscosity of 4×10^6 Pa-S, this is max. temperature at which glass may be handled without causing significant dimensional alterations.
- **Annealing point** : At viscosity 10^{12} Pa-S. At this temperature the atomic diffusion is sufficiently rapid that any residual stress may be removed within about 15 minutes.
- **Strain point** : At viscosity level (4×10^{13}) Pa-S. For temperature below strain point, fracture will occur before the onset of plastic deformation. The glass transition temperature will be above strain point temperature.

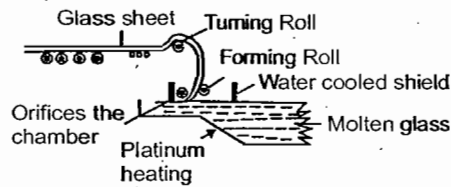
12.7.2 Glass Forming

Various glass forming methods are as follow :

Glass Manufacturing Stages

- Pressing** : Here a glass piece is formed by pressure application in a graphite coated cast mold having shape. The mold is ordinarily heated to ensure an even surface. This method is used for producing thick walled pieces such as plates and dishes.
- Blowing** : Done for art objects, the process is completely automated for production of glass bottles and light bulbs.
First a temporary shape is given to the gob of glass by pressing it in a mold and then it is inserted in a blow mold and forced to conform to mold contour by blowing a blast of air.
- Drawing** : It is used to form long glass pieces such as sheet, rod, tube and fibres which have constant cross section flatness and surface finish can be greatly improved by floating the sheet in a bath of molten tin at elevated temperature.
The piece is then slowly cooled and heat treated by annealing.

- (iv) **Fibre forming** : Here the molten glass contained in a platinum heating chamber fibres are formed by drawing molten glass through small orifices at the base of the chamber. Glass viscosity is controlled by chamber and orifice temperatures. By this glass wool would be made.



Float process in which flat glass sheet will be made. Glass can be processed in the form of fibers, tubing, tempered glass and laminated glass.

For tubing we require glass as flat sheet

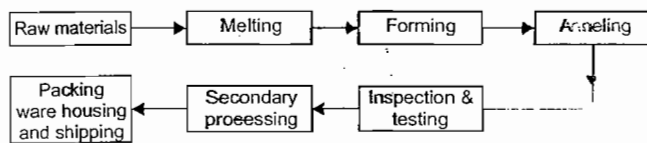


FIGURE : Glass manufacturing stages.

Glass-Forming Constituents

(a) Glass formers, (b) Intermediates and (c) Modifiers

- Glass formers and network formers include oxide such as SiO_2 , B_2O_3 , V_2O_6 and GeO_2 . They form the basis of random three-dimensional network of glass.
- Intermediates include Al_2O_3 , ZrO_2 , PbO , BeO , TiO_3 and ZnO . These oxides are added in high proportions for linking-up with the basic glass network to retain structural continuity.
- Modifiers include MgO , LiO_2 , BaO , CaO , SrO , Na_2O and K_2O . These oxides are added to modify the properties of glasses.

12.7.3 Types of Glasses

Devitrified Glass

- It is made by mixing of glass with fluxes which lower-down the fusion temperature of glass, and render the molten glass workable at reasonable temperatures.
- But fluxes may reduce the resistance of glass against chemical attack.
- Devitrified glass is undesirable since the crystalline areas are extremely weak and brittle. Stabilizers are therefore added to this type of glass to overcome these problem.

Heat Treat

- Anneal are introduced between in extreme by heat
- Glass the surface transition temperature due to
- As the slowly, complete
- There a surface

Soda Lime

- Mainly a small amount of soda lime
- They are where

Lead Glass

- Contain
- They are
- Glasses high electrical

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P_2O_5 , V_2O_5
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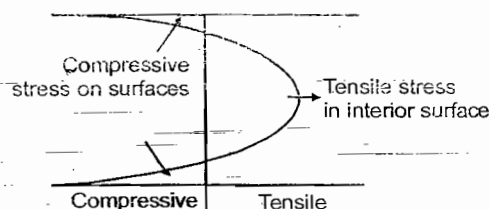
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Heat Treating Glasses

- **Annealing** : When glass is cooled from an elevated temperature thermal stresses are introduced as a result of difference in cooling rates and thermal contraction between the surface and interior regions. These stresses weaken the material and in extreme cases leads to fracture which is called 'thermal shock'. Annealing is done by heating glass to annealing point and then slowly cooling to room temperature.
- **Glass Tempering** : In this process compressive residual stresses are induced at the surface of the glass. Here, the glass is heated to a temperature above the glass transition temperature but below the softening temperature. It is then cooled to room temperature by a jet of air or in an oil bath. The residual stresses then are induced due to difference in cooling rates for surface and interior regions.
- As the cooling advanced, the surfaces cools more rapidly and becomes rigid, but slowly, it tries to contract but the rigid outer surface prevents it when the cooling is complete.
- There are net tensile stresses in the interior and net compressive stresses on the surfaces.
- Applications of tempered glass are making of large doors, automobile windshields, eyeglass lenses.



Soda Lime Glasses

- Mainly contain oxides of sodium and calcium, and silica. Its formula is $\text{Na}_2\text{O} \cdot \text{CaO} \cdot 6\text{SiO}_2$. Small amount of alumina and magnesium oxides are added to it to improve the chemical resistance and durability of the glass.
- Soda lime glasses are cheap, resistance to water and devitrification.
- They are widely used as window glass, in electric bulbs, bottles and tableware where high temperature resistance and chemical stability are not essentially required.

Lead Glasses

- Contain 15 to 40% lead oxide. They are also known as flint glasses.
- They are used to make high quality tableware, optical devices, neon sign tubing etc.
- Glasses having a high lead content, upto 80%, have relatively low melting points, high electrical resistivity and high refractive index.

- They are used for extra dense optical glasses, windows and protective shields to protect against X-ray radiations.

Borosilicate Glasses

- Contain mainly silica and boron oxide. Small amounts of alumina and alkaline oxide are also added to it.
- It has low coefficient of thermal expansion and high chemical resistance. They are used in scientific piping, gauge glasses, laboratory ware, electrical insulators and domestic items. This glass is known as Pyrex glass by trade name.

High Silica Glasses

- Containing upto 96% silica are made by removing alkalies from a borosilicate glass. They are much more expensive than other types of glasses.
- They have very low thermal expansion and high resistance to thermal shock. High-silica glasses are mainly used where high temperature resistance is required.

Photochromatic and Zena Glasses

- Photochromatic and zena glasses are also in common application. Photochromatic glasses are used in making lens for goggles. Silver chloride is mixed in ordinary glass to make them. Zena glass is used to make chemical containers.
- The world's telescope situated on Mount Semivodnke in USSR, which utilizes 6 metre diameter mirror of 1 metre thickness and 70 tonnes weight is example of glass.

Wired Glass

Made by meshing steel wire into molten glass by rolling process. It is used for low cost fire resistant glass which automatically break at high temperature

Patterned Glass

It is made by Passing the glass through rollers of 1050°C. Mode in single pass. Gap between rollers are adjusted to get the desired thickness of flat glass. Molten metal and then moves through the temperature controlled kiln (also known as lehr) and solidifies.

12.7 CLAY PRODUCTS

- It is an inexpensive raw material and can be formed with ease.
- When mixed in proper proportions with water it forms a plastic mass that is very easy to shape.
- The formed piece is dried to remove some of the moisture, after which it is fired at an elevated temperature to improve its mechanical strength.

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- Clay products can be classified into :
 - (i) **Structural clay products** : Bricks, tiles and sewer pipes i.e applications in which structural integrity is important.
 - (ii) **White wares** : white ceramics become white after the high temperature firing
- Example** : Porcelain, pottery, tableware, chinaware, sanitary wares.

12.7.1 Fabrication and Processing of Clay Products

- When water is added to clay, they become very plastic, and a condition termed as **hydroplasticity**.
- This property is very important for forming of clay when water is added.
- The water molecules fit between layers sheet of clay crystals and form a thin film around clay particals.
- The particals are thus free to move over one another, which accounts for resulting plasticity of the water clay mixture.
- Clay melts over a range of temperature, thus a dense and strong piece of ceramic may be produced during firing without complete melting such that desired shape is maintained.
- Generally, clays are Aluminium Silicates ($\text{Al}_2\text{O}_3 - \text{SiO}_2$).
- In addition to clay, the clay products also contain flint, finely ground quartz and a flux called feldspar. Quartz is used as a filler material (inexpensive, hard and chemically unreactive). It experiences a little change during high temperature heat treatment.
- Feldspar when mixed with clay forms a glass that has a relatively low melting point. They are group of aluminum silicate materials that contain K^+ , Na^+ and Ca^{2+} ions. A Typical poreceline might contain 50% clays, 25% quartz and 25% feldspar.

12.8 REINFORCED CEMENT CONCRETE (RCC)

- Concrete has high compressive strength but poor tensile strength. It is prone to crack when open for tension to provide sufficient tensile strength, reinforcements in the form of steel bars are provided. The combination of concrete and steel reinforcement results in a material known as Reinforced Cement Concrete (RCC).
- It contains favourable properties of both the concrete and the steel. Steel is used as reinforcing material due to its high tensile strength and elasticity, and its thermal coefficient is nearly same as that of concrete.

12.8.1 Ingredients of RCC

1. Cement
2. Fine aggregate (or coarse sand)
3. Coarse aggregate
4. Water
5. Reinforcement

Cement used should be as per the specifications of BIS (Bureau of Indian Standard). Generally sand is used as fine aggregate. Sand should be coarse with fineness modulus 2.90 to 3.20. Coarse aggregate may be stone grit, gravel or some other inert material. It should be hard, durable and free from other injurious materials such as saltpeter, salts etc. Generally crushed stone grit, granite chips, stone ballast is used for this purpose. For RCC work, the size of coarse aggregate varies from 2cm to 3cm. Potable water which is free from impurities like sulphates, chlorides etc. is better use for RCC.

12.8.2 Grades and Strength of RCC

Concrete mix in RCC works is classified into the following categories.

M10		1 : 3 : 6 mix
M15		1 : 2 : 4 mix
M20		1 : 1.5 : 3 mix
M25		1 : 1 : 2 mix
M30		1 : 4 : 8 mix, 1 : 5 : 10 mix, 1 : 6 : 12 mix
M35		Post-tensioned prestressed concrete
M40		Pre-tensioned prestressed concrete

The mix-1 : 3 : 6 indicates proportions of cement, aggregate and sand respectively.

M10 and M20 grade of concrete is used in mass concrete work. M15 is generally used for all purpose of general nature such as RCC slabs, and flooring. M20 and M25 is used for thin RCC members such as precast members, shed roofs, thin shell etc. M35 and M40 are used in prestressed concrete structures i.e. for post-tensioned and pre-tensioned concrete members respectively. Strength of concrete depends on the water cement ratio.

1. Mild steel bars (Plain bars)
2. High yield strength deformed (HYSD) bars
3. Twisted bars
4. Steel wires (or Tendons)

- **Mild steel bars (Plain bars)** : The main drawback of these bars is their poor bond stress.
- **Deformed bars (HYSD bars)** : These bars are more suitable in comparison to plain bars.
- **Twisted bars** : Cold worked twisted bars are used to improve the bond between concrete and reinforcing materials. These bars increase the yield stress by about 50% and thus save reinforcing material by 33%. These bars have greater bond

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strength and hence are very useful for water retaining structures such as retaining walls, dams etc. The size of bars varies from 5 mm to 50 mm.

- **Steel wires** : Steel wires with high elasticity are used in prestressed concrete members. They have a diameter of about 6mm and are known as tendons. They are also used in the form of wire mats.
- RCC has many advantages. It can be moulded into any desired shape due to its plastic properties. It is fire resistant, damp proof, rigid, durable and impermeable to moisture. Its structures can bear the shocks of earthquake effectively. Maintenance of RCC work is less while its appearance is good.

12.9 REFRACTORIES

- These material have capacity of withstand high temperature without melting or decomposition, and the capacity to remain unreactive and inert when exposed to severe environments. This are good heat insulators, low electrical conductivity.
- General applications are furnace linings, insulation coating, glass manufacturing metallurgical heat treatment and power generation.
- Upon firing, the fine particles are involved in formation of bonding phases.
- This phase may be glass or crystalline.
- Porosity has detrimental effect on brick properties strength, load bearing capacity and resistance to attack by corrosive material.
- All of the above increase with porosity reduction at the same time thermal insulation and resistance to thermal shock are diminished.
- **Refractoriness** : It is the ability of a material to sustain the action of heat without appreciable deformation or softening. Refractoriness of material is measured by its melting point. e.g. Alumine-silica composition Refractories are expected to resist mechanical abrasion, infuson of molten metals, slag or metallic vapours and also action of superheated steam, sulphurous oxides, chlories and other gases.

12.9.1 Classification

(ii) Fireclay Refractories

Composition (in percentage) (MgO is in max)

Al_2O_3	SiO_2	MgO	Fe_2O_3	CaO	TiO_2	Porosity
25-45%	70-50%	0-1	0-1	0-1	1-2	20%

- Its melting point is 1587°C.
- Below this temperature equilibrium phases present are mullite and silica (cristobalite). Upgrading the alumina (Al_2O_3) content increases the maximum service temperature.
- Fireclay bricks are used primarily furnace construction to confine hot atmospheres and to thermally insulate structural members from excessive temperature.
- Strength is not an important criteria but dimensional accuracy and stability are to be maintained.

(ii) Silica Refractories (Acidic Refractories)

Composition (in percentage)

Al_2O_3	SiO_2	MgO	CaO	Porosity
0.2	96.3	0.62	2.2	25%

- It is also termed as acid refractories have a major constituent as Silica.
- These materials have high temperature load bearing capacity and are commonly temperature may reach as high as 1600°C.
- Presence of even small quantities of composite on (7.7 wt% Al_2O_3) is very mean to silica extremity of phase diagram.
- Even small additions of Al_2O_3 lower the liquidified temperature significantly, which means that substantial amount of liquid may be present at temperature around 1600°C.
- These materials are resistant to acidic slags but are readily attacked by basic slags.

(iii) Basic Refractories

Composition (in percentage)

Al_2O_3	SiO_2	MgO	Cr_2O_3	Fe_2O_3	CaO	Porosity
1	3	90	0.3	3	2.5	22

- Resistant to basic slags containing high quantities of CaO and MgO.
- These find extensive use in steel making open hearth furnaces.

(iv) Special Refractories Zirconia (ZrO_2)

- It is white in colour has good resistance to thermal shock, wear and corrosion.
- Partially and stabilized Zirconia (PSZ) has high strength and toughness and better reliability than Zirconia.

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- It is obtained by doping Zirconia with oxides of calcium, yttrium or magnesium.
- This process forms fine particles of tetragonal zirconia in a cubic lattice.
- Typical applications are dies for hot extrusion grinding beads, for automotive primers and topcoats. Partially Stabilized Zirconia is very suitable for heat engine components such as cylinder liners and valve bushings.

(v) Neutral Refractories

These neither acidic nor basic with increasing alumina content, silica-alumina refractories may gradually change from an acidic to a neutral type. e.g. Sic, chrome etc.

Note : Quartz is an example of crystalline form and silica glass of amorphous form. Quartz exhibits Piezoelectric effects.

12.10 RECENT ADVANCES IN CERAMICS

- Chemically Bonded ceramics (CBC) are invented recently and have high performance, low cost. CBC materials are generally silicates, aluminates and phosphates.
- Their low cost obtained from processing temperature for below 1000°C for producing conventional ceramics.
- CBC have 10 to 20 times the tensile strength of concrete about 32% cheaper than Al, 20 times, steel and 4 to 6 times less expensive than plastic.
 - CBC armor-brake lining
 - CBC roofing, CBC flooring, CBC electrical fixture
 - CBC wall panel

Future application : Aircraft & rocket parts, cryogenic containers, etc.

□□□

QUESTIONS

1. Which one of the following refractory materials is recommended for steel furnaces containing CaO slag?

(a) Alumina (b) Silica
(c) Magnesite (d) Fireclay

2. Match List-I (Material) with List-II (Applications) and select the correct answer using the codes given below the lists:

List-I

- A. Tungsten carbide
B. Silicon nitride
C. Aluminium oxide
D. Silicon carbide

List-II

1. Abrasive wheels
2. Heating elements
3. Pipes for conveying liquid metals
4. Drawing dies

Codes:

	A	B	C	D
(a)	3	4	1	2
(b)	4	3	2	1
(c)	3	4	2	1
(d)	4	3	1	2

3. Match List-I (Material) with List-II (Application) and select the correct answer using the codes given below the lists:

List-I

- A. Ceramics
B. Refractories
C. Stones
D. High silica glass

List-II

1. Construction of chemical plants
2. Columns and pillars
3. Lining of furnaces
4. Tiles

Codes:

	A	B	C	D
(a)	4	3		
(b)	2	1		
(c)	4	1	2	
(d)	2	3	4	

4. Which one of the following is not a ceramic?
(a) Alumina (b) Porcelain
(c) Whisker (d) Pyrosil
5. Which one of the following is correct? When "devitrification" of inorganic glasses done
(a) glass transforms from crystalline to non-crystalline
(b) glass transforms into a fully transparent material
(c) glass transforms from mono-crystalline state to poly-crystalline state
(d) glass is relieved of internal stresses

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6. The type of bonding in ceramic is
 (a) Purely covalent
 (b) Predominantly covalent with small ionic character
 (c) Predominantly ionic with small covalent character
 (d) Purely ionic
7. Among the following ceramics which one has the highest hardness?
 (a) Aluminum oxide
 (b) Quartz
 (c) Boron carbide
 (d) Silicon carbide
8. A refractory material must
 (a) Be capable of with standing high temperature
 (b) Be resistant to action of molten metal and slag
 (c) Not crumble or cracks easily
 (d) All of the above
9. The nature of magnesite as refractory materials is
 (a) Acidic
 (b) Basic
 (c) Neutral
 (d) None of the above
10. The chemical formula of sillimanite is
 (a) Al_2O_3 (b) SiO_2
 (c) $\text{Al}_2\text{O}_3, \text{SiO}_2$ (d) $\text{Al}_2\text{O}_3, 2\text{SiO}_2$
11. Reinforced cement concrete is generated by casting
 (a) In moulds
 (b) In blocks
 (c) Over steel rods
 (d) All of the above
12. What is silica?
 (a) It is an organic polymer
 (b) It is a ceramic polymer
 (c) It is a composite material
 (d) None of the above
13. An example of crystalline ceramic material is
 (a) Window glass (b) MgO
 (c) Fired clay (d) Cement
14. The main function of refractories is
 (a) Thermal radiation
 (b) Reflection of heat
 (c) Thermal insulation
 (d) Absorption of heat
15. Which one is an example of basic refractory?
 (a) Lime (b) Ganalister
 (c) Dolomite (d) Silica brick
16. FRP is a
 (a) Composite material
 (b) Highly conducting material
 (c) High strength material then steel
 (d) Highly ductile material than copper
17. For communication applications we require
 (a) Glass rods
 (b) Thicker glass fibres
 (c) Thin glass fibres
 (d) Thin glass fibres with a coating of cladding material

18. Addition of germania in SiO_2 will
- Increase its refractive index
 - Decrease its refractive index
 - Not change its refractive index
 - None of these

19. Fibreglass is a composite of
- Glass fibres in a polymer matrix
 - Polymer fibres in a glassy matrix
 - Glass fibres in metal matrix
 - All of these

Fill in the Blanks :

20. Ceramics normally exhibit fracture
21. Ceramics exhibit strength in tension than in compression
22. is not a ceramic material
- Glass
 - Bakelite
 - Clay
 - Aluminium oxide
23. is not the neutral refractory materials
- Graphite
 - Kaynite
 - Chromite
 - Dolomite

ANSWERS

1. (c)	6. (c)	11. (c)	16. (a)	21. (c)
2. (d)	7. (d)	12. (b)	17. (d)	22. (b)
3. (a)	8. (d)	13. (b)	18. (a)	23. (d)
4. (d)	9. (b)	14. (c)	19. (a)	
5. (c)	10. (c)	15. (a)	20. Brittle	

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13.1 IN'IntroductionParticulate ReInfluence ofConcentratiFibre PhasePolymer MaGlass FibreCompositesMatrix(OF) CorArchit. LinCompositesMetal MatrixCeramic MaCarbon-CarHybrid CorStructure CVarious MaMylar : A FWood-PlasNatural FitHigh PerfoAspect RatGlass FibrStress-StraiMatrix andManufacturiCompositesManufactunThermoplasBulk Mold

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13.1 INTRODUCTION

Introduction

Partial Reinforced Composites

Influence of Fibre Orientation and Concentration

Fibre Phase

Polymer Matrix Composites

Glass Fibre Reinforced Plastic (GFRP) Composites

Carbon Fibre Reinforced Polymer (CFRP) Composites

Aramid Fibre Reinforced Polymer Composites

Metal Matrix Composites

Ceramic Matrix Composites (CMC)

Carbon-Carbon Composites (CCC)

Hybrid Composites

Structure Composites

Various Matrix Materials

Mylar : A Form of Flake

Wood-Plastic Composite

Natural Fibres

High Performance Fibres

Aspect Ratio and Fibres

Glass Fibres

Stress-Strain Behaviour of Fibres, Matrix and Composites

Manufacturing Processes for Thermoset Composites

Manufacturing Processes for Thermoplastic Composites

Bulk Molding Compounds (BMCs)

- A composite is a multiphase material that exhibits a significant proportion of properties of both constituent phases. It is based on the principle of combined action, better properly combination are achieved through liquidious combination of two or more distinct materials.
- One phase is termed as matrix which is continuous and surrounds the other phase often called dispersed phase.
- Properties of composites depends upon concentration, size, shape, distribution and oreintation of the dispersed phase.
- Ceramics (refractories) are high temperature resisting brittle material and metal are ductile and melting point varying from low to high.
- Composites posses the nature of orthotropy and anisotropy. They can be homogeneous or hetrogeneous.
- A composition of ceramics and metal in different proportion gives desired thermal and mechanical properties in cermets.

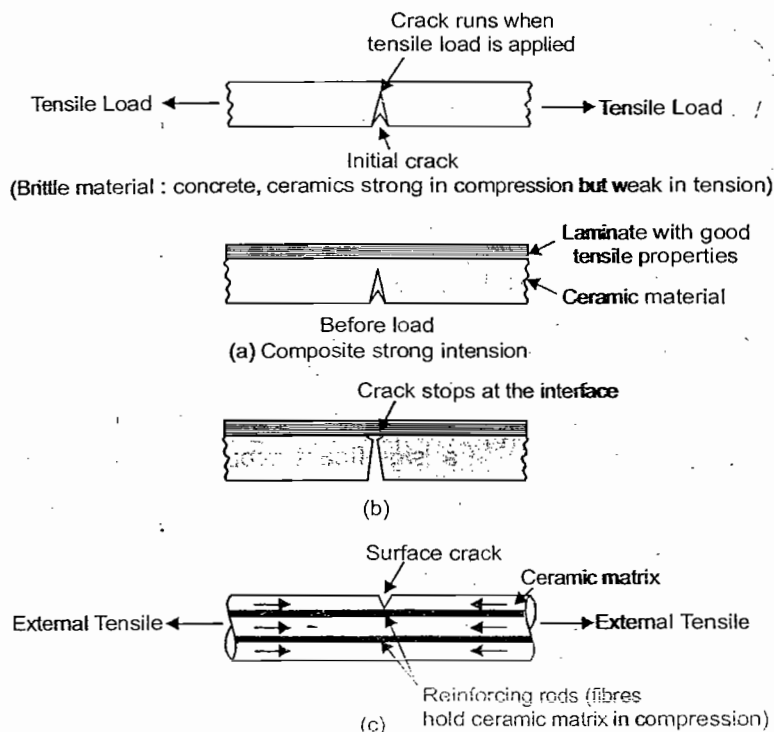


FIGURE : Principles of reinforced composite materials: (a) crack propagation in a non-reinforced ceramic material, (b) behavior of a laminated composite when in tension; (c) fibre reinforcement

13.2 PARTIAL REINFORCED COMPOSITES

(i) Large partial composites

- Particals should be equiaxed. For effective reinforcement, the particals should be small and evenly distributed throughout the matrix.
- Further, the mechanical properties are enhanced with increasing volume fraction of particals. Elastic modulus depends upon volume fraction of both phases. Hence particle size $1\mu\text{m}$.

(ii) Cermets (Cer + met $\approx$ Ceramics + Metal)

- Most common eg. of partial reinforced composites. Most common cermets is cemented carbide, which is composed of extremely hard particals of carbide ceramic such as tungsten carbide or titanium carbide embedded in a matrix of a metal such as cobalt and Nickel.
- These composite are extensively utilized as cutting tool for hardened steels.

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- The hard carbide particulates provide the cutting surface but, being extremely brittle, are not themselves capable of withstanding the cutting stresses. Toughness is improved by their inclusion in metal matrix, which isolates the carbide particles from one another and prevents particulate to particulate crack propagation.
- Relatively large volume fraction of the particulate phase may be utilized after exceeding 90% of volume, thus abrasive action of the composite is maximized.

(iii) Concrete

- (It is a ceramic-ceramic composite). Portland cement concrete is the most common example.
- The ingredients of portland cement are, a fine aggregate (sand), a coarse aggregate (gravel) and water. Aggregate particulates act as a filler material to reduce the overall cost of the concrete products because they are cheap and cement is expensive.
- Dense packing of aggregates and good interfacial contact are achieved by having particles of two different sizes i.e. the fine sand particulates should fill the void spaces between gravel particulates.
- Aggregates account for 60-70% of the total volume.
- The amount of cement water paste should be sufficient to coat all the sand and gravel particulates, otherwise, excessive porosity.
- Surface of the aggregates should be free from clay and silt in order to have a sound bond with cement. This concrete is a major structural material, get hardness at room temperature and even when submerged in water.
- It also has some disadvantage as it is extremely brittle and its tensile strength is 10 to 15 times smaller than its compressive strength. Also large concrete structures experience considerable thermal expansion and contraction with temperature fluctuations.
- In addition water penetrates into external pores, which may cause severe cracking in cold weather.

(iv) Reinforced Concrete

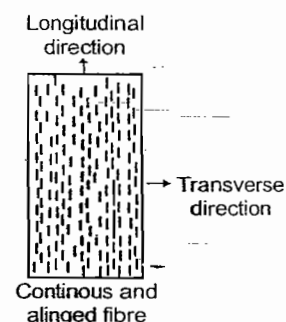
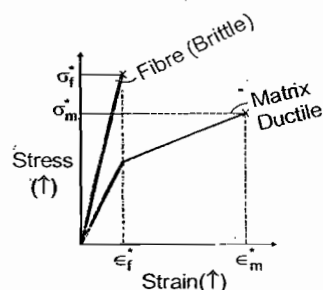
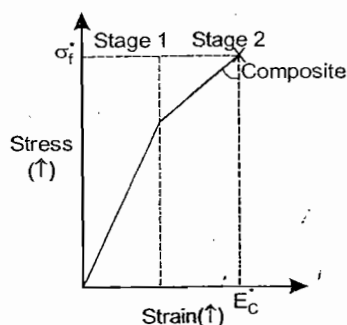
- The strength of portland concrete may be increased reinforcement by steel rods, wires, bars or mesh which are embedded into fresh and uncured concrete.
- Thus reinforced structure is capable of supporting greater tensiles, compressive and shear stresses. Even if cracks develop in concrete, considerable reinforcement is maintained.
- Steel serves as a suitable reinforcement material because its coefficient of thermal expansion is nearly same as that of concrete. Also, steel is not rapidly corroded in cement environment and a relatively strong adhesive bond is formed between steel and concrete.

- Another reinforcement technique for strengthening concrete is to introduce residual compressive stress into the structural member, the resulting material is called prestressed concrete.
- In this process, high strength steel wires are positioned inside the empty molds and allowed to harden, the tension is then released. Now the wires contract, and they put structure in a state of compression.
- Another technique of inducing compressive stress is "tensioning".
- Sheet metal or rubber tubes are situated in concrete structure and is allowed to harden. The holes created are fed with steel wires.
- Tension is applied to steel wires through Jacks, attached and abutted to the faces of structure. Again a compressive stress is imposed on concrete structure by the jacks.

13.3 INFLUENCE OF FIBRE ORIENTATION AND CONCENTRATION

(i) Continuous and Aligned Fibre Composites

- Stress strain Behaviour when tensile stress is applied in the direction of alignment for the composite in stage 1 both fibre and matrix behave elastically.
- Typically matrix deformed plastically while fibre continues to stretch elastically. Tensile strength of fibre is much higher than matrix from stage 1 to stage 2 the proportion of applied load that is borne by the fibre increases. The onset of composite failure begins as fibre starts to fracture at strain ϵ_f . Composite failure is not sudden as all fibres do not fracture at the same time and even if all fibres fail, the matrix remains intact as long as $\epsilon_m > \epsilon_f$.
- In the elastic region, condition of equal strain exists in fibre and matrix (Isostrain condition).



When tensile strength is applied in Transverse Direction

- Tensile stress in longitudinal direction corresponds to fibre fracture stress and marks onset of composite failure. Generally $E_f > E_m$, so when fibers get fractured the entire load is taken by the matrix.

- Proper strength which low.

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Material

Glass-

Carbon

Kevlar

(iii) Discontinuity

Their strength continues

(iii) Discontinuity

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13.4 FIBRE

- Fibre:

(i) Whisker

- These As a result are visible

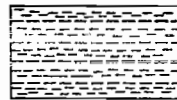
- Properties of continuous and aligned fibrous composites are highly anisotropic (i.e., longitudinal strength). Under actual circumstances some transverse loading may also be present which may lead to premature failure of composite as its transverse strength is very low.

Example of Continuous fibre composite with their strength

Material	Longitudinal strength (MPa)	Transverse Strength (MPa)
Glass-polyester	700	20
Carbon epoxy	1000	35
Kevlar epoxy	1200	20

(iii) Discontinuous and Aligned Fiber Composites

Their reinforcement efficiency is lower than continuous fibre composites and have strength and moduli of elasticity that approach 50% and 90% respectively of their continuous fibre counterparts.



(iii) Discontinuous and Randomly Oriented fibre Composites

These fibre are used in :

- Applications involving multi directional stresses use discontinuous fibres randomly oriented in matrix.
- Production rates of short fibre composites are rapid.
- Intricate shapes can be formed that are not possible with continuous fibre reinforcement.
- Fabrication costs are considerably lower compared to continuous and aligned fibre composites.

13.4 FIBRE PHASE

- Fibre are classified according to their diameter and character :

(i) Whiskers

- These are very thin single crystals that have extremely large length to diameter ratios. As a result of their small size they have a higher degree of crystalline perfection and are virtually flaw free.

- This accounts for their exceptionally high strengths, they are strongest materials.
- Whiskers are not extensively used as reinforcement medium because they are extremely expensive. Moreover, it is very difficult to incorporate whiskers into a matrix.

Examples are : SiC, Al_2O_3 , graphite, Silicon nitride.

(ii) Fibers

- These are not single crystals but polycrystalline amorphous and have small diameters. These are either polymer or ceramics.
e.g. are Al_2O_3 , Aramide, Carbon, Boron, SiC.

(iii) Wires

- Relatively large diameters. Typical materials are steel, Mo, W. They find application in radial steel reinforcement in automobile tyres, filament winding of rocket motors, wire windings of higher pressure hoses.



Discontinuous & Random
Orientation

Matrix Phase

- It may be metal, polymer or a ceramic. Generally metals are preferred because of their higher ductility and strength. It performs the following functions :
 - (i) It binds the fiber together and act as a medium by which externally applied stress is transmitted and distributed to fibers, only a very small portion of applied stress is carried by a matrix phase. Elastic modulus of fiber material should be much higher than matrix material.
 - (ii) It protects individual fibers from surface damage as a result of chemical reactions with environment and mechanical abrasion. Such interactions may introduce surface flaws on composites surface and may lead to crack initiation.
 - (iii) It separates individual fibers and prevents the propagation of crack between fibers, which could result in sudden failure.

13.5 POLYMER MATRIX COMPOSITES

Polymer is used as a matrix with fibers as the reinforcement medium. These materials are used in largest quantities and varieties due to their low cost and ease of fabrication.

13.5.1 Glass Fiber Reinforced Plastic (GFRP) Composites

- It consists of glass fibers in a polymer matrix. It is produced in largest quantities. Glass is drawn into fibers of diameter range between 3-20 μ m. Glass is popular as reinforcement material as :
 - (i) It is easily drawn into fibers from the molten state.
 - (ii) Readily available and economical to fabricate
 - (iii) Wide variety of composite manufacturing technique can be used.
 - (iv) It produces composites of very high specific strength.
 - (v) When combined with polymer matrix it possesses a chemical inertness that renders the composite useful in variety of corrosive environments.
- Newly drawn fibres of glass are coated during drawing with a 'size' a thin layer of substance that protects the fiber surface from damage and undesirable environmental interactions.
- This size is removed prior to composite fabrication and replaced with a "coupling agent" that promotes bond between the fiber and matrix.

These materials have high strengths but lack rigidity and stiffness for use in structural applications (e.g. structure of aeroplane and bridges). Service temperature are limited to 200°C as at high temperature polymer begins to flow.

Applications : Automotive and marine bodies, plastic pipes, storage container, industrial floorings, transportation industries etc.

13.5.2 Carbon Fiber Reinforced Polymer (CFRP) Composites

Carbon as a fiber phase has following advantages

- Carbon fibers have highest specific strength and specific modulus among all reinforcing fiber materials.
- Retain their strength and modulus at elevated temperature.
- At room temperature carbon fibers are not affected by moisture, bases, acids etc.
- Composite properties can be engineered according to applications.
- Manufacturing processes are relatively inexpensive and cost effective.
- Here, carbon fibers are represented by both graphite and non crystalline regions. Polymer matrix materials are rayon, poly acrylonitrile (PAN) and pitch.
- Carbon fibers are normally coated with a protective epoxy size that also improves adhesion with the polymer matrix.

Application : Extensively used in sports and recreational equipment (fishing rods, golf clubs), filament wound rocket motor, cars (pressure vessels and air craft structural components) both military and commercial, helicopters (wing, body etc).

13.5.3 Aramid-Fiber Reinforced Polymer Composites

- They are desirable for their outstanding strength to weight ratio.
- Chemically, this group of materials is known as poly paraphenylene terephthalamide.
- Two most common aramid materials are Kevlar & Nomex.
- The rigid molecule are arranged in the direction of fibre axis.
- These fibers have high longitudinal tensile strength & moduli.
- However, these are relatively weak in compression. In addition, aramide have high resistance to creep and fatigue failure.
- They are stable at higher temperatures (-200°C to 200°C).
- Chemically they are susceptible to degradation by strong acid and bases.
- Typical applications are Bullet proof vests, sporting goods, ropes, missile cases, automotive brake and clutch lining gaskets etc.

13.5.4 Metal Matrix Composites

- It is a matrix of ductile metal.
- Further, the reinforcement may improve stiffness specific strength, resistance to abrasion, creep resistance and dimensional stability.
- Advantage of MMC over PMC include higher operating temperature, non-flammability and resistance to degradation by organic fluids.
- Alloy of Al, Cu Ni, Titanium are employed as matrix materials, Reinforcement may be in the form of particulates, continuous or discontinuous fibers and whiskers.
- Concentration normally range between 10 to 50%.
- Cermets fall under the MMC category.
- Some MMC are reactive at elevated temperature, which may cause degradation at high temperature processing. This problem is resolved by a protective coating to the reinforcement.
- Processing of MMC's involve synthesis followed by shaping operations. Discontinuous fiber MMC's can be shaped by standard metal forming operations (forging, extrusion, Rolling).

Application : Engine component, extruded stabilizers, forged suspension and transmission component, space shuttle structure etc. Super alloy (Ni & Co) based alloys matrix are used to counter high temperature creep in gas turbine engine etc.

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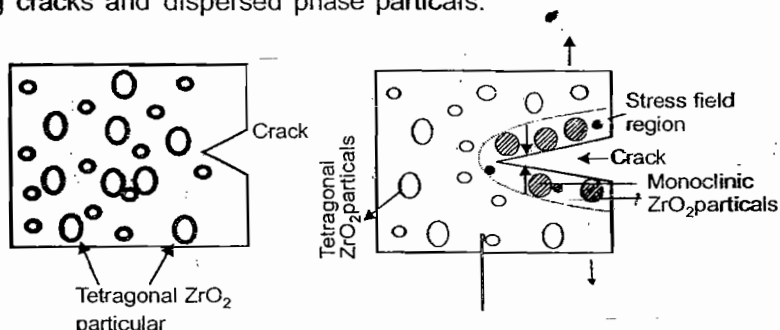
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- cement

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- strength

13.5.5 Ceramics Matrix Composite

- Here particulates, fibers or whiskers of internal toughness of ceramic are embedded in the matrix of other ceramic.
- This improves the internal toughness of ceramic.
- This improvement in fracture toughness properties results from interaction between advancing cracks and dispersed phase particulates.



- One such technique is "transformation toughening".
- Small particulates of partially stabilized zirconia are dispersed within the matrix material phase at ambient condition allow retention of the metastable tetragonal phase at ambient conditions rather than stable monoclinic phase.
- The stress field in front of the propagating crack causes these metastable tetragonal particulates to undergo transformation to stable monoclinic phase.
- Accompanying this transformation in a slight partial volume increase and the net result is that compressive stresses are established on the crack surface near the crack tip that tends to pinch the crack shut, thereby arresting its growth.
- Ceramic whiskers also inhibit crack propagation by
 - (i) Deflecting crack tips.
 - (ii) Forming bridges across crack faces.
 - (iii) Absorbing energy during pullout as whiskers debond from the matrix.
 - (iv) Causing redistribution of stresses in the region adjacent to crack tips.
- CMC's have high creep resistance and thermal shock resistance. CMC's are fabricated by hot pressing, hot isostatic pressing and liquid phase sintering techniques.
- Used as cutting tool inserts for machining hard metal alloys with tool life greater than cemented carbides.

13.5.6 Carbon-Carbon Composites (CCC)

- It is a carbon fiber reinforced carbon matrix composite. These have high tensile strength and moduli, that are retained at temperature above than 2000°C.

- High resistances to creep, and relatively large fracture toughness.
- These are highly resistant to thermal shocks.
- Their major draw back apart from being expensive is that they are susceptible to oxidation at high temperature.

Application : CCC find application in rocket motors, friction materials in aircraft and high performance automobiles, hot pressing molds, components of turbine engines and as ablative shields for reentry vehicles.

- These are expensive because of complex processing techniques. Carbon fibers formed are impregnated with a liquid polymer resin. The workpiece is then formed into final shape and the resin is allowed to cure.
- Now, the part is heated in an inert atmosphere where molecular components consisting of oxygen, hydrogen and nitrogen are driven off, leaving behind large carbon chain molecule. Subsequent heat treatments at higher temperature will cause the carbon matrix to densify and increase in strength.

Fibers in resin → forming → pyrolyses → Heat treatment → Matrix become dense and strengthened.

13.5.7 Hybrid Composites

- Glass fibers + Carbon fibers. First carbon fibers will fail and then load is taken by glass fibers and matrix. Typical applications are sports goods and orthopedic components.
- Types of Hybrid composite :
 - (i) Interply hybrid (alternate lamina of some matrix different fibers)
 - (ii) Intraply hybrid (contains each lamina having two or more kinds of fibres system)
 - (iii) Interply - Intraply - combination of both
 - (iv) Super hybrid

Applications :

- (i) Antenna dishes of CFRP and aluminium honeycomb.
- (ii) CFRP & GRP used in leaf & springs and drive shaft of automobile.
- (iii) Helicopter rotors and thin-walled tube of CFRP & GRP.
- (iv) Artificial limb and external bearing made of CFRP. S.S. Squash and golf club rackets with shafts made of CFRP/GRP/Wood hybrid.

13.5.8 Structure Composites

Sandwich Panels

- These consist of two strong outer sheets, or faces separated by a less dense material, or core which has lower stiffness and lower strength.

- The face
- Typical plywood
- The core
- The two perpendicular
- Second rigidity
- Synthetic panels.
- These are aircraft
- Sandwich laminates
- The thickness
- The core

In this impregnated with fit

- Its core

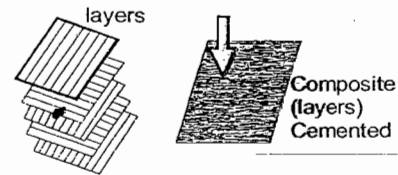
Laminated

These are 0.1mm to thickness.

Example

- Ply
- Me
- Sh
- BM
- Lin
- Tur

- The faces bear most of the in plane loading and also any transverse bending stresses. Typical face materials include aluminium alloys, fiber reinforced plastics, steel and plywood.
- The core serves two function first is separates the two faces and resists the deformation perpendicular to the face plane.
- Secondly, it provides a certain degree of shear rigidity along planes that are perpendicular, synthetic structures are sandwiched between face panels.
- These found wide variety of application one such as roofs, floors, walls of buildings, aircraft wings.
- Sandwich composite is constructed by sandwich foam between two skins of FRP laminates.
- The thickness of skin is kept upto 3 mm and thickness of core is kept deeper.
- The core is either foamed or made of honeycomb material.
- As thickness of core is deep, the area moment of inertia of cross-section is enhanced too much. leads to increase in flexure rigidity of sandwich beam which make it suitable to use as beam.
- In this core of self supporting skin sandwiched between layers of carbon fiber tape impregnated with an epoxy resin, had honey combed paper like material threaded with fibres.
- Its composite air craft except engine



Laminated Composite

These are made of many laminae. Lamina also known as ply or a layer is very thin, about 0.1mm to 1mm thick. These are glued or joined together to form a laminate of desired thickness. Number of lamina in a laminate can be few to many tens.

Examples :

- Plywood
- Metal to metal laminate (cladded metal)
- Sheet moulding compounds
- BMC
- Linoleum
- Tufnol

13.6 VARIOUS MATRIX MATERIALS

13.6.1 Mylar : A form of flake

- Mylar, (polyester) is used as thin flake (sheet of 25 to 150 μm thickness) in magnets and as an insulating material.
- Aluminium diboride is a new material for planer reinforcement in flaked composites. Planer-stiffness of its flake measures 265 GPa which is four times higher than the cross-plyed planer reinforced graphite fibres.
- The flakes have excellent damage tolerance and are easy to process, and holes can be drilled into them for attachments. However, they suffer from limited stretchability under application of pressure.

13.6.2 Wood-Plastic Composite

- Wood-plastics composite is made by impregnating natural wood with liquid monomers such as methyl methacrylate, acrylonitrile, or styrene.
- Fibres are transformed to other forms for reinforcement. Various forms obtained from continuous filaments. Usually the transformed forms are the following.
1. Strands, and 2. Yarns
- **Strands:** In order to minimise self-abrasion and mechanical damage to the fibres, they are collected and size (starch) is applied. Then sized fibres are binded together to form a strand. Thus a strand is combination of large number of fibres which can be termed as unified multi-fibres.
- **Yarn:** Yarn is produced from sized cake by first twisting the strand then followed by playing a number of twisted strands together to form a doubled balanced yarn. It is designated by its 'Count' which is expressed in the unit of Tex'. One Tex is a measure of linear density and is defined as weight in gms per km. Yarns are used for manufacturing woven fabrics.

13.7 NATURAL FIBRES

- **Ramie** is one of the strongest natural fibres. It posses greater strength when wet. It is not as durable, is usually used as a blend with other fibres such as cotton or wool.
- It is stiff and brittle, and breaks if folded repeatedly in the same place. Low resilient and is low in elasticity and elongation potential.
- **Sisal fibre** is fairly coarse and inflexible. It is used for its strength, durability, ability to stretch, affinity for certain dyestuffs, and resistance to deterioration in saltwater.
- **Coir fibres** are gained from coconut husks. Coir fibres are light in weight, strong and elastic.

- Flax substiti fibre i
- Jute i again
- Hemp
- Palm

13.8 HI

- High- Fibres specti
- Glass calciu

Types of

- A - g
- C - g
- D - g
- E - g
- S - g

Boron Fi

- Boron or ca (CVD)
- The fi 0.15 GPa.
- It is r fibres

Carbon i

- Carbon betwe carb
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- **Flax** is obtained from flax fibre plant. It generally known as 'patsan' which is a substitute of jute'. The flax fibre is strong and wiry, longer and finer in nature. Flax fibre is used for its strength, luster, durability and moisture absorbency.
- **Jute** is a bast and one of the cheapest natural fibres. It possesses a poor resistance against moisture, brittles under influence of light, absorbs paint easily.
- **Hemp fibre** is a bast fibre, and is yellow-brown in colour.
- **Palmyra fibre** is obtained from palm (toddy) plants. It is a bast fibre.

13.8 HIGH PERFORMANCE FIBRES

- High-performance fibres are fibres based on polyester, nylon, aramid and polyfoam. Fibres such as aramid (kevlar and nomex), polybenzimidazole (PBI), sulfar and spectra have increased the range of choice for materials.
- Glass developed for use as continuous fibres. It is composed of 55% silica, 20% calcium oxide, 15% aluminum oxide, and 10% boron oxide.

Types of Glass Fibres

- A – glass fibre for acid resistance.
- C – glass fibre for improved acid resistance.
- D – glass fibre for electronic applications.
- E – glass fibre for electrical insulation.
- S – glass fibre for high strength. (65%, SiO_2 , 25%, Al_2O_3 , 10%, MgO)

Boron Fibre

- Boron fibres are composites of the substrates tungsten, silica coated with graphite or carbon filaments upon which boron is deposited by a vapor-deposition process (CVD).
- The final boron fibre has a specific gravity of about 2.6, a diameter between 0.01 and 0.15 mm; a tensile strength of about 3.5 GPa, and a tensile modulus of around 415 GPa.
- It is more expensive than graphite and requires expensive equipment to place the fibres in a resin matrix with a high degree of precision.

Carbon and Graphite Fibres

- Carbon fibre usually has a modulus of less than 345 GPa and a carbon content between 80% and 95%. Graphite fibres have a modulus of over 345 GPa and a carbon content of 99% or greater.
- Another distinguishing feature is the pyrolyzing temperature. For carbon, this temperature is around 1315°C, and for graphite it is around 190° to 280°C. Pyrolysis is the thermal decomposition of a polymer.

Kevlar Fibre

- Kevlar, is an organic fibre termed as an aramid or aromatic polyamide fibre. This organic fibre is melt-spun from a liquid polymer solution.
- The aromatic ring structure results in high thermal stability. The rod-like nature of the molecules classifies Kevlar as a liquid-crystalline polymer characterized by its ability to form ordered domains in which the stiff, rodlike molecules line up in parallel arrays.

Grades of Kevlar Fibres

(i) Kevlar 29 (ii) Kevlar 49, and (iii) Kevlar 149 (ultra high tensile strength)

Synthetic fibres produced in industries these are cheaper and more uniform in cross-section than the natural fibres. Their diameters vary between $10\mu\text{m}$ to $100\mu\text{m}$. Example.

- Glass
- Boron
- Carbon
- Graphite
- Kevlar

Organic fibres carbon and graphite fibres are light in weight, flexible, elastic and heat-sensitive. Commercial carbon fibres are available by the trade names such as:

- Hyfil
- Grafil
- Fortafil
- Thornel
- PAN etc.

Inorganic fibres, have high strength, low fatigue resistance.

Their examples are:

- Glass
- Tungsten
- Ceramic

Note : Advanced fibres and composites. Composites using kevlar, graphite and boron fibres are termed as advanced composites.

13.9 ASPECT RATIO AND FIBRES

Composites may be termed as particulate composite, continuous fibre composite, or short fibre composite depending on the aspect ratio (l/d) as mentioned here width:

$$\frac{l}{d} \approx 1$$

for particulate composite

$$\frac{l}{d} \approx 10 \text{ to } 1000$$

for short fibre composite

$$\frac{l}{d} \approx \infty$$

for continuous fibre composite

where, l = length, d = diameter or shortest dimension in a non-circular section fibre.

13.10 GLASS FIBRES

- Glass fibres manufactured by molten 'glass drop' through minute orifices and then lengthening them by air jet.
- The standard glass fibre used in glass-reinforced composite materials is E-glass, a borosilicate type of glass.
- The glass fibres produced, with diameters from 5 to $25\ \mu\text{m}$, are formed into strands having a tensile strength of 5 GPa. Chopped glass used as a filler material in polymeric resins for moulding consists of glass fibres chopped into very short lengths.

13.11 STRESS-STRAIN BEHAVIOUR OF FIBRES, MATRIX AND COMPOSITES

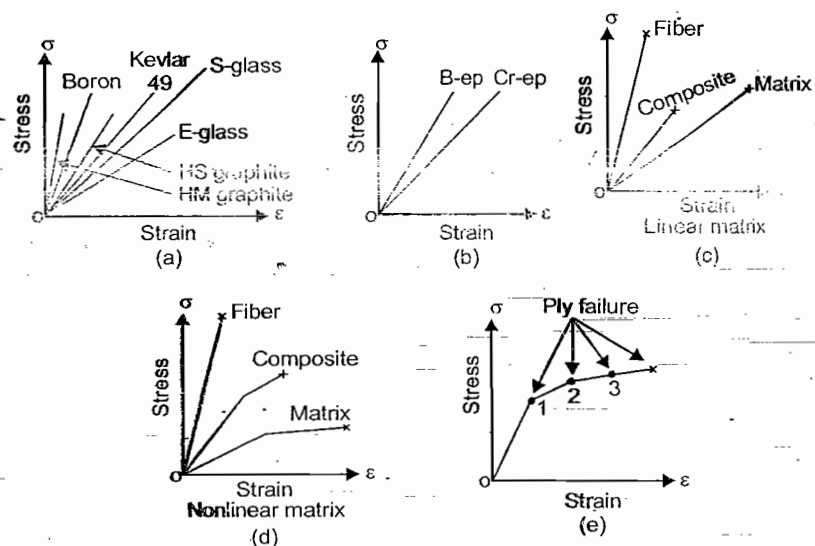


FIGURE : Stress-strain curves of (a) various fibres (b) U/D-composite (c) linear matrix composite (d) nonlinear matrix composite, and (e) laminate.

13.11.1 Manufacturing Processes for Thermoset Composites

1. Hand lay-up (or wet lay-up) process
2. Spray-up process
3. Filament winding process
4. Pultrusion process
5. Resin transfer moulding process

6. Structural reaction injection moulding (SRIM) process
7. Compression moulding process
8. Roll wrapping process
9. Injection moulding process

13.11.2 Manufacturing Processes for Thermoplastic Composites

1. Thermoplastic tape winding process
2. Thermoplastic pultrusion process
3. Compression moulding of glass mat thermoplastic (GMT)
4. Hot press technique
5. Autoclave processing
6. Diaphragm forming process
7. Injection moulding process.

13.12 BULK MOLDING COMPOUNDS (BMCS)

- These are premixed material of short fibre (Chopped glass strands) pre-impregnated with resin and various additives.
- Dough moulding compound (DMC) is an alternative of BMC. BMCs are limited to 400 mm in their longest dimension due to problems with separation of the components of moulding compound during molding.
- Sheet moulding compounds (SMC). These are non-metallic plastic reinforced-composite laminate made up by pressing together many unidirectional (U/D) laminates.
- One over the other. Desired mechanical properties achieved by playing U/D laminates in different orientation.



QUESTIONS

1. Which one of the following refractory materials is recommended for steel furnaces containing CaO slag?
 - (a) Alumina
 - (b) Silica
 - (c) Magnesia
 - (d) Fireclay
2. Which of the following fibre materials are used for reinforcement in composite materials:
 1. Glass
 2. Boron carbide
 3. Graphite

Select the correct answer using the codes given below:

 - (a) 1 and 2
 - (b) 1 and 3
 - (c) 2 and 3
 - (d) 1, 2 and 3
3. Wood is a natural composite consisting of which of the following?
 - (a) Lignin fibres in collagen matrix
 - (b) Lignin fibres in apatite matrix
 - (c) Cellulose fibres in apatite matrix
 - (d) Cellulose fibres in lignin matrix
4. Nano composite materials are highly preferable in design consideration for their
 - (a) high resistance to crack propagation
 - (b) vibration resistance
 - (c) impact resistance
 - (d) high resilience
5. Which one of the following materials is not a composite?
 - (a) Wood
 - (b) Concrete
 - (c) Plywood
 - (d) Sialon
6. Which of the following composites are 'dispersion-strengthened composites'?
 - (a) Particulate composites
 - (b) Laminar composites
 - (c) Fiber reinforced composites
 - (d) Short-fiber discontinuous composites
7. Consider the following statements regarding composite materials:
 1. Material is termed as advanced composite, if fibres are directionally oriented and continuous.
 2. Reinforced fibre glass products are strong and light weight.
 3. Concrete is reinforced with steel rebar, the rebar becomes matrix.
 4. Pearlitic steels are composite materials.

Which of these statements are correct?

 - (a) 1, 2 and 3 only
 - (b) 2, 3 and 4 only
 - (c) 1, 2 and 4 only
 - (d) 1, 2, 3 and 4

ANSWERS

1. (c)	3. (d)	5. (d)	7. (c)
2. (d)	4. (b)	6. (a)	

14.1 INTRODUCTION

Introduction

Porous Non-Porous Corrosion

Wet Corrosion (Occurs in Presence of a Liquid or Water)

Galvanic Cell

Water Line Corrosion

Stress Corrosion

Pitting

Inter-Granular Corrosion

Dry Corrosion or Aqueous Corrosion

Laws of Corrosion

Corrosion of Ceramics

Degradation of Polymers

Oxidation

Rate of Oxidation

Methods of Reduce Oxidation

Various Method to avoid Corrosion

Passivity

Use of Protective Coatings

Deaeration of Water

Protective Coatings

Metallic Coatings

Non-Metallic Coatings

Anodized Coatings

Surface Conversion (or Chemical Dip.) Coating

- Depletion of metals by chemical or electro chemical reactions with the environment is called as *corrosion*. Freedom of valence electrons and their conduction is responsible for corrosion in metals.
- **Gold and platinum, are most inactive.**
- Products of corrosion are either porous or non-porous. These products in interfere in the process of corrosion and therefore influence the rate of corrosion.
- Rate of corrosion depends on the relative activity or the passivity of metals in different environmental conditions.
- Passivity is used to prevent corrosion.
- Corrosion can occur at all temperatures.
- A metal liquid and a metal-gas system corrode when a galvanic cell is formed.

Note : Mild steel has maximum corrosion rate in humid condition while in dry state it is very less (0.001 mm/year).

14.2 POROUS NON-POROUS CORROSION

1. **Porous :** If the corrosion products are not dense, and is occurring (because the electrolyte is able to penetrate through the powder) then it is known as porous corrosion.

2. Non-porous corrosion allows corrosion to occur in a localized manner.

14.3 WEAR AND CORROSION

It occurs due to the combined action of corrosion and wear.

- Phase transformation
- Concentration gradient
- Stress

14.3.1 Galvanic Corrosion

- Galvanic corrosion occurs when two different metals are in contact in an electrolyte.
- Out of the two metals, the more active metal will corrode preferentially (Galvanic series).
- Also called as bimetallic corrosion.

An

Li = m

Au =

Example

- Corrosion of steel in seawater.
- The corrosion of steel from cuts and scratches.
- In a corrosive environment, the steel will corrode.

2. **Non-porous.** When the corrosion products (powder form) are very dense and do not allow corrosion to proceed further, then it is termed as non-porous corrosion.

14.3 WET CORROSION (OCCURS IN PRESENCE OF A LIQUID OR WATER)

It occurs due to following :

- Phase cell or galvanic couple.
- Concentration cell, and
- Stress cell.

14.3.1 Galvanic Cell

- Galvanic cell forms in the presence of two dissimilar electrodes (metals) and an electrolyte.
- Out of the two electrodes, one becomes anode which is the positive end, and the other cathode, which is the negative end. The criteria of being anode or cathode depends on the relative position of a metal in electromotive force (e.m.f.) series (Galvanic series).
- Also called Galvanic series.

Relative Position of Metals in Electromotive Force Series

Anodic (active end) ←	Li, K, Ca, Na, Mg, Be, U, Al, Ti,
	Zr, Mn, Zn, Cr, Ga, Fe, Cd, In, Tl,
Li = most anodic / least noble	Co, Ni, Mo, Sn, Pb, H, Bi, Cu, Hg,
Au = most cathodic / noble	Ag, Pd, Pt, Au →
	Cathodic (inactive end)

Examples :

- Corrosion of steel propeller shafts of ships running on bronze bearings is an example of corrosion under salty (sea) environment due to galvanic cell formation.
- The galvanized iron pipe (G.I. pipe) used in drinking water supply have zinc coating on iron pipe. Zinc provides mechanical protection and prevents electrolyte from reaching iron. A galvanic cell forms when the zinc coating gets scratches, cuts or other failure exposing iron to the electrolyte in the process. Then zinc becomes anodic to iron, and corrodes.
- In aluminium-copper (Al-Cu) system, aluminium corrodes. Here Al is anode & Cu is cathode.

A galvanic cell may also be formed due to some other reasons such as

- two different phases in the same metal.
- fine and coarse grains in the same metal.
- difference in metal ion-concentration
- difference in oxygen concentration
- different residual stresses in the same metal.

Type of Galvanic Cell Corrosions

Single Metal Corrosion

- These reasons have their effects on corrosion and will be discussed in detail now. Corrosion in a single metal can occur due to presence of
 - different phases, or
 - different grain size.
- Pearlite, a microconstituent, has a mixture of two phases viz ferrite and cementite of which ferrite is more anodic than cementite. A phase cell or galvanic couple is formed by them. Under corrosive conditions ferrite corrodes, and thus causes single metal corrosion.
- Presence of more finer grains results in the formation of more galvanic cells, hence the rate of corrosion is fast.
- Tempering of steel during heat treatment produces finer ferrite and cementite below 400°C and coarser cementite above 500°C. Therefore number of galvanic cells formed below 400°C are more. Hence rate of corrosion is faster below 400°C and slower above 500°C.
- **Concentration corrosion** : Such corrosion may occur due to difference in concentrations of metal-ion.

Crevice Corrosion

- Galvanic cell is also formed due to concentration of oxygen in the path of electrolyte flow.
- Oxygen plays an important role and corrosion depends on the rate at which oxygen diffuses to cathode.
- The oxygen rich region becomes cathodic with respect to oxygen lean region, thus resulting in crevice corrosion.
- Corrosion at the corners, holes and discontinuities such as in coupled pipe joints and threaded connections are the example.

14.3.2 Water Line Corrosion

- Corrosion occurs in a water storage tank just below the water line. The same is applicable for an object which is partly dipped in water and partly is above the water.
- It also corrodes below the water line. This is known as *water line corrosion*.
- The concentration of oxygen is higher just above the water line as compared to the submerged portion near the water line. The latter zone acts as anode and therefore corrodes. Water line corrosion is a type of crevice corrosion.

14.3.3 Stress Corrosion

- Difference in stresses at various regions of a metal is responsible for creating a *stress galvanic cell* in the metal. This cell is also known as *stress cell*.
- The stress variation may be due to the presence of residual stresses produced during cold working or hardening of metals.
- The grain boundaries in a polycrystalline metal also corrodes being anodic to the crystals.
- A plastically deformed metal piece corrodes more readily than the elastically deformed metal piece.
- A folded metal sheet is likely to corrode more at the folds due to high plastic deformation.
- A bent wire corrodes more at its bends as regions of bends are overstressed than rest of the wire.
- A nail corrodes more at its head and tip than the shank as head and tip are heavily stressed than rest of the body. Stress corrosion in (a) grain boundary, (b) folded metal sheet, (c) bent wire, and (d) nail.

14.3.4 Pitting

- It is another form of localized corrosion. As a consequence of this, small pits, and holes form, hence the name.
- This occurs in normal direction to the surface exposed. It is extremely dangerous form of corrosion, as material loss is often undetectable till the component fails.

14.3.5 Inter-Granular Corrosion

This occurs again due to concentration difference, but now along grain boundaries, which are usually of different chemical composition compared with rest of the grains. Thus grain boundaries are highly susceptible to corrosion.

- Degradation of polymers, thus involves a wide variety of reactions and results like absorption and swelling, dissolution, bond rupture due to heat, chemical effects, or radiation; weathering, etc.
- Degradation of polymers may be due to exposure to light (specially UV), humidity, oxygen, bacteria, heat and external loads.
- **Swelling and dissolution** : Polymers, when exposed to liquids, they get swelling as a result of solute diffusion and absorption of solute. Because of swelling i.e. separation of chains, secondary bonds become weaker. It results in the material becomes softer and more ductile.
- Swelling and dissolution effects are influenced by temperature because of their physiochemical nature.
- **Bond rupture** : Bond rupture in polymers due to degradation is known as scission. Polymers bond may get rupture due to radiation, heat energy, or chemical reactions.
- At elevated temperatures, bonds in polymers may get weakened, leading to deterioration of polymers.

Some chemical elements like oxygen, ozone may alter the chain scission rate as a result of chemical reactions. This is especially accelerated in vulcanized rubbers.

- A degradation of polymers due to outdoor circumstances is termed as weathering, which in fact is a combination of several different processes.

Examples :

- Deterioration of acrylic painting and pieces of art
- Decomposition of photographic films
- Decolorization of plastics pieces preserved in museums
- **Solutions to polymer degradation** : Tailor made scavengers such as activated charcoal or Ageless help to create a low oxygen environment. Ageless is a reactive powdered iron and is normally used to prolong the shelf-life of dry foods by absorbing oxygen. Epoxidised soya bean oil (ESBO), has also been tested with encouraging results as an acid absorbing coating on degrading cellulose nitrate.

14.8 OXIDATION

- Oxidation is a high temperature environmental effect on materials.
- An adherent oxide layer has good oxidation resistance. Addition of nickel, chromium and aluminium in steel improves its oxidation resistance.

14.8.1 Rate of Oxidation

The rate of oxidation may be very fast as in tungsten and molybdenum or very slow as in tin, silver and gold.

14.8.2 Methods to Reduce Oxidation

- Oxidation of materials follows linear and parabolic laws.
- Their rates can be expressed by an Arrhenius type equation.
- Oxidation rates can be decreased by addition of some oxidation-resistant elements. Rate of oxidation in steel decreases by about :
 - (i) 30 times on adding 5% Al, 20 times on adding 5% Si, and
 - (ii) 100 times on adding 18% Cr at 900°C.

14.9 VARIOUS METHOD TO AVOID CORROSION

14.9.1 Passivity

- Condition of a metal or an alloy that allow them higher corrosion resistance than its position on the galvanic series is termed as *passivity* or *passivation*.
- Chromium, aluminium, stainless steels shown passivity as a thin, invisible, nonporous and insoluble film forms on their surface.
- The protecting film on the metal surfaces is formed when a layer of oxygen is adsorbed; or some chemical compound reacts.
- Iron when exposed to concentrated nitric acid gets oxidized and becomes passive and is further not attacked by its strong solution.
- Opposite of this, iron is not oxidized by dilute solution of nitric acid and hence is attacked by its weak solution.
- The potential of metal electrodes can be increased electrically.
- During passivation, the current density attains a peak value and then falls abruptly.
- The occurrence is associated with the formation of thin oxide layer on the metal.
- Zinc chromates and nitrates are used as passivators in paints.

Name of alloy	Composition of chromium and others in steel	Application
Chromium steel	Cr upto 10%	Oil refinery
Chromel	Cr 10% and Ni	Thermocouples
Stainless steel	Cr 12 to 17%	Gas and steam turbine blades, ovens and furnaces, exhaust valves of I.C. engines
Inconel	Cr 16%, Ni 76%	—
18-8 Stainless steel	Cr 18%, Ni 8%	Utencils, pressure vessels, heat exchangers
Nichrome	Cr 20%, Ni 80%	Strain gauges
Kanthal	Cr 24%, Al 16%, Co 2%	Windings of ovens and furnaces
Alumel	Al 2%, Mn 2%, Si 1%, Ni	Heat resistant wires

14.9.2 Use of Protective Coatings

- Organic coatings such as paints, grease etc.
- inorganic coatings such as enamels etc.
- Electroplating by tin and noble metals.
- Plastic coatings and adhesives.
- Iron by zinc coating as in galvanized iron (G.I.) pipes
- Iron by aluminium and cadmium etc.
- Zinc chromate is applied as pigment in the paints.

Use of Inhibitors

Inhibitors are the chemicals added to the electrolyte to form an insoluble layer on the metal. By doing so, they make the system passive. Different kinds of inhibitors are

- (a) Anodic inhibitors such as chromates and nitrites.
- (b) Cathodic inhibitors
- (c) Vapour phase inhibitors such as bicarbonate.

Note : Anodic inhibitors form a thin passivating oxide film while cathodic inhibitors promote a thick film on the metallic surface. The vapour phase inhibitor compounds are placed in the vicinity of metals to be protected.

14.9.3 Deaeration of Water

- Corrosion of iron and steel by water may be controlled by removing dissolved oxygen, a cathodic reactant, from water. Dissolved oxygen is removed by either deaeration or by chemical reagents such as sulphites.
- This method is used in boilers where feed water is recirculated.

14.9.4 Protective Coatings

Protective coatings on metals are used to prevent corrosion and to enhance the outer appearance. The coatings may be broadly classified as follows.

- Metallic coating
- Non-metallic coating, and
- Chemical protective coating

Metallic Coatings

- **Electroplating** : Electroplating is an electro-deposition process of metals. The coating material is deposited on the base metal by passing direct current through an electrolytic solution.
- **Dipping** : Here the material to be coated is cleaned and dipped in a bath of molten metal. The coating metal has melting point lower than the base metal. *Galvanising* and *tinning* are the applications of this method.
- **Galvanising** : In this process, coating of zinc is done on iron. Galvanised iron is used for making buckets, roofing articles and G.I. pipes etc.
- **Tinning** : In this process a coating of tin is obtained on iron. Tinning process is carried out in the same way as galvanising.
- **Spraying** : A metallic coating is obtained on the base metal surface by spraying heated metal on it.

The molten metal particles interlock the irregularities of the base metal surface.

- **Cladding** : It is a method of putting a thick lining of one metal on the surface of another metal.
Nickel clad steel, copper and aluminium alloys are the examples of cladding.
- **Cementation** : In this the base metal is heated with another powdered metal. Diffusion of powdered metal takes place on the hot base metal surface. Examples of cementation are (i) *sheavdizing* (ii) *Calorizing*, and (iii) *Chromizing*.
- **Sheavdizing** : Here cleaned iron or steel is packed in zinc dust. When it is heated for an hour or so upto a temperature of about 350° to 450°C , it becomes coated with a continuous film of zinc.
- **Calorizing** : In this process, aluminium is used to coat the steel surface.
- **Chromizing** : By this process, steel is coated with a thin layer of chromium.

Non-Metallic Coatings

- Enamels are non-metallic materials. Porcelain enamel is essentially a vitreous coating containing an oxide coloured pigment. Vitreous enamel coat consists of a thin adherent layer composed of borosilicates.
- The chemical resistance of vitreous enamels increases with silica content.
- High silica compositions give very hard enamels of high fusion, low tensile strength, low thermal coefficient of expansion and poor adhesion to the base metal. Low silicon compositions give enamel a low chemical resistance.

Anodized Coatings

- Anodized coatings are done by electrolyte processes on zinc, aluminium, magnesium and their alloys. Aluminium coatings are formed in an acid electrolyte at moderate temperature and current densities.

- The base metal is made anodic. The nature and thickness of the coating depends on the type of electrolyte, temperature, current density and duration of application.

Surface Conversion (or Chemical Dip.) Coating

- These coatings are done by immersion or spraying. The base metal is covered with a chemical solution.
- Solution reacts with the metal surface to produce an adherent coating.
- The obtained coating surface are insoluble in the environment.

Examples :

- 'Chromate conversion coating' used for the protection of zinc and cadmium plated parts.
- Phosphate coatings are applied to iron, steel, zinc, aluminum, cadmium and tin by chemical reaction of aqueous solution of phosphate and phosphoric acid.
- The chemical reaction between the phosphatic solution and the base metal provide the formation of a film which consists of crystalline zinc-iron or manganese-iron phosphates firmly embedded into the crystal lattice of the metal surface.

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QUESTIONS

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| <ol style="list-style-type: none"> 1. Following is not the main form of polymers deterioration
(a) Corrosion
(b) Swelling and Dissolution
(c) Weathering
(d) Scission 2. The following influences deterioration of polymers
(a) Weather (b) Radiation
(c) Temperature (d) All 3. Which of the following can be used for cathodic protection :
(a) Al (b) Cd
(c) Cu (d) Either 4. Passivity is because of
(a) Higher EMF (b) Lower EMF
(c) Oxide film (d) Neither 5. Passivity is not reason for inertness of the following—
(a) Au (b) Al
(c) Ti (d) Ni 6. Difficult to monitor and very dangerous form of corrosion
(a) Galvanic (b) Pitting
(c) Crevice (d) Stress 7. This form of corrosion occurs due to concentration difference in a component | <ol style="list-style-type: none"> (a) Uniform (b) Galvanic
(c) Inter-granular (d) Stress 8. Main form of ceramic degradation
(a) Corrosion (b) Weathering
(c) Dissolution (d) Swelling 9. The following factors play vital role in corrosion process
(a) Temperature
(b) Solute concentration
(c) Both
(d) None 10. Corrosion of metals is
(a) Physical reactions
(b) Chemical reactions
(c) Both
(d) None 11. When Pt and Co are electrically connected, which one gets corroded
(a) Pt (b) Co
(c) None (d) Can't decide 12. Following equation is related to corrosion rate
(a) Nernst equation
(b) Faraday's equation
(c) Either
(d) Neither |
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ANSWERS

1. (a)	4. (c)	7. (c)	10. (b)
2. (d)	5. (a)	8. (c)	11. (b)
3. (a)	6. (b)	9. (c)	12. (b)

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15.1 SMART MATERIALS (OR INTELLIGENT MATERIALS)Smart Materials (or Intelligent Materials)Shape Memory AlloysDifferent Type of Smart MaterialsNanotechnologyFunctionally Graded MaterialsICMPiezoelectric Materials

- These are magical materials which are suitable to our needs. These materials can sense, process, stimulate and actuate a response.
- Their functioning is somewhat similar to human brain, slow and fast muscles action. The intelligent material have three basic components which are given as follows:
 - (i) **Sensors:** Piezoelectric polymers (polyvinylidene), optical fibres,
 - (ii) **Processors:** Conductive electroactive polymers, microchips, and
 - (iii) **Actuators:** Shape memory alloys (Ni-Ti i.e. nitinol), chemically responding polymers (polypyrrole).
- **Piezoelectric ceramics:** Linear and shear deformations occur along longitudinal, transverse and thickness directions.
e.g. Quartz, Pb Zr titanate
Application : Aircraft airfoils, identifying Braille alphabet (an aid for blinds).
- **Viscoelastic (VE):** These relax any stress produced in it by external strain.
Application: Damping in space-crafts, earthquake prone structures, aircrafts.
- **Electrorheological (ER) fluids:** These are like suspended fine polarizable particles cohesive, and tend to coalesce. They form new chains even when old chains are broken.
e.g. zeolite in silicone oil, starch in corn oil.

Application : In filling of graphite-epoxy beams to provide variable stiffness in them.

- **Shape memory alloys (SMA):** Below a critical transition temperature, they can deform plastically.

e.g. Ni Ti (nitinol)

Application : Fire alarm due to change of shape at transition temperature.

15.2 SHAPE MEMORY ALLOYS

- Shape memory alloys (SMAs) are metals that possess two very unique properties (1) pseudoelasticity (2) 'shape memory effect'. The most effective and widely used shape memory alloys include NiTi (Nickel-Titanium), CuZnAl, and CuAlNi.
- The two unique properties described above are possible through a solid state phase-change i.e. a molecular rearrangement, which occurs in shape memory alloy.

Applications :

- Coffepots
- Thermostat
- Hydraulic fittings for aeroplanes
- Space shuttle
- Vascular stents etc.

15.3 DIFFERENT TYPE OF SMA

- **Dumb materials :** These materials exhibit only a limited set of responses.
 - Such responses are usually non-optimal for any single set of conditions, but 'optimised' to best fulfill the range of scenarios to which a material or structure may be exposed. example: the wings of an aircraft should be optimised for take-off and landing, fast and slow cruise etc.
- **Biomimetics :** These materials are similar to animals and plants exhibits the clear ability to adapt to their environment in real time. The field of biomimetics, which looks at the extraction of engineering design concepts from biological materials and structures, are helpful to human being on the design of future manmade materials.
- The process of balance is a truly 'smart' or intelligent response, allowing in engineering terms a flexible structure to adapt its form in real time to minimise the effects of an external force, thus avoiding catastrophic collapse.
- **Electro-rheostatic and Magneto-rheostatic :** These materials are fluids, which can experience a dramatic change in their viscosity.
 - These fluids can change from a thick fluid (similar to motor oil) to nearly a solid substance within millisecond when a bring in magnetic or electric field; the effect can be completely reversed just as quickly when the field is off.
 - MR fluids experience a viscosity change when exposed to a magnetic field, while ER fluids similar changes in an electric field.

- The most common form of MR fluid consists of tiny iron particles suspended in oil. ER fluids can be as simple as milk chocolate or cornstarch and oil.
- **Photochromic materials :** These materials change reversibly colour with change in temperature. They can be manufactured as semi-conductor compounds, from liquid crystals or using metal compounds.
- The change in colour found at a determined temperature, which can be varied by doping the material.
- Used in production of paints, inks or are mixed to moulding or casting materials for different applications.
- **Electroluminescent materials :** These materials produce a brilliant light of different colours when stimulated electronically (e.g. by AC current). During emitting light no heat is produced. Like a capacitor, the material is made from an insulating substance with electrodes on each side.
- One of the electrodes is transparent and allows the light to pass. The insulating substance that emits can be made of zinc sulphide.
- They can be used for making light stripes for decorating buildings, or for industrial and public vehicles safety precautions.

Fluorescent materials : These materials give visible or invisible light as a result of light of a shorter wavelength (i.e. X-rays, UV-rays, etc.)

Fluorescent materials disappear as soon as the source of excitement is removed. Fluorescent materials in daylight have a white or light colour, whereas under excitation by UV radiation they irradiate an intensive fluorescent colour.

- They can be used for paints, inks or mixed to moulding or casting materials for different applications.

Other smart materials :

- Phosphorescent materials
- Conducting polymers
- Dielectric elastomers
- Polymer gels
- Magnetostrictive alloys
- Electrostrictive materials
- Piezoelectric materials
- Sensual materials
- **Thermoelectric materials :** Special types of semiconductors that, when coupled, behave as a "heat pump". By applying a low voltage DC power source, heat is moved in the direction of the current positive to negative.
- Generally, used in thermoelectric modules where a single couple or many couples to obtain larger cooling capacity are combined. One face of the module cools down while the other remains in heating state, and the effect is reversible.
- Thermoelectric cooling allows for small size and light devices, high reliability and precise temperature control, and quiet operation.

Disadvantages: High prices and high operating costs, due to low energy efficiency.

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Smart Materials Application

- Fast response valves
- High-power-density hydraulic pumps
- Sports equipment
- Vibration and acoustic sensors
- Active bearings for reduction of machinery noise
- Dampers
- Footwear
- Precision machining, etc.

15.4 NANOTECHNOLOGY

- Nano is the prefix of a unit. One nano is equal to 10^{-9} , and 1 nano meter means 10^{-9} m (i.e. $1\text{nm} = 10^{-9}\text{m}$).
- Technology involving processes, operations, applications and development of devices of such small dimension is referred to as nanotechnology.
- In nanotechnology, the size of material is reduced to the size of nano-domain (one nano-domain) generally refers to 1 to 100 nm).
- By this the changes in different properties of material eg. mechanical, thermal, electrical, optical etc. occur at each level.
- For so small sized material the surface to volume ratios plays an important role and most of the molecules make the material hyperactive by coming on the surface.
- Result of this effect is to change the 'chemical activeness' of material due to which the probability exists for origination of newer alloys, composites, sensors and catalysts.

Uses of Nanotechnology

- **Computer Field**

- In supercomputer** : Now a days 'nanowire' is used instead of a computer 'connector'. Which leads to the memory and speed of computer increases many times. Increase in memory may be as high as 1 million.
- In chips and ICs** : Computer chips, circuits, transistors and registers etc. can be made more useful and of much improved quality as compared to existing chips.

Medical Sciences

- Cancer treatment** : Bacteria tumor cells of gold particle are developed for changing the structure of cancer. It destroy the dangerous element of tumor to the extent possible.

- (ii) **Disease detecting devices** : Nanotechnology based devices such as 'wrist watch' is developed, already, which can to predict the probable diseases/illnesses of the body. Since the disease will be detected at its original stage, an appropriate treatment can be started without delay.

Industries

- **Nanotechnology based paints** : Here titanium dioxide (TiO_2) as nanomaterial) is mixed with the paint; the hardness, shining and life of the paint thus obtained can be many times more than the conventional paint. Carbon & boron nitride nanotubes are promising materials for hydrogen storage.
- **Nanotechnology based clothes** : Such type of clothes are being manufactured by textile industry, which absorb human sweat easily. These clothes are more durable also as compared to conventional clothes.

Other Uses

- **Water purification** : Nano-mineral, nano-gold and nano-silver nitrate are useful to eliminate the harmful element arsenic (As) from water.
- Nanofoster material is used to improve the quality of brightness and contrast of pictures on television.

Future Prospects

Nano material in different forms such as given below.

- | | |
|---------------------------------------|------------------------|
| • Quantum-dot | • Nano-particles |
| • Nano-cluster | • Nano wells and wires |
| • Bulk nanostructured materials | • Magnetic clusters |
| • Carbon nanostructures | • Superfluid clusters |
| • Nanostructured ferromagnetism, etc. | |

Nano-Devices

- | | |
|--|-------------------------|
| • Atom switches | • Drug delivery systems |
| • Nano-electromechanical systems (NEMs) etc. | |
| • Molecular machine | • Nano robots |
| • Single electron transistors | • Nano biometrics |

Nano Electro-Mechanical Systems (NEMs)

- Development of ultra-miniature systems eg. nano-electromechanical systems (NEMs) will ease the maintenance, safety and updating of computers and other hardware.

- Systems will provide almost troublefree services. Installations/equipments into a smaller chamber is possible.
- Many electronic systems may be mounted-on or housed-in the watches, shirt pockets, pens, other body parts and their belongings.

The future expectations of nanotechnology can be viewed in the light of the following development:

Note : Nanoparticles of cadmium selenide (cdSe) are quantum dots, which glow when exposed to ultraviolet light.

- Gold nanoshells are new composite nanoparticles. They consist of a dielectric core (either gold sulphide or silica), with a metal (gold) outer shell. The shell has the same surface properties as colloidal gold and can bind to a variety of biomolecules. By varying the relative thickness of the core and the shell, the optical resonance of gold nanoshell can be shifted from the visible range to the infrared range, which is the range of the highest physiological transmissivity.
- The lithium-ion secondary (rechargeable) batteries have a voltage of ~3.5V, which is three times that of the conventional Ni-Metal hydride batteries. Here lithium cobaltate (LiCoO_2) form the cathode and C or LiC_6 forms the anode. The electrolyte is an organic liquid with a dissolved lithium salt. During charging, the Li^+ ions migrate towards the anode. During discharge, they migrate in the reverse direction towards the cathode.
- Alternate electrode materials like LiFePO_4 could benefit from nanotechnology.

15.5 FUNCTIONALLY GRADED MATERIALS (FGMS)

- An FGM is an inhomogeneous material in which the physical, chemical and mechanical properties change continuously from point to point. No any discontinuities inside.
- Due to gradual change of material properties with position, hence, termed as 'gradient materials'. The property gradient is found due to position dependent parameters as written below.
 - Micro structure
 - Atomic order
 - Chemical composition
- The property variation can extend over a large part of material, on to the surface of the material, or may be limited to a smaller interfacial region only.
- The FGM are useful in the sense that the microstructural gradients produce optimum functional performance with minimum material use.

(NEMs)
hardware.

Example :

- A natural example of FGM is the culm of bamboo in which the high-strength natural fibres are embedded in a matrix of ordinary cells. In that the fibre content is not homogeneous over the entire cross-section of the culm, rather decreases from outside to inside.
- A synthetic example of FGM is case-hardened steel in which the material has a gradation i.e. the surface is hard but the interior is tough.

Types of FGMs

- Based on shape and size of gradient, different types of functionally graded materials are found :
 - (a) fraction gradient type,
 - (b) shape gradient type,
 - (c) orientation gradient type and
 - (d) size gradient type

Application of FGMs**Thermal Protection Systems**

- **Space re-entry vehicles:** A nose cone with a graded SiC protection interlayer on C/C* composite exposed to high temperature supersonic gas flow provide improved thermal protection.
- **Gas turbine blades** made of superalloy and coated with a bond coat of NiCrAlY and heat-insulating layer of ZrO₂, considerably improves the resistance of the coating.
- **Thermal barrier coating (TBC):** By using a 2mm thick graded TBC on piston crowns and cylinder heads of diesel engines, about 5% reduction in fuel consumption can be achieved.

Wear Protection

Wear resistance of tools increases by hard surface layer in a compressive stress state e.g. a WC/Co (stellite) FGM with a gradual variation in Co develops a compressive stress state at the surface.

Medical Implants

Cementless artificial joints: A coating of glass on a Ti-6Al-4 V (titanium-aluminium-vanadium) substrate possessing hydroxyapatite and pores close to its outer surface is an excellent material for making cementless artificial joints and dental implants. The above-mentioned material is a graded composite material.

EnergyThermoelectric
emitter :**Electronics**

Graded composites

Acoustics

Acoustic materials

Optics

X-ray mirrors

15.6 Biomaterials1. Biomaterials
wearExam
resistance(ii) Tissue
production2. Bioceramics
relative

Exam

Applications**Pacemakers**

- Sheath as insulator
- Metal electrodes

Dental Materials

- Tooth (or denture)
- To prevent calcium

Energy Conservation

Thermoelectric converter: $\text{Bi}_2\text{Te}_3/\text{PbTe}/\text{SiGe}$ for improved conversion efficiency. Radiation emitter : A/N/W for improved emissivity.

Electronics

Graded capacitor: $\text{BaTiO}_3/\text{SrTiO}_3$ for zero temperature coefficient of capacitance.

Acoustics

Acoustic coupler: CuMn/WC for acoustic impedance machine.

Optics

X-ray mirror: Si/Ge for graded lattice constant.

15.6 BIOMEDICAL MATERIALS

1. **Biometals** : High strength, good toughness, and biocompatible, Generation of fine wear particles leading to implant loosening and inflammation.

Example : (i) CoCrMo alloy, Excellent wear resistance and excellent corrosion resistance, but release harmful Co, Ni, Cr ions into the body

(ii) Ti alloys, Allows bone growth at the interface, unsatisfactory wear resistance, may produce wear debris

2. **Bioceramics** : Stiff, hard, chemically stable, and very good wear resistant, Brittle and relatively difficult to process.

Example : (i) Alumina, Excellent bio-compatibility and inertness in body.

Application of Biomaterials**Pacemakers**

- Sheathed wires acting as sensing and stimulating electrodes made by Polyurethane as insulation on these wires, silicone.
- Metal casing to house a battery (i.e. pacemaker housing) made by Ti, Pt and Pt-Ir electrodes for providing resistance to galvanic corrosion.

Dental Materials

- Tooth replacement consisting of an implant that is fixed into the bone and a crown (or denture superstructure) made of Alumina, Pure Ti, single crystal sapphire.
- To promote bone growth into implant interface is made by Glass ceramic coatings, calcium phosphate ceramics.

- Tooth crown is made of dental porcelains: Example borosilicate, feldspar glass.
- Crown fusing metals are : Au, Au-Pd, Ag-Pd, Cu-Pd, Ni-Cr

Ophthalmology Materials

- Hydrogel soft contact lenses made of Poly HEMA (hydroxyethylmethacrylate).
- Rubbery soft lenses made of Si-rubbers, fluoropolymers.
- Rigid contact lenses made of PMMA (Polymethylmethacrylate).

Orthopaedics

- Hip and knee implants is done by Ti-6Al-4V, stainless steel.
- Screws, fittings and wires made of Ti-6Al-4V, stainless steels.
- Hip replacement is done by Alumina (polycrystalline).
- Bone repair such as maxillofacial and periodontal defects are cured by Tri-calcium phosphate $\text{Ca}_3(\text{PO}_4)_2$ ceramic.
- Bone plates are made of Polyorthoesters.
- Bone and joint replacement is done by Austenitic 316L stainless steels, Co-Cr alloys, Pure Ti, Ti-6Al-4V, Alumina, Zirconia PMMA, UHMWPE (ultrahighmolecular weight polyethylene).

Cardiovascular Devices

- (i) Hemodialysis machines
 - Arterial feeding catheters are made of Polyurethane, silicone.
 - Membrane inside the dialyzer are made of Cellulosic.
- (ii) Vascular grafts is made of woven fabrics of expanded PTEE, Polyesters and PET (polyester terphthalate).
- (iii) Membrane in oxygenator are made of Perfluorobutyl ethyl cellulose.
- (iv) Cardiac valves :
 - Metal valves made by Ti-alloy, CoCrMo.
 - Non-metal valves made by Silicone elastomer.
- (v) Artificial heart
 - Heart valves made by Polydimethyl siloxane, polyurethane.
 - Pump bladders made by Polyurethanes with layers of butyl rubbers inside.
 - Blood contacting inlet and outlet connectors made by PET.
 - Housing for devices is made by Epoxy, kevlar, polyurethane, polycarbonates, Ti.

Miscellaneous

- Block
- Soft
- Wood
- Tensile
- Drug

Note :

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Miscellaneous

- Blood bags, tubings made by PVC, polyurethanes, silicones.
- Soft tissue reconstruction made by Silicones.
- Wound closure made by Cyanoacrylates.
- Tendon repair made by Polylactic acid.
- Drug delivery system made by Ferrofluids.

Note : Bucky Ball : (buckminster fullerene) A large carbon crystal made up of 60 carbon atoms. Known as C₆₀, having 20 hexagonal and 12 pentagonal planes. The C₆₀ crystal of 0.7mm diameter is completely a bad conductor. This is used in making super conductors, lubricants, catalysts in chemical reactions etc. This is in the shape of football.

- **Chirality :** Variation of the orientation of the rolling axis relative to the hexagonal network of the graphene sheet can produce different types of single walled tubes. This property is known as chirality. Depending on chirality a nano tube can be a semiconductor or a metallic condensor.

QUESTIONS

1. The nanosize range is
 - (a) 1–100 nm
 - (b) 10–1000 nm
 - (c) 0.001–0.1 μm
 - (d) 10–1000 $\text{\AA}$
2. Nanorobots
 - (a) do not exist yet
 - (b) exist in laboratory experiments
 - (c) are used in nanomedicine to remove plaque from the walls of arteries
 - (d) will be used by NASA in the next unmanned mission to Mars
3. A quantum dot is
 - (a) the sharpest possible tip of the Atomic Force Microscope
 - (b) a nanoparticle with electrons confined in all directions
 - (c) a term used in science fiction
 - (d) an unexplained spot of less than 1 nm seen in electron microscope images
4. The name buckminsterfullerene is
 - (a) another name for football
 - (b) polystyrene filled with carbon
 - (c) C_{60} molecule
 - (d) a carbon nanotube
5. Graphene is
 - (a) new material made from carbon nanotubes
 - (b) one-atom thick sheet of graphite
 - (c) a thin film made from fullerene
 - (d) a graphical representation of C_{60} molecule
6. The energy in a fuel cell is produced through
 - (a) oxidation of Pt
 - (b) reducing of Pt
 - (c) an electrochemical reaction
 - (d) burning of a fuel

ANSWERS

1. (a,c,d)	3. (b)	5. (b)
2. (a)	4. (c)	6. (c)