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Chapter – 5: Magnetic Materials

) GANDAKI COLLEGE OF
.. ENGINEERING AND SCIENCE

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 eS)

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¢ In general for a coil, the magnitude of dipole moment is
[Mm = 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 eS)

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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, [,;-y

2
—ewr -
orb = I(ar7) = 3 (Since, N= 1&1 = charge flow per unit time = —)

2

¢ Angular momentum of electronis L = m,.vr = (M,wr)r = M,wr

a= —, since Lis quantized L = lh where 1 is the orbital quantum number.
° So, orbital magnetic moment is Lt,,-, = ——

° @Tr
L Angular momentum in orbit > L

¢ The intrinsic angular momentum of electron denoted by S gives rise to

¢ Since Sis quantized S = sh _

spin magnetic moment [l,,in = —-S = —Sh—
spin ~ in, 2m,

* The overall magnetic moment of the electron consists of Hy,, and LUs,;,appropriately added (both are vector quantities).

Magnetization Vector (M)

The magnetic field inside the solenoid with free space inside is By given by
Bo = Upnl

where n is number of turns per unit length,
I is current through the solenoid,

Lois absolute permeability of free space= 47 x 1077 =,

Te .
Mis current per unit length An orbiting electron is equivalent to a magnetic dipole moment moxz

* If a cylindrical material is placed inside the solenoid, the magnetic field will be changed from Bo to B.

* Each atom of the material responds to the applied field and develops a net magnetic moment [Lm 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.
M= 1 ON _ ; where Ngtomic= NuMber of atoms per unit volume,
7 y dix Pmi — "atomicHav: Uay= 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.

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

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Magnetic Permeability and Susceptibility

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

h= 7H 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.

jis absolute permeability,

HW; =, =]
Bo MoH L, is relative permeability,

= Moby:
" Ho is absolute permeability of the free space = 47 x 10-7 H

The magnetization M produced in the material depends on the net magnetic field B.
Magnetization M is related to magnetizing field H as M = ¥,,H ; xm is magnetic susceptibility
Now, B = By + UpM

B = [MoH (due to vacuum) + fy9M (due to material)

B= MoH + HoXmH This expression relates the relative permeability

B= (1+ X¥m)MoH with magnetic susceptibility of the material.
B = U,UoH; where pw, = (1 + Xm)

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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 [oH 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.. called Curie temperature.

At temperature above this, ferromagnetism is lost.

6/20/2023 MK/EEM 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, FeClzMn0Q,, 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 [5 }#696—++o Coen | suffer from eddy current losses. |
This is the reason for these materials being used in high Ore-O O-meO frequency electronic applications.

These materials are generally known as ferrites and represented by XFe304_ where X= Mg, Cu, Mn, Ni, Zn, Cd etc.

. 5.7 Magnetic ordering i i tal
 g g in ferrimagnetic crys

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, ,,, does not equal zero and depends upon the applied field [HoH and hence the magnetization is also non – zero and is equal to 7,,,H.

Magnetization increase with f4gH 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 Q yA) Q -o Pr
along the direction of B and there is a net OF 6) . O— iS

force toward greater field. Ow =o ie OF OO SO
Many gases and metals are paramagnetic. es

E.g. Pt, Al, Cr, Mn and dilute solutions of (0) Hay #0, M = og

ferromagnetic materials. Fig. 5.8 Without external field (a), with external field (b)
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(a) Hy = 0, M=0

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 y,, = —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 —10~°

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.

Domain wall (180°) Closure domain Closure domains

\ \ 90° domain wall
Thus, there is a boundary between the N
two domains where the magnetization I

changes from one direction to the /
opposite direction called as Domain wall
or Bloch wall. :

External field

(a () G a

6/20/2023 MK/ EEM 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 Domain wall (180°) Ces bor dor ain watt COUT domains continues until the magnetostatic energy

. "ae . . N
reduction by addition of domains is
balanced by increase in potential energy As
in the walls due to addition of walls. I

S

In this condition, there is minimum
potential _ energy with no_ net Saernal field
magnetization. " 's - id

Figure:- creation of magnetic domain

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 (e) Figure (f)

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. |||||

Gradual rotation
of magnetic moments

| 77 0\\\|

Domain A gi BOC wall———>

The Domain Wall is not simply one atomic spacing wide.

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NIL

Domain B

eee eee ene eee eee

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

crystal imperfections, impurities and so on.
Sudden changes in magnetization induce

eddy currents (circulating current) that 4 £2 Ms }-------

dissipate energy via joule heating (/7R) c Bre * § ots
a _b c d

called eddy current losses.
Reversible Irreversible —_ Rotation Saturation

boundary bounda
wcll aoe of M of M

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 -x
reaches saturation magnetization M,,; "A. o

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,.), 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,, also
called as coercivity. _B

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,,,;in reverse direction.

Decreasing the magnetizing field
from —H, q; to zero again leaves
residual magnetization.

To eliminate this we need to apply
magnetizing field in reverse aH
direction.

The energy dissipated during
magnetization & demagnetization
process is given by the area of
hysteresis loop.

—B
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,,;)
* 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,,;)
° 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).

e e Be.
Ferrites for high frequency transformers Co)

° Ferrites are ferromagnetic materials which are typically oxides of mixed transition metals, one of which is

* Ferrites are ferromagnetic materials, normally insulators, so do not suffer from eddy current losses (ver resistance allows only very small current and hence very small or no losses) > thus suitable for high freque 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 uppe 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 o 200 MHz.

* Garnets are ferrimagnetic materials, used at highest frequencies covering the microwave range (1 — 300 GHz). Yttrium Iron Garnet YIG (Y3 Fe;0;2)
* 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 (FE), is hysteresis loss i.e. energy dissipated per unit volume per cycle, J/m? at B,, = 1T)
ee ee ee

Magnetic

Material tots, £ Beat, T B,, T. Hej Himax

Ideal soft

iron 0 Large 0 Large Large

(commercial

grade, 0.2%

impuriries a 10bo. 46860
ani 107% 2 ~~ =

Silicon tron < 400000

(2-4% Si)

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E,, dm?

0

250

30 - 100

Applications

Transformer cores,
inductors, magnetic
recording heads, re-
lays, electromagnet
cores, machines

Due to large eddy
current losses used
only in some elect-
magnets and relays
Wide range of ac
machinery

Supermalloy 2 x 107"
(79%Ni,
15%Fe,
5%Mo,
0.5%Mn)
Permalloy
(78.5%Ni,
21.5%Fe)

5 x 107°

Glassy 2x 10°
metals
iFe -

Si - B)
Ferrites
Mrn- Zn
territe

10°

0.7–
0.8

0.86

1.6

0.4

<0.1

<0.1

<10°

<0.01

105

8000

2000

10°

10°

108

5000

<0.5

<0.1

20

<0.01

Selected soft magnetic materials (FE), is hysteresis loss i.e. energy dissipated per unit volume per cycle, J/m? at B,, = 1T)

High permeability low
loss electrical
devices, e.g. speci-
ality transformers,
magnetic amplifier
Low loss electrical
devices, audio tran-
sformers, HF trans-
formers, recording
heads, filters

Low loss transfor-
mer cores

HF low loss appli-
cations. HF trans-
formers, recording
heads, inductors (E

and U cores)

Néel temperature (T,) and paramagnetic Curie temperature (6..) for some anti-ferrimagnetic materials

Material Ty,K 8., K

MnF, "Ey Re 113

MnO, 84 316

MnO 122 610

MnsS 165 528

FeO | a. '4 198 570

NiF, 3 | 73 116

CoO 292 280

BO ag wn ea a ge ed es a er a ee
Table 5.5 Susceptibility of some diamagnetic materials

a A ae ee eT
Material % = u,-1,x10° Material X= My 1,x10°
Al, -0.5 Cu -0.9

BaCl, -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
NEE Heee eee ee Ee SS a aac aeaaacaamermmaaaaiaaeiamaamamemeal
Table 5.3 Susceptibilities of some paramagnetic materials at 300K

Substance x =p,-1, x10° Substance X =y,-1, x10%
CrCl, 1.5 Fe,O, LAA
Cr,0, 1.7 Fes(SO,)3 2.2

CoO 5:8 FeCl, 3.7
CoSO, 2.0 FeSO, 2.8

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