ELECTRICITY AND MAGNETISM

(e-content for Physics)

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MAGNETIC PROPERTIES OF MATERIALS-II

FERROMAGNETISM

A sample of ferromagnet is composed of domains in which all spins are directed alone a particular direction. The interaction between the neighbouring magnetic dipoles is very strong known as spin exchange interaction. The energy of two neighbouring atomic magnets is the least when their magnetic moments are parallel. So , they tend to align along parallel over a small finite volume. This small volume of the bulk is known as domain. All the domains are orinetd in specific directions so that the total magnetic moment is the vector sum of moment of domains. Thus the phenomenon of ferromagnetism is studied by the hypothesis of domain put forward by Weiss.

Domain Theory of Ferromagnetism

A ferromagnet has a spontaneous magnetization i.e.even in zero applied field, M is non-zero. Above a critical temperature θ known as paramagnetic curie temperature , the spontanerous magnetization vanishes and the material becomes paramagnet. Well above the Curie temperature, the susceptibility follows a Curie-Weiss law.

It is centred about two hypothesis put forward by Weiss:

(i) A ferromagnet specimen of macroscopic dimensions in general contains a number of small regions called domains which are spontaneously magnetized. The magnitude of this spontaneous magnetization is the vector sum of moment of individual domains.

(ii) The spontaneous magnetization of each domain is due to the existence of an internal molecular field. This tend to produce a parallel alignment of the atomic dipoles.

Weiss assumed that internal molecular field H_i is proportional to the magnetization M,

$$H_i = \gamma M \qquad (1)$$ where γ is a constant .

When the external field acts on the dipole, then the effective field H_{eff} is given by

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$$H_{eff} = H + \gamma M \quad (2)$$

According to the Langevin's theory of Paramagnetism, at high temperatures,

$$M = \frac{nm^2 \mu_0}{3KT} H \quad (3)$$

Where m represents the permanent magnetic moment of an atomic dipole,

n is the number of atomic magnets in unit volume, K is the Boltzmann constant, and T is the temperature in Kelvin.

Eqn. (3) for ferromagnetic material will be

$$M = \frac{nm^2 \mu_0}{3KT} (H + \gamma M)$$

$$M = \frac{nm^2 \mu_0 H}{3K(T - \frac{nm^2 \gamma \mu_0}{3K})} \quad (4)$$

Then the magnetic susceptibility is

$$\chi_{ferro} = \frac{M}{H} = \frac{nm^2 \mu_0}{3K(T - \frac{nm^2 \gamma \mu_0}{3K})}$$

$$\Rightarrow \chi_{ferro} = \frac{nm^2 \mu_0 H}{3K(T - \frac{nm^2 \gamma \mu_0}{3K})} = \frac{C}{T - \theta} \quad (5)$$

Here $C = \frac{nm^2 \mu_0}{3K}$ is the Curie constant.

$\theta = \frac{nm^2 \gamma \mu_0}{3K}$ is the paramagnetic Curie temperature.

Eqn.(5) gives the Curie Weiss law.

HYSTERESIS : RETENTIVITY: COERCIVITY

By hysteresis ,we mean the lagging behind of the intensity of magnetization (or magnetic induction B) behind the magnetizing field . This phenomenon is exhibited in ferromagnets.

The real distinguishing characteristics of a ferromagnetic material is not that it can be strongly magnetized but that the intensity of magnetization M is not directly proportional to the magnetizing field H. (susceptibilty is high)

Suppose that an unmagnetized bar of Iron is placed in a magnetizing field of intensity H of almost negligible value and it is gradually increased. As H is increased , magnetic induction vector B first increases linearly and reversibly and then more sharply but irreversibly and finally increases very slowly upto a point D known as saturation point after which there is a very slow increase of B with H. this curve is known as the magnetization curve. After this, as H decreases, B decreases along AE and stays at OE $=B_r$ when H=0

This property of a magnetic substance to retain its magnetism is known as retentivity or remanence. On increasing H in the reverse direction , B decreases and falls to zero when H=OF=H_c . It represents the reverse field to wipe out magnetism . It is a measure of the capacity of the material to retain its magnetism against demagnetizing effects. This property of retaining magnetism against demagnetizing effects is called its coercivity.

On further increasing H in the same direction, it is magnetized in the opposite direction and attains a similar saturation point G at $-H_s$. After this again as H is taken from $-H_s$ to $+H_s$, B follows a similar path . thus magnetic induction vector does not change in phase with the intensity of magnetizing field. This lagging behind of B with respect to H is called hysteresis and the loop DEFGEJD is known as hysteresis loop.

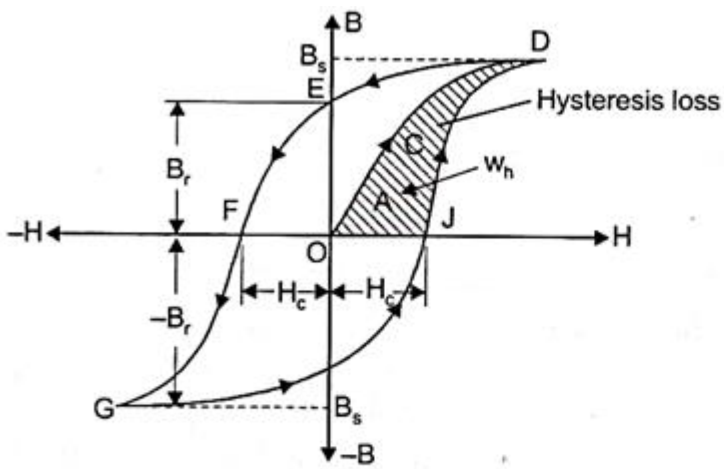
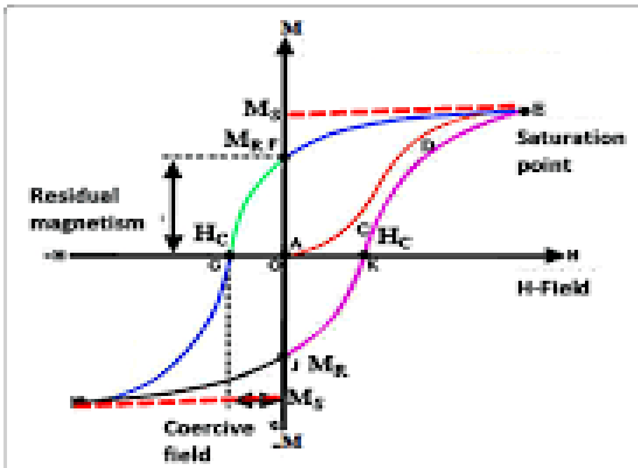


FIGURE : Magnetization curve OACD, and magnetic hysteresis loop ODEFGHJD showing variation of magnetic induction and the magnetic field.

Hystersis Loss:

Due to hysteresis, there is always some loss of energy and this loss per unit volume per cycle of magnetization is called hysteresis loss. Only ferromagnetic materials exhibit this phenomenon. The smallest unit of these substances are domains arranged randomly. When field is decreased, the domains do not turn back through the same angle in the reverse process. So, B lags behind H.

Also the energy given in the process of magnetization is not equal to the energy recovered from the specimen. Hence , there is always loss of energy from the specimen.



A specimen with n domains per unit volume is considered. The magnetic intensity is changed from 0 to H_s, H_s to 0, 0 to $-H_s$, $-H_s$ to 0.

M_R represents the residual magnetization

M_S represents the saturation magnetization

Let M be the magnitude of magnetization of specimen with intensity of magnetization H. if a domain makes an angle θ with H, then it gets resolved into two components mcos θ along H and msinθ perpendicular to H.

$$M=\sum m\cos\theta \qquad (1)$$

Let us consider a small strip of area under M-H curve showing differential change in magnetization dM, which is given by

$$dM=d(\sum m\cos\theta)= -\sum m\sin\theta d\theta \qquad (2)$$

Now, torque on the domain is mBsin θ or $\mu_0 m H\sin\theta$

$\tau = \mu_0 \mathrm{mHsin}\ \theta$ (3)

Then work done in turning the domain through an angle dθ $= \sum \mu_0 \mathrm{mHsin}\ \theta(-d\theta)$ (4)

Work done in increasing M to M+dM=

$$\sum -\mu_0 mH \sin\theta d\theta = \mu_0 H \sum -m\sin\theta d\theta = \mu_0 H \times dM$$

$$= \mu_0 \times area\ \ of\ \ abcd \quad (5)$$

Work done in increasing M from $-M_R$ to M_S= $\mu_0 \times \int_{-M_R}^{M_S} HdM = \mu_0 \times area\, C'D'AEC$

Work done on the domains when H is changed from 0 to H_s =

$\mu_0 \times area\, C'D'AEC'$

Similarly, work done by domains when H is changed from 0 to H_s

= $\mu_0 \times area\ \ ACEA$

Therefore, loss of energy in half cycle of magnetization=

$$\mu_0 \times (area\, C'D'AEC' - area\, ACEA)$$
$$= \mu_0 \times area\, C'D'ACC' = \mu_0 \times area\, of\ one\, half\ of\ the\, loop \quad (6)$$

Loss of energy per unit volume per cycle of magnetization=

$\mu_0 \times area$ of the M-H loop.

i.e. $\rho_H = \mu_0 \oint HdM$ (7)

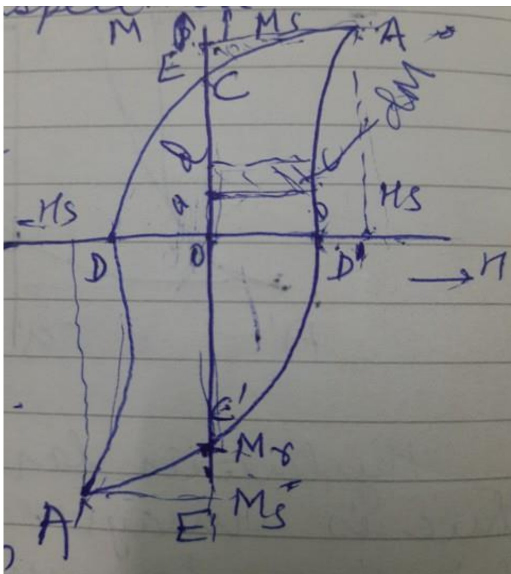
Since $B = \mu_0 (H + M) \Rightarrow dB = \mu_0 (dH + dM)$

$$\therefore \oint HdB = \mu_0 \oint HdH + \mu_0 \oint HdM$$

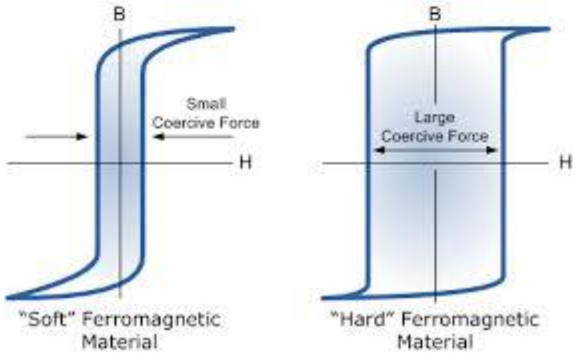
But $\oint HdH = 0 \Rightarrow \oint Hd\mathbf{B} = \mu_0 \oint HdM$

Thus ρ_H =area of the B-H loop (hysteresis loop) (8)

Thus, the area of B-H loop or μ_0 times the area of M-H loop gives the energy spent per cycle. H is in Am^{-1} and B is in Wbm^{-2}, so the energy is in Joules per cycle per cubic metre. (Refer to the figure below for understanding calculation)



Materials can be classified according to the area of hysteresis loop such as soft and hard iron.


B
Small
Coercive Force
H
"Soft" Ferromagnetic
Material
B
Large
Coercive Force
H
"Hard" Ferromagnetic
Material