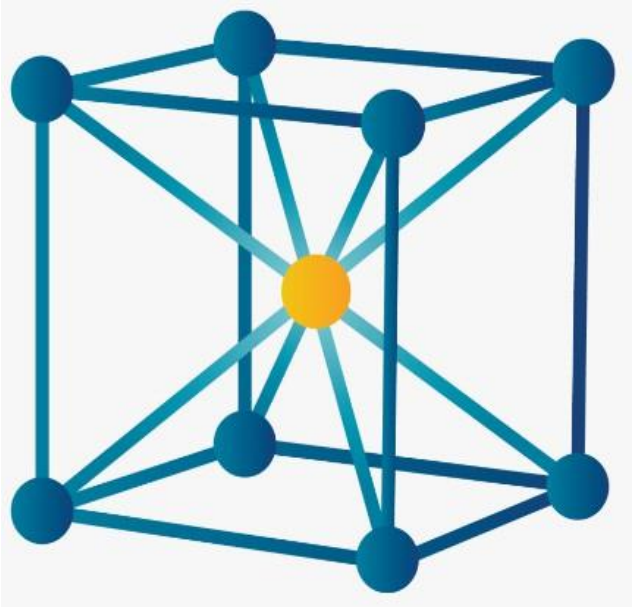


Engineering Materials & Applications

Edited by
Prof. Joydip Ray
Prof. Barun Das

Published by
Department of Mechanical Engineering
IEM Kolkata

Subject Code : PCCME301	**Category** : Engineering Science Courses
Subject Name : Engineering Materials & Applications	**Semester** : Third
L-T-P : 3-0-0	**Credit: 3**
Pre-Requisites: Basic Knowledge of structure of materials	

Course Objective:

1. Broad understanding of different types of engineering materials and their applications.
2. Correlation between the internal structure of materials and their mechanical properties.
3. Various methods to quantify the mechanical integrity of materials and their failure criteria.
4. Interpretation of equilibrium phase diagrams of alloys.
5. Different heat treatment methods to tailor the properties of Fe-C alloys.

Course Content:

Module No.	Module Name with details	Lecture (L)
1.	**Engineering Materials and Classification**: Metals, plastics, ceramics and composites; Relevant properties (physical, mechanical, thermal, electrical, chemical), cost; Range of applications; Material designation and standards; Ashby diagrams; Selection criteria and process	6
2.	**Mechanical Properties and Testing:** Tensile, compression, torsion, fatigue, fracture and wear tests; Young's modulus; Relations between true and engineering stress-strain curves; Generalized Hooke's law; Yielding and yield strength; ductility, resilience, toughness and elastic recovery; Hardness measurement their relation to strength; SN curve, endurance and fatigue limits; Introduction to non-destructive testing (NDT).	8
3.	**Metal and Alloys:** Iron and steel; Stainless steel and tool steels; Copper & its alloys – brass, bronze &cupro-nickel; Aluminium& Al-Cu-Mg alloys; Nickel based superalloys& Titanium alloys; Phase diagrams and interpretation of microstructure; Iron Iron-carbide phase diagram and cooling (TTT) diagrams.	8

4.	**Heat Treatment:** Heat treatment of Steel; Annealing, tempering, normalizing, spheroidising, austempering, martempering, case hardening, carburizing, nitriding, cyaniding, carbo-nitriding, flame and induction hardening, vacuum and plasma hardening	8
5.	**Polymers, Ceramics and Composites:** Polymers – Classification and applications; Polymerization techniques; Ceramics – Oxide ceramics, ceramic insulators, bio-ceramics and Glasses; Composites – Reinforcement, matrix, metal matrix composites, ceramic composites, polymer composites; Other advanced materials – biomaterials, optical materials, high temperature materials, energy materials, and nano materials.	6
6.	**Electrical and Magnetic Materials:** Conducting and resisting materials – types, properties and applications; Semiconducting materials – properties and applications; Magnetic materials – Soft and hard magnetic materials and applications; Superconductors and dielectric materials – properties and applications; Smart materials; Sensors and actuators; Piezoelectric, magnetostrictive and electrostrictive materials.	6

Course Outcomes

CO1: Student will be able to identify crystal structures for various materials.
CO2: Student will be able to understand defects in crystal structures.
CO3: Understand how to tailor material properties of ferrous and non-ferrous alloys.
CO4: How to quantify mechanical integrity and failure in materials.

Learning Resources

Text Book:

1. A Textbook of material science and metallurgy by O P Khanna

Reference Book:

1. R.K.Rajput, “Material Science and Engineering”, 5th Edition, Katson Publications.

2. W. D. Callister, 2006, “Materials Science and Engineering-An Introduction”, 6th Edition, Wiley India.

3. William F Smith, Hashemi, Prakash, “Materials Science and Engineering" Mc Graw Hill

4. V. Raghavan, “Material Science and Engineering’, Prentice Hall of India Private Limited, 1999.

5. U. C. Jindal, “Engineering Materials and Metallurgy”, Pearson, 2011.

6. 3.. M.F. Ashby and D.R.H. Jones, Engineering Materials 1 - An Introduction to Properties, Applications and Design, Butterworth-Heinemann, USA, 2011.

Online Resources:

1. https://onlinecourses.nptel.ac.in/noc22_me90/preview

Module 1
Engineering Materials and Classification

Topics:

Metals, plastics, ceramics and composites; Relevant properties (physical, mechanical, thermal, electrical, chemical), cost; Range of applications; Material designation and standards; Ashby diagrams; Selection criteria and process

The chapter explores the distinct classes of materials that play crucial roles in modern engineering and manufacturing. Metals, Polymers, ceramics, and composites each possess unique properties and offer a wide range of applications in various industries. Throughout this chapter, we will delve into the characteristics, processing techniques, applications, and advantages of different metals, polymers, ceramics, and composites.

Module 2
Mechanical Properties and Testing

Topics:

Tensile, compression, torsion, fatigue, fracture and wear tests; Young's modulus; Relations between true and engineering stress-strain curves; Generalized Hooke's law; Yielding and yield strength; ductility, resilience, toughness and elastic recovery; Hardness measurement their relation to strength; SN curve, endurance and fatigue limits; Introduction to non-destructive testing (NDT).

MECHANICAL PROPERTIES OF ENGINEERING MATERIALS

Often materials are subject to forces (loads) when they are used. Mechanical engineers calculate those forces and material scientists how materials deform (elongate, compress, twist) or break as a function of applied load, time, temperature, and other conditions.

Materials scientists learn about these mechanical properties by testing materials. Results from the tests depend on the size and shape of material to be tested (specimen), how it is held, and the way of performing the test. That is why we use common procedures, or standards.

The engineering tension test is widely used to provide basic design information on the strength of materials and as an acceptance test for the specification of materials. In the tension test a specimen is subjected to a continually increasing uniaxial tensile force while simultaneous observations are made of the elongation of the specimen. The parameters, which are used to describe the stress-strain curve of a metal, are the tensile strength, yield strength or yield point, percent elongation, and reduction of area. The first two are strength parameters; the last two indicate ductility.

In the tension test a specimen is subjected to a continually increasing uniaxial tensile force while simultaneous observations are made of the elongation of the specimen. An engineering stress-strain curve is constructed from the load elongation measurements.

The tensile test is probably the simplest and most widely used test to characterize the mechanical properties of a material. The test is performed using a loading apparatus such as the Tinius Olsen machine. The capacity of this machine is 10,000 pounds (tension and compression). The specimen of a given material (i.e. steel, aluminum, cast iron) takes a cylindrical shape that is 2.0 in. long and 0.5 in. in diameter in its undeformed (with no permanent strain or residual stress), or original shape.

The results from the tensile test have direct design implications. Many common engineering structural components are designed to perform under tension. The truss is probably the most common example of a structure whose members are designed to be in tension (and compression).

Concepts of Stress and Strain

Stress can be defined by ratio of the perpindicular force applied to a specimen divided by its original cross sectional area, formally called engineering stress

To compare specimens of different sizes, the load is calculated per unit area, also called normalization to the area. Force divided by area is called stress. In tension and compression tests, the relevant area is that perpendicular to the force. In shear or torsion tests, the area is perpendicular to the axis of rotation. The stress is obtained by dividing the load (F) by the original area of the cross section of the specimen (AO).

$$\sigma = \frac{F}{A_0}$$

The unit is the Mega pascal = 10^6 Newtons/m2.

There is a change in dimensions, or deformation elongation, □L as a result of a tensile or compressive stress. To enable comparison with specimens of different length, the elongation is also normalized, this time to the length lo. This is called strain. So, Strain is the ratio of change in length due to deformation to the original length of the specimen, formally called engineering strain. strain is unitless, but often units of m/m (or mm/mm) are used

The strain used for the engineering stress-strain curve is the average linear strain, which is obtained by dividing the elongation of the gage length of the specimen, by its original length.

$$\varepsilon = \frac{l_i - l_o}{l_o} = \frac{\Delta l}{l_o}$$

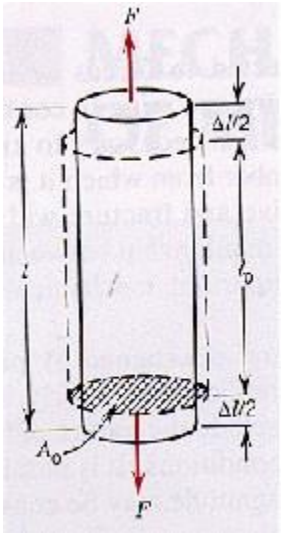
Since both the stress and the strain are obtained by dividing the load and elongation by constant factors, the load-elongation curve will have the same shape as the engineering stress-strain curve. The two curves are frequently used interchangeably.

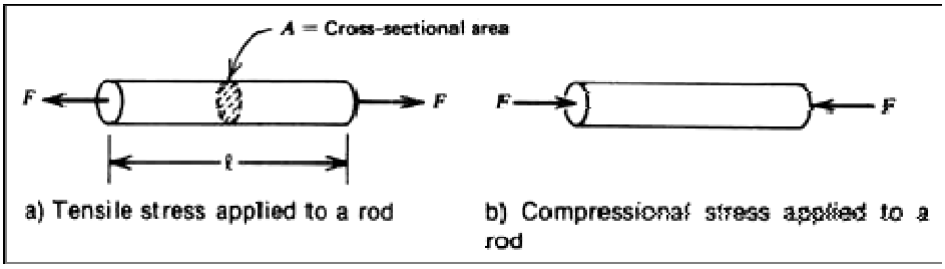
The shape and magnitude of the stress-strain curve of a metal will depend on its composition, heat treatment, prior history of plastic deformation, and the strain rate, temperature, and state of stress imposed during the testing. The parameters used to to describe stress-strain curve are tensile strength, yield strength or yield

point, percent elongation, and reduction of area. The first two are strength parameters; the last two indicate ductility.

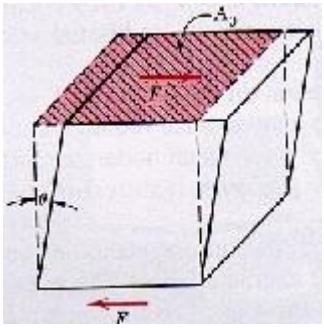
The general shape of the engineering stress-strain curve requires further explanation. In the elastic region stress is linearly proportional to strain. When the load exceeds a value corresponding to the yield strength, the specimen undergoes gross plastic deformation. It is permanently deformed if the load is released to zero. The stress to produce continued plastic deformation increases with increasing plastic strain, i.e., the metal strain-hardens. The volume of the specimen remains constant during plastic deformation, $A \cdot L = A0 \cdot L0$ and as the specimen elongates, it decreases uniformly along the gage length in cross-sectional area.

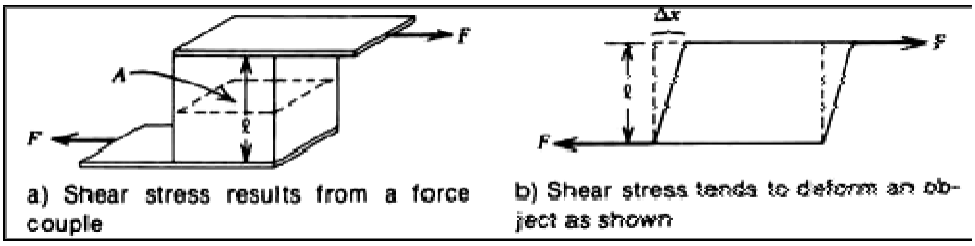
Initially the strain hardening more than compensates for this decrease in area and the engineering stress (proportional to load P) continues to rise with increasing strain. Eventually a point is reached where the decrease in specimen cross- sectional area is greater than the increase in deformation load arising from strain hardening. This condition will be reached first at some point in the specimen that is slightly weaker than the rest. All further plastic deformation is concentrated in this region, and the specimen begins to neck or thin down locally. Because the cross- sectional area now is decreasing far more rapidly than strain hardening increases the deformation load, the actual load required to deform the specimen falls off and the engineering stress likewise continues to decrease until fracture occurs.





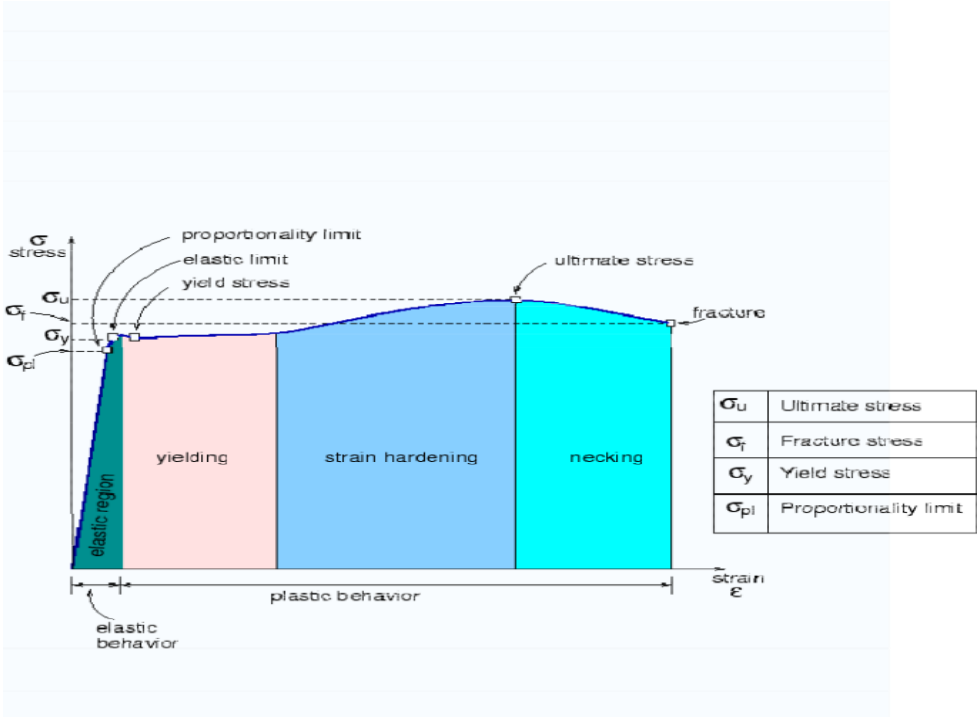
Tensile and compression stress can be defined in terms of forces applied to a uniform rod.



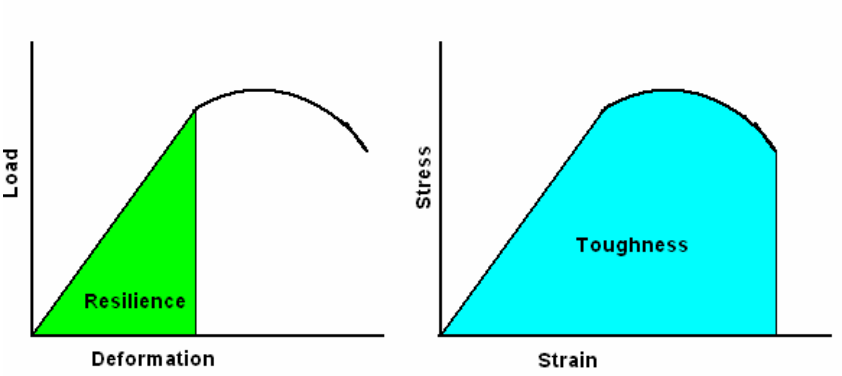


Shear stress is defined in terms of a couple that tends to deform a joining member

A stress-strain curve is a graph derived from measuring load (stress - σ) versus extension (strain - ε) for a sample of a material. The nature of the curve varies from material to material. The following diagrams illustrate the stress-strain behaviour of typical materials in terms of the engineering stress and engineering strain where the stress and strain are calculated based on the original dimensions of the sample and not the instantaneous values. In each case the samples are loaded in tension although in many cases similar behaviour is observed in compression.



Various regions and points on the stress-strain curve



Comparison between resilience and toughness of metals

Impact Toughness

Three of the toughness properties that will be discussed in more detail are 1) impact toughness, 2) notch toughness and 3) fracture toughness.

The impact toughness (AKA Impact strength) of a material can be determined with a Charpy or Izod test. These tests are named after their inventors and were developed in the early 1900's before fracture mechanics theory was available.
Impact properties are not directly used in fracture mechanics calculations, but the economical impact tests continue to be used as a quality control method to assess notch sensitivity and for comparing the relative toughness of engineering materials.

The two tests use different specimens and methods of holding the specimens, but both tests make use of a pendulum-testing machine. For both tests, the specimen is broken by a single overload event due to the impact of the pendulum. A stop pointer is used to record how far the pendulum swings back up after fracturing the specimen. The impact toughness of a metal is determined by measuring the energy absorbed in the fracture of the specimen. This is simply obtained by noting the height at which the pendulum is released and the height to which the pendulum swings after it has struck the specimen . The height of the pendulum times the weight of the pendulum produces the potential energy and the difference in potential energy of the pendulum at the start and the end of the test is equal to the absorbed energy.

Since toughness is greatly affected by temperature, a Charpy or Izod test is often repeated numerous times with each specimen tested at a different temperature. This produces a graph of impact toughness for the material as a function of temperature. An impact toughness versus temperature graph for a steel is shown in the image. It can be seen that at low temperatures the material is more brittle and impact toughness is low. At high temperatures the material is more ductile and impact toughness is higher. The transition temperature is the boundary between brittle and ductile behavior and this temperature is often an extremely important consideration in the selection of a material.

Notch-Toughness

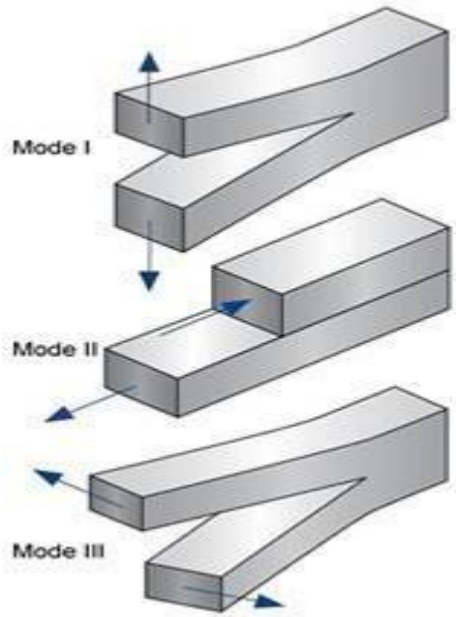
Notch toughness is the ability that a material possesses to absorb energy in the presence of a flaw. As mentioned previously, in the presence of a flaw, such as a notch or crack, a material will likely exhibit a lower level of toughness. When a flaw is present in a material, loading induces a triaxial tension stress state adjacent to the flaw. The material develops plastic strains as the yield stress is exceeded in the region near the crack tip. However, the amount of plastic deformation is restricted by the surrounding material, which remains elastic. When a material is prevented from deforming plastically, it fails in a brittle manner.

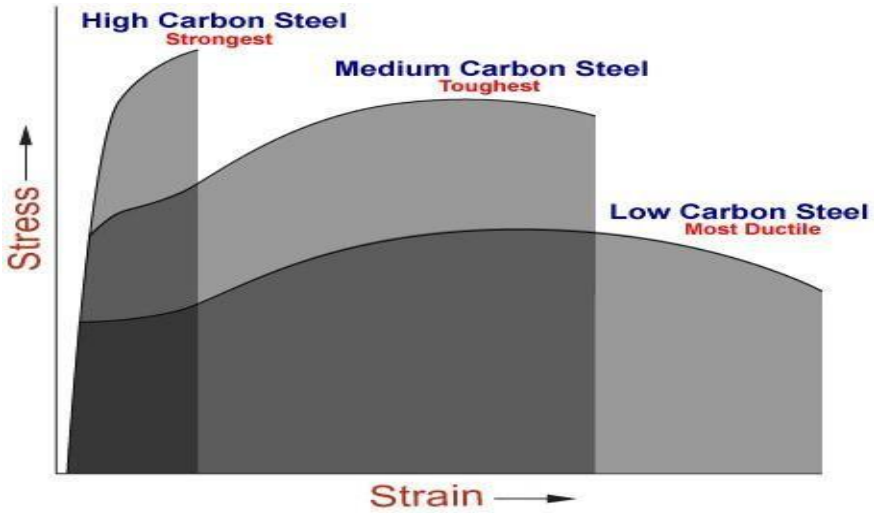
Notch-toughness is measured with a variety of specimens such as the Charpy V- notch impact specimen or the dynamic tear test specimen. As with regular impact testing the tests are often repeated numerous times with specimens tested at a different temperature. With these specimens and by varying the loading speed and the temperature, it is possible to generate curves such as those shown in the graph. Typically only static and impact testing is conducted but it should be recognized that many components in service see intermediate loading rates in the range of the dashed red line.

Fracture toughness

It is an indication of the amount of stress required to propagate a preexisting flaw. It is a very important material property since the occurrence of flaws is not completely avoidable in the processing, fabrication, or service of a material/component. Flaws may appear as cracks, voids, metallurgical inclusions, weld defects, design discontinuities, or some combination thereof. Since engineers can never be totally sure that a material is flaw free, it is common practice to assume that a flaw of some chosen size will be present in some number of component.

This approach uses the flaw size and features, component geometry, loading conditions and the material property called fracture toughness to evaluate the ability of a component containing a flaw to resist fracture.





There are several variables that have a profound influence on the toughness of a material. These variables are:

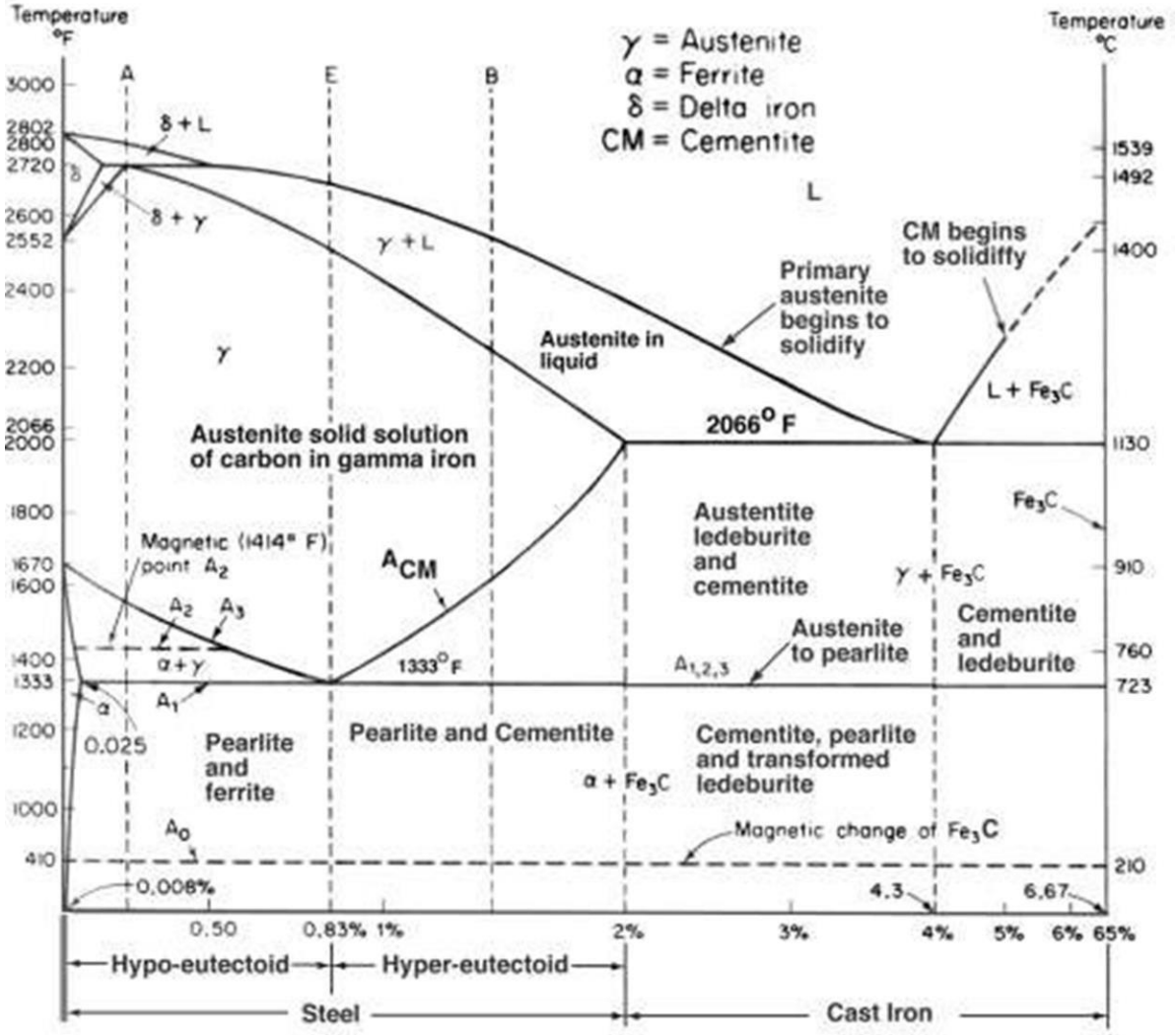
Strain rate (rate of loading)
Temperature
Notch effect

A metal may possess satisfactory toughness under static loads but may fail under dynamic loads or impact. As a rule ductility and, therefore, toughness decrease as the rate of loading increases. Temperature is the second variable to have a major influence on its toughness. As temperature is lowered, the ductility and toughness

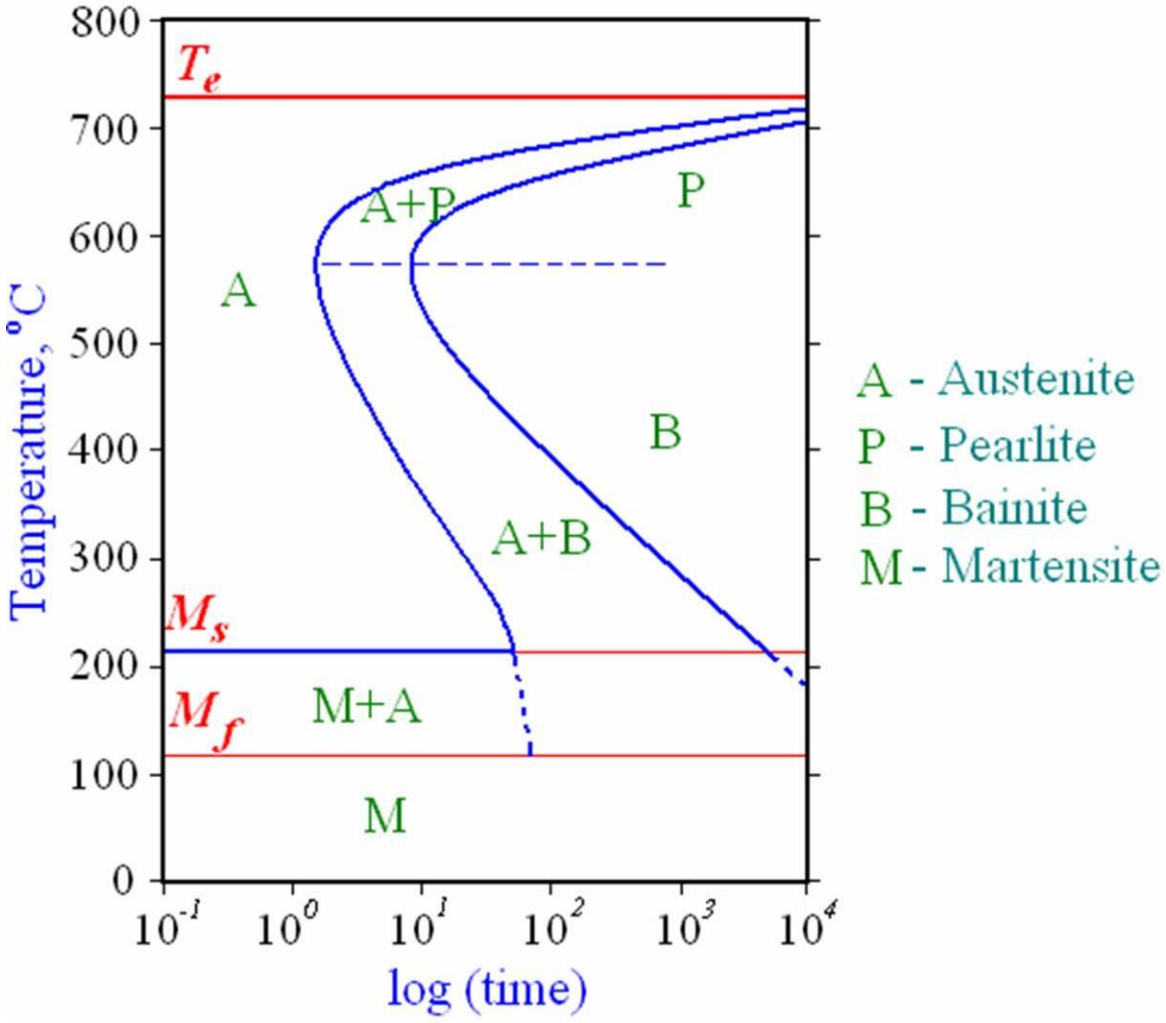
Module 3
Metal and Alloys

Topics:

Iron and steel; Stainless steel and tool steels; Copper & its alloys – brass, bronze &cupro-nickel; Aluminium& Al-Cu-Mg alloys; Nickel based superalloys& Titanium alloys; Phase diagrams and interpretation of microstructure; Iron Iron-carbide phase diagram and cooling (TTT) diagrams.



Fe-Fe_3C diagram



Complete TTT (isothermal transformation) diagram for eutectoid steel

Module 4
Heat treatment

Topics: Heat treatment of Steel; Annealing, tempering, normalizing, spheroidising, austempering, martempering, case hardening, carburizing, nitriding, cyaniding, carbo-nitriding, flame and induction hardening, vacuum and plasma hardening

Heat treatment is a vital and widely used process in the field of metallurgy and materials science. It involves the controlled heating and cooling of materials to alter their physical and sometimes chemical properties. This transformative process aims to enhance the material's mechanical properties, such as hardness, toughness, strength, and ductility, while also improving its microstructure. In this chapter, we will explore the fundamental principles of heat treatment, the various techniques and processes involved, and the impact of heat treatment on material properties.

Heat treatment- Introduction

Heat treatment is a process used to alter the physical and sometimes chemical properties of materials, particularly metals and alloys. The treatment involves heating and cooling the material in a controlled manner to achieve desired characteristics such as hardness, toughness, strength, ductility, and even specific microstructures.

Heat treatment of Steel

Heat treatment of steel is a critical process used to alter the microstructure and properties of steel, a widely used alloy composed primarily of iron and carbon. Through controlled heating and cooling, heat treatment enables engineers and metallurgists to achieve specific characteristics in steel, such as hardness, toughness, strength, and ductility, making it suitable for various applications.

Figure 4.1 shows the temperature ranges and heat treatment processes. Common microstructure of steel obtained during heat treatment is shown in Fig. 4.2. Figure shows the iron-iron carbide phase diagram in the vicinity of the eutectoid.

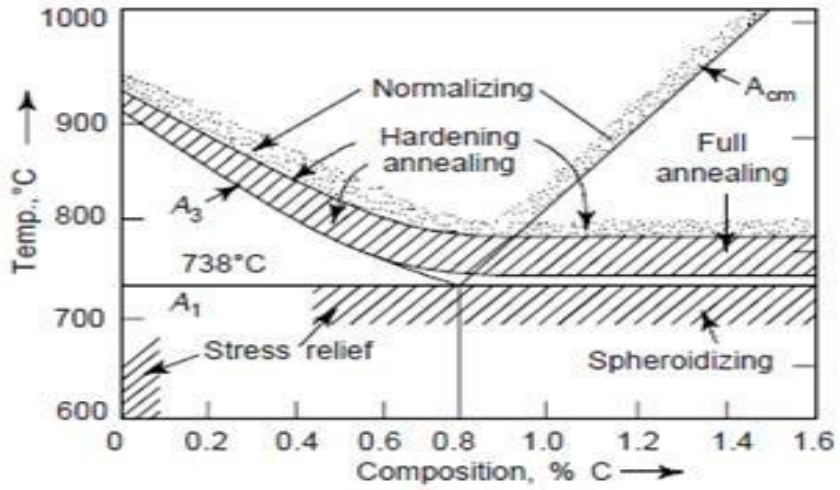
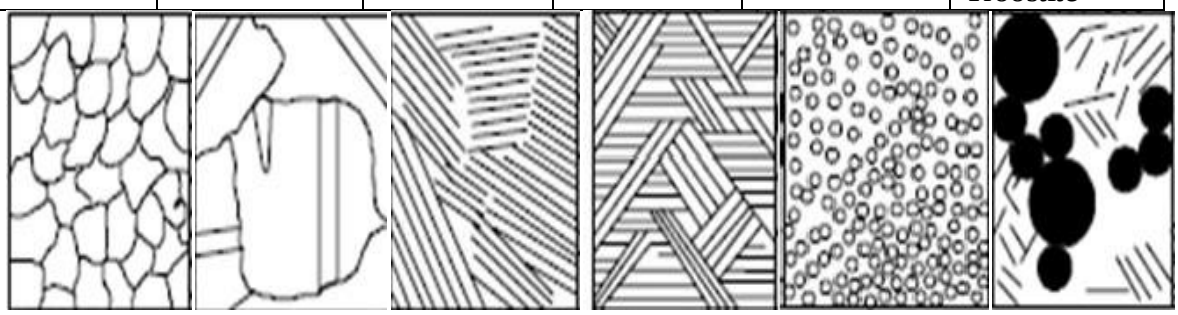


Fig. 4.1 Heat treatment process for various temperature ranges of steel

Ferrite	Austenite	Pearlite	Martensite	Sorbite	Nodular Troostite

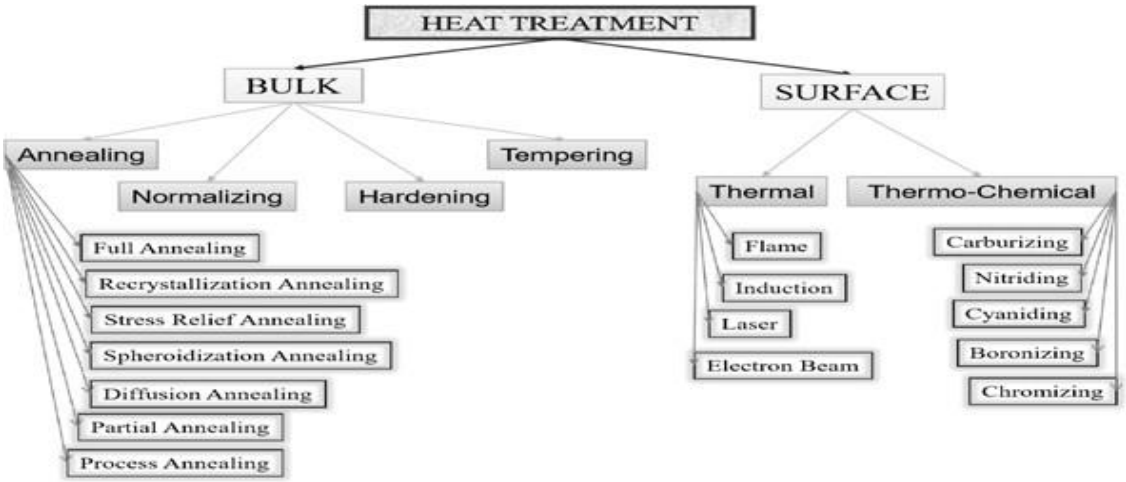


The purpose of heat treatment

- To remove strain hardening of a cold worked metal and to improve its ductility.
- To relieve internal stresses set up during cold-working, casting, welding and hot-working treatments.
- To remove gases from castings, to soften a metal to improve its machinability, and to increase the resistance to wear, heat and corrosion.
- To improve the cutting ability, i.e., hardness of a steel tool, to improve grain structure after hot working a metal and to remove effects of previously performed heat-treatment operations.
- To improve magnetization property, especially of steels, for producing permanent magnets.
- To refine grain structure after hot working a metal.
- To soften and toughen a high carbon steel piece.
- To produce a single phase alloy in stainless steel, and to produce a hard, wear resistant case on a tough core of a steel part.
-

- To harden non-ferrous metals and alloys, especially aluminium alloys and to produce a single phase alloy in stainless steel.
- To produce a hard, wear resistant case on a tough core of a steel part and to toughen a hardened steel piece at the cost of its hardness.

Classification of Heat Treatment process



The principal kinds of heat treatment are:

(i) *Annealing*

(ii) *Normalising*

(iii) *Hardening*

(iv) *Tempering*

(v) *Case hardening*

(vi) *Surface hardening*

(vii) *Ageing.*

Each of them has a number of varieties.

(i) Annealing:

Annealing refers to a process in which a material, usually a metal or glass, is heated to a high temperature and then slowly cooled to alter its physical or chemical properties. The purpose of annealing is to relieve internal stresses, improve ductility, and refine the microstructure of the material. This process is widely used in metallurgy, glassmaking, and certain types of semiconductor manufacturing.

In metallurgy, annealing is used to soften a metal and make it more workable. During the heating phase, the metal's grain structure grows larger and more uniform, and any defects or dislocations in the crystal lattice are reduced or eliminated. When the material is cooled slowly, the stresses are minimized, making the metal less brittle and more ductile. Annealing can also be used to remove the effects of cold working or to homogenize the composition of an alloy.

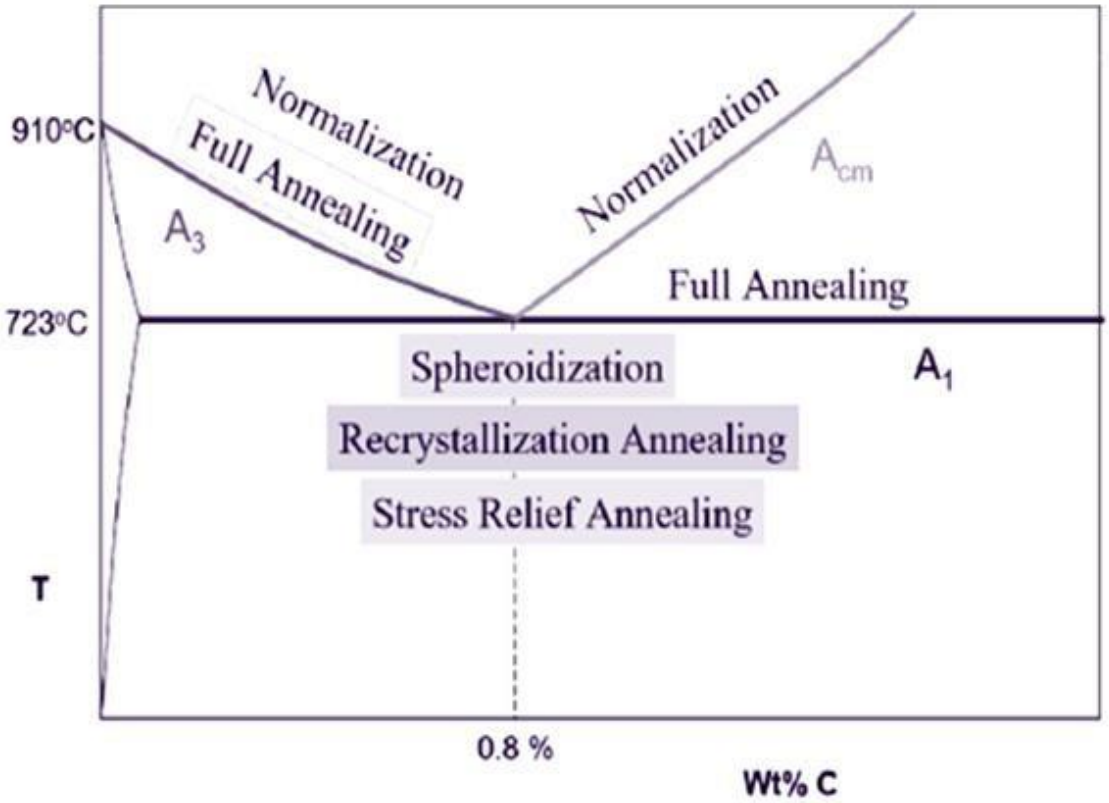
The various types of annealing operations are:

1. *Full annealing,*
2. *Process annealing,*
3. Partial annealing
4. *Stress relief Annealing*
5. *Recrystallization annealing*
6. *Spheroidise annealing*
7. *Diffusion annealing.*

1. *Full annealing,:* This operation removes all structural imperfections by complete recrystallization. This operation is often utilized in low and medium carbon steels that will be machined or will experience extensive plastic deformation during a forming operation. This operation consist of:

a. *Heating the hypoeutectoid steel to about 50-70°C above the upper critical temperature (for hypoeutectoid* steels*) and by the same temperature above the lower critical temperature for hypereutectoid steels* until equilibrium is achieved. This ensures that the metal is heated thoroughly and phase transformation has taken place throughout the whole volume.

b. *The alloy is then furnace cooled; i.e., the heat-treating furnace is turned off and both furnace and steel* cool to room temperature at the same rate, which takes several hours. The microstructural product of full anneal is coarse pearlite (in addition to any proeutectoid phase) that is relatively soft and ductile. The full-annealing cooling procedure is time consuming; however, a microstructure having small grains and a uniform grain structure results.



2. **Process annealing or sub-critical annealing**

Process annealing or sub-critical annealing which is done on cold worked low carbon steel sheet, wire or tubing to relieve internal stresses and to soften the material. The process is as follows:

(i) *The steel is heated to 550-650°C, which is just below the lower* critical temperature on iron-carbon diagram for steel.

(ii) Stresses throughout the metal are relieved and recrystallization causes new grains to form and grow. Changes taking place during process annealing are shown in Fig.

Heating period is followed by slow cooling.

3. Partial annealing is also referred to as inter critical annealing or incomplete annealing. In this process, steel is heated between the A_1 and the A_3 or A_{cm}. It is followed by slow cooling. Generally, hypereutectoid steels are subjected to this treatment.

Resultant microsructure consists of fine pearlite and cementite. The reason for this is that grain refinement takes place at a temperature of about 10 to 30°C above Ac1 for hypereutectoid steels.

As low temperature are involved in this process, so it is cost effective than full annealing.

4. **Stress relief Annealing**

Internal residual stresses may develop in metal pieces due to:

(i) plastic deformation processes such as matching and grinding; *(ii) non uniform cooling of a piece that was processed or fabricated at an elevated*
temperature, such as a weld or a casting; and *(iii) a phase transformation that is induced upon cooling where* in parent and product phases have different densities.
(ii) Distortion and warpage may result in case if residual stresses are not removed. They can be eliminated by this process-in which the piece is heated to the recommended temperature, held there long enough to attain a uniform temperature, and finally cooled to room temperature in air.
We may note that the annealing temperature is ordinarily a relatively low one such that effects resulting from cold working and other heat treatments are not affected, castings, forgings, weldment and other work pieces may have residual stresses.

5. **Recrystallization annealing** is a heat treatment process used to eliminate the effects of cold work or strain hardening in metals and alloys. Cold work refers to the plastic deformation of a material at temperatures below its recrystallization temperature, which leads to an increase in its strength and hardness but also induces internal stresses and reduces ductility.

   The purpose of recrystallization annealing is to restore the material's ductility and improve its mechanical properties by inducing the growth of new, strain-free grains. The process involves heating the cold-worked material to a specific temperature below its melting point, but above its recrystallization temperature. The recrystallization temperature varies depending on the material and its composition.

6. **Spheroidization annealing** is a heat treatment process applied to certain types of metals and alloys, particularly carbon steels and certain non-ferrous alloys, to achieve a microstructure with spheroidal or globular carbides. This annealing process is primarily used to improve the machinability, ductility, and toughness of the material.

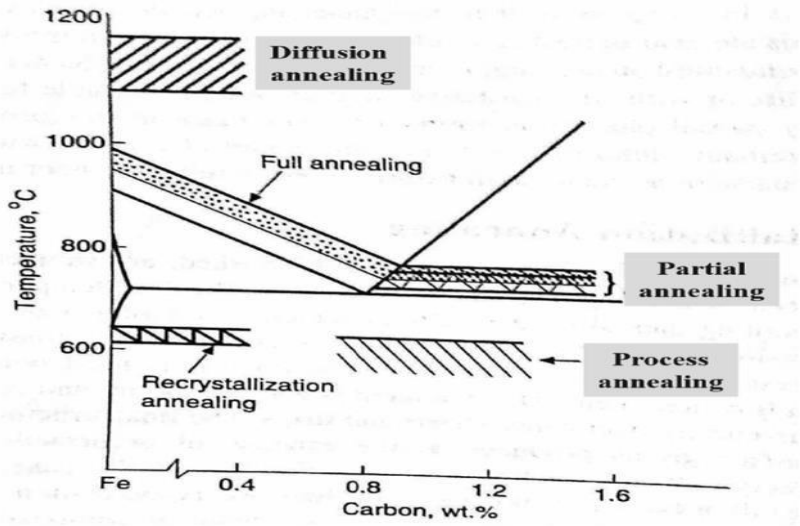
   The starting microstructure of the material typically contains cementite (Fe3C) or other carbides in a lamellar or needle-like form, which can make the material hard and brittle. Spheroidization annealing aims to transform these carbides into rounded, spheroidal shapes, leading to enhanced mechanical properties and machinability.

   Spheroidization annealing is commonly employed in the production of high-carbon steels, such as bearing steels, where good machinability and resistance to wear are essential. It is also used in some non-ferrous alloys where carbides are present, to enhance their formability and overall mechanical properties.

7. **Diffusion Annealing**: This process also known as homogenizing annealing, is employed to remove any structural non-uniformity. Dendrites, columnar grains and chemical in homogeneities are generally observed in the case of ingots, heavy plain carbon steel casting, and high alloy steel castings. These defects promote brittleness and reduce ductility and toughness of steel.

In diffusion annealing treatment, steel is heated sufficiently above the tipper critical temperature (say, 1000-1200°C), and is held at this temperature for prolonged periods, usually 10-20 hours, followed by slow cooling. Segregated zones are eliminated and chemically homogeneous coarse grain steel is obtained by this treatment as a result of diffusion.

The coarse grained structure can be refined either by plastic working for ingots or by employing a second heat treatment for castings. Hypoeutectoid and eutectoid steel castings are given full annealing treatment, whereas hypereutectoid steel castings are either normalized or partially annealed for this purpose.



Temperature range for various Annealing process

(ii) **Normalizing:** This is used as a finishing treatment for carbon steels giving higher strength than annealing. There is no serious loss of ductility too. Heating and soaking in this process is same as in the full annealing but part is allowed to cool in air so that cooling rate is much faster. An annealing heat treatment called normalizing is used to refine the grains (i.e., to decrease the average grain size) and produce a more uniform and desirable size distribution.

Fine grained pearlite steels are tougher than coarse-grained ones. The fine grain structure increases the yield and ultimate strengths, hardness and impact strength. Normalizing is accomplished by heating at approximately 55 to 85°C above the upper critical temperature, which is, of course, dependent on composition.

Normalizing often applied to castings and forgings as stress relieving process. To some extent, it increases strength of medium carbon steel. It improves machinability, when applied to low carbon steel.

The advantages of this method are:

- In comparison to fully annealed material, normalizing produces stronger material.
- Normalizing refines the grains.
- Normalizing produces homogenised structure.
- Normalizing is used to improve properties of steel castings instead of hardening and tempering.
- Strength and hardness are increased.
- Better surface finish is obtained in machining.
- Resistance to brittle fracture is increased in hot-rolled steel.
- Crack propagation is checked.

Annealed Vs Normalised

Sr. No.	**Annealed**	**Normalised**
1	Less hardness tensile strength and toughness	Slightly more hardness tensile strength and toughness
2	Pearlite is coarse and usually gets resolved by the optical microscope	Pearlite is fine and usually appears unresolved with optical microscope
3	Grain size distribution is more uniform	Grain size distribution is slightly less uniform
4.	Internal stresses are least	Internal stresses are slightly *more*

(iii) Tempering

Tempering is a heat treatment process used to improve the mechanical properties of metals, particularly steel, after they have been quenched or hardened. Quenching is a rapid cooling process used to harden the material, but it often results in a very hard and brittle structure that may be too brittle for practical use. Tempering is then applied to reduce this brittleness and achieve a balance of hardness and toughness in the material.

The tempering process involves reheating the hardened steel to a specific temperature below its critical point (the temperature at which the steel undergoes a phase change) and holding it at that temperature for a certain period. The exact temperature and holding time depend on the desired mechanical properties for the specific application.

The tempering process is widely used in various industries, including automotive, aerospace, tool manufacturing, and general engineering, to achieve the desired combination of strength and toughness in steel components.

(iv) **Hardening:**

Hardening is a heat treatment process used to increase the hardness and strength of a metal by transforming its microstructure, typically through rapid cooling (quenching) from a high temperature. The main objective of hardening is to achieve a hard and wear-resistant surface while maintaining a relatively tough and ductile core. Hardening is widely used for various applications, including tool manufacturing, gears, bearings, and cutting edges.

Here's a more detailed explanation of the hardening process:

1. Heating: The metal is heated to a temperature above its critical temperature, which varies depending on the material's composition. For steel, the critical temperature is typically above the upper transformation temperature, known as A3. Heating is usually done in a furnace to ensure uniform temperature throughout the metal.
2. Soaking: After reaching the desired temperature, the metal is held at that temperature for a certain period. This soaking time is crucial as it allows the internal microstructural changes to occur uniformly throughout the metal. The soaking time is determined based on the metal's size, composition, and desired properties.
3. Quenching: The most critical step of the hardening process is the rapid cooling, also known as quenching. Quenching is typically done by immersing the heated metal into a quenching medium, such as water, oil, brine, or air. The choice of quenching medium determines the cooling rate, which directly affects the resulting microstructure and hardness of the metal.

   During quenching, the metal transforms from austenite (a high-temperature phase) to martensite (a hard and brittle phase). The rapid cooling suppresses the formation of other phases, such as pearlite or bainite, resulting in the martensitic structure. Martensite is known for its high hardness and strength but can also be brittle.

   After the hardening process, the metal is usually too hard and brittle for practical use, and further heat treatment steps like tempering may be required to improve its toughness and reduce internal stresses.

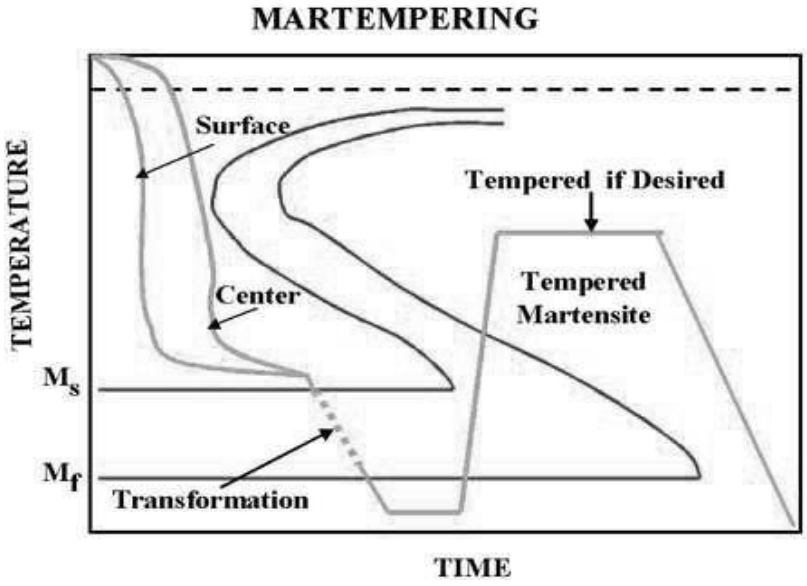
   Quenching Media: Quenching media refers to the various substances used to rapidly cool the heated metal during the hardening process. The choice of quenching media significantly influences the cooling rate and, consequently, the resulting microstructure and material properties. Common quenching media include:

   - Water: Provides the fastest cooling rate, leading to high hardness but also an increased risk of distortion and cracking.
   - Oil: Offers a moderate cooling rate, providing a balance between hardness and reduced risk of cracking.

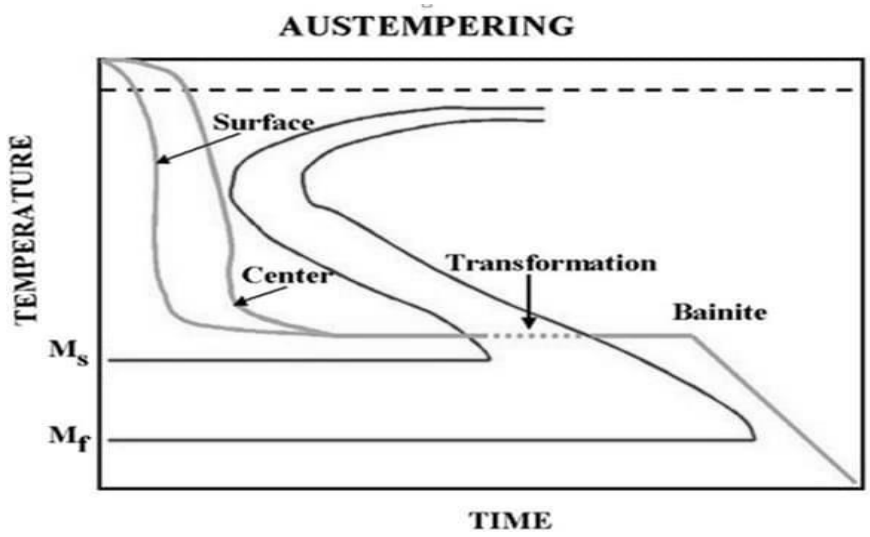
- Brine: Provides a faster cooling rate than oil but slower than water, offering a compromise between hardness and distortion.
- Air: Provides slower cooling, leading to a softer structure compared to liquid quenching.

Types of Hardening:

1. **Quench Hardening (Austenitizing and Quenching):** This is the most common form of hardening for steel. The material is heated above its critical temperature to form austenite, a high-temperature phase. It is then rapidly quenched in water, oil, or polymer to transform the austenite into martensite, a hard and brittle phase responsible for the increased hardness and strength.
2. **Martempering (Marquenching):** In martempering, the material is quenched to a temperature just above the martensite start temperature and then held at that temperature until the transformation to bainite is complete. This process reduces distortion and cracking that can occur during conventional quenching and tempering.



3. **Austempering:** Austempering involves quenching the material to a temperature just above the martensite start temperature and then holding it at that temperature until the transformation to bainite is complete. This results in a microstructure with improved toughness and reduced distortion compared to conventional quenching and tempering.



4. **Flame Hardening:** In flame hardening, a localized area of the material's surface is heated using an oxy-acetylene torch or similar flame source. After heating, the surface is rapidly quenched with water or another medium to achieve surface hardening while maintaining a softer core.
5. **Induction Hardening:** Induction hardening uses electromagnetic induction to heat a localized area of the material's surface. The heated area is then rapidly quenched to achieve surface hardening while retaining a relatively softer core.

(v) Case hardening:

Case hardening is a heat treatment process used to increase the surface hardness of low-carbon steels and certain other alloys while maintaining a relatively soft and ductile core. This method involves introducing additional carbon, nitrogen, or other hardening elements into the surface of the material, creating a hardened "case" with a tough and resilient core. Case hardening is commonly employed to achieve wear resistance and toughness in parts that undergo friction and wear on the surface. Let's explore the main types of case hardening:

1. **Carburizing:** Carburizing is one of the most common and widely used case hardening techniques. The process involves introducing additional carbon into the surface of the low-carbon steel. Carburizing is achieved by heating the material in a carbon-rich environment, such as the presence of carbonaceous gases or solids (e.g., charcoal). Carbon atoms diffuse into the surface of the material at elevated temperatures, creating a high-carbon layer. After carburizing, the material is typically quenched and followed by tempering to achieve the desired hardness and core properties.
2. **Nitriding:** Nitriding is a case hardening process that introduces additional nitrogen into the surface of the material. The material is heated in an atmosphere containing

3. nitrogen, which causes nitrogen atoms to diffuse into the surface and form hard nitride compounds. Nitriding is particularly useful for parts that require excellent wear and corrosion resistance. There are two main types of nitriding processes:
    - Gas Nitriding: The material is placed in a furnace with a controlled nitrogen atmosphere.
    - Plasma Nitriding: The material is subjected to a low-pressure plasma containing nitrogen ions.
4. **Carbonitriding:** Carbonitriding is a combination of carburizing and nitriding. In this process, both carbon and nitrogen are introduced into the surface of the material simultaneously. Carbonitriding produces a hard case with improved wear and fatigue resistance.
5. **Cyaniding:** Cyaniding is a case hardening process that introduces carbon and nitrogen into the surface of low-carbon steels using cyanide salts. The material is immersed in a cyanide salt bath containing carbon and nitrogen sources, and then heated to promote diffusion of these elements into the surface. Cyaniding produces a very hard and uniform case with excellent wear resistance.
6. **Induction Hardening (Surface Hardening):** Induction hardening is a localized case hardening process used to harden specific areas of the material's surface. It involves the use of electromagnetic induction to heat a localized area of the material quickly. The heated area is then rapidly quenched to achieve surface hardening while retaining a relatively softer core. Induction hardening is commonly used for components like gears, shafts, and bearing races.

(vi) Surface hardening

Surface hardening is a specialized heat treatment process used to increase the hardness and wear resistance of the outer layer (surface) of a material while maintaining a relatively softer and more ductile core. The process is typically applied to low-carbon steels and certain other alloys, where increased surface hardness is desired to improve the material's resistance to wear, abrasion, and other surface-related stresses. Surface hardening is commonly used in the manufacturing of components like gears, bearings, shafts, and cutting tools.

Surface hardening techniques provide an advantage over through-hardening processes, as they enable manufacturers to achieve specific mechanical properties on the surface while maintaining a tougher and more ductile core. This combination of properties enhances the overall performance and durability of components exposed to wear and abrasion. The choice of surface hardening method depends on the material type, application requirements, and the desired mechanical properties of the final product.

Surface hardening techniques include carburizing, nitriding, carbonitriding, induction hardening, flame hardening, and plasma hardening, among others.

Vacuum hardening and plasma hardening are two specialized methods of surface hardening used to increase the hardness and wear resistance of materials, particularly steel and certain alloys. Both processes are conducted in a controlled environment to achieve specific material properties. Let's explore each method in more detail:

Vacuum Hardening: Vacuum hardening is a surface hardening process that takes place in a vacuum chamber, where the atmospheric air is removed to create a low-pressure environment. This controlled atmosphere prevents unwanted chemical reactions and ensures uniform heating and cooling of the material.

The main steps involved in vacuum hardening are as follows:

1. **Loading:** The material is placed inside the vacuum chamber in a sealed container or a specially designed fixture to ensure that the atmosphere remains free of contaminants.
2. **Heating:** The vacuum chamber is heated to the desired temperature, typically using electric resistance heating or induction heating. The material is heated in the absence of air or other gases that could react with the material's surface.
3. **Soaking:** The material is held at the elevated temperature for a specified time to allow for the transformation of the microstructure and the diffusion of carbon and/or nitrogen into the surface.
4. **Cooling:** After the required soaking time, the material is rapidly cooled by quenching in a vacuum, inert gas, or oil. The vacuum environment helps prevent oxidation and distortion during cooling.

Vacuum hardening is particularly suitable for materials that are sensitive to oxidation or decarburization at high temperatures. It allows for precise control of the hardening process and produces uniform and predictable results. This method is commonly used for aerospace components, medical instruments, and high-precision tools.

Plasma Hardening: Plasma hardening is a surface hardening process that uses plasma, an ionized gas, as the heat source to harden the material's surface. The plasma is created by ionizing a gas, typically nitrogen or a nitrogen-hydrogen mixture, using an electric field.

The main steps involved in plasma hardening are as follows:

1. **Preparation:** The material is cleaned and preheated to ensure uniform heating and to eliminate surface contaminants.
2. **Plasma Generation:** Plasma is created by applying an electric field to the gas surrounding the material.

3. **Surface Hardening:** The material is exposed to the high-temperature plasma, which causes the surface to heat rapidly.
4. **Cooling:** After the desired hardening depth is achieved, the material is rapidly cooled using a suitable quenching method.

Plasma hardening offers several advantages, including precise control over the hardening depth and minimal distortion compared to conventional heating methods. It is commonly used for localized hardening of specific areas of components, such as gears and camshafts, where only certain surfaces require increased hardness.

In summary, vacuum hardening and plasma hardening are specialized surface hardening methods that offer precise control over the heat treatment process. Vacuum hardening is conducted in a low-pressure environment to prevent oxidation and is well-suited for materials sensitive to high-temperature exposure. Plasma hardening uses ionized gas to generate high-temperature heat for localized hardening of specific surfaces. Both processes are valuable in achieving wear resistance and surface hardness for various engineering components.

Module 5: Polymers – Ceramics and Composites

Topics: Polymers – Classification and applications; Polymerization techniques; Ceramics – Oxide ceramics, ceramic insulators, bio-ceramics and Glasses; Composites – Reinforcement, matrix, metal matrix composites, ceramic composites, polymer composites; Other advanced materials – biomaterials, optical materials, high temperature materials, energy materials, and nano materials.

The "Polymers - Ceramics and Composites" chapter explores the three distinct classes of materials that play crucial roles in modern engineering and manufacturing. Polymers, ceramics, and composites each possess unique properties and offer a wide range of applications in various industries. Throughout this chapter, we will delve into the characteristics, processing techniques, applications, and advantages of polymers, ceramics, and composites.

5.1 Introduction to Polymers

Polymers are large molecules composed of repeating units called monomers, covalently bonded together in long chains. These versatile materials have become an essential part of our daily lives, finding applications in a wide range of industries due to their unique properties. The classification of polymers is based on their source, structure, and behavior, which plays a significant role in determining their applications.

The structure of a polymer refers to the arrangement of its repeating units, called monomers, in a long-chain structure. Polymers are large molecules composed of thousands or even millions of these monomer units covalently bonded together.

There are two main types of polymer structures:

1. Linear Polymer Structure: In a linear polymer, the monomer units are connected end-to-end in a straight chain, forming a linear structure. The chain can be very long, and the monomers are arranged in a single continuous line. Examples of linear polymers include polyethylene and polypropylene.
2. Branched Polymer Structure: In a branched polymer, the monomer units are connected to the main chain, forming side branches. This branching can occur at regular intervals or randomly along the main chain. The presence of branches alters the properties of the polymer compared to its linear counterpart. Examples of branched polymers include low-density polyethylene (LDPE) and some types of polyethylene.

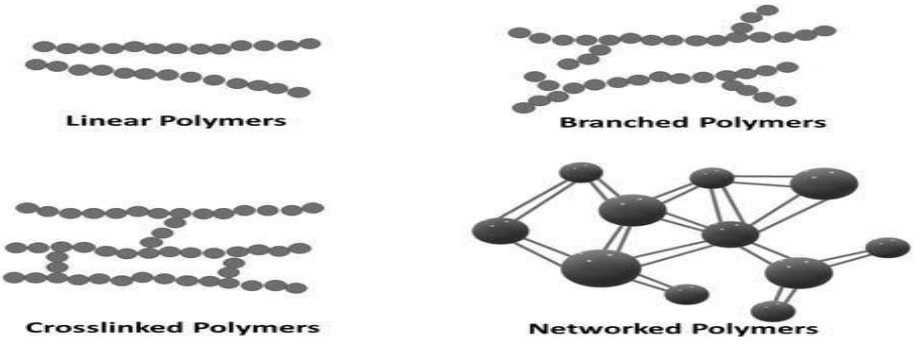


Fig 5.1 Polymer Structure

In addition to linear and b e more complex architectures, such as:

3. Crosslinked Polymer Structure: Crosslinked polymers have covalent bonds between different polymer chains, creating a three-dimensional network structure. This crosslinking makes the polymer rigid and less flexible, leading to increased strength and dimensional stability. Crosslinked polymers are used in applications requiring high strength and chemical resistance, such as rubber tires and thermosetting plastics.
4. Network Polymer Structure: Network polymers are highly crosslinked structures where all the monomers are connected in a continuous three-dimensional network. The resulting materials are often rigid, hard, and have excellent mechanical properties. Examples of network polymers include epoxy resins and certain types of thermosetting plastics.

The specific arrangement of monomers and the overall polymer structure significantly impact the properties and behavior of the polymer. The type of polymerization process and the choice of monomers influence the final polymer structure and its performance in various applications.

5.2 Classification of Polymers:

5.2.1 Based on Source:

a. Natural Polymers: Natural polymers are derived from plant or animal sources and have been used for centuries by humans. Examples include cellulose, found in plants, and proteins like collagen and silk, sourced from animals. Rubber, such as natural rubber (polyisoprene), is also considered a natural polymer. These polymers often exhibit biodegradability and are environmentally friendly.

b. Synthetic Polymers: Synthetic polymers are man-made through various chemical

processes. They can be tailored to have specific properties for different applications. Examples of synthetic polymers include polyethylene, used in packaging materials, polypropylene, employed in textiles and automotive components, and polyvinyl chloride (PVC), utilized in pipes, cables, and construction materials.

c. Semi-Synthetic Polymers: Semi-synthetic polymers are derived from natural polymers but undergo chemical modifications to enhance their properties. Rayon, for instance, is derived from cellulose and is used in textiles, while cellulose acetate is a semi-synthetic polymer used in photographic film and eyewear.

5.2.2 Based on Structure:

a. Linear Polymers: In linear polymers, the monomer units are linked together in a straight chain without any branching. They often have high tensile strength and can be easily processed. Examples include high-density polyethylene (HDPE) and polyvinyl chloride (PVC).

b. Branched Polymers: Branched polymers have side branches or offshoots that extend from the main polymer chain. These branches can influence the polymer's physical properties, such as elasticity and flexibility. Low-density polyethylene (LDPE) is a typical example of a branched polymer.

c. Cross linked Polymers: Cross linked polymers form a three-dimensional network due to covalent bonds between polymer chains. This structure results in increased rigidity and resistance to deformation. Vulcanized rubber is a well-known example of a cross linked polymer.

d. Network Polymers: Network polymers are a subset of cross linked polymers, but they form a permanent three-dimensional network structure. These materials are usually rigid and have high chemical and thermal stability. Epoxy resins are a common type of network polymer used in adhesives and coatings.

5.2.3 Based on Behavior:

a. Thermoplastics: Thermoplastics can be melted and reshaped multiple times without undergoing significant chemical degradation. This characteristic allows for easy processing and recycling. Common thermoplastics include polyethylene, polypropylene, and polystyrene.

b. Thermosetting Plastics: Thermosetting plastics undergo irreversible chemical changes upon curing, resulting in a permanent and rigid structure. They cannot be reshaped once they have set. Thermosetting plastics are used in applications where high heat and chemical resistance are required, such as electrical insulation and automotive parts.

c. Elastomers: Elastomers are polymers that exhibit high elasticity and can return to their original shape after deformation. These materials are widely used in applications requiring flexibility and resilience, such as tires, gaskets, and shoe soles.

5.3 Applications of Polymers:

The diverse properties of polymers have led to a wide range of applications in various industries:

- Packaging: Polymers like polyethylene, polypropylene, and PET are extensively used in packaging materials for food and beverages due to their lightweight, flexibility, and barrier properties.
- Construction: Polymers find applications in pipes, insulation, roofing materials, adhesives, and coatings in the construction industry, offering durability and weather resistance.
- Textiles: Synthetic polymers like polyester and nylon are used to make clothing, carpets, and other textiles, providing comfort, strength, and ease of care.
- Medicine: Biodegradable polymers like polylactic acid (PLA) are used in medical sutures and drug delivery systems, enabling controlled drug release and reducing the need for repeated surgeries.
- Electronics: Polymers are used in insulators, coatings, and flexible displays due to their electrical insulation properties and mechanical flexibility.
- Automotive: Polymers are widely used in automotive parts like bumpers, dashboards, and interior trims due to their lightweight, impact resistance, and design versatility.

5.4 Constituents of Plastics

Plastics are composed of a wide range of chemical constituents, each contributing to the overall properties and characteristics of the material. The main constituents of plastic include:

1. Polymers: The primary component of plastics is the polymer itself. Polymers are large molecules made up of repeating units called monomers, covalently bonded together in long chains. Different types of polymers can be used to produce various types of plastics, each with its unique set of properties. Some common polymers used in plastics include:

   a. Polyethylene (PE): This polymer is widely used in packaging materials, bottles, and various household items. b. Polypropylene (PP): PP is commonly found in containers, automotive parts, and textiles. c. Polyvinyl Chloride (PVC): PVC is used in pipes, electrical cables, and construction materials. d. Polystyrene (PS): PS is used in disposable cutlery, packaging, and foam insulation. e. Polyethylene Terephthalate (PET): PET is commonly used in beverage bottles and food containers. f.

Polycarbonate (PC): PC is known for its high impact resistance and is used in safety glasses, CDs, and electronic devices.

2. Additives: Plastics often contain various additives to improve or modify their properties. Some common additives include:

   a. Plasticizers: These additives increase the flexibility and workability of plastics. They are commonly used in PVC to make it more flexible for applications like vinyl flooring and medical tubing.

   b. Stabilizers: Stabilizers help prevent the degradation of plastics due to heat, light, or other environmental factors. They extend the material's lifespan and maintain its properties over time.

   c. Colorants: Colorants are added to give plastics their desired color or to create a specific visual appeal for the end product.

   d. Fillers: Fillers like calcium carbonate and talc can be added to reduce cost, improve mechanical properties, and enhance the appearance of the plastic.

   e. Flame Retardants: Flame retardants are used to reduce the flammability of plastics and make them safer in certain applications.

3. Reinforcements: Some plastics are reinforced with other materials to enhance their mechanical properties. Reinforcements may include fibers, such as glass fibers or carbon fibers, which improve the strength and stiffness of the plastic. These reinforced plastics are often referred to as composites.
4. Foaming Agents: Foaming agents are used to create foamed or cellular structures in plastics, resulting in materials with reduced density and improved insulation properties. Expanded polystyrene (EPS) and polyurethane foams are examples of foamed plastics.
5. Processing Aids: Processing aids are substances that assist in the manufacturing process of plastics. They may help in the melt processing, molding, or extrusion of the material, ensuring smooth and efficient production.

Overall, the combination of polymers, additives, and other constituents gives rise to the diverse range of plastics available in the market, each tailored to meet specific application requirements and performance criteria.

5.5 Thermoplastic Materials & its Types

Thermoplastic materials are a class of polymers that possess a unique property - they can be repeatedly heated and cooled without undergoing significant chemical degradation. This characteristic allows thermoplastics to be melted, reshaped, and recycled, making them highly versatile and widely used in various industries. In this

chapter, we will explore some common types of thermoplastic materials, their properties, and their diverse applications.

5.5.1 Polyethylene (PE): Polyethylene is one of the most widely used thermoplastics, known for its excellent chemical resistance and toughness. It can be further categorized into two main types:

a. Low-Density Polyethylene (LDPE): - Properties: LDPE is flexible, transparent, and has good electrical insulating properties. It exhibits good impact strength but has lower tensile strength compared to other polyethylenes. - Uses: LDPE is commonly used in packaging films, plastic bags, squeeze bottles, and electrical cable insulation.

b. High-Density Polyethylene (HDPE): - Properties: HDPE is more rigid and has higher tensile strength compared to LDPE. It offers excellent impact resistance, good chemical resistance, and is less flexible. - Uses: HDPE finds applications in pipes, containers, automotive fuel tanks, toys, and various molded products.

5.5.2 Polypropylene (PP): Polypropylene is a versatile thermoplastic known for its high chemical resistance, low density, and good mechanical properties.

- Properties: PP is lightweight, rigid, and has a high melting point. It exhibits excellent fatigue resistance and is resistant to moisture and many chemicals.
- Uses: PP is used in food containers, automotive parts, packaging, textiles, medical devices, and laboratory equipment.

5.5.3 Polyvinyl Chloride (PVC): PVC is a widely used thermoplastic known for its versatility, low cost, and ease of processing.

- Properties: PVC can be rigid or flexible, depending on the plasticizers used. It offers good electrical and thermal insulation properties and is flame-retardant.
- Uses: Rigid PVC is used in pipes, window frames, and flooring. Flexible PVC is used in electrical cables, inflatable structures, and medical tubing.

5.5.4 Polystyrene (PS): Polystyrene is a transparent and rigid thermoplastic with good electrical insulating properties.

- Properties: PS is lightweight, offers excellent optical clarity, and can be easily molded.
- Uses: It is commonly used in packaging materials, disposable cutlery, CD cases, and insulation for construction.

5.5.5 Polyethylene Terephthalate (PET): PET is a popular thermoplastic known for its excellent barrier properties and recyclability.

- Properties: PET is transparent, lightweight, and has good mechanical strength. It is resistant to water and gas permeation.
- Uses: PET is commonly used in beverage bottles, food containers, polyester fibers for textiles, and packaging films.

5.5.7 **Applications of Thermoplastic Materials:** Thermoplastic materials are used in a wide range of applications due to their diverse properties and processability. Some common applications include:

- Packaging: Thermoplastics like LDPE, HDPE, and PET are extensively used in food packaging, bottles, and containers due to their barrier properties and cost-effectiveness.
- Automotive: PP is widely used in automotive components like bumpers, dashboards, and interior trim due to its lightweight and durability.
- Construction: PVC and HDPE find applications in pipes, electrical conduits, and construction materials for their chemical resistance and durability.
- Consumer Goods: Polystyrene is used in various consumer goods, such as disposable cutlery, packaging, and toys, due to its clarity and ease of molding.
- Medical: Thermoplastics like PVC and PET are used in medical tubing, IV bags, and containers for their biocompatibility and sterilization capabilities.
- Textiles: PET is commonly used in polyester fibers for clothing, upholstery, and textiles due to its strength and wrinkle resistance.

5.6 Types of Thermosetting Materials and Their Properties and Uses

Thermosetting materials are a class of polymers that undergo a chemical reaction during the curing process, leading to a three-dimensional crosslinked network structure. Once cured, these materials cannot be melted or reshaped like thermoplastics, making them permanently solid and rigid. Thermosetting materials offer exceptional mechanical and thermal properties, making them ideal for applications requiring high strength, dimensional stability, and resistance to heat and chemicals. In this chapter, we will explore some common types of thermosetting materials, their properties, and their diverse applications.

5.6.1 Types of Thermosetting Materials:

a. Epoxy Resins: Epoxy resins are widely used thermosetting materials known for their excellent adhesion, chemical resistance, and mechanical properties.

- Properties: Epoxy resins are rigid, have high tensile strength, and exhibit low shrinkage during curing. They are highly resistant to chemicals and have good electrical insulating properties.
- Uses: Epoxy resins are used in adhesives, coatings, composite materials, electrical insulators, and in the construction of aircraft and boats.

b. Phenolic Resins: Phenolic resins, also known as phenol formaldehyde resins, are one of the oldest and most versatile thermosetting materials.

- Properties: Phenolic resins are hard, rigid, and offer excellent heat resistance and electrical insulation properties. They have good dimensional stability and are flame-retardant.
- Uses: Phenolic resins are used in molded products, electrical components, automotive parts, and as binders in plywood and particleboard.

c. Urea Formaldehyde Resins (UF Resins): UF resins are widely used in wood-based composite materials due to their cost-effectiveness and ease of processing.

- Properties: UF resins provide good dimensional stability, are scratch-resistant, and have excellent adhesion to wood fibers.
- Uses: UF resins are commonly used as adhesives in the production of particleboard, medium-density fiberboard (MDF), and plywood.

d. Melamine Formaldehyde Resins: Melamine formaldehyde resins are a type of thermosetting material with exceptional hardness and chemical resistance.

- Properties: Melamine resins offer high heat resistance, excellent dimensional stability, and resistance to staining and scratching.
- Uses: Melamine resins are used in the production of decorative laminates, dinnerware, and coatings for high-pressure laminates.

e. Polyester Resins: Polyester resins are widely used in composite materials and as binders for various applications.

- Properties: Polyester resins offer good mechanical properties, chemical resistance, and are relatively low in cost.
- Uses: Polyester resins are used in fiberglass-reinforced composites, boat hulls, automotive parts, and as adhesives and sealants.

5.6.2 Applications of Thermosetting Materials: Thermosetting materials find applications in various industries where their unique properties are advantageous:

- Aerospace and Defense: Epoxy resins are used in aircraft structures and components due to their high strength-to-weight ratio and excellent adhesion properties.
- Electrical and Electronics: Phenolic resins and epoxy resins are widely used in electrical insulators, circuit boards, and encapsulation materials due to their excellent electrical insulation and thermal properties.

- Automotive: Thermosetting materials like polyester resins are used in the production of automotive body parts, such as bumpers and hoods, due to their rigidity and impact resistance.
- Construction: Phenolic resins and UF resins are used in the production of wood-based composite materials, such as plywood and particleboard, for their durability and moisture resistance.
- Consumer Goods: Melamine formaldehyde resins are used in the production of melamine dinnerware and decorative laminates for their durability and aesthetic appeal.
- Composites: Epoxy resins, polyester resins, and other thermosetting materials are widely used as matrices in composite materials, combining with reinforcing fibers like fiberglass or carbon fibers to create high-performance, lightweight structures in aerospace, marine, and automotive industries.

5.7 : Polymerization Techniques

5.7.1 Introduction to Polymerization:

Polymerization is the process by which monomers are chemically linked together to form polymer chains. This process can be initiated by various methods, resulting in different types of polymers with unique properties. The polymerization technique employed plays a crucial role in determining the molecular structure, molecular weight, and overall performance of the polymer.

Polymerization techniques refer to the various methods used to carry out the process of polymerization, where monomers are chemically bonded together to form polymers. These techniques differ in their initiation mechanisms, reaction conditions, and chain growth mechanisms, resulting in polymers with distinct properties suitable for specific applications.

Common polymerization techniques include:

1. Radical Polymerization: Initiated by free radicals, highly reactive monomers undergo addition polymerization at room temperature to elevated temperature. It is used in the production of plastics, rubber, and adhesives.
2. Anionic Polymerization: Initiated by anionic initiators, less reactive monomers undergo addition polymerization at low temperature to room temperature. This technique is applied in specialty polymers and elastomers.
3. Cationic Polymerization: Initiated by cationic initiators, less reactive monomers undergo addition polymerization at low temperature to room temperature. It is used in specialty polymers and coatings.

4. Coordination Polymerization: Initiated by coordination complexes, monomers with variable reactivity undergo coordination polymerization under high pressure and high temperature. This technique is used in specialty polymers and elastomers.
5. Step-Growth Polymerization: Condensation polymerization occurs without any initiators, and monomers with variable reactivity undergo step-growth polymerization at elevated temperature. It is used in the production of polyesters and polyamides.
6. Ring-Opening Polymerization: Initiated by metal catalysts, reactive cyclic monomers undergo ring-opening polymerization at elevated temperature. This technique is applied in polycarbonates and polyesters.
7. Living Polymerization: Initiated by special initiators, highly reactive monomers undergo controlled radical or anionic/cationic polymerization at room temperature to elevated temperature. It is used to produce block copolymers and nanomaterials.

Each polymerization technique offers unique advantages and allows for the tailored synthesis of polymers with specific properties, making them suitable for a wide range of industrial and commercial applications

5.7.2 Polymerization Methods:

a. Addition Polymerization: Addition polymerization involves the repetitive addition of monomers without the elimination of any byproducts. It typically occurs through the breaking of double bonds, initiating the polymerization reaction. One of the most common examples of addition polymerization is the production of polyethylene from ethylene monomers.

b. Condensation Polymerization: Condensation polymerization occurs when monomers with two or more functional groups react, releasing small molecules, such as water or alcohol, as byproducts. The reaction continues until the polymer is formed. Polyester and nylon are well-known examples of polymers produced through condensation polymerization.

5.7.3 Control of Polymerization:

- Molecular Weight Control: The molecular weight of the polymer can be controlled through the choice of initiators and reaction conditions. Higher molecular weights can be achieved with controlled polymerization techniques, yielding polymers with specific desired properties.
- Copolymerization: By incorporating different monomers during the polymerization process, copolymers with unique properties can be produced. Random, block, and graft copolymers are examples of coplymerization.

5.8 Ceramics

Ceramics are a class of inorganic, non-metallic materials that are known for their exceptional hardness, heat resistance, and mechanical properties. They are typically composed of metallic and non-metallic elements bonded together through ionic or covalent bonding, resulting in a crystalline structure. Unlike metals, ceramics lack free electrons and have a wide band gap, which contributes to their electrical insulating properties.

Ceramics have been used by humans for thousands of years, dating back to ancient civilizations like the Egyptians and Chinese, where they were used for pottery, decorative items, and structural elements. Over time, advances in materials science and technology have led to the development of a wide range of ceramics, each tailored to specific applications and industries.

Ceramics encompass a wide range of materials, and they can be classified into several categories based on their composition, properties, and applications. The main types of ceramics include:

1. Traditional Ceramics: Traditional ceramics are based on naturally occurring raw materials and have been used for thousands of years in pottery and decorative items. They are typically fired at lower temperatures compared to advanced ceramics.

   a. Earthenware: Earthenware is a type of traditional ceramic fired at relatively low temperatures. It is porous and has a reddish-brown or beige appearance. Common uses include pottery, decorative items, and dishes.

   b. Stoneware: Stoneware is fired at higher temperatures than earthenware, making it more durable and less porous. It has a denser structure and is suitable for making tableware, cookware, and decorative items.

   c. Porcelain: Porcelain is a high-fired ceramic known for its elegance, translucency, and strength. It is made from fine-grained clay and is often used in fine china, dinnerware, and decorative objects.

2. Advanced Ceramics: Advanced ceramics, also known as technical or fine ceramics, are engineered materials with exceptional mechanical, thermal, and electrical properties. They are typically manufactured from carefully controlled synthetic powders and can withstand extreme conditions.

   a. Oxide Ceramics: These ceramics consist primarily of metal oxides. Common examples include alumina (aluminum oxide) and zirconia (zirconium dioxide). They offer high mechanical strength, thermal stability, and excellent electrical insulation properties.

   b. Nitride Ceramics: Nitride ceramics are composed of metal nitrides, such as silicon nitride (Si_3N_4) and aluminum nitride (AlN). They have high thermal conductivity

and electrical insulation properties, making them suitable for high-temperature applications.

c. Carbide Ceramics: Carbide ceramics, like silicon carbide (SiC) and tungsten carbide (WC), are known for their high hardness and wear resistance. They are used in cutting tools, abrasives, and wear-resistant components.

d. Silicate Ceramics: Silicate ceramics are based on silicate minerals and include materials like clay, feldspar, and mica. They are used in refractory materials, electrical insulators, and structural components.

3. Engineering Ceramics: Engineering ceramics are a subset of advanced ceramics specifically designed for engineering applications. They possess high strength, wear resistance, and chemical stability.

   a. Piezoelectric Ceramics: Piezoelectric ceramics, such as lead zirconate titanate (PZT), exhibit the piezoelectric effect, converting mechanical stress into electrical voltage and vice versa. They are used in sensors, actuators, and transducers.

   b. Dielectric Ceramics: Dielectric ceramics have high electrical resistivity and are used in capacitors and insulating components.

   c. Bioceramics: Bioceramics are biocompatible ceramics used in medical and dental applications. Hydroxyapatite (HA) and alumina are examples of bioceramics used in dental implants, bone grafts, and joint replacements.

Each type of ceramic offers unique properties and applications, making them indispensable in various industries, from electronics and aerospace to automotive and biomedical fields. The diverse properties and wide-ranging applications of ceramics continue to contribute significantly to modern technology and industrial progress.

5.7.1 Oxide ceramics

Oxide ceramics are a class of advanced ceramics composed primarily of metal oxides. They are known for their excellent mechanical, thermal, and electrical properties, making them valuable materials for a wide range of applications. Oxide ceramics are engineered materials, carefully synthesized from metal oxide powders, and processed to achieve specific properties tailored to various industries. Let's explore the characteristics, types, and applications of oxide ceramics:

1. Characteristics of Oxide Ceramics:
   - High Mechanical Strength: Oxide ceramics exhibit high mechanical strength, making them suitable for structural components and applications requiring load-bearing capacity.

- Thermal Stability: Oxide ceramics have excellent thermal stability, allowing them to withstand high temperatures without significant degradation.
- Electrical Insulation: These ceramics have good electrical insulating properties, making them useful in electrical and electronic components.
- Chemical Inertness: Oxide ceramics are chemically inert and resistant to corrosion, making them ideal for applications in aggressive environments.
- Biocompatibility: Some oxide ceramics, like alumina, exhibit biocompatibility, making them suitable for biomedical applications.

2. Types of Oxide Ceramics: a. Alumina (Aluminum Oxide, Al2O3): Alumina is one of the most widely used oxide ceramics. It offers high mechanical strength, excellent electrical insulation, and good thermal conductivity. Alumina is used in a variety of applications, including electrical insulators, cutting tools, wear-resistant components, and biomedical implants.

   b. Zirconia (Zirconium Dioxide, ZrO2): Zirconia is known for its exceptional mechanical properties and high-temperature resistance. It exhibits a phase transformation at elevated temperatures, which imparts enhanced toughness, making it suitable for dental crowns, cutting tools, and thermal barrier coatings in gas turbine engines.

   c. Magnesia (Magnesium Oxide, MgO): Magnesia offers high electrical insulation and thermal stability. It is commonly used in heating elements, refractory crucibles, and insulating components.

   d. Beryllia (Beryllium Oxide, BeO): Beryllia has excellent thermal conductivity and is used in heat sinks, microwave components, and semiconductor devices.

   e. Yttria (Yttrium Oxide, Y2O3): Yttria is used as a stabilizer for zirconia, enhancing its mechanical properties and making it suitable for dental implants, oxygen sensors, and solid oxide fuel cells.

   f. Ceria (Cerium Oxide, CeO2): Ceria is used as a catalyst support, in oxygen storage systems for automotive exhaust catalysts, and as a polishing agent in ceramics and glass manufacturing.

3. Applications of Oxide Ceramics:
   - Electronics and Electrical Engineering: Oxide ceramics, such as alumina and zirconia, are used as insulating substrates, electrical insulators, and components for electronic devices and integrated circuits.
   - Mechanical and Structural Components: Oxide ceramics are employed in cutting tools, bearings, wear-resistant parts, and high-temperature furnace components due to their mechanical strength and thermal stability.

- Aerospace and Gas Turbines: Oxide ceramics are used in thermal barrier coatings for gas turbine engines, improving engine efficiency and performance at high temperatures.
- Biomedical and Dental Implants: Biocompatible oxide ceramics, like alumina and zirconia, are used in dental crowns, implants, and orthopedic replacements due to their biocompatibility and mechanical properties.
- Refractory and High-Temperature Applications: Oxide ceramics are used as refractory materials in kilns, crucibles, and furnace linings due to their ability to withstand high temperatures and chemical resistance.
- Environmental and Energy Applications: Oxide ceramics, such as yttria-stabilized zirconia (YSZ), are used in solid oxide fuel cells (SOFCs) and oxygen sensors, contributing to clean energy and environmental monitoring.

5.7.2 Bioceramics

Bioceramics are a class of ceramic materials specifically designed and engineered for biomedical and healthcare applications. These materials are utilized in direct contact with living tissues and biological systems, and they are known for their biocompatibility and ability to interact with the body without causing adverse reactions. Bioceramics play a critical role in various medical and dental applications, contributing to advancements in healthcare and improving patients' quality of life.

1. Characteristics of Bioceramics:

Bioceramics possess several key characteristics that make them suitable for biomedical use:

1. Biocompatibility: Bioceramics are biocompatible, meaning they are well-tolerated by living tissues and do not provoke an immune response or toxicity.
2. Bioactivity: Some bioceramics exhibit bioactivity, the ability to form a bond with living bone tissue. This property promotes osseointegration, allowing the bioceramic implant to become part of the surrounding bone structure.
3. Mechanical Properties: Bioceramics have tailored mechanical properties to match those of natural bone, enabling them to provide adequate support and load-bearing capabilities.
4. Degradation and Resorption: Some bioceramics are designed to degrade and be resorbed by the body over time, gradually being replaced by natural tissue.
5. Chemical Stability: Bioceramics are chemically stable, maintaining their integrity in the body's physiological environment.

2. Types of Bioceramics:

Several types of bioceramics are used in biomedical applications:

1. Bioinert Ceramics: Bioinert ceramics, like alumina and zirconia, are stable and do not react with the surrounding biological tissues. They are often used for joint replacements and dental implants.
2. Bioactive Ceramics: Bioactive ceramics, such as hydroxyapatite (HA) and tricalcium phosphate (TCP), bond directly to living bone tissue and promote osseointegration. They are used in dental implants, bone graft substitutes, and bone repair materials.
3. Resorbable Ceramics: Resorbable or biodegradable ceramics, like beta-tricalcium phosphate (β-TCP), gradually degrade over time and are eventually replaced by natural tissue. They are used for temporary support and bone regeneration applications.

3. Applications of Bioceramics:

Bioceramics find applications in various medical and dental fields:

1. Orthopedics: Bioceramics are used in joint replacements, bone plates, and screws to provide mechanical support and improve bone healing.
2. Dentistry: Bioceramics are employed in dental implants, dental fillings, and dental bone graft substitutes.
3. Tissue Engineering: Bioceramics are used as scaffolds in tissue engineering to promote the growth and regeneration of damaged or lost tissues.
4. Drug Delivery: Bioceramics are used as carriers for drug delivery systems, enabling controlled and targeted drug release.
5. Maxillofacial Surgery: Bioceramics are used in craniofacial reconstructions and repairs.

5.8 Composites

Composites are a class of materials composed of two or more distinct components with different properties, combined to create a material with enhanced performance and specific characteristics. The components of composites include a reinforcement phase and a matrix phase. Composites are widely used in various industries due to their tailored properties and versatility. Let's explore the components and types of composites, focusing on metal matrix composites, ceramic composites, and polymer composites:

1. Components of Composites:

a. Reinforcement:

- The reinforcement phase provides the composites with the desired properties and is responsible for enhancing specific characteristics such as strength, stiffness, or wear resistance.
- Reinforcements can be in the form of fibers, particles, or sheets, depending on the type of composite and the intended application.

- Common reinforcement materials include carbon fibers, glass fibers, aramid fibers, nanoparticles, and particulate materials.

b. Matrix:

- The matrix phase holds the reinforcement materials together, providing a medium for their distribution and transferring loads between the reinforcements.
- The matrix phase can be made of various materials such as metals, ceramics, polymers, or their combinations.
- The matrix material contributes to other important properties, such as toughness, ductility, and thermal stability.

5.8.1 Classification of composites:

Composites can be classified based on various criteria, including the nature of the reinforcement, the type of matrix material, and the structural arrangement of the reinforcement within the matrix. Here are the primary classifications of composites:

1. Based on the Nature of Reinforcement:

   a. Fiber-Reinforced Composites:

      - In these composites, the reinforcement consists of continuous or discontinuous fibers embedded in the matrix material.
      - Examples include carbon fiber-reinforced composites, glass fiber-reinforced composites, and aramid fiber-reinforced composites.

   b. Particle-Reinforced Composites:

      - These composites have discrete particles, such as nanoparticles or microparticles, dispersed within the matrix material.
      - Examples include metal matrix composites (MMCs) and ceramic particle-reinforced composites.

   c. Structural Composites:

      - In structural composites, a combination of fibers and particles is used to tailor specific mechanical properties.
      - Examples include hybrid composites used in aircraft components and automotive applications.

2. Based on the Type of Matrix Material:

   a. Polymer Matrix Composites (PMCs):

- These composites have a polymer matrix, such as epoxy, polyester, or phenolic resin.
- PMCs are lightweight and widely used in aerospace, automotive, and sporting goods industries.

b. Metal Matrix Composites (MMCs):

- MMCs have a metal matrix, such as aluminum, magnesium, or titanium, reinforced with ceramic or non-metallic materials.
- MMCs offer high strength, thermal conductivity, and wear resistance, making them suitable for aerospace and automotive applications.

c. Ceramic Matrix Composites (CMCs):

- CMCs have a ceramic matrix, such as silicon carbide (SiC) or alumina (Al2O3), reinforced with ceramic fibers or particles.
- CMCs exhibit excellent high-temperature performance and are used in aerospace and engineering applications.

d. Carbon-Carbon Composites (C/C):

- These composites have a carbon matrix reinforced with carbon fibers, providing excellent high-temperature properties and dimensional stability.
- C/C composites are used in aerospace, nuclear, and high-temperature applications.

3. Based on Structural Arrangement:

a. Laminate Composites:

- Laminate composites consist of multiple layers (plies) of different materials stacked in a specific sequence and bonded together.
- The layering provides tailored mechanical properties and allows control over the material's response to loads.

b. Sandwich Composites:

- Sandwich composites have a core material, such as foam or honeycomb, sandwiched between two outer layers (skins) of different materials.
- The core provides stiffness and support, while the skins offer strength and protection.

c. Particulate Composites:

- Particulate composites have reinforcement in the form of discrete particles, randomly or uniformly dispersed in the matrix.
- These composites can be isotropic or anisotropic, depending on the distribution of particles.

4. Based on Functionality:

a. Structural Composites:

- These composites are designed for load-bearing and structural applications, such as aerospace components and automotive chassis.

b. Functional Composites:

- Functional composites are engineered to have specific electrical, thermal, or magnetic properties, making them suitable for electronic devices, sensors, and actuators.

5.8.3 Metal Matrix Composites (MMCs)

Metal Matrix Composites (MMCs) are a class of advanced materials that consist of a metal matrix reinforced with one or more other materials, typically non-metallic materials. The primary purpose of adding reinforcements is to enhance specific properties and performance characteristics of the metal matrix, creating a material with improved mechanical, thermal, and physical properties compared to traditional monolithic metals.

Key points about Metal Matrix Composites:

1. Reinforcement: The reinforcement phase in MMCs can be in the form of particles, fibers, or whiskers. Common reinforcement materials include ceramic particles (e.g., silicon carbide, alumina), carbon fibers, and other advanced materials.
2. Matrix Material: The metal matrix acts as the base material that provides the overall structural integrity and mechanical properties. Common matrix materials include aluminum, magnesium, titanium, and copper, among others.
3. Properties: The incorporation of reinforcements into the metal matrix imparts several desirable properties to MMCs, including high strength, stiffness, enhanced hardness, improved wear resistance, and tailored thermal conductivity.
4. Manufacturing Methods: MMCs are produced using various manufacturing techniques, including powder metallurgy, in situ fabrication, liquid phase infiltration, and pressure infiltration.
5. Applications: MMCs find applications in various industries and advanced technologies, including aerospace, automotive, electronics, and defense. They are used in aerospace components, automotive parts like brake discs and pistons, heat sinks, electronic substrates, military equipment, and more.

6. Advantages: MMCs offer high strength-to-weight ratios, making them ideal for weight-sensitive applications. They also provide improved dimensional stability, thermal management, and corrosion resistance.

5.8.4 Ceramic composites

Ceramic composites refer to materials composed of a combination of ceramic and other materials, typically reinforcing fibers or particles. These composites are designed to take advantage of the desirable properties of ceramics, such as high temperature resistance, hardness, and chemical stability, while overcoming their inherent brittleness. By incorporating reinforcing elements, the resulting composite materials can exhibit improved mechanical strength, toughness, and fracture resistance.

There are two primary types of ceramic composites:

1. Ceramic Matrix Composites (CMCs): In these composites, a ceramic material serves as the matrix, while another material, often ceramic fibers or whiskers, acts as the reinforcement. CMCs have applications in aerospace, gas turbines, automotive components, and other industries where lightweight materials with high-temperature capabilities are crucial. The combination of the ceramic matrix with the reinforcing phase enhances fracture toughness and damage tolerance, making CMCs suitable for high-stress environments.
2. Polymer Matrix Composites (PMCs) with Ceramic Fillers: These composites consist of a polymer matrix (such as epoxy) infused with ceramic particles or fibers. The addition of ceramic components imparts improved mechanical properties, thermal stability, and wear resistance to the composite. These materials find application in various industries, including electronics, aerospace, and automotive sectors.

Advantages of ceramic composites include:

- High-temperature resistance: Ceramics inherently withstand high temperatures, and their incorporation into composites maintains this property.
- Low density: Ceramic composites can have lower densities than traditional metals, making them lightweight and attractive for applications where weight reduction is essential.
- High hardness and wear resistance: Ceramics are known for their exceptional hardness and wear resistance, contributing to the durability of the composite.
- Chemical stability: Ceramics are chemically inert, which can be advantageous in corrosive environments.

5.8.5 Polymer composites

Polymer composites, also known as composite materials or simply composites, are materials composed of a combination of polymers (plastics) and reinforcing materials. The

reinforcing materials can be fibers, particles, or other additives, which are embedded within the polymer matrix. The goal of incorporating these reinforcements is to enhance the overall mechanical, thermal, electrical, or other specific properties of the resulting composite material.

There are different types of polymer composites, depending on the nature of the reinforcement and the polymer matrix:

1. Fiber-Reinforced Polymer Composites (FRPs): In FRPs, continuous fibers (e.g., carbon fibers, glass fibers, aramid fibers) are embedded within a polymer matrix (e.g., epoxy, polyester, or polyamide). The combination of the strong and stiff fibers with the flexible polymer matrix results in a material with improved strength, stiffness, and specific properties, such as tensile and flexural strength.
2. Particulate-Reinforced Polymer Composites: These composites consist of polymer matrices infused with discrete particles (e.g., silica, alumina, carbon black). The particles can modify the mechanical properties and add functionalities to the composite, such as increased hardness, thermal stability, and electrical conductivity.
3. Nanocomposites: Nanocomposites involve incorporating nanoscale reinforcements (such as carbon nanotubes, nanoclays, or graphene) into the polymer matrix. The addition of nanomaterials can lead to exceptional improvements in mechanical, thermal, and barrier properties compared to traditional composites.

Advantages of polymer composites include:

- High strength-to-weight ratio: Polymer composites are lightweight yet strong, making them suitable for applications where weight reduction is critical (e.g., aerospace and automotive industries).
- Design flexibility: The combination of various polymers and reinforcements allows tailoring of composite properties to meet specific application requirements.
- Corrosion resistance: Unlike metals, polymer composites are generally resistant to corrosion, which can be beneficial in harsh environments.
- Damping properties: Some polymer composites exhibit excellent damping characteristics, reducing vibrations and noise in applications like aerospace and construction.
- Electrically insulating: Many polymer composites are good electrical insulators, making them suitable for electrical and electronic components.

However, polymer composites also have some limitations:

- Temperature limitations: Some polymers may have limited high-temperature capabilities, restricting their use in certain applications.
- Cost: High-performance reinforcing materials can be expensive, impacting the cost of the composite.

- Anisotropic behavior: The direction of reinforcement can significantly affect the composite's properties, leading to anisotropic behavior that requires careful design considerations.

Polymer composites find applications in various industries, including aerospace, automotive, marine, construction, electronics, and sports equipment, among others.

5.9 Biomaterials:

Biomaterials are specialized materials designed for use in medical and biological applications. They interact with living tissues and organisms, either temporarily or permanently, without causing harm or adverse reactions. Biomaterials are essential components in various medical fields, including regenerative medicine, tissue engineering, medical implants, drug delivery systems, and diagnostic tools.

Key characteristics of biomaterials include biocompatibility, bioactivity (stimulating specific cellular responses), degradability (for temporary applications), appropriate mechanical properties, sterilization capability, and infection resistance.

5.10 Optical Materials

Optical materials are a class of materials that interact with light in various ways, making them crucial components in a wide range of optical and photonic devices. These materials possess unique optical properties that enable them to manipulate and control light for specific applications.

The study of optical materials is a multidisciplinary field that combines physics, chemistry, materials science, and engineering. Researchers in this field aim to understand the fundamental principles governing light-matter interactions and develop materials with desired optical characteristics.

Key optical properties of materials include:

1. **Transparency:** Transparent materials allow light to pass through them with minimal scattering or absorption, making them suitable for lenses, windows, and optical fibers.
2. **Refraction:** Materials with varying refractive indices bend light as it passes through them, leading to phenomena like lens focusing and prism dispersion.
3. **Reflection:** Materials with high reflectivity are used in mirrors and reflective coatings for various applications.
4. **Absorption:** Some materials selectively absorb specific wavelengths of light, influencing their color and potential for use in light filters.
5. **Emission:** Luminescent materials can absorb light at one wavelength and emit light at another, enabling applications in light-emitting devices and displays.

Optical materials find applications in diverse fields like **Telecommunications, Displays, Lighting, Sensors, Lasers, Imaging etc.**

5.11 High-temperature materials

High-temperature materials are a class of materials specifically designed to withstand and perform reliably at elevated temperatures. These materials are essential in various industrial applications, aerospace, automotive, and power generation sectors, where exposure to extreme heat is common. High-temperature materials must maintain their mechanical strength, chemical stability, and other properties under prolonged exposure to high temperatures, typically above 500°C (932°F). Some common types of high-temperature materials include:

1. **Refractory Materials:** These materials have high melting points and excellent resistance to heat. Examples include refractory ceramics like alumina, silica, and zirconia used in furnaces and high-temperature processing applications.
2. **Heat-Resistant Alloys:** These are metallic alloys specifically engineered to maintain their strength and integrity at high temperatures. Examples include nickel-based alloys like Inconel and Hastelloy, and iron-chromium-aluminum (FeCrAl) alloys used in gas turbines and industrial heating elements.
3. **Ceramic Matrix Composites (CMCs):** CMCs are composite materials consisting of ceramic fibers embedded in a ceramic matrix. They combine high-temperature resistance with improved toughness and fracture resistance, making them suitable for aerospace and gas turbine applications.
4. **Superalloys:** Superalloys are a class of high-temperature alloys that retain their mechanical strength, creep resistance, and corrosion resistance at extremely high temperatures, making them ideal for gas turbines, jet engines, and rocket propulsion systems.
5. **Refractory Metals:** These metals, such as tungsten, molybdenum, and tantalum, have exceptionally high melting points and are used in high-temperature applications like rocket nozzles and heat shields.
6. **Carbon-Carbon Composites:** Carbon-carbon composites have high thermal conductivity and exceptional resistance to high temperatures, making them suitable for aerospace applications like heat shields and rocket nozzles.

5.12 Energy materials

Energy materials are a class of materials specifically developed for energy-related applications, including energy generation, conversion, storage, and efficiency improvement. These materials play a vital role in various sectors, such as renewable energy technologies, batteries, fuel cells, and energy-efficient devices. Some key types of energy materials include:

1. **Photovoltaic Materials:** These materials convert sunlight into electricity in solar cells. Examples include silicon-based solar cells, thin-film solar cells, and emerging perovskite solar cells.
2. **Thermoelectric Materials:** Thermoelectric materials can convert waste heat into electricity or provide cooling when an electric current is applied. They are used in power generation and energy-efficient cooling devices.
3. **Battery Materials:** Battery materials are critical for energy storage, such as lithium-ion batteries that power portable electronic devices and electric vehicles. Components include cathodes, anodes, electrolytes, and separators.
4. **Fuel Cell Materials:** Fuel cells convert chemical energy into electricity through electrochemical reactions. Materials like proton-conducting electrolytes and catalysts are essential for their operation.

5.13 Nanomaterials

Nanomaterials are materials with structures or features at the nanoscale, typically ranging from 1 to 100 nanometers. At this size, materials exhibit unique properties and behaviors that differ from their bulk counterparts, making nanomaterials a rapidly growing and diverse field of research and application. Nanomaterials can be engineered and tailored to have specific properties, opening up numerous opportunities in various industries. Some common types of nanomaterials include:

1. **Nanoparticles:** Particles with nanoscale dimensions, such as metal nanoparticles (e.g., gold, silver) and semiconductor nanoparticles (e.g., quantum dots). These are used in catalysis, drug delivery, and imaging applications.
2. **Nanotubes:** Cylindrical structures with a diameter on the nanoscale, such as carbon nanotubes. They have high mechanical strength and electrical conductivity and are used in electronics, composites, and energy storage devices.
3. **Nanowires:** Long, thin structures with nanoscale dimensions, often made of semiconductors. They have potential applications in nanoelectronics and sensors.
4. **Nanocomposites:** Materials composed of a matrix material with dispersed nanoscale particles or fibers, leading to improved mechanical, electrical, or thermal properties. They are used in aerospace, automotive, and construction industries.
5. **Nanofilms:** Thin films with nanoscale thickness, used for various applications such as coatings, sensors, and electronic devices.

Nanomaterials offer several advantages:

- **Improved Properties:** Nanomaterials can have enhanced mechanical, electrical, optical, and catalytic properties compared to bulk materials.
- **Surface Area:** Their high surface area-to-volume ratio provides more opportunities for interactions in various applications.
- **Versatility:** Nanomaterials can be engineered to have specific properties, making them highly versatile for different applications.

Nanomaterials find applications in a wide range of industries, including electronics, healthcare, energy, aerospace, and environmental sectors. However, their unique properties also raise concerns about potential health and environmental impacts, necessitating responsible handling and risk assessment during their development and use. As research in nanomaterials continues, their potential to revolutionize technology and address global challenges becomes increasingly evident.

Module 6 Electrical and Magnetic Materials

Topics: Conducting and resisting materials – types, properties and applications; Semiconducting materials – properties and applications; Magnetic materials – Soft and hard magnetic materials and applications; Superconductors and dielectric materials – properties and applications; Smart materials; Sensors and actuators; Piezoelectric, magnetostrictive and electrostrictive materials.

This chapter delves into the fascinating world of electrical and magnetic materials, providing a comprehensive exploration of their fundamental principles, properties, and applications. From conductors that facilitate the seamless flow of electric charges to magnets that exhibit mysterious attractive forces, we embark on a journey to understand the inner workings of these materials and how they have shaped modern society.

Introduction

The electrons in the outermost shell of atoms control the electrical and magnetic behaviour of substances. Recent developments in the field of electronic structure of substances have accelerated the growth of number of useful solid state devices. The prime objective of this chapter is to explore the electrical and magnetic properties of materials.

Electrical conduction:

One of the most important characteristics of a solid material is the ease with which it transmits an electric current. Ohm's law relates the current I (i.e., the time rate of charge passage, Q/t, Q =Charge and t = time) to the applied voltage V as follows:

$$V = I R \qquad (1)$$

Where R is the resistance of the material through which the current I is passing. The units of V, I and R are Volt, ampere and Ohm respectively. The electrical resistivity (ρ) of solids is probably the most important of all physical properties. The value of electrical resistance is influenced by specimen configuration, and for many materials is independent of current. However, the resistivity (ρ) of material is independent of specimen geometry but it is related to R through the relation

$$\rho = \frac{RA}{l} \qquad (2)$$

Where l is the distance between the two points of the specimen at which the voltage is measured, and A is the area of cross-section perpendicular to the direction of the current. The units of ρ are Ohm-meters (Ω– m). From Eqs. (1) and (2),

$$\rho = \frac{VA}{Il} \qquad (3)$$

Many factors influence the value of ρ for a given material. Values of resistivity of common materials at 20°C are given in Table 1 and few engineering materials are given in Table 2

Table 1: Resistivity of common materials at 20°C

Material	*Resistivity (ρ) (Ω – m)*	*Material*	*Resistivity ( ) (Ω -m)*
Silver	1.6×10^{-8}	Germanium	10^{-5} to 0.6
Aluminium	2.66×10^{-8}	Silicon	10^{-5} to 2.5×10^{3}
Iron	9.1×10^{-8}	PVC	1.0×10^{10}
Copper	1.67×10^{-8}	Bakelite	1.0×10^{11}
Nickel	13.3×10^{-8}	Mica	1.0×10^{11}
Carbon-steel	1.7×10^{-7}	Glass	1.0×10^{16}
Polythene	1.0×10^{16}	Stainless steel	7.0×10^{-7}
Graphite	1.4×10^{-7}	Steatite Porcelain	1.0×10^{13}
		Alumina	10^{11}
		Diamond	10^{12}

The resistivity of some widely used metal and their alloys along with their temperature coefficient are given in Table 2.

Table 2 Electrical resistivity of some metals and their alloys

Metals and alloys	*Resistivity (ρ) at 20°C (Ω-m)*	*Temperature coefficient α/°C*
• Copper, annealed	1.67×10^{-8}	4.29×10^{-3} (0-100°C)
• Copper, reduced 75% by cold drawing	1.71×10^{-8}	—
• Cartridge brass annealed 70% Cu and 30% Zn	6.20×10^{-8}	1.48×10^{-3} (20°C)
• Aluminium, annealed	2.65×10^{-8}	4.29×10^{-3} (20°C)
• Iron, annealed	9.71×10^{-8}	6.57×10^{-3} (20°C)
• Constantan 55% Cu and 45% Ni	49×10^{-5}	0.02×10^{-3} (25°C)
• Manganin 84% Cu, 12% Mn and 4% Ni	44×10^{-7}	0.009×10^{-3} (25°C) -0.42×10^{-3} (100°C)
• Nichrome 80% Ni and 20% Cr	108×10^{-5}	0.14×10^{-3} (0-500°C)

Electrical conductivity (σ)

Sometimes, electrical conductivity (σ) is used to specify the electrical character of a material. Electrical conductivity is simply the reciprocal of resistivity (ρ), i.e

$$\sigma = \frac{1}{\rho}$$

Electrical conductivity, also known as electrical conductance, is a property of materials that describes their ability to conduct electric current. In other words, it measures how easily electric charges (usually electrons) can flow through the material when a voltage difference is applied across it.

Conductivity is an essential characteristic in various fields, including physics, engineering, and materials science. It is typically represented by the Greek letter sigma (σ) and is measured in units of siemens per meter (S/m) or mhos/meter (mho/m), where 1 S/m equals 1 A/V (ampere per volt).

Materials can be broadly classified into three categories based on their electrical conductivity:

1. Conductors: Materials with high electrical conductivity are called conductors. In these materials, electric charges can move freely due to the abundance of mobile charge carriers (such as free electrons). Metals like copper, silver, and aluminum are excellent conductors and are commonly used in electrical wires and circuits.
2. Insulators: Insulators, also known as non-conductors, have very low electrical conductivity. In these materials, electric charges are strongly bound to atoms or molecules and cannot move easily. Examples include rubber, glass, and most plastics. Insulators are used to prevent or reduce the flow of electric current in certain applications.
3. Semiconductors: Semiconductors have conductivity values that lie between those of conductors and insulators. They can conduct electricity under certain conditions but have limited conductivity compared to conductors. Semiconductors are crucial components in electronics and are used in devices such as transistors, diodes, and integrated circuits.

The electrical conductivity of a material depends on various factors, including temperature, impurities, and the presence of defects or imperfections. In general, higher temperatures tend to increase the conductivity of conductors while reducing the conductivity of semiconductors and insulators.

The ability to control electrical conductivity is vital for designing and optimizing electronic devices and electrical systems, making it a fundamental concept in modern technology and engineering.

Table- 3 Comparison between conductors, semiconductors, insulators

Conductors	*Semiconductors*	*Insulators*
1. Conductivity decreases with increase in temperature upto nearly zero value	• Conductivity increases with increase in temperature. Conductivity is particularly sensitive to impurity type and content.	• Conductivities increases with increase in temperature
2. Conductivity of metals is of the order of 10^7 $(\Omega\text{-m})^{-1}$	• Conductivity of semiconductors range from 10^{-6} to 10^4 $(\Omega\text{-m})^{-1}$	• Conductivity of insulators range between 10^{-10} to 10^{-20} $(\Omega\text{-m})^{-1}$
3. Electrical resistivity is very low and range from 10^{-9} to 10^{-4} $(\Omega\text{-m})$	• Resistivity is normally high and range between 10^{-3} to 10^3 $(\Omega\text{-m})$	• Resistivity is very high and range between 10^4 to $10^{17}(\Omega\text{-m})$
4. Temperature coefficient of resistance is not constant	• Temperature coefficient of resistance is negative	• Negative resistance temperature coefficient. Probably with the rise in temperature some electrons reach to the conduction band.
5. At low temperatures they exhibit semiconductivity. At very low temperatures, some elements and their alloys exhibit infinite conductivity, i.e. super conductivity	• At low temperature semiconductors become *dielectrics* (insulators)	• No change in the properties of the insulators observed
6. Have unfilled overlapping energy bands	• Have filled energy bands and small forbidden zones	• There is a large energy gap in between valence and conduction band
7. Current carriers in conductors are free electrons which exist whether external field is applied or not	• Current carriers are originated due to absorption of electrical, radiant or thermal energy from external source. Electrons and holes, both serve as current carriers	• Energy required for electrons to cross the energy gap between conduction band and valence band is very large and hence no conduction

Applications of Conductive Materials

1. Electrical Wiring and Power Transmission

Metals, particularly copper and aluminum, are extensively used in electrical wiring and power transmission due to their high electrical conductivity and mechanical strength.

2. Electronic Components

Semiconductors are the backbone of modern electronics. Transistors, diodes, and integrated circuits made from semiconductor materials enable information processing and signal amplification in various electronic devices.

3. Printed Circuit Boards (PCBs)

PCBs are essential components of electronic devices, providing mechanical support and electrical connections. Conductive materials like copper traces on PCBs facilitate the flow of electrical signals between components.

4. Sensors and Actuators

Conductive materials are vital in sensor technologies. For instance, conductive polymers can be used in flexible and wearable sensors, while piezoelectric materials like certain ceramics can serve as actuators in mechanical systems.

5. Energy Storage Devices

Carbon-based materials, such as graphite in lithium-ion batteries and carbon nanotubes in supercapacitors, are crucial in energy storage applications.

6. Electromagnetic Shielding

Conductive materials are used for electromagnetic shielding to protect sensitive electronic components from external electromagnetic interference.

7. Biomedical Applications

Conductive materials find applications in bioelectronics and medical devices. For example, conductive polymers can be integrated with biological tissues for neural interfaces and prosthetics.

Electronic and ionic conduction

We have seen that an electric current results from the motion of electrically charged particles in response to the forces that act on them from an externally applied field. Positively charged particles are accelerated in the electric field direction, and negatively charged particles in the direction opposite to the electric field direction. A current arises within most solid materials due to flow of electrons and this is termed as electronic conduction. In addition, for ionic materials a net motion of charged ions is possible that produces a electric current; such is termed ionic conduction.

Band structure in solids

A solid may be thought of as consisting of a large number, say N, of atoms initially separated from one another, which are subsequently brought together and bonded to form the ordered atomic arrangement exhibited by the crystalline material. At relatively large separation distances, each atom is independent of all the other atoms as will have the atomic energy levels and electron configuration as if isolated. However, as the atoms in a solid come within the close proximity of one another, electrons are acted upon, or perturbed, by the electrons and nuclei of adjacent atoms. This influence is such that each distinct atomic state may split into a series of closely spaced electron states in the solid, to form what is termed an electron energy band. The extent of splitting of atomic states depends on interatomic separation (Fig. 1) and begins with the outermost electron shells, since they are the first to be perturbed as the atoms coalesce. Within each band, the energy states are discrete, yet the difference between

adjacent states is exceedingly small. At the equilibrium spacing, band formation may not occur for the electron subshells nearest the nucleus (Fig. 2(b)). Moreover, gaps may exist between adjacent bands, as also shown in Fig. 2(a), normally energy lying within these band gaps are not available for electron occupancy. The conventional way of representing electron band structure is shown in Fig. 2(a).

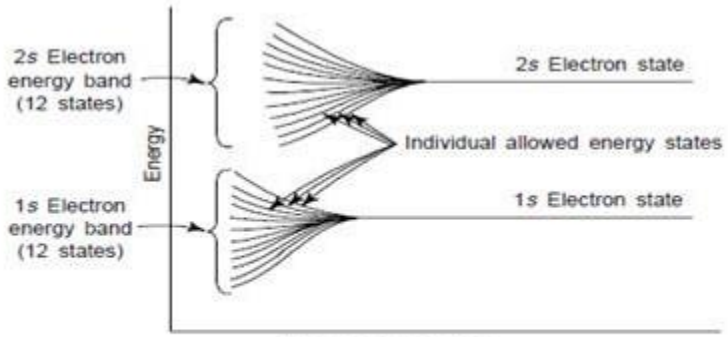


Fig-1

A schematic plot of electron energy vs. interatomic separation of an aggregate of 12 atoms, i.e. for $N = 12$. Upon close approach, each of the 1s and 2s atomic states splits to form an electron energy band consisting of 12 states

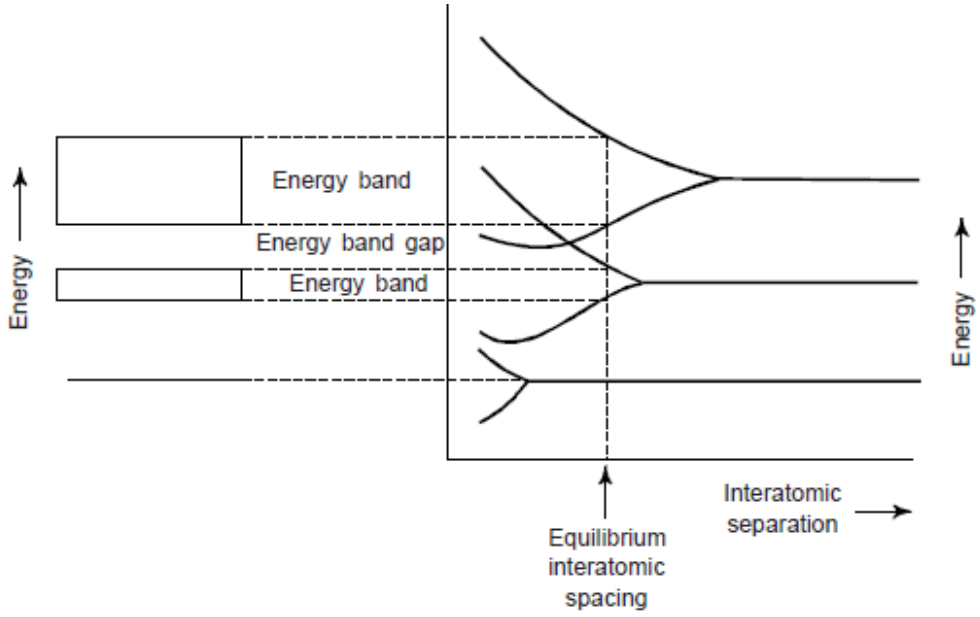


Fig-2 (a) Fig-2 (b)

(a) The conventional representation of the electron energy band structure for a solid material at the equilibrium interatomic separation. (b) Electron energy vs. interatomic separation for an aggregate of atoms, exhibiting how the energy band structure at the equilibrium separation in (a) is generated

The number of states within each band will equal the total of all states contributed by the N atoms, e.g. a s-band will consists of N-states, and a p-band of 3 N states. With regard to occupancy, each energy state with accommodate two electrons, which must have oppositely directed spins. Moreover, bands will contain the electrons that resided in the corresponding levels of the isolated atoms; for e.g., a 4s energy band in the solid will contain those isolated atom's 4s electrons. Of course, there will be empty band and, possibly, bands that are only partially filled. The electrical properties of a solid material are a consequence of its electron

band structure, i.e. the arrangement of outermost electrons in bands and the way in which they are filled with electrons. A distinctive band structure type exists for metals, for semiconductor, and for insulators.

The band structure in a solid determines whether the solid is an insulator or a conductor or a semiconductor. The bands are filled upto a certain level by the electrons within each atom. The highest band in which electrons are still predominantly attached to their atoms are found is called valence band. This is the band in which the valence (outermost) electrons from each atom will be located. These are the electrons that are the possible carriers of electricity. However, in order for an electron to conduct, it must get up to slightly higher energy so that it is free of the grip of its atom. At 0 K four different types of band structures are possible. In the first (Fig. 3(a)), one outermost band is only partially filled with electrons. The energy corresponding to the highest filled energy state of 0 K is called the Fermi energy EF, as indicated in future. This energy band structure is typified by some metallic conductors in particular those that have a single s valence electron, e.g. copper, etc. Each copper atom has one 4s electron. However, for a solid comprised of N atom, the 4s band is capable of accommodating 2N electrons. Obviously, only half the available electron positions within this 4s band are filled.

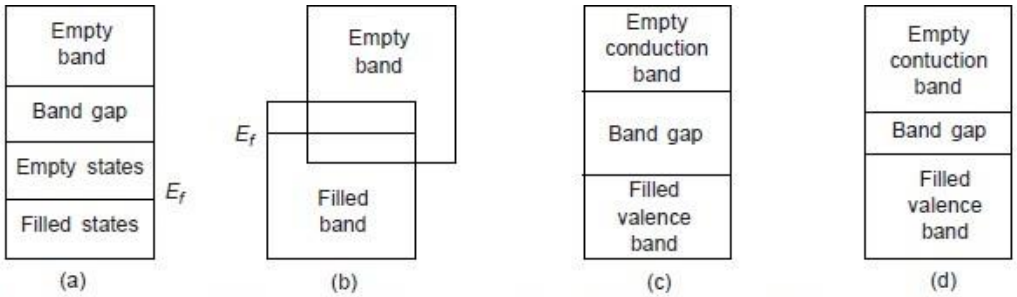


Fig- 3 **Various possible electron band structure in solids at 0 K. (a) and (b) for conductors. Band structure (a) is found in metals such as copper, in which there are available electron states above and adjacent to filled states, in the same band. Band structure (b) is for metals such as magnesium, where in there is an overlap of filled and empty outer bands. (c) The electronic band structure characteristic of insulators; the band gap > 2 eV or more. (d) The electron band structure found in semiconductors; E_g < 2 eV**

For the second band structure, also found in metallic conductors (Fig. 3(b)), there is an overlap of an empty band and a filled band. Magnesium has this type of band structure. Each isolated Mg has two 3s electrons. However, when a solid is formed, the 3s and 3p bands overlap. In this instance and at 0K, the Fermi energy, EF is taken as that energy below which, for N atoms, N states are filled, two electrons per state. Therefore, the band theory tells us that we have a conductor, when (i) the valence band is not filled, so electron can move to higher states in the valence band and be free (energy gaps between valence band and conduction band are very small), or (ii) when there is no energy gap between the valence band and the conduction band, i.e. there is overlapping, so electrons can easily make the transitions from the valence to the conduction bands.

The final two band structures (Fig. 3(c) and (d)) are similar; one band (the valence band) that is completely filled with electrons that is separated from an empty conduction band and an energy band gap lies between them. When energy band gap is of the order of 1 eV (for Si, E_g = 1.12 eV; and for Ge, E_g = 0.72 eV). These materials with narrow band gap are called semiconductors. When the energy band gap is relatively wide ~ 5 eV or even more, the materials are called insulators. The band theory of solids tells us that an insulator is a material

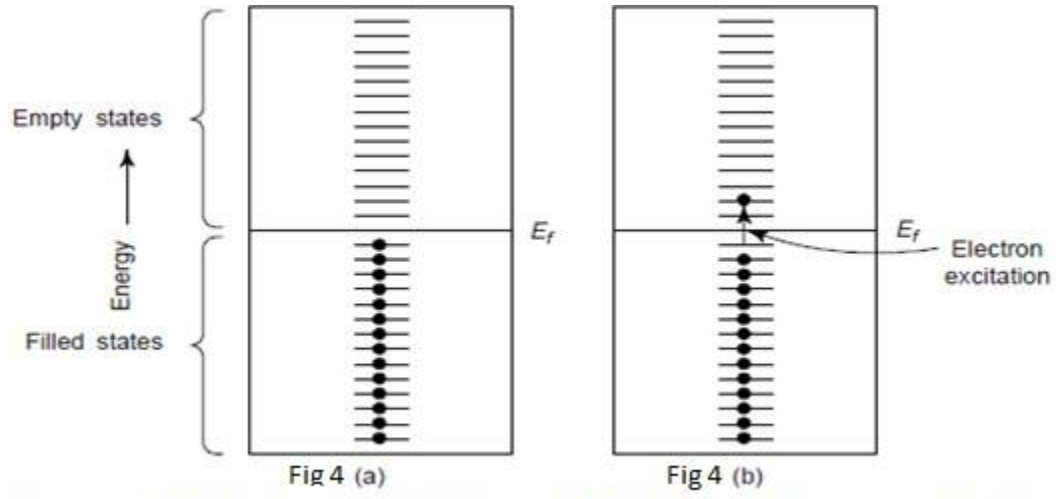
in which the valence band (VB) are filled and the energy band gap E_g between VB and conduction band (CB) is too large so that valence electrons cannot jump at normal temperatures from VB to CB. An insulator does not conduct at 0 K or even at room temperature because there are no conduction electrons in it. However, an insulator may conduct if its temperature is very high or if a high voltage is applied across it. This is known as breakdown of an insulator.

Conduction in terms of band and atomic bonding models

We have seen that as far as solid state theory is concerned only the upper energy bands (valence bands) are of interest, since electrons at lower levels practically do not take part in interactions among atoms. This means that only electrons with greater than the Fermi energy (The energy corresponding to the highest filled electron filled state at 0 K in metal is called Fermi energy and designated by E_F) may be acted on and accelerated in the presence of an electric field. These are the electrons that participate in the conduction process, which are termed *free electrons*. As mentioned earlier that another charge entity called a *hole* is found in semiconductors and insulators. Holes have energies less than Fermi energy, E_F and also participate in electronic conduction. Thus the ensuing discussion reveals, the electrical conductivity is a direct function of the number of free electrons and holes. We may also note that the distinction between conductors, semiconductors and insulators lies in the number of these free electron and hole charge carriers.

M**etals**

For an electron to become free, it has to be excited or promoted into one of the vacant or empty and available energy states above Fermi energy, E_F (Fig. 3 (a) and 3 (b)). In Figs. 3(a) and 3(b), there are vacant energy states adjacent to the highest filled state at E_F. Obviously, very little energy is required to promote electrons into the low-lying empty states Fig. 4. Generally, the energy supplied by an electric field is sufficient to excite large numbers of electrons into these conducting states.

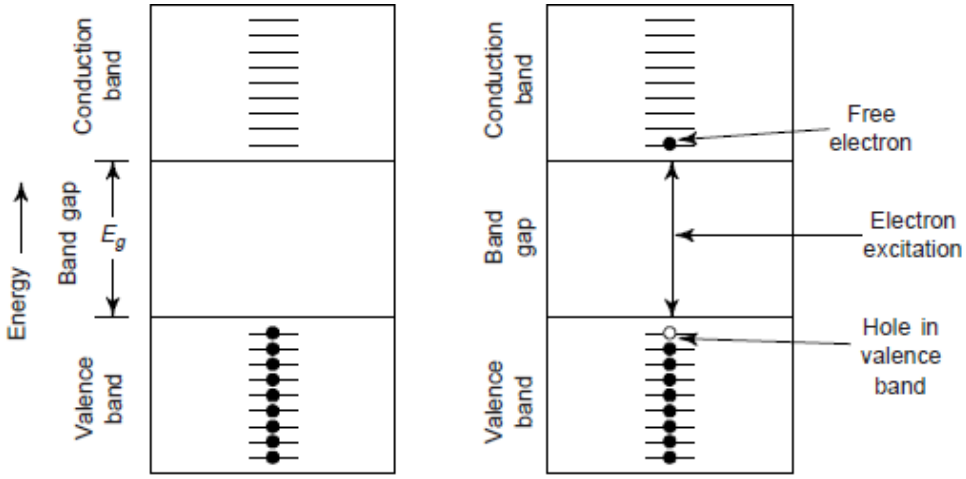


Occupancy of electron states (a) bafore and (b) after an electron excitation for a metal

In a metallic bonding model it is assumed that all the valence electrons have freedom of motion and form an 'electron gas', which is uniformly distributed throughout the lattice of ion cores. Although these electrons are not locally bound to any particular atom, nevertheless, they must experience some excitation to become conducting electrons that are free in true sense. Obviously, only a fraction are excited, this still gives rise to a relatively large number of free, i.e. conducting electrons and, consequently, metals exhibit a high conductivity.

Semiconductor and insulator

We have seen that for insulators and semiconductors, empty states adjacent to the top of the filled valence band are not available. To become free, we have to promote electrons across the energy band gap and into empty states at the bottom of the conduction band. This is possible only by supplying to an electron the difference in energy between these two states, which is approximately equal to the band gap energy, E_g (Fig.5).



Occupancy of electron states for an insulator and or semiconductor (a) before and (b) after an electron excitation from the valence band into the condution band, in which both a free electron and hole are generated

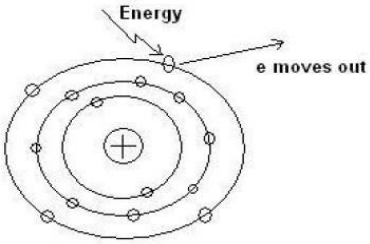
The number of electrons excited thermally, i.e., by heat energy into the conduction band depends on the energy band gap width as well as temperature. At a given temperature, the larger the band gap energy E_g, the lower is the probability that a valence electron will be promoted into an energy state within the conduction band; this results in very few conduction electrons. This means that larger the band gap, the lower is the electrical conductivity at a given temperature. Obviously, the distinction between semiconductors and insulators lies in the width of the band gap; for semiconductors it is narrow, whereas for insulators it is relatively wide.

With the rise in temperature, the thermal energy that is available for electron excitation increases.Obviously, more electrons are promoted into the conduction band which gives rise to an enhanced conductivity.

Let us now examine the conductivity of insulators and semiconductors in the light of atomic bonding models. For electrically insulating materials, interatomic bonding is ionic or strongly covalent. Obviously, the valence electrons are tightly bound to or shared with the individual

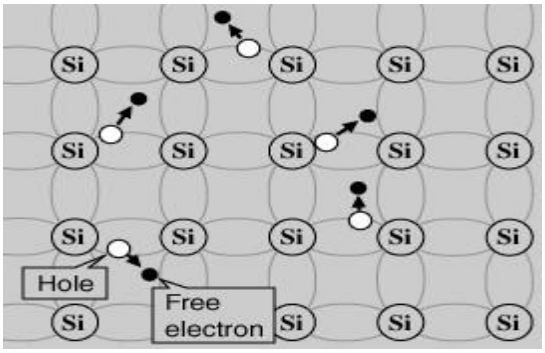
atoms. This means that these electrons are highly localized and are not in any sense free to wander throughout the crystal. In case of semiconductors, the bonding is covalent (or predominantly covalent) and relatively weak. This means that the valence electrons in semiconductors are not as strongly bound to the atoms. Consequently, these electrons are more easily freed by thermal excitation than they are for insulators.

A semiconductor is a substance, usually a solid chemical element or compound that can conduct electricity under some conditions but not others, making it a good medium for the control of electrical current.
It has almost filled valence band, empty conduction band and very narrow energy gap i.e., of the order of 1 eV. Energy gap of Silicon (Si) and Germanium (Ge) are 1.0 and 0.7 eV respectively. Consequently Si and Ge are semiconductors.
Effect of temperature on conductivity of semiconductors: At 0 K, all semiconductors are insulators. At finite temperature, the electrical conductivity of a semiconductor material increases with increasing temperature. With increase in temperature, outermost electrons acquire energy and hence by acquiring energy, the outermost electrons leave the shell of the atom.
Hence with increase in temperature, number of carriers in the semiconductor material increases and which leads to increase in conductivity of the material.



Types of semiconductors:

Intrinsic Semiconductor:
An intrinsic semiconductor material is chemically very pure and possesses poor conductivity. It has equal numbers of negative carriers (electrons) and positive carriers (holes). A silicon crystal is different from an insulator because at any temperature above absolute zero temperature, there is a finite probability that an electron in the lattice will be knocked loose from its position, leaving behind an electron deficiency called a "hole". This hole can travel from one atom to the adjacent atom by accepting an electron from later one. This process involves formation of new covalent bond and breaking an existing bond by filling up the hole and creating a new hole.in this way, the holes travel fromone atom to the adjacent atoms in crystal lattice. If a voltage is applied, then both the electron and the hole can contribute to a small current flow.

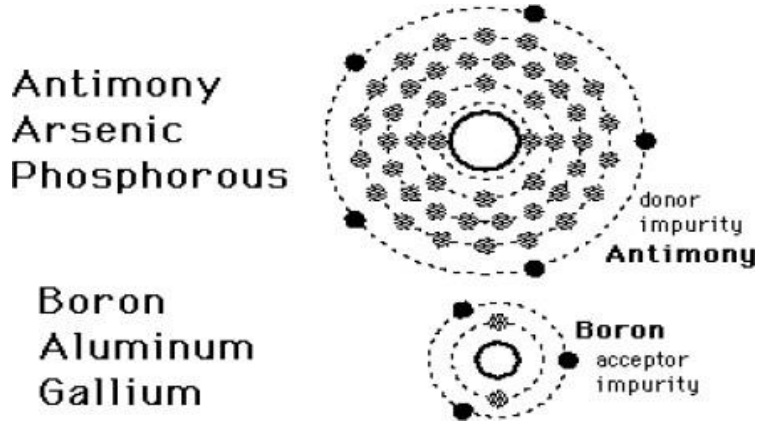


Extrinsic Semiconductor:
Extrinsic semiconductor is an improved intrinsic semiconductor with a small amount of impurities added by a process, known as doping, which alters the electrical properties of the semiconductor and improves its conductivity. Introducing impurities into the semiconductor materials (doping process) can control their conductivity.
Doping process produces two groups of semiconductors: the negative charge conductor (n-type) and the positive charge conductor (p-type). Semiconductors are available as either elements or compounds. Silicon and Germanium are the most common elemental semiconductors.
Compound Semiconductors include InSb, InAs, GaP, GaSb, GaAs, SiC,
GaN. Si and Ge both have a crystalline structure called the diamond lattice. That is, each atom has its four nearest neighbours at the corners of a regular tetrahedron with the atom itself being at the centre.
In addition to the pure element semiconductors, many alloys and compounds are semiconductors. The advantage of compound semiconductor is that they provide the device engineer with a wide range of energy gaps and mobilities, so that materials are available with properties that meet specific requirements. Some of these semiconductors are therefore called wide band gap semiconductors.

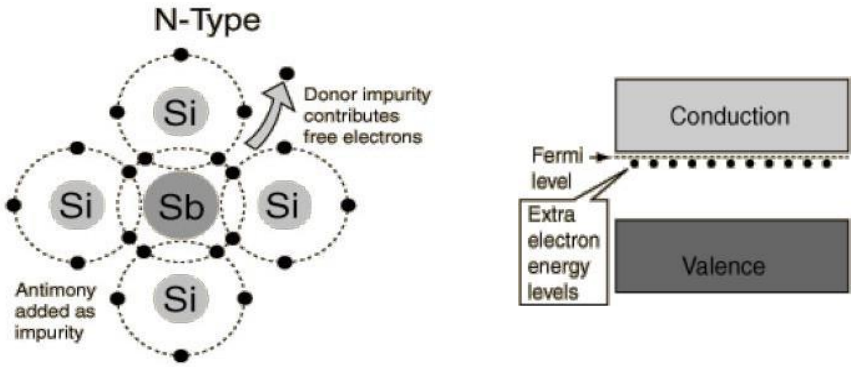
The Doping of Semiconductors
The addition of a small percentage of foreign atoms in the regular crystal lattice of silicon or germanium produces dramatic changes in their electrical properties, producing n-type and p-type semiconductors.

Pentavalent impurities
(5 valence electrons) produce n-type semiconductors by contributing extra electrons.

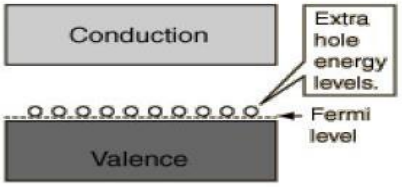
Trivalent impurities
(3 valence electrons) produce p-type semiconductors by producing a "hole" or electron deficiency.

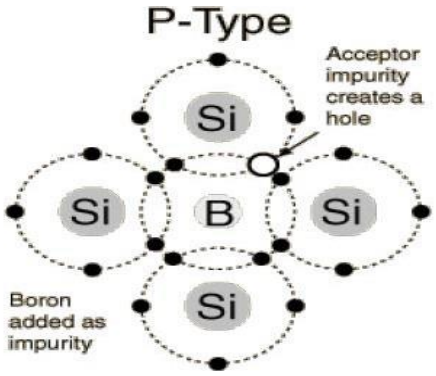


N-Type Semiconductor:
The addition of pentavalent impurities such as antimony, arsenic or phosphorous contributes free electrons, greatly increasing the conductivity of the intrinsic semiconductor. Phosphorous may be added by diffusion of phosphine gas (PH3).



P-Type Semiconductor
The addition of trivalent impurities such as boron, aluminum or gallium to an intrinsic semiconductor creates deficiencies of valence electrons, called "holes". It is typical to use B2H6 diborane gas to diffuse boron into the silicon material.
Note: positive holes are less mobile than free electrons so the conductivity of a P-type semiconductor is inherently less than that of N-type semiconductor.





Electrical resistivity of metals

Most metals are extremely good conductors of electricity. Room temperature conductivities of few common metals are given in Table 3. Metals have high conductivities due to the large number of free electrons that have been excited into empty states above the Fermi energy.

5 Room-temperature electrical conductivity for few metals and alloys

Metal or alloy	*Electrical conductivity* $(\Omega\text{-m})^{-1}$
Copper	6.0×10^7
Silver	6.8×10^7
Gold	4.3×10^7
Aluminium	3.8×10^7
Iron	1.0×10^7
Platinum	0.94×10^7
Brass (70 Cu – 30 Zn)	1.6×10^7
Plain carbon steel	0.6×10^7
Stainless steel	0.2×10^7

Let us now discuss conduction in metals in terms of the resistivity (the reciprocal of conductivity). The crystalline defects serve as scattering centers for conduction electrons in metals and increase in their number raises the resistivity, i.e. lowers the conductivity. The concentration of these imperfections depends on temperature, composition, and the degree of cold work of a metal specimen. It has been observed experimentally that the total resistivity of a metal is the sum of the contributions from the thermal vibrations, impurities and plastic deformation; i.e., the scattering mechanism act independently of one another. Mathematically, we can write this as follows:

$$\rho_{total} = \rho_t + \rho_i + \rho_d \quad \textbf{(1)}$$

where ρ_t, ρ_i and ρ_d are the individual thermal, impurity and deformation resistivity contributions, respectively. Equation (1) is sometimes called as Matthiessen's rule. Figure 6 shows a plot of resistivity versus temperature for copper and several copper-nickel alloys in annealed and deformed states. Figure also show the influence of each variable on the total resistivity. The additive character of the individual resistivity contributions is demonstrated at –100°C.

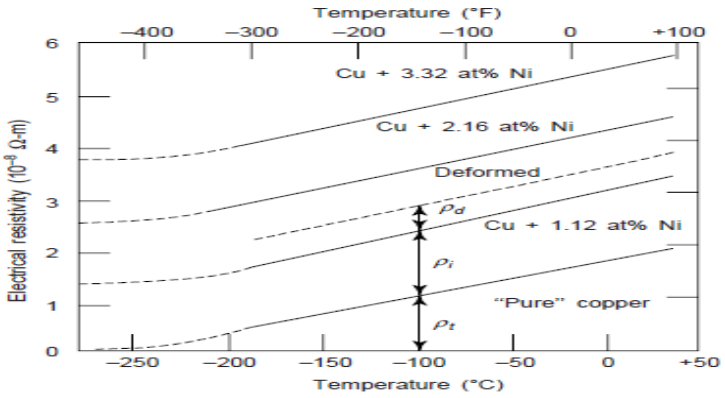


Fig- 6
The electrical resistivity vs. temperature curves for Cu and three copper-nickel alloys, one of which has been deformed. The contributions to the resistivity due to thermal, impurity and deformation are shown at –100°C

Factors affecting resistivity

(i) Influence of Temperature: Any rise in temperature of a conductor (which contains small amounts of impurities) increases thermal agitation of the metallic ions as they vibrate about their mean position. This reduces the mean free path and restricts the free movement of electrons, thus reducing the conductivity of the metal, i.e. this increases the resistivity of metal. For the pure metal and all the copper-nickel alloys shown in Fig. 6, the resistivity rises linearly with temperature above about –200°C. Thus

$$\rho_t = \rho_o + \alpha T \qquad (2)$$

where ρ_o and α are constants for each particular metal.

(ii) Influence of Impurities: Another factor which reduces the mean free path of electrons is the impurity or solute atoms. The solute atoms provide the breakage in the regular crystalline structure, thus presenting an obstacle in the movement of electron waves. A solid solution alloy will always have lower conductivity than its pure components though both individual components have higher conductivity than the alloy. For additions of a single impurity that forms a solid solution, the impurity resistivity ρ_i is related to the impurity concentration C_i in terms of the atom fraction (at %/100) as follows:

$$\rho i = AC_i (1-C_i) \qquad (3)$$

where A is a composition-independent constant that is a function of both the impurity and host metals. The influence of Ni impurity additions at about room temperature resistivity of Cu is shown in Fig. 7, upto 50 Wt% Ni; over this composition range Ni is completely soluble in Cu. We may note that Ni atoms in Cu act as scattering centres, and increasing the concentration of Ni in Cu results in the enhancement of resistivity.

One can use the rule of mixtures expression for a two-phase alloy consisting of α and β phases to approximate the resistivity as follows:

$$\rho_i = \rho_\alpha V_\alpha + \rho_\beta V_\beta \qquad (4)$$

where the V's and ρ's represent volume fractions and individual resistivities for the respective phases.

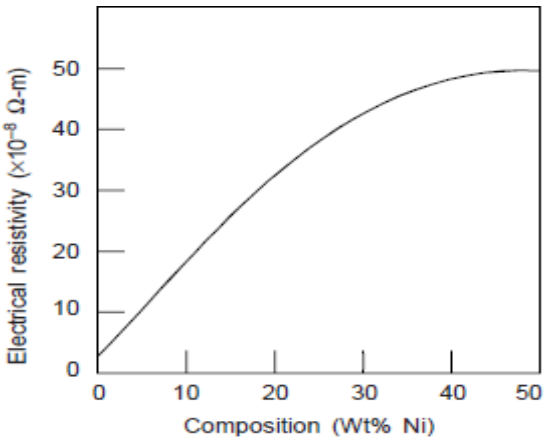


Fig. 7 Room temperature electrical resistivity vs. composition for Cu-Ni alloys

(iii) Influence of Plastic Deformation: Plastic deformation also raises the electrical resistivity as a result of increased number of electron-scattering dislocations. The effect of Plastic deformation on resistivity is also shown in Fig.6.

(iv) *Effect of Pressure:* At room temperature the general behaviour of ρ of metal is to decrease initially with increasing pressure and it may pass through a minimum. The initial decrease is due to the effect of pressure in reducing the amplitude of lattice vibrations. The subsequent increase is probably due to modification of the electron band structure which leads to increased phonon scattering.

Insulators

We have read that in an ideal insulator, all valence electrons are occupied in bond formation and almost no free electrons are available for electrical conduction. Thus an insulator (electrical) is a non-metallic material that has a filled valence band at 0 K and relatively wide energy band gap. Consequently, the room temperature electrical conductivity is very low, less than about 10^{-10} $(\Omega\text{-m})^{-1}$. A good insulator may have a resistivity as high as 10^{14} $(\Omega$ -m). Common electrical insulating materials are polyethylene, bakelite, lucite, mica, PVC, rubber, porcelain etc. Most polymers and ionic ceramics are insulating materials at room temperatures. Thermal agitation and imperfections adversely affect the insulating properties of a material but, as is real materials, a few free electrons are always there to conduct electricity. Non-metallic crystals are held together by ionic and covalent bonds and valence electrons are much more closely associated with their atoms than in the metallic bond. Generally, insulators are those materials which have the electrons completely filled in the Brillouin Zone and also at the same time have wide energy gaps.

The conductivity of insulators increases with the rise in temperature because more and more conducting electrons are released. However, the materials which are insulators at 0 K but develop significant conductivities at room temperature become semiconductors. Of course, many insulating materials are used on the basis of their ability to insulate, and thus a high electrical resistivity is desirable.

Table .4 Room temperature conductivities for some selected non-metallic materials

Material	*Electrical conductivity* $[(\Omega - m)^{-1}]$	*Material*	*Electrical conductivity* $[(\Omega - m)^{-1}]$
Graphite	$3 \times 10^4 - 2 \times 10^5$	POLYMERS	
CERAMICS		Phenol-formal-dehyde	10^{-9}-10^{-10}
Concrete (Dry)	10^{-9}	Polymethyl-methacrylate	$< 10^{-12}$
Soda lime glass	10^{-10}-10^{-11}	Nylon 6, 6	10^{-12}-10^{-13}
Porcelain	10^{-10}-10^{-12}	Polystyrene	$< 10^{-14}$
Borosilicate glass	$\sim 10^{-13}$	Polyethylene	10^{-15}-10^{-17}
Aluminium oxide	$< 10^{-13}$	Polytetra fluoroethylene	$< 10^{-17}$
Fused silica	$< 10^{-13}$		

One can classify the requirements of good insulating materials as electrical, mechanical, thermal and chemical. Electrically the insulating material should have high resistivity to reduce the leakage current and high dielectric strength so that it may withstand higher voltage without being punctured or broken down.

Moreover, the insulator should have small dielectric loss. Insulators are used on the basis of volume and not weight and hence a low density is preferred. A uniform viscosity and for liquid insulators ensures uniform thermal and electrical properties.

Liquid and gaseous insulators are used also as coolants, e.g. transformer oil, hydrogen and helium are used for insulation and cooling purposes. Obviously, for such materials good thermal conductivity is a desirable property. To prevent mechanical damage, the insulator should also have small thermal expansion.

Moreover, it should be non-ignitable or if ignitable it should be self extinguishable. Chemically, the insulating materials should be resistant to oils, liquid gas fumes, acids and alkalies. Moreover, the insulator should not absorb water particles as water lowers the insulation resistance and the dielectric strength.

Insulators should have certain mechanical properties depending on the use to which they are put. Thus when insulators are used for electric machine insulation, they should have sufficient mechanical strength to withstand vibration. In such cases, good heat conducting property is also desirable.

In making dielectric capacitors insulating materials with large electronic and ionic polarizabilities and therefore large permittivity are used. Titanium oxide with a permittivity ~100 is a good example of such a material. We may note that the use of molecules with a permanent dipole moment is not desirable because of possibility of large dielectric losses at high frequencies.

Properties of the some of the insulating materials are given in Table 5.

Table 5 Properties of few insulating materials at room temperature

Material	*Dielectric constant (ε_r)*	*Dielectric strength (kV/mm)*	*Density ($\times 10^{-3}$) (kg/m^3)*	*Resistivity (ρ) (Ω-m)*
Mica	4-5.5	60-125	2.5-2.7	10^{14}-10^{19}
Glass	4-10	20-30	2.2-4.0	10^{13}-10^{16}
Ebonite (RP)	4-4.5	25	1.3	1×10^{20}
Bakelite	4-4.6	10-40	1.2	—
Asbestos	—	2	2.3-2.6	2×10^{7}
Rubber (soft)	2.6-3.0	15-25	1.7-2.9	4×10^{15}
Silk (natural)	4.5	—	—	—
Polystyrene	2.2-2.8	25-50	1.05-1.65	$5 \times 10^{13} - 5 \times 10^{19}$
Polyvinyl chloride (PVC) resin	3.1-3.5	50	1.38	—

Dieelectric

These are the materials or insulators which have the unique characteristic of being able to store electric charge. The electrons in these substances are localized in the process of bonding the atoms together.

Obviously, covalent or ionic bonds, a mixture of both, or Vander Waals bonding between closed shell atoms give rise to solids or gases which exhibit dielectric or insulating properties. Dielectric materials may be gases, liquids or solids with the exception of air which is the insulating material between the bare conductors of the overhead electric grid system. Liquid dielectrics are used mainly as impregnants for high voltage paper insulated cables and capacitors as filling and cooling media for transformers and circuit breakers. Most common properties of dielectric materials are: (i) dielectric constant (ii) dielectric strength (iii) insulation resistance (iv) surface resistivity (v) loss factor (vi) tangent of loss factor in terms of a capacitor or phase difference (vii) polar and non-polar materials.

Materials, which are capable of separating electrical conductors circuit breakers, e.g. silicon, oils, liquid dielectrics have high dielectric constant, high resistance, high dielectric strength when moisture and impurities are removed from them. They have high temperature dissipation capacity and least dielectric losses.

Their dielectric constant is greater than one. Following materials are important from engineering point of view:

Mica is the widely used insulating material in switch gears armature windings, electrical heating devices like iron, hot plates etc. It is also used in capacitors for high frequency application. Mica is an inorganic compound of silicates of aluminium, soda potash and magnesia. It is crystalline in nature and can be easily split into very thin flat sheets. The two important types of mica are: (i) muscovite and (ii) phlogopite. Mica has a good dielectric strength and mechanical strength. Its dielectric constant varies between 5 and 7.5, loss tangent between 0.0003 and 0.015 and dielectric strength between 700 and 1000 kV/mm.

Asbestos is also used as an insulator in the form of paper, tape, cloth and board. Asbestos is widely used in panel boards, insulating tubes and cylinders in the construction of air cooled transformers. Asbestos is an inorganic material, which is used to designate a group of naturally occurring fibre material. Asbestos has good dielectric and mechanical properties.

Ceramics are generally non-metallic inorganic compounds, e.g. silicates, aluminates, oxides,

carbides, borides, nitrides and hydroxides. Ceramics used as dielectrics may be broadly described as alumina, porcelains, ceramics, titanates, etc. These have excellent dielectric and mechanical properties. The dielectric constant of most commonly used ceramics varies between 4 and 10. These are used in switches in plug holders, thermocouples, cathode heaters, vacuum type ceramic metal seals etc. Ceramic capacitors may be operated at high temperatures and can be moulded into any shape and size. Electric grade ceramics are used for the manufacturing of insulators, terminal blocks, plates, frames, coils, etc. They must have low losses, good insulating properties and high strength.

Insulators for operation at low frequencies are made of electric-grade porcelain which possesses fairly good electric properties. A drawback is that it has high losses which increase sharply on heating above 200°C, and a low strength.

Insulating parts for operation at high frequencies are mostly made of steatite, a talc base material. Steatites contain no harmful impurities and retain their properties at temperatures upto 100°C. They can be pressed easily, shrink on burning by only 1-2%, and are suitable for making parts in which dense but porous structure and accurate dimensions are essential. In contrast to other kinds of ceramics, steatite can be cut quite easily (after burning). Among their drawbacks are cracking under the action of rapidly varying temperatures and some difficulties the burning involves.

Glass is an inorganic insulating material, which comprises of complex system of oxides. Silica (SiO_2) is the most essential constituent of many commercially used glasses. It is fused with alkali (like potash, soda etc.) and some base (like lime, lead oxide etc.). The silica glass (having 100% SiO_2) is the best insulating material. The dielectric constant of glass varies between 3.7 and 10 and loss tangent between 0.0003 and 0.01 and dielectric strength between 2.5 and 50 kV/mm. Glass is used in electric bulbs, X-ray tubes,
mercury switches, electronic valves as insulating material. It is also used in capacitors as dielectric material. Resins are organic polymers and may be natural or synthetic. The synthetic resins are produced artificially.

The commonly used synthetic resins are polyethylene, polystyrene, polyvinyl chloride, acrylic resins, teflon, nylon, etc. These have good dielectric and mechanical properties. The dielectric constant of resins varies between 2 and 4.5, the loss tangent between 0.0002 to 0.04 and dielectric strength is quite high. These are used in transformers, high frequency capacitors. These are also used as a dielectric material in d.c. capacitors.

Rubber

These are organic polymers and may be natural or synthetic. The natural rubber obtained from rubber tree has limited applications due to its resistance to low and high temperatures. The synthetic rubbers are produced artificially by copolymerisation of isobutylene and isoprene. These have good electrical and thermal properties. The dielectric constant of rubber varies between 2.5 and 5, and loss tangent between 0.01 and 0.03. Rubber's are used as an insulating material for electric wires, tapes, cables, coatings, motor windings, transformers, etc. Gaseous dielectrics, e.g. nitrogen, hydrogen, etc. have dielectric constant 1.0. The best dielectrics are polystyrene, polycarbonate, polyethylene, polymide, mineral oil, pure alumina and pure silica.

Dielectric Constant:

In an electric field, the charge density D is directly proportional to the applied field, i.e.

$$D = \varepsilon E \qquad (1)$$

where ε is the dielectric constant or permittivity of the material placed between the electrodes. For vacuum,

$$D = \varepsilon o\, E \qquad (1(a))$$

where $\varepsilon\, o = 8.854 \times 10^{-12}$ farad/m is called the absolute permittivity.

One can define the relative permittivity (εr) of a dielectric as:

(i) The ratio of electric field density produced in the dielectric medium (*Eo*) to that produced in vacuum

(*E*) by the same electric field strength, i.e.

$$\varepsilon_r = E_0 / E$$

ε_r is also called as macroscopic dielectric constant.

(ii) The ratio of capacitance of a condenser containing a given dielectric to the same condenser with

vacuum as dielectric.

Thus relative permittivity can be express as

$$\varepsilon_r = \varepsilon / \varepsilon_0 \qquad (2)$$

Now, charge density = $\varepsilon_0\, \varepsilon_r E = \varepsilon_0 E + \varepsilon_0\, (\varepsilon r + 1)\, E$

where $\varepsilon r - 1 =$ is called electric susceptibility. = Bound charge density/free charge density.

Permittivity is influenced by permeability (μ), stress distribution, temperature and frequency.

Classification of Dielectric

One can classify dielectric as under following three groups:

Class	*Effect of electric field*
Simple	dielectrics Creates dipoles
Paraelectrics	Orients dipoles
Ferroelectrics	Orients domains of aligned permanent dipoles

Magnetism:

This comprises those physical phenomena involving magnetic fields and their effects upon materials.Magnetic fields may be set up on a macroscopic scale by electric currents or by magnets. On atomic scale, individual atoms cause magnetic fields when their electrons have a net magnetic moment as a result of their angular momentum. A magnetic moment arises whenever a charged particle has an angular momentum. It is the cooperative effect of the atomic magnetic moments which causes the macroscopic magnetic field of a permanent magnet. However, the underlying principles and mechanisms that explain the magnetic phenomenon are complex and subtle, and their understanding has eluded physicists until relatively recent times.

Several of our modern technological devices rely on magnetism and magnetic materials; these include electric motors, electric power generators and transformers, components of sound and video reproduction systems, telephones, radio, television, computers, etc.

Well known examples of magnetic materials which exhibit magnetic properties are: iron, some steels and the naturally occurring mineral lodestone. The important facts about the magnetic materials are:

(i) There are some materials which exhibit magnetic properties even without the application of any magnetic field and become more magnetic when a weak magnetic field is applied to them.

(ii) There are many other materials which lose their initially strong magnetism when heated above a certain critical temperature and become comparatively weakly magnetised.

(iii) There are some materials which show a magnetic response in a direction opposite to that of any externally applied field.

(iv) Magnetic materials are all media capable of being magnetized in a magnetic field, i.e. of creating their own magnetic field. According to their magnetic properties, such materials are

divided into three principal groups: diamagnetic, paramagnetic and ferromagnetic materials. From the applications point of view all the magnetic materials can be placed under two groups: (i) Soft and (ii) Hard magnetic materials.

Iron, some steels, and the naturally occurring mineral lodestone are well-known examples of materials which exhibit magnetism. Ferro and ferromagnetic materials are the most important magnetic materials from the point of view of practical applications. We will first consider the terms and definitions used in magnetism.

BASIC CONCEPTS

Natural Magnet

'Load stone 'is an example of a natural magnet. It is a mineral called magnetite. Chemically it is an oxide of iron, having the formula Fe_3O_4. It contains about 72% of iron. It is heavy and dark grey to black in color.

Magnetic Dipoles

Magnetic dipoles are found to exist in magnetic materials, which, in some respects, are analogous to electric dipoles. Magnetic dipoles may be thought of as small bar magnets composed of north and south poles instead of positive and negative electric charges.

Magnetic dipoles are influenced by magnetic fields in a manner similar to the way in which electric dipoles are affected by electric fields. Within a magnetic field, the force of the field itself exerts a torque that tends to orient the dipoles with the field. A familiar example is the way in which a magnetic compass needle lines up with the earth's magnetic field.

Magnetic Field

The space around a magnet, where magnetic force can be felt, is called a magnetic field. This field can be represented by drawing lines, called magnetic lines of forces. A line of force in a magnetic field is a line, straight or curved, the tangent to which at any point gives the direction of the magnetic field, at that point. Magnetic field can be produced by different sources which are shown in Fig. 8. Magnetic fields are produced by electric currents, which can be macroscopic currents in wires, or microscopic currents associated with electrons in atomic orbits. The interaction of magnetic field with charge leads to many practical applications. Magnetic field sources are essentially dipolar in nature, having a north and south magnetic pole. The SI unit for magnetic field is the Tesla. A smaller magnetic field unit is the Gauss (1 Tesla = 10,000 Gauss).

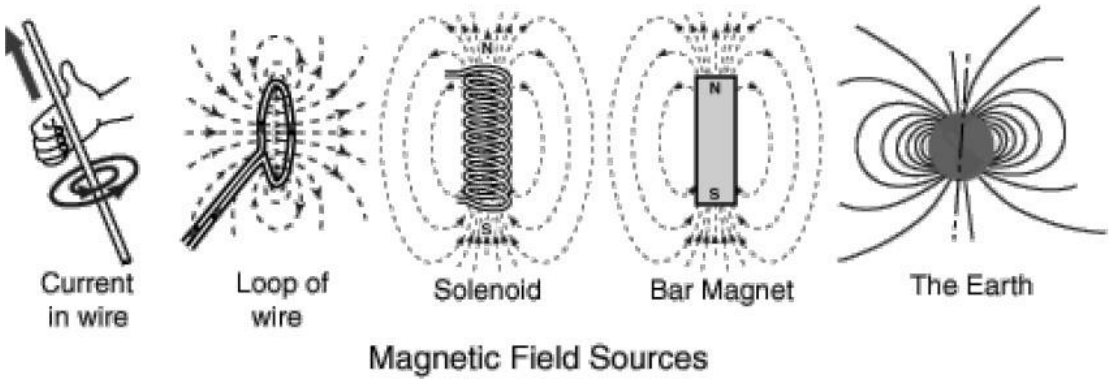


Fig. 8 Shows various sources to produce magnetic field.

Magnetic Field Strength or Magnetic Field Intensity (H)

It is the externally applied magnetic field. H describes field outside the material. Magnetic field intensity at any point in a magnetic field is the force experienced by a unit North Pole placed at a given point in a magnetic field. Its unit is A/m. If the magnetic field is generated

by means of a cylindrical coil (or solenoid) consisting of N closely spaced turns, having a length l, and carrying a current of magnitude I, then (Fig. 9)

$$H = NI / l$$

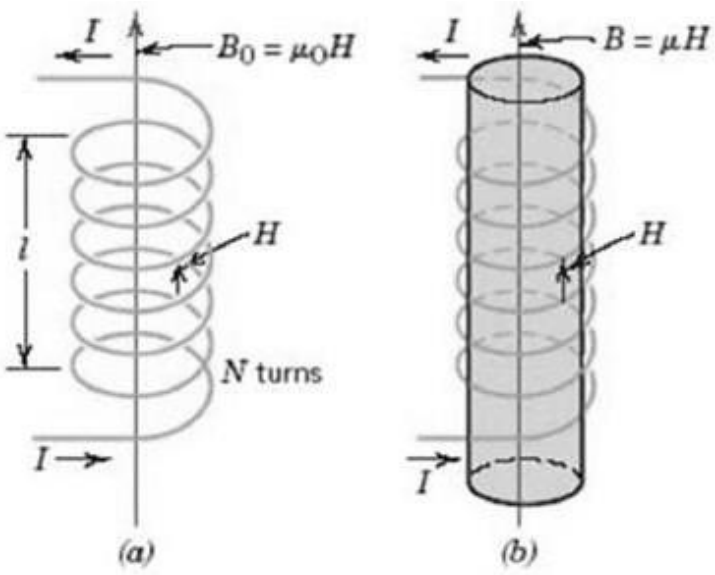


Fig- 9 The magnetic field H generated by a cylindrical coil in vacuum and in a medium.

Magnetic induction (or) Magnetic flux density (B)

Magnetic induction or magnetic flux density in any material is the number of magnetic lines of force passing normally through unit area. The units are w/m^2 or Tesla. B represents the magnitude of the internal field strength within a substance that is subjected to an H field. Mathematically B can be represented as

$$B = \phi / A$$

Where ϕ is the magnetic flux and A is the area of cross section.

Magnetic permeability (μ)

Permeability describes the nature of the material i.e. it is a material property. It is the ease with which the material allows magnetic lines of force to pass through it or the degree to which magnetic field can penetrate a given medium is called its permeability. Mathematically permeability is equal to the ratio of the magnetic induction B inside the material to the applied magnetic intensity H. Its units are H/m.

$$\mu = B / H$$

The value of permeability of free space or $\mu_o = 4\pi \times 10^{-7}$ H/m.

Relative Permeability (μ_r)

It is defined as the ratio of permeability of the medium to the permeability of free space i.e.

$$\mu_r = \mu / \mu_0$$

The magnetic field strength and flux density are related according to

$$B = \mu H$$

The above equation for vacuum can be written as

$$B_0 = \mu_0 H$$

Magnetisation

Magnetisation refers to the process of converting a non-magnetic sample into a magnetic

sample. The Intensity of magnetisation (M or I) is defined as the magnetic moment per unit volume in a material. Its unit is A/m. It is totally depends on the nature of material.

Magnetization of a material is proportional to the magnetic field intensity applied i.e. $M \propto H$.

Magnetic susceptibility (χ)

Susceptibility describes the nature of the material i.e. it is a material property. It the ease with which a magnetic material can be magnetised by the magnetising force. The magnetic susceptibility of a material is the ratio of intensity of magnetisation (M) inside the material to the magnetising field (H).

$$\chi = M / H$$

Relationship between B, H, M, μ_r, χ:

$$B = \mu H$$
$$B = \mu_0 \mu_r H$$
$$B = \mu_0 \mu_r H + \mu_0 H - \mu_0 H$$
$$B = \mu_0 H + \mu_0 H (\mu_r - 1)$$
$$B = \mu_0 H + \mu_0 M$$

Where magnetization M is equal to $H (\mu_r - 1)$

i.e. $B = \mu_0 (H + M)$

The first term on the right side of the above equation is due to the external field and the second term is due to the magnetization.

Thus the magnetic induction (B) in a solid is

$$B = \mu_0 (H + M)$$
$$\mu_0 = B / (H + M)$$

The relative permeability,

$$\mu_r = \frac{\mu}{\mu_o} = \frac{B/H}{B/H + M} = \frac{H + M}{H} = 1 + \frac{M}{H}$$

$$\mu_r = 1 + \chi$$

CLASSIFICATION OF MAGNETIC MATERIALS

Now we are going to study the various properties of magnetic materials in terms of the magnetic properties of the atomic dipoles and the interaction between them. The first distinction is based on whether the atoms carry permanent magnetic dipoles or not. Materials which lack permanent dipoles are called diamagnetic. If the atoms of the materials carry permanent magnetic dipoles such a material may be paramagnetic, ferromagnetic, anti ferromagnetic, and ferrimagnetic depending on the interaction between the individual dipoles. If the permanent dipoles do not interact among themselves the material is called paramagnetic. If the interaction among permanent dipoles is strong such that all dipoles line up in parallel, the material is ferromagnetic. If permanent dipoles line up in anti parallel direction, then the material can be anti ferromagnetic or ferrimagnetic. In anti ferromagnetic material the magnitudes of permanent dipoles aligned parallel and anti parallel are equal and hence the magnetisation vanishes. In case of ferrimagnetic materials, magnitudes of permanent dipoles aligned anti parallel are not equal thus exhibiting magnetization.

Diamagnetic Materials

Diamagnetism is a fundamental property of all matter. Diamagnetism is a very weak form of magnetism. Diamagnetism persists only in presence of an external magnetic field. It is induced by a change in the orbital motion of electrons due to an applied magnetic field. Diamagnetic material does not possess permanent dipoles. Dipoles are induced only in presence of external magnetic field. The magnitude of the induced magnetic moment is

extremely small, and in a direction opposite to that of the applied field and hence tends to decrease the magnetic induction present in the material. Thus diamagnetism is the phenomenon by which the induced magnetic moment is always in the opposite direction of the applied field. Thus, the relative permeability is less than unity (however, only very slightly), and the magnetic susceptibility is negative; that is, the magnitude of the B field within a diamagnetic solid is less than that in a vacuum. The volume susceptibility for diamagnetic solid materials is on the order of -10^{-5}. When placed between the poles of a strong electromagnet, diamagnetic materials are attracted toward regions where the field is weak. Though diamagnetism is present in all materials but it is masked by other types of magnetism because it is very weak. It can be observed only when other types of magnetism are absent. Fig. 10 shows that there is a repulsion of magnetic flux from the centre of the material indicating the diamagnetic behaviour of the magnetic material. Fig. 11 shows the atomic magnetic dipole configuration for a diamagnetic material both with and without external magnetic field When no field is applied the atoms does not contain atomic dipoles where as ones the external magnetic field is applied the dipoles are induced and they are aligned in a direction opposite to the applied field. Fig. 12 shows the dependence of B on H for a diamagnetic material. The slope of the curve gives the permeability of the diamagnetic material which is a small value. Table lists the susceptibilities of several diamagnetic materials. The dependence of M and H and χ and T are represented in fig. 13. The curve in the fourth quadrant indicates that both M and H are in the opposite directions i.e. the ratio of M and H which is susceptibility is a negative value. Fig. 13 shows that the susceptibility of a diamagnetic material is independent of temperature.

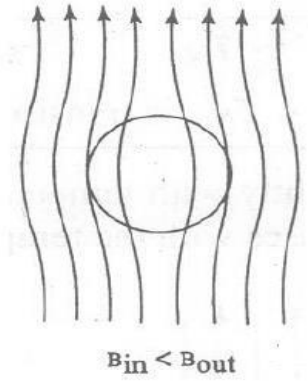


Fig. 10 : Behaviour of diamagnetic material in presence of magnetic field

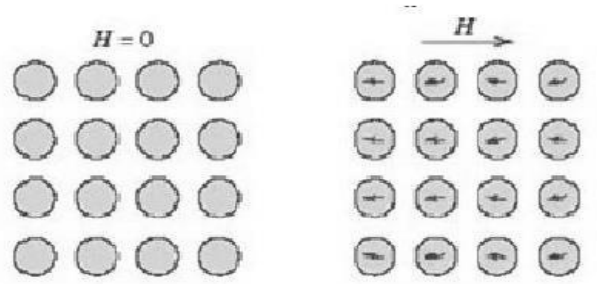


Fig. 11 : Atomic dipole configuration with and without magnetic field

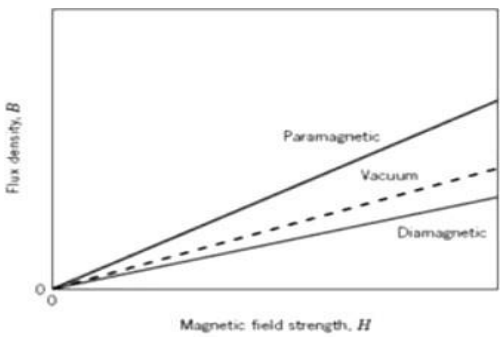


Fig. 12 : B Versus H for diamagnetic and paramagnetic materials

Diamagnetics	
Material	*Susceptibility χ_m (volume) (SI units)*
Aluminum oxide	-1.81×10^{-5}
Copper	$+^{\circ}>96 \times 10^{-5}$
Gold	-3.44×10^{-5}
Mercury	-2.85×10^{-5}
Silicon	$+^{\circ}>41 \times 10^{-5}$
Silver	-2.38×10^{-5}
Sodium chloride	-1.41×10^{-5}
Zinc	-1.56×10^{-5}

Examples of diamagnetic materials: Bismuth (Bi), Zinc (Zn), copper (Cu), Silver (Ag), Gold (Au), Salt (NaCl), Water (H_2O), Mercury (Hg), Hydrogen (H_2), Ge, Si.

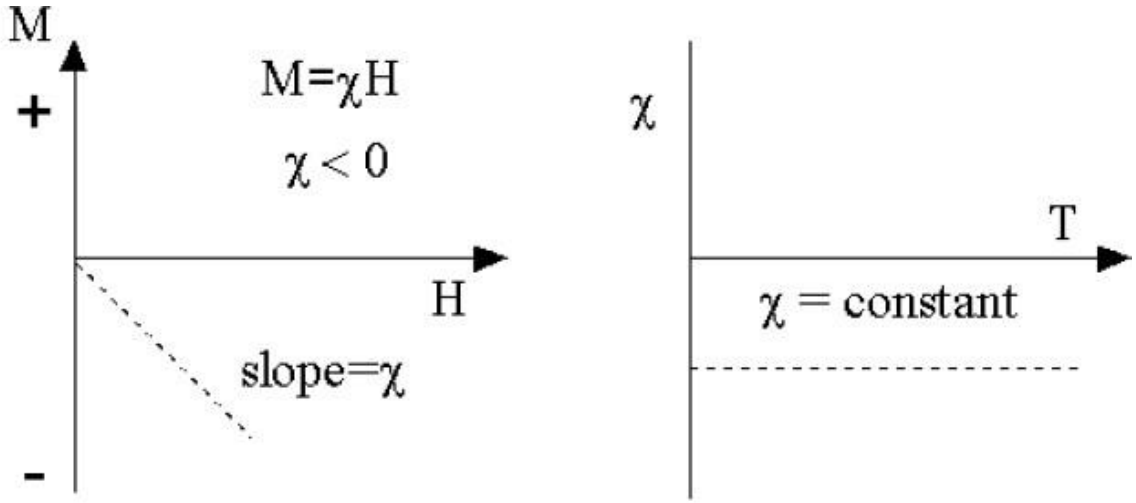


Fig. 13.: Curves showing M Vs H and χ Vs T for diamagnetic materials

Properties of diamagnetic materials

1. An atom of this material does not contain permanent dipoles.
2. An atom of this material has no magnetic dipole moment.
3. The effect is weak and often masked by other kinds of magnetism.
4. A Diamagnet is weakly repelled by a normal magnet.
5. Relative permeability is less than 1 but only slightly less than unity.
6. Magnetic susceptibility is negative but only slightly less than unity.
7. Magnetic susceptibility is independent of temperature.
8. Magnetic susceptibility is independent of applied magnetic field strength.
9. Atomic orbitals are completely filled. (no electron is un-paired).

Paramagnetic Materials

A paramagnetic material contains permanent dipoles which are because of incomplete cancellation of electron spin and orbital magnetic moments which results in a resultant magnetic moment even in the absence of applied field. In the absence of external magnetic field the dipoles are randomly oriented resulting in zero net magnetic moment. When external magnetic field is applied, some of the permanent dipoles try to align in the direction of the magnetic field (fig. 14). Since few dipoles try to align in the direction of the magnetic field the net magnetic moment produced in the material is small so the material is feebly magnetised. When placed inside the magnetic field the material allows magnetic lines of force to pass through it as shown in Fig. 15. There is no interaction between the adjacent dipoles they are acted upon individually. The relative permeability is greater than unity. Magnetic susceptibility is positive but relatively small value. The susceptibilities of paramagnetic values range from 10^{-5} to 10^{2}. These materials are used in lasers and masers. Where one can create the required energy levels of transition. Paramagnetic property of oxygen is used in the NMR imaging instrument which is used to diagnose the brain tumour or blood clot in the brain.

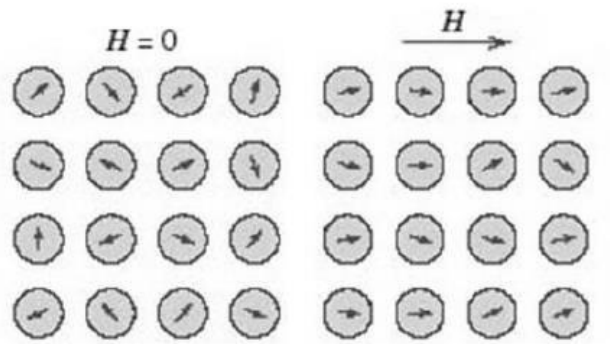


Fig. 14 Atomic dipole configuration with and without external magnetic field for a paramagnetic material

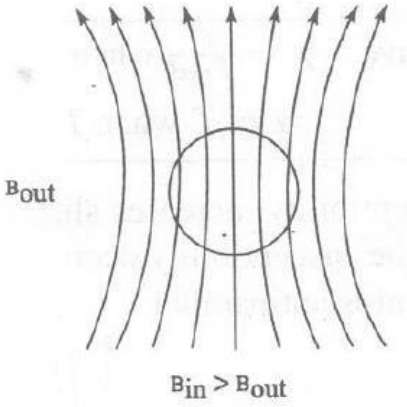


Fig. 15 Behaviour of paramagnetic material in external magnetic field.

Properties of paramagnetic materials

1. They attract magnetic lines of force when placed in magnetic field.
2. In the absence of external magnetic field the dipoles are randomly oriented.
3. An atom of this material possesses a non-zero magnetic dipole moment.
4. Possess permanent dipole moment.
5. Relative permeability is slightly greater than unity.
6. Magnetic susceptibility is positive and small.
7. Magnetic susceptibility is independent of applied magnetic field strength but depend on temperature.
8. With increase in temperature the susceptibility of the material decreases.
9. Examples: Aluminium, Platinum, Manganese, Copper Chloride, Oxygen, solutions of salts of iron.

Ferromagnetic Materials

Certain metallic materials possess a permanent magnetic moment even in the absence of external magnetic field which results in very large and permanent magnetisation. Permanent magnetic moment in ferromagnetic materials is due to un-cancelled spins of the electron, there is some amount of orbital magnetic moment but its value is small when compared with spin magnetic moment. In a ferromagnetic material the dipoles of the adjacent atoms interact with each other which results in parallel alignment of all the dipoles (Fig. 16). This interaction between the adjacent atoms is called exchange interaction or exchange coupling. Due to the parallel alignment if we apply a small value of magnetic field to a ferromagnetic material a large value of magnetisation is produced. Due to the parallel alignment of the atomic dipoles the material possesses a characteristic feature called spontaneous magnetisation. In presence of magnetic field the material allows more number of lines to pass through it as shown in fig. 17. In presence of external magnetic field all the atomic dipoles are aligned in the direction of external magnetic field which results in a characteristic feature called saturation magnetisation (Ms) there is also corresponding saturation flux density (Bs). The saturation magnetisation is equal to the product of the net magnetic moment for each atom and the number of atoms present. For each of iron, cobalt and nickel, the net magnetic moments per atom are 2.22, 1.72 and 0.60 Bohr magnetons respectively. Ferromagnetic materials possess a characteristic feature called Hysteresis.

The susceptibility of a ferromagnetic material is temperature dependent. A ferromagnetic material exhibits two different properties. Below a particular temperature called Curie

temperature it behaves as a ferromagnetic and above that Curie temperature it behaves as a paramagnetic material (Fig.18). The relative permeability is very large. Magnetic susceptibility is as high as 10^6. Thus H<<<M such that B can be written as

$$B \cong \mu_o M$$

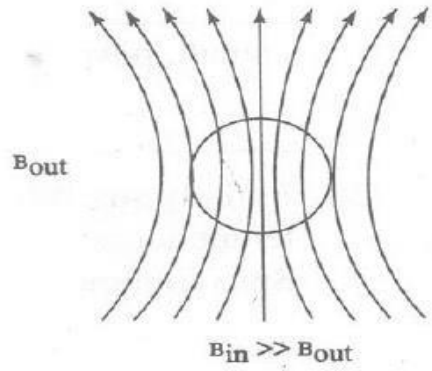


Fig. 16 : Behaviour of ferromagnetic material in external magnetic field

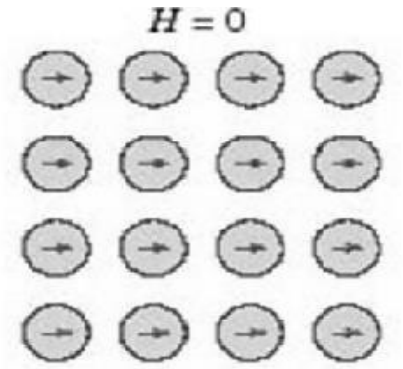


Fig. 17 : Shows the alignment of atomic dipoles in ferromagnetic materials

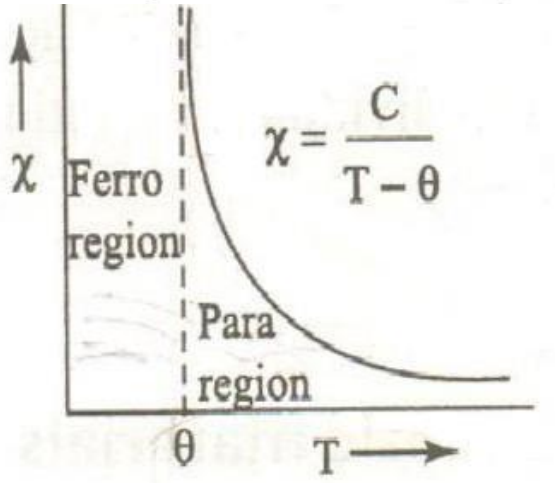


Fig. 18: Shows the variation of magnetic susceptibility with temperature for ferromagnetic material.

Properties of ferromagnetic materials

1. The origin for magnetism in ferromagnetic materials is because of spin of electrons i.e. because of spin magnetic moment.
2. The materials possess permanent dipoles.
3. The dipoles or spins of the adjacent atoms interact with each other and due to this interaction all dipoles are aligned parallel to each other. This interaction between the adjacent atoms is called exchange interaction or exchange coupling. Since all dipoles are aligned along the same direction the material possess net dipole moment.
4. The one of the characteristic feature of the ferromagnetic materials is spontaneous magnetisation i.e. the material shows magnetic properties even in the absence of the external magnetic field.
5. When a ferromagnetic material is placed in external magnetic field the material get strongly magnetised resulting in saturation magnetisation i.e. the material gets strongly

magnetised. Spontaneous magnetisation is another characteristic feature of ferromagnetic materials.

6. The susceptibility of ferromagnetic materials is positive and very large.
7. The susceptibility of ferromagnetic materials is dependent on temperature and independent of applied magnetic field.
8. Inside the ferromagnetic material the material is divided into small regions or volumes called domains. Within each domain all the dipoles are aligned along the same direction resulting in spontaneous magnetisation. All these domains are randomly oriented thus resulting in zero net dipole moment.
9. In ferromagnetic materials the flux density (B) or magnetisation (M) is not directly proportional to applied magnetic field (H), i.e. the ferromagnetic material possess magnetisation for sometime even when magnetizing field is removed thus exhibiting the property of hysteresis. This is a characteristic feature of ferromagnetic materials.

Anti ferromagnetic Materials

This is a special class of ferromagnetic material. The material contains permanent dipoles. Like Ferro-magnetism, anti-Ferro-magnetism is associated with domain structure and exchange coupling between adjacent spins but the alignment of spins within a domain is anti parallel (Fig. 19). The spins are of equal magnitude. So the net magnetisation in a domain is zero and over all domains is very small. In antiferromagnetic materials the distance between the interacting atoms is small such that the exchange forces results in antiparallel alignment of the dipoles.

The susceptibility of antiferromagnetic material is temperature dependent. The characteristic feature of antiferromagnetic material is the occurrence of sharp maximum in the susceptibility versus temperature curve (Fig. 20). As temperature increases this spin alignment is disturbed and magnetization increases. Beyond a temperature called Neel temperature (TN), susceptibility drops. The atoms are molecules of anti ferromagnetic materials possess magnetic dipole moment due to spin of the electrons. Examples are copper chloride, oxides of iron, manganese, cobalt and nickel. The magnetic susceptibility is small and positive.

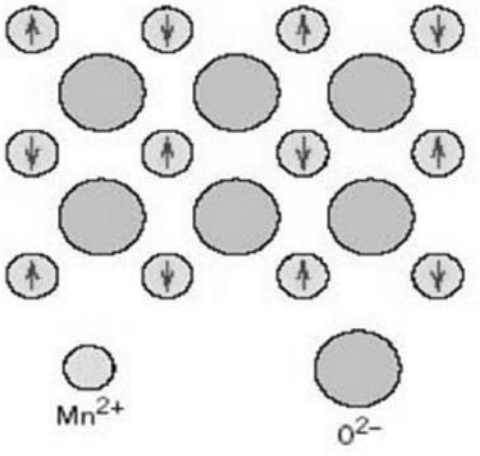


Fig. 19 : Shows the antiparallel alignment of spin magnetic moments for antiferromagnetic material MnO

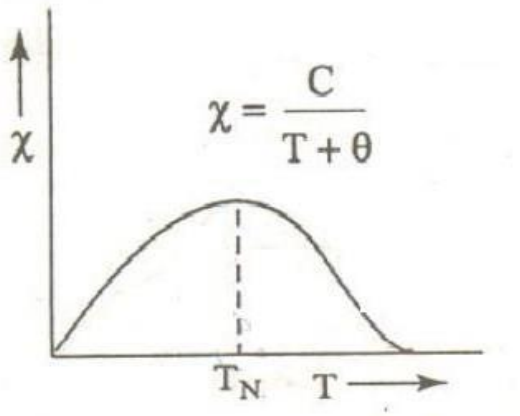


Fig. 20 : Variation of susceptibility with temperature for antiferromagnetic materials.

Properties of antiferromagnetic materials

1. Electron spins of neighbouring atoms in a domain are aligned anti-parallel.
2. Anti ferromagnetism depends on temperature.
3. The adjacent dipoles are aligned in antiparallel direction.
4. Initially m increases slightly with temperature and beyond the Neel temperature it χ_m decreases.
5. Above the Neel temperature susceptibility is given by $\chi_m = C / (T + T_n)$.

Ferrimagnetic Materials or Ferrites

It is a special case of both ferromagnetic and antiferromagnetic materials. These are also ceramic and ionic in nature. They exhibit permanent magnetisation. Similar to ferromagnetic materials ferrimagnetic materials also possess spontaneous magnetisation and saturation magnetisation. They also exhibit hysteresis curve. Magnetic susceptibility of ferromagnetic materials is very large and positive. The magnetic susceptibility is temperature dependent. Fig. 21 shows the variation of susceptibility with temperature for ferromagnetic materials. Ferrimagnetic materials are composed of two sets of different transition metal ions having different values of magnetic moments with antiparallel alignment. Saturation magnetisation of ferrimagnetic materials is not as high as ferromagnetic materials. Since they are ceramic in nature they are suitable for high frequency applications and in special magnetic devices.

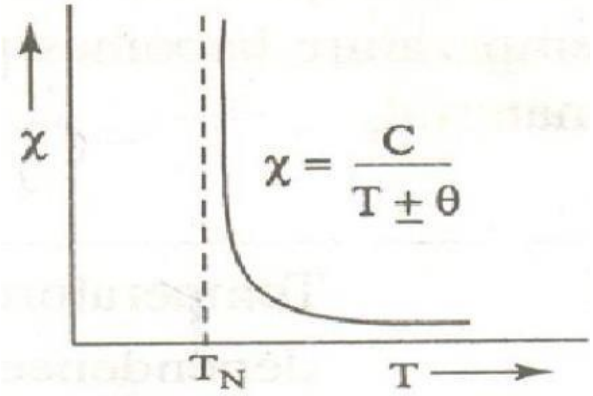


Fig. 21 : Variation of susceptibility with temperature for ferrimagnetic material.

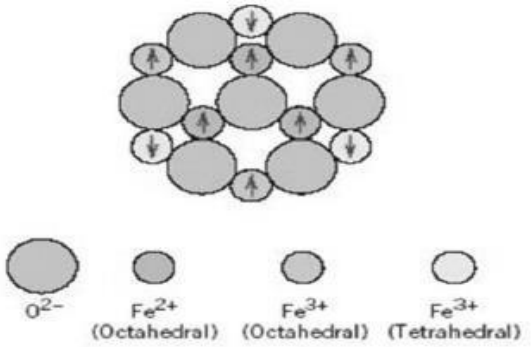


Fig. 22 : Diagram showing the spin magnetic moment of Fe^{2+} and Fe^{3+} ions in Fe_3O_4

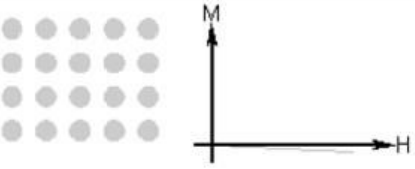
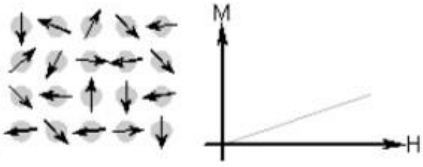
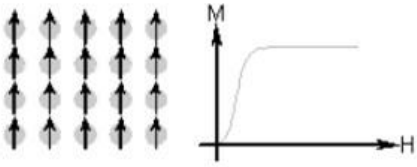
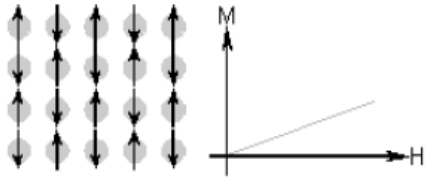
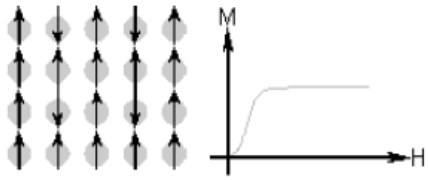
The special feature of ferrites is that in the magnetised state all the spins magnetic moments are not oriented in the same direction. Some of them are oriented in the opposite direction. But since the spin magnetic moments are of different magnitudes the net magnetic moment will be finite. Cubic ferrites are represented by the chemical formula MFe_2O_4 ($M^{2+}O.Fe^{3+}O_3$), where M stands for divalent metal such as Fe, Mn, Co, Ni, Cu, Mg, Zn or Cd. Let us consider an example of ferrous ferrite (Fe_3O_4 or $Fe^{2+}O.Fe^{3+}O_3$). Fig. 22 shows the spin magnetic moment configuration of Fe^{2+} and Fe^{3+} ions in Fe_3O_4.

Properties of ferrimagnetic materials

1. Ferrimagnetic materials possess net magnetic moment.
2. Above Curie temperature it becomes paramagnetic.
3. Magnetic susceptibility is very large
4. Spin alignment is anti parallel of different magnitudes.
5. They have the characteristic property like spontaneous magnetisation and saturation magnetisation.
6. Ferromagnetic materials behave like Ferromagnetic materials and have hysteresis, domain structure etc., but being oxide compounds they have large resistivities.

7. They are also called ferrites.
8. Above the Curie temp susceptibility is given by $\chi_m = C / (T - T_c)$.

Table Differences between various magnetic materials.

Type of Magnetism	Susceptibility	Atomic / Magnetic Behavior	Example / Susceptibility
Diamagnetism	Small & negative.	Atoms have no magnetic moment 	-2.74x10^{-6} Au Cu -0.77x10^{-6}
Paramagnetism	Small & positive.	Atoms have randomly oriented magnetic moments 	0.19x10^{-6} β-Sn 21.04x10^{-6} Pt Mn 66.10x10^{-6}
Ferromagnetism	Large & positive, function of applied field, microstructure dependent.	Atoms have parallel aligned magnetic moments 	Fe ~100,000
Antiferromagnetism	Small & positive.	Atoms have mixed parallel and anti-parallel aligned magnetic moments 	Cr 3.6x10^{-6}
Ferrimagnetism	Large & positive, function of applied field, microstructure dependent	Atoms have anti-parallel aligned magnetic moments 	Ba ferrite ~3

HYSTERESIS

Hysteresis means lagging or retardation of effect behind the cause. It refers to the lag of magnetization behind the magnetising field. When the temperature is less than the ferromagnetic Curie temperature hysteresis is exhibited. A part of the hysteresis curve is shown Fig. 23.

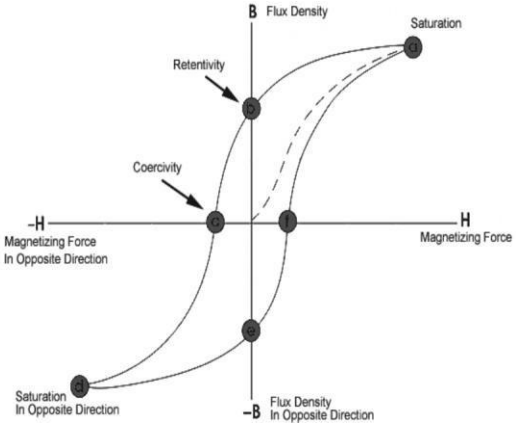


Fig. 23: Hysteresis curve for ferromagnetic materials.

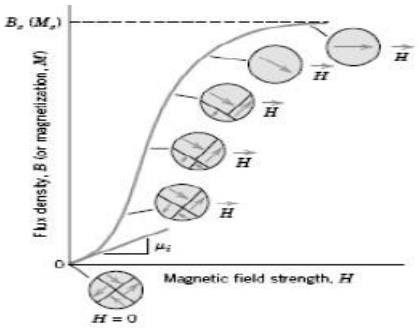


Fig. 24 : Domain configurations during several stages of magnetisation are represented.

The domain concept is well suited to explain hysteresis behaviour of ferromagnetism. The increase in magnetization under the action of an applied magnetic field is attributed to (i) motion of domain walls and (ii) rotation of domains. When a magnetic field is applied, for small fields, domains that are favourably oriented to the field and in the easy direction of magnetization grow in size at the expense of less favourably oriented domains. (Fig. 24). This results in Block wall movement and when the weak field is removed the domains revert back to their original state. This reversible wall movement is indicated by OA in the plot given above. In region 'A' the growth of magnetization is slow.

When the field becomes stronger Block wall movement continues but it is mostly irreversible movement. AB is this region in the plot.

At the point B all domains have got magnetized along their easy directions. A still larger magnetic field rotates the domains into the field direction, which may be away from the easy direction thereby storing anisotropy energy. Once the domain rotation is complete the magnetization reaches to a saturation value (point C on the plot) On removal of the external field the specimen tends to attain the original configuration by movement of Block walls. But this movement is hampered by impurities and lattice imperfections and so some energy is wasted trying to overcome opposition. Further domain wall movement is irreversible. When the field becomes zero, magnetization has not vanished. There is a remanent magnetization 'Br' at H=0. This means that a coercive field '–Hc' has to be applied to demagnetize the specimen. The amount of energy spent in a hysteresis cycle is energy lost (heat). The area of hysteresis loop represents energy lost during magnetisation and demagnetisation of the material. This energy lost is manifested as heat that is generated within the magnetic specimen and is capable of raising its temperature. The area of the hysteresis loop also classifies soft and hard magnets.

SOFT AND HARD MAGNETIC MATERIALS

Soft Magnetic Materials

Both ferromagnetic and ferrimagnetic materials are classified as either soft or hard on the basis of their hysteresis characteristics. Soft magnetic materials are used in applications requiring frequent reversals of the directions of magnetization such as cores of transformers, motors, inductors and generators. In soft magnetic materials the hysteresis losses must be small. More over the soft magnetic materials are characterised by low remanent magnetisation, low coercivity, low hysteresis losses, high magnetic permeability, high initial permeability and high susceptibility so that they can be easily magnetised and demagnetised.

A material possessing these properties can reach its saturation magnetization with low applied field. Consequently the area is small and hysteresis loss also reduced. The hysteresis curve is shown in Fig. 25.

A low value of coercivity corresponds to the easy movement of domain walls as the magnetic field changes in magnitude or direction. Structural defects such as imperfections, irregularities, inclusions, impurities and voids in the magnetic material tend to restrict the motion of domain walls and thus increase the coercivity. Consequently, a soft magnetic material must be free of such structural defects.

There is another energy loss in soft magnetic materials i.e. eddy current loss. When the magnetic flux in a medium is changing, an emf is induced. According to Lenz's law, the induced emf is proportional to the frequency of the alternating current. The induced emf sets up eddy currents in the medium and the power loss due to these eddy currents is equal to V^2/R. Where V is the induced emf and R is the resistance of the medium. Eddy current losses can be minimized by increasing the resistivity of the magnetic medium. This is accomplished in ferromagnetic materials: iron-silicon alloys and iron-nickel alloys. The ceramic ferrites are commonly used for applications requiring soft magnetic materials because they are naturally electrical insulators.

The eddy currents produce a magnetic field of their own which opposes the main magnetic field. As the effect of eddy currents is not uniform over the cross section of the material, these results in a flux distribution which is not uniform, the flux density in the outer portions being greater than that at the centre. Thus there is a reduction in effective cross section.

So, the magnetic materials used for varying magnetic fields are laminated (made up of thin sheets insulated from each other) so as to reduce eddy currents and associated losses, due to lamination the area of path of eddy currents is reduced giving rise to a large value of resistance. Eddy current losses are reduced by using thinner plates and a material of higher resistivity.

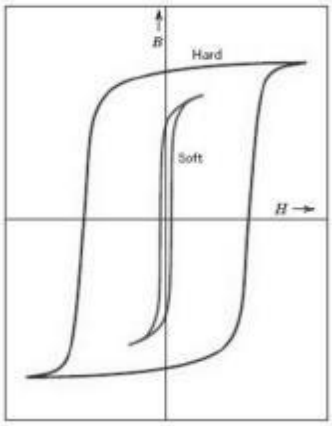


Fig. 25 : Magnetisation curves for soft and hard magnetic materials.

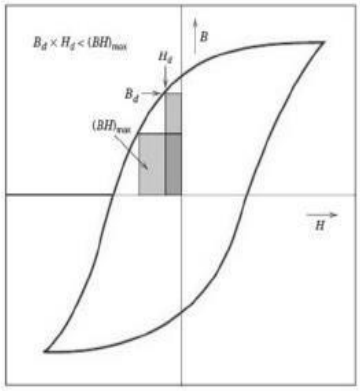


Fig. 26 : Hysteresis curve having two B-H energy product rectangles, the area of that rectangle labelled $(BH)_{max}$ is the largest possible, which is greater than the area defined by B_d-H_d.

Hard Magnetic Materials

Hard magnetic materials are used in permanent magnets, which must have a high resistance to demagnetization. A hard magnetic material is characterised by a high remanence, high coercivity, high saturation flux density as well as a low initial permeability and high hysteresis energy losses. The hysteresis curve for hard magnetic material is as shown in Fig.

25.

The two most important characteristics relative to applications for these materials are the coercivity and energy product (BH) max. The value of the energy product represents the amount of energy required to demagnetize a permanent magnet. If (BH) max is large, that material will be hard in terms of its magnetic characteristics as shown in Fig. 26.

Hysteresis behaviour depends upon the movement of domain walls. The movement of domain walls depends on the final microstructure i.e. the size, shape and orientation of crystal domains and impurities. Of course, microstructure will depend upon how the material is processed. The hard magnetic materials are prepared by heating the magnetic materials to the required temperature and then suddenly cooling them by dipping in a cold liquid. In a hard magnetic material, impurities are purposely introduced, to make it hard. Due to these impurities domain walls cannot move easily. In this way we can increase the coercivity and decrease the susceptibility values by obstructing domain wall motion. So large external field is required for demagnetization.

Hard Magnetic Material	**Soft Magnetic Material**
Have large hysteresis loss	Have low hysteresis loss.
Domain wall moment is difficult	Domain wall moment is relatively easier.
Coercivity&Retentivity are large	Coercivity&Retentivity are small
Cannot be easily magnetized & demagnetized	Can be easily magnetized & demagnetized.
Magneto static energy is large.	Magneto static energy is small
Have small values of permeability and susceptibility.	Have large values of susceptibility and permeability.
Used to make permanent magnets	Used to make electromagnets
Examples: Iron-nickel-aluminum alloys, copper nickel iron alloys, copper – nickel – cobalt alloys.	Examples: Iron- silicon alloys, ferrous-nickel alloys, ferrites, garnets.

FERRITE APPLICATIONS

1. Being Ferro-magnetic but with high resistivity helps ferrites to cut down on eddy currents in transformer cores up to microwave frequencies.
2. They are used as induction cores, antennas for medium and long wave broad casting, electronic tuning, auto frequency control, fm, switching etc.
3. Since ferrites have a hysteresis loop they are used as memory elements for rapid storage and retrieval of digital information by switching the direction of magnetization in very small toroidal cores.
4. Garnets ($Y_3Fe_5O_{12}$) are useful in microwave applications.
5. Ferrite domains are also useful for memory.
6. Magnetic recording uses ferrite material in powder form.
7. Ferrites can be used as magnets.

Superconductor:

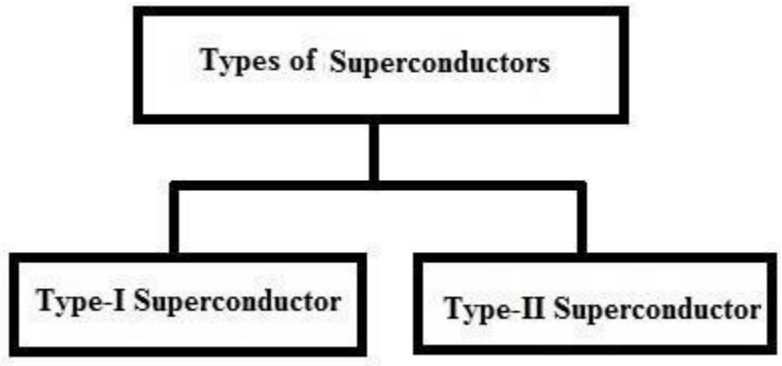
There are two types of materials like metals as well as insulators. Metals allow the flow of electrons and carry electric charge with them like silver, copper, etc, whereas insulators hold electrons and they will not allow the flow of electrons like wood, rubber, etc. In the 20th century, new laboratory methods were developed by physicists to cool materials to zero temperature. He began investigating on some elements to know how the electricity will be changed in such conditions like lead & mercury, as they conduct electricity under a certain temperature without resistance. They have discovered the same behavior in several compounds like from ceramics to carbon nanotubes. This article discusses an overview of the superconductor.

Definition: A material that can conduct electricity without resistance is known as a superconductor. In most of the cases, in some materials like compounds otherwise metallic elements offers some amount of resistance at room temperature, although they offer low resistance at a temperature is called its critical temperature.

The electrons flow from atom to atom is frequently done using certain materials once attaining the critical temperature, therefore the material can be called superconductive material. These are employed in numerous fields like magnetic resonance imaging & medical science. Most of the materials available in the market are not superconductive. So they must be in a very low energy state to turn into superconductive. Current research is focusing on compounds development to develop into superconductive at high temperatures.

Types of Superconductors

Superconductors are classified into two types namely type-I & type-II.



types-of-superconductors

Type-I Superconductor

This kind of superconductor includes basic conductive parts and these are utilized in different fields from electrical cabling to microchips on the computer. These types of superconductors lose their superconductivity very simply when it is placed in the magnetic field at the critical

magnetic field (Hc). After that, it will become like a conductor. These types of semiconductors are also named as soft superconductors due to the reason of loss of superconductivity. These superconductors obey the Meissner effect completely. The **superconductor examples** are Zinc and Aluminum.

Type-II Superconductor

This kind of superconductor will lose their superconductivity slowly but not simply as it is arranged within the exterior magnetic field. When we observe the graphical representation between magnetization vs. the magnetic field, when the second type semiconductor is placed within a magnetic field, then it will lose its superconductivity slowly.

This kind of semiconductors will start to lose their superconductivity on the less significant magnetic field & totally drop their superconductivity at the higher critical magnetic field. The condition between the slighter critical magnetic field & higher critical magnetic field is called an intermediate state otherwise vortex state.

This type of semiconductor is also named as hard superconductors due to the reason they lose their superconductivity slowly but not simply. These semiconductors will obey the effect of Meissner but not totally. The best examples of these are NbN and Babi3. These superconductors are applicable for strong field superconducting magnets.

Superconductivity Materials

We know that there are a lot of materials available where some of them will superconduct. Excluding mercury, the original superconductors are metals, semiconductors, etc. Every different material will turn into a superconductor at a little diverse temperature

The main problem by using most of these materials is that they will superconduct in a few degrees of complete zero. This means any benefit you achieve from the lack of resistance; you almost certainly lose from including cooling them down within the primary place.

The power plant that obtains electricity to your home in downward then superconducting wires will noise brilliantly. So it will conserve enormous amounts of exhausted energy. However, if you want to cool huge parts & all the transmission wires within the plant to complete zero, probably you will waste more energy.

Properties of Superconductor

The superconducting materials show some amazing properties which are essential for current technology. The research on these properties is still going on to recognize and utilize these properties in various fields which are listed below.

- Infinite Conductivity/ Zero Electric Resistance
- Meissner Effect
- Transition Temperature/Critical Temperature
- Josephson Currents

- Critical Current
- Persistent Currents

Infinite Conductivity/ Zero Electric Resistance

In the Superconducting condition, the superconducting material illustrates the zero electric resistance. When the material is cooled under its transition temperature, then its resistance will be reduced to zero suddenly. For instance, Mercury shows zero resistance under 4k.

Meissner Effect

When a superconductor is cooled under the critical temperature, then it doesn't permit the magnetic field to go through in it. This occurrence in superconductors is known as the Meissner effect.

Transition Temperature

This temperature is also known as critical temperature. When the critical temperature of a superconducting material is changing the conducting state from normal to superconducting.

Josephson Current

If the two superconductors are divided with the help of thin-film in insulating material, then it forms a junction of low resistance to found the electrons with copper pair. It can tunnel from one surface of the junction to the other surface. So the current because of the flow of cooper pairs is known as Josephson Current.

Critical Current

When the current supplied through a conductor under the condition of superconducting, then a magnetic field can be developed. If the current flow increases beyond a certain rate then the magnetic field can be enhanced, which is equivalent to the critical value of the conductor at which this returns to its usual condition. The flow of current value is known as the critical current.

Persistent Currents

If a superconductor ring is arranged in a magnetic field above its critical temperature, at the present cool the superconductor ring under its critical temperature. If we eliminate this field, then the flow of current can be induced within the ring because of its self-inductance. From Lenz law, the induced current opposes the change within flux that flows through the ring. When the ring is placed in a superconducting condition, then the flow of current will be induced to continue the flow of current is named as the persistent current. This current generates a magnetic flux to make the flux flowing throughout the constant ring.

Difference between Semiconductor and Superconductor

The difference between semiconductor & superconductor is discussed below.

Semiconductor	Superconductor
The resistivity of semiconductor is finite	The resistivity of a superconductor is zero electrical resistivity
In this, electron repulsion leads to finite resistivity.	In this, electron attraction leads to the loss of resistivity
Superconductors do not show perfect diamagnetism	Superconductors show perfect diamagnetism
The energy gap of a superconductor is the order of a few eV.	The energy gap of superconductors is of the order of 10^-4 eV.
Flux quantization in superconductors is 2e units .	The unit of a superconductor is e.

Applications of Super Conductor

The applications of superconductors include the following.

- These are used in generators, particle accelerators, transportation, electric motors, computing, medical, power transmission, etc.
- Superconductors mainly used for creating powerful electromagnets in MRI scanners. So these are used to divide. They can also be used to separate magnetic and non-magnetic materials
- This conductor is used to transmit power for long distances
- Used in memory or storage elements.

Smart materials

Definition: The materials that have the ability to sense external environmental stimuli (temperature, light, stress, electric and magnetic fields) and respond to them by changing their appearance, structure, functions and properties are called smart materials.

Description: systems that use smart materials consist of sensors and actuators. The sensor components detect a change in the environment and the actuators component performs a specific function or a response

Smart materials, also known as intelligent or responsive materials, are a class of materials that have the ability to respond to external stimuli by changing their properties. These materials can sense changes in their environment and adapt their behavior accordingly. The key characteristics of smart materials include responsiveness, sensitivity, and the ability to transform energy from one form to another. In this chapter, we will explore the various types of smart materials, with a focus on sensors and actuators that utilize piezoelectric, magnetostrictive, and electrostrictive effects.

Classification of Smart Materials

Smart materials can be categorized based on their response mechanisms:

1. Piezoelectric materials.
2. Magnetostrictive materials
3. Electrostrictive materials

Applications of Smart Materials

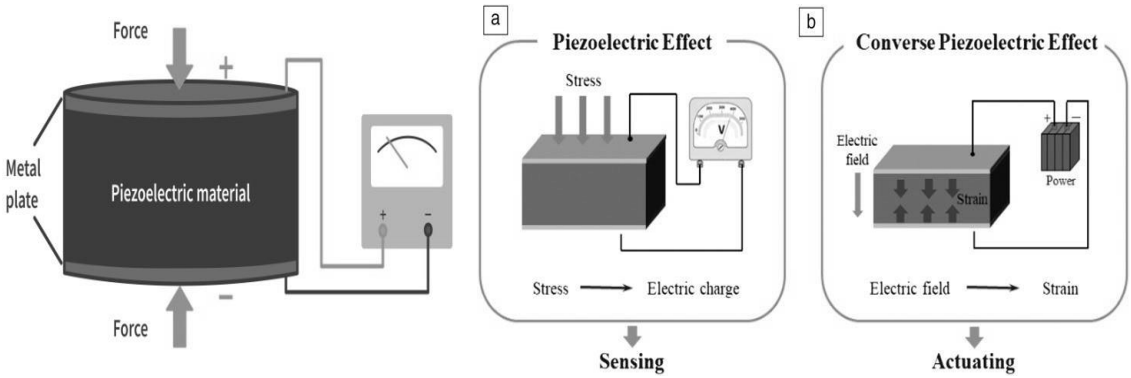
Smart materials have found a wide range of applications across various industries due to their unique properties. Some common applications include:

- Vibration and noise control in engineering structures
- Precision positioning in mechatronics and robotics
- Biomedical devices, such as ultrasonic transducers and artificial muscles
- Energy harvesting from mechanical vibrations
- Adaptive optics for telescopes and cameras
- Pressure sensors and accelerometers in automotive and aerospace industries
- Active flow control in aerodynamics
- Smart textiles for wearable technology

Piezoelectric Materials

Piezoelectric materials are a class of crystalline substances that possess a unique property known as the piezoelectric effect. This effect refers to their ability to generate an electric charge when subjected to mechanical stress or deformation, and conversely, they can also change shape or deform when exposed to an electric field. The word "piezoelectric" is derived from the Greek word "piezo," which means to squeeze or press, emphasizing the materials' response to mechanical forces.

The piezoelectric effect was first discovered by Pierre and Jacques Curie in 1880 when they observed that certain crystals, such as quartz, exhibited electric polarization when mechanically stressed. The discovery laid the foundation for the development of various applications based on this phenomenon.

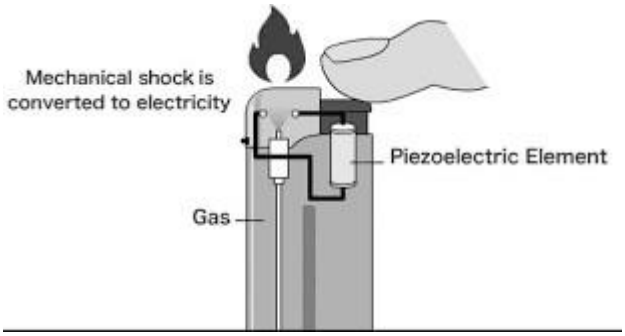


Properties of Piezoelectric Materials:

1. Electric Polarization: Piezoelectric materials have electric dipoles within their crystal structure. When they are mechanically stressed, the dipoles become misaligned, resulting in the generation of electric charges on the material's surface.
2. Direct and Inverse Piezoelectric Effect: The direct piezoelectric effect is the generation of an electric charge when mechanical stress is applied, while the inverse piezoelectric effect is the deformation of the material when an electric field is applied.
3. Anisotropy: The piezoelectric effect in crystals is highly dependent on their crystallographic orientation. Different directions in the crystal lattice exhibit varying degrees of piezoelectric response.
4. Reversibility: The piezoelectric effect is reversible. When the mechanical stress is removed, the material returns to its original state with no residual charge.

Applications of Piezoelectric Materials:

1. Sensors: Piezoelectric materials are widely used in various sensors, such as pressure sensors, force sensors, and accelerometers. When mechanical forces are applied to the material, it generates an electric charge proportional to the applied force, allowing the measurement of pressure, force, and acceleration.



2. Actuators: Piezoelectric actuators are devices that convert electrical energy into mechanical motion. When an electric field is applied to the piezoelectric material, it deforms, resulting in mechanical displacement. Piezoelectric actuators are utilized in precision positioning systems, nanopositioning stages, and adaptive optics.

3. Transducers: Piezoelectric transducers are devices that convert one form of energy to another. They are commonly used in ultrasonic transducers, where an electrical signal is converted into ultrasonic waves, or vice versa, for applications in medical imaging, distance measurement, and non-destructive testing.
4. Energy Harvesting: Piezoelectric materials can be employed to harvest energy from mechanical vibrations or movements. When subjected to vibrations, the material generates electric charges that can be harnessed to power low-energy devices or sensors.
5. Acoustic Devices: Piezoelectric materials find applications in acoustic devices like speakers, buzzers, and microphones. When an alternating electric field is applied, the material vibrates at the same frequency, producing sound waves.
6. Piezoelectric Motors: Piezoelectric materials can be used in various types of motors, including linear motors and piezoelectric motors, where the motion is driven by the deformation of the material in response to an electric field.

Piezoelectric Sensor:

A piezoelectric sensor is a device that utilizes the piezoelectric effect to measure various physical quantities, such as pressure, force, acceleration, and strain. The sensor converts mechanical signals into electrical signals, making it a valuable tool for detecting and monitoring changes in the physical environment. The key component of a piezoelectric sensor is a piezoelectric material, typically in the form of a crystal or ceramic.

Working Principle of Piezoelectric Sensor:

When mechanical stress or force is applied to the piezoelectric material, it undergoes deformation, causing the electric charges within the crystal lattice to shift and create an electric potential across the material. This phenomenon is known as the direct piezoelectric effect. The magnitude of the generated electrical charge is proportional to the applied force, allowing for accurate measurement of the physical quantity.

Applications of Piezoelectric Sensors:

1. Pressure Sensors: Piezoelectric pressure sensors are widely used in industrial and automotive applications to measure pressure in gas and liquid systems. They are employed in tire pressure monitoring systems, process control, and aerospace.
2. Accelerometers: Piezoelectric accelerometers are used to measure acceleration in various systems, including vibration monitoring in machinery, structural health monitoring, and seismic sensing.
3. Force Sensors: Piezoelectric force sensors are employed in biomechanical studies, robotics, and industrial force measurement applications.
4. Impact and Shock Sensors: Piezoelectric sensors are utilized in impact and shock detection systems to measure sudden changes in force or acceleration.
5. Touch Sensors: In consumer electronics, piezoelectric sensors are used as touch sensors in touch-sensitive screens and buttons.

Piezoelectric Actuator:

A piezoelectric actuator is a device that uses the piezoelectric effect to produce mechanical motion or displacement in response to an applied electrical voltage. These actuators are highly regarded for their precise control, rapid response, and compact size, making them suitable for various applications requiring precise motion control.

Working Principle of Piezoelectric Actuator:

When an electric voltage is applied to the piezoelectric material, it undergoes a small deformation due to the inverse piezoelectric effect. This deformation causes a change in the shape of the material, leading to mechanical displacement. The extent of the displacement is directly related to the applied voltage.

Applications of Piezoelectric Actuators:

1. Precision Positioning: Piezoelectric actuators are used in precision positioning systems, such as nanopositioning stages in microscopy and semiconductor manufacturing.
2. Micro/Nano Manipulation: These actuators find applications in micro and nano-scale manipulation tasks, such as microinjection in biological research and atomic force microscopy.
3. Adaptive Optics: Piezoelectric actuators are used in adaptive optics systems to correct for aberrations in optical systems, improving the quality of images obtained from telescopes and cameras.
4. Active Vibration Control: In structural engineering and aerospace applications, piezoelectric actuators are used for active vibration control to dampen vibrations and reduce noise.
5. Microfluidics: Piezoelectric actuators are utilized in microfluidic devices for precise control of fluid flow and mixing.

Piezoelectric sensors and actuators have revolutionized various industries by providing accurate sensing and precise motion control capabilities. Their unique properties and versatility continue to drive innovations in engineering, healthcare, and consumer electronics. Ongoing research and advancements in piezoelectric materials and technologies are expected to further expand their applications and impact on the modern world.

Magnetostrictive Materials

Magnetostrictive materials are a class of materials that undergo mechanical deformation when subjected to a magnetic field. This phenomenon is known as the magnetostrictive effect. Unlike piezoelectric materials, which respond to mechanical stress or deformation with electric charge generation, magnetostrictive materials respond to changes in magnetic fields with changes in their shape or dimensions.

The magnetostrictive effect is due to the interaction between the crystal lattice of the material and the magnetic domains within it. When a magnetic field is applied, the magnetic domains

align, resulting in a change in the material's shape or size. Conversely, when the magnetic field is removed or reversed, the material returns to its original state with no residual deformation.

Key Properties of Magnetostrictive Materials:

1. Magnetostrictive Coefficient: The magnetostrictive coefficient (λ) is a measure of the strain or deformation exhibited by the material per unit of magnetic field strength. It quantifies the material's sensitivity to changes in the magnetic field.
2. Anisotropy: Magnetostrictive materials are often anisotropic, meaning that the magnetostrictive effect is dependent on the direction of the magnetic field relative to the crystallographic orientation of the material.
3. Hysteresis: Similar to other magnetic materials, magnetostrictive materials may exhibit hysteresis, where the strain response lags behind the magnetic field changes during magnetization and demagnetization processes.

Commonly Used Magnetostrictive Materials:

1. Terfenol-D: Terfenol-D is one of the most widely used magnetostrictive materials. It is an alloy composed mainly of terbium, dysprosium, and iron. Terfenol-D exhibits a large magnetostrictive effect, making it suitable for various applications.
2. Galfenol: Galfenol is another magnetostrictive alloy composed mainly of gallium and iron. It has a lower magnetostrictive coefficient than Terfenol-D but is less expensive and easier to process.

Applications of Magnetostrictive Materials:

1. Magnetostrictive Sensors: Magnetostrictive materials are used in sensors to measure various physical quantities, including stress, strain, and magnetic fields. Magnetostrictive sensors find applications in structural health monitoring, industrial process control, and non-destructive testing.
2. Actuators: Magnetostrictive actuators are devices that utilize the magnetostrictive effect to produce mechanical displacement or force. They are used in various applications, including precision positioning systems, vibration dampers, and robotics.
3. Energy Harvesting: Magnetostrictive materials can be employed in energy harvesting devices, where mechanical vibrations or motion are converted into electrical energy using the magnetostrictive effect.
4. Sonar and Underwater Applications: Magnetostrictive materials are used in underwater sonar systems for communication, navigation, and detection of underwater objects.
5. Smart Materials: Magnetostrictive materials can be integrated into smart materials and structures for adaptive and morphing applications in aerospace and civil engineering.

Magnetostrictive materials can be utilized as both sensors and actuators due to their unique properties that respond to changes in magnetic fields. Let's explore their applications in both roles:

1. **Magnetostrictive Sensors:**

Magnetostrictive sensors are devices that utilize the magnetostrictive effect to measure various physical quantities, such as stress, strain, and magnetic fields. The change in dimensions of the magnetostrictive material in response to an applied magnetic field is translated into measurable signals. Some common types of magnetostrictive sensors include:

1.1 Stress and Strain Sensors: Magnetostrictive materials can be used to measure mechanical stress and strain in structures. They are employed in structural health monitoring systems to detect changes in stress levels, ensuring the safety and integrity of infrastructure.

1.2 Magnetic Field Sensors: Magnetostrictive materials can act as magnetic field sensors, measuring the strength and direction of magnetic fields. They find applications in magnetic imaging, non-destructive testing, and geophysical exploration.

1.3 Pressure Sensors: Magnetostrictive sensors can be used to measure pressure indirectly by detecting the mechanical deformation caused by pressure-induced stress on the magnetostrictive material.

1.4 Torque Sensors: Magnetostrictive materials can be integrated into torque sensors to measure the torque applied to a shaft or rotating component. These sensors are commonly used in automotive and industrial applications.

2. **Magnetostrictive Actuators:**

Magnetostrictive actuators are devices that utilize the magnetostrictive effect to produce mechanical displacement or force in response to an applied magnetic field. These actuators can be controlled precisely by varying the intensity of the magnetic field. Some common types of magnetostrictive actuators include:

2.1 Positioning Systems: Magnetostrictive actuators are widely used in precision positioning systems, offering high accuracy and fast response times. They find applications in optics, micro-positioning, and robotics.

2.2 Vibration Dampers: Magnetostrictive materials can be employed as active vibration dampers to mitigate vibrations in structures and machinery, enhancing stability and performance.

2.3 Micro/Nano Actuators: Magnetostrictive actuators can be miniaturized to micro or nano scales, making them suitable for microfluidic devices, lab-on-a-chip systems, and biomedical applications.

2.4 Morphing Structures: Magnetostrictive actuators can be integrated into smart materials and structures to achieve morphing capabilities. In aerospace engineering, morphing wings can adjust their shape for improved aerodynamic performance.

2.5 Valves and Pumps: Magnetostrictive actuators can be used in valves and pumps to control

fluid flow and pressure in industrial processes.

The advantages of magnetostrictive sensors and actuators include their ability to operate in harsh environments, high sensitivity, and fast response times. However, they also have limitations, such as the need for external magnetic fields, power consumption, and relatively low strain levels compared to other actuator technologies like piezoelectric actuators. Nevertheless, ongoing research and development continue to explore innovative applications and improvements in magnetostrictive materials for enhanced sensing and actuation capabilities.

Electrostrictive Materials

Electrostrictive materials are a class of materials that change shape or deform when subjected to an electric field. This phenomenon is known as the electrostrictive effect, and it is similar to the piezoelectric effect, but with some differences in the underlying mechanism. In electrostrictive materials, the mechanical deformation is induced by the applied electric field, whereas in piezoelectric materials, it is induced by mechanical stress.

Electrostrictive materials are typically insulators, and their electrostrictive effect is usually much smaller than the piezoelectric effect. However, they still find valuable applications in various fields, especially where high mechanical stresses are involved.

Key Properties of Electrostrictive Materials:

1. Electrostrictive Coefficient: The electrostrictive coefficient is a measure of the strain or deformation exhibited by the material per unit of electric field strength. It quantifies the material's sensitivity to changes in the electric field.
2. Anisotropy: Like piezoelectric materials, electrostrictive materials can be anisotropic, meaning that their electrostrictive response depends on the crystallographic orientation of the material.
3. Non-linear Behavior: The relationship between the electric field and the resulting strain in electrostrictive materials is often nonlinear, especially at higher electric field strengths.

Commonly Used Electrostrictive Materials:

1. PVDF (Polyvinylidene Fluoride): PVDF is a commonly used electrostrictive polymer. It exhibits a modest electrostrictive effect and is flexible, lightweight, and relatively easy to process. PVDF is extensively used in applications such as sensors, actuators, and energy harvesting devices.
2. Relaxor Ferroelectric Materials: Relaxor ferroelectric materials, such as lead magnesium niobate-lead titanate (PMN-PT), have enhanced electrostrictive properties compared to regular ferroelectric materials. They find applications in high-performance electrostrictive actuators and sensors.

Applications of Electrostrictive Materials:

1. Electrostrictive Sensors: Electrostrictive materials can be used as sensors to measure parameters like pressure, strain, and displacement. Electrostrictive sensors are employed in pressure sensors, strain gauges, and touch-sensitive devices.
2. Electrostrictive Actuators: Electrostrictive actuators convert electrical energy into mechanical motion. Although their displacement is typically smaller than piezoelectric actuators, they offer advantages in specific applications that require higher mechanical stresses. Electrostrictive actuators are used in nanopositioning systems, adaptive optics, and microfluidic devices.
3. Energy Harvesting: Electrostrictive materials can be utilized in energy harvesting devices, where mechanical vibrations or motion are converted into electrical energy using the electrostrictive effect.
4. Smart Materials: Electrostrictive materials can be integrated into smart materials and structures for adaptive and morphing applications in aerospace, robotics, and civil engineering.

Electrostrictive materials can be utilized as both sensors and actuators due to their ability to change shape or deform in response to an applied electric field. Let's explore their applications in both roles:

1. **Electrostrictive Sensors:**

Electrostrictive sensors are devices that utilize the electrostrictive effect to measure various physical quantities, such as pressure, strain, and displacement. When an electric field is applied to the electrostrictive material, it undergoes deformation, which is translated into measurable signals. Some common types of electrostrictive sensors include:

1.1 Pressure Sensors: Electrostrictive materials can be used as pressure sensors to measure changes in pressure. The deformation of the material in response to the applied electric field can be correlated to the pressure being applied.

1.2 Strain Gauges: Electrostrictive strain gauges are used to measure changes in strain in structures. When the material experiences deformation due to mechanical stress, the applied electric field further induces additional deformation, which can be measured and correlated to the strain.

1.3 Displacement Sensors: Electrostrictive materials can act as displacement sensors by measuring the displacement or deflection of a structure or object in response to the applied electric field.

1.4 Touch Sensors: Electrostrictive materials can be used in touch-sensitive devices to detect touch or pressure from a user. The material's deformation due to the applied electric field changes when touched, allowing for touch detection.

2. **Electrostrictive Actuators:**

Electrostrictive actuators are devices that utilize the electrostrictive effect to produce mechanical displacement or force in response to an applied electric field. The deformation of

the material under the electric field leads to the actuation. Some common types of electrostrictive actuators include:

2.1 Micro/Nano Actuators: Electrostrictive materials can be miniaturized to micro or nano scales, making them suitable for precise micro/nano-positioning and manipulation tasks. They find applications in microfluidic devices, lab-on-a-chip systems, and biomedical devices.

2.2 Adaptive Optics: Electrostrictive actuators are used in adaptive optics systems to correct for aberrations in optical systems, improving the quality of images obtained from telescopes and cameras.

2.3 Smart Structures: Electrostrictive materials can be integrated into smart structures for morphing and shape-changing applications. In aerospace engineering, smart wings can adjust their shape for improved aerodynamic performance.

2.4 Robotics: Electrostrictive actuators can be used in robotics for precise motion control and manipulation of robotic limbs and grippers.

2.5 Vibration Control: Electrostrictive actuators can be used in vibration control systems to dampen vibrations in structures and machinery.

The advantages of electrostrictive materials in sensors and actuators include their ability to provide precise control, rapid response, and the ability to operate in harsh environments. However, they may have limitations such as relatively lower displacement compared to other actuator technologies like piezoelectric actuators and higher power consumption. Ongoing research and advancements in electrostrictive materials and technologies aim to enhance their performance and expand their applications in various engineering and technological fields.

Future Directions and Challenges

1. Advancements in Smart Materials Researchers continue to explore new materials and enhance the properties of existing smart materials, leading to improvements in sensitivity, response time, and efficiency.

2. Integration with Other Technologies Smart materials are increasingly being integrated with other cutting-edge technologies like artificial intelligence and the Internet of Things, enabling the development of more sophisticated and autonomous systems.

3. Challenges and Limitations Despite their vast potential, smart materials also face challenges such as high manufacturing costs, material fatigue, and environmental considerations. Research efforts are focused on overcoming these limitations.

Module 1
Engineering Materials and Classification

1. Electrical conductivity of steel is much higher than that of plastic materials. Defend the statement from the point of view of forbidden energy gap with suitable diagram. **(Mod. 1, BL5) (5 mark)**

Hint: Conductivity depends on energy gap between conduction band & valance band. Less gap between the two the more conductive the material is.

2. Compare mechanical properties of mild steel and white cast iron from point of view of microstructure with industry application of both. {**(Mod. 1, BL4) (5 mark)}**

Hint: Mild steel has less amount of carbon percentage than cast iron.

3. Analyze and summarize the general properties of polymers. {**(BL: 4, Analyze) (5 mark)}**

Hint: The general properties of polymers include low density, flexibility, electrical insulation, chemical resistance, and a wide range of physical and mechanical properties.

4. How the various factors are effecting the selection of materials? {**(BL: 4) (5 mark)}**

Hint: It is depend on mechanical properties, performance requirement and reliability of material

5. Show how the true stress and true strain affect the stress- strain behavior of a ductile material and justify. {**(BL: 5) (5 mark)}**

Hint: Based on the stress strain effect of ductile and brittle materials.

Module 2
Mechanical Properties and Testing

1. How Brinell hardness testing is different from Rockwell hardness testing. {**(Mod. 2,BL: 4) (5 mark)}**

Hint: Destructive material testing process

2. A 12.5 mm diameter bar was subjected to under a load of 2500 kg-force, by which length of the bar transformed from 50 mm to 65 mm evaluate the True stress on the bar in MPa and ductility in % of reduced cross-sectional area. {**(Mod. 2, BL5) (5 mark)}**

Hint: Mechanical properties

3. If the diameter of standard WC indenter sphere is 10 mm and diameter of indentation of a C25 steel specimen is 0.39 mm under 15 kg load, find the Brinell hardness number. {**(Mod. 2, BL5) (5 mark)}**

Hint: Mechanical properties

4. A 14 mm diameter bar was subjected to under a load of 2800 kg-force, by which length of the bar transformed from 55 mm to 70 mm. Calculate the True stress on the bar in MPa and ductility in % of reduced cross-sectional area {**(Mod. 2, BL5) (5 mark)}**

Hint: Mechanical properties

5. How does the Notch sensitivity increase the deformation rate of material? {**(Mod. 2, BL4) (5 mark)}**

Hint: Destructive material testing process and stress strain behavior.

Module 3
Metal and Alloys

1. In a hyper eutectoid steel, methodically explain the formation process of (50% peralite +50% bainite) structure from 100% pearlitic structure with proper diagram. **(Mod. 3, BL4) (10 mark)**

Hint: Time-Temperature-Transformation diagram is the key diagram.

2. Compressive strength of gray cast iron is higher than its tensile strength. Justify from the point of view of microstructure & industry perspective with proper diagram.**(Mod. 3, BL5) (5 mark)**

Hint: Gray cast iron has graphite/free carbon in flaky form.

3. Graphite forms as spheroid in ductile cast Iron. Justify from the point of view of microstructure with proper diagram.**(Mod. 3, BL5) (5 mark)**

Hint: Due to presence of Mg graphite forms as spheroid shape in ductile cast iron.

4. Bainitic Structure is more preferable than pearlitic structure in industry ready instruments. Defend the statement from point of view of microstructure with proper diagram. **(Mod. 3, BL5) (5 mark)**

Hint: Bainite is non-lamellar mixture of ferrite and cementite, whereas pearlite is a lamellar mixture of ferrite and cementite.

5. Industry application of HSS is far more preferable than HCS, now days.Defend the statement from point of view of alloying element percentage. **(Mod. 3, BL5) (5 mark)**

Hint: In HSS tungsten and Vanadium plays key role at high temperature.

Module 4
Heat Treatment

1. Compare and contrast the microstructural changes that occur during austenitizing and martempering processes in steel. Analyze how each treatment affects the material's hardness, ductility, and resistance to wear. **(BL: 4, Analyze)**

Hint: To compare and contrast the microstructural changes during austenitizing and martempering, begin by understanding the basic steps and conditions of each process. Focus on the different phases formed during both treatments and how they affect the material's properties.

2. Analyze the microstructural changes during the nitriding process and its impact on wear resistance and corrosion resistance in steel. **(BL: 4, Analyze)**

Hint: Nitriding introduces a hard layer of iron nitrides on the steel surface, improving wear resistance and forming a corrosion-resistant compound layer for enhanced protection against corrosion.

3. Compare the advantages and disadvantages of induction hardening and flame hardening in terms of cost-effectiveness and distortion. **(BL: 4, Analyze)**

Hint: Compare the cost-effectiveness and distortion characteristics of induction hardening and flame hardening processes, considering factors such as equipment costs, energy efficiency, heating control, part complexity, and potential post-treatment requirements.

4. Analyze the differences in the mechanical properties of steel after annealing and normalizing. How does each process affect the material's hardness, ductility, and impact resistance? **(BL: 4, Analyze)**

Hint: Compare the effects of annealing and normalizing on steel's mechanical properties by examining their cooling rates, microstructural changes, and subsequent impact on hardness, ductility, and impact resistance

5. Compare and contrast different hardening techniques, such as quenching and precipitation hardening. **(BL: 4, Analyze)**

Hint: Compare and contrast quenching and precipitation hardening techniques in terms of process mechanisms, material types suitable for each method, heat treatment procedures, resulting microstructural changes, and the impact on material properties like hardness, strength, and ductility.

6. Critically evaluate the advantages and limitations of Annealing process and discuss their suitability for different engineering applications. **(BL: 5, Evaluate)**

Hint: Critically evaluate the advantages and limitations of the annealing process in terms of its impact on steel's mechanical properties, microstructure, and performance.

7. Evaluate the suitability of annealing as a heat treatment process for improving the machinability of a specific steel alloy used in manufacturing. **(BL: 5, Evaluate)**

Hint: Evaluate considering its effects on reducing hardness, relieving internal stresses, and enhancing ductility, which can lead to improved chip formation and reduced tool wear during machining.

8. Evaluate the benefits of case hardening in increasing the wear resistance of steel parts. **(BL: 5, Evaluate)**

Hint: Evaluate the benefits of case hardening in increasing wear resistance by focusing on the formation of a hard and wear-resistant outer layer while maintaining a tough and ductile core in steel parts, which results in enhanced performance and longevity in abrasive or high-stress applications.

9. Evaluate the advantages of heat treatment in improving material properties? **(BL: 5, Evaluate)**

Hint: Heat treatment improves material properties by altering the microstructure, leading to increased hardness, strength, ductility, toughness, and wear resistance for enhanced performance in diverse applications.

10. Evaluate the potential drawbacks of heat treatment on a material's physical properties? **(BL: 5, Evaluate)**

Hint: The potential drawbacks of heat treatment on a material's physical properties include increased brittleness, distortion, reduced corrosion resistance, and the risk of cracking or grain growth in certain cases.

11. Suggest different Quenching media and also write the effect of quenching media on Fe-C system. **(BL: 6, Create)**

Hint: Different quenching media include water, oil, brine, and air. The effect of quenching media on the Fe-C system involves influencing the cooling rate, resulting in variations in microstructures, hardness, and phase transformations in steel alloys

12. Propose a heat treatment process to enhance the wear resistance of tool steel. **(BL: 6, Create)**

Hint: Propose a process of hardening and tempering for tool steel to achieve increased wear resistance by forming a hard martensitic structure and then tempering to balance hardness with toughness.

13. Suggest a heat treatment process for bearing steels, to achieve a microstructure with spheroidal or globular carbides and for good machinability and good resistance to wear. **(BL: 6, Create)**

Hint: Consider a heat treatment process involving annealing, followed by spheroidizing annealing, to achieve a microstructure with spheroidal or globular carbides for improved machinability and wear resistance in bearing steels.

14. Construct a time temperature curve for different annealing process and describe the temperature range for different annealing process. **(BL: 6, Create)**

Hint: Construct time-temperature curves for full annealing, process annealing, and stress relieving etc. Describe the temperature ranges for each process, including heating, soaking, and cooling stages.

15. Create a comprehensive comparison table between the annealing and normalizing processes, focusing on the effects of each treatment on hardness, microstructure, grain size, and internal stresses in metals. **(BL: 6, Create)**

Hint: Create a table comparing annealing and normalizing processes, highlighting their impact on hardness, microstructure, grain size, and internal stresses in metals.

Module 5
Polymers, Ceramics and Composites

1. Analyze the impact of polymer structure on its chemical and physical properties. **(BL: 4, Analyze)**

Hint: The arrangement of monomers, polymer chain length, presence of side groups, and crosslinking affect the chemical and physical properties of a polymer, such as solubility, melting point, mechanical strength, and thermal stability.

2. Analyze the relationship between ceramic microstructure and its mechanical properties. **(BL: 4, Analyze)**

Hint: The ceramic microstructure, including grain size, porosity, and phase distribution, influences mechanical properties such as hardness, strength, toughness, and fracture behavior.

3. Analyze the advantages and disadvantages of using thermoset plastics in comparison to thermoplastic materials.**(BL: 4, Analyze)**

Hint: Thermoset plastics offer superior heat resistance and dimensional stability due to irreversible crosslinking, but they lack recyclability and are challenging to remold. On the other hand, thermoplastic materials are easily recyclable and moldable but have lower heat resistance and may experience creep under long-term stress.

4. Compare and contrast the properties of thermoplastic and thermosetting polymers, and discuss their respective applications in industry. **(BL: 5, Evaluate)**

Hint: Thermoplastic polymers can be melted and reshaped multiple times with good recyclability, while thermosetting polymers undergo irreversible crosslinking with superior heat resistance. Discuss their distinct mechanical properties, processing behavior, and applications in industries like automotive, construction, and electronics.

5. Evaluate the biocompatibility and long-term performance of bio-ceramic implants. **(BL: 5, Evaluate)**

Hint: Analyze the interaction between bio-ceramic implants and the human body, considering factors like tissue response, biodegradability, and potential long-term complications. Assess the implant's stability and effectiveness over extended periods in medical applications.

6. Evaluate the factors influencing the mechanical properties of different oxide ceramic materials. **(BL: 5, Evaluate)**

Hint: Consider crystal structure, grain size, porosity, presence of dopants, and temperature as key factors affecting the mechanical properties of oxide ceramic materials. Analyze how these factors influence hardness, strength, toughness, and other mechanical characteristics.

7. Compare and contrast the properties of glasses with other ceramic materials. **(BL: 5, Evaluate)**

Hint: Compare the amorphous structure of glasses with the crystalline structure of other ceramic materials, such as oxides and carbides. Analyze their mechanical properties, thermal behavior, transparency, electrical conductivity, and applications in industries like electronics, construction, and optics

8. Create a flowchart illustrating the steps involved in the manufacturing process of a specific oxide ceramic. **(BL: 6, Create)**

Hint: The flowchart should include steps such as raw material preparation, milling, forming, drying, sintering, optional machining, quality control, post-treatment, and final inspection/packaging.

9. Analyze the factors influencing the mechanical properties of a polymer. {**(BL4, Analyze) (5 marks)}**

Hint: Consider the molecular structure, degree of polymerization, crystallinity, crosslinking, and intermolecular forces as key factors influencing the mechanical properties of a polymer.

10. Create a comprehensive table comparing various polymerization techniques, highlighting their initiation methods, monomer reactivity, chain growth mechanisms, and common applications. **(BL: 6, Create)**

Hint: Organize the table with different polymerization techniques such as radical, anionic, cationic, coordination, step-growth, ring-opening, and living polymerization. Include their respective initiation methods (e.g., free-radical, anionic initiators), monomer reactivity (highly reactive, less reactive), chain growth mechanism (e.g., addition, coordination polymerization), and common applications (e.g., plastics, specialty polymers).

Module 6
Electrical and Magnetic Materials

1. Compare and contrast the properties of soft and hard magnetic materials, and discuss their respective applications in electrical devices **(BL:4, Analyse)**

Hint: Soft magnetic materials and hard magnetic materials have distinct magnetic properties that make them suitable for different applications in electrical devices. Consider their magnetization behavior, coercivity, hysteresis loops, and applications in transformers, motors, and magnetic storage devices

2. Analyse the advantages and disadvantages of different types of sensors (e.g., piezoelectric, magnetostrictive, electrostrictive) for different application. **(BL:4, Analyse)**

Hint: To analyze the advantages and disadvantages of different types of sensors, consider their sensing mechanisms, sensitivity, response time, cost, and suitability for specific applications

3. Analyze the impact of doping on the electrical conductivity of semiconducting materials. **(BL:4, Analyse)**

Hint: To analyze the impact of doping on the electrical conductivity of semiconducting materials, consider how the introduction of dopant atoms affects the number of charge carriers (electrons or holes) and their mobility in the semiconductor crystal lattice. Explore the differences between n-type and p-type doping and their influence on the overall conductivity of the material

4. Evaluate the factors affecting the critical temperature of superconducting materials. **(BL:4, Analyse)**

Hint: To evaluate the factors affecting the critical temperature of superconducting materials, consider the role of electron-phonon interactions, crystal structure, and the type of material used. Additionally, explore the influence of external factors such as pressure and magnetic fields on the critical temperature

5. Compare and contrast the primary characteristic of piezoelectric materials with other types of smart materials, such as magnetostrictive and electrostrictive materials, and discuss their specific applications in sensors and actuators. **(BL:4, Analyse)**

Hint: To compare and contrast piezoelectric materials with magnetostrictive and electrostrictive materials, focus on their fundamental characteristics related to sensing and actuation mechanisms. Then, explore their specific applications in sensors and actuators, emphasizing the unique advantages of each type of smart material in various engineering fields.

6. Evaluate the effectiveness of different piezoelectric materials in various actuator systems. **(BL:5,Evaluate)**

Hint: To evaluate the effectiveness of different piezoelectric materials in actuator systems, consider factors such as piezoelectric coefficients, mechanical properties, and thermal stability. Compare the performance of various piezoelectric materials in terms of their actuation range, response time, and energy efficiency.

7. Compare and contrast the properties of ferromagnetic, paramagnetic, and diamagnetic materials, and analyze how each type of magnetic material is utilized in different industrial and scientific applications. **(BL:5, Evaluate)**

Hint: To compare and contrast ferromagnetic, paramagnetic, and diamagnetic materials, focus on their magnetic susceptibility, response to external magnetic fields, and atomic/molecular magnetic moments.

8. Evaluate the importance of resistivity as a fundamental property in understanding the electrical behavior of resisting materials. Compare and contrast how materials with high and low resistivities behave in electrical circuits and their respective applications. **(BL:5, Evaluate)**

Hint: To evaluate the importance of resistivity, focus on how it quantifies a material's ability to resist the flow of electrical current. Compare and contrast materials with high and low resistivities, emphasizing their behavior in electrical circuits and their applications in conductors and insulators.

9. Assess the significance of the primary characteristic of piezoelectric materials in comparison to other smart materials, such as magnetostrictive and electrostrictive materials. Analyze how this unique property enables piezoelectric materials to be utilized effectively in sensors and actuators for various engineering applications. **(BL:5, Evaluate)**

Hint: To assess the significance of piezoelectric materials, compare their ability to convert mechanical stress into electrical charge with the sensing mechanisms of magnetostrictive and electrostrictive materials. Analyze how this unique property allows piezoelectric materials to offer precise and rapid responses, making them well-suited for sensors and actuators in diverse engineering applications like ultrasonic imaging, vibration control, and energy harvesting.

10. Evaluate the importance of choosing the right conducting or resisting material for specific applications in electronics, automotive, and electrical engineering. **(BL:5, Evaluate)**

Hint: To evaluate the importance of material selection, consider the impact of electrical conductivity and resistivity on the efficiency, safety, and performance of electronic, automotive, and electrical engineering systems. Analyze how the right choice of materials can optimize power transmission, heat dissipation, and overall reliability in various applications.

11. Propose an innovative application of superconducting materials in a renewable energy technology. **(BL:6, Create)**

Hint: To propose an innovative application, consider how the zero electrical resistance of superconducting materials can enhance energy efficiency and reduce losses in renewable energy systems. Analyze potential applications in high-capacity energy storage, transmission, or magnetic levitation systems for wind turbines or hydroelectric generators.

12. Create a comprehensive diagram illustrating the energy band diagram of a p-n junction in a semiconductor device. Label the energy levels, including the valence band, conduction band, and Fermi level, for both the p-type and n-type regions. **(BL:6, Create)**

Hint: To create the energy band diagram, consider the relative positions of the valence band, conduction band, and Fermi level in the p-type and n-type regions of the semiconductor. Pay attention to how doping affects the energy levels and the formation of the depletion region at the p-n junction. Use arrows to depict the direction of electron and hole movement under different bias conditions.

13. Devise a classification system for magnetic materials based on their temperature-dependent magnetic behavior, providing insights into their potential applications in extreme environments. **(BL:6, Create)**

Hint: To devise a classification system, consider how magnetic materials behave at different temperature ranges, such as ferromagnetic, paramagnetic, antiferromagnetic, and ferrimagnetic. Analyze the suitability of each type for extreme environments, such as high or low temperatures, and their applications in fields like aerospace, geophysics, and magnetic data storage.

14. Design a graphical representation of the table to visualize the advantages and limitations of each smart material in comparison to conventional materials. **(BL:6, Create)**

Hint: Create a comparative bar chart or radar chart to visually represent the advantages and limitations of smart materials (piezoelectric, magnetostrictive, and electrostrictive) in contrast to conventional materials. Include key attributes like sensitivity, response time, force output, and temperature sensitivity to showcase their relative strengths and weaknesses in various applications.

15. Create an educational presentation explaining the principles and applications of magnetostrictive materials to a non-technical audience, emphasizing their significance in modern engineering and technology. **(BL:6, Create)**

Hint: Use simple language and visuals to explain how magnetostrictive materials change shape in response to magnetic fields, emphasizing their role in sensors and actuators in everyday devices. Highlight real-world applications like pressure sensors, vibration dampers, and smart materials to showcase their relevance and impact in modern technology.