Magnetic and Dielectric materials in Material science

We know that current through a circular coil produces magnetic moment along the axis of the coil. When the electrons revolve around the positive nucleus, orbital magnetic moment arises. Similarly when the electron spins, spin magnetic moment arises. Magnetism arises from the magnetic moment or magnetic dipole of the magnetic materials. Any material that can be magnetized by application of external magnetic field is called a magnetic material.

Types of Magnetic materials :

1. Diamagnetic
2. Paramagnetic
3. Ferro –magnetic
4. Anti Ferromagnetic
5. Ferromagnetic

Important terms used in magnetism :

Magnetic flux density (B) :

Magnetic flux density (B) in any material is the number of lines of magnetic force passing through unit area perpendicularly.

Unit : Wb/m^2 or Tesla

Magnetic field intensity (H) :

Magnetic field intensity at any point in the magnetic field is the force experienced by an unit north pole placed at that point.

Unit : A/m

$$B = \mu_0 H$$

Where μ_0 = permeability of free space (vacuum)

$$\mu_0 = 4\pi \times 10^{-7}\ H_1 m^{-1}$$

Instead of vacuum, it the field is applied in a solid medium, the magnetic induction in the solid is given by

$$B = \mu H$$

where μ = permeability of the solid material through which the magnetic lines of force pass

$$\mu = \frac{B}{H}$$

Hence the magnetic permeability (μ) of any material is the ratio of the magnetic induction in the sample to the applied magnetic field intensity.

Relative permeability,

$$\mu_r = \frac{\mu}{\mu_o}$$

The intensity of magnetization (M)

The intensity of Masgnetisation of a sampkle of a material is the magnetic moment per unit volume.

Unit : A/m

M & H are related by magnetic succeptibility x.

$$x = \frac{M}{H}$$

Magnetic Susceptibility (x) :

Magnetic susceptibility (x) of a material is the ratio of the intensity of magnetization produced in the sample to the magnetic field intensity which produces the magnetization. It has no units. Momentic induction (B) is given by

$$B = \mu_o (H + M)$$

Hence

$$\mu_o = \frac{B}{H+m}$$

Relative permeability, $\mu_r = 1 + x$

Classification of Magnetic materials.

- If the atoms do not carry permanent magnetic dipoles, those materials are called diamagnetic.
- If the atoms of the material carry permanent magnetic dipoles, further classification is based on the interaction between the individual dipoles.
- If the permanent dipoles do not interact among themselves, the material is paramagnetic.
- If the interaction among the permanent dipoles is strong such that all the dipoles line up in parallel, the material is ferromagnetic.
- If the permanent dipoles line up in antiparallel direction, and are equal the material is antiferromagnetic and the magnetization vanishes.
- If the magnitudes of permanent dipoles aligned antiparallel are not equal thus exhibiting magnetization then the material is ferrmagnetic.

Different sources of permanent magnetic moment are

1. The orbital magnetic moment of the electrons.
2. The spin magnetic moment of the electrons $
3. The spin magnetic moment of the nucleus.

Properties of diamagnetic materials. :

1. Permanent dipoles are absent.
2. Effect is weak and often marked by other kinds of magnetism.
3. When placed inside a magnetic field, magnetic lines of force are repeled.
4. Magnetic susceptibility is negative.
5. Magnetic susceptibility is independent of applied magnetic field strength.
6. Relative permeability is slightly less than unity.

Properties of paramagnetic materials. :

1. They posses permanent magnetic dipoles.
2. These dipoles are non-interacting
3. The dipoles are randomly oriented and hence in the absence of external applied magnetic field, the net magnetization in any given direction is zero.
4. When placed inside a magnetic field, it attracts the magnetic lines of force.
5. Paramagnetic succeptibility is positive and depends greatly on temperature.

Bohr Magneton :

When the atom is placed in a magnetic field, the orbital magnetic moment of the electrons is quantized.

A quantum of magnetic moment of an atomic system is known as Bohr magneton.

$$\mu_B = \frac{eh}{4\pi m}$$

Curie Law :

Langevin showed that classical paramagnetic susceptibility (x) due to the alignment of magnetic moments along field direction is given by

$$x = \frac{h_o N\mu^2}{3kT} = \frac{C}{T}$$

where C = Curie constant and the relation is known as Curie Law

Curie – Weiss Law :

Ferromagnetic materials exhibit spontaneous magnetization below a characteristic temperature called the ferromagnetic curie temperature. Above this temperature, the substance becomes paramagnetic and obey Curie – Weiss Law.

$$x = \frac{C}{T-\theta}$$

where c is Curie constant

q is paramagnetic Curie temperature

Heisenberg theory of Ferromagnetism :

The molecular field based on simple dipole – dipole interaction was found to be less and hence cannot account for the existence of ferromagnetism.

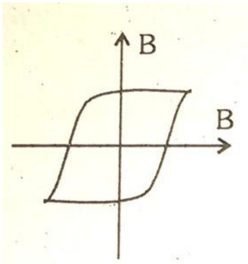
Heisenberg removed this discrepancy by assuming the quantum exchange interaction between the electrons spins instead of dipole – dipole interaction.

Domain theory of ferromagnetism :

According to Weiss, a virgin specimen of ferromagnetic material consists of a number of regions or domains which are spontaneously magnetized due to parallel alignment of all magnetic dipoles. The direction of spontaneous magnetization varies from domain to domain.

Hysteresis in magnetic materials :

The hysteresis of ferromagnetic material refers to the log of magnetization behind the magnetising field. It is irreversible B-H characteristic curve of ferromagnetic or ferromagnetic materials.



Hysteresis loss :

Hysteresis loss is the loss of energy in taking a ferromagnetic body through a complete cycle of magnetization. This loss is represented by the area enclosed by the hysteresis loop.

Properties of hard and soft magnetic materials.

Properties	Hard	soft
1. Area of hysteresis loop	Large	Small
2. Hysteresis loss	Large	Small
3. Domain wall movement	Difficult	Relatively earlier
4. Coercivity	Large	Small
5. Retentivity	Large	Small
6. Magnetization & Demagnetization	Not easy	Easy
7. Magnetostatic energy	Large	Small
8. Permeability & Susceptibility	Small	Large
9. Type of magnet that could be made	Permanent magnet	Electro-magnets

Antiferromagnetism :

In antiferromagnetism, electron spin of neighbouring atoms are aligned antiparallel. Anti-ferromagnetic susceptibility is small and positive and it depends greatly on temperature.

Ferrites :

In a material of the magnitudes of permanent dipoles aligned antiparallel are not equal, such an uncompensated antiferromagnetism is known as ferrimagnetism and the corresponding materials are said to be ferromagnetic or ferrites.

Applications of Ferrites :

1. They are used in transformer cores for high frequencies upto microwaves.
2. They are used in radio receivers to increase the sensitivity and selectivity of the receiver.
3. Ferrites are used in digital computers and data processing circuits as magnetic storage elements.
4. They are used as isolator.

uses in Transformer cores :

Ferrites are used as transformer cores for frequencies upto microwaves. This is because the eddy current problem preventing penetration of magnetic flux into the material is much less severe in ferrites than in iron.

Magneto Resistance Effect :

In some magnetically soft materials the electrical resistance changes when the material is magnetized. The resistance goes back to its original value when the magnetizing field is turned off. This effect is called magneto resistance effect.

Importance of magnetic materials :

Magnetic materials used for high density data storage. some materials are easily magnetized when placed in a weak magnetic field. When the field is turned off, the material rapidly demagnetizes. These materials are called soft magnetic materials.

In Hard magnetic materials through strong field is required for magnetization, they retain their magnetization even on removal of the field.

In some materials, the electrical resistance varies on magnetization. This effect is called Magneto Resistance Effect.

These effects are utilized in manufacture of magnetic recording heads for write and read the date for storage and retrival.

Basic parts of a digital magnetic – tape system :

i) Magnetic tape : Flexible plastic tape with their ferromagnetic material coating.

ii) Tape Transport : Mechanism to run the tape part the recording / reading head.

iii) Translators : Electronic part to convert given analog signal into digital for recording purposes and digital into analog for reading purposes.

iv) Reading / writing Heads : Magnetic read / write heads to record / retrieve the data in / from the magnetic tape.

v) switching and buffering equipment : This is to select the correct tape mechanism and to provide tasks such as winding /rewinding of the tape etc.

Bubble storage :

Data can be stored in this crystals of canted antiferromagnetic oxides ($B_aFe_{12}O_{19}$, $YFeo_3$), or in amorphous alloyed films (Gd-Co, Gd-Fe), or in ferromagnetic materials such as Yttrium –iron – garnet ($Y_3Fe_5O_{12}$). They are tiny cylindrical regions called bubbles (as small as 1 mm in diameter) having a reversed momentisation compared to the matrix.

Hole burning :

The recording medium consists of an inert crystal host (such as Y_2SiO_5 with a low concentration of rare-earth impurity ions (such as Eu^{3+}) distributed randomly.

Information is stored in the impurity ions by absorption of light resulting in a mechanism called hole burning.

Stimulated echo ;

The recorded information is retrieved by a mechanism called the stimulated echo-when the recorded crystal is illuminated by another lager beam called the read pulse, coherent radiation is emitted from the already recorded impurity ion. This phenomenon is called stimulated echo.

Dielectrics :

Dielectrics are insulating materials. In dielectrics all the electrons are bound to their parent molecules and there are no free charges. Even with normal voltage or thermal energy, electrons are not released. Dielectrics are non-metallic materials of high specific resistance and have negative temperature coefficient of resistance.

Dielectric constant 'ε_r' :

The dielectric characteristics of a material are determined by the dielectric constant or relative permittivity 'ε_r'. Of that material. It is the ratio between the permittivity of the medium and the permittivity of free space.

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_o}$$

ε_r has no unit.

It is a measure of polarization in the dielectric material.

Electric Plarization :

Let us consider an atom placed inside an electric field. The centre of positive charge is displaced along the applied field direction while the centre of negative charge is displaced in the opposite direction. Thus a dipole is produced. When a dielectric material is placed inside an electric filed such dipoles are created in all the atoms inside. This process of producing electric dipoles which are oriented along the field direction is called polarization in dielectrics.

Polarizability (α) :

When the strength of the electric field E is increased the strength of the induced dipole also increases. Thus the induced dipole moment is proportional to the intensity of the electric field.

i.e. $\mu = \alpha$ E

where α , the constant of proportionality is called polarizability.

Electric flux density (D) :

The electric flux density D at a point in a material is given by

D = $\varepsilon_r \, \varepsilon_o$ E

where E is the electric field strength.

e_o – dielectric constant or permittivity of free space (vacuum)

e_r – relative dielectric constant or relative permittivity of the material.

Electric Susceptibility (X_e) :

Polarization vector p can be written as

P = $\varepsilon_o \, X_e$ E

where the constant X_e is the electric susceptibility.

There $X_e = \frac{P}{\varepsilon_o E} = \frac{\varepsilon_o \, (\varepsilon_r - 1)E}{\varepsilon_o E}$

$\therefore\ X_e = (\varepsilon_r - 1)$

Polarization process ;

Polarization occurs due to several atomic mechanisms. when the specimen is placed inside a d.c. electric field, polarization is due to four types of processes.

a) electronic polarization
b) ionic polarization
c) orientation polarization &
d) Space charge polarization

Electronic polarization :

The displacement of the positively charged nucleus and the electrons of an atom in opposite directions on application of an electric field is called electronic polarization.

Dielectric loss ;

When a dielectric material is subjected to the a.c. voltage, the electrical energy is absorbed by the material and is dissipated in the form of heat. This dissipation of energy is called dielectric loss.

Loss angle :

In a perfect insulator polarization is complete during each cycle and there is no consumption of energy and the charging current leads the applied voltage by 90° But for commercial dielectrics this phase angle is less then 90° by an angel δ called dielectric loss angle. Tan δ is taken as measure of dielectric loss and is known as loss tangent.

Also $\tan\delta = \frac{\varepsilon_r''}{\varepsilon_r'}$

Dielectric brak down :

When a dielectric material loses its resistivity and permits very large current to flow through it, then the phenomenon is called dielectric breakdown.

Different dielectric breakdown mechanisms :

i) Intrinsic breakdown
ii) Thermal breakdown
iii) Discharge breakdown
iv) Electrochemical breakdown
v) Defect breakdown

Piezoelectrics and pyroelectrics are the two active dielectrics.

Piezoelectrics such as Barium titanate ($B_a\ T_i\ O_3$), Pottassium dihydrogen phosphate (KPP), Lithium Niobate ($LiNbO_3$) are used for making pressure transducers, ultrasonic transducers and microphones. Pyroelectrics such as Barium titanate (BaTiOe), Triglycine suplhate (TGS) and Lithium Niobate ($LiNbo_3$) are used to make high sensitive infrared detectors.

Requirement of good insulating materials ;

i) high electrical resistivity
ii) high dielectric strength
iii) Sufficient mechanical strength to withstand vibration &
iv) good heat conducting property

Classification of insulating materials ;

a) Solid insulating materials
b) Liauid insulating materials
c) Gaseous insulating materials

a) Solid insulating materials :

1. Mica
2. Ceramics

3. Asbestos
4. Rubber
5. PVC materials

b) Liquid insulating materials :

i) Mineral insulating oil,

1. Transformer oil
2. Cable oil
3. Capacitor oil

ii) synthetic insulating oil

iii) Miscellaneous insulating oils

1. Vegetable oil
2. Vaseline
3. Silicon liquids

c) Gaseous insulating materials :

i) Air
ii) Nitrogen
iii) Inert gases
iv) Sulphur hexafluoride

Important applications of dielectric materials:

i) Electical conductors made of aluminium or copper which are used for electric wiring are insulated with a outer jacket of plastic or rubber.

ii) In heater coils ceramic beads are used to avoid short circuiting as well as to insulate the outer body from electric current.

iii) In electric iron, mica or asbestos insulation is provided to prevent the flow of electric current to the outer body of the iron

iv) In transformers as well as in motor and generator windings vanished cotton is used as insulator.