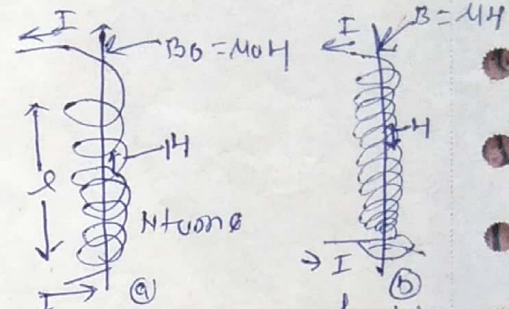# Magnetic Materials

Magnetic field Vector :— The externally applied magnetic field, sometimes called the magnetic field strength, is designated by H. If the magnetic field is generated by means of a cylindrical coil (or solenoid) consisting of N closely spaced turns, having length l, and carrying a current of magnitude I, then

$$H = \frac{NI}{l} \qquad —①$$

unit of H ampere/meter

Magnetic induction, or magnetic flux density, denoted by B, represents the magnitude of the internal field strength within a substance that is subjected to an H field. The unit of B is teslas (webers/square meter (Wb/m²)). Both B and H are field vectors, being characterized not only by magnitude. The magnetic field strength and flux density are related.

$$B = \mu H \qquad —②$$

unit of μ = weber/ampere-meter $\left(Wb/A\text{-}m\right)$ or 1

in vacuum,

$$B_0 = \mu_0 H \qquad —③$$

Where μ_0 is the permeability of a vacuum, which has a value of $4\pi \times 10^{-7}$ H/m.

ie

$$\mu_r = \frac{\mu}{\mu_0} \qquad —④$$

μ_r is relative permeability, which is unit less. A M is called the magnetization .

$$B = \mu_0 H + \mu_0 M \qquad —⑤$$

ie $\qquad M = \chi_m H$

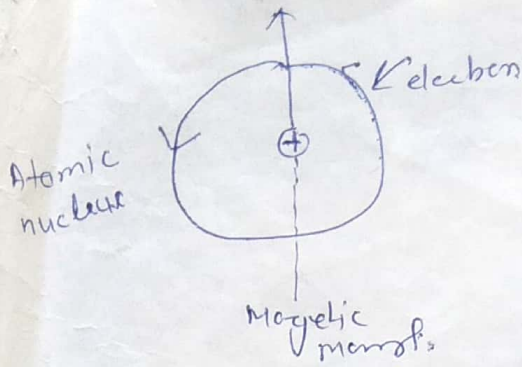χ_m is called the magnetic susceptibility, which is unit less.

ie $\qquad \chi_m = \mu_r - 1 \qquad —⑥$

Table

Quantity	Symbol	SI Unit		cgs-emu Unit	Conversion
		Derived	Primary		
				gauss ←	$1 \, wb/m^2 = 10^4 \, gauss$
Magnetic Induction (Flux density)	B	Tesla (wb/m^2)	$kg/s-c$		$1 \, amp-turn/m =$ $4\pi \times 10^{-3} \, oersted.$
Magnetic field strength	H	am-turn/m	$c/m-s$	oersted	$1 \, amp-turn/m = 10^{-3}$ maxwell$/cm^2$
Magnetization	M (SI) I (cgs-emu)	amb-turn/m	$kg-m/c^2$	maxwell$/cm^2$	
Permeability of a vacuum	μ_0	henry/m	$kg-m/c^2$	unit less (emu)	$4\pi \times 10^{-7}$ henry/m $= 1 \, emu$
Relative Permea-bility	μ_r (SI) μ' (cgs-emu)	Unit less	"	"	$\mu_r = \mu'$
Susceptibility	χ_m (SI) χ_m' (cgs-emu)	Unit less	"	"	$\chi_m = 4\pi \chi_m'$

Origine of Magnetic Moment:→

The macroscopic magnetic properties of a materials are a consequence of magnetic moments associated with individual electrons. Each electron in an atom has a magnetic moments that originate from two sources. One is related to its <u>orbital motion around the nucleus</u>; being a moving charge, an electron may be considered to be a small current loop, generating a very small magnetic field, and having a magnetic moment along it axis of rotation, (fig 1). On the other side each electron may also be thought of as <u>spining around an axis</u>; the other magnetic moment originates from this electron spin, which directed along the spin axis. Spin magnetic moments may be only in an 'up' direction or in an antiparallel 'down' direction. Thus <u>each electron</u> in an atom may be thought of as being a <u>small magnet</u> having permanent orbital and spin magnetic moments. ie μ_B is which is the magnitude 9.27 × 10^{-24} A-m^2.

Atomic nucleus

electron

Magnetic moment

(a) orbiting electron

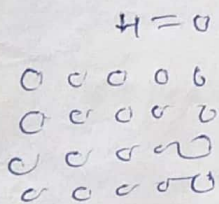magnetic moment

electron

direction of spin

(b) spining electron

- Thus materials composed of atoms having filled electron shells are not capable of being permanently magnetized. This category include the inert gas (He, Ne, Areh) as well as some ionic materials.

DIAMAGNETISM AND PARAMAGNETISM :—

Diamagnetism is a very weak form of magnetism and is nonpermanent and persists only while an external field is being applied. It is induced by a change in the orbital motion of electrons due to an applied magnetic field. The magnitude of the induced magnetic moment is extremely small, and in a direction opposite to that of the applied field. Thus the relative permeability μ_r is less than unity, and the magnetic susceptibility is negative; ie. the volume susceptibility χ_m 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.
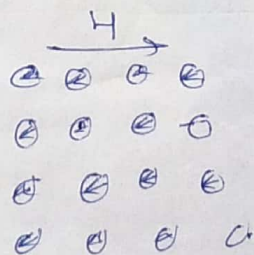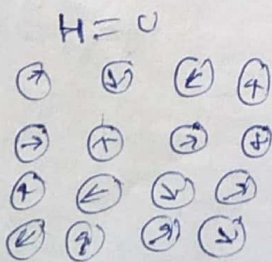
$H=0$

$H \rightarrow$

(a)

fig:9 — Atomic dipole configuration for a diamagnetic materials with a without field. In the absence of an external field, no dipole exist;
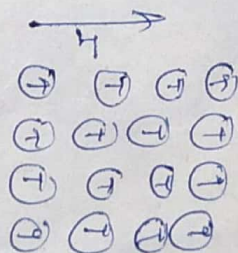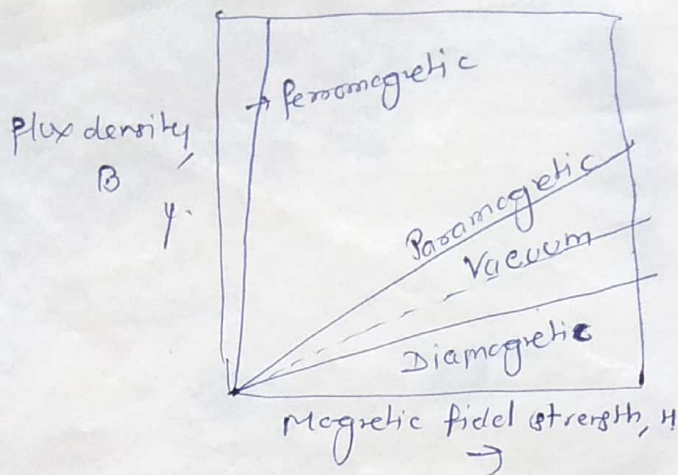
$H=0$

$H \rightarrow$

fig b — for a paramagnetic materials

(b)

Scanned with CamScanner

Fig: schematic reprodution of flux density B versus the magnetic field strength H for diamagetic, parastic and ferrostic only

• In the absence of an external magnetic field, the orientations of these atomic magnetic moment are random, such that a piece of material possesses no net (macroscopic magnetization). These atomic dipoles are free to rotate, and paramagtism results when they preferentially align, by rotation, with an external field. These magnetic dipoles are acted on individually with no mutual interaction between adjacent dipoles ie it gives relative permeability μ_r ie greater than unity, and to a relatively small but positive magnetic susceptibility. Susceptibility for parastic material ranges from about 10^{-5} to 10^{-2}

• Both diamagtic and parastic material are considered to be nonmagnetic because the exihibit magnetization only when in the presence of an external field.

R.T. magtic susceptibility for Dia & para Materials

Dia--tic.   Pa--tic

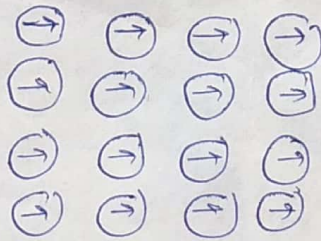| Material	Susceptibility χ_m (volume) SI unit		Material	Susceptibility χ_m (volume) SI unit
Aluminum oxide	—	-1.81×10^{-5}	Aluminum	2.07×10^{-5}
Copper gold	—	-0.96×10^{-5}	Chromium	3.13×10^{-4}
Mercury		-3.44×10^{-5}	Chromium chloride	1.51×10^{-3}
		-2.85×10^{-5}	Maganese sulfate	3.70×10^{-3}
Silicon	—	-0.41×10^{-5}	Molybdenum	1.19×10^{-4}
Silver	—	-2.38×10^{-5}	Sodium	8.04×10^{-6}
Sodium chloride	—	-1.41×10^{-5}	Titanium	1.81×10^{-4}
Zinc	—	-1.56×10^{-5}	Zirconium	1.09×10^{-4}

Ferromagnetism :— Certain metallic materials possess a permanent magnetic moment in the absence of a external field, and manifest very large and permanent magnetizations.

These are the characteristic of ferromagnetism, and they are displayed by the transition metal ions @ Mn, Co, Ni and some of rare earth metal Gd. Mvglic susce. as high as 10^6 are possible for ferromagnetic materials. Consequently, $H << M$ and from eqn.

$$B \cong \mu_0 M \quad — (1)$$

Permanent magnetic moments in ferromagnetic materials result form atomic magnetic moments due to electron spin — uncancelled electron spins as a consequence of the electron structure. There is also an orbital magnetic moment contribution that is small in comparison to the spin moment. Futhermore, in a ferromatic material, coupling interactions cause net spin magnetic moments of adjacent atoms to align with one another, even in the absence of an external field. The mutual spin alignment exists over relatively large volume regions of the crystal called domains → domains.

$$H = 0$$

Fig. Schematic illustration of the mutual alignment of atomic dipoles for a ferromagnetic material, which will exist even in the absence of an external magnetic field.
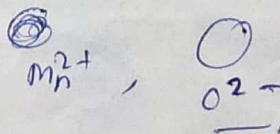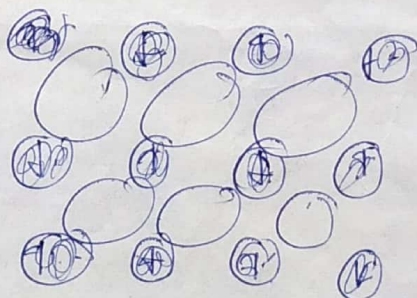
. The maximum possible magnetization, or saturation magnetization M_s, of a ferromagnetic material represents the magnetization that results when all the magnetic dipoles in a solid piece are mutually aligned with the external field; there is also a corresponding saturation flux density B_s. The saturation magnetization is equal to the product of the net magnetic moment for each atom and the number of atom present. For each of iron, Co, Ni, the net magnetic moment @ per atom are 2.22, 1.72 and 0.60 Bohr magnetons, respectively.

Antiferromagnetism –

Coupling between adjacent atoms or ions occurs in materials other than those that are ferromagnetic. In one such group, this coupling results in an antiparallel alignment; the alignment of the spin moments of neighbouring atoms or ions is exactly opposite directions in termed antiferromatic. (MnO), is one material that displays this behaviour. Mn^{+2}, rd O^{2-} ions here net behaviour. MnO is a ceramic material that is ionic in character, having both Mn^{+2} and O^{2-} ions. No net magnetic moment is associated with the O^{2-} ions, since there is a total cancellation of both spin and orbital moments. However, the Mn^{+2} ions possess a net magnetic moment that is predominantly of spin origin. These Mn^{+2} ions are arranged in the crystal structure such that the moments of adjacent ions are antiparallel. Obviously, the opposing magnetic moments cancel one another, and, as a consequence, the solid as a whole possesses no net magnetic moment.
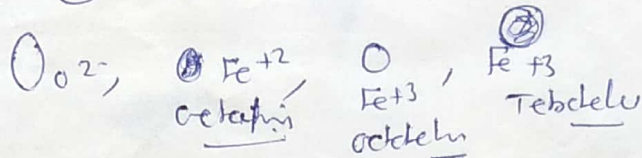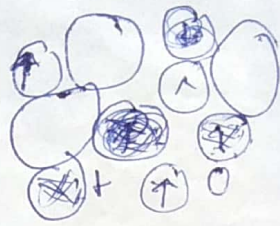
~~Ferrimagnetism~~ –

Pts:- MnO_2

Mn^{2+} , O^{2-}

FERRIMAGNETISM :→

Fe_3O_4, mineral magnetite, lodestone. The formula for Fe_3O_4 may be written as $Fe^{+2}O^{2-} — (Fe^{+3})_2(O^{2-})_3$ in which the Fe ions exist in both +2 and +3 valence state in the ratio of 1:2. A net spin magnetic moment exists for each Fe^{+2} and Fe^{+3} ion, which corresponds to 4 d 5 μ_B, respectively, for the two ion types. Furthermore, the O^{2-} ions are magnetically neutral. There are antiparallel spin-coupling interactions between the

between the Fe ions, similar in character to antiferro—. However the net ferrimagnetic moment arises from the incomplete cancellation of spin moments.

$O_{O^{2-}}$, ⊗ Fe^{+2} octahln , $O_{Fe^{+3}}$ octdeln , ⊗ Fe^{+3} Tebdelu

The distribution of spin magnetic moments for Fe^{+2} & Fe^{+3} ions in a unit cell of Fe_3O_4

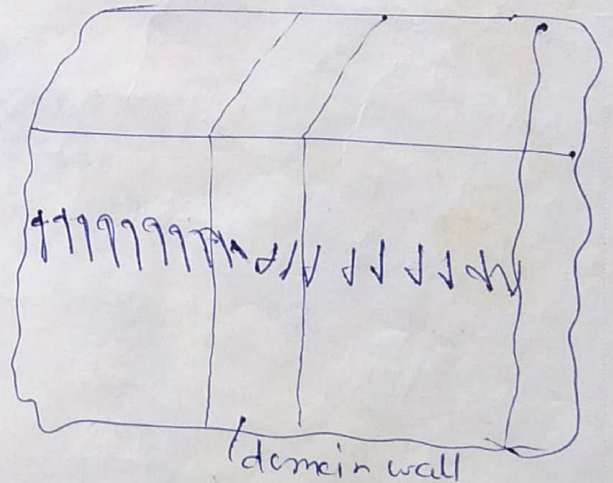| Cation	Octahedral lattice site	Tetrahel lattic site	Net magnetic Moment
Fe+3	↑↑↑↑↑	↓↓↓↓	complete cancellu.
	↑↑↑↑	↓↓↓↓	
	↓↑↑↑↑		↑↑↑↑
Fe+2	↑↑↑↑↑		↓↑↑↑

Influence of Temp. on Magnetic Behavior: → Raising the temp. of a solid results in an increase in the magnitude of the thermal vibrations of atoms. The atomic magnetic moments are free to rotate; hence, with rising temp, the increased thermal motion of the atoms tends to randomize the direction of any moment that may be aligned. The saturation magnetization is a maximum at 0 K, at which temp the thermal vibrations are a minimum. With increasing temp, the Ms diminishes gradually and then abruptly drops to zero at what is called the Curie temp (Tc). At Tc the mutual spin coupling forces are completely destroyed, such that for temps above Tc both ferromagnetic and ferrimagnetic materials are paramagnetic.
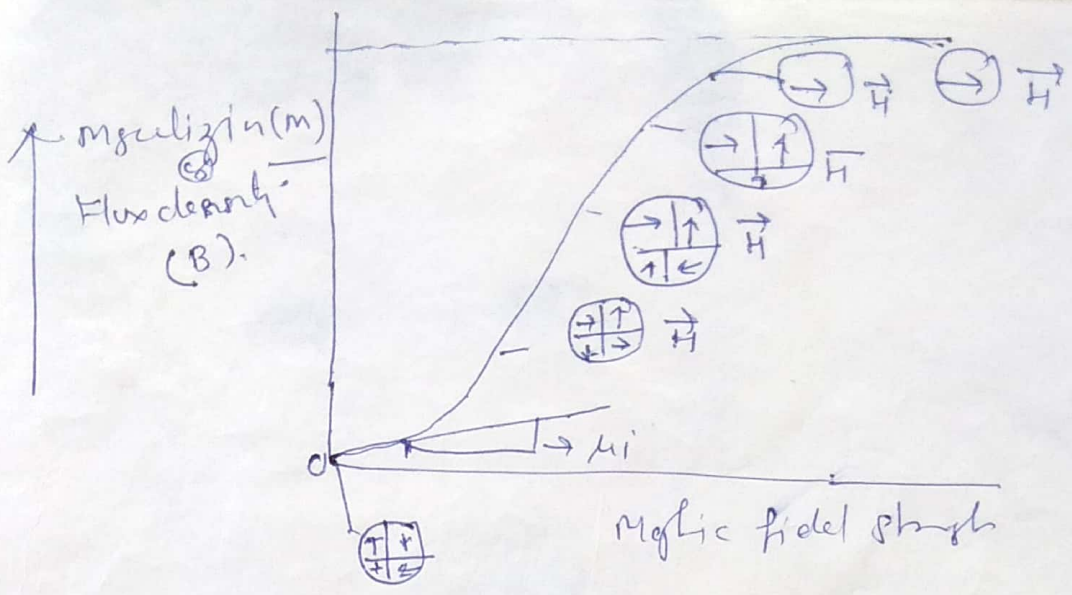
Domains and Hysteresis :—

Any ferro ferri material that is at a temp below Tc ie composed of small volume regions in which there is a mutual alignment in the same direction of all magnetic dipole moments. ie. is a region called domain and each one is magnetized to its saturation magnetization. Adjacent domains are seperated by domain boundaries or walls, across which the direction of magnetization gradually changes. The the magnitude of the M field for the entire solid is the vector sum of the magnetization of all the domains.

As an H field is applied, the domains change shape and size by the movement of domain boundaries. Initially, the moments of the constituent domains are randomly oriented such that there is no net B (or M) field. As the external field is applied, the domains that are oriented in direction favorable to (or nearly aligned) the applied field grow at the expense of those that are unfavorably oriented. This process continues with increasing field strength until the macroscopic specimen becomes a single domain, which is nearly aligned with the field.
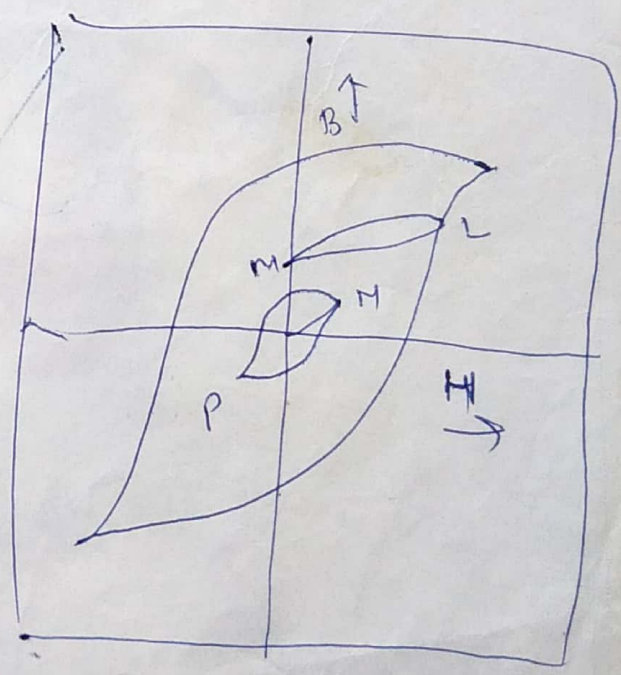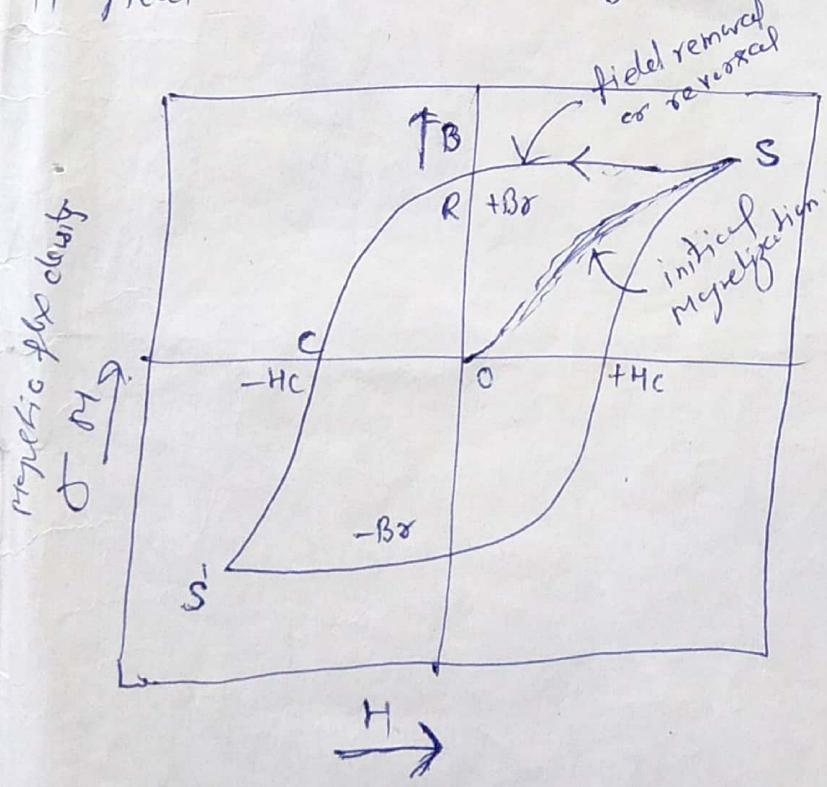

one domain | Another domain
Another 8.

Within each domain, all dipoles are aligned, whereas the direction of alignment varies from one domain to another.

domain wall

H : The gradual chge in magnetic dipole orientation across a domain wall.

Magnetic field strength

- From saturation point S, as the H field is reduced by ~~reversal~~ reversal of field direction, the curve does not retrace its original path. A hysteresis effect is produced in which the B field lags behind the applied H field, or decreases at a lower rate. At zero H field (point R on the curve), there exist a residual B field that is called the remanence or remanent flux density, Bг, the material remains magnetized in the absence of an external H field.

Hysteresis behaviour and permanent magnetization may be explained by the motion of domain walls. Upon reversal of the field direction from saturation, the process by which the domain structure changes is reversed. First, there is a rotation of the single domain with the reversed field. Next, domains having magnetic moments aligned with the new field form and grow at the expense of the former domains. Critical to this explanation is the resistance of the magnetic field in the opposite direction; this accounts for the lag of B with H, or the hysteresis. When the applied field reaches zero, there is still some net volume fraction of domains oriented in the former direction, which @ explains the existence of the remanence B_r.

'To reduce the B field within the specimen to zero an H field of magnitude $-H_c$ must be applied in a direction opposite to that of the original field; H_c is called the coercivity, or sometimes the coercive force. Upon continuation of the applied field in this reverse direction, @ saturation is ultimately achieved in the opposite sense S A second reversal of the field to the point of the initial saturation (part S) completes the symmetrical hysteresis loop and also yields both a negative remanence $(-B_r)$ and a positive coercivity $(+H_c)$.