Module-16

Magnetic properties

Contents

1) Dia-, Para-, and Ferro-magnetism (Anti-ferro-magnetism and ferri-magnetism)
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Introduction

- Engineering materials are important in everyday life because of their versatile structural properties.
- Other than these properties, they do play an important role because of their physical properties.
- Prime physical properties of materials include: electrical properties; thermal properties; **magnetic properties**; and optical properties.
- The magnetic properties of engineering materials are diverse, and so are their uses in different applications.

  Ex.: motors, telephones, medical applications, etc.

Magnetism

- *Magnetism* is a phenomenon by which a material exerts either attractive or repulsive force on another.
- Basic source of magnetic force is movement of electrically charged particles. Thus magnetic behavior of a material can be traced to the structure of atoms.
- Electrons in atoms have a planetary motion in that they go around the nucleus. This orbital motion and its own spin cause separate magnetic moments, which contribute to the magnetic behavior of materials. Thus every material can respond to a magnetic field.
- However, the manner in which a material responds depend much on its atomic structure, and determines whether a material will be strongly or weakly magnetic.

Bohr magneton

- Magnetic moment due to spin of an electron is known as *Bohr magneton*,M_B.

$$M_B = \frac{qh}{4\pi m_e} = 9.274 X 10^{-24} A.m^2$$

where q is the charge on the electron, h – Planck's constant,

m_e – mass of electron.

- Bohr magneton is the most fundamental magnetic moment.

Why not all materials are magnets?

- As every material consists spinning electrons, each of them could be a magnet. Fortunately, not so!
- There are two reasons for it.

  First: according to Pauli exclusion rule, two electrons with same energy level must have opposite spins – thus so are their magnetic moments, which cancel out each other.

  Second: orbital moments of electrons also cancel out each other – thus no net magnetic moments if there is no unpaired electron(s).
- Some elements such as transition elements, lanthanides, and actinides have a net magnetic moment since some of their energy levels have an unpaired electron.

Magnetic dipoles

- Magnetic dipoles are found to exist in magnetic materials, analogous to electric dipoles.
- A magnetic dipole is a small magnet composed of north and south poles instead of positive and negative charges.
- Within a magnetic field, the force of field exerts a torque that tends to orient the dipoles with the filed.
- Magnetic forces are generated by moving electrically charged particles. These forces are in addition to any electrostatic forces that may already exist.
- It is convenient to think magnetic forces in terms of distributed field, which is represented by imaginary lines. These lines also indicate the direction of the force.

Magnetic field

- If a magnetic field is generated by passing current *I* through a coil of length *l* and number of turns *n*, then the magnetic field strength is given by

$$H = \frac{nI}{l}$$

- Magnetic flux density (induction) is defined as $B = \mu H$

- Relative magnetic permeability is defined as $\mu_r = \frac{\mu}{\mu_0}$

- If *M*- magnetization (χ_mH), then $B = \mu_0 H + \mu_0 M = \mu_0 \mu_r H$

- Magnetic susceptibility is given as $\chi_m = \mu_r - 1$

Magnetisms

- A material is magnetically characterized based on the way it can be magnetized.
- This depends on the material's magnetic susceptibility – its magnitude and sign.
- Dia-magnetism: very weak; exists ONLY in presence of an external field.
- Para-magnetism: slightly stronger; When an external field is applied dipoles line-up with the field, resulting in a positive magnetization. However, the dipoles do not interact.
- Ferro-magnetism: very strong; dipoles line-up permanently upon application of external field. Has two sub-classes:-

  Anti-ferro-magnetism: dipoles line-up, but in opposite directions, resulting in zero magnetization.

  Ferri-magnetism: similar to anti-ferro-magnetism, BUT dipoles of varying strength cannot cancel each other out.

Magnetisms

Magnetism	Magnetic susceptibility		Examples
	sign	magnitude	
Dia	-	Small, Constant	Organic materials, superconducting materials, metals like Bi
Para	+	Small, Constant	Alkali and transition metals, rare earth elements
Ferro	+	Large, Function of H	Transition metals (Fe, Ni, Co), rare earth elements (Gd)
Anti-Ferro	+	Small, Constant	Salts of transition elements (MnO)
Ferri	+	Large, Function of H	Ferrites ($MnFe_2O_4$, $ZnFe2O_4$) and chromites

Temperature effect

- Temperature does have an definite effect on a materials’ magnetic behavior.
- With rising temperature, magnitude of the atom thermal vibrations increases. This may lead to more randomization of atomic magnetic moments as they are free to rotate.
- Usually, atomic thermal vibrations counteract forces between the adjacent atomic dipole moments, resulting in dipole misalignment up to some extent both in presence and absence of external field.
- As a consequence of it, saturation magnetization initially decreases gradually, then suddenly drops to zero at a temperature called *Curie temperature, Tc*.
- The magnitude of the Curie temperatue is dependent on the material. For example: for cobalt – 1120 ˚C, for nickel – 335 ˚C, for iron – 768 ˚C, and for Fe_3O_4 – 585 ˚C.

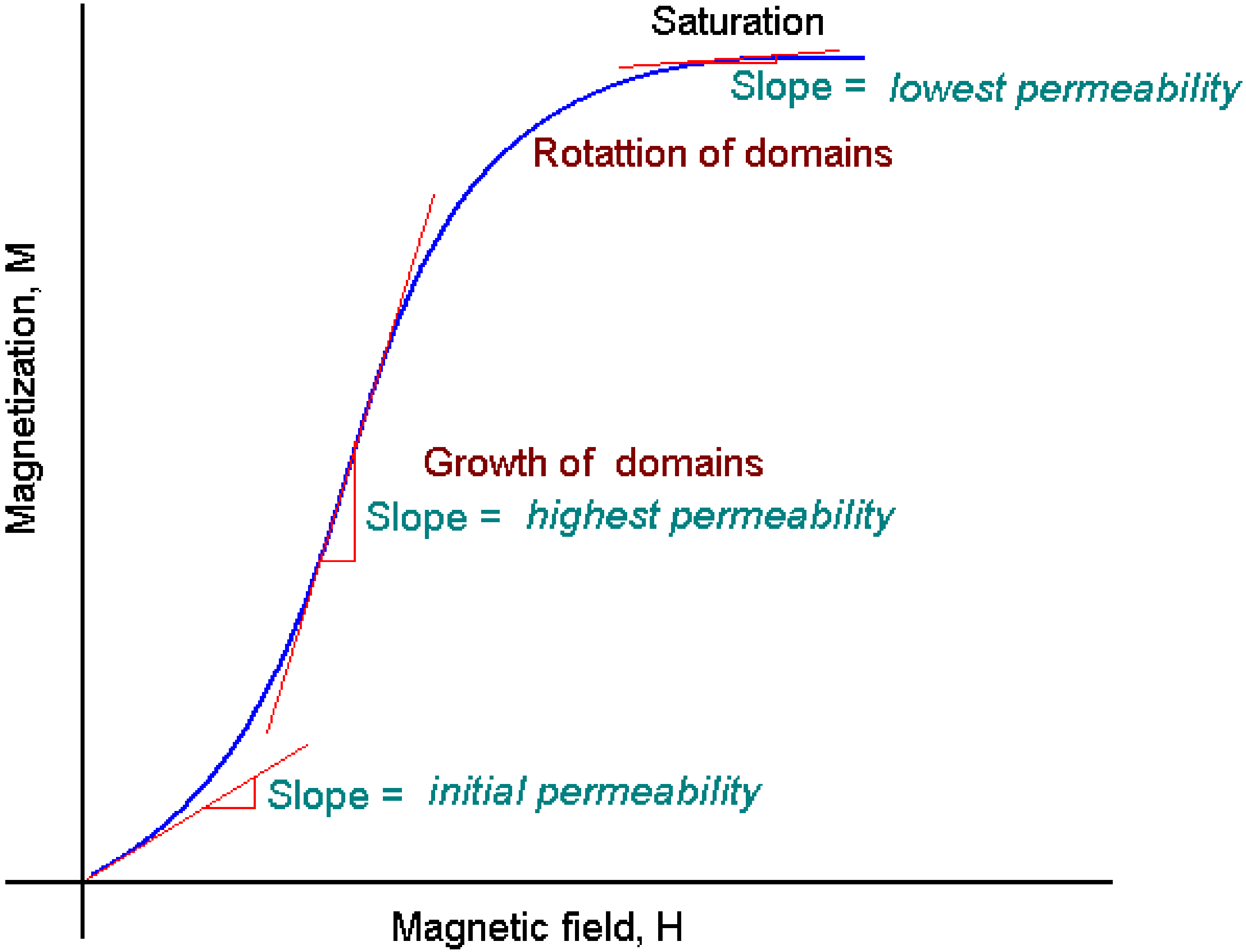
Magnetic domains

- In addition to susceptibility differences, the different types of magnetism can be distinguished by the structure of the magnetic dipoles in regions called domains.
- Each domain consists of magnetic moments that are aligned, giving rise to a permanent net magnetic moment per domain.
- Each of these domains is separated from the rest by domain boundaries / domain walls. Boundaries, also called *Bolch walls*, are narrow zones in which the direction of the magnetic moment gradually and continuously changes from that of one domain to that of the next.
- The domains are typically very small about 50 μm or less, while the Bloch walls are about 100 nm thick. For a polycrystalline specimen, each grain may have more than one microscopic sized domain.
- Domains exists even in absence of external field.

Magnetic domains

- The average magnetic induction of a ferro-magnetic material is intimately related to the domain structure.
- When a magnetic field is imposed on the material, domains that are nearly lined up with the field grow at the expense of unaligned domains. This process continues until only the most favorably oriented domains remain.
- In order for the domains to grow, the Bloch walls must move, the external field provides the force required for this moment.
- When the domain growth is completed, a further increase in the magnetic field causes the domains to rotate and align parallel to the applied field. At this instant material reaches saturation magnetization and no further increase will take place on increasing the strength of the external field.

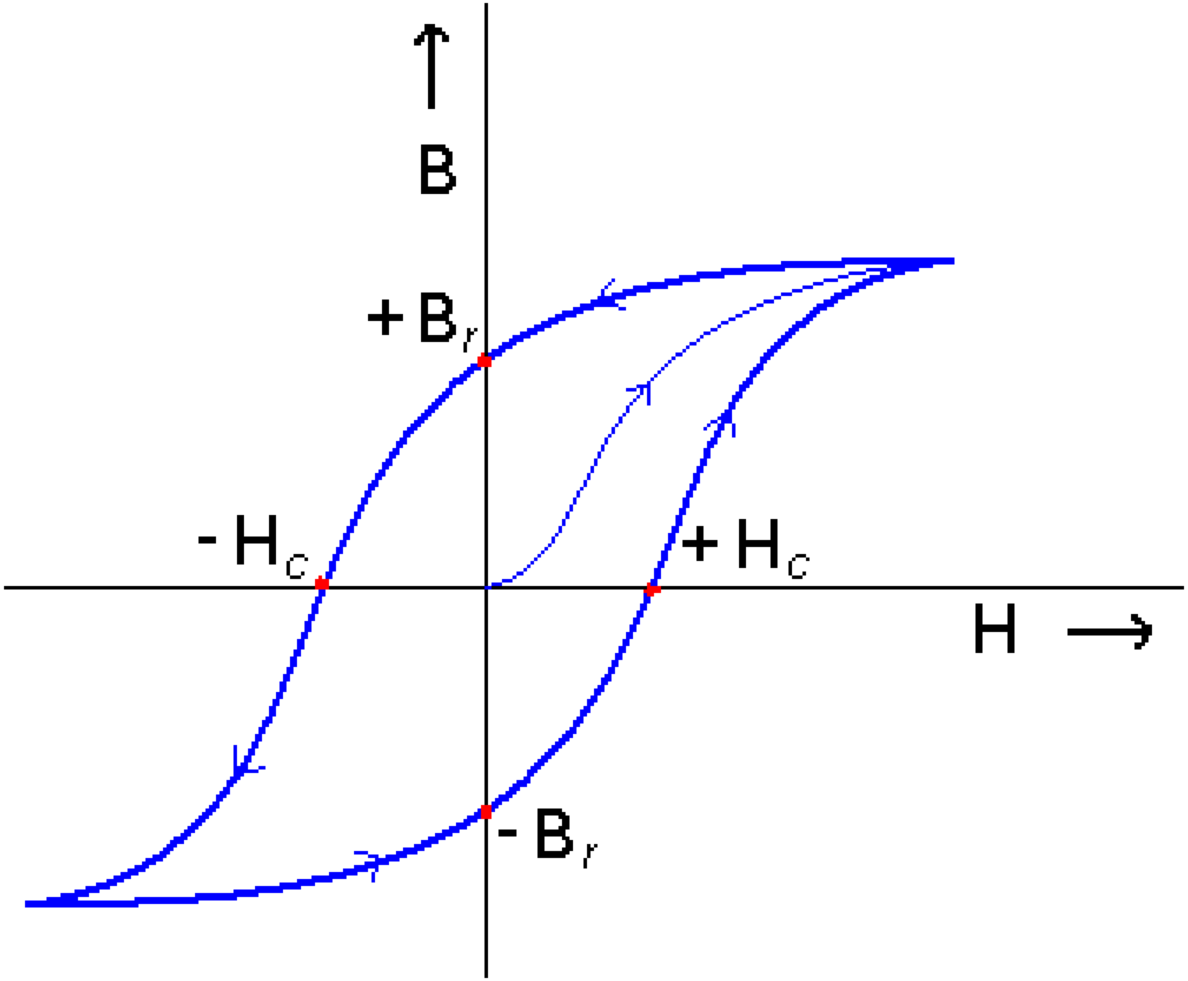
Magnetic domains



Magnetic hysteresis

- Once magnetic saturation has been achieved, a decrease in the applied field back to zero results in a macroscopically permanent or residual magnetization, known as *remanance*, M_r. The corresponding induction, B_r, is called *retentivity* or *remanent induction* of the magnetic material. This effect of retardation by material is called *hysteresis*.
- The magnetic field strength needed to bring the induced magnetization to zero is termed as *coercivity*, H_c. This must be applied anti-parallel to the original field.
- A further increase in the field in the opposite direction results in a maximum induction in the opposite direction. The field can once again be reversed, and the field-magnetization loop can be closed, Tthis loop is known as *hysteresis loop* or *B-H plot* or *M- H plot*.

Magnetic hysteresis



Semi-hard magnets

- OnceThe area within the hysteresis loop represents the energy loss per unit volume of material for one cycle.
- The coercivity of the material is a micro-structure sensitive property. This dependence is known as *magnetic shape anisotropy*.
- The coercivity of recording materials needs to be smaller than that for others since data written onto a data storage medium should be erasable. On the other hand, the coercivity values should be higher since the data need to be retained. Thus such materials are called magnetically semi-hard.

  Ex.: Hard ferrites based on Ba, CrO_2, γ-Fe_2O_3; alloys based on Co-Pt-Ta-Cr, Fe-Pt and Fe-Pd, etc.

Soft magnets

- *Soft magnets* are characterized by low coercive forces and high magnetic permeabilities; and are easily magnetized and de-magnetized.
- They generally exhibit small hysteresis losses.
- Application of soft magnets include: cores for electro-magnets, electric motors, transformers, generators, and other electrical equipment.

  Ex.: ingot iron, low-carbon steel, Silicon iron, superalloy (80% Ni-5% Mo-Fe), 45 Permalloy (55%Fe-45%Ni), 2-79 Permalloy (79% Ni-4% Mo-Fe), MnZn ferrite / Ferroxcube A (48% $MnFe_2O_4$-52%$ZnFe_2O_4$), NiZn ferrite / Ferroxcube B (36% $NiFe_2O_4$-64% $ZnFe_2O_4$), etc.

Hard magnets

- *Hard magnets* are characterized by high remanent inductions and high coercivities.
- These are also called *permanent magnets* or *hard magnets*.
- These are found useful in many applications including fractional horse-power motors, automobiles, audio- and video- recorders, earphones, computer peripherals, and clocks.
- They generally exhibit large hysteresis losses.

Ex.: Co-steel, Tungsten steel, $SmCo_5$, $Nd_2Fe_{14}B$, ferrite $Bao.6Fe_2O_3$, Cunife (60% Cu 20% Ni-20% Fe), Alnico (alloy of Al, Ni, Co and Fe), etc.