Magnetic Materials

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MAGNETIC MATERIALS

DEFINITIONS

1. **Magnetic flux**

   It is the total number of magnetic lines of force passing through a surface. It is represented by the *symbol Φ and its unit is weber (Wb).*

2. **Magnetic Field**

   It is the region around a magnet in which its influence is felt. In can be measured interms of magnetic flux density.

3. **Magnetic flux density (or) Magnetic induction**

   Magnetic flux density at any point in a magnetic field is defined as the magnetic flux (Φ) passing normally through unit area of cross section (A) at that point. Its unit is weber / metre^2 *or tesla.* i.e., $B = \frac{\Phi}{A}$

4. **Magnetic dipole**

   System consisting of two equal and opposite magnetic poles separated by a small distance '2l' is called as magnetic dipole.

5. **Magnetic dipole moment**

   It is product of magnitude of pole strength and length of the magnet.

6. Magnetization

The process of converting a non – magnetic material into a magnetic material is called as magnetization.

7. Intensity of magnetization

Intensity of magnetization (I) is the measure of magnetization of a magnetized specimen. It can be defined as the magnetic moment(M) per unit volume (V=1)

$$I = \frac{M}{V}$$

weber / metre^3

8. Magnetic field intensity (or) strength (H)

It is defined as the force experienced by a unit north pole placed at a point in a magnetic field. Its unit is N / Wb or A turns / m.

9.Magnetic permeability or absolute permeability (μ)

It is defined ratio of the magnetic induction (B) inside the substance to the magnetizing field intensity (H). Magnetic permeability of a substance measures the degree to which it can be penetrated by a magnetic field.

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

10. Relative permeability (μ_r)

It is defined as the ratio between the absolute permeability (μ) to the permeability of the free space (μ_o).

i.e.,

$$\mu_r = \frac{\mu}{\mu_0}$$

It has no unit. For air and non-magnetic material $\mu_r = 1$.

11. Magnetic susceptibility (χ)

It is the measure of how easily a specimen can be magnetised in a magnetic field.

It is defined as the ratio of the intensity of magnetization (I) induced in it to the intensity of magentising field (H).

$$\chi = \frac{\mathrm{I}}{\mathrm{H}}$$

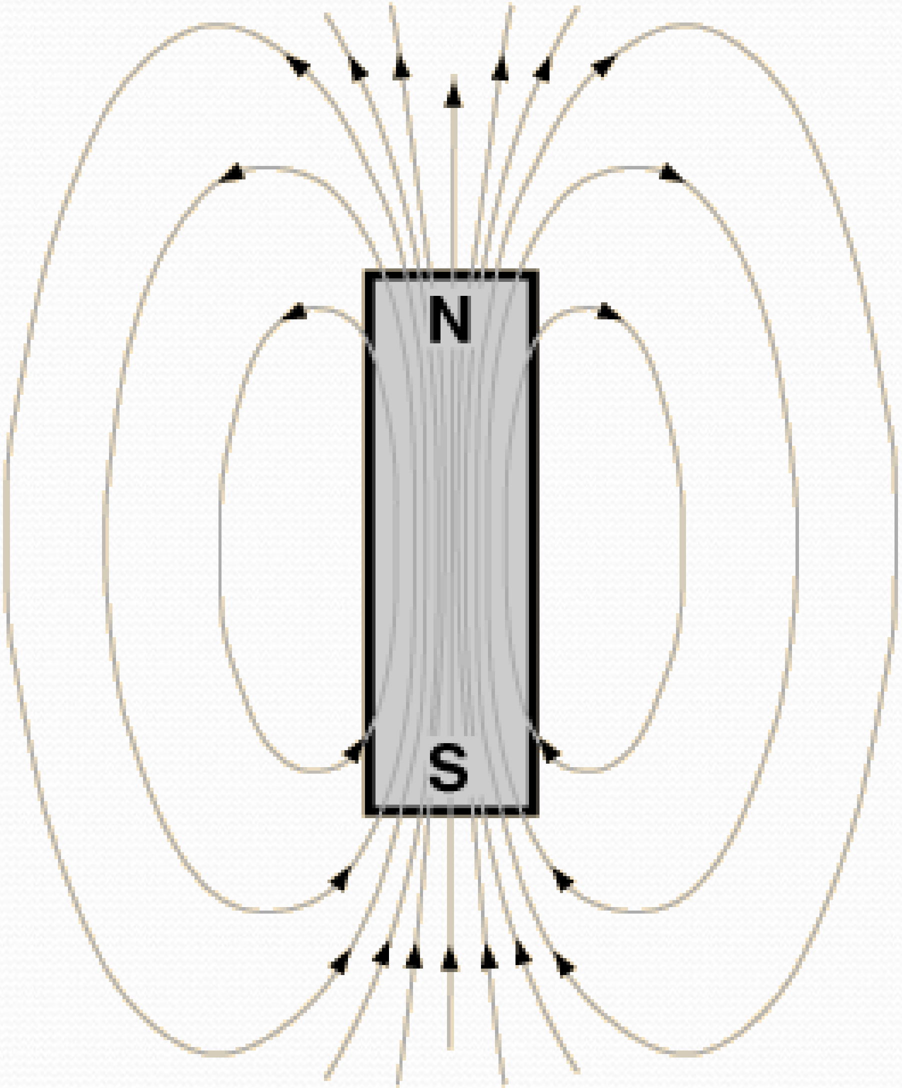
It is a dimensionless quantity and it is purely a number.

Magnetic Forces and Poles

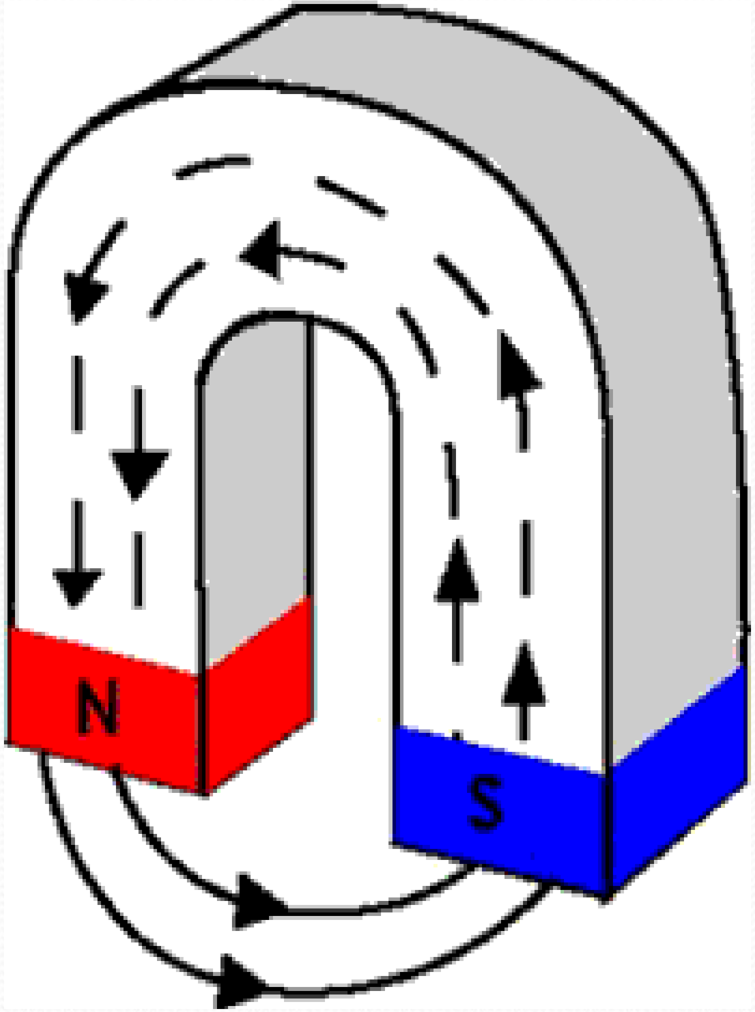
- Like the electrostatic force it can repel or attract
- “regions” of magnets called magnetic poles give rise to magnetic forces
- All magnets have both a north and south pole
- Like poles repel, opposite poles attract
- No magnetic monopoles exist in nature
- The space around a magnet is “altered”… the alteration is called a magnetic field
- Lines of force… always in closed loops

Bar magnet, Horseshoe magnet

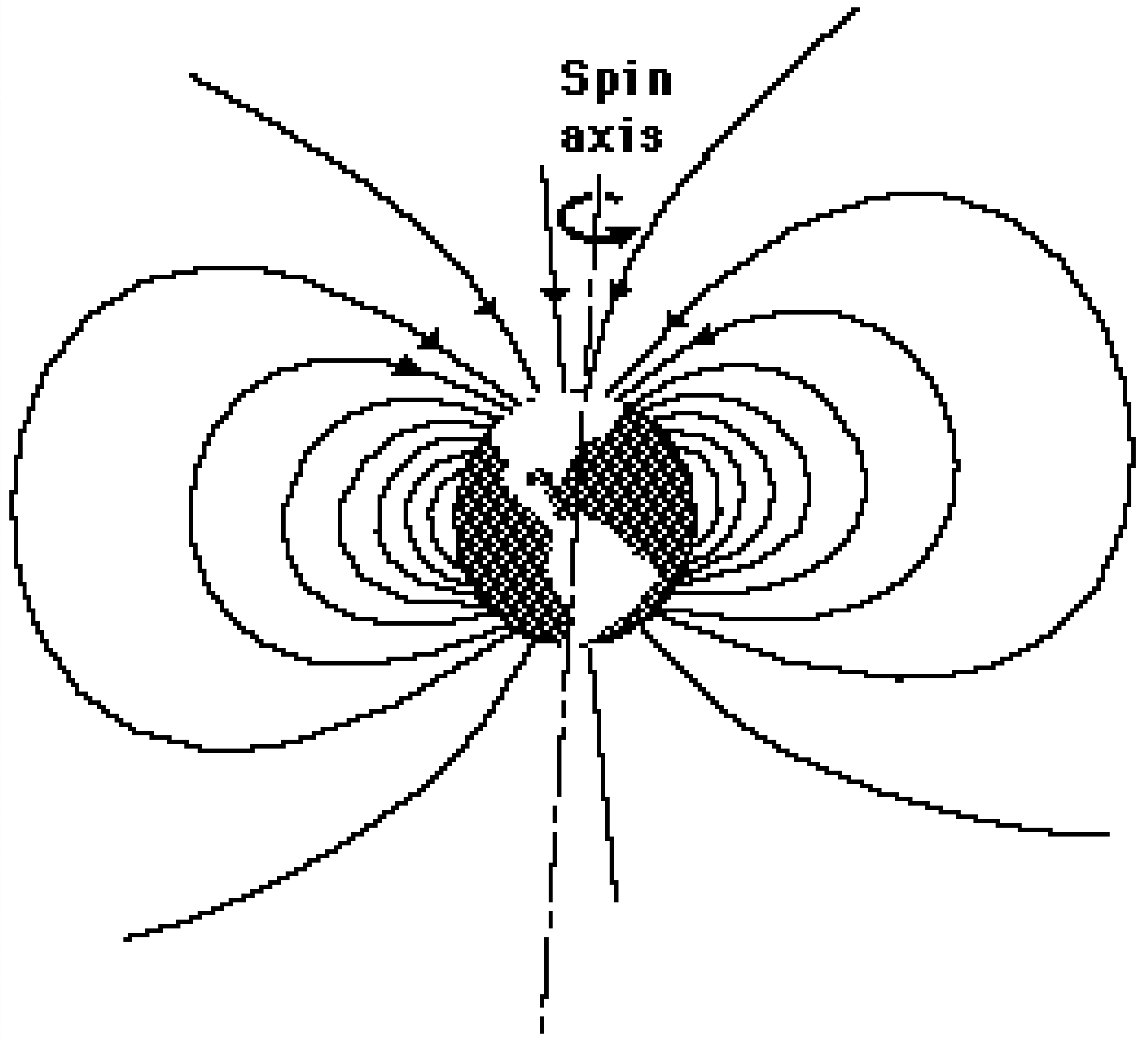
Magnetic Field of a Bar Magnet



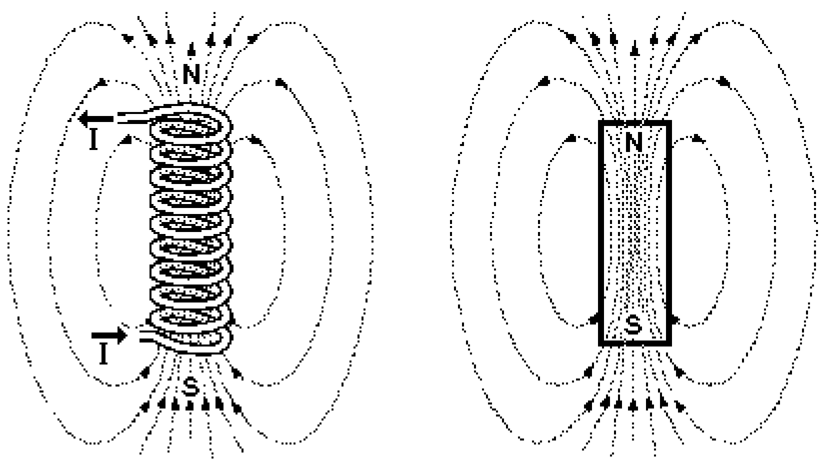
Magnetic Field of a Horseshoe Magnet



Earth has a magnetic field



Magnetic Field for a coil of wire called a solenoid



Origion of Magentic Moment

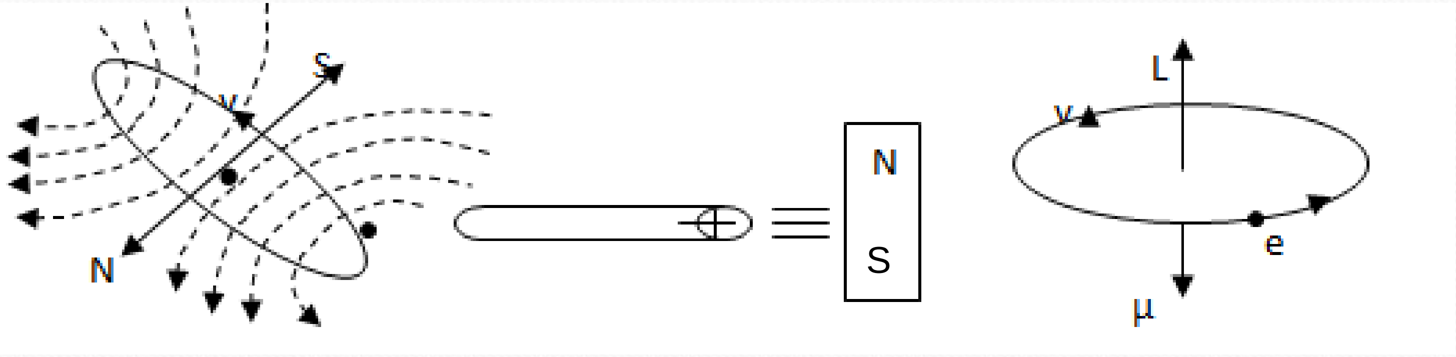
- All materials are basically composed of atoms.
- Magnetic materials is associated with the magnetic property of its constituent atoms.
- The magnetic dipole moment of an atom depends on

(a) The **orbital magnetic moment** due to the orbital motion of electrons around the nucleus and its magnitude is very small.

(b) The **spin magnetic moment** due to the spin motion of electrons about their own axes.

(c) The magentic moment due to the **nuclear spin**. Since this value it is not involved in calculation.

ORBITAL MAGNETIC MOMENT

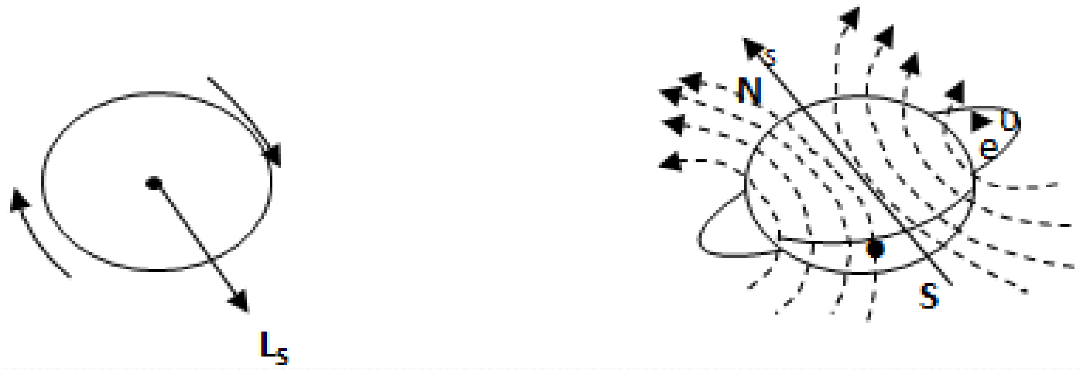


$$\mu_l = -\left(\frac{eL}{2m}\right)$$

Where $L = mvr$ is the orbital angular momentum of the electron.

An electron revolving about a nucleus is equivalent to a tiny current loop which produces a magnetic field perpendicular to the plane of the electron orbit

SPIN MAGNETIC MOMENT



$$\mu_e = \left(\frac{e}{m}\right)S$$

where S the spin angular momentum $= \frac{1}{2}\left(\frac{h}{2\pi}\right)$ = ħ / 2

Bohr Magneton

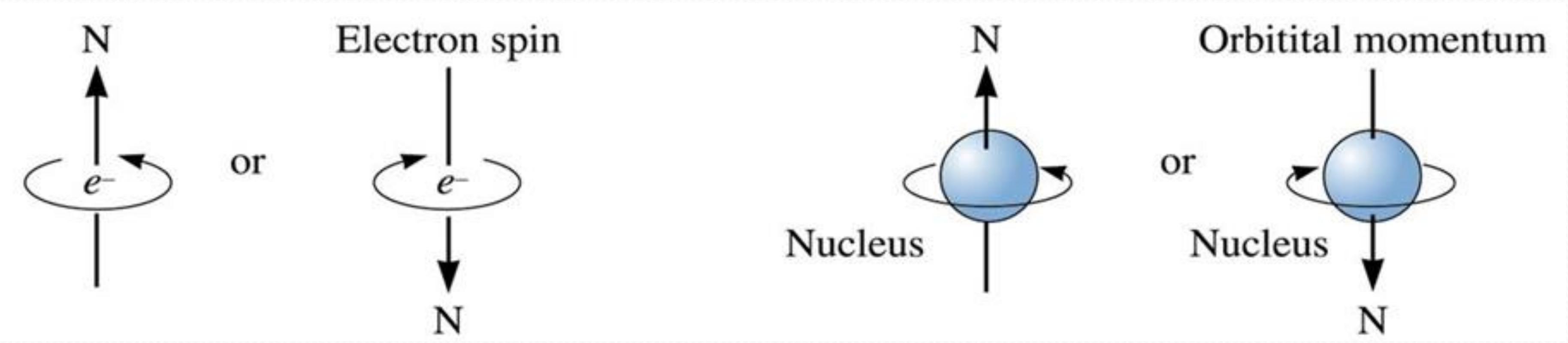
It is the elementary magnetic moment. i.e no electron can have a magnetic moment below μ_B*. It represents the minimum non-zero value of the projection of the magnetic moment of the electron in arbotrary directions.*

$$\mu_B = \frac{e\hbar}{2m} = \frac{eh}{4\pi m}$$

Quantum theory L=nh/2π

μ_B = 9.274 x 10^{-24} Am^2

- Bohr magneton - The strength of a magnetic moment of an electron ($\boldsymbol{\mu}_B$) due to electron spin.



Magnetic Materials

- Magnetic force is due to the motion of electric charges
- Magnetism is produced by two motions of electrons… their spin and their orbiting motion about the nucleus
- In many substances, magnetism produced cancels out
- In some materials… such cancellation does not occur… called Ferromagnetic materials such as iron, nickel, cobalt, and alloys e.g. alnico… an alloy of aluminum – nickel - cobalt

Diamagnetism

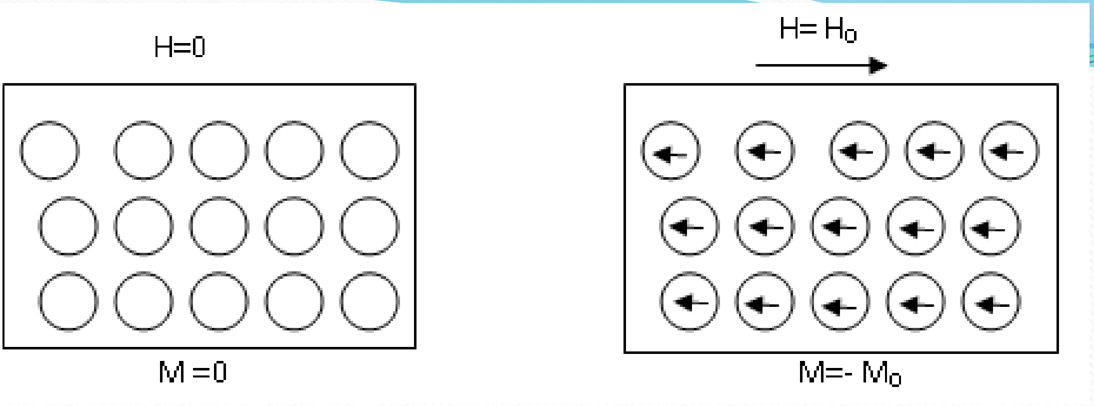
- *Diamagnetic materials are the magentic materials which have zero net magnetic moment per atom.*

  E.g. copper, silver, and gold,

- The meaning of term “diamagnetic” in Greek is “across magnetic”.

- When a short rod of diamagnetic material is placed in a magnetic field, it alligns itself at right angles to or across the direction of the magnetic lines of force.

- In the absence of an external field, the magnetic fields of the orbiting electrons balance each other and add up to zero.



- However, when placed in an external magnetic field, the current loops tends to align in a direction opposite to the applied field.

- This effect on atomic scale is similar to that due to Lenz's law induced magnetic fields tend to oppose the change which created them.

- This magnetic response called as diamagnetism. This present/ dominant in a material, it is called diamagnetic.

Properties

i) $\mu_r < 1$ for these materials.

ii) They have **negative value of magnetic susceptibility (10^{-6})** and it is independent of temperatrure.

iii) Since there is no permanent magnetic dipole moments, they are called as weak magnets.

iv) They are magnetised in a direction opposite to the external magnetizing field.

v) They repel the magnetic lines of forces. (Meissner Effect)

vi) Induced magnetic moment is proportional to the applied magnetic field.

vii)The induced dipoles and magnetization vanishes as soon as the applied field is removed.

viii) When temperature is less than critical temperature they become normal material.

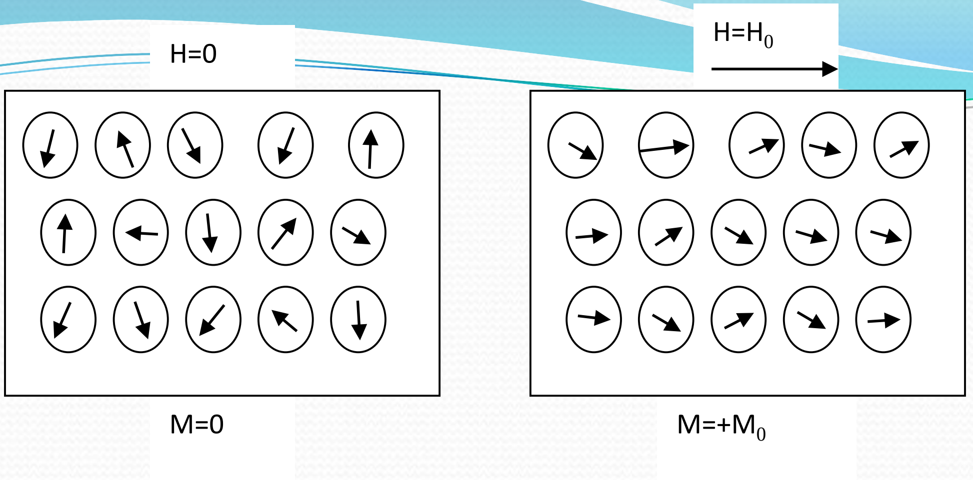
Exapmles ; Ge, Si, Ag, Hydrogen, Bi, Niobium etc..

Langevin’s theory

$$\chi = \frac{\mu_{ind}}{H} = -\frac{e^2 r^2 \mu_0 N}{6m}$$

Paramagnetism

- Materials with unpaired electron spins in the atomic/ molecular electron orbitals, have permanent magnetic dipoles even in the absence of an applied field.
- They are randomly oriented, do not interact with one another due to thermal agitation and net magnetic moment is zero.
- Paramagnetic materials are weakly attracted by magnetic fields.
- When a small rod of paramagnetic material is placed in a magnetic field, it aligns with or alongside the lines of force.



- The term paramagnetic is derived from a Greek word meaning "alongside magnetic".

- when a magnetic field is applied, dipoles tend to align with the applied field, hence the material has induced magnetization.

- When the magnetic field is removed, the dipoles relax back to their normal random motion, the net magnetic alignment is lost and magnetization vanishes.

Properties

Langevin's theory

$$\chi = \frac{\mu_m^2 \mu_0 N}{3kT}$$

i) $\mu_r > 1$ for these materials.

ii)They have **positive value** of magnetic susceptibility.

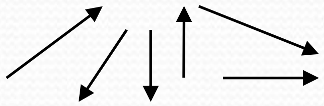
iii) Magnetic susceptibility is inversly proportional to the temperature.

Curie law: $\chi \alpha \frac{1}{T} \Rightarrow \chi = \frac{C}{T}$

where C-Curie constant; T-Asolute temperature; θ- Curie temperature

iv) They are magnetised along the direction of the external magnetizing field.

vi) They posses permanent magnetic dipole moments in random directions.



vii) Magnetic lines of forces can penetrate through these materials.

viii) When the temperature is than curie temperature, these materials become diamagnetic nature.

Ferromangnetism

- *The materials which exhibit ferromagnetism show permanent magnetic moment due to spin magnetic moments pointed in one direction even in the absence of magnetic field and give rise to the spontaneous magnetization.*

- Materials having unpaired electron spins line up parallel with each other due to quantum mechanical effect called the exchange interaction which is very much stronger than the dipole-dipole interaction.

- This is called as "spontaneous magnetization" since domains attain saturation magnetization in the absence of an external magnetic field.

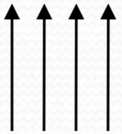
- When a small magnetic field is applied to these materials, the magnetic moments align themselves along the field direction and become strong magnets.

Properties

- $\mu_{r} >> 1$.
- They have positive and high susceptibility and it depends on temperature. It obeys **Curie-Weiss law.**

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

- Due to spin exchange interaction, it exhibits strong magnetization even in the absence of magnetic field.
- They have permanent dipole moment.
- Ferro magnetic materials consists of small spontaneously magnetized regions called domains.
- Ferromagnetic material become paramagnetic material if the temperature is greater than curie temperature.
- Magnetic moments of these materials are orderly oriented.

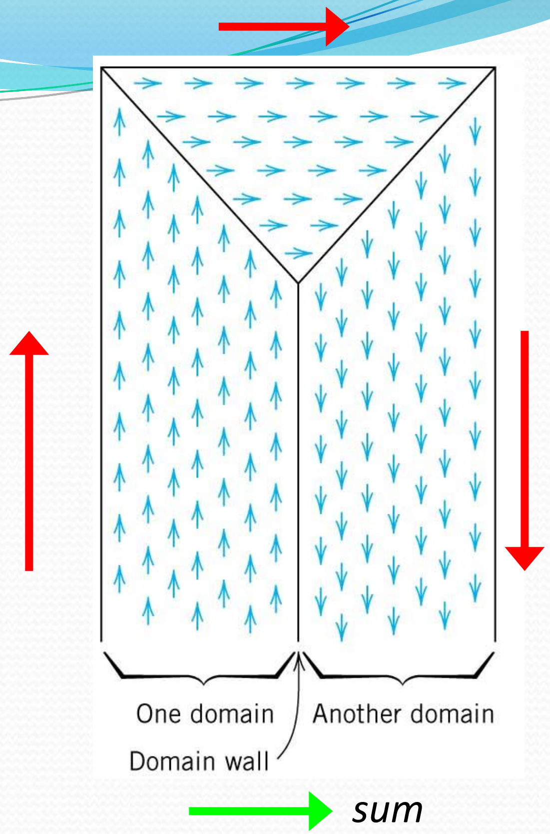


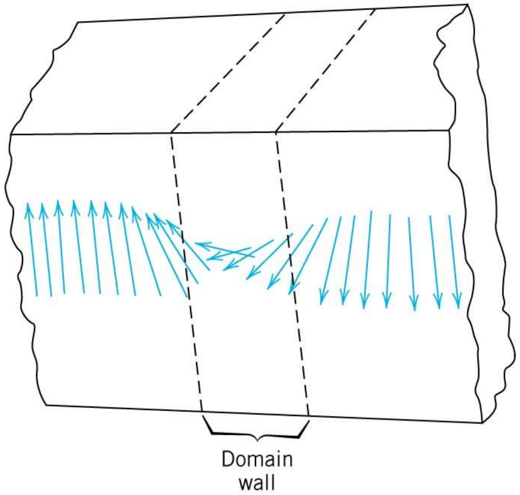
- They have hysteresis poperties.

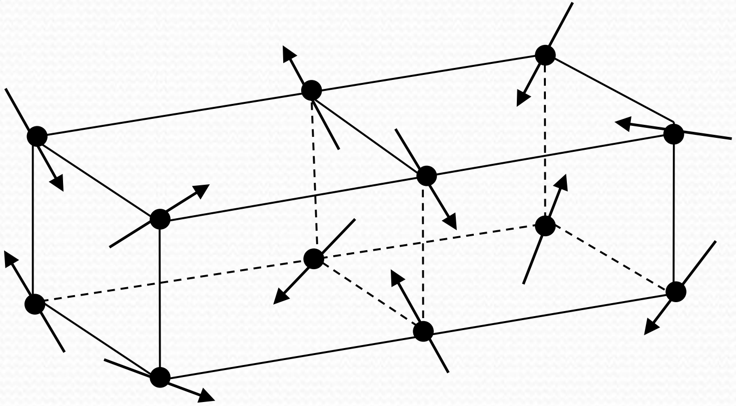
Examples: Fe, Co, Ni, etc…

Magnetic Domains

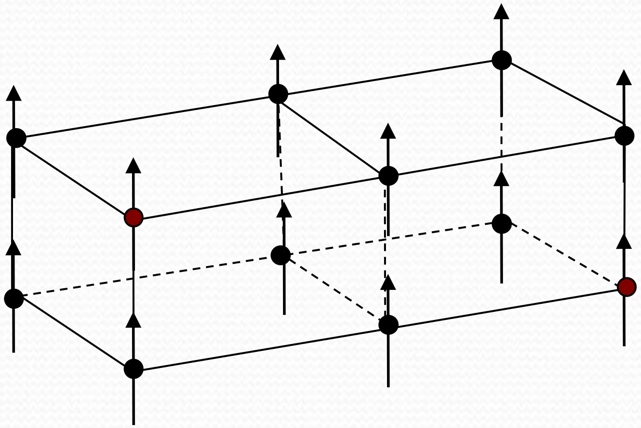
- Ferromagnet is comprised of many regions ("domains") with mutual alignment of the individual atomic magnetic dipole moments.
- These domains are not necessarily aligned with respect to each other.
- Domain walls between the domains are characterized by a gradual transition from one orientation to the next.
- The overall magnetization of the material (M) is the vector sum of the magnetization vectors for all of the individual domains.
- If not magnetized, the overall magnetization is simply zero.



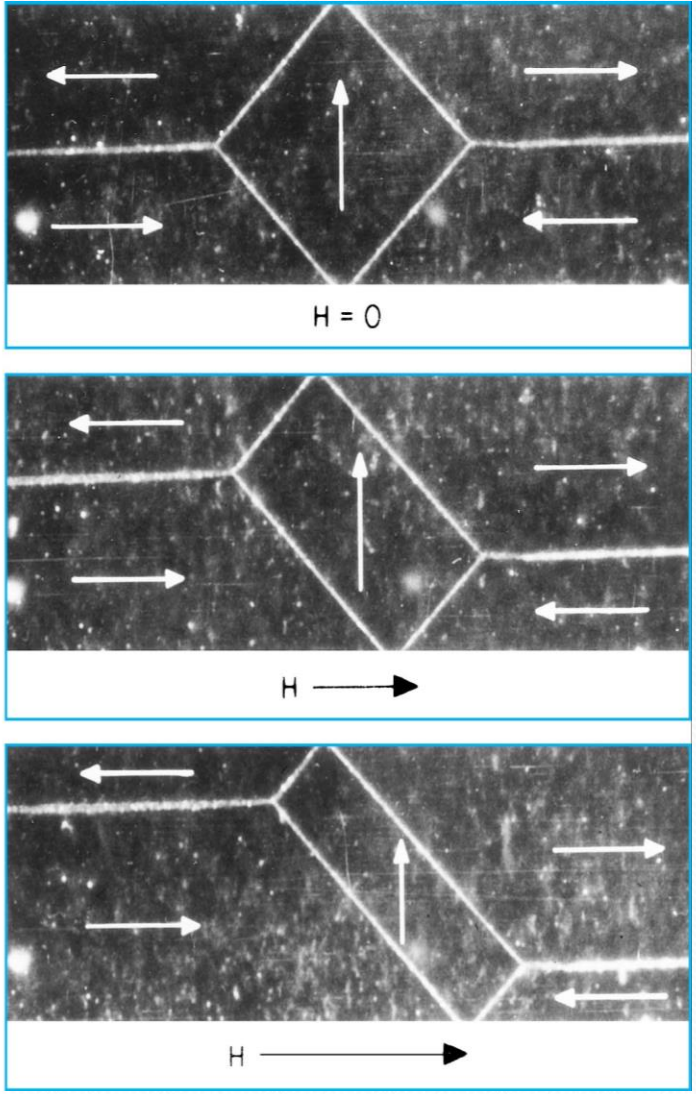




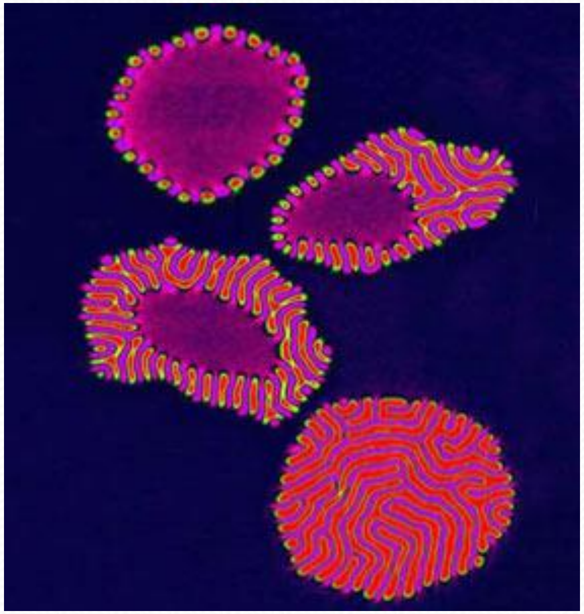
T> cuire temp



T < cuire temp

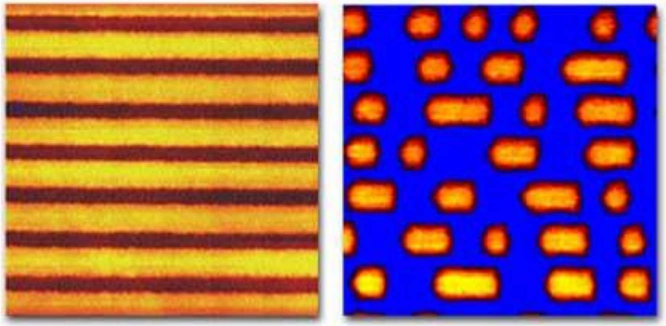


More magnetic domains



antiferromagnetically coupled
[Co/Pt/Ru] multilayer

terfenol

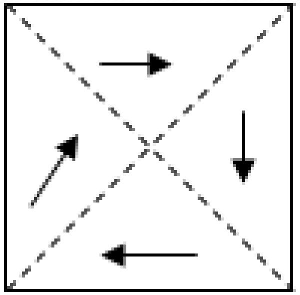


Magneto-optical: DVD-RW

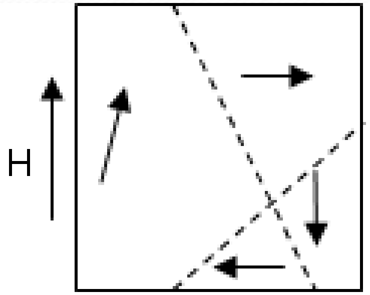
Process of Domain Magnetisation

(i) By the movement of domain walls

When a weak magnetic field is applied the domains which have the direction parallel or nearly parallel to the field, grow at the expense of other domains which are not parallel to the field



a) Without field

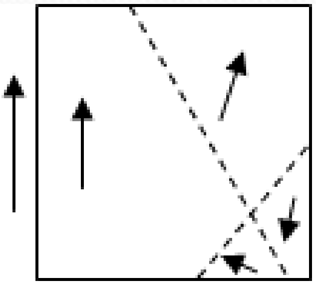


b) With field (weak)

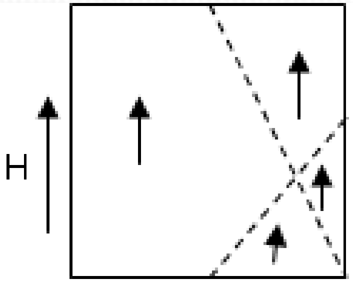
(ii) By rotation of domains

As the strong magnetic field is applied the rotation of the domain walls takes place.

When the field is very strong the direction of rotation of the domains will be towards the direction of the applied field.



c) With field (strong)



d) With field (very strong)

Domains theory of ferromagnetism

- Domains are formed to minimise the total energy of a ferromagnetic solid (theromodynamics)
- The total internal energy of the domain in a ferromagnetic material is the sum of the following energies.

a)Magnetostatic energy or magnetic field energy

or exchange energy

b)Crystalline energy or anisotropy energy

c)Domain wall energy or Bloch wall energy

d)Magnetistriction energy.

(i) Exchange energy

The interaction energy which makes the adjacent dipoles align themselves is known as the exchange energy or the magnetic field energy.

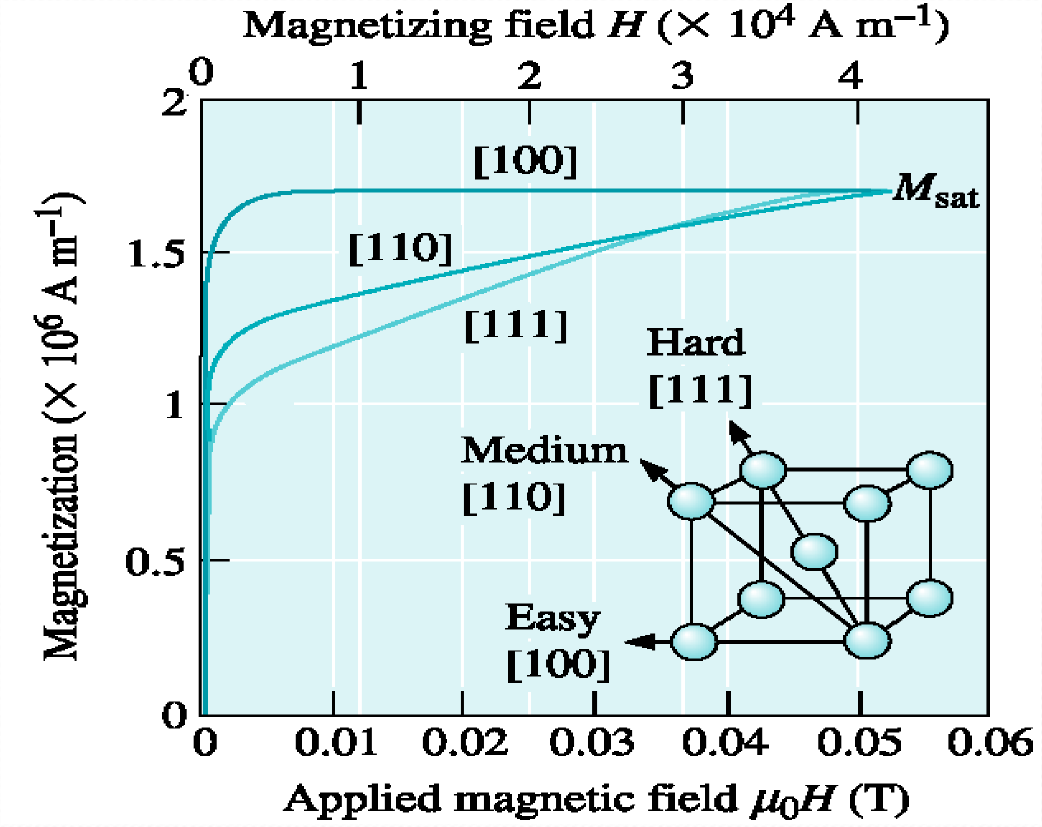
It arises from the interaction of electron spins and it depends upon the interatomic distance. In fact, this is the energy required in assembling the atomic magnets into single domain and this workdone is stored as potential energy.

(ii) Anisotropy energy

- There are two directions of magnetization namely easy direction and hard direction.

- In easy direction of magnetization, weak field can be applied and in hard direction of magnetization, strong field should be applied.

- *The excess energy required to magnetize a specimen and in particular direction over that required to magnetize it along the easy direction is called the crystalline anisotropy energy.*



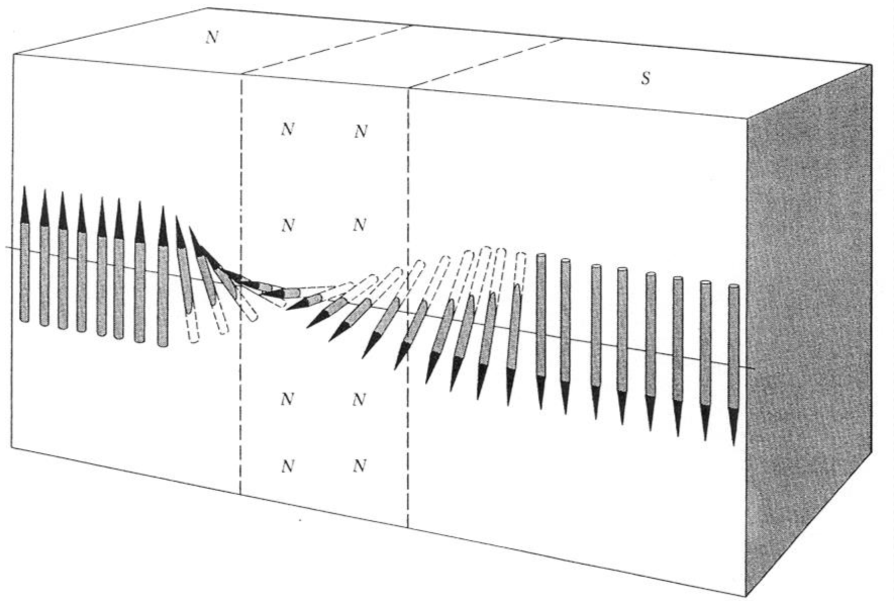
The initial magnetization curve for iron is highly anisotropic; magnetization is easiest when the $\langle 100 \rangle$ directions are aligned with the field and hardest along [111].

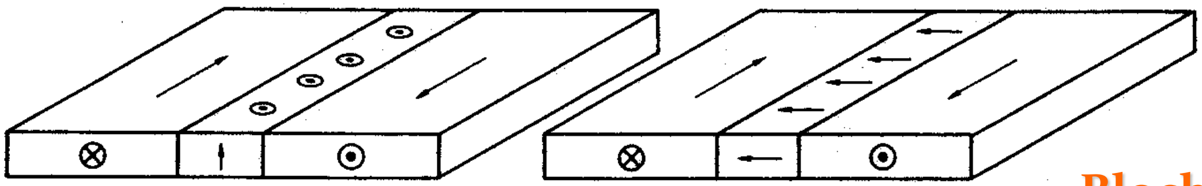
(iii) Domain wall energy or Block wall energy

- *A thin boundary line or region which separates adjacent domains magnetized in different directions is called domain wall or Bloch wall.*
- The size of the bloch walls are about 200 to 300 lattice constant thickness.
- In going from one domain to another domain, the electron spin changes gradually.
- the exchange energy is lower, when the change is gradual. But, the anisotropy energy is less only when spin change abruptly.

Domain Walls

Bloch Wall





Bloch wall

Néel wall

Bloch Wall and Nèel Wall

Figure 40 A Bloch wall and a Néel wall in a thin film. The magnetization in the Bloch wall is normal to the plane of the film and adds to the wall energy a demagnetization energy $\sim M_s^2 \delta d$ per unit length of wall, where δ is the wall thickness and d the film thickness. In the Néel wall the magnetization is parallel to the surface; the addition to the wall energy is negligible when $d \ll \delta$. The addition to the Néel wall energy when $d \gg \delta$ is the subject of Problem 7. (After S. Middelhoek.)

(iv) Magnetostriction energy

- *The change in the dimension of a ferromagnetic material when it is magnetized is known as magnetostriction.*

- The deformation is different along different crystal directions but it is independent of the direction of the field.

- The magnetostriction energy is the energy due to the mechanical stresses generated by domain rotation.

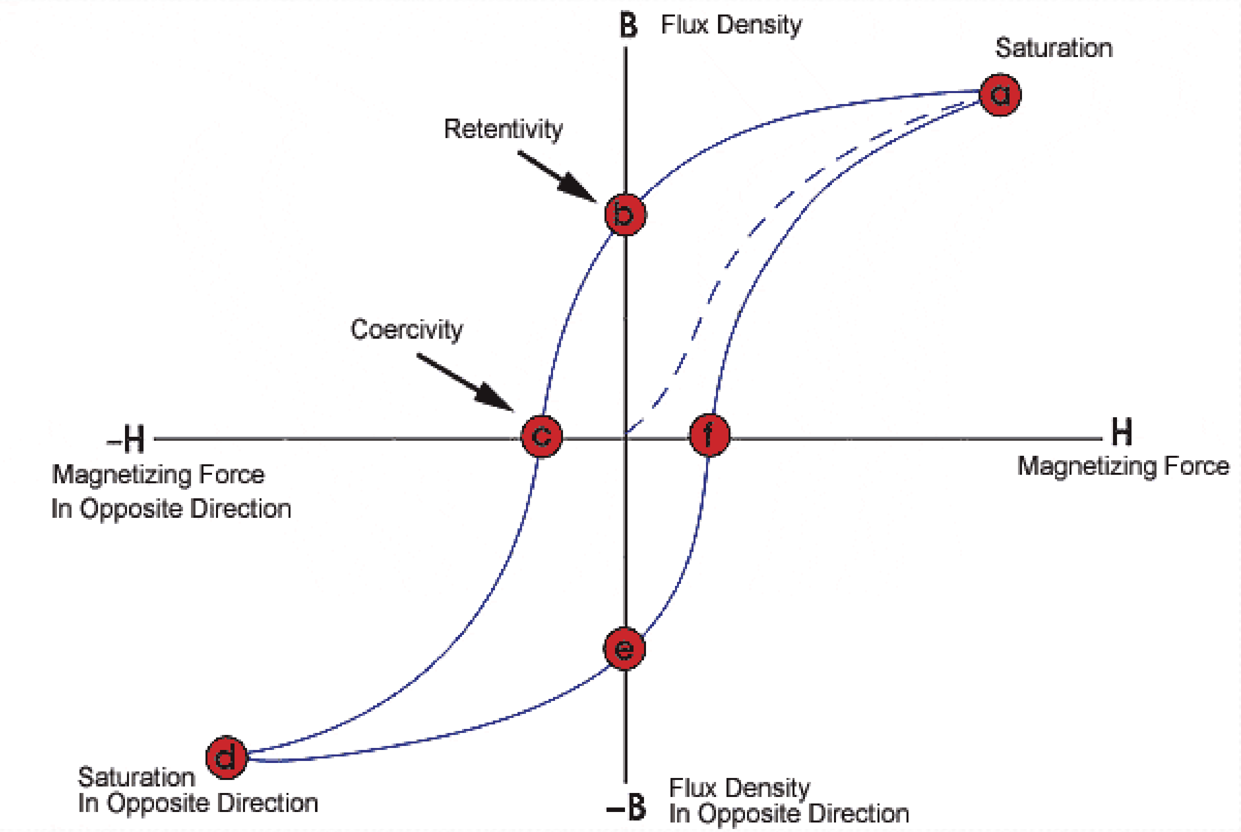
Hysteresis

- *When a ferromagnetic material is made to undergo through a cycle of magnetization, the variation of B with respect to H can be represented by a closed* ***hysteresis loop(or) curve.***

- *It refers to the lagging of magnetic filed behind the intensity of magnetic field applied.*

- A hysteresis loop is often referred to as the B-H loop.

- Once a magnetic material is saturated, decreasing H again does not return M (or B) to the same position. -**residual magnetism or Retentivity.**


B Flux Density
Saturation
a
Retentivity
b
Coercivity
c
f
–H
H
Magnetizing Force
In Opposite Direction
Magnetizing Force
e
d
Saturation
In Opposite Direction
–B
Flux Density
In Opposite Direction

- For no external magnetic field,
  - a **remanent induction (±B_r)** will remain.
  - Some domains remain aligned in the ‘old’ direction.

- A ‘negative’ field, the “**Coercive Field (±H_c)**,” must be applied to eliminate all B_r.
  - The opposite mechanism occurs for increasing the external field after total saturation in the reverse direction.

Hysteresis- Domain Theory