Chapter 20

Magnetic Materials

Have You Ever Wondered?

- *What materials are used to make audio and video cassettes?*
- *What affects the "lifting strength" of a magnet?*
- *What are "soft" and "hard" magnetic materials?*
- *Are there "nonmagnetic" materials?*
- *Are there materials that develop mechanical strain upon the application of a magnetic field?*

Every material in the world responds to the presence of a magnetic field. Magnetic materials are used to operate such things as electrical motors, generators, and transformers. Much of data storage technology (computer hard disks, computer disks, video and audio cassettes, and the like) is based on magnetic particles. Magnetic materials are also used in loudspeakers, telephones, CD players, telephones, televisions, and video recorders. Superconductors can also be viewed as magnetic materials. Magnetic materials, such as iron oxide (Fe_3O_4) particles, are used to make exotic compositions of "liquid magnets" or ferrofluids. The same iron oxide particles are also used to bind DNA molecules, cells, and proteins.

In this chapter, we look at the fundamental basis for responses of certain materials to the presence of magnetic fields. We will also examine the properties and applications of different types of magnetic materials.

20-1 Classification of Magnetic Materials

Strictly speaking, there is no such thing as a "nonmagnetic" material. Every material consists of atoms; atoms consist of electrons spinning around them, similar to a current-carrying loop that generates a magnetic field. Thus, every material responds to a magnetic field. The manner in which this response of electrons and atoms in a material is scaled determines whether a material will be strongly or weakly magnetic. Examples of **ferromagnetic** materials are materials such as Fe, Ni, Co, and some of their alloys. Examples of **ferrimagnetic** materials include many ceramic materials such as nickel zinc ferrite and manganese zinc ferrite. The term "nonmagnetic," usually means that the material is neither ferromagnetic nor ferrimagnetic. These "nonmagnetic" materials are further classified as **diamagnetic** (e.g., superconductors) or **paramagnetic**. In some cases, we also encounter materials that are **antiferromagnetic** or **superparamagnetic**. We will discuss these different classes of materials and their applications later in the chapter. Ferromagnetic and ferrimagnetic materials are usually further classified as either soft or hard magnetic materials. High-purity iron or plain carbon steels are examples of a magnetically soft material as they can become magnetized, but when the magnetizing source is removed, these materials lose their magnet-like behavior.

Permanent magnets or **hard magnetic materials** retain their magnetization. These are permanent "magnets." Many ceramic ferrites are used to make inexpensive refrigerator magnets. A hard magnetic material does not lose its magnetic behavior easily.

20-2 Magnetic Dipoles and Magnetic Moments

The magnetic behavior of materials can be traced to the structure of atoms. The orbital motion of the electron around the nucleus and the spin of the electron about its own axis (Figure 20-1) cause separate magnetic moments. These two motions (i.e., spin and orbital) contribute to the magnetic behavior of materials. When the electron spins, there is a magnetic moment associated with that motion. The **magnetic moment** of an electron due to its spin is known as the **Bohr magneton** (μ_B). This is a fundamental constant and is defined as

$$\mu_B = \text{Bohr magneton} = \frac{qh}{4\pi m_e} = 9.274 \times 10^{-24} \text{A} \cdot \text{m}^2 \tag{20-1}$$

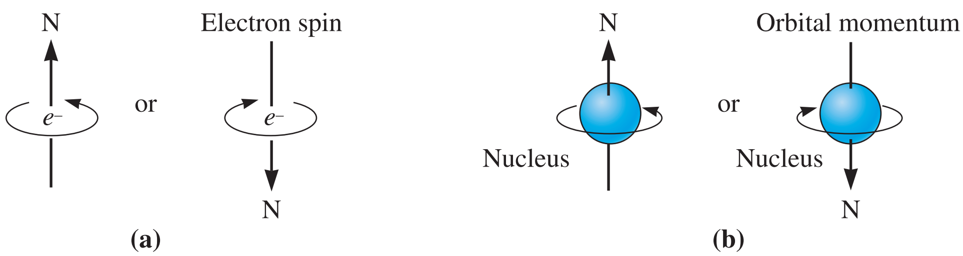


Figure 20-1 Origin of magnetic dipoles: (a) The spin of the electron produces a magnetic field with a direction dependent on the quantum number m_s. (b) Electrons orbiting around the nucleus create a magnetic field around the atom.

where q is the charge on the electron, h is Planck's constant, and m_e is the mass of the electron. This moment is directed along the axis of electron spin.

The nucleus of the atom consists of protons and neutrons. These also have a spin; however, the overall magnetic moment due to their spin is much smaller than that for electrons. We normally do not encounter the effects of a magnetic moment of a nucleus with the exception of such applications as nuclear magnetic resonance (NMR).

We can view electrons in materials as small elementary magnets. If the magnetic moments due to electrons in materials could line up in the same direction, the world would be a magnetic place! However this, as you know, is not the case. Thus, there must be some mechanism by which the magnetic moments associated with electron spin and their orbital motion get canceled in most materials, leaving behind only a few materials that are "magnetic." There are two effects that, fortunately, make most materials in the world not "magnetic."

First, we must consider the magnetic moment of atoms. According to the Pauli exclusion principle, two electrons within the same orbital must have opposite spins. This means their electron spin derived magnetic moments have opposite signs (one can be considered "up ↑" and the other one "down ↓") and cancel. The second effect is that the orbital moments of electrons also cancel each other. Thus, in a completely filled shell, all electron spin and orbital moments cancel. This is why atoms of most elements do not have a net magnetic moment. Some elements, such as transition elements (3*d*, 4*d*, 5*d* partially filled), the lanthanides (4*f* partially filled), and actinides (5*f* partially filled), have a net magnetic moment due to an unpaired electron.

Certain elements, such as the transition metals, have an inner energy level that is not completely filled. The elements scandium (Sc) through copper (Cu), the electronic structures of which are shown in Table 20-1, are typical. Except for chromium and copper, the valence electrons in the 4*s* level are paired; the unpaired electrons in chromium and copper are canceled by interactions with other atoms. Copper also has a completely filled 3*d* shell and thus does not display a net magnetic moment.

The electrons in the 3*d* level of the remaining transition elements do not enter the shells in pairs. Instead, as in manganese, the first five electrons have the same spin. Only after half of the 3*d* level is filled do pairs with opposing spins form. Therefore, each atom in a transition metal has a permanent magnetic moment, which is related to the number of unpaired electrons. Each atom behaves as a magnetic dipole.

In many elements, these magnetic moments exist for free individual atoms, however, when the atoms form crystalline materials, these moments are "quenched" or canceled out. Thus, a number of materials made from elements with atoms that have a net magnetic moment do not exhibit magnetic behavior. For example, the Fe^{+2} ion has a net magnetic moment of $4\mu_B$ (four times the magnetic moment of an electron); however, $FeCl_2$ crystals are not magnetic.

TABLE 20-1 ■ ***The electron spins in the 3d energy level in transition metals with arrows indicating the direction of spin***

Metal			3*d*			4*s*
Sc	↑					⇵
Ti	↑	↑				⇵
V	↑	↑	↑			⇵
Cr	↑	↑	↑	↑	↑	↑
Mn	↑	↑	↑	↑	↑	⇵
Fe	⇵	↑	↑	↑	↑	⇵
Co	⇵	⇵	↑	↑	↑	⇵
Ni	⇵	⇵	⇵	↑	↑	⇵
Cu	⇵	⇵	⇵	⇵	⇵	↑

The response of the atom to an applied magnetic field depends on how the magnetic dipoles of each atom react to the field. Most of the transition elements (e.g., Cu, Ti) react in such a way that the sum of the individual atoms' magnetic moments is zero. The atoms in nickel (Ni), iron (Fe), and cobalt (Co), however, undergo an exchange interaction, whereby the orientation of the dipole in one atom influences the surrounding atoms to have the same dipole orientation, producing a desirable amplification of the effect of the magnetic field. In the case of Fe, Ni, and Co, the magnetic moments of the atoms line up in the same directions, and these materials are known as ferromagnetic.

In certain materials, such as BCC chromium (Cr), the magnetic moments of atoms at the center of the unit cell are opposite in direction to those of the atoms at the corners of the unit cell; thus, the net moment is zero. Materials in which there is a complete cancellation of the magnetic moments of atoms or ions are known as anti-ferromagnetic.

Materials in which magnetic moments of different atoms or ions do not completely cancel out are known as ferrimagnetic materials. We will discuss these materials in a later section.

20-3 Magnetization, Permeability, and the Magnetic Field

Let's examine the relationship between the magnetic field and magnetization. Figure 20-2 depicts a coil having n turns. When an electric current is passed through the coil, a magnetic field H is produced, with the strength of the field given by

$$H = \frac{nI}{l} \tag{20-2}$$

where n is the number of turns, l is the length of the coil (m), and I is the current (A). The units of H are therefore ampere turn/m, or simply A/m. An alternate unit for magnetic field is the oersted, obtained by multiplying A/m by $4\pi \times 10^{-3}$ (see Table 20-2).

When a magnetic field is applied in a vacuum, lines of magnetic flux are induced. The number of lines of flux, called the flux density, or *inductance* B, is related to the applied field by

$$B = \mu_0 H \tag{20-3}$$

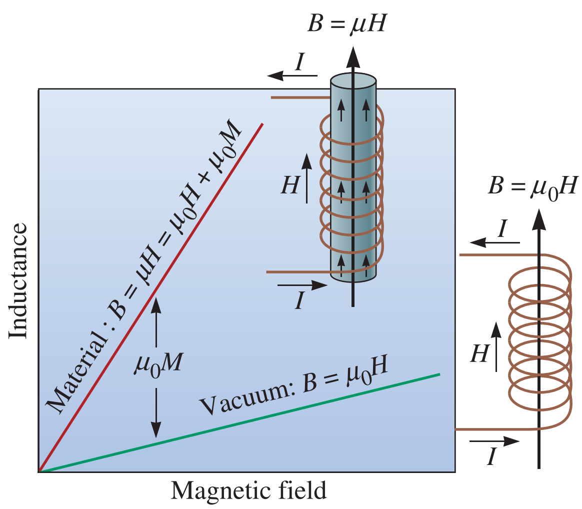


Figure 20-2 A current passing through a coil sets up a magnetic field H with a flux density B. The flux density is higher when a magnetic core is placed within the coil.

TABLE 20-2 ■ *Units, conversions, and values for magnetic materials*

	Gaussian and cgs emu (*Electromagnetic Units*)	*SI Units*	*Conversion*
Inductance or magnetic flux density (*B*)	gauss (G)	Tesla [or weber (Wb)/m^2]	1 tesla = 10^4 G, Wb/m^2
Magnetic flux (ϕ)	maxwell (Mx), G · cm^2	Wb, volt · second	1 Wb = 10^8 G-cm^2
Magnetic potential difference or magnetic electromotive force (*U, F*)	gilbert (Gb)	ampere (A)	1 A = $4\pi \times 10^{-1}$ Gb
Magnetic field strength, magnetizing force (*H*)	oersted (Oe), gilbert (Gb)/cm	A/m	1 A/m = $4\pi \times 10^{-3}$ Oe
(Volume) magnetization (*M*)	emu/cm^3	A/m	1 A/m = 10^{-3} emu/cm^3
(Volume) magnetization ($4\pi M$)	G	A/m	1 A/m = $4\pi \times 10^{-3}$ G
Magnetic polarization or intensity of magnetization (*J* or *I*)	emu/cm^3	T, Wb/m^2	1 tesla = $(1/4\pi) \times 10^4$ emu/cm^3
(Mass) magnetization (σ, *M*)	emu/g	A · m^2/kg Wb-m/kg	1 A · m^2/kg = 1 emu/g 1 Wb · m/kg = $(1/4\pi) \times 10^7$ emu/g
Magnetic moment (*m*)	emu, erg/G	A · m^2, Joules per tesla (J/T)	1 J/T = 10^3 emu
Magnetic dipole moment (*j*)	emu, erg/G	Wb · m	1 Wb · m = $(1/4\pi) \times 10^{10}$ emu
Magnetic permeability (μ)	Dimensionless	Wb/(A · m) [henry (H)/m]	1 Wb/(A · m) = $(1/4\pi) \times 10^7$
Magnetic permeability of free space (μ_0)	1 gauss/oersted	$\mu_0 = 4\pi \times 10^{-7}$ H/m	
Relative permeability (μ_r)	Not defined	Dimensionless	
(Volume) energy density, energy product (*W*)	erg/cm^3	J/m^3	1 J/m^3 = 10 erg/cm^3

where B is the inductance, H is the magnetic field, and μ_0 is a constant called the **magnetic permeability of vacuum**. If H is expressed in units of oersted, then B is in gauss and μ_0 is 1 gauss/oersted. In an alternate set of units, H is in A/m, B is in tesla (also called weber/m^2), and μ_0 is $4\pi \times 10^{-7}$ weber/(A · m) (also called henry/m).

When we place a material within the magnetic field, the magnetic-flux density is determined by the manner in which induced and permanent magnetic dipoles interact with the field. The flux density now is

$$B = \mu H \tag{20-4}$$

where μ is the permeability of the material in the field. If the magnetic moments reinforce the applied field, then $\mu > \mu_0$, a greater number of lines of flux that can accomplish work are created, and the magnetic field is magnified. If the magnetic moments oppose the field, however, $\mu < \mu_0$.

We can describe the influence of the magnetic material by the relative permeability μ_r, where

$$\mu_r = \frac{\mu}{\mu_0} \tag{20-5}$$

A large relative permeability means that the material amplifies the effect of the magnetic field. Thus, the relative permeability has the same importance that conductivity has in dielectrics. A material with higher magnetic permeability (e.g., iron) will carry magnetic flux more readily. We will learn later that the permeability of ferromagnetic or ferrimagnetic materials is not constant and depends on the value of the applied magnetic field (H).

The **magnetization** M represents the increase in the inductance due to the core material, so we can rewrite the equation for inductance as

$$B = \mu_0 H + \mu_0 M \tag{20-6}$$

The first part of this equation is simply the effect of the applied magnetic field. The second part is the effect of the magnetic material that is present. This is similar to our discussion on dielectric polarization and the mechanical behavior of materials. In materials, stress causes strain, electric field (E) induces dielectric polarization (P), and a magnetic field (H) causes magnetization ($\mu_0 M$) that contributes to the total flux density B.

The **magnetic susceptibility** χ_m, which is the ratio between magnetization and the applied field, gives the amplification produced by the material:

$$\chi_m = \frac{M}{H} \tag{20-7}$$

Both μ_r and χ_m refer to the degree to which the material enhances the magnetic field and are therefore related by

$$\mu_r = 1 + \chi_m \tag{20-8}$$

As noted before, the μ_r and, therefore, the χ_m values for ferromagnetic and ferrimagnetic materials depend on the applied field (H). For ferromagnetic and ferrimagnetic materials, the term $\mu_0 M \gg \mu_0 H$. Thus, for these materials,

$$B \cong \mu_0 M \tag{20-9}$$

We sometimes interchangeably refer to either inductance or magnetization. Normally, we are interested in producing a high inductance B or magnetization M. This is accomplished by selecting materials that have a high relative permeability or magnetic susceptibility.

The following example shows how these concepts can be applied for comparing actual and theoretical magnetizations in pure iron.

Example 20-1 *Theoretical and Actual Saturation Magnetization in Fe*

Calculate the maximum, or saturation, magnetization that we expect in iron. The lattice parameter of BCC iron is 2.866 Å. Compare this value with 2.1 tesla (a value of saturation flux density experimentally observed for pure Fe).

SOLUTION

Based on the unpaired electronic spins, we expect each iron atom to have four electrons that act as magnetic dipoles. The number of atoms per m^3 in BCC iron is

$$\text{Number of Fe atoms/m}^3 = \frac{2 \text{ atoms/cell}}{(2.866 \times 10^{-10}\text{m})^3} = 8.496 \times 10^{28}$$

The maximum volume magnetization (M_{sat}) is the total magnetic moment per unit volume:

$$M_{sat} = \left(8.496 \times 10^{28}\,\frac{\text{atoms}}{\text{m}^3}\right)(9.274 \times 10^{-24}\,\text{A}\cdot\text{m}^2)\left(4\,\frac{\text{Bohr magnetons}}{\text{atom}}\right)$$

$$M_{sat} = 3.15 \times 10^6\,\frac{\text{A}}{\text{m}}$$

To convert the value of saturation magnetization M into saturation flux density B in tesla, we need the value of $\mu_0 M$. In ferromagnetic materials $\mu_0 M \gg \mu_0 H$ and therefore, $B \cong \mu_0 M$.

Thus, the saturation induction or saturation flux density in tesla is given by $B_{sat} = \mu_0 M_{sat}$.

$$B_{sat} = \left(4\pi \times 10^{-7}\,\frac{\text{Wb}}{\text{A}\cdot\text{m}}\right)\left(3.15 \times 10^6\,\frac{\text{A}}{\text{m}}\right)$$

$$B_{sat} = 3.96\,\frac{\text{Wb}}{\text{m}^2} = 3.96\ \text{tesla}$$

This is almost two times the experimentally observed value of 2.1 tesla. Reversing our calculations, we can show that the each iron atom contributes only about 2.1 Bohr magneton and not 4. This is the difference between behavior of individual atoms and their behavior in a crystalline solid. It can be shown that in the case of iron, the difference is due to the $3d$ electron orbital moment being quenched in the crystal.

20-4 Diamagnetic, Paramagnetic, Ferromagnetic, Ferrimagnetic, and Superparamagnetic Materials

As mentioned before, there is no such thing as a "nonmagnetic" material. All materials respond to magnetic fields. When a magnetic field is applied to a material, several types of behavior are observed (Figure 20-3).

Diamagnetic Behavior A magnetic field acting on any atom induces a magnetic dipole for the entire atom by influencing the magnetic moment caused by the orbiting electrons. These dipoles oppose the magnetic field, causing the magnetization to be less than zero. This behavior, called **diamagnetism**, gives a relative permeability of about 0.99995 (or a negative susceptibility approximately -10^{-6}, note the negative sign). Materials such as copper, silver, silicon, gold, and alumina are diamagnetic at room temperature. Superconductors are perfect diamagnets ($\chi_m = -1$); they lose their superconductivity at higher temperatures or in the presence of a magnetic field. In a diamagnetic material, the magnetization (M) direction is opposite to the direction of applied field (H).

Paramagnetism When materials have unpaired electrons, a net magnetic moment due to electron spin is associated with each atom. When a magnetic field is applied,

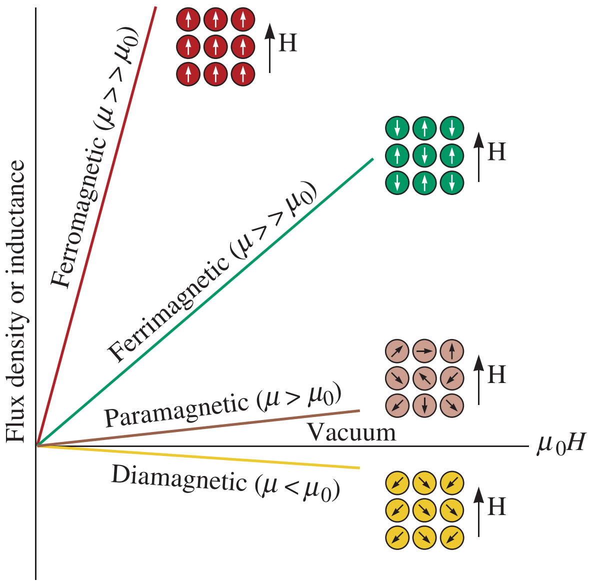


Figure 20-3
The effect of the core material on the flux density. The magnetic moment opposes the field in diamagnetic materials. Progressively stronger moments are present in paramagnetic, ferrimagnetic, and ferromagnetic materials for the same applied field.

the dipoles align with the field, causing a positive magnetization. Because the dipoles do not interact, extremely large magnetic fields are required to align all of the dipoles. In addition, the effect is lost as soon as the magnetic field is removed. This effect, called **paramagnetism**, is found in metals such as aluminum, titanium, and alloys of copper. The magnetic susceptibility (χ_m) of paramagnetic materials is positive and lies between 10^{-4} and 10^{-5}. Ferromagnetic and ferrimagnetic materials above the Curie temperature also exhibit paramagnetic behavior.

Ferromagnetism Ferromagnetic behavior is caused by the unfilled energy levels in the 3*d* level of iron, nickel, and cobalt. Similar behavior is found in a few other materials, including gadolinium (Gd). In ferromagnetic materials, the permanent unpaired dipoles easily line up with the imposed magnetic field due to the exchange interaction, or mutual reinforcement of the dipoles. Large magnetizations are obtained even for small magnetic fields, giving large susceptibilities approaching 10^6. Similar to ferroelectrics, the susceptibility of ferromagnetic materials depends upon the intensity of the applied magnetic field. This is similar to the mechanical behavior of elastomers with the modulus of elasticity depending upon the level of strain. Above the Curie temperature, ferromagnetic materials behave as paramagnetic materials and their susceptibility is given by the following equation, known as the Curie-Weiss law:

$$\chi_m = \frac{C}{(T - T_c)} \tag{20-10}$$

In this equation, C is a constant that depends upon the material, T_c is the Curie temperature, and T is the temperature above T_c. Essentially, the same equation also describes the change in dielectric permittivity above the Curie temperature of ferroelectrics. Similar to ferroelectrics, ferromagnetic materials show the formation of hystereis loop domains and magnetic domains. These materials will be discussed in the next section.

Antiferromagnetism In materials such as manganese, chromium, MnO, and NiO, the magnetic moments produced in neighboring dipoles line up in

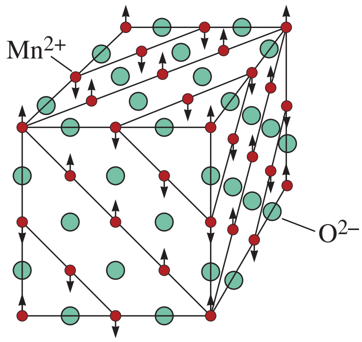


Figure 20-4
The crystal structure of MnO consists of alternating layers of {111} type planes of oxygen and manganese ions. The magnetic moments of the manganese ions in every other (111) plane are oppositely aligned. Consequently, MnO is antiferromagnetic.

opposition to one another in the magnetic field, even though the strength of each dipole is very high. This effect is illustrated for MnO in Figure 20-4. These materials are **antiferromagnetic** and have zero magnetization. The magnetic susceptibility is positive and small. In addition, CoO and $MnCl_2$ are examples of antiferromagnetic materials.

Ferrimagnetism

In ceramic materials, different ions have different magnetic moments. In a magnetic field, the dipoles of cation *A* may line up with the field, while dipoles of cation *B* oppose the field. Because the strength or number of dipoles is not equal, a net magnetization results. The **ferrimagnetic** materials can provide good amplification of the imposed field. We will look at a group of ceramics called ferrites that display this behavior in a later section. These materials show a large, magnetic-field dependent magnetic susceptibility similar to ferromagnetic materials. They also show Curie-Weiss behavior (similar to ferromagnetic materials) at temperatures above the Curie temperature. Most ferrimagnetic materials are ceramics and are good insulators of electricity. Thus, in these materials, electrical losses (known as eddy current losses) are much smaller compared to those in metallic ferromagnetic materials. Therefore, ferrites are used in many high-frequency applications.

Superparamagnetism

When the grain size of ferromagnetic and ferrimagnetic materials falls below a certain critical size, these materials behave as if they are paramagnetic. The magnetic dipole energy of each particle becomes comparable to the thermal energy. This small magnetic moment changes its direction randomly (as a result of the thermal energy). Thus, the material behaves as if it has no net magnetic moment. This is known as superparamagnetism. Thus, if we produce iron oxide (Fe_3O_4) particles in a 3 to 5 nm size, they behave as superparamagnetic materials. Such iron-oxide superparamagnetic particles are used to form dispersions in aqueous or organic carrier phases or to form "liquid magnets" or ferrofluids. The particles in the fluid move in response to a gradient in the magnetic field. Since the particles form a stable sol, the entire dispersion moves and, hence, the material behaves as a liquid magnet. Such materials are used as seals in computer hard drives and in loudspeakers as heat transfer (cooling) media. The permanent magnet used in the loudspeaker holds the liquid magnets in place. Superparamagnetic particles of iron oxide (Fe_3O_4) also can be coated with different chemicals and used to separate DNA molecules, proteins, and cells from other molecules.

The following example illustrates how to select a material for a given application.

Example 20-2 Design/Materials Selection for a Solenoid

We want to produce a solenoid coil that produces an inductance of at least 2000 gauss when a 10 mA current flows through the conductor. Due to space limitations, the coil should be composed of 10 turns over a 1 cm length. Select a core material for the coil. Refer to Table 20-4.

SOLUTION

First, we can determine the magnetic field H produced by the coil. From Equation 20-2,

$$H = \frac{nI}{l} = \frac{(10)(0.01\ \text{A})}{0.01\ \text{m}} = 10\ \text{A/m}$$

$$H = (10\ \text{A/m})[4\pi \times 10^{-3}\ \text{oersted/(A/m)}] = 0.12566\ \text{oersted}$$

If the inductance B must be at least 2000 gauss, then the permeability of the core material must be

$$\mu = \frac{B}{H} = \frac{2000}{0.12566} = 15{,}916\ \text{gauss/oersted}$$

The relative permeability of the core material must be at least

$$\mu_r = \frac{\mu}{\mu_0} = \frac{15{,}916}{1} = 15{,}916$$

If we examine the magnetic materials listed in Table 20-4, we find that 4750 alloy has a maximum relative permeability of 80,000 and might be a good selection for the core material.

20-5 Domain Structure and the Hysteresis Loop

From a phenomenological viewpoint, ferromagnetic materials are similar to ferroelectrics. A single crystal of iron or a polycrystalline piece of low-carbon steel is ferromagnetic; however, these materials ordinarily do not show a net magnetization. Within the single crystal or polycrystalline structure of a ferromagnetic or ferrimagnetic material, a substructure composed of magnetic domains is produced, even in the absence of an external field. This spontaneously happens because the presence of many domains in the material, arranged so that the net magnetization is zero, minimizes the magnetostatic energy. **Domains** are regions in the material in which all of the dipoles are aligned in a certain direction. In a material that has never been exposed to a magnetic field, the individual domains have a random orientation. Because of this, the net magnetization in the virgin ferromagnetic or ferrimagnetic material as a whole is zero [Figure 20-5(a)]. Similar to ferroelectrics, application of a magnetic field (poling) will coerce many of the magnetic domains to align with the magnetic field direction.

Boundaries, called **Bloch walls**, separate the individual magnetic domains. The Bloch 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 [Figure 20-5(b)]. The domains are typically very small, about 0.005 cm or less, while the Bloch walls are about 100 nm thick.

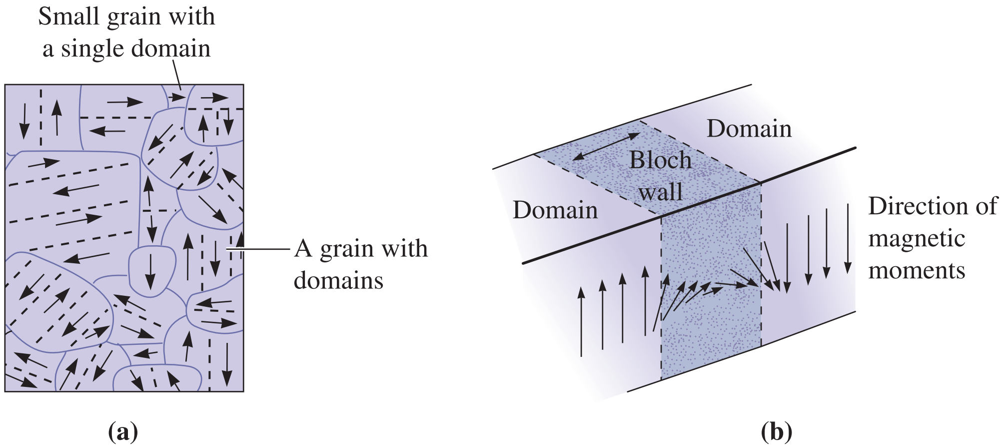


Figure 20-5 (a) A qualitative sketch of magnetic domains in a polycrystalline material. The dashed lines show demarcation between different magnetic domains; the dark curves show the grain boundaries. (b) The magnetic moments change direction continuously across the boundary between domains.

Movement of Domains in a Magnetic Field

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. In order for the domains to grow, the Bloch walls must move; the field provides the force required for this movement. Initially, the domains grow with difficulty, and relatively large increases in the field are required to produce even a little magnetization. This condition is indicated in Figure 20-6 by a shallow slope, which is the initial permeability of the material. As the field increases in strength, favorably oriented domains grow more easily, with permeability increasing as well. A maximum permeability can be defined as shown in the figure. Eventually, the unfavorably oriented domains disappear, and rotation completes the alignment of the domains with the field. The **saturation magnetization**, produced when all

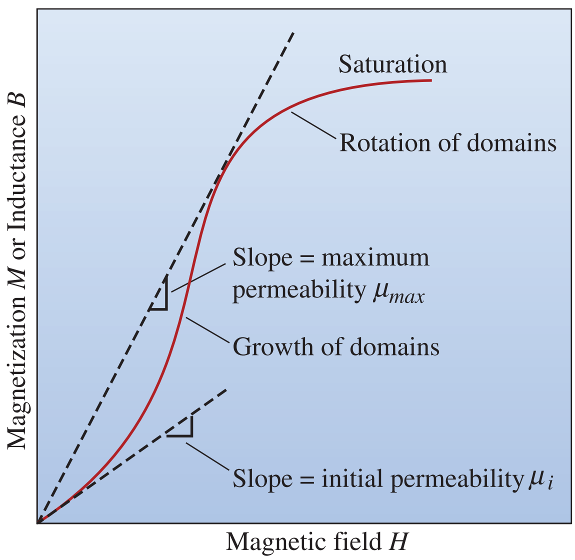


Figure 20-6 When a magnetic field is first applied to a magnetic material, magnetization initially increases slowly, then more rapidly as the domains begin to grow. Later, magnetization slows, as domains must eventually rotate to reach saturation. Notice the permeability values depend upon the magnitude of H.

of the domains are oriented along with the magnetic field, is the greatest amount of magnetization that the material can obtain. Under these conditions, the permeability of these materials becomes quite small.

Effect of Removing the Field

When the field is removed, the resistance offered by the domain walls prevents regrowth of the domains into random orientations. As a result, many of the domains remain oriented near the direction of the original field and a residual magnetization, known as the **remanance** (M_r) is present in the material. The value of B_r (usually in Tesla) is known as the retentivity of the magnetic material. The material acts as a permanent magnet. Figure 20-7(a) shows this effect in the magnetization-field curve. Notice that the *M-H* loop shows saturation, but the *B-H* loop does not. The magnetic field needed to bring the induced magnetization to zero is the **coercivity** of the material. This is a microstructure-sensitive property.

For magnetic recording materials, Fe, γ-Fe_2O_3, Fe_3O_4, and needle-shaped CrO_2 particles are used. The elongated shape of magnetic particles leads to higher coercivity (H_c). The dependence of coercivity on the shape of a particle or grain is known as **magnetic shape anisotropy**. The coercivity of recording materials needs to be smaller than that for permanent magnets since data written onto a magnetic data storage medium should be erasable. On the other hand, the coercivity values should be higher than soft magnetic materials since we want to retain the information stored. Such materials are described as magnetically semi-hard.

Effect of Reversing the Field

If we now apply a field in the reverse direction, the domains grow with an alignment in the opposite direction. A coercive field H_c (or coercivity) is required to force the domains to be randomly oriented and cancel

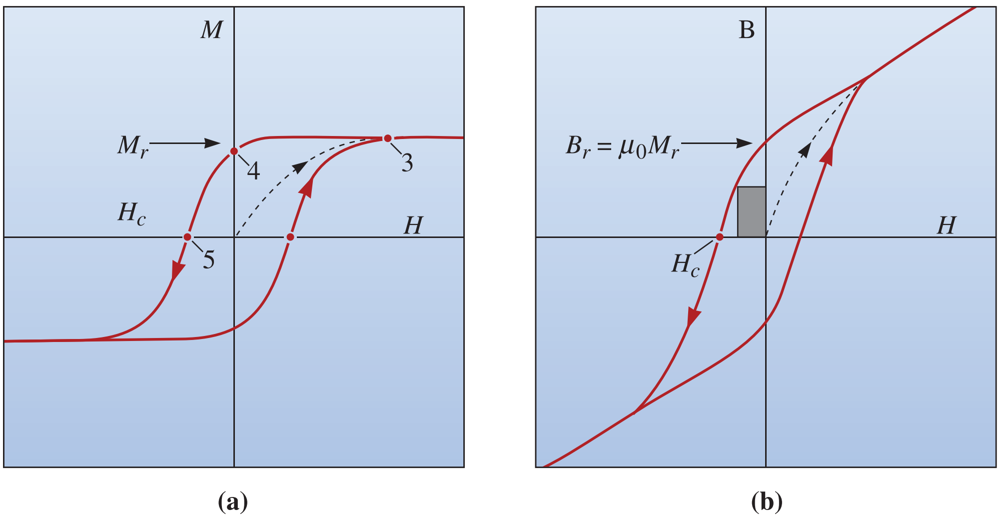


Figure 20-7 (a) The ferromagnetic hysteresis *M-H* loop showing the effect of the magnetic field on inductance or magnetization. The dipole alignment leads to saturation magnetization (point 3), a remanance (point 4), and a coercive field (point 5). (b) The corresponding *B-H* loop. Notice the *B* value does not saturate since $B = \mu_0 H + \mu_0 M$. (*Adapted from Permanent Magnetism, by R. Skomski and J.M.D. Coey, p. 3, Fig. 1-1. Edited by J.M.D. Coey and D.R. Tilley. Copyright © 1999 Institute of Physics Publishing. Adapted by permission.*)

one another's effect. Further increases in the strength of the field eventually align the domains to saturation in the opposite direction.

As the field continually alternates, the magnetization versus field relationship traces out a **hysteresis loop**. The hysteresis loop is shown as both *B*-*H* and *M*-*H* plots. The area contained within the hysteresis loop is related to the energy consumed during one cycle of the alternating field. The shaded area shown in Figure 20-7(b) is the largest *B*-*H* product and is known as the power of the magnetic material.

20-6 The Curie Temperature

When the temperature of a ferromagnetic or ferrimagnetic material is increased, the added thermal energy increases the mobility of the domains, making it easier for them to become aligned, but also preventing them from remaining aligned when the field is removed. Consequently, saturation magnetization, remanance, and the coercive field are all reduced at high temperatures (Figure 20-8). If the temperature exceeds the **Curie temperature** (T_c), ferromagnetic or ferrimagnetic behavior is no longer observed. Instead, the material behaves as a paramagnetic material. The Curie temperature (Table 20-3), which depends on the material, can be changed by alloying elements. French scientists Marie and Pierre Curie (the only husband and wife to win a Nobel prize; Marie Curie actually won two Nobel prizes) performed research on magnets, and the Curie temperature refers to their name. The dipoles still can be aligned in a magnetic field above the Curie temperature, but they become randomly aligned when the field is removed.

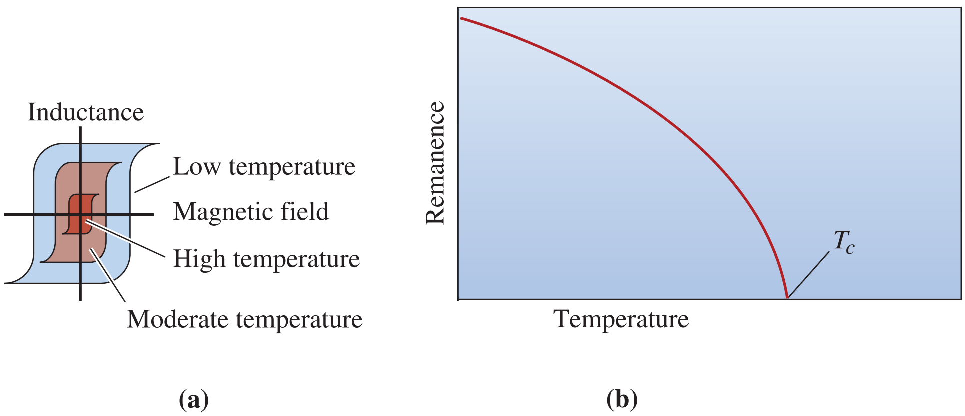


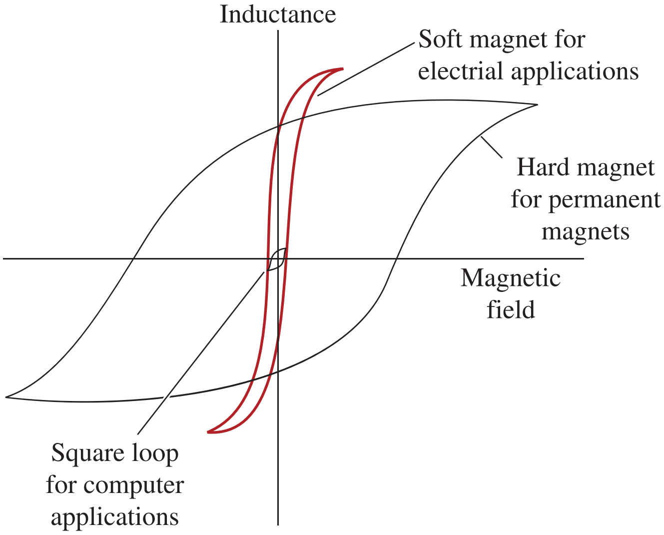
Figure 20-8 The effect of temperature on (a) the hysteresis loop and (b) the remanance. Ferromagnetic behavior disappears above the Curie temperature.

TABLE 20-3 ■ ***Curie temperatures for selected materials***

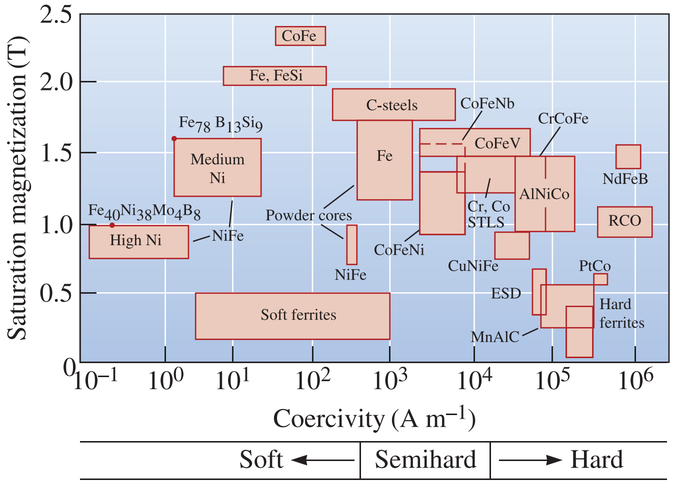
Material	Curie Temperature (°C)	Material	Curie Temperature (°C)
Gadolinium	16	Iron	771
$Nd_2Fe_{12}B$	312	Alnico 1	780
Nickel	358	Cunico	855
$BaO \cdot 6Fe_2O_3$	469	Alnico 5	900
Co_5Sm	747	Cobalt	1117

20-7 Applications of Magnetic Materials

Ferromagnetic and ferrimagnetic materials are classified as magnetically soft or magnetically hard depending upon the shape of the hysteresis loop [Figure 20-9(a)]. Generally, if the coercivity value is $\sim > 10^4\ \mathrm{A \cdot m^{-1}}$, we consider the material as magnetically hard. If the coercivity values are less than $10^3\ \mathrm{A \cdot m^{-1}}$, we consider the materials as magnetically soft. Figure 20-9(b) shows classification of different commercially important magnetic materials. Note that while the coercivity is a strongly *microstructure-sensitive* property, the saturation magnetization is constant (i.e., it is not microstructure dependent) for a material of a given composition. This is similar to the way the yield strength of metallic materials is strongly dependent on the



(a)



(b)

Figure 20-9
(a) Comparison of the hysteresis loops for three applications of ferromagnetic and ferrimagnetic materials. (b) Saturation magnetization and coercivity values for different magnetic materials. (*Adapted from "Magnetic Materials: An Overview, Basic Concepts, Magnetic Measurements, Magnetostrictive Materials," by G.Y. Chin et al. In D. Bloor, M. Flemings, and S. Mahajan (Eds.),* Encyclopedia of Advanced Materials, *Vol. 1, 1994, p. 1424, Table 1. Copyright © 1994 Pergamon Press. Reprinted with permission of the editor.*)

microstructure, while the Young's modulus is not. Many factors, such as the structure of grain boundaries and the presence of pores or surface layers on particles, affect the coercivity values. The coercivity of single crystals depends strongly on crystallographic directions. There are certain directions along which it is easy to align the magnetic domains. There are other directions along which the coercivity is much higher. Coercivity of magnetic particles also depends upon shape of the particles. This is why in magnetic recording media we use acicular and not spherical particles. This effect is also used in Fe-Si steels, which are textured or grain oriented so as to minimize energy losses during the operation of an electrical transformer.

Let's look at some applications for magnetic materials.

Soft Magnetic Materials

Ferromagnetic materials are often used to enhance the magnetic flux density (B) produced when an electric current is passed through the material. The magnetic field is then expected to do work. Applications include cores for electromagnets, electric motors, transformers, generators, and other electrical equipment. Because these devices utilize an alternating field, the core material is continually cycled through the hysteresis loop. Table 20-4 shows the properties of selected soft, magnetic materials. *Note that in these materials the value of relative magnetic permeability depends strongly on the strength of the applied field* (Figure 20-6).

These materials often have the following characteristics:

1. High-saturation magnetization.
2. High permeability.
3. Small coercive field.

TABLE 20-4 *Properties of selected soft magnetic materials*

Name	Composition	Permeability μ_r Initial	Permeability μ_r Maximum	Coercivity $H_c (A \cdot m^{-1})$	Retentivity B_r (T)	B_{max} (T)	Resistivity $(\mu\Omega \cdot m)$
Ingot Iron	99.8% Fe	150	5000	80	0.77	2.14	0.10
Low-carbon steel	99.5% Fe	200	4000	100		2.14	1.12
Silicon iron, unoriented	Fe-3% Si	270	8000	60		2.01	0.47
Silicon iron, grain-oriented	Fe-3% Si	1400	50,000	7	1.20	2.01	0.50
4750 alloy	Fe-48% Ni	11,000	80,000	2		1.55	0.48
4-79 permalloy	Fe-4% Mo-79% Ni	40,000	200,000	1		0.80	0.58
Superalloy	Fe-5% Mo-80% Ni	80,000	450,000	0.4		0.78	0.65
2V-Permendur	Fe-2% V-49% Co	800	450,000	0.4		0.78	0.65
Supermendur	Fe-2% V-49% Co		100,000	16	2.00	2.30	0.40
Metglas[a] 2650SC	$Fe_{81}B_{13.5}Si_{3.5}C_2$		300,000	3	1.46	1.61	1.35
Metglas[a] 2650S-2	$Be_{78}B_{13}S_9$		600,000	2	1.35	1.56	1.37
MnZn Ferrite	H5C2[b]	10,000		7	0.09	0.40	1.5×10^5
MnZn Ferrite	H5E[b]	18,000		3	0.12	0.44	5×10^4
NiZn Ferrite	K5[b]	290		80	0.25	0.33	2×10^{12}

[a] *Allied Corporation trademark.*
[b] *TDK ferrite code.*
(Adapted from "Magnetic Materials: An Overview, Basic Concepts, Magnetic Measurements, Magnetostrictive Materials," by G.Y. Chin et al. In R. Bloor, M. Flemings, and S. Mahajan (Eds.), Encyclopedia of Advanced Materials, *Vol. 1, 1994, p. 1424, Table 1. Copyright © 1994 Pergamon Press. Reprinted with permission of the editor.)*

4. Small remanance.
5. Small hysteresis loop.
6. Rapid response to high-frequency magnetic fields.
7. High electrical resistivity.

High saturation magnetization permits a material to do work, while high permeability permits saturation magnetization to be obtained with small imposed magnetic fields. A small coercive field also indicates that domains can be reoriented with small magnetic fields. A small remanance is desired so that almost no magnetization remains when the external field is removed. These characteristics also lead to a small hysteresis loop, therefore minimizing energy losses during operation.

If the frequency of the applied field is so high that the domains cannot be realigned in each cycle, the device may heat due to dipole friction. In addition, higher frequencies naturally produce more heating because the material cycles through the hysteresis loop more often, losing energy during each cycle. For high frequency applications, materials must permit the dipoles to be aligned at exceptionally rapid rates.

Energy can also be lost by heating if eddy currents are produced. During operation, electrical currents can be induced into the magnetic material. These currents produce power losses and Joule, or I^2R, heating. Eddy current losses are particularly severe when the material operates at high frequencies. If the electrical resistivity is high, eddy current losses can be held to a minimum. Soft magnets produced from ferrimagnetic ceramic materials have a high resistivity and therefore are less likely to heat than metallic ferromagnetic materials. Recently, a class of smart materials, known as magnetorheological or MR fluids based on soft magnetic carbonyl iron (Fe) particles, has been introduced in various applications related to vibration control, such as Delphi's MagneRide™ system. These materials are like magnetic paints and can be made to absorb energy from shocks and vibrations by turning on a magnetic field. The stiffening of MR fluids is controllable and reversible. Some of the models of Cadillac and Corvette ofter a suspension based on these smart materials.

Data Storage Materials

Magnetic materials are used for data storage. Memory is stored by magnetizing the material in a certain direction. For example, if the "north" pole is up, the bit of information stored is 1. If the "north" pole is down, then a 0 is stored.

For this application, materials with a square hysteresis loop, a low remanance, a low saturation magnetization, and a low coercive field are preferable. Hard ferrites based on Ba, CrO_2, acicular iron particles, and γ-Fe_2O_3 satisfy these requirements. The stripe on credit cards and bank machine cards are made using γ-Fe_2O_3 or Fe_3O_4 particles. The square loop ensures that a bit of information placed in the material by a field remains stored; a steep and abrupt change in magnetization is required to remove the information from storage in the ferromagnet. Furthermore, the magnetization produced by small external fields keeps the coercive field (H_c), saturation magnetization, and remanance (B_r) low.

The B_r and H_c values of some typical magnetic recording materials are shown in Table 20-5.

Many new alloys based on Co-Pt-Ta-Cr have been developed for the manufacture of hard disks. Computer hard disks are made using sputtered thin films of these materials. As discussed in earlier chapters, many different alloys, such as those based on nanostructured Fe-Pt and Fe-Pd, are being developed for data storage applications. More recently, a technology known as *spintronics* (*spin-based electronics*) has evolved. In spintronics, the main idea is to make use of the spin of electrons as a way of affecting the flow of electrical

TABLE 20-5 ■ ***Properties of typical magnetic recording materials in a powder form***

	Particle Length (μm)	Aspect Ratio	Magnetization B_r (Wb/m^2)	(emu/cm^3)	Coercivity H_c (kA/m)	(Oe)	Surface Area (m^2/g)	Curie Temp. T_c(°C)
γ-Fe_2O_3	0.20	5:1	0.44	350	22–34	420	15–30	600
Co-γ-Fe_2O_3	0.20	6:1	0.48	380	30–75	940	20–35	700
CrO_2	0.20	10:1	0.50	400	30–75	950	18–55	125
Fe	0.15	10:1	1.40[a]	1100[a]	56–176	2200	20–60	770
Barium Ferrite	0.05	0.02 μm thick	0.40	320	56–240	3000	20–25	350

[a]*For overcoated, stable particles use only 50 to 80% of these values due to reduced magnetic particle volume (From* The Complete Handbook of Magnetic Recording, Fourth Edition, *by F. Jorgensen, p. 324, Table 11-1. Copyright © 1996. The McGraw-Hill Companies. Reprinted by permission of The McGraw-Hill Companies.)*

current (known as spin-polarized current) to make devices such as field effect transistors (FET). The spin of the electrons (up or down) is also being considered as a way of storing information. A very successful example of a real-world spintronic-based device is a giant magnetoresistance (GMR) sensor that is used for reading information from computer hard disks.

Permanent Magnets

Finally, magnetic materials are used to make strong permanent magnets (Table 20-6). Strong permanent magnets, often called hard magnets, require the following:

1. High remanance (stable domains).
2. High permeability.
3. High coercive field.
4. Large hysteresis loop.
5. High power (or BH product).

The *record* for any energy product is obtained for $Nd_2Fe_{14}B$ magnets with an energy product of $\sim$445 kJ $\cdot$ m^{-3} [$\sim$56 Mega-Gauss-Oersteds (MGOe)]. These magnets are made in the form of a powder by the rapid solidification of a molten alloy. Powders are either bonded in a polymer matrix or by hot pressing, producing bulk materials. The

TABLE 20-6 ■ ***Properties of selected hard, or permanent, or magnetic materials***

Material	Common Name	$\mu_0 M_r$ (T)	$\mu_0 H_c$ (T)	$(BH)_{max}$ (kJ $\cdot$ m^{-3})	T_c (°C)
Fe-Co	Co-steel	1.07	0.02	6	887
Fe-Co-Al-Ni	Alnico-5	1.05	0.06	44	880
$BaFe_{12}O_{19}$	Ferrite	0.42	0.31	34	469
$SmCo_5$	Sm-Co	0.87	0.80	144	723
$Nd_2Fe_{14}B$	Nd-Fe-B	1.23	1.21	290–445	312

(Adapted from Permanent Magnetism, *by R. Skomski and J.M.D. Coey, p. 23, Table 1-2. Edited by J.M.D. Coey and D.R. Tilley. Copyright © 1999 Institute of Physics Publishing. Adapted by permission.)*

energy product increases when the sintered magnet is "oriented" or poled. Corrosion resistance, brittleness, and a relatively low Curie temperature of ~312°C are some of the limiting factors of this extraordinary material.

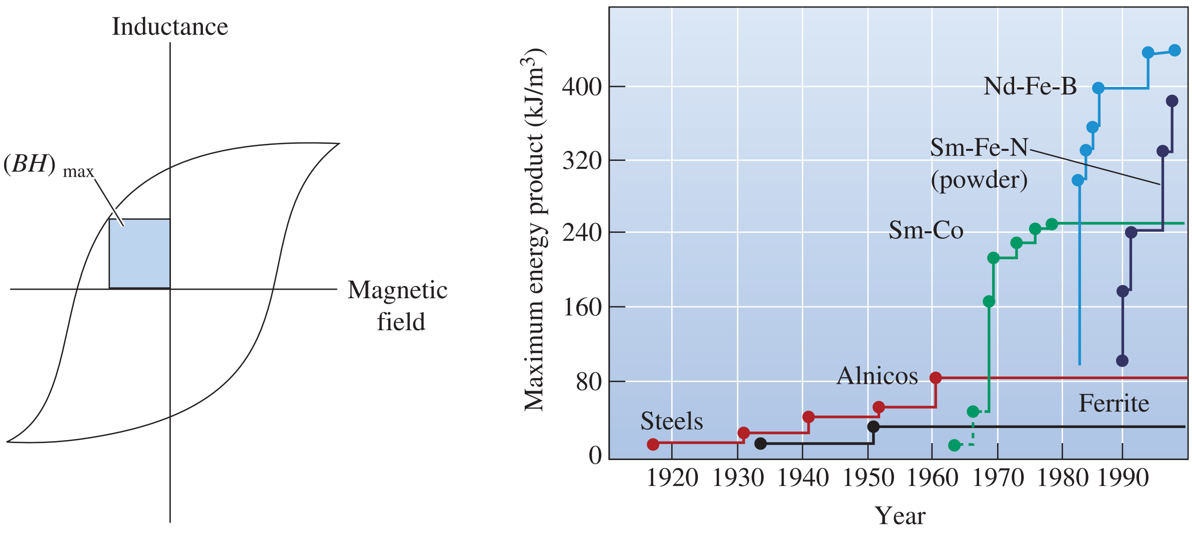
The **power** of the magnet is related to the size of the hysteresis loop, or the maximum product of B and H. The area of the largest rectangle that can be drawn in the second or fourth quadrants of the B-H curve is related to the energy required to demagnetize the magnet [Figure 20-10(a) and Figure 20-10(b)]. For the product to be large, both the remanance and the coercive field should be large.

In many applications, we need to calculate the lifting power of a permanent magnet. The magnetic force obtainable using a permanent magnet is given by

$$F = \frac{\mu_0 M^2 A}{2} \tag{20-11}$$

In this equation A is the cross-sectional area of the magnet, M is the magnetization, and μ_0 is the magnetic permeability of free space.

One of the most successful examples of the contributions by materials scientists and engineers in this area is the development of strong rare earth magnets. The progress made in the development of strong permanent magnets is illustrated in Figure 20-10(b). Permanent magnets are used in many applications including loudspeakers, motors, generators, holding magnets, mineral separation, and bearings. Typically, they offer a nonuniform magnetic field; however, it is possible to use geometric arrangements known as Halbach arrays to produce relatively uniform magnetic fields. The following examples illustrate applications of some of these concepts related to permanent magnetic materials.



(a) **(b)**

Figure 20-10 (a) The largest rectangle drawn in the second or fourth quadrant of the B-H curve gives the maximum BH product. $(BH)_{max}$ is related to the power, or energy, required to demagnetize the permanent magnet. (b) Development of permanent magnet materials. The maximum energy product is shown on the vertical axis. (*Adapted from* Permanent Magnetism, *by R. Skomski and J.M.D. Coey, p. 25, Fig. 1-15. Edited by J.M.D. Coey and D.R. Tilley. Copyright © 1999 Institute of Physics Publishing. Adapted by permission.)*

Example 20-3 Energy Product for Permanent Magnets

Determine the power, or *BH* product, for the magnetic material with the properties shown in Figure 20-11.

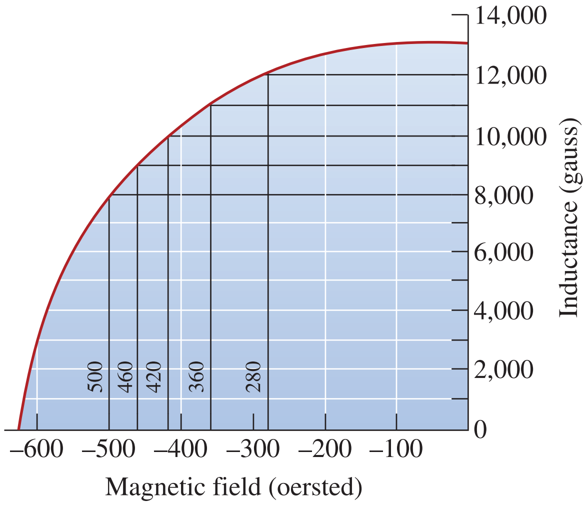


Figure 20-11 The fourth quadrant of the *B-H* curve for a permanent magnetic material (for Example 20-3).

SOLUTION

Several rectangles have been drawn in the fourth quadrant of the *B-H* curve. The *BH* product in each is

$$BH_1 = (12{,}000)(280) = 3.4 \times 10^6 \text{ gauss} \cdot \text{oersted}$$
$$BH_2 = (11{,}000)(360) = 4.0 \times 10^6 \text{ gauss} \cdot \text{oersted}$$
$$BH_3 = (10{,}000)(420) = 4.2 \times 10^6 \text{ gauss} \cdot \text{oersted} = \text{maximum}$$
$$BH_4 = (9{,}000)(460) = 4.1 \times 10^6 \text{ gauss} \cdot \text{oersted}$$
$$BH_5 = (8{,}000)(500) = 4.0 \times 10^6 \text{ gauss} \cdot \text{oersted}$$

Thus, the power is about 4.2×10^6 gauss · oersted.

Example 20-4 Design/Selection of Magnetic Materials

Select an appropriate magnetic material for the following applications: a high electrical-efficiency motor, a magnetic device to keep cupboard doors closed, a magnet used in an ammeter or voltmeter, and magnetic resonance imaging.

SOLUTION

High electrical-efficiency motor: To minimize hysteresis losses, we might use an oriented silicon iron, taking advantage of its anisotropic behavior and its small hysteresis loop. Since the iron-silicon alloy is electrically conductive, we would produce a laminated structure with thin sheets of the silicon iron sandwiched between a nonconducting dielectric material. Sheets thinner than about 0.5 mm might be recommended.

Magnet for cupboard doors: The magnetic latches used to fasten cupboard doors must be permanent magnets; however, low cost is a more important design feature than high power. An inexpensive ferritic steel or a low-cost ferrite would be recommended.

Magnets for an ammeter or voltmeter: For these applications, alnico alloys are particularly effective. We find that these alloys are among the least sensitive to changes in temperature, ensuring accurate current or voltage readings over a range of temperatures.

Magnetic resonance imaging: One of the applications for MRI is in medical diagnostics. In this case, we want a very powerful magnet. A $Nd_2Fe_{12}B$ magnetic material, which has an exceptionally high *BH* product, might be recommended for this application. We can also make use of very strong electromagnets fabricated from superconductors.

The example that follows shows how the lifting power of a permanent magnet can be calculated.

Example 20-5 *Lifting Power of a Magnet*

Calculate the force in kN for one square meter area of a permanent magnet with a saturation magnetization of 1.61 tesla.

SOLUTION

As noted before, the attractive force from a permanent magnet is given by

$$F = \frac{\mu_0 M^2 A}{2}$$

We have been given the value of $\mu_0 M = 1.61$ tesla. We can rewrite the equation that provides the force due to a permanent magnet as follows:

$$F = \frac{\mu_0 M^2 A}{2} = \frac{(\mu_0 M)^2 A}{2\mu_0}$$

$$\therefore \frac{F}{A} = \frac{(1.61\ \mathrm{T})^2}{2\left(4\pi \times 10^{-7}\ \dfrac{\mathrm{H}}{\mathrm{m}}\right)} = 1031.4\ \frac{\mathrm{kN}}{\mathrm{m}^2}$$

Note that the force in this case will be 1031 kN since the area (A) has been specified as 1 m^2.

20-8 Metallic and Ceramic Magnetic Materials

Let's look at typical alloys and ceramic materials used in magnetic applications and discuss how their properties and behavior can be enhanced. Some polymeric materials have shown magnetic activity; however, the Curie temperatures of these materials are too low compared to those for metallic and ceramic magnetic materials.

Magnetic Alloys

Pure iron, nickel, and cobalt are not usually used for electrical applications because they have high electrical conductivities and relatively large hysteresis loops, leading to excessive power loss. They are relatively poor permanent magnets; the domains are easily reoriented and both the remanance and the *BH* product are small compared with those of more complex alloys. Some change in the magnetic properties is obtained by introducing defects into the structure. Dislocations, grain boundaries, boundaries between multiple phases, and point defects help pin the domain boundaries, therefore keeping the domains aligned when the original magnetizing field is removed.

Iron-Nickel Alloys. Some iron-nickel alloys, such as Permalloy, have high permeabilities, making them useful as soft magnets. One example of an application for these magnets is the "head" that stores or reads information on a computer disk (Figure 20-12). As the disk rotates beneath the head, a current produces a magnetic field in the head. The magnetic field in the head, in turn, magnetizes a portion of the disk. The direction of the field produced in the head determines the orientation of the magnetic particles embedded in the disk and, consequently, stores information. The information can be retrieved by again spinning the disk beneath the head. The magnetized region in the disk induces a current in the head; the direction of the current depends on the direction of the magnetic field in the disk.

Silicon Iron. Silicon irons are processed into grain-oriented steels. Introduction of 3 to 5% Si into iron produces an alloy that, after proper processing, is useful in electrical applications such as motors and generators. We take advantage of the anisotropic magnetic behavior of silicon iron to obtain the best performance. As a result of rolling and subsequent annealing, a sheet texture is formed in which the $\langle 100 \rangle$ directions in each grain are aligned. Because the silicon iron is most easily magnetized in $\langle 100 \rangle$ directions, the field

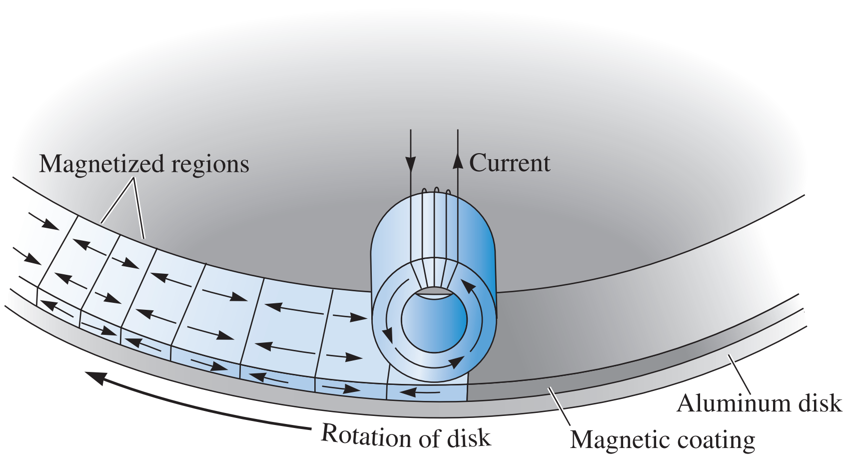


Figure 20-12 Information can be stored or retrieved from a magnetic disk by use of an electromagnetic head. A current in the head magnetizes domains in the disk during storage; the domains in the disk induce a current in the head during retrieval.

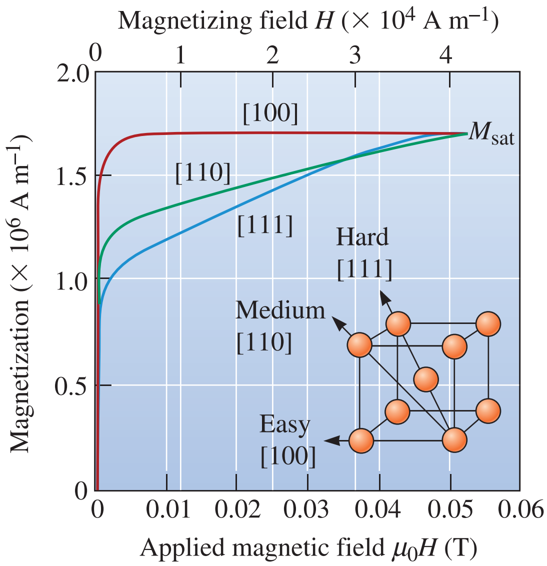


Figure 20-13
The initial magnetization curve for iron is highly anisotropic; magnetization is easiest when the ⟨100⟩ directions are aligned with the field and hardest along [111]. (*From* Principles of Electrical Engineering Materials and Devices, *by S.O. Kasap, p. 623, Fig. 8-24. Copyright © 1997 Irwin. Reprinted by permission of The McGraw-Hill Companies.*)

required to give saturation magnetization is very small, and both a small hysteresis loop and a small remanance are observed (Figure 20-13). This type of anisotropy is known as **magnetocrystalline anisotropy**.

Composite Magnets. Composite magnets are used to reduce eddy current losses. Thin sheets of silicon iron are laminated with sheets of a dielectric material. The laminated layers are then built up to the desired overall thickness. The laminate increases the resistivity of the composite magnets and makes them successful at low and intermediate frequencies.

At very high frequencies, losses are more significant because the domains do not have time to realign. In this case, a composite material containing domain-sized magnetic particles in a polymer matrix may be used. The particles, or domains, rotate easily, while eddy current losses are minimized because of the high resistivity of the polymer.

Data Storage Materials. Magnetic materials for information storage must have a square loop and a low coercive field, permitting very rapid transmission of information. Magnetic tape for audio or video applications is produced by evaporating, sputtering, or plating particles of a magnetic material such as γ-Fe_2O_3 or CrO_2 onto a polyester tape.

Hard disks for computer data storage are produced in a similar manner. In a hard disk, magnetic particles are embedded in a polymer film on a flat aluminum substrate. Because of the polymer matrix and the small particles, the domains can rotate quickly in response to a magnetic field. These materials are summarized in Table 20-5.

Complex Metallic Alloys for Permanent Magnets. Improved permanent magnets are produced by making the grain size so small that only one domain is present in each grain. Now the boundaries between domains are grain boundaries rather than Bloch walls. The domains can change their orientation only by rotating, which requires greater energy than domain growth. Two techniques are used to produce these magnetic materials: phase transformations and powder metallurgy. Alnico, one of the most common of the complex metallic alloys, has a single-phase BCC structure at high temperatures, but when alnico slowly cools below 800°C, a second BCC phase rich in iron

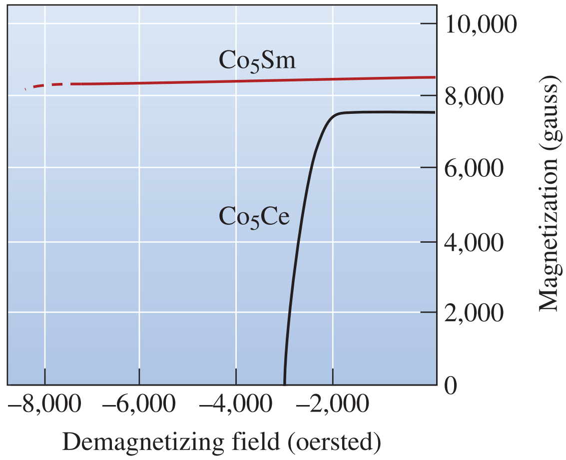


Figure 20-14
Demagnetizing curves for Co_5Sm and Co_5Ce, representing a portion of the hysteresis loop.

and cobalt precipitates. This second phase is so fine that each precipitate particle is a single domain, producing a very high remanance, coercive field, and power. Often the alloys are permitted to cool and transform while in a magnetic field to align the domains as they form.

A second technique—powder metallurgy—is used for a group of rare earth metal alloys, including samarium-cobalt. A composition giving Co_5Sm, an intermetallic compound, has a high *BH* product (Figure 20-14) due to unpaired magnetic spins in the 4*f* electrons of samarium. The brittle intermetallic is crushed and ground to produce a fine powder in which each particle is a domain. The powder is then compacted while in an imposed magnetic field to align the powder domains. Careful sintering to avoid growth of the particles produces a solid-powder metallurgy magnet. Another rare earth magnet based on neodymium, iron, and boron has a *BH* product of 45 mega-gauss-oersted (MGOe). In these materials, a fine-grained intermetallic compound, $Nd_2Fe_{14}B$, provides the domains, and a fine HfB_2 precipitate prevents movement of the domain walls.

Ferrimagnetic Ceramic Materials

Common magnetic ceramics are the ferrites, which have a spinel crystal structure (Figure 20-15). These ferrites have nothing to do with the *ferrite phase* we encountered in studying the Fe-C phase diagram (Chapters 12 and 13). Ferrites are used in wireless communications and in microelectronics in such applications as inductors. Ferrite powders are made using ceramic processing techniques.

We can understand the behavior of these ceramic magnets by looking at magnetite, Fe_3O_4. Magnetite contains two different iron ions, Fe^{2+} and Fe^{3+}, so we could rewrite the formula for magnetite as $Fe^{2+}Fe_2^{3+}O_4^{2-}$. The magnetite, or spinel, crystal structure is based on an FCC arrangement of oxygen ions, with iron ions occupying selected interstitial sites. Although the spinel unit cell actually contains eight of the FCC arrangements, we need examine only one of the FCC subcells:

1. Four oxygen ions are in the FCC positions of the subcell.
2. Octahedral sites, which are surrounded by six oxygen ions, are present at each edge and the center of the subcell. One Fe^{2+} and one Fe^{3+} ion occupy octahedral sites.

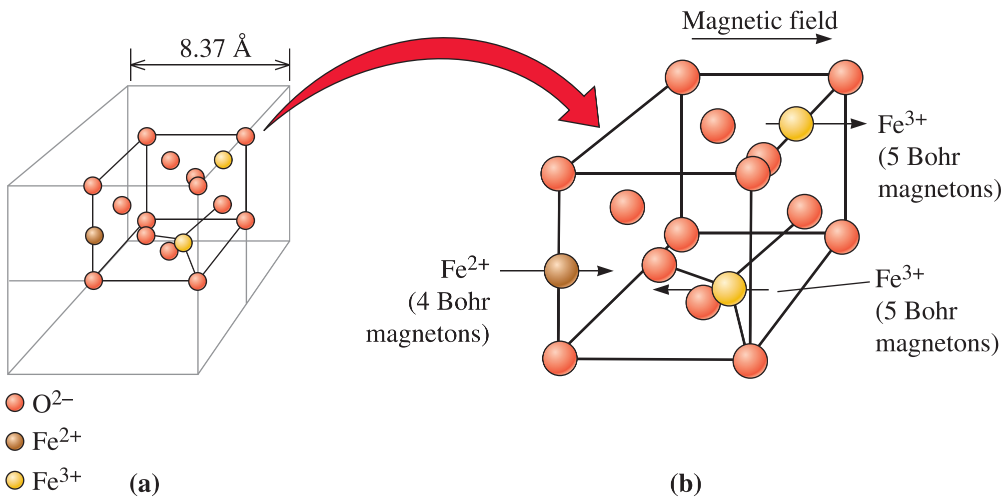


Figure 20-15 (a) The structure of magnetite, Fe_3O_4. (b) The subcell of magnetite. The magnetic moments of ions in the octahedral sites line up with the magnetic field, but the magnetic moments of ions in tetrahedral sites oppose the field. A net magnetic moment is produced by this ionic arrangement.

3. Tetrahedral sites have positions in the subcell such as (1/4, 1/4, 1/4). One Fe^{3+} ion occupies one of the tetrahedral sites.
4. When Fe^{2+} ions form, the two 4*s* electrons of iron are removed, but all of the 3*d* electrons remain. Because there are four unpaired electrons in the 3*d* level of iron, the magnetic strength of the Fe^{2+} dipole is four Bohr magnetons. When Fe^{3+} forms, both 4*s* electrons and one of the 3*d* electrons are removed. The Fe^{3+} ion has five unpaired electrons in the 3*d* level and, thus, has a strength of five Bohr magnetons.
5. The ions in the tetrahedral sites of the magnetite line up so that their magnetic moments oppose the applied magnetic field, but the ions in the octahedral sites reinforce the field [Figure 20-15(b)]. Consequently, the Fe^{3+} ion in the tetrahedral site neutralizes the Fe^{3+} ion in the octahedral site (the Fe^{3+} ion coupling is antiferromagnetic). The Fe^{2+} ion in the octahedral site is not opposed by any other ion, and it therefore reinforces the magnetic field. The following example shows how we can calculate the magnetization in Fe_3O_4, which is one of the ferrites.

Example 20-6 *Magnetization in Magnetite (Fe_3O_4)*

Calculate the total magnetic moment per cubic centimeter in magnetite. Calculate the value of the saturation flux density (B_{sat}) for this material.

SOLUTION

In the subcell [Figure 20-15(b)], the total magnetic moment is four Bohr magnetons obtained from the Fe^{2+} ion, since the magnetic moments from the two Fe^{3+} ions located at tetrahedral and octahedral sites are canceled by each other.

In the unit cell overall, there are eight subcells, so the total magnetic moment is 32 Bohr magnetons per cell.

The size of the unit cell, with a lattice parameter of 8.37×10^{-8} cm is

$$V_{cell} = (8.37 \times 10^{-8})^3 = 5.86 \times 10^{-22}\,\text{cm}^3$$

The magnetic moment per cubic centimeter is

$$\begin{aligned}\text{Total moment} &= \frac{32 \text{ Bohr magnetons/cell}}{5.86 \times 10^{-22}\,\text{cm}^3/\text{cell}} = 5.46 \times 10^{22}\,\text{magnetons/cm}^3 \\ &= (5.46 \times 10^{22})(9.274 \times 10^{-24}\ \text{A} \cdot \text{m}^2/\text{magneton}) \\ &= 0.51\,\text{A} \cdot \text{m}^2/\text{cm}^3 = 5.1 \times 10^5\,\text{A} \cdot \text{m}^2/\text{m}^3 = 5.1 \times 10^5\,\text{A/m}\end{aligned}$$

This expression represents the magnetization M at saturation (M_{sat}). The value of $B_{sat} \simeq \mu_0 M_{sat}$ will be $= (4\pi \times 10^{-7})(5.1 \times 10^5) = 0.64$ Tesla.

When ions are substituted for Fe^{2+} ions in the spinel structure, the magnetic behavior may be changed. Ions that may not produce ferromagnetism in a pure metal may contribute to ferrimagnetism in the spinels, as shown by the magnetic moments in Table 20-7. Soft magnets are obtained when the Fe^{2+} ion is replaced by various mixtures of manganese, zinc, nickel, and copper. The nickel and manganese ions have magnetic moments that partly cancel the effect of the two iron ions, but a net ferrimagnetic behavior, with a small hysteresis loop, is obtained. The high electrical resistivity of these ceramic compounds helps minimize eddy currents and permits the materials to operate at high frequencies. Ferrites used in computer applications may contain additions of manganese, magnesium, or cobalt to produce a square hysteresis loop behavior.

Another group of soft ceramic magnets is based on garnets, which include yttria iron garnet, $Y_3Fe_5O_{12}$ (YIG). These complex oxides, which may be modified by substituting aluminum or chromium for iron or by replacing yttrium with lanthanum or praseodymium, behave much like the ferrites. Another garnet, based on gadolinium and gallium, can be produced in the form of a thin film. Tiny magnetic domains can be produced in the garnet film; these domains, or *magnetic bubbles*, can then serve as storage units for computers. Once magnetized, the domains do not lose their memory in case of a sudden power loss.

Hard ceramic magnets used as permanent magnets include another complex oxide family, the hexagonal ferrites. The hexagonal ferrites include $SrFe_{12}O_{19}$ and $BaFe_{12}O_{19}$.

The example that follows highlights materials selection for a ceramic magnet.

TABLE 20-7 ■ ***Magnetic moments for ions in the spinel structure***

Ion	Bohr Magnetons	Ion	Bohr Magnetons
Fe^{3+}	5	Co^{2+}	3
Mn^{2+}	5	Ni^{2+}	2
Fe^{2+}	4	Cu^{2+}	1
		Zn^{2+}	0

Example 20-7 *Design/Materials Selection for a Ceramic Magnet*

Design a cubic ferrite magnet that has a total magnetic moment per cubic meter of 5.5×10^5 A/m.

SOLUTION

We found in Example 20-6 that the magnetic moment per cubic meter for Fe_3O_4 is 5.1×10^5 A/m. To obtain a higher saturation magnetization, we must replace Fe^{2+} ions with ions having more Bohr magnetons per atom. One such possibility (Table 20-7) is Mn^{2+}, which has five Bohr magnetons.

Assuming that the addition of Mn ions does not appreciably affect the size of the unit cell, we find from Example 20-6 that

$$V_{cell} = 5.86 \times 10^{-22}\ \text{cm}^3 = 5.86 \times 10^{-28}\ \text{m}^3$$

Let x be the fraction of Mn^{2+} ions that have replaced the Fe^{2+} ions, which have now been reduced to $1 - x$. Then, the total magnetic moment is

Total moment

$$= \frac{(8\ \text{subcells})[(x)(5\ \text{magnetons}) + (1 - x)(4\ \text{magnetons})](9.274 \times 10^{-24}\ \text{A} \cdot \text{m}^2)}{5.86 \times 10^{-28}\ \text{m}^3}$$

$$= \frac{(8)(5x + 4 - 4x)(9.274 \times 10^{-24})}{5.86 \times 10^{-28}} = 5.5 \times 10^5$$

$$x = 0.344$$

Therefore we need to replace 34.4 at % of the Fe^{2+} ions with Mn^{2+} ions to obtain the desired magnetization.

Magnetostriction

Certain materials can develop strain when their magnetic state is changed. This effect is used in actuators. The magnetostrictive effect can be seen either by changing the magnetic field or by changing the temperature. Iron, nickel, Fe_3O_4, $TbFe_2$, DyFe, and $SmFe_2$ are examples of some materials that show this effect. Terfenol-D, which is named after its constituents terbium (Tb), iron (Fe), and dysprosium (Dy) and its developer, the Naval Ordnance Laboratory (NOL), is one of the best known magnetostrictive materials. Its composition is $\sim Tb_xDy_{1-x}Fe_y$ $(0.27 < x < 0.30,\ 1.9 < y < 2)$. The magnetostriction phenomenon is analogous to electrostriction. Recently, some ferromagnetic alloys that also show magnetostriction have been developed.

Summary

- All materials interact with magnetic fields. The magnetic properties of materials are related to the interaction of magnetic dipoles with a magnetic field. The magnetic dipoles originate with the electronic structure of the atom, causing several types of behavior.
- Magnetic materials have enabled numerous technologies that range from high intensity superconducting magnets for MRI; semi-hard materials used in magnetic data storage;

permanent magnets used in loud speakers, motors, and generators; to superparamagnetic materials used to make ferrofluids and for magnetic separation of DNA molecules and cells.

- In diamagnetic materials, the magnetic dipoles oppose the applied magnetic field.
- In paramagnetic materials, the magnetic dipoles weakly reinforce the applied magnetic field, increasing the net magnetization or inductance.
- Ferromagnetic and ferrimagnetic materials are magnetically nonlinear. Their permeability depends strongly on the applied magnetic field. In ferromagnetic materials (such as iron, nickel, and cobalt), the magnetic dipoles strongly reinforce the applied magnetic field, producing large net magnetization or inductance. In ferrimagnetic materials, some magnetic dipoles reinforce the field, whereas others oppose the field. A net increase in magnetization or inductance occurs. Magnetization may remain even after the magnetic field is removed. Increasing the temperature above the Curie temperature destroys the ferromagnetic or ferrimagnetic behavior.
- The structure of ferromagnetic and ferrimagnetic materials includes domains, within which all of the magnetic dipoles are aligned. When a magnetic field is applied, the dipoles become aligned with the field, increasing the magnetization to its maximum, or saturation, value. When the field is removed, some alignment of the domains may remain, giving a remanant magnetization.
- For soft magnetic materials, little remanance exists, only a small coercive field is required to remove any alignment of the domains, and little energy is consumed in reorienting the domains when an alternating magnetic field is applied.
- For hard, or permanent, magnetic materials, the domains remain almost completely aligned when the field is removed, large coercive fields are required to randomize the domains, and a large hysteresis loop is observed. This condition provides the magnet with a high power.
- Magnetostriction is the development of strain in response to an applied magnetic field or a temperature change that induces a magnetic transformation. Terfenol type magnetostrictive materials have been developed for actuator applications.

Glossary

Antiferromagnetism Arrangement of magnetic moments such that the magnetic moments of atoms or ions cancel out causing zero net magnetization.

Bloch walls The boundaries between magnetic domains.

Bohr magneton The strength of a magnetic moment of an electron (μ_B) due to electron spin.

Coercivity The magnetic field needed to force the domains in a direction opposite to the magnetization direction. This is a microstructure-sensitive property.

Curie temperature The temperature above which ferromagnetic or ferrimagnetic materials become paramagnetic.

Diamagnetism The effect caused by the magnetic moment due to the orbiting electrons, which produces a slight opposition to the imposed magnetic field.

Domains Small regions within a single or polycrystalline material in which all of the magnetization directions are aligned.

Ferrimagnetism Magnetic behavior obtained when ions in a material have their magnetic moments aligned in an antiparallel arrangement such that the moments do not completely cancel out and a net magnetization remains.

Ferromagnetism Alignment of the magnetic moments of atoms in the same direction so that a net magnetization remains after the magnetic field is removed.

Hard magnet Ferromagnetic or ferrimagnetic material that has a coercivity $> 10^4$ A $\cdot$ m^{-1}. This is the same as a permanent magnet.

Hysteresis loop The loop traced out by magnetization in a ferromagnetic or ferrimagnetic material as the magnetic field is cycled.

Magnetic moment The strength of the magnetic field associated with a magnetic dipole.

Magnetic permeability The ratio between inductance or magnetization and magnetic field. It is a measure of the ease with which magnetic flux lines can "flow" through a material.

Magnetic susceptibility The ratio between magnetization and the applied field.

Magnetization The total magnetic moment per unit volume.

Magnetocrystalline anisotropy In single crystals, the coercivity depends upon crystallographic direction creating easy and hard axes of magnetization.

Paramagnetism The net magnetic moment caused by the alignment of the electron spins when a magnetic field is applied.

Permanent magnet A hard magnetic material.

Power The strength of a permanent magnet as expressed by the maximum product of the inductance and magnetic field.

Remanance The polarization or magnetization that remains in a material after it has been removed from a magnetic field. The remanance is due to the permanent alignment of the dipoles.

Saturation magnetization When all of the dipoles have been aligned by the field, producing the maximum magnetization.

Shape anisotropy The dependence of coercivity on the shape of magnetic particles.

Soft magnet Ferromagnetic or ferrimagnetic material that has a coercivity $\leqslant 10^3$ A $\cdot$ m^{-1}.

Superparamagnetism In the nanoscale regime, materials that are ferromagnetic or ferrimagnetic but behave in a paramagnetic manner (because of their nano-sized grains or particles).

Section 20-1 Classification of Magnetic Materials

Section 20-2 Magnetic Dipoles and Magnetic Moments

20-1 State any four real-world applications of different magnetic materials

20-2 Explain the following statement "Strictly speaking, there is no such thing as a non-magnetic material."

20-3 Normally we disregard the magnetic moment of the nucleus. In what application does the nuclear magnetic moment become important?

20-4 What two motions of electrons are important in determining the magnetic properties of materials?

20-5 Explain why only a handful of solids exhibit ferromagnetic or ferrimagnetic behavior.

20-6 Calculate and compare the maximum magnetization we would expect in iron, nickel, cobalt, and gadolinium. There are seven electrons in the $4f$ level of gadolinium. Compare the calculated values with the experimentally observed values.

Section 20-3 Magnetization, Permeability, and the Magnetic Field

Section 20-4 Diamagnetic, Paramagnetic, Ferromagnetic, Ferrimagnetic, and Superparamagnetic Materials

Section 20-5 Domain Structure and Hysteresis Loop

20-7 Define the following terms: magnetic induction, magnetic field, magnetic susceptibility, and magnetic permeability.

20-8 Define the following terms: ferromagnetic, ferrimagnetic, diamagnetic, paramagnetic, superparamagnetic, and antiferromagnetic materials.

20-9 What is a ferromagnetic material? What is a ferrimagnetic material? Explain and provide examples of each type of material.

20-10 How does the permeability of ferromagnetic and ferrimagnetic materials change with temperature when the temperature is greater than the Curie temperature?

20-11 Derive the equation $\mu_r = 1 + \chi_m$ using Equations 20-4 through 20-7.

20-12 A 4-79 permalloy solenoid coil needs to produce a minimum inductance of 1.5 Wb/m^2. If the maximum allowed current is 5 mA, how many turns are required in a wire 1 m long?

20-13 An alloy of nickel and cobalt is to be produced to give a magnetization of 2×10^6 A/m. The crystal structure of the alloy is FCC with a lattice parameter of 0.3544 nm. Determine the atomic percent cobalt required, assuming no interaction between the nickel and cobalt.

20-14 Estimate the magnetization that might be produced in an alloy containing nickel and 70 at% copper, assuming that no interaction occurs.

20-15 An Fe-80% Ni alloy has a maximum permeability of 300,000 when an inductance of 3500 gauss is obtained. The alloy is placed in a 20-turn coil that is 2 cm in length. What current must flow through the conductor coil to obtain this field?

20-16 An Fe-49% Ni alloy has a maximum permeability of 64,000 when a magnetic field of 0.125 oersted is applied. What inductance is obtained and what current is needed to obtain this inductance in a 200-turn, 3-cm-long coil?

20-17 Draw a schematic of the *B*-*H* and *M*-*H* loops for a typical ferromagnetic material. What is the difference between these two loops?

20-18 Is the magnetic permeability of ferromagnetic or ferrimagnetic materials constant? Explain.

20-19 From a phenomenological viewpoint, what are the similarities between elastomers, ferromagnetic and ferrimagnetic materials, and ferroelectrics?

20-20 What are the major differences between ferromagnetic and ferrimagnetic materials?

20-21 Compare the electrical resistivities of ferromagnetic metals and ferrimagnetic ceramics.

20-22 Why are eddy current losses important design factors in ferromagnetic materials but less important in ferrimagnetic materials?

20-23 Which element has the highest saturation magnetization? What alloys have the highest saturation magnetization of all materials?

20-24 What material has the highest energy product of all magnetic materials?

20-25 Is coercivity of a material a microstructure sensitive property? Is remanance a microstructure sensitive property? Explain.

20-26 Is saturation magnetization of a material a microstructure sensitive property? Explain.

20-27 Can the same material have different hysteresis loops? Explain.

20-28 The following data describe the effect of the magnetic field on the inductance in a silicon steel. Calculate the initial permeability and the maximum permeability for the material.

H (A/m)	*B* (tesla)
0.00	0
20	0.08
40	0.30
60	0.65
80	0.85
100	0.95
150	1.10
250	1.25

20-29 A magnetic material has a coercive field of 167 A/m, a saturation magnetization of 0.616 tesla, and a residual inductance of 0.3 tesla. Sketch the hysteresis loop for the material.

20-30 A magnetic material has a coercive field of 10.74 A/m, a saturation magnetization of 2.158 tesla, and a remanance induction of 1.183 tesla. Sketch the hysteresis loop for the material.

20-31 Using Figure 20-16, determine the following properties of the magnetic material: remanance, saturation magnetization, coercive field, initial permeability, maximum permeability, and power (maximum *BH* product).

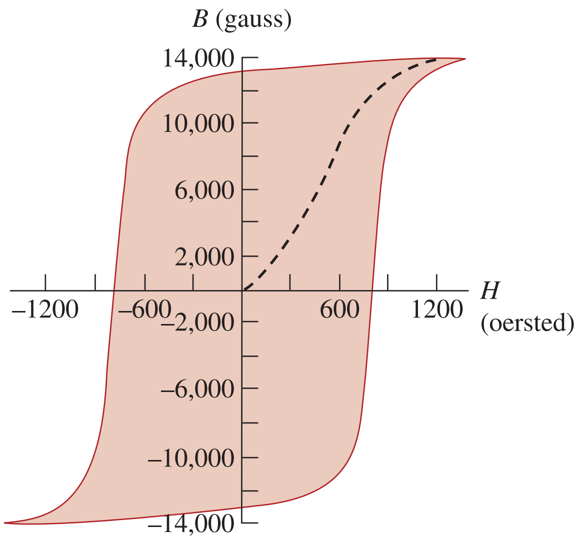


Figure 20-16 Hysteresis curve for a hard magnetic material (for Problem 20-31).

20-32 Using Figure 20-17, determine the following properties of the magnetic material: remanance, saturation magnetization, coercive field, initial permeability, maximum permeability, and power (maximum *BH* product).

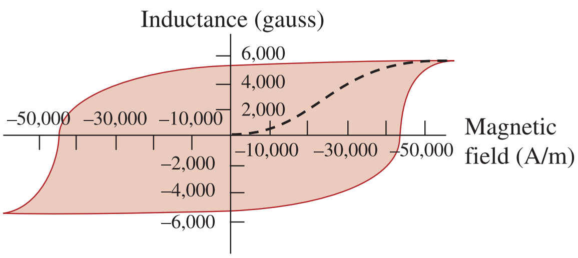


Figure 20-17 Hysteresis curve for a hard magnetic material (for Problem 20-32).

Section 20-6 The Curie Temperature

Section 20-7 Applications of Magnetic Materials

Section 20-8 Metallic and Ceramic Magnetic Materials

20-33 Sketch the *M-H* loop for Fe at 300 K, 500 K, and 1000 K.

20-34 Define the terms soft and hard magnetic materials. Draw a typical *M-H* loop for each material.

20-35 What important characteristics are associated with soft magnetic materials?

20-36 Are materials used for magnetic data storage magnetically hard or soft? Explain.

20-37 Give examples of materials used in magnetic recording.

20-38 What are the advantages of using Fe-Nd-B magnets? What are some of their disadvantages?

20-39 Estimate the power of the Co_5Ce material shown in Figure 20-14.

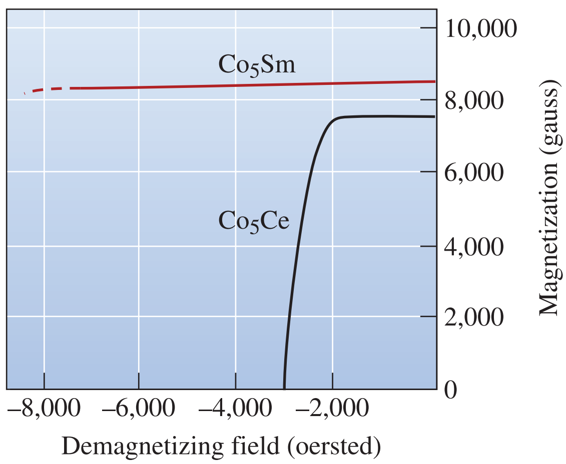


Figure 20-14 (Repeated for Problem 20-39.) Demagnetizing curves for Co_5Sm and Co_5Ce, representing a portion of the hysteresis loop.

20-40 What advantages does the Fe-3% Si material have compared with permalloy for use in electric motors?

20-41 The coercive field for pure iron is related to the grain size of the iron by the relationship $H_c = 1.83 + 4.14/\sqrt{A}$, where A is the area of the grain in two dimensions (mm^2) and H_c has units of A/m. If only the grain size influences the 99.95% iron (coercivity 0.9 oersted), estimate the size of the grains in the material. What happens to the coercivity value when the iron is annealed to increase the grain size?

20-42 Calculate the attractive force per square meter from a permanent magnet with a saturation magnetization of 1.0 tesla.

20-43 Suppose we replace 10% of the Fe^{2+} ions in magnetite with Cu^{2+} ions. Determine the total magnetic moment per cubic centimeter.

20-44 Suppose that the total magnetic moment per cubic meter in a spinel structure in which Ni^{2+} ions have replaced a portion of the Fe^{2+} ions is 4.6×10^5 A/m. Calculate the fraction of the Fe^{2+} ions that have been replaced and the wt% Ni present in the spinel.

20-45 What is magnetostriction? How is this similar to electrostriction? How is it different from the piezoelectric effect?

20-46 State examples of materials that show the magnetostriction effect.

20-47 What is spintronics? Give an example of a spintronics-based device used in personal and laptop computers.

Design Problems

20-48 Design a solenoid no longer than 1 cm that will produce an inductance of 3000 gauss.

20-49 Design a permanent magnet that will have a remanance of at least 5000 gauss, that will not be demagnetized if exposed to a temperature of 400°C or to a magnetic field of 1000 oersted, and that has good magnetic power.

20-50 Design a spinel-structure ferrite that will produce a total magnetic moment per cubic meter of 5.6×10^5 A/m.

20-51 Design a spinel-structure ferrite that will produce a total magnetic moment per cubic meter of 4.1×10^5 A/m.

20-52 Design a permanent magnet to lift a 1000 kg maximum load under operating temperatures as high as 750°C. Which material(s) listed in Table 20-6 will meet the above requirement?

Computer Problems

20-53 *Converting Magnetic Units*. Write a computer program that will convert magnetic units from the cgs or Gaussian system to the SI system. For example, if the user provides a value of flux density in Gauss, the program should provide a value in Wb/m^2 or tesla.