University of Anbar
College of Science
Department of Physics

فيزياء المواد

Physics of Materials

المرحلة الثالثة

الكورس الاول

اعداد
م.د. قيس عبدالله عباس

11. Magnetic Properties of Materials

Magnetism التمغنط, the phenomenon ظاهرة by which materials have an attractive تجاذب or repulsive تنافر force or influence تاثير on other materials, Many of our modern technological devices اجهزة تكنلوجية rely يعتمد on magnetism and magnetic materials; these include يتضمن electrical power generators مولدات and transformers محولات, electric motors موطورات, radio, television, telephones, computers, and components of sound and video reproduction systems.

11.1 Magnetic Dipoles

Magnetic forces القوى المغناطيسية are generated تتولد by moving بحركة electrically charged particles جسيمات مشحون كهربائيا; these magnetic forces are in addition to بالاضافة الى any electrostatic forces القوى الالكتروستاتيكية that may prevail سائدة. Imaginary lines خطوط وهمية of force may be drawn ترسم to indicate لتشير الى the direction اتجاه of the force at positions في موقع in the vicinity مجاور of the field source. The magnetic field distributions توزيع as indicated متمثلا by lines of force بخطوط قوى are shown for a current loop حلقة تيار and also a bar magnet قطعة مغناطيس in Figure 11.1

Magnetic dipoles ثنائي الاقطاب are found to exist in magnetic materials, Magnetic dipoles may be thought of as small bar magnets composed of north and south poles. Magnetic dipole moments العزوم المغناطيسية are represented تمثل by arrows باسهم. Magnetic dipoles are influenced by magnetic fields.

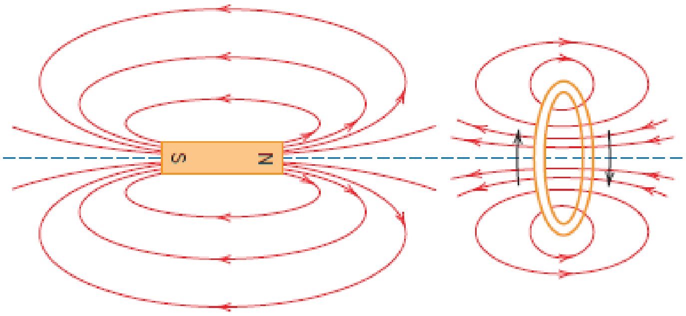


Figure 11.1 Magnetic field lines of force around a current loop and a bar magnet.

11.2 Magnetic Field Vectors

We describe magnetic behavior in terms of several field vectors. 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 a length l, and carrying a current of magnitude I, then,

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

The magnetic field that is generated by the current loop and the bar magnet is an H field. The units of H are ampere-turns per meter, or just amperes per meter.

The magnetic induction الحث المغناطيسي, or magnetic flux density كثافة الفيض المغناطيسي, denoted by B, represents the magnitude of the internal field strength within a substance that is subjected to an H field. The units for B are teslas [or webers per square meter (Wb/m2)].

Both B and H are field vectors, being characterized not only by magnitude, but also by direction in space.

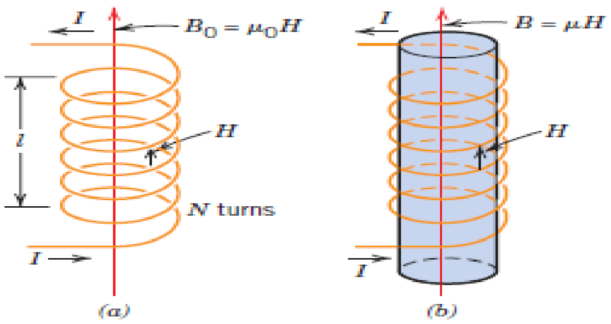


Figure 11.2 (a) The magnetic field H as generated by a cylindrical coil (b) The magnetic flux density B within a solid material.

The magnetic field strength and flux density are related according to

$$B = \mu H$$

The parameter μ is called the permeability, which is a property of the specific medium through which the H field passes and in which B is measured,

$$B_0 = \mu_0 H$$

where μ_o is the permeability of a vacuum,

Several parameters may be used to describe the magnetic properties of solids. One of these is the ratio of the permeability in a material to the permeability in a vacuum, or

$$\mu_r = \frac{\mu}{\mu_0}$$

where μ_r is called the relative permeability, which is unitless. The permeability or relative permeability of a material is a measure of the degree to which the material can be magnetized.
Another field quantity, M, called the magnetization of the solid, is defined by the expression

$$B = \mu_0 H + \mu_0 M$$

In the presence of an H field, the magnetic moments within a material tend to become aligned تصطف with the field and to reinforce تعزز it by their magnetic fields.

The magnitude of **M** is proportional to the applied field as follows:

$$M = \chi_m H$$

and x_m is called the magnetic susceptibility, which is unitless. The magnetic susceptibility and the relative permeability are related as follows:

$$\chi_m = \mu_r - 1$$

11.3 Origins of Magnetic Moments

The macroscopic magnetic properties of materials are a consequence of magnetic moments العزوم المغناطيسي associated المرافقة with individual electrons. Each electron in an atom has magnetic moments that originate from two sources. **One** is related to its orbital motion around the nucleus; 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 its axis of rotation, as schematically illustrated in Figure 11.3. a.

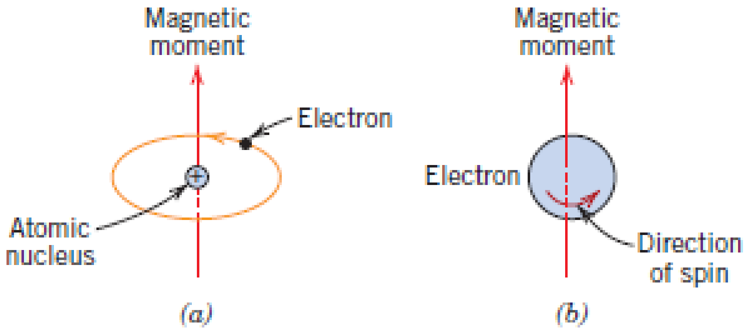


Figure 11.3 Demonstration of the magnetic moment associated with (a) an orbiting electron and (b) a spinning electron.

The second, each electron may also be thought of as spinning around an axis; the other magnetic moment originates from this electron spin, which is directed along the spin axis as shown in Figure 11.3.b. Spin magnetic moments may be only in an "up" direction or in an antiparallel "down" direction. Thus, each electron in an atom may be thought of as being a small magnet having permanent orbital and spin magnetic moments.
The net magnetic moment, then, for an atom is just the sum of the magnetic moments of each of the constituent electrons, including both orbital and spin contributions,

11.4 Diamagnetism And Paramagnetism

Diamagnetism is a very weak form of magnetism that 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. Diamagnetic materials are attracted toward regions where the field is weak.

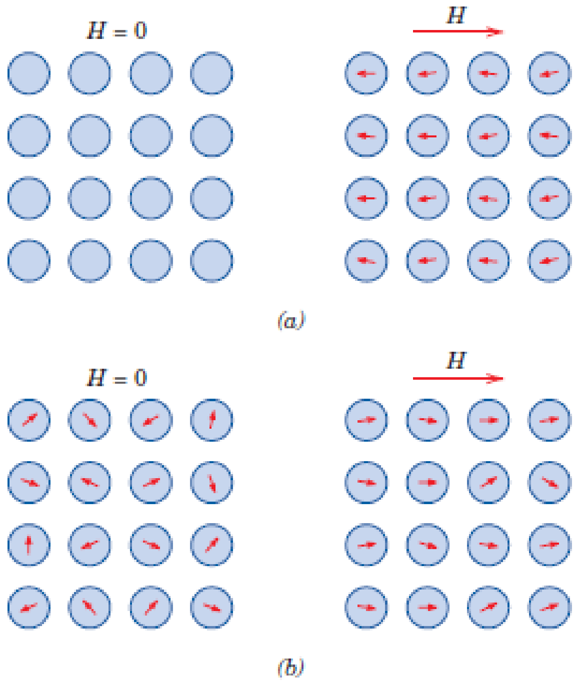


Figure 11.4 (a) The atomic dipole configuration for a diamagnetic material with and without a magnetic field. (b) Atomic dipole configuration with and without an external magnetic field for a paramagnetic material.

Figure 11.4 (a) illustrates schematically the atomic magnetic dipole configurations for a diamagnetic material with and without an external field; here, the arrows represent atomic dipole moments, arrows denoted only electron moments. Diamagnetism is found in all materials, but because it is so weak, it can be observed only when other types of magnetism are totally absent.

Paramagnetism results when they preferentially align, by rotation, with an external field as shown in Figure 11.4 (b). These magnetic dipoles are acted on individually with no mutual interaction between adjacent dipoles. the dipoles align with the external field, they enhance it, giving rise to a relative permeability μ_r that is greater than unity, and to a relatively small but positive magnetic susceptibility.

Both diamagnetic and paramagnetic materials are considered nonmagnetic because they exhibit magnetization only when in the presence of an external field.

11.5 FERROMAGNETISM

Certain metallic materials possess a permanent magnetic moment in the absence of an external field, and manifest very large وتظهر بشكل كبير and permanent magnetizations. These are the characteristics of ferromagnetism, and they are displayed by the transition metals iron (as BCC -ferrite), cobalt, nickel, and some of the rare earth metals such as gadolinium (Gd). Magnetic susceptibilities as high as 106 are possible for ferromagnetic materials. Consequently, and from Equation we write

$$B \cong \mu_0 M$$

Permanent magnetic moments in ferromagnetic materials result from atomic magnetic moments due to 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.
Furthermore, in a ferromagnetic material, coupling interactions cause net spin magnetic moments of adjacent atoms to align with one another, even in the absence of an external field. This is schematically illustrated in Figure 11.5.
The maximum possible magnetization, or saturation magnetization **Ms**, 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;

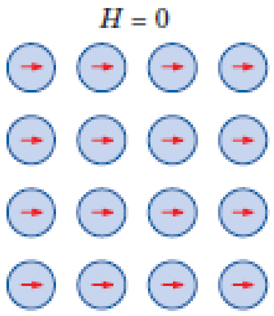


Figure 11.5 Schematic illustration of the mutual alignment of atomic dipoles for a ferromagnetic material,

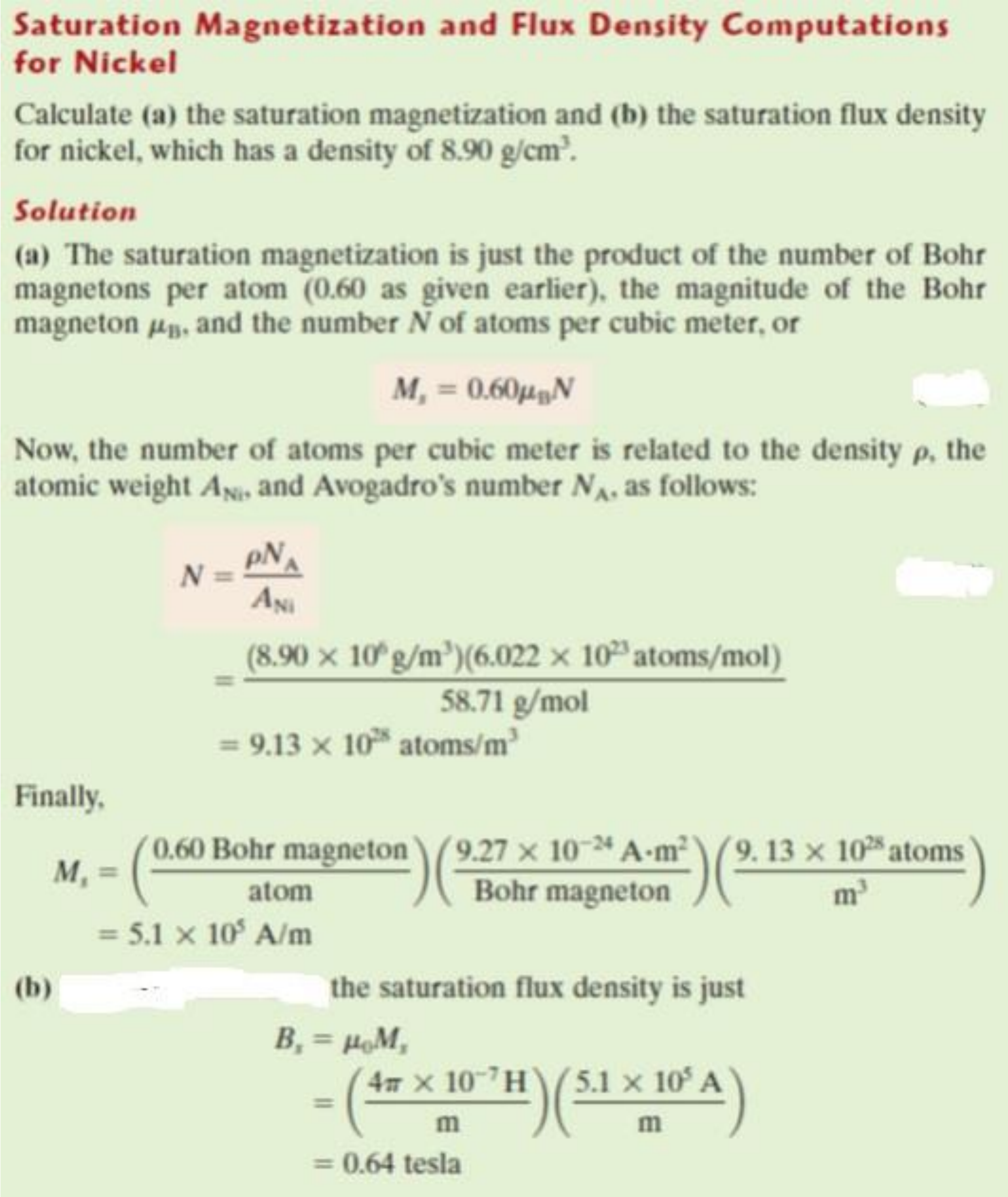
There is also a corresponding saturation flux density Bs. The saturation magnetization is equal to the product of the net magnetic moment for each atom and the number of atoms present. For each of iron, cobalt, and nickel,

$$M_s = N'\mu_B$$ Saturation magnetization for a ferrimagnetic material

$$M_s = 0.60\mu_B N$$ Saturation magnetization for Ni

N is the number of atoms.

Example 11.1



Saturation Magnetization and Flux Density Computations for Nickel

Calculate **(a)** the saturation magnetization and **(b)** the saturation flux density for nickel, which has a density of 8.90 g/cm^3.

Solution

(a) The saturation magnetization is just the product of the number of Bohr magnetons per atom (0.60 as given earlier), the magnitude of the Bohr magneton μ_B, and the number N of atoms per cubic meter, or

$$M_s = 0.60\mu_B N$$

Now, the number of atoms per cubic meter is related to the density ρ, the atomic weight A_{Ni}, and Avogadro's number N_A, as follows:

$$N = \frac{\rho N_A}{A_{Ni}}$$

$$= \frac{(8.90 \times 10^6\ \text{g/m}^3)(6.022 \times 10^{23}\ \text{atoms/mol})}{58.71\ \text{g/mol}}$$

$$= 9.13 \times 10^{28}\ \text{atoms/m}^3$$

Finally,

$$M_s = \left(\frac{0.60\ \text{Bohr magneton}}{\text{atom}}\right)\left(\frac{9.27 \times 10^{-24}\ \text{A}\cdot\text{m}^2}{\text{Bohr magneton}}\right)\left(\frac{9.13 \times 10^{28}\ \text{atoms}}{\text{m}^3}\right)$$

$$= 5.1 \times 10^5\ \text{A/m}$$

(b) the saturation flux density is just

$$B_s = \mu_0 M_s$$

$$= \left(\frac{4\pi \times 10^{-7}\ \text{H}}{\text{m}}\right)\left(\frac{5.1 \times 10^5\ \text{A}}{\text{m}}\right)$$

$$= 0.64\ \text{tesla}$$

11.6 Antiferromagnetism

This phenomenon of magnetic moment coupling between adjacent atoms or ions occurs in materials other than those that are ferromagnetic. This coupling results in an **antiparallel alignment**; the alignment of the spin moments of neighboring atoms or ions in exactly opposite directions is termed antiferromagnetism. Manganese oxide (MnO) is one material that displays this behavior.

This arrangement is represented schematically in Figure 11.6. the opposing magnetic moments cancel one another, and, as a consequence, the solid as a whole possesses no net magnetic moment.

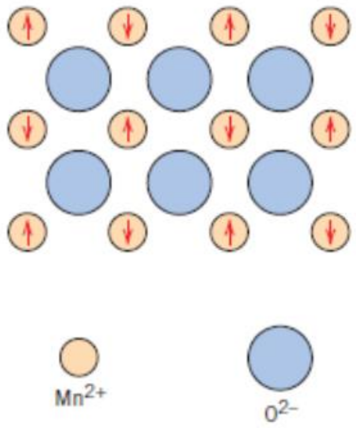
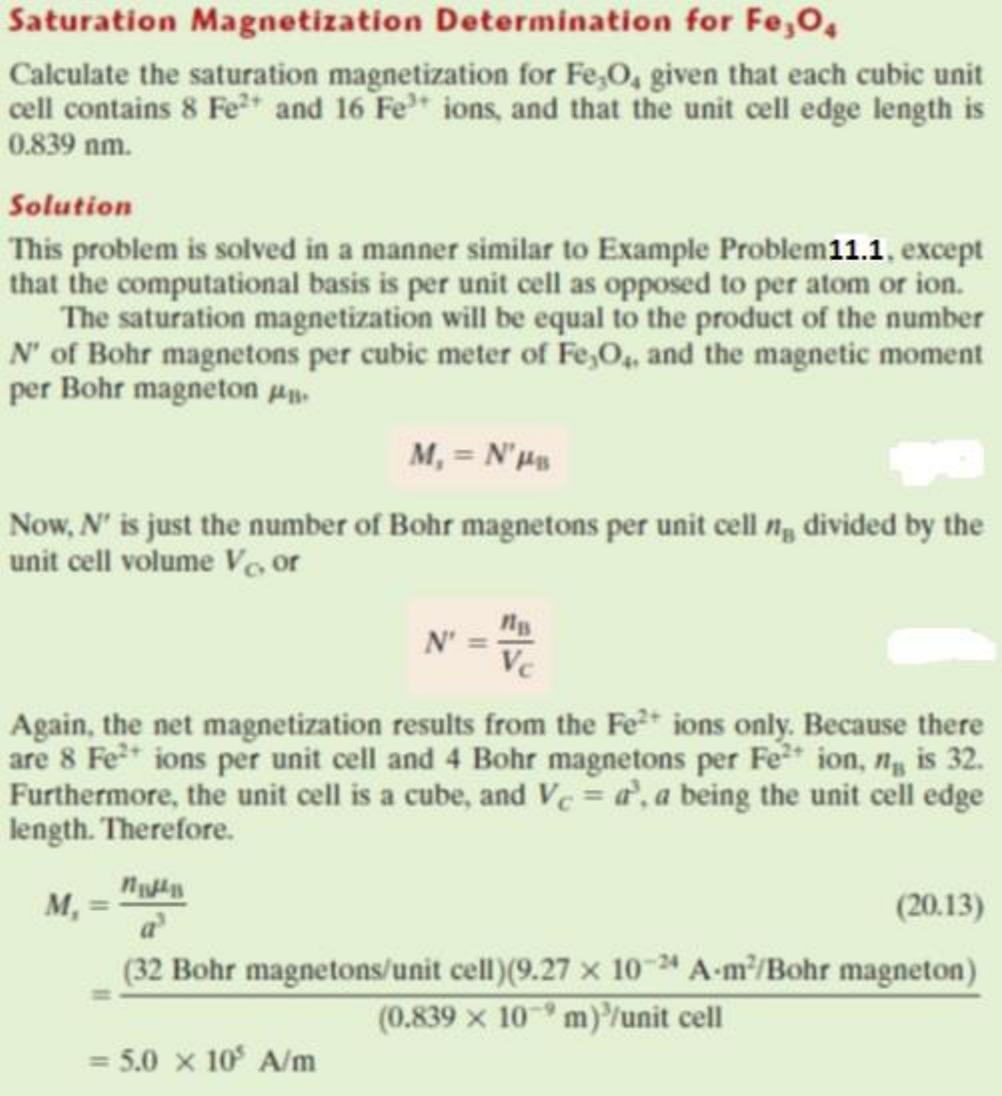


Figure 11.6

11.7 Ferrimagnetism

Ferrimagnetism Some ceramics also exhibit a permanent magnetization, termed ferrimagnetism. The macroscopic magnetic characteristics of ferromagnets and ferrimagnets are similar; the distinction lies in the source of the net magnetic moments. The principles of ferrimagnetism
are illustrated with the cubic ferrites. These ionic materials may be represented by the chemical formula MFe2O4, in which M represents any one of several metallic elements. The prototype ferrite is Fe3O4, the mineral magnetite, sometimes called lodestone.

Example 11.2



Saturation Magnetization Determination for Fe_3O_4

Calculate the saturation magnetization for Fe_3O_4 given that each cubic unit cell contains 8 Fe^{2+} and 16 Fe^{3+} ions, and that the unit cell edge length is 0.839 nm.

Solution

This problem is solved in a manner similar to Example Problem**11.1**, except that the computational basis is per unit cell as opposed to per atom or ion.

The saturation magnetization will be equal to the product of the number N' of Bohr magnetons per cubic meter of Fe_3O_4, and the magnetic moment per Bohr magneton μ_B,

$$M_s = N'\mu_B$$

Now, N' is just the number of Bohr magnetons per unit cell n_B divided by the unit cell volume V_C, or

$$N' = \frac{n_B}{V_C}$$

Again, the net magnetization results from the Fe^{2+} ions only. Because there are 8 Fe^{2+} ions per unit cell and 4 Bohr magnetons per Fe^{2+} ion, n_B is 32. Furthermore, the unit cell is a cube, and $V_C = a^3$, a being the unit cell edge length. Therefore,

$$M_s = \frac{n_B\mu_B}{a^3} \tag{20.13}$$

$$= \frac{(32 \text{ Bohr magnetons/unit cell})(9.27 \times 10^{-24} \text{ A}\cdot\text{m}^2/\text{Bohr magneton})}{(0.839 \times 10^{-9} \text{ m})^3/\text{unit cell}}$$

$$= 5.0 \times 10^5 \text{ A/m}$$

11.8 The Influence Of Temperature On Magnetic Behavior

Temperature can also influence the magnetic characteristics of materials. Where a raising the temperature 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 temperature, the increased thermal motion of the atoms tends to randomize the directions of any moments that may be aligned.

For ferromagnetic, antiferromagnetic, and ferrimagnetic materials, the atomic thermal motions counteract the coupling forces between the adjacent atomic dipole moments, causing some dipole misalignment, regardless of whether an external field is present. This results in a decrease in the saturation magnetization for both ferro and ferrimagnets. The saturation magnetization is a maximum at 0 K, at which temperature the thermal vibrations are a minimum. With increasing temperature, the saturation magnetization diminishes gradually and then abruptly drops to zero at what is called the Curie temperature Tc.

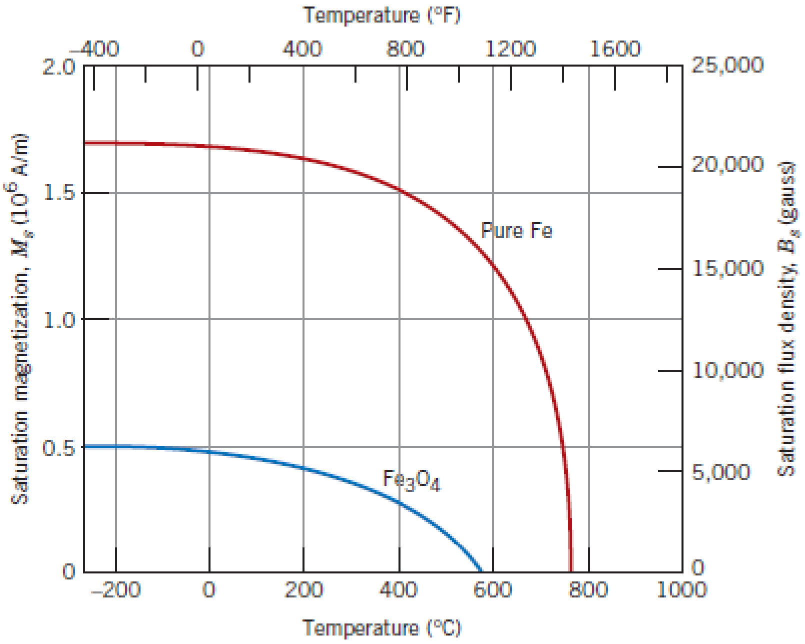


Figure 11.7

11.9 Domains And Hysteresis

Any ferromagnetic or ferrimagnetic material that is at a temperature below Tc is composed of small-volume regions in which there is a mutual alignment in the same direction of all magnetic dipole moments, as illustrated in Figure 20.11. Such a region is called a domain, and each one is magnetized to its saturation magnetization.

Adjacent domains are separated by domain boundaries or walls, across which the direction of magnetization gradually changes (Figure 11.8). Normally, domains are microscopic in size, and for a polycrystalline specimen, each grain may consist of more than a single domain. Thus, in a macroscopic piece of material, there will be a large number of domains, and all may have different magnetization orientations.

The magnitude of the M field for the entire solid is the vector sum of the magnetizations of all the domains.

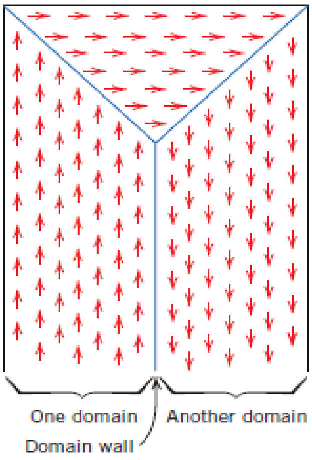


Figure 11.8 Schematic depiction of domains in a ferromagnetic or ferrimagnetic material; arrows represent atomic magnetic dipoles. Within each domain, all dipoles are aligned, whereas the direction of alignment varies from one domain to another.

As an H field is applied, the domains change shape and size by the movement of domain boundaries.

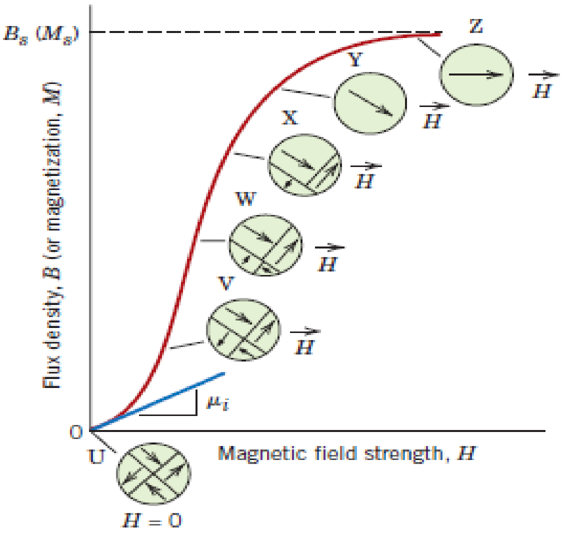


Figure 11.9 The B-versus-H behavior for a ferromagnetic or ferrimagnetic material that was initially unmagnetized. Domain configurations during several stages of magnetization are represented.

Reference

1- Materials _Science_ and _Engineering_9th .pdf · version 1