GANDAKI COLLEGE OF ENGINEERING AND SCIENCE

Chapter – 5: Magnetic Materials

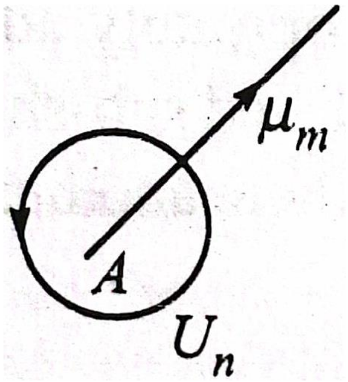
5.1 Ferromagnetism, Ferrimagnetism, Paramagnetism
5.2 Domain Structure, Hysteresis loop, Eddy Current losses, Soft magnetic materials
5.3 Fe – Si alloys, Ni – Fe alloys, Ferrites for high frequency transformers
5.4 Square loop materials for magnetic memory, Relaxation Oscillators, Hard magnetic materials such as carbon steels alnico and barium ferrites

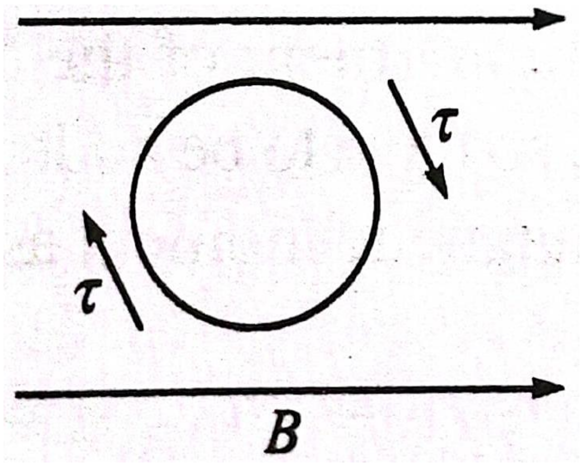
- Many **electrical engineering devices** such as inductors, transformers, rotating machines etc. are based on the **utilization of magnetic properties** of materials.
- To understand magnetic materials and magnetism properly, following must be made clear.
  - **Magnetic Dipole Moment**
  - **Magnetization Vector**
  - **Magnetizing Field or Magnetic Field Intensity**
  - **Magnetic Permeability and Susceptibility**

Magnetic Dipole Moment & Atomic Magnetic Moments

- In general for a coil, the **magnitude of dipole moment** is
  $\mu_m = NIA$; where N is the number of turns, I is the current, A is the cross sectional area

- When a **magnetic dipole is placed in a magnetic field**, it **experiences a torque** that tries **to rotate the magnetic moment** to **align its axis with the magnetic field.**





Magnetic Dipole Moment & Atomic Magnetic Moments

Magnetic Dipole Moment in atomic form:

- An **orbiting electron** in an atom behaves much **like a current loop** and **has a magnetic dipole moment** associated with it called **orbital magnetic moment, μ_{orb}**

$$\mu_{orb} = I(\pi r^2) = \frac{-e\omega r^2}{2}$$ (Since, N = 1 & $I =$ charge flow per unit time $= \frac{-e\omega}{2\pi}$)

- **Angular momentum** of electron is $L = m_e v r = (m_e \omega r) r = m_e \omega r^2$
  - $\omega r^2 = \frac{L}{m_e}$ Since **L is quantized** $L = l\hbar$ where l is the orbital quantum number.
  - So, **orbital magnetic moment is** $\mu_{orb} = \frac{-e}{2m_e} L$

Angular momentum in orbit → L

- The **intrinsic angular momentum** of electron **denoted by S** gives rise to
  - Since **S is quantized** $S = s\hbar$

spin magnetic moment $\mu_{spin} = \frac{-e}{m_e} S = -s\hbar \frac{e}{2m_e}$

Intrinsic Angular momentum →S

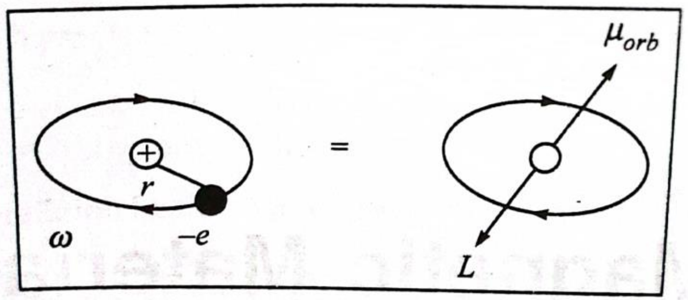
- The **overall magnetic moment** of the electron **consists of μ_{orb} and μ_{spin} appropriately added** (both are vector quantities).

Magnetization Vector (M)

- The **magnetic field inside the solenoid with free space inside** is B_0 given by

$$\boldsymbol{B_0 = \mu_0 nI}$$

where n is number of turns per unit length,
I is current through the solenoid,
$\mu_0$is absolute permeability of free space= $4\pi \times 10^{-7}\frac{H}{m}$,
$I'$is current per unit length



An orbiting electron is equivalent to a magnetic dipole moment m_{orb}

- If a **cylindrical material is placed inside** the solenoid, the magnetic field will be **changed from $\mathbf{B_0}$ to B.**
- Each atom of the material **responds to the applied field** and **develops a net magnetic moment $\boldsymbol{\mu_m}$ along the applied field.**
- The medium **gets magnetized**, **Magnetization vector M** describes the **extent of magnetization** of the medium.
- **Magnetization vector M** is defined as **magnetic dipole moment per unit volume.**

$$\boldsymbol{M = \frac{1}{V}\sum_{i=1}^{N}\mu_{mi} = n_{atomic}\mu_{av};}$$

where n_{atomic}= number of atoms per unit volume,
μ_{av}= average magnetic dipole moment per atom.

Magnetizing Field, Magnetic Field Intensity

- The field inside the magnetized material is the **sum of the applied field H** and **a contribution from the magnetization M** at the material.
- **Magnetizing field H is the cause** and **magnetic field B is its effect**.
- H solely depends upon **external conduction currents** only whereas the **magnetic field B** depends on the **magnetization capability of the material.**

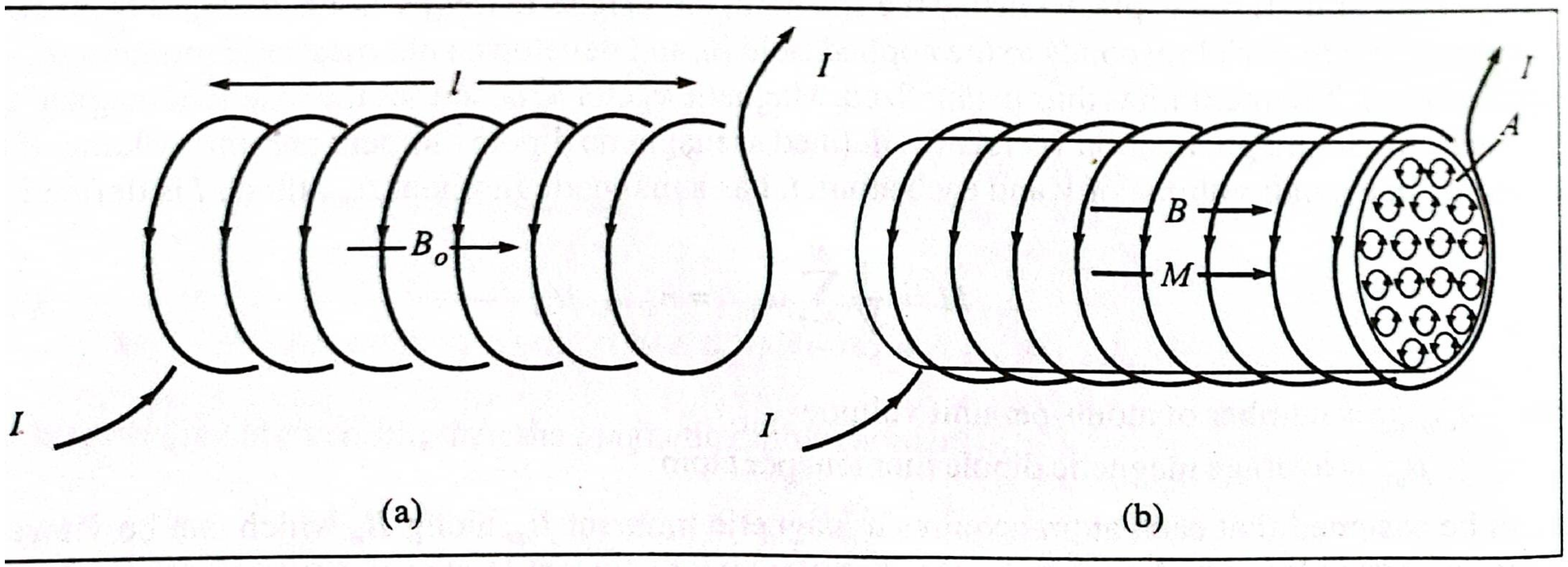


Fig. 5.4 Magnetic field of a solenoid with and without medium.

Magnetic Permeability and Susceptibility

- The **magnetic permeability** of the medium at any point is defined as the **magnetic field per unit magnetizing field**

$$\mu = \frac{B}{H};$$ μ represents to what extent a medium is permeable by a magnetic field.

- **Relative permeability** of the medium is defined as the **fractional increase in the magnetic field with respect to the magnetic field in free space** when a material medium is introduced.

$$\mu_r = \frac{B}{B_0} = \frac{B}{\mu_0 H}$$
$$\mu = \mu_0 \mu_r;$$

μ is absolute permeability,
μ_r is relative permeability,
μ_0 is absolute permeability of the free space $= 4\pi \times 10^{-7}\frac{H}{m}$

- The **magnetization M** produced in the material depends on the **net magnetic field B**.
- **Magnetization M** is related to **magnetizing field H** as $M = \chi_m H$; χ_m **is magnetic susceptibility**
- Now, $B = B_0 + \mu_0 M$

$$B = \mu_0 \mathrm{H}\ (\text{due to vacuum}) + \mu_0 M (\textit{due to material})$$
$$B = \mu_0 \mathrm{H} + \mu_0 \chi_m H$$
$$B = (1 + \chi_m)\mu_0 H$$
$$B = \mu_r \mu_0 H; \text{ where } \mu_r = (1 + \chi_m)$$

This expression relates the relative permeability with magnetic susceptibility of the material.

Ferromagnetism

- Ferromagnetic materials can possess **large permanent magnetization even in the absence of an applied field.**
- The **magnetic susceptibility is positive** and **very large** and **depends on the applied field intensity.**
- The **relationship** between **magnetization M** and $\mu_0\mathrm{H}$ is **highly non – linear.**
- At **sufficiently high fields**, **magnetization saturates.**
- The ferromagnetic crystal has **magnetic moments** of all crystal **aligned in an orderly manner** so as to give rise to the **net magnetization vector M.**

- Ferromagnetism **occurs below a critical temperature T_c** called Curie temperature.

- At temperature **above this, ferromagnetism is lost.**

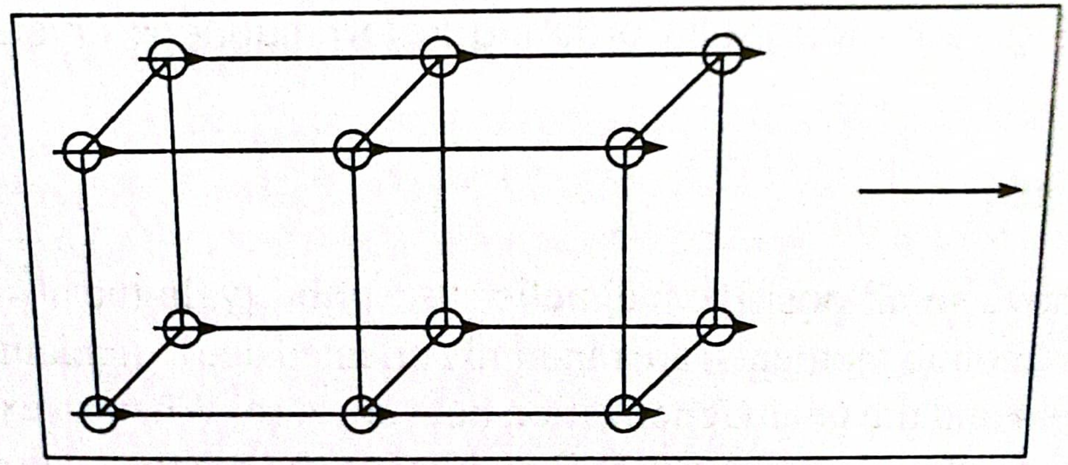
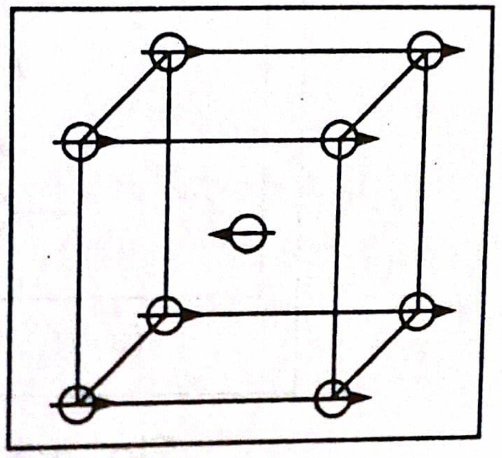


Fig. 5.5 Magnetized region of Ferromagnetic material

Anti-ferromagnetism

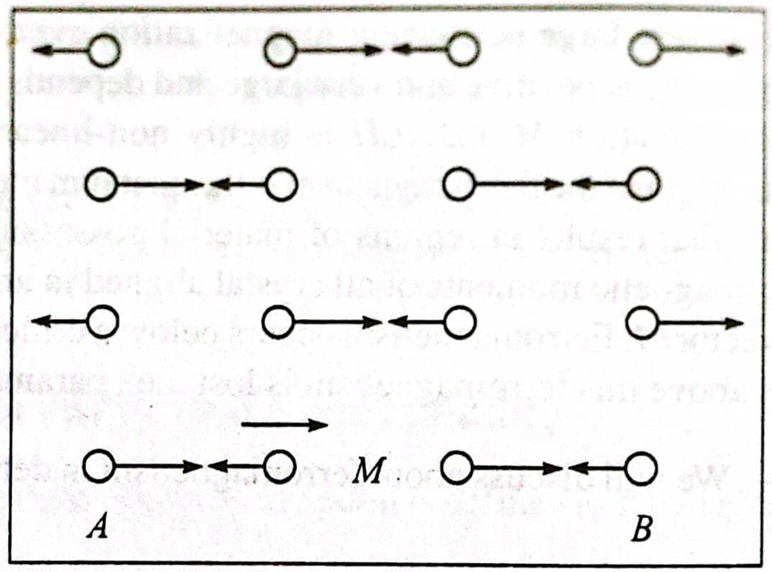
- Antiferromagnetism materials have **small positive susceptibility.**
- In the **absence of external field,** there is **not net magnetization** of the material.
- They possess magnetic ordering in which the **magnetic moments** on **alternating atoms in the crystals align in opposite directions** → due to quantum mechanical exchange interaction.
- **Occurs below a critical temperature called Néel temperature.** **Above this they are paramagnetic.**
- These substances are **freely magnetized when subjected to a strong magnetic field.**
- Example: MnO, FeO, CoO, NiO, FeCl_3MnO_4, Cr, Mn, MnS etc



Antiferromagnetic crystal (Cr)

Ferrimagnetism

- Ferrimagnetic materials exhibit **magnetic behavior similar to ferromagnetism below a critical temperature** called Curie temperature.
- As shown in the figure, **all atoms A** have their **spins aligned in one direction** and **all atoms B** have their **spins aligned in opposite direction.**
- **Magnetic moment of atom A is greater than that of atom B** because of which there will be **net magnetization in the crystal even in the absence of external applied field.**
- These materials are **non- conducting**, so they **do not suffer from eddy current losses.**
- This is the reason for these materials being **used in high frequency electronic applications.**
- These materials are generally known as **ferrites** and represented by XFe_3O_4 , where $X = Mg, Cu, Mn, Ni, Zn, Cd\ etc.$



. 5.7 Magnetic ordering in ferrimagnetic crystal

Paramagnetism

- Paramagnetic materials have **small positive magnetic susceptibility.**
- In the **absence of external magnetic field**, **molecular moments (atomic moments) are randomly oriented** due to random collision of molecules.
- So, the **average dipole moment and the net magnetization both are zero.**
- When an **external field is applied**, μ_{av} does not equal zero and **depends upon the applied field** $\boldsymbol{\mu_0}\mathbf{H}$ and hence the **magnetization is also non – zero** and is **equal to $\boldsymbol{\chi_m H}$.**
- **Magnetization increase with $\boldsymbol{\mu_0}\mathbf{H}$** but **decreases with increase in temperature.**
- At **higher temperature**, the **molecular collisions destroy the alignment of molecular magnetic moments** with applied field i.e. Curie law is obeyed.
- When they are **placed in a non- uniform magnetic field**, the induced magnetization is along the **direction of B and there is a net force toward greater field.**
- Many **gases and metals** are paramagnetic. E.g. Pt, Al, Cr, Mn and dilute solutions of ferromagnetic materials.

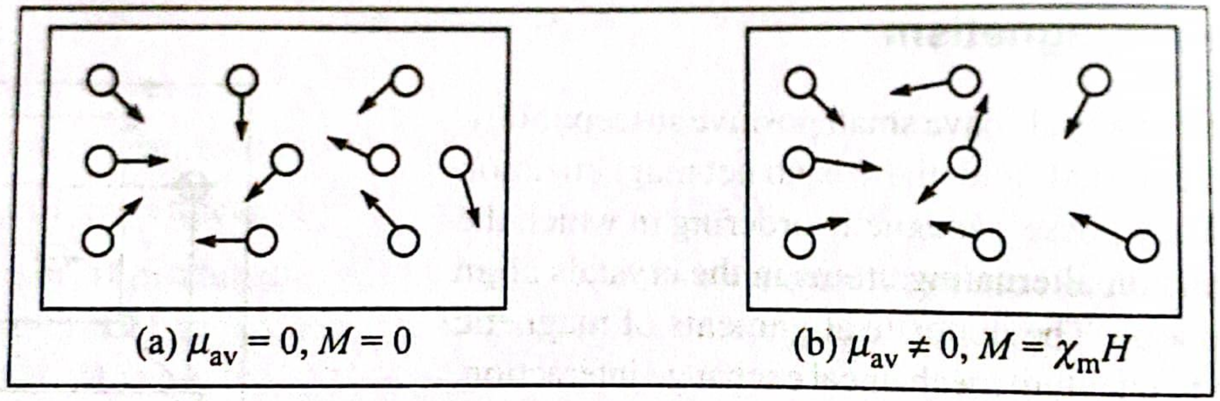


Fig. 5.8 Without external field (a), with external field (b)

Diamagnetism

- Materials with **negative magnetic susceptibility** are termed as diamagnetic substances.
- **Relative permeability is slightly less than unity**.
- When placed **in magnetic field**, the **magnetization vector M is in opposite direction to the applied field** → causing **magnetic field within the material to be less than the applied field.**
- **Negative susceptibility** → these substances **trying to expel the applied field** from within the material.
- **Covalent crystals and many ionic crystals** are diamagnetic because the constituent atoms **have no unfilled sub-shell.**
- **Superconductors are perfect diamagnet** with $\chi_m = -\mathbf{1}$ and **totally expel the applied field**.
- Other examples are Bi, Sb, Au, Cu, Hg, water, air, alkali halides, organic materials, many polymers, covalent solids like Si, Ge, diamond etc.
- The average value of **magnetic susceptibility** of diamagnetic materials is in the range of $-\mathbf{10^{-6}}$

Domain Structure / Domain Theory of Ferromagnetism

- A **magnetic domain** is **a region of the crystal** in which **all the spin magnetic moments are aligned to produce a magnet in one direction only.**
- Figure alongside shows a single crystal of iron that has a **permanent magnetization.**
- There is **a potential energy stored** in a magnetic field called **magnetostatic energy** which can be reduced **in the external field by dividing the crystal** into **two domains** where **the magnetizations are in opposite directions.**
- Thus, there is **a boundary between the two domains** where the **magnetization changes from one direction to the opposite** direction called as **Domain wall or Bloch wall.**

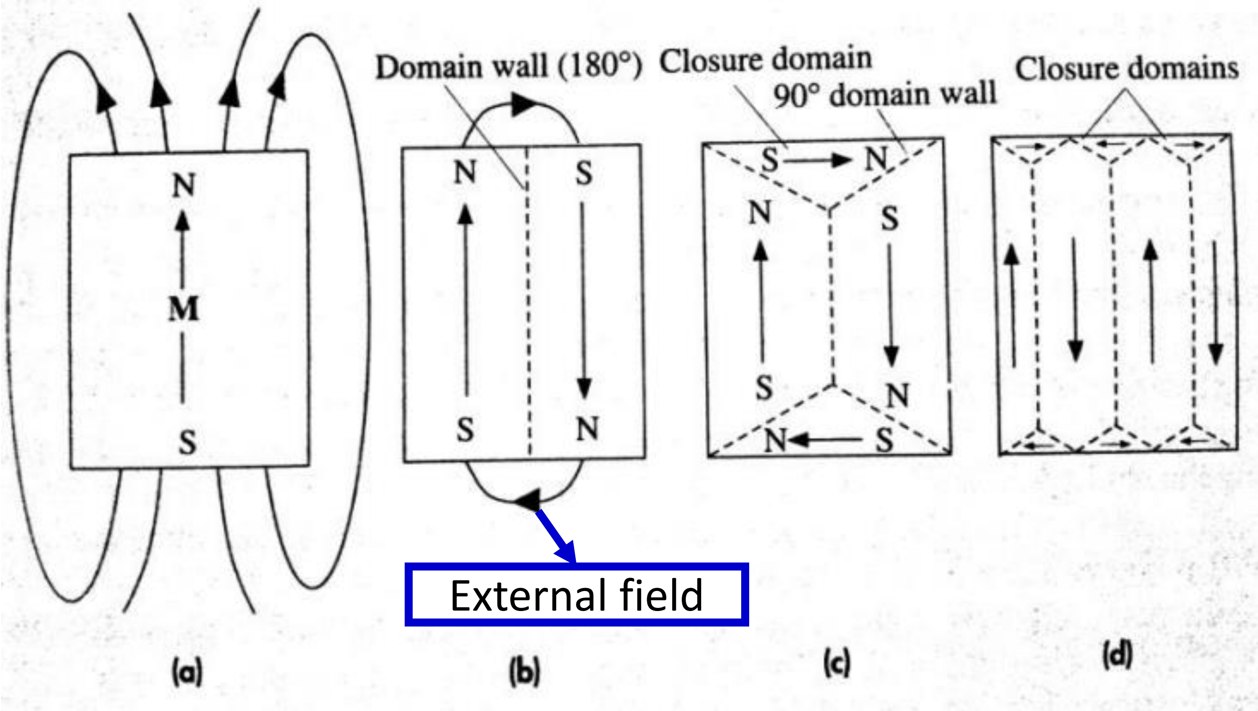


Figure:- creation of magnetic domain

Domain Structure / Domain Theory of Ferromagnetism

- The **magnetostatic energy** can be **further reduced** by eliminating these external field lines by **closing the ends with sideway domains (Closure domain)** *with magnetization at 90°.*
- **Forming domains reduces magnetostatic energy** but **potential energy in the walls increases due to addition of walls.**
- Thus, **creation of magnetic domains continues until the magnetostatic energy reduction** by addition of domains is **balanced by increase in potential energy** in the walls **due to addition of walls.**
- In this condition, there is **minimum potential energy with no net magnetization.**

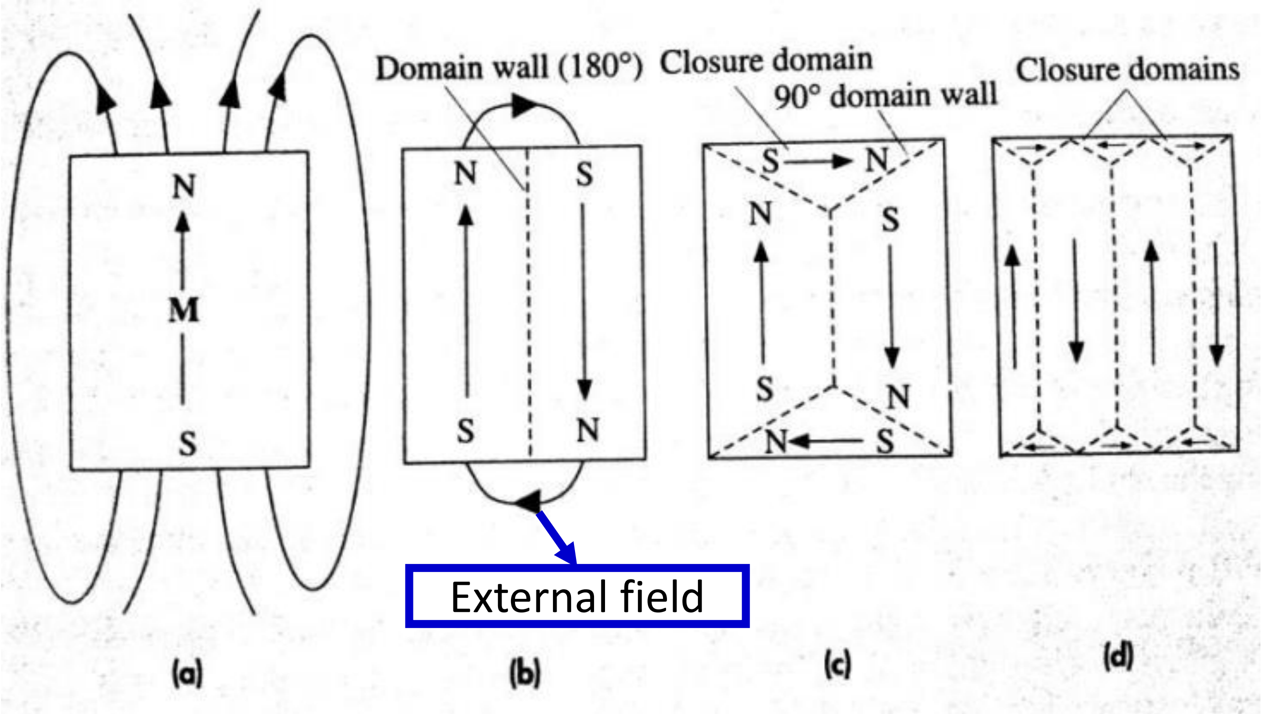


Figure:- creation of magnetic domain

Domain Structure / Domain Theory of Ferromagnetism

- When we apply **an external magnetic field** to the crystal with domains as in the figure, the **magnetization of crystal along the field occurs**, in principle, **by the growth of domains with magnetization along the field 'H'**.
- i.e. the **wall** between domain A and domain B **migrates towards right enlarging domain A and shrinking domain B** which is **caused by spins in the wall**, and also spins in region B adjacent to the wall.

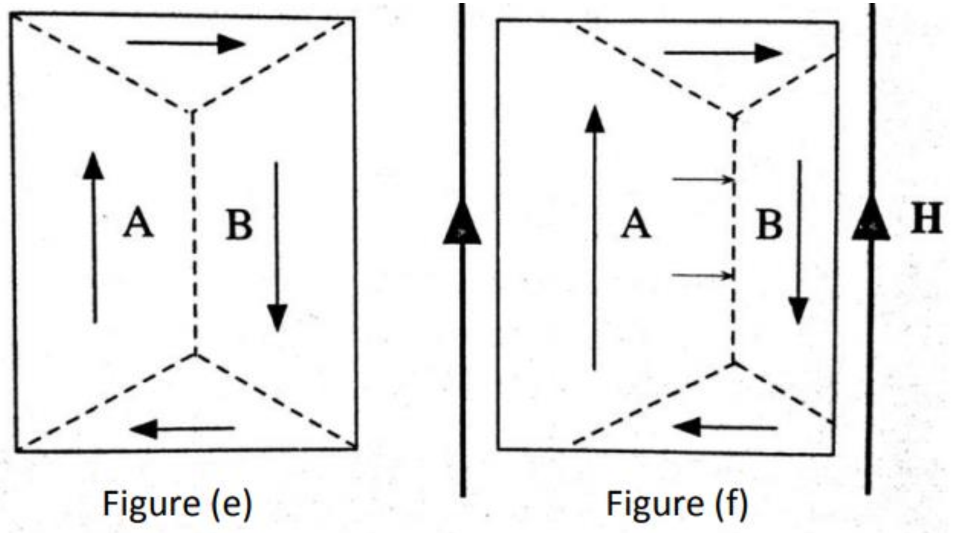
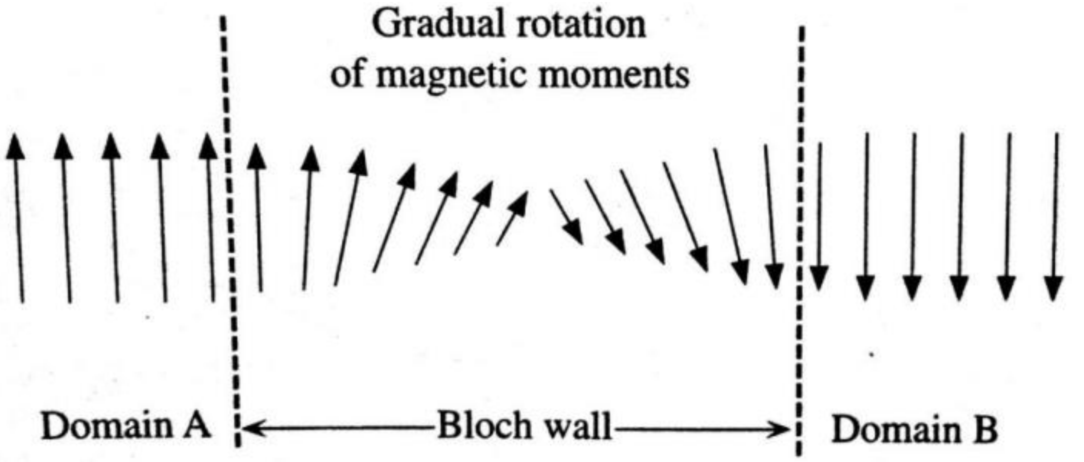


Figure:- Domain Wall Motion

- Gradually rotated by the applied field in the direction of field. The **magnetization process involves the motions of wall** which is called **Domain Wall Motion.**
- **The Domain Wall is not simply one atomic spacing wide.**

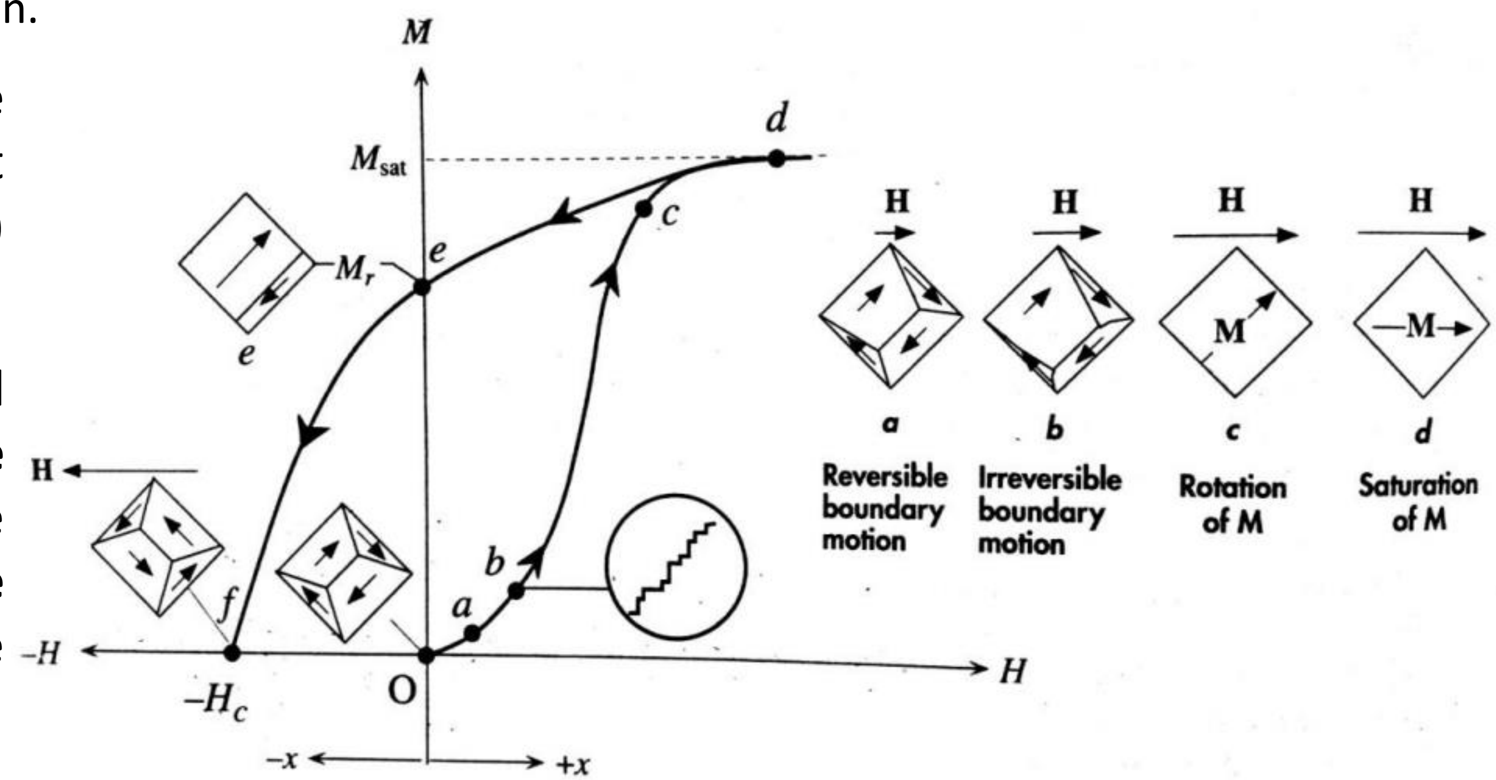


Losses in magnetic materials

- When **magnetic materials are subjected to changing magnetic field (flux), two types of losses occur** which are:
  - **Eddy current loss**
  - **Hysteresis loss**
- **Eddy Current Loss:**
  - Eddy currents **are loops of electric currents induced within materials by a changing magnetic field** because of **Faraday's laws of induction.**
  - Eddy current flow in closed path **perpendicular to the applied magnetic field.**
  - Eddy current **creates its own magnetic field that oppose the magnetic field that created it**, following Lenz' Law.
  - Eddy currents **generate resistive losses** that transform some form of energy to heat which **reduces efficiency of iron - core of transformers and electric motors and other devices** that use changing magnetic field.
  - Eddy currents are **minimized in these devices by selecting magnetic core materials that have low electrical conductivity** (e.g. Ferrites) or by **using thin sheet of core forming laminations.**

Hysteresis Loop and loss

- **The complete M versus H curve obtained by changing magnetizing field (H) from positive x to negative x for corresponding values of magnetization is a closed loop called as hysteresis loop.**
- When an **external magnetic field 'H' is applied to an unmagnetized iron** sample,
  - at **start there is very small net magnetization**
  - as the value of **'H' is increased**, the **domain motion extend to larger shapes** encountering various obstacles such as crystal imperfections, impurities and so on.
- Sudden changes in magnetization induce eddy currents (circulating current) that dissipate energy via joule heating (I^2R) called **eddy current losses.**
- As we go on **increasing the external magnetic field**, **eventually a single domain is created** and further increase in field, **causes M to align in the direction of H** and then the sample reaches saturation magnetization M_{sat}



Hysteresis Loop and loss

- Now, if the **magnetizing force is reduced** then **magnetization** of iron sample **decreases**
- Even when the **magnetizing force is reduced to zero, induced magnetization does not reduced to zero**
- Some residual remains called as **residual magnetization (M_r),** also called as **retentivity**. This is useful in a magnetic memory device.
- If magnetizing **field is applied** in the **reverse direction**, **magnetization** of the sample **decreases** and at a certain value, **magnetization 'M' becomes zero.**
- The magnetizing field **required to totally demagnetize** the sample is called **coercive field H_c**, also called as **coercivity**.

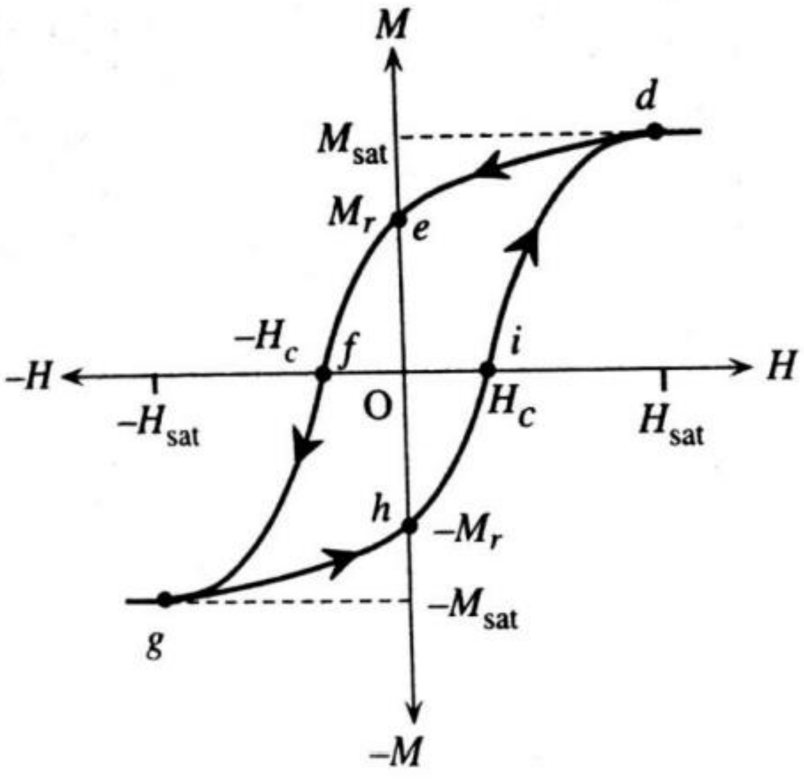


Figure (a): M - H hysteresis curve

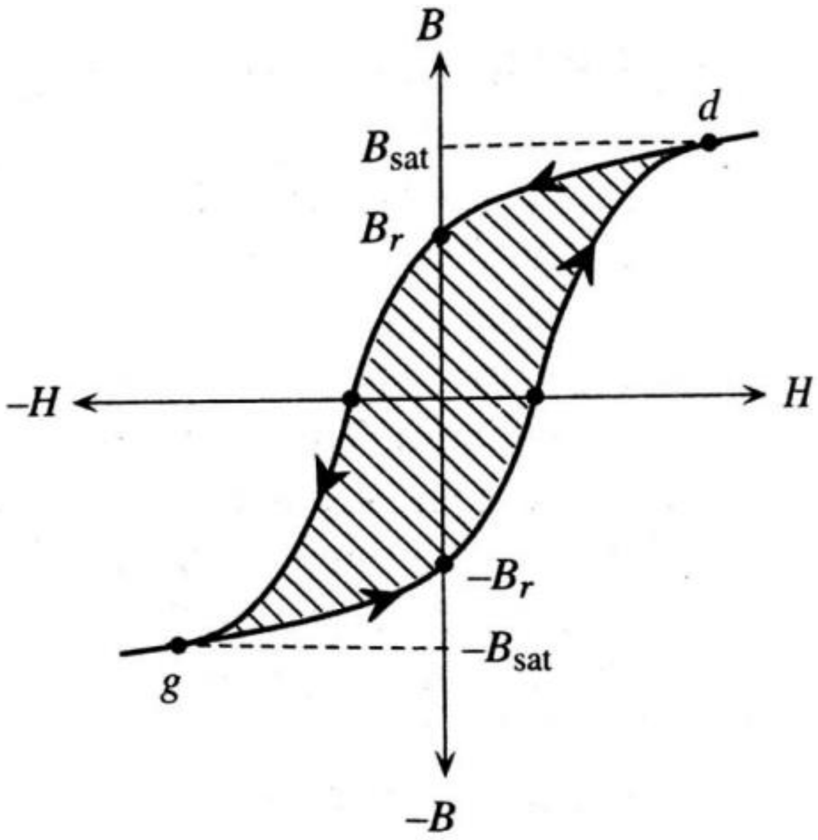


Figure (b): corresponding B - H hysteresis curve

Hysteresis Loop and loss

- If the demagnetization is further **increased in reverse direction**, the process from point e will be similar to that when **magnetizing the sample in reverse direction.**
- Point g represents **saturation magnetization $-M_{sat}$ in reverse direction.**
- Decreasing the magnetizing field from $-H_{sat}$ **to zero** again **leaves residual magnetization.**
- **To eliminate** this we need to apply **magnetizing field in reverse direction.**
- The **energy** dissipated during **magnetization & demagnetization** process is given by the **area of hysteresis loop.**

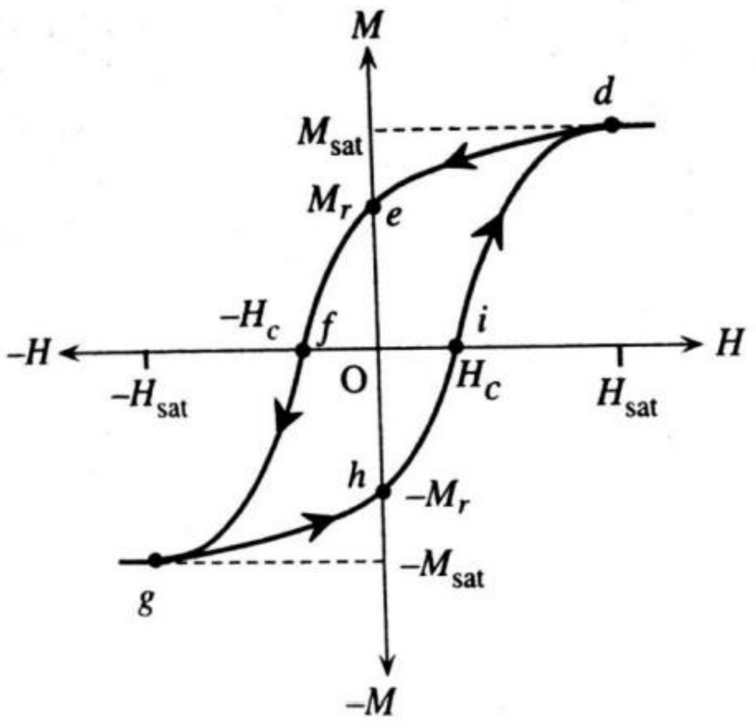


Figure (a): M - H hysteresis curve

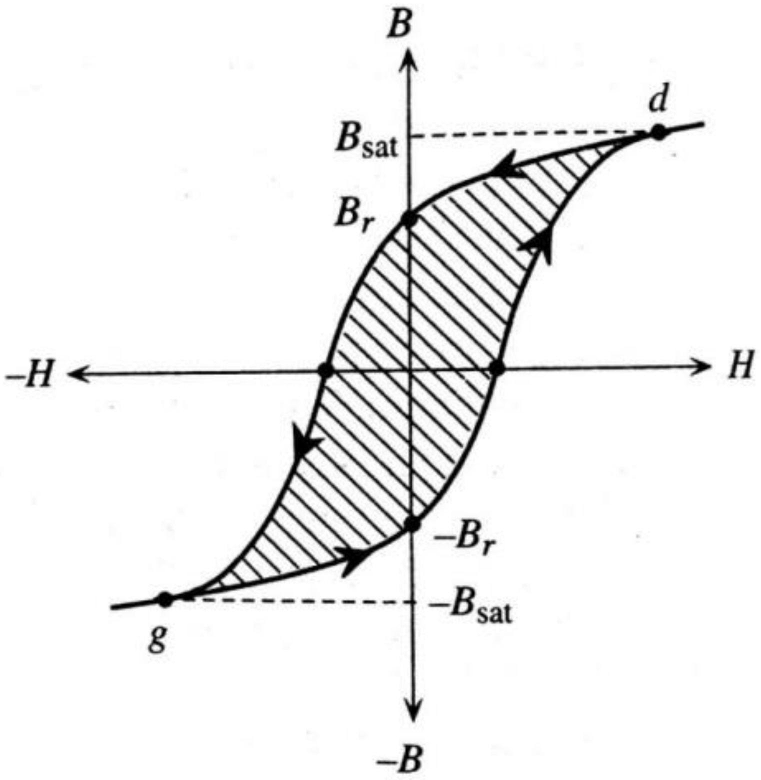
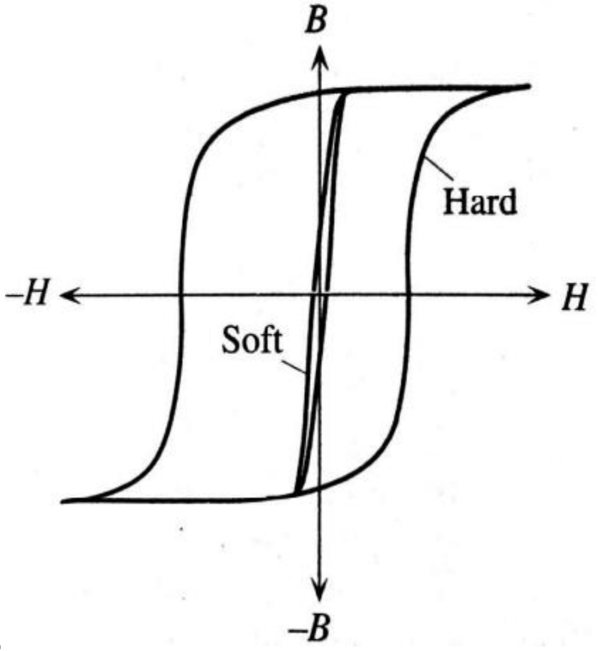


Figure (b): corresponding B - H hysteresis curve

Soft Magnetic material

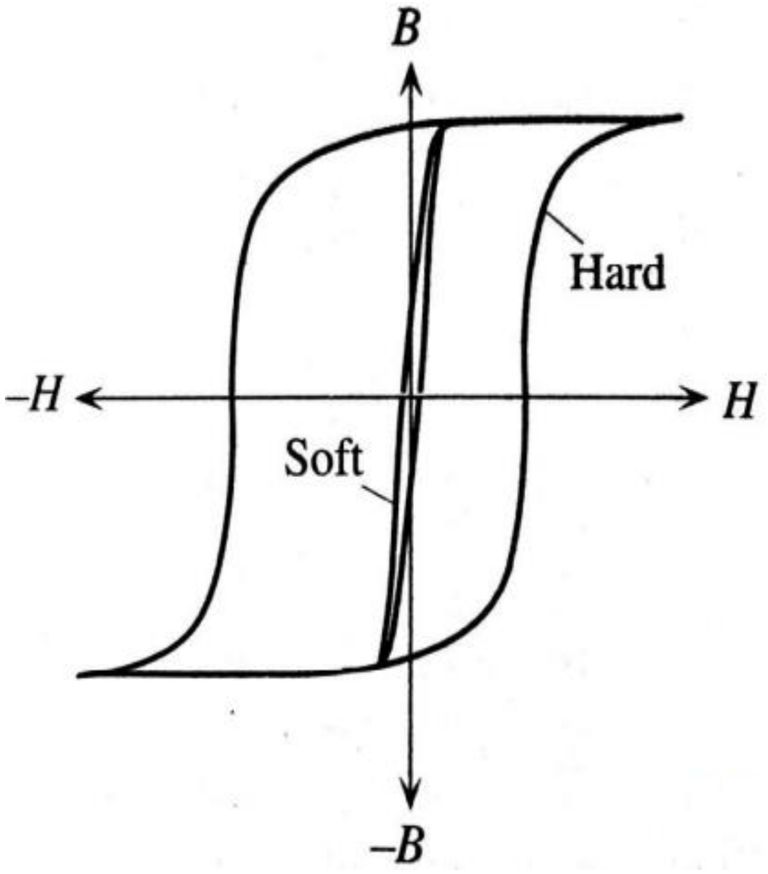
- That magnetic material which can be **easily magnetized and demagnetized** is called **soft magnetic material.**
- These materials have
  - **very low value of coercivity**,
  - **very large saturation magnetization (M_{sat})**
  - **small hysteresis area.**
  - **Ideally zero coercivity**,
  - **zero retentivity**
  - **very large saturation magnetization.**



- Their **B-H curve has small area**, so the **power loss per unit cycle is small.**
- Thus, **suitable** for applications where **repeated cycles of magnetization and demagnetization are involved.**
- Examples: electric motors, transformers, inductor having varying field, electromagnetic relay.

Hard Magnetic materials

- That magnetic material which is **difficult to magnetized and demagnetized** is called hard magnetic material.
- These materials have
  - **very large coercivity,**
  - **very large saturation magnetization (M_{sat})**
  - **large hysteresis area**.
- The **coercive field** for hard magnetic materials is **millions of times greater than those for soft magnetic materials.**
- Their **B-H curve is broad** and almost rectangular in shape, so the **power loss per unit cycle is high.**
- They are **useful for making permanent magnets and in magnetic storage of digital data.**



Fe – Si alloys, Ni –Fe alloys

- **Pure iron (Fe)** despite being **soft magnetic material** is **not normally used** as magnetic material because its **conductivity allows large eddy currents** to be induced under varying fields.
- By adding **(2 – 4%) of Silicon to Iron, Silicon Steel** is obtained which is still **soft magnetic material** with **increased resistivity but reduced eddy current loss.**
- Mostly **used in manufacture of transformers and other electrical machineries** for alternating current applications.
- Similarly, **Nickel – Iron alloys** with composition around **77% Ni and 23% Fe** constitute a soft magnetic material with **low coercivity, low hysteresis loss and high initial and maximum relative permeabilities.**
  - **High initial relative permeability** useful **in low magnetic field applications** that are typically found in **high frequency works** in electronics like audio and wide band transformers. More applications on: sensitive relays, current transformers, magnetic recording heads, magnetic shielding etc.
- Alloying Iron with Nickel **increases resistivity and hence reduces the eddy current losses** in the machinery.
- The **domain wall motions are easy in Nickel composition** resulting **smaller hysteresis losses** in the material.
- There are number of commercial Ni – Fe alloys whose application **depends on exact composition** (which may also have a few percentages of Mo, Cr, Cu, etc) **and method of preparation** (e.g. mechanical rolling).

Ferrites for high frequency transformers

- Ferrites are ferromagnetic materials which are **typically oxides of mixed transition metals**, one of which is iron.
- **Ferrites are ferromagnetic materials**, normally **insulators**, so **do not suffer from eddy current losses** (very high resistance allows only very small current and hence very small or no losses) → thus **suitable for high frequency applications**
- Ferrites can have **high initial permeabilities and low losses**, but they **do not possess large saturation magnetization** like that in ferromagnets.
- There are **many types of ferrites** available **depending on the application, tolerable losses and required upper frequency of operation.**
  - **Manganese Zinc Ferrites** have **high initial relative permeability** of 2000 but are only useful up to 1 MHz.
  - **Nickel Zinc Ferrites** have **lower initial relative permeability** of 200 but they can be used up to a frequency of 200 MHz.
  - **Garnets** are ferrimagnetic materials, used at **highest frequencies** covering the microwave range (1 – 300 GHz). Yttrium Iron Garnet YIG ($Y_3\ Fe_5O_{12}$)
    - one of the simplest garnets with **very low hysteresis loss at microwave frequencies.**
    - Have **excellent dielectric properties with high resistivities and consequently low losses.**
    - Main disadvantage of garnets is the **low saturation magnetization and low Curie temperature.**
- The **initial relative permeability** in the high frequency region **decreases with increase in frequency.**

Square Loop Magnetic Materials

- Materials having **very high coercivities** are termed as square loop magnetic materials because of **the B-H loop imitating the square shape.**
- To **store any information in the form of digitalized data**, these materials are most suited.
- Uses different patterns of magnetization in a magnetizable material to store data and is a form **of non –volatile memory**
- The **magnetic surface** is conceptually **divided into many small sub-mm sized magnetic regions**, referred as **magnetic domains**. Information is stored on these domains.
- Have **high (BH)max values, used in stepper motors, servomotors, gyroscope**
- The only **drawback** of these materials are **lower Curie temperature** compared to other magnetic materials.

Selected soft magnetic materials (E_h is hysteresis loss i.e. energy dissipated per unit volume per cycle, J/m^3 at $B_m = 1\,T$)

Magnetic Material	$\mu_0 H_c$, T	B_{sat}, T	B_r, T	μ_{ri}	μ_{rmax}	E_h, Jm^{-3}	Applications
Ideal soft iron	0	Large	0	Large	Large	0	Transformer cores, inductors, magnetic recording heads, relays, electromagnet cores, machines
Iron (commercial grade, 0.2% impuriries	$<10^{-4}$	2.2	<0.1	150	10^4	250	Due to large eddy current losses used only in some electmagnets and relays
Silicon Iron (2-4% Si)	$<10^{-4}$	2	0.5-1	1000	10000 - 400000	30 - 100	Wide range of ac machinery

Selected soft magnetic materials (E_h is hysteresis loss i.e. energy dissipated per unit volume per cycle, J/m^3 at $B_m = 1\ T$)

Supermalloy (79%Ni, 15%Fe, 5%Mo, 0.5%Mn)	2×10^{-7}	0.7–0.8	<0.1	10^5	10^6	<0.5	High permeability low loss electrical devices, e.g. speciality transformers, magnetic amplifier
Permalloy (78.5%Ni, 21.5%Fe)	5×10^{-6}	0.86	<0.1	8000	10^5	<0.1	Low loss electrical devices, audio transformers, HF transformers, recording heads, filters
Glassy metals (Fe – Si – B)	2×10^{-6}	1.6	$<10^{-6}$	–	10^5	20	Low loss transformer cores
Ferrites Mn- Zn ferrite	10^{-5}	0.4	<0.01	2000	5000	<0.01	HF low loss applications. HF transformers, recording heads, inductors (E and U cores)

Néel temperature (T_N) and paramagnetic Curie temperature (θ_c) for some anti-ferrimagnetic materials

Material	T_N, K	θ_c, K
MnF_2	72	113
MnO_2	84	316
MnO	122	610
MnS	165	528
FeO	198	570
NiF_2	73	116
CoO	292	280

Table 5.5 Susceptibility of some diamagnetic materials

Material	$\chi = \mu_r - 1, \times 10^{-5}$	Material	$\chi = \mu_r - 1, \times 10^{-5}$
Al_2O_3	-0.5	Cu	-0.9
$BaCl_2$	-2.0	Au	-3.6
NaCl	-1.2	Ge	-0.8
Diamond	-2.1	Si	-0.3
Graphite	-12	Se	-1.7

Occurrence of permanent atomic magnetic dipoles and interaction between neighboring dipoles

Type of material	*Permanent dipoles*	*Interaction between neighboring dipoles*
Paramagnetic	Yes	Negligible
Ferromagnetic	Yes	Parallel orientation
Antiferrimagnetic	Yes	Antiparallel orientation of equal moments
Ferrimagnetic	Yes	Antiparallel orientation of unequal moments

Table 5.3 Susceptibilities of some paramagnetic materials at 300K

Substance	$\chi = \mu_r - 1, \times 10^{-3}$	*Substance*	$\chi = \mu_r - 1, \times 10^{-3}$
$CrCl_2$	1.5	Fe_2O_3	1.4
Cr_2O_3	1.7	$Fe_2(SO_4)_3$	2.2
CoO	5.8	$FeCl_2$	3.7
$CoSO_4$	2.0	$FeSO_4$	2.8
$MnSO_4$	3.6	$NiSO_4$	1.2