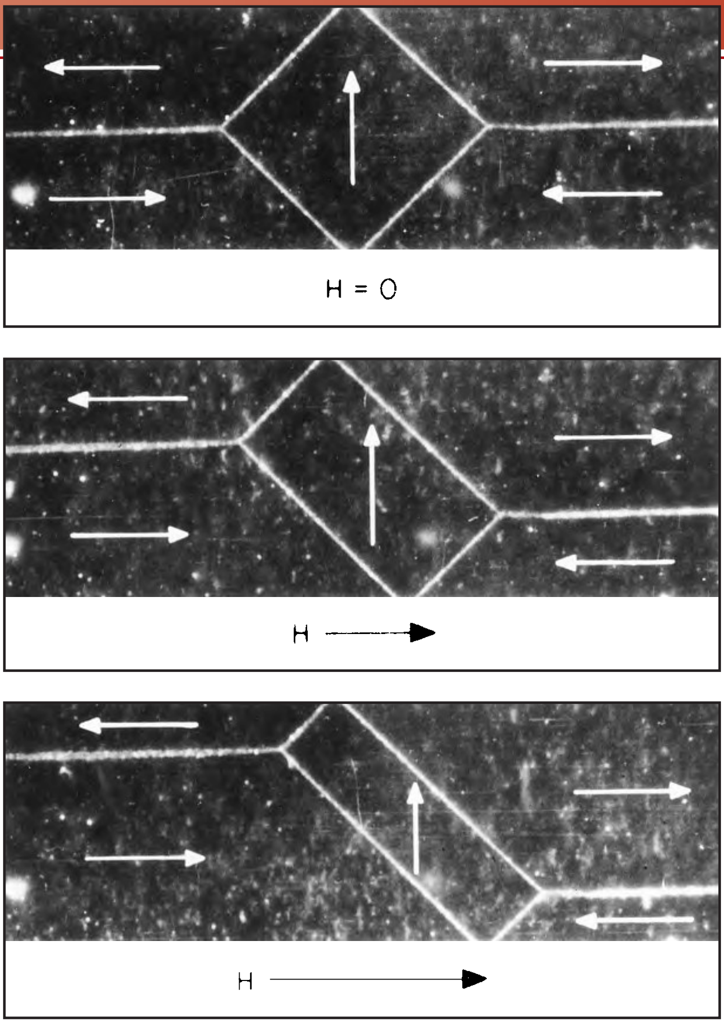
Chapter 20 Magnetic Properties



Photomicrographs of an iron single crystal, showing magnetic domains and their change in shape as a magnetic field (H) is applied. The magnetization direction of each domain is indicated by an arrow. Those domains that are favorably oriented with the applied field grow at the expense of the unfavorably oriented domains. (Photomicrographs courtesy of General Electric Research Laboratory.)

WHY STUDY *the Magnetic Properties of Materials?*

An understanding of the mechanism that explains the permanent magnetic behavior of some materials may allow us to alter and in some cases tailor the magnetic properties. For example, in Design Example 20.1 we note how the behavior of a ceramic magnetic material may be enhanced by changing its composition.

Learning Objectives

After careful study of this chapter you should be able to do the following:

1. Determine the magnetization of some material given its magnetic susceptibility and the applied magnetic field strength.
2. From an electronic perspective note and briefly explain the two sources of magnetic moments in materials.
3. Briefly explain the nature and source of (a) diamagnetism, (b) paramagnetism, and (c) ferromagnetism.
4. In terms of crystal structure, explain the source of ferrimagnetism for cubic ferrites.
5. (a) Describe magnetic hysteresis; (b) explain why ferromagnetic and ferrimagnetic materials experience magnetic hysteresis; and (c) explain why these materials may become permanent magnets.
6. Note the distinctive magnetic characteristics for both soft and hard magnetic materials.
7. Describe the phenomenon of *superconductivity*.

20.1 INTRODUCTION

Magnetism, the phenomenon by which materials assert an attractive or repulsive force or influence on other materials, has been known for thousands of years. However, the underlying principles and mechanisms that explain the magnetic phenomenon are complex and subtle, and their understanding has eluded scientists until relatively recent times. Many of our modern technological devices rely on magnetism and magnetic materials; these include electrical power generators and transformers, electric motors, radio, television, telephones, computers, and components of sound and video reproduction systems.

Iron, some steels, and the naturally occurring mineral lodestone are well-known examples of materials that exhibit magnetic properties. Not so familiar, however, is the fact that all substances are influenced to one degree or another by the presence of a magnetic field. This chapter provides a brief description of the origin of magnetic fields and discusses the various magnetic field vectors and magnetic parameters; the phenomena of diamagnetism, paramagnetism, ferromagnetism, and ferrimagnetism; some of the different magnetic materials; and the phenomenon of superconductivity.

20.2 BASIC CONCEPTS

Magnetic Dipoles

Magnetic forces are generated by moving electrically charged particles; these magnetic forces are in addition to any electrostatic forces that may prevail. Many times it is convenient to think of magnetic forces in terms of fields. Imaginary lines of force may be drawn to indicate the direction of the force at positions in the vicinity of the field source. The magnetic field distributions as indicated by lines of force are shown for a current loop and also a bar magnet in Figure 20.1.

Magnetic dipoles are found to exist in magnetic materials, which, in some respects, are analogous to electric dipoles (Section 18.19). Magnetic dipoles may be thought of as small bar magnets composed of north and south poles instead of positive and negative electric charges. In the present discussion, magnetic dipole moments are represented by arrows, as shown in Figure 20.2. Magnetic dipoles are influenced by magnetic fields in a manner similar to the way in which electric dipoles are affected by electric fields (Figure 18.30). Within a magnetic field, the force of the field itself exerts a torque that tends to orient the dipoles with the field. A familiar example is the way in which a magnetic compass needle lines up with the earth's magnetic field.

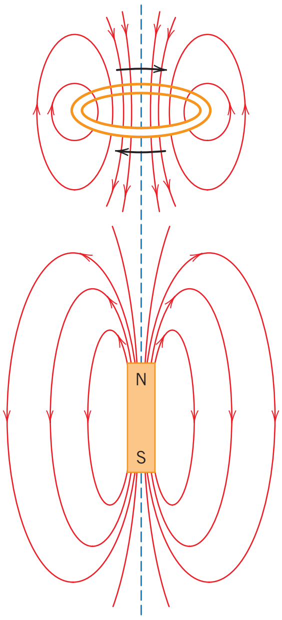


Figure 20.1 Magnetic field lines of force around a current loop and a bar magnet.

Magnetic Field Vectors

magnetic field strength

Before discussing the origin of magnetic moments in solid materials, 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

Magnetic field strength within a coil—dependence on number of turns, applied current, and coil length

$$H = \frac{NI}{l} \tag{20.1}$$

A schematic diagram of such an arrangement is shown in Figure 20.3*a*. The magnetic field that is generated by the current loop and the bar magnet in Figure 20.1 is an H field. The units of H are ampere-turns per meter, or just amperes per meter.

magnetic induction, magnetic flux density

The **magnetic induction,** or **magnetic flux density,** 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/m^2)]. Both B and H are field vectors, being characterized not only by magnitude, but also by direction in space.

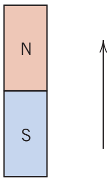
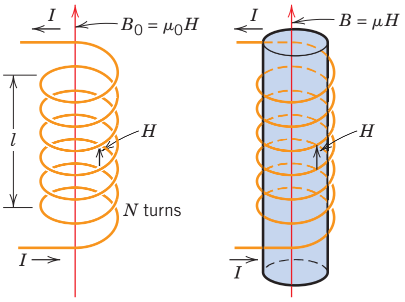


Figure 20.2 The magnetic moment as designated by an arrow.



(a) (b)

Figure 20.3 (*a*) The magnetic field H as generated by a cylindrical coil is dependent on the current I, the number of turns N, and the coil length l, according to Equation 20.1. The magnetic flux density B_0 in the presence of a vacuum is equal to $\mu_0 H$, where μ_0 is the permeability of a vacuum, $4\pi \times 10^{-7}$ H/m. (*b*) The magnetic flux density B within a solid material is equal to μH, where μ is the permeability of the solid material. (Adapted from A. G. Guy, *Essentials of Materials Science,* McGraw-Hill Book Company, New York, 1976.)

Magnetic flux density in a material—dependence on permeability and magnetic field strength

The magnetic field strength and flux density are related according to

$$B = \mu H \tag{20.2}$$

permeability

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, as illustrated in Figure 20.3*b*. The permeability has dimensions of webers per ampere-meter (Wb/A-m) or henries per meter (H/m).

In a vacuum,

Magnetic flux density in a vacuum

$$B_0 = \mu_0 H \tag{20.3}$$

where μ_0 is the *permeability of a vacuum,* a universal constant, which has a value of $4\pi \times 10^{-7}$ (1.257×10^{-6}) H/m. The parameter B_0 represents the flux density within a vacuum as demonstrated in Figure 20.3*a*.

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

Definition of relative permeability

$$\mu_r = \frac{\mu}{\mu_0} \tag{20.4}$$

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, or the ease with which a B field can be induced in the presence of an external H field.

magnetization

Another field quantity, M, called the **magnetization** of the solid, is defined by the expression

Magnetic flux density—as a function of magnetic field strength and magnetization of a material

$$B = \mu_0 H + \mu_0 M \tag{20.5}$$

In the presence of an H field, the magnetic moments within a material tend to become aligned with the field and to reinforce it by virtue of their magnetic fields; the term $\mu_0 M$ in Equation 20.5 is a measure of this contribution.

Table 20.1 Magnetic Units and Conversion Factors for the SI and cgs–emu Systems

		SI Units			
Quantity	*Symbol*	*Derived*	*Primary*	*cgs–emu Unit*	*Conversion*
Magnetic induction (flux density)	B	tesla (Wb/m^2)[a]	kg/s-C	gauss	1 Wb/m^2 = 10^4 gauss
Magnetic field strength	H	amp-turn/m	C/m-s	oersted	1 amp-turn/m = $4\pi \times 10^{-3}$ oersted
Magnetization	M (SI) I (cgs–emu)	amp-turn/m	C/m-s	maxwell/cm^2	1 amp-turn/m = 10^{-3} maxwell/cm^2
Permeability of a vaccum	μ_0	henry/m[b]	kg-m/C^2	Unitless (emu)	$4\pi \times 10^{-7}$ henry/m = 1 emu
Relative permeability	μ_r (SI) μ' (cgs–emu)	Unitless	Unitless	Unitless	$\mu_r = \mu'$
Susceptibility	χ_m (SI) χ'_m (cgs–emu)	Unitless	Unitless	Unitless	$\chi_m = 4\pi\chi'_m$

[a] Units of the weber (Wb) are volt-seconds.

[b] Units of the henry are webers per ampere.

Magnetization of a material—dependence on susceptibility and magnetic field strength

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

$$\boxed{M = \chi_m H} \tag{20.6}$$

magnetic susceptibility

and χ_m is called the **magnetic susceptibility,** which is unitless.[1] The magnetic susceptibility and the relative permeability are related as follows:

Relationship between magnetic susceptibility and relative permeability

$$\boxed{\chi_m = \mu_r - 1} \tag{20.7}$$

There is a dielectric analogue for each of the foregoing magnetic field parameters. The B and H fields are, respectively, analogous to the dielectric displacement D and the electric field $\mathscr{E}$, whereas the permeability μ parallels the permittivity ϵ (cf. Equations 20.2 and 18.30). Furthermore, the magnetization M and polarization P are correlates (Equations 20.5 and 18.31).

Magnetic units may be a source of confusion because there are really two systems in common use. The ones used thus far are SI [rationalized *MKS* (meter-kilogram-second)]; the others come from the *cgs–emu* (centimeter-gram-second-electromagnetic unit) system. The units for both systems as well as the appropriate conversion factors are contained in Table 20.1.

Origins of Magnetic Moments

The macroscopic magnetic properties of materials are a consequence of *magnetic moments* associated with individual electrons. Some of these concepts are relatively complex and involve some quantum-mechanical principles beyond the scope of this discussion; consequently, simplifications have been made and some of the details omitted. 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

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[1] This χ_m is taken to be the volume susceptibility in SI units, which, when multiplied by H, yields the magnetization per unit volume (cubic meter) of material. Other susceptibilities are also possible; see Problem 20.3.

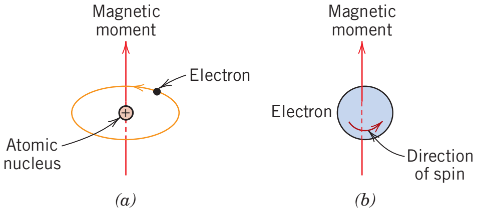

Figure 20.4 Demonstration of the magnetic moment associated with (*a*) an orbiting electron and (*b*) a spinning electron.

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 20.4*a*.

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 20.4*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.

Bohr magneton

The most fundamental magnetic moment is the **Bohr magneton** μ_B, which is of magnitude 9.27×10^{-24} A-m^2. For each electron in an atom the spin magnetic moment is $\pm\mu_B$ (plus for spin up, minus for spin down). Furthermore, the orbital magnetic moment contribution is equal to $m_l\mu_B$, m_l being the magnetic quantum number of the electron, as mentioned in Section 2.3.

In each individual atom, orbital moments of some electron pairs cancel each other; this also holds for the spin moments. For example, the spin moment of an electron with spin up will cancel that of one with spin down. 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, and taking into account moment cancellation. For an atom having completely filled electron shells or subshells, when all electrons are considered, there is total cancellation of both orbital and spin moments. Thus materials composed of atoms having completely filled electron shells are not capable of being permanently magnetized. This category includes the inert gases (He, Ne, Ar, etc.) as well as some ionic materials. The types of magnetism include diamagnetism, paramagnetism, and ferromagnetism; in addition, antiferromagnetism and ferrimagnetism are considered to be subclasses of ferromagnetism. All materials exhibit at least one of these types, and the behavior depends on the response of electron and atomic magnetic dipoles to the application of an externally applied magnetic field.

20.3 DIAMAGNETISM AND PARAMAGNETISM

diamagnetism

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 (however, only very slightly), and the magnetic susceptibility is negative; that is, the magnitude of the B field within a diamagnetic solid is less than that in a vacuum. The volume susceptibility χ_m for diamagnetic solid materials is on the order of -10^{-5}. When placed between the poles of a strong electromagnet, diamagnetic materials are attracted toward regions where the field is weak.

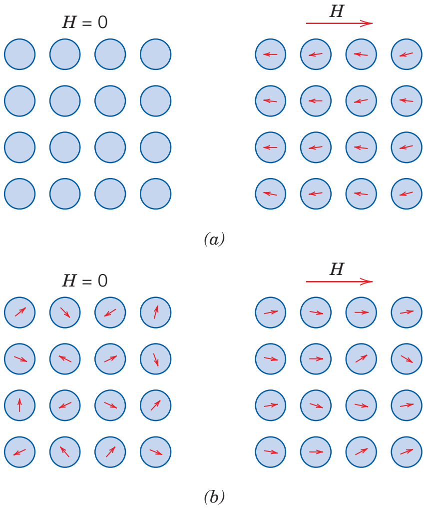

Figure 20.5 (*a*) The atomic dipole configuration for a diamagnetic material with and without a magnetic field. In the absence of an external field, no dipoles exist; in the presence of a field, dipoles are induced that are aligned opposite to the field direction. (*b*) Atomic dipole configuration with and without an external magnetic field for a paramagnetic material.

Figure 20.5*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, whereas for the preceding discussion, arrows denoted only electron moments. The dependence of B on the external field H for a material that exhibits diamagnetic behavior is presented in Figure 20.6. Table 20.2 gives the susceptibilities of several diamagnetic materials. 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. This form of magnetism is of no practical importance.

paramagnetism

For some solid materials, each atom possesses a permanent dipole moment by virtue of incomplete cancellation of electron spin and/or orbital magnetic moments. In the absence of an external magnetic field, the orientations of these atomic magnetic moments are random, such that a piece of material possesses no net macroscopic magnetization. These atomic dipoles are free to rotate, and **paramagnetism** results when they preferentially align, by rotation, with an external field as shown in Figure 20.5*b*. These magnetic dipoles are acted on individually with no mutual

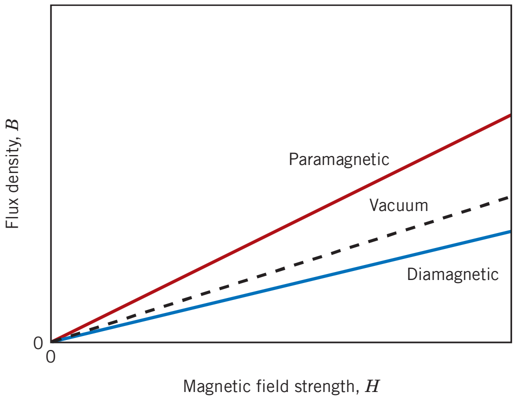

Figure 20.6 Schematic representation of the flux density B versus the magnetic field strength H for diamagnetic and paramagnetic materials.

Table 20.2 **Room-Temperature Magnetic Susceptibilities for Diamagnetic and Paramagnetic Materials**

Diamagnetics		*Paramagnetics*	
Material	*Susceptibility χ_m (volume) (SI units)*	*Material*	*Susceptibility χ_m (volume) (SI units)*
Aluminum oxide	-1.81×10^{-5}	Aluminum	2.07×10^{-5}
Copper	-0.96×10^{-5}	Chromium	3.13×10^{-4}
Gold	-3.44×10^{-5}	Chromium chloride	1.51×10^{-3}
Mercury	-2.85×10^{-5}	Manganese sulfate	3.70×10^{-3}
Silicon	-0.41×10^{-5}	Molybdenum	1.19×10^{-4}
Silver	-2.38×10^{-5}	Sodium	8.48×10^{-6}
Sodium chloride	-1.41×10^{-5}	Titanium	1.81×10^{-4}
Zinc	-1.56×10^{-5}	Zirconium	1.09×10^{-4}

interaction between adjacent dipoles. Inasmuch as 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. Susceptibilities for paramagnetic materials range from about 10^{-5} to 10^{-2} (Table 20.2). A schematic B-versus-H curve for a paramagnetic material is also shown in Figure 20.6.

Both diamagnetic and paramagnetic materials are considered to be nonmagnetic because they exhibit magnetization only when in the presence of an external field. Also, for both, the flux density B within them is almost the same as it would be in a vacuum.

20.4 FERROMAGNETISM

ferromagnetism

Certain metallic materials possess a permanent magnetic moment in the absence of an external field, and manifest very large and permanent magnetizations. These are the characteristics of **ferromagnetism,** and they are displayed by the transition metals iron (as BCC α ferrite), cobalt, nickel, and some of the rare earth metals such as gadolinium (Gd). Magnetic susceptibilities as high as 10^6 are possible for ferromagnetic materials. Consequently, $H \ll M$, and from Equation 20.5 we write

For a ferromagnetic material, relationship between magnetic flux density and magnetization

$$B \cong \mu_0 M \tag{20.8}$$

Permanent magnetic moments in ferromagnetic materials result from atomic magnetic moments due to electron spin—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 20.7. The origin of these coupling forces is not completely understood, but it is thought to arise from the electronic structure of the metal. This mutual spin alignment exists over relatively large volume regions of the crystal called **domains** (see Section 20.7).

domain

saturation magnetization

The maximum possible magnetization, or **saturation magnetization** M_s, 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; there

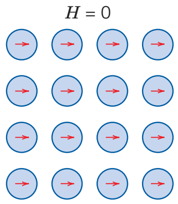

Figure 20.7 Schematic illustration of the mutual alignment of atomic dipoles for a ferromagnetic material, which will exist even in the absence of an external magnetic field.

is also a corresponding saturation flux density B_s. 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, the net magnetic moments per atom are 2.22, 1.72, and 0.60 Bohr magnetons, respectively.

EXAMPLE PROBLEM 20.1

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 above), the magnitude of the Bohr magneton μ_B, and the number N of atoms per cubic meter, or

Saturation magnetization for nickel

$$M_s = 0.60\mu_B N \tag{20.9}$$

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:

For nickel, computation of the number of atoms per unit volume

$$N = \frac{\rho N_A}{A_{Ni}} \tag{20.10}$$

$$= \frac{(8.90 \times 10^6\ \text{g/m}^3)(6.023 \times 10^{23}\ \text{atoms/mol})}{58.71\ \text{g/mol}}$$

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

Finally,

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

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

(b) From Equation 20.8, the saturation flux density is just

$$B_s = \mu_0 M_s$$

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

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

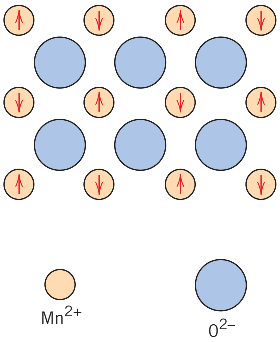

Figure 20.8 Schematic representation of antiparallel alignment of spin magnetic moments for antiferromagnetic manganese oxide.

20.5 ANTIFERROMAGNETISM AND FERRIMAGNETISM

Antiferromagnetism

antiferromagnetism

This phenomenon of magnetic moment coupling between adjacent atoms or ions occurs in materials other than those that are ferromagnetic. In one such group, 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. Manganese oxide is a ceramic material that is ionic in character, having both Mn^{2+} and O^{2-} ions. No net magnetic moment is associated with the O^{2-} ions, since there is a total cancellation of both spin and orbital moments. However, the Mn^{2+} ions possess a net magnetic moment that is predominantly of spin origin. These Mn^{2+} ions are arrayed in the crystal structure such that the moments of adjacent ions are antiparallel. This arrangement is represented schematically in Figure 20.8. Obviously, the opposing magnetic moments cancel one another, and, as a consequence, the solid as a whole possesses no net magnetic moment.

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.[2] These ionic materials may be represented by the chemical formula MFe_2O_4, in which M represents any one of several metallic elements. The prototype ferrite is Fe_3O_4, the mineral magnetite, sometimes called lodestone.

The formula for Fe_3O_4 may be written as $Fe^{2+}O^{2-}$–$(Fe^{3+})_2(O^{2-})_3$ in which the Fe ions exist in both +2 and +3 valence states in the ratio of 1:2. A net spin magnetic moment exists for each Fe^{2+} and Fe^{3+} ion, which corresponds to 4 and 5 Bohr magnetons, respectively, for the two ion types. Furthermore, the O^{2-} ions are magnetically neutral. There are antiparallel spin-coupling interactions between the Fe ions, similar in character to antiferromagnetism. However, the net ferrimagnetic moment arises from the incomplete cancellation of spin moments.

Cubic ferrites have the inverse spinel crystal structure, which is cubic in symmetry, and similar to the spinel structure (Section 12.2). The inverse spinel crystal

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ferrite

[2] Ferrite in the magnetic sense should not be confused with the ferrite α-iron discussed in Section 9.18; in the remainder of this chapter, the term **ferrite** implies the magnetic ceramic.

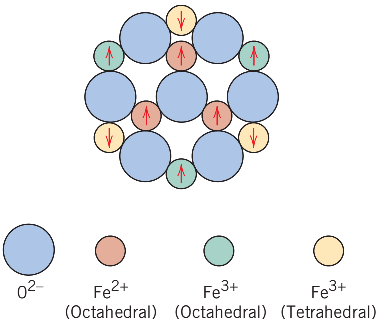

Figure 20.9 Schematic diagram showing the spin magnetic moment configuration for Fe^{2+} and Fe^{3+} ions in Fe_3O_4. (From Richard A. Flinn and Paul K. Trojan, *Engineering Materials and Their Applications,* 4th edition. Copyright © 1990 by John Wiley & Sons, Inc. Adapted by permission of John Wiley & Sons, Inc.)

structure might be thought of as having been generated by the stacking of close-packed planes of O^{2-} ions. Again, there are two types of positions that may be occupied by the iron cations, as illustrated in Figure 12.7. For one, the coordination number is 4 (tetrahedral coordination); that is, each Fe ion is surrounded by four oxygen nearest neighbors. For the other, the coordination number is 6 (octahedral coordination). With this inverse spinel structure, half the trivalent (Fe^{3+}) ions are situated in octahedral positions, the other half, in tetrahedral positions. The divalent Fe^{2+} ions are all located in octahedral positions. The critical factor is the arrangement of the spin moments of the Fe ions, as represented in Figure 20.9 and Table 20.3. The spin moments of all the Fe^{3+} ions in the octahedral positions are aligned parallel to one another; however, they are directed oppositely to the Fe^{3+} ions disposed in the tetrahedral positions, which are also aligned. This results from the antiparallel coupling of adjacent iron ions. Thus, the spin moments of all Fe^{3+} ions cancel one another and make no net contribution to the magnetization of the solid. All the Fe^{2+} ions have their moments aligned in the same direction; this total moment is responsible for the net magnetization (see Table 20.3). Thus, the saturation magnetization of a ferrimagnetic solid may be computed from the product of the net spin magnetic moment for each Fe^{2+} ion and the number of Fe^{2+} ions; this would correspond to the mutual alignment of all the Fe^{2+} ion magnetic moments in the Fe_3O_4 specimen.

Cubic ferrites having other compositions may be produced by adding metallic ions that substitute for some of the iron in the crystal structure. Again, from the

Table 20.3 The Distribution of Spin Magnetic Moments for Fe^{2+} and Fe^{3+} Ions in a Unit Cell Fe_3O_4[a]

Cation	*Octahedral Lattice Site*	*Tetrahedral Lattice Site*	*Net Magnetic Moment*
Fe^{3+}	↑ ↑ ↑ ↑ ↑ ↑ ↑ ↑	↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓	Complete cancellation
Fe^{2+}	↑ ↑ ↑ ↑ ↑ ↑ ↑ ↑	—	↑ ↑ ↑ ↑ ↑ ↑ ↑ ↑

[a] Each arrow represents the magnetic moment orientation for one of the cations.

Table 20.4 **Net Magnetic Moments for Six Cations**

Cation	*Net Spin Magnetic Moment (Bohr magnetons)*
Fe^{3+}	5
Fe^{2+}	4
Mn^{2+}	5
Co^{2+}	3
Ni^{2+}	2
Cu^{2+}	1

ferrite chemical formula, $M^{2+}O^{2-}$–$(Fe^{3+})_2(O^{2-})_3$, in addition to Fe^{2+}, M^{2+} may represent divalent ions such as Ni^{2+}, Mn^{2+}, Co^{2+}, and Cu^{2+}, each of which possesses a net spin magnetic moment different from 4; several are listed in Table 20.4. Thus, by adjustment of composition, ferrite compounds having a range of magnetic properties may be produced. For example, nickel ferrite has the formula $NiFe_2O_4$. Other compounds may also be produced containing mixtures of two divalent metal ions such as $(Mn,Mg)Fe_2O_4$, in which the $Mn^{2+}:Mg^{2+}$ ratio may be varied; these are called mixed ferrites.

Ceramic materials other than the cubic ferrites are also ferrimagnetic; these include the hexagonal ferrites and garnets. Hexagonal ferrites have a crystal structure similar to the inverse spinel, with hexagonal symmetry rather than cubic. The chemical formula for these materials may be represented by $AB_{12}O_{19}$, in which A is a divalent metal such as barium, lead, or strontium, and B is a trivalent metal such as aluminum, gallium, chromium, or iron. The two most common examples of the hexagonal ferrites are $PbFe_{12}O_{19}$ and $BaFe_{12}O_{19}$.

The garnets have a very complicated crystal structure, which may be represented by the general formula $M_3Fe_5O_{12}$; here, M represents a rare earth ion such as samarium, europium, gadolinium, or yttrium. Yttrium iron garnet ($Y_3Fe_5O_{12}$), sometimes denoted YIG, is the most common material of this type.

The saturation magnetizations for ferrimagnetic materials are not as high as for ferromagnets. On the other hand, ferrites, being ceramic materials, are good electrical insulators. For some magnetic applications, such as high-frequency transformers, a low electrical conductivity is most desirable.

Concept Check 20.1

Cite the major similarities and differences between ferromagnetic and ferrimagnetic materials.

[*The answer may be found at www.wiley.com/college/callister (Student Companion Site.)*]

Concept Check 20.2

What is the difference between the spinel and inverse spinel crystal structures? *Hint:* You may want to consult Section 12.2.

[*The answer may be found at www.wiley.com/college/callister (Student Companion Site.)*]

EXAMPLE PROBLEM 20.2

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 20.1, 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,

Saturation magnetization for a ferrimagnetic material (Fe_3O_4)

$$M_s = N'\mu_B \tag{20.11}$$

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

Computation of the number of Bohr magnetons per unit cell

$$N' = \frac{n_B}{V_C} \tag{20.12}$$

Again, the net magnetization results from the Fe^{2+} ions only. Since 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.

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

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

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

DESIGN EXAMPLE 20.1

Design of a Mixed Ferrite Magnetic Material

Design a cubic mixed-ferrite magnetic material that has a saturation magnetization of 5.25×10^5 A/m.

Solution

According to Example Problem 20.2 the saturation magnetization for Fe_3O_4 is 5.0×10^5 A/m. In order to increase the magnitude of M_s it is necessary to replace some fraction of the Fe^{2+} with a divalent metal ion that has a greater magnetic moment—for example Mn^{2+}; from Table 20.4, note that there are 5 Bohr magnetons/Mn^{2+} ion as compared to 4 Bohr magnetons/Fe^{2+}. Let us first employ Equation 20.13 to compute the number of Bohr magnetons per unit cell

(n_B), assuming that the Mn^{2+} addition does not change the unit cell edge length (0.839 nm). Thus,

$$
\begin{aligned}
n_B &= \frac{M_s a^3}{\mu_B} \\
&= \frac{(5.25 \times 10^5\ \text{A/m})(0.839 \times 10^{-9}\ \text{m})^3/\text{unit cell}}{9.27 \times 10^{-24}\ \text{A-m}^2/\text{Bohr magneton}} \\
&= 33.45\ \text{Bohr magnetons/unit cell}
\end{aligned}
$$

If we let x represent the fraction of Mn^{2+} that have substituted for Fe^{2+}, then the remaining unsubstituted Fe^{2+} fraction is equal to $(1 - x)$. Furthermore, inasmuch as there are 8 divalent ions per unit cell, we may write the following expression:

$$8[5x + 4(1 - x)] = 33.45$$

which leads to $x = 0.181$. Thus, if 18.1 at% of the Fe^{2+} in Fe_3O_4 are replaced with Mn^{2+}, the saturation magnetization will be increased to 5.25×10^5 A/m.

20.6 THE INFLUENCE OF TEMPERATURE ON MAGNETIC BEHAVIOR

Temperature can also influence the magnetic characteristics of materials. Recall that 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** T_c. The magnetization-temperature behavior for iron and Fe_3O_4 is represented in Figure 20.10. At T_c the mutual spin coupling forces are completely destroyed, such that for temperatures above T_c both ferromagnetic and ferrimagnetic materials are paramagnetic. The magnitude of the Curie temperature varies from material to material; for example, for iron, cobalt, nickel, and Fe_3O_4, the respective values are 768, 1120, 335, and 585°C.

Curie temperature

Antiferromagnetism is also affected by temperature; this behavior vanishes at what is called the *Néel temperature.* At temperatures above this point, antiferromagnetic materials also become paramagnetic.

Concept Check 20.3

Explain why repeatedly dropping a permanent magnet on the floor will cause it to become demagnetized.

[*The answer may be found at www.wiley.com/college/callister (Student Companion Site.)*]

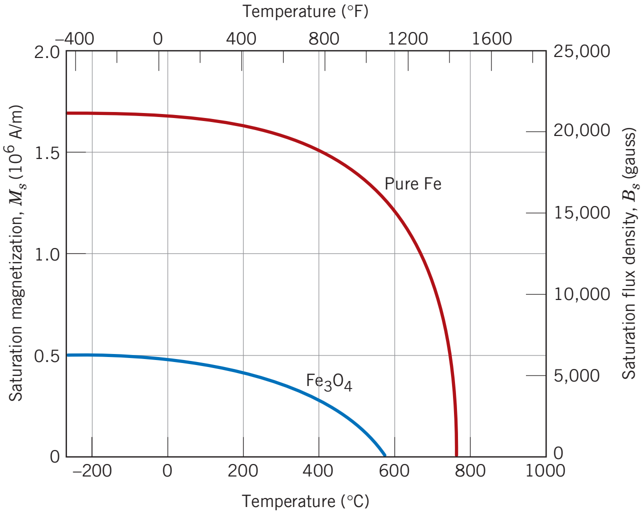

Figure 20.10 Plot of saturation magnetization as a function of temperature for iron and Fe_3O_4. [Adapted from J. Smit and H. P. J. Wijn, *Ferrites.* Copyright © 1959 by N. V. Philips Gloeilampenfabrieken, Eindhoven (Holland). Reprinted by permission.]

20.7 DOMAINS AND HYSTERESIS

Any ferromagnetic or ferrimagnetic material that is at a temperature below T_c 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 20.12). 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, each domain contribution being weighted by its volume fraction. For an unmagnetized specimen, the appropriately weighted vector sum of the magnetizations of all the domains is zero.

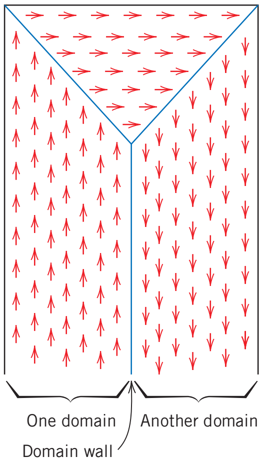

Figure 20.11 Schematic depiction of domains in a ferromagnetic or ferrimagnetic material; arrows represent atomic magnetic dipoles. Within each domain, all dipoles are aligned, whereas the direction of alignment varies from one domain to another.

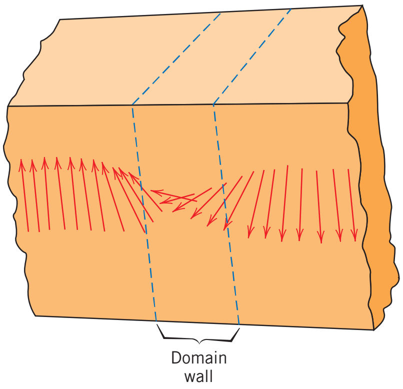

Figure 20.12 The gradual change in magnetic dipole orientation across a domain wall. (From W. D. Kingery, H. K. Bowen, and D. R. Uhlmann, *Introduction to Ceramics,* 2nd edition. Copyright © 1976 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

Flux density B and field intensity H are not proportional for ferromagnets and ferrimagnets. If the material is initially unmagnetized, then B varies as a function of H as shown in Figure 20.13. The curve begins at the origin, and as H is increased, the B field begins to increase slowly, then more rapidly, finally leveling off and becoming independent of H. This maximum value of B is the saturation flux density B_s, and the corresponding magnetization is the saturation magnetization M_s, mentioned previously. Since the permeability μ from Equation 20.2 is the slope of the B-versus-H curve, note from Figure 20.13 that the permeability changes with and is dependent on H. On occasion, the slope of the B-versus-H curve at $H = 0$ is specified as a material property, which is termed the *initial permeability* μ_i, as indicated in Figure 20.13.

As an H field is applied, the domains change shape and size by the movement of domain boundaries. Schematic domain structures are represented in the insets (labeled U through Z) at several points along the B-versus-H curve in Figure 20.13. Initially, the moments of the constituent domains are randomly oriented such that there is no net B (or M) field (inset U). As the external field is applied, the domains that are oriented in directions favorable to (or nearly aligned with) the applied field

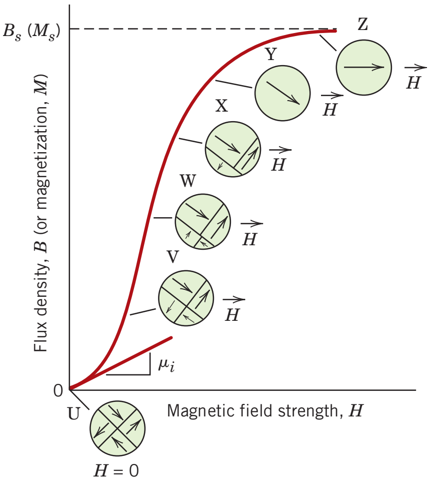

Figure 20.13 The B-versus-H behavior for a ferromagnetic or ferrimagnetic material that was initially unmagnetized. Domain configurations during several stages of magnetization are represented. Saturation flux density B_s, magnetization M_s, and initial permeability μ_i are also indicated. (Adapted from O. H. Wyatt and D. Dew-Hughes, *Metals, Ceramics and Polymers,* Cambridge University Press, 1974.)

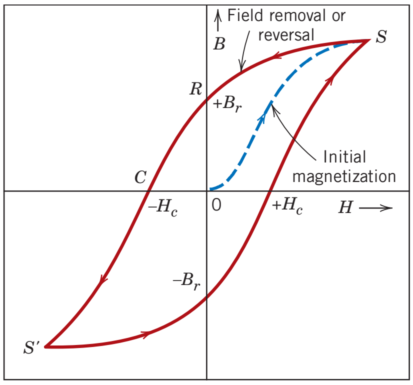

Figure 20.14 Magnetic flux density versus the magnetic field strength for a ferromagnetic material that is subjected to forward and reverse saturations (points S and S'). The hysteresis loop is represented by the solid curve; the dashed curve indicates the initial magnetization. The remanence B_r and the coercive force H_c are also shown.

grow at the expense of those that are unfavorably oriented (insets V through X). This process continues with increasing field strength until the macroscopic specimen becomes a single domain, which is nearly aligned with the field (inset Y). Saturation is achieved when this domain, by means of rotation, becomes oriented with the H field (inset Z). Alteration of the domain structure with magnetic field for an iron single crystal is shown in the chapter-opening photographs for this chapter.

hysteresis

remanence

From saturation, point S in Figure 20.14, as the H field is reduced by reversal of field direction, the curve does not retrace its original path. A **hysteresis** effect is produced in which the B field lags behind the applied H field, or decreases at a lower rate. At zero H field (point R on the curve), there exists a residual B field that is called the **remanence,** or remanent flux density, B_r; the material remains magnetized in the absence of an external H field.

Hysteresis behavior and permanent magnetization may be explained by the motion of domain walls. Upon reversal of the field direction from saturation (point S in Figure 20.14), the process by which the domain structure changes is reversed. First, there is a rotation of the single domain with the reversed field. Next, domains having magnetic moments aligned with the new field form and grow at the expense of the former domains. Critical to this explanation is the resistance to movement of domain walls that occurs in response to the increase of the magnetic field in the opposite direction; this accounts for the lag of B with H, or the hysteresis. When the applied field reaches zero, there is still some net volume fraction of domains oriented in the former direction, which explains the existence of the remanence B_r.

coercivity

To reduce the B field within the specimen to zero (point C on Figure 20.14), an H field of magnitude $-H_c$ must be applied in a direction opposite to that of the original field; H_c is called the **coercivity,** or sometimes the coercive force. Upon continuation of the applied field in this reverse direction, as indicated in the figure, saturation is ultimately achieved in the opposite sense, corresponding to point S'. A second reversal of the field to the point of the initial saturation (point S) completes the symmetrical hysteresis loop and also yields both a negative remanence ($-B_r$) and a positive coercivity ($+H_c$).

The B-versus-H curve in Figure 20.14 represents a hysteresis loop taken to saturation. Of course, it is not necessary to increase the H field to saturation before reversing the field direction; in Figure 20.15, loop NP is a hysteresis curve corresponding to less than saturation. Furthermore, it is possible to reverse the direction

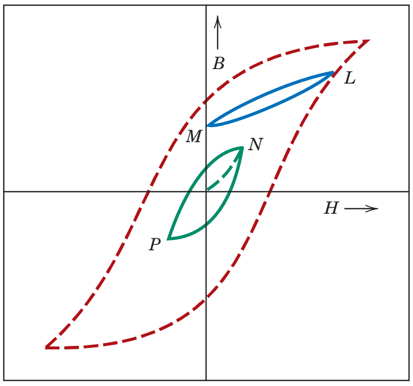

Figure 20.15 A hysteresis curve at less than saturation (curve *NP*) within the saturation loop for a ferromagnetic material. The *B*–*H* behavior for field reversal at other than saturation is indicated by curve *LM*.

of the field at any point along the curve and generate other hysteresis loops. One such loop is indicated on the saturation curve in Figure 20.15: for loop *LM*, the *H* field is reversed to zero. One method of demagnetizing a ferromagnet or ferrimagnet is to repeatedly cycle it in an *H* field that alternates direction and decreases in magnitude.

At this point it is instructive to compare the *B*-versus-*H* behaviors of paramagnetic, diamagnetic, and ferromagnetic/ferrimagnetic materials; such a comparison is shown in Figure 20.16. The linearity of paramagnetic and diamagnetic materials may be noted in the small inset plot, whereas the behavior of a typical ferromagnetic/ferrimagnetic is nonlinear. Furthermore, the rationale for labeling paramagnetics and diamagnetics as nonmagnetic materials is verified by comparing the *B* scales on the vertical axes of the two plots—at an *H* field strength of 50 A/m,

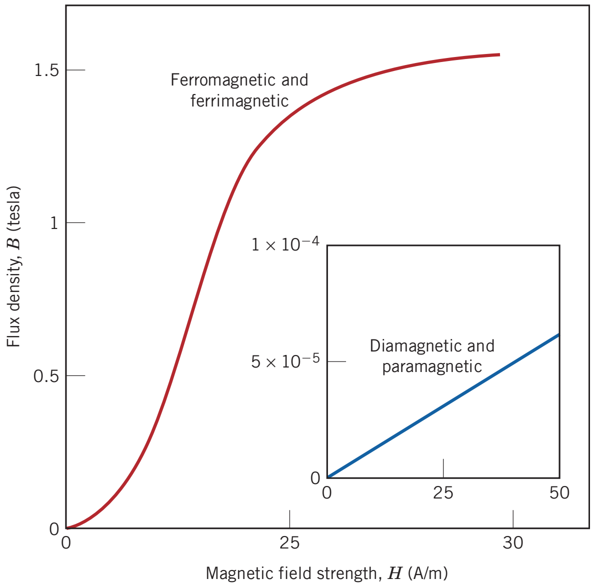

Figure 20.16 Comparison of *B*-versus-*H* behaviors for ferromagnetic/ferrimagnetic and diamagnetic/paramagnetic materials (inset plot). Here it may be noted that extremely small *B* fields are generated in materials that experience only diamagnetic/paramagnetic behavior, which is why they are considered to be nonmagnetics.

the ferromagnetic/ferrimagnetic materials flux density is on the order of 1.5 tesla, whereas for the parmagnetic and diamagnetic materials it is on the order of 5×10^{-5} tesla.

Concept Check 20.4

Schematically sketch on a single plot the *B*-versus-*H* behavior for a ferromagnetic material (a) at 0 K, (b) at a temperature just below its Curie temperature, and (c) at a temperature just above its Curie temperature. Briefly explain why these curves have different shapes.

[*The answer may be found at www.wiley.com/college/callister (Student Companion Site.)*]

Concept Check 20.5

Schematically sketch the hysteresis behavior for a ferromagnet which is gradually demagnetized by cycling in an *H* field that alternates direction and decreases in magnitude.

[*The answer may be found at www.wiley.com/college/callister (Student Companion Site.)*]

20.8 MAGNETIC ANISOTROPY

The magnetic hysteresis curves discussed in the previous section will have different shapes depending on various factors: (1) whether the specimen is a single crystal or polycrystalline; (2) if polycrystalline, any preferred orientation of the grains; (3) the presence of pores or second-phase particles; and (4) other factors such as temperature and, if a mechanical stress is applied, the stress state.

For example, the *B* (or *M*) versus *H* curve for a single crystal of a ferromagnetic material depends on its crystallographic orientation relative to the direction of the applied *H* field. This behavior is demonstrated in Figure 20.17 for single

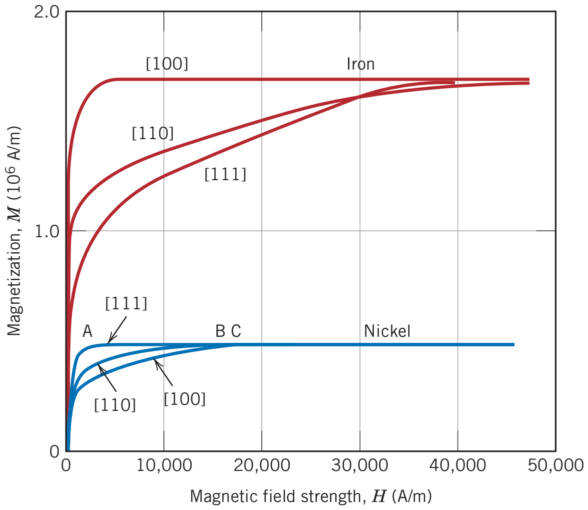

Figure 20.17 Magnetization curves for single crystals of iron and nickel. For both metals, a different curve was generated when the magnetic field was applied in each of [100], [110], and [111] crystallographic directions. [Adapted from K. Honda and S. Kaya, "On the Magnetisation of Single Crystals of Iron," *Sci. Rep. Tohoku Univ.*, **15,** 721 (1926); and from S. Kaya, "On the Magnetisation of Single Crystals of Nickel," *Sci. Rep. Tohoku Univ.*, **17,** 639 (1928).]

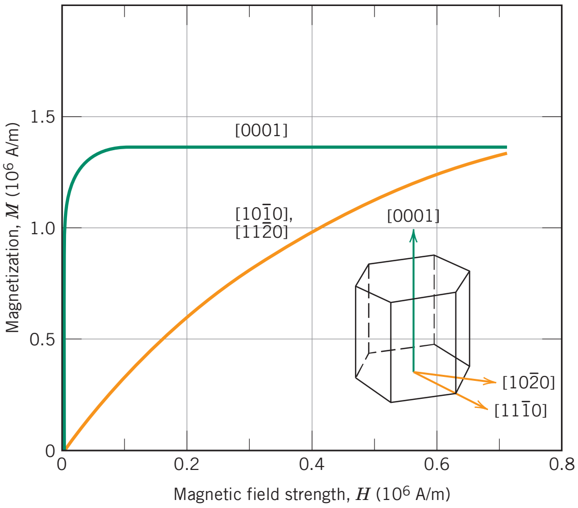

Figure 20.18 Magnetization curves for single crystals of cobalt. The curves were generated when the magnetic field was applied in [0001] and $[10\bar{1}0]/[11\bar{2}0]$ crystallographic directions. [Adapted from S. Kaya, "On the Magnetisation of Single Crystals of Cobalt," *Sci. Rep. Tohoku Univ.*, **17,** 1157 (1928).]

crystals of nickel (FCC) and iron (BCC), where the magnetizing field is applied in [100], [110], and [111] crystallographic directions; and in Figure 20.18 for cobalt (HCP) in [0001] and $[10\bar{1}0]/[11\bar{2}0]$ directions. This dependence of magnetic behavior on crystallographic orientation is termed *magnetic* (or sometimes *magnetocrystalline*) *anisotropy.*

For each of these materials there is one crystallographic direction in which magnetization is easiest—that is, saturation (of M) is achieved at the lowest H field; this is termed a direction of *easy magnetization.* For example, for Ni (Figure 20.17) this direction is [111] inasmuch as saturation occurs at point A; whereas, for [110] and [100] orientations, saturation points correspond, respectively, to points B and C. Correspondingly, easy magnetization directions for Fe and Co are [100] and [0001], respectively (Figures 20.17 and 20.18). Conversely, a *hard* crystallographic direction is that direction for which saturation magnetization is most difficult; hard directions for Ni, Fe, and Co are [100], [111], and $[10\bar{1}0]/[11\bar{2}0]$.

As noted in the previous section, the insets of Figure 20.13 represent domain configurations at various stages along the B (or M) versus H curve during the magnetization of a ferromagnetic/ferrimagnetic material. Here, each of the arrows represents a domain's direction of easy magnetization; and domains whose directions of easy magnetization are most closely aligned with the H field grow, at the expense of the other domains that shrink (insets V through X). Furthermore, the magnetization of the single domain in inset Y also corresponds to an easy direction. And saturation is achieved as the direction of this domain rotates away from the easy direction into the direction of the applied field (inset Z).

20.9 SOFT MAGNETIC MATERIALS

The size and shape of the hysteresis curve for ferromagnetic and ferrimagnetic materials is of considerable practical importance. The area within a loop represents a magnetic energy loss per unit volume of material per magnetization–demagnetization cycle; this energy loss is manifested as heat that is generated within the magnetic specimen and is capable of raising its temperature.

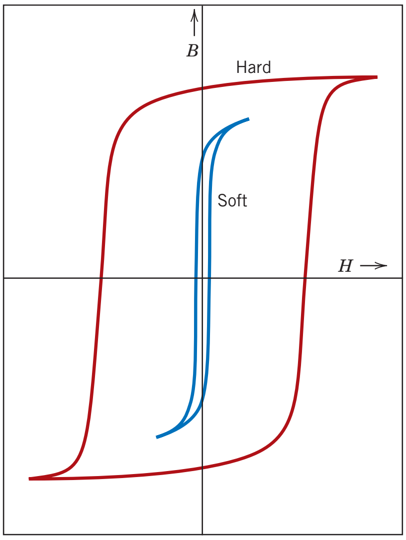

Figure 20.19 Schematic magnetization curves for soft and hard magnetic materials. (From K. M. Ralls, T. H. Courtney, and J. Wulff, *Introduction to Materials Science and Engineering*. Copyright © 1976 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

soft magnetic material

Both ferromagnetic and ferrimagnetic materials are classified as either *soft* or *hard* on the basis of their hysteresis characteristics. **Soft magnetic materials** are used in devices that are subjected to alternating magnetic fields and in which energy losses must be low; one familiar example consists of transformer cores. For this reason the relative area within the hysteresis loop must be small; it is characteristically thin and narrow, as represented in Figure 20.19. Consequently, a soft magnetic material must have a high initial permeability and a low coercivity. A material possessing these properties may reach its saturation magnetization with a relatively low applied field (i.e., is easily magnetized and demagnetized) and still has low hysteresis energy losses.

The saturation field or magnetization is determined only by the composition of the material. For example, in cubic ferrites, substitution of a divalent metal ion such as Ni^{2+} for Fe^{2+} in $FeO–Fe_2O_3$ will change the saturation magnetization. However, susceptibility and coercivity (H_c), which also influence the shape of the hysteresis curve, are sensitive to structural variables rather than to composition. For example, a low value of coercivity corresponds to the easy movement of domain walls as the magnetic field changes magnitude and/or direction. Structural defects such as particles of a nonmagnetic phase or voids in the magnetic material tend to restrict the motion of domain walls, and thus increase the coercivity. Consequently, a soft magnetic material must be free of such structural defects.

Another property consideration for soft magnetic materials is electrical resistivity. In addition to the hysteresis energy losses described above, energy losses may result from electrical currents that are induced in a magnetic material by a magnetic field that varies in magnitude and direction with time; these are called *eddy currents.* It is most desirable to minimize these energy losses in soft magnetic materials by increasing the electrical resistivity. This is accomplished in ferromagnetic materials by forming solid solution alloys; iron–silicon and iron–nickel alloys are examples. The ceramic ferrites are commonly used for applications requiring soft magnetic materials because they are intrinsically electrical insulators. Their applicability is somewhat limited, however, inasmuch as they have relatively small

MATERIAL OF IMPORTANCE

An Iron-Silicon Alloy That is Used in Transformer Cores

As mentioned earlier in this section, transformer cores require the use of soft magnetic materials, which are easily magnetized and demagnetized (and also have relatively high electrical resistivities). One alloy commonly used for this application is the iron–silicon alloy listed in Table 20.5 (97 wt% Fe-3 wt% Si). Single crystals of this alloy are magnetically anisotropic, as are also single crystals of iron (as explained above). Consequently, energy losses of transformers could be minimized if their cores were fabricated from single crystals such that a [100]-type direction [the direction of easy magnetization (Figure 20.17)] is oriented parallel to the direction of an applied magnetic field; this configuration for a transformer core is represented schematically in Figure 20.20. Unfortunately, single crystals are expensive to prepare, and, thus, this is an economically unpractical situation. A better alternative—one that is used commercially, being more economically attractive—is to fabricate cores from polycrystalline sheets of this alloy that are anisotropic.

It is often the case that the grains in polycrystalline materials are randomly oriented, with the result that their properties are isotropic (Section 3.15). However, one way of developing anisotropy in polycrystalline metals is via plastic deformation, for example by rolling (Section 11.4, Figure 11.8*b*); rolling is the technique by which sheet transformer cores are fabricated. A flat sheet that has been rolled is said to have a *rolling* (or *sheet*) *texture,* or there is a preferred crystallographic orientation of the grains. For this type of texture, during the rolling operation, for most of the grains in the sheet, a specific crystallographic plane (*hkl*) becomes is aligned parallel (or nearly parallel) to the surface of the sheet, and, in addition a direction [*uvw*] in that plane lies parallel (or nearly parallel) to the rolling direction. Thus, a rolling texture is indicated by the plane–direction combination, (*hkl*)[*uvw*]. For body-centered cubic alloys (to include the iron–silicon alloy mentioned above), the rolling texture is (110) [001], which is represented schematically in Figure 20.21. Thus, transformer cores of this iron–silicon alloy are fabricated such the direction in which the sheet was rolled (corresponding to a [001]-type direction for most of the grains) is aligned parallel to the direction of the magnetic field application.[3]

The magnetic characteristics of this alloy may be further improved through a series of deformation and heat-treating procedures that produce a (100)[001] texture.

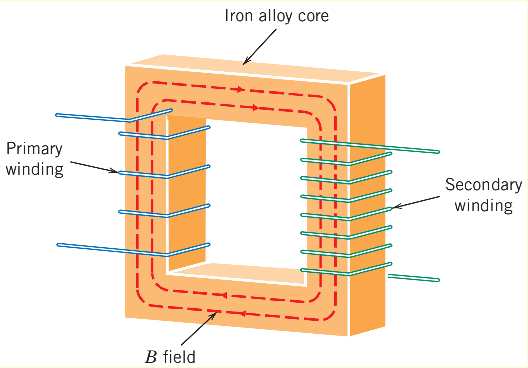

Figure 20.20 Schematic diagram of a transformer core, including the direction of *B* field that is generated.

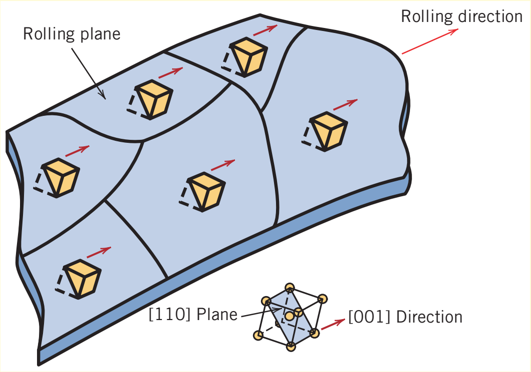

Figure 20.21 Schematic representation of the (110)[001] rolling texture for body-centered cubic iron.

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[3] For body-centered cubic metals and alloys, [100] and [001] directions are equivalent (Section 3.10)—that is, both are directions of easy magnetization.

Table 20.5 Typical Properties for Several Soft Magnetic Materials

Material	*Composition (wt %)*	*Initial Relative Permeability* μ_i	*Saturation Flux Density* B_s *[tesla (gauss)]*	*Hysteresis Loss/Cycle* $[J/m^3\ (erg/cm^3)]$	*Resistivity* ρ *(Ω-m)*
Commercial iron ingot	99.95Fe	150	2.14 (21,400)	270 (2700)	1.0×10^{-7}
Silicon–iron (oriented)	97Fe, 3Si	1400	2.01 (20,100)	40 (400)	4.7×10^{-7}
45 Permalloy	55Fe, 45Ni	2500	1.60 (16,000)	120 (1200)	4.5×10^{-7}
Supermalloy	79Ni, 15Fe, 5Mo, 0.5Mn	75,000	0.80 (8000)	—	6.0×10^{-7}
Ferroxcube A	$48MnFe_2O_4$, $52ZnFe_2O_4$	1400	0.33 (3300)	~40 (~400)	2000
Ferroxcube B	$36NiFe_2O_4$, $64ZnFe_2O_4$	650	0.36 (3600)	~35 (~350)	10^7

Source: Adapted from *Metals Handbook: Properties and Selection: Stainless Steels, Tool Materials and Special-Purpose Metals,* Vol. 3, 9th edition, D. Benjamin (Senior Editor), American Society for Metals, 1980.

susceptibilities. The properties of a half-dozen soft magnetic materials are shown in Table 20.5.

The hysteresis characteristics of soft magnetic materials may be enhanced for some applications by an appropriate heat treatment in the presence of a magnetic field. Using such a technique, a square hysteresis loop may be produced, which is desirable in some magnetic amplifier and pulse transformer applications. In addition, soft magnetic materials are used in generators, motors, dynamos, and switching circuits.

20.10 HARD MAGNETIC MATERIALS

hard magnetic material

Hard magnetic materials are utilized in permanent magnets, which must have a high resistance to demagnetization. In terms of hysteresis behavior, a **hard magnetic material** has a high remanence, coercivity, and saturation flux density, as well as a low initial permeability, and high hysteresis energy losses. The hysteresis characteristics for hard and soft magnetic materials are compared in Figure 20.19. The two most important characteristics relative to applications for these materials are the coercivity and what is termed the "energy product," designated as $(BH)_{\max}$. This $(BH)_{\max}$ corresponds to the area of the largest B-H rectangle that can be constructed within the second quadrant of the hysteresis curve, Figure 20.22; its units are kJ/m^3 (MGOe).[4] The value of the energy product is representative of the energy required

---

[4] MGOe is defined as

$$1\ \text{MGOe} = 10^6\ \text{gauss-oersted}$$

Furthermore, conversion from cgs–emu to SI units is accomplished by the relationship

$$1\ \text{MGOe} = 7.96\ \text{kJ/m}^3$$

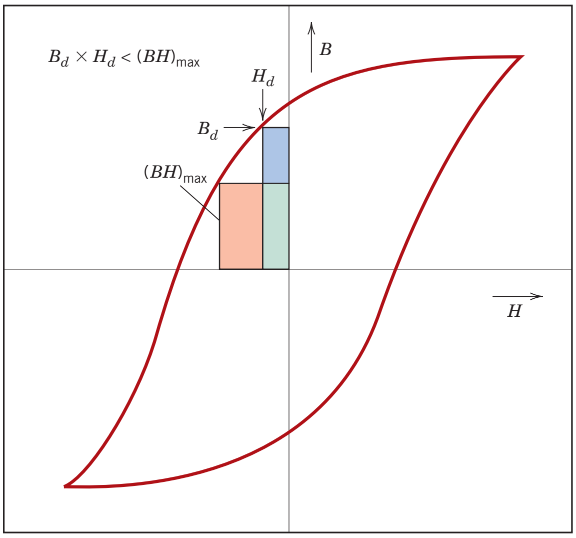

Figure 20.22 Schematic magnetization curve that displays hysteresis. Within the second quadrant are drawn two B–H energy product rectangles; the area of that rectangle labeled $(BH)_{max}$ is the largest possible, which is greater than the area defined by B_d–H_d.

to demagnetize a permanent magnet; that is, the larger $(BH)_{max}$ the harder is the material in terms of its magnetic characteristics.

Again, hysteresis behavior is related to the ease with which the magnetic domain boundaries move; by impeding domain wall motion, the coercivity and susceptibility are enhanced, such that a large external field is required for demagnetization. Furthermore, these characteristics are interrelated to the microstructure of the material.

Concept Check 20.6

It is possible, by various means (i.e., alteration of microstructure and impurity additions), to control the ease with which domain walls move as the magnetic field is changed for ferromagnetic and ferrimagnetic materials. Sketch a schematic B-versus-H hysteresis loop for a ferromagnetic material, and superimpose on this plot the loop alterations that would occur if domain boundary movement were hindered.

[*The answer may be found at www.wiley.com/college/callister (Student Companion Site.)*]

Conventional Hard Magnetic Materials

Hard magnetic materials fall within two main categories—conventional and high energy. The conventional materials have $(BH)_{max}$ values that range between about 2 and 80 kJ/m^3 (0.25 and 10 MGOe). These include ferromagnetic materials—magnet steels, cunife (Cu–Ni–Fe) alloys, alnico (Al–Ni–Co) alloys—as well as the hexagonal ferrites ($BaO–6Fe_2O_3$). Table 20.6 presents some of the critical properties of several of these hard magnetic materials.

The hard magnet steels are normally alloyed with tungsten and/or chromium. Under the proper heat-treating conditions these two elements readily combine with carbon in the steel to form tungsten and chromium carbide precipitate particles, which are especially effective in obstructing domain wall motion. For the other metal

Table 20.6 Typical Properties for Several Hard Magnetic Materials.

Material	*Composition (wt %)*	*Remanence B_r [tesla (gauss)]*	*Coercivity H_c [amp-turn/m (Oe)]*	*$(BH)_{max}$ [kJ/m^3 (MGOe)]*	*Curie Temperature T_c [°C(°F)]*	*Resistivity ρ (Ω-m)*
Tungsten steel	92.8 Fe, 6 W, 0.5 Cr, 0.7 C	0.95 (9500)	5900 (74)	2.6 (0.33)	760 (1400)	3.0×10^{-7}
Cunife	20 Fe, 20 Ni, 60 Cu	0.54 (5400)	44,000 (550)	12 (1.5)	410 (770)	1.8×10^{-7}
Sintered alnico 8	34 Fe, 7 Al, 15 Ni, 35 Co, 4 Cu, 5 Ti	0.76 (7600)	125,000 (1550)	36 (4.5)	860 (1580)	—
Sintered ferrite 3	$BaO{-}6Fe_2O_3$	0.32 (3200)	240,000 (3000)	20 (2.5)	450 (840)	$\sim 10^4$
Cobalt rare earth 1	$SmCo_5$	0.92 (9200)	720,000 (9,000)	170 (21)	725 (1340)	5.0×10^{-7}
Sintered neodymium-iron-boron	$Nd_2Fe_{14}B$	1.16 (11,600)	848,000 (10,600)	255 (32)	310 (590)	1.6×10^{-6}

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alloys, an appropriate heat treatment forms extremely small single-domain and strongly magnetic iron-cobalt particles within a nonmagnetic matrix phase.

High-Energy Hard Magnetic Materials

Permanent magnetic materials having energy products in excess of about 80 kJ/m^3 (10 MGOe) are considered to be of the high-energy type. These are recently developed intermetallic compounds that have a variety of compositions; the two that have found commercial exploitation are $SmCo_5$ and $Nd_2Fe_{14}B$. Their magnetic properties are also listed in Table 20.6.

Samarium–Cobalt Magnets

$SmCo_5$ is a member of a group of alloys that are combinations of cobalt or iron and a light rare earth element; a number of these alloys exhibit high-energy, hard magnetic behavior,but $SmCo_5$ is the only one of commercial significance. The energy products of these $SmCo_5$ materials [between 120 and 240 kJ/m^3 (15 and 30 MGOe)] are considerably higher than the conventional hard magnetic materials (Table 20.6); in addition, they have relatively large coercivities. Powder metallurgical techniques are used to fabricate $SmCo_5$ magnets. The appropriately alloyed material is first ground into a fine powder; the powder particles are aligned using an external magnetic field and then pressed into the desired shape. The piece is then sintered at an elevated temperature, followed by another heat treatment that improves the magnetic properties.

Neodymium–Iron–Boron Magnets

Samarium is a rare and relatively expensive material; furthermore, the price of cobalt is variable and its sources are unreliable. Consequently, the $Nd_2Fe_{14}B$ alloys have become the materials of choice for a large number and wide diversity of applications requiring hard magnetic materials. Coercivities and energy products of these materials rival those of the samarium–cobalt alloys (Table 20.6).

The magnetization–demagnetization behavior of these materials is a function of domain wall mobility, which, in turn, is controlled by the final microstructure—that is, the size, shape, and orientation of the crystallites or grains, as well as the nature and distribution of any second-phase particles that are present. Of course, microstructure will depend on how the material is processed. Two different processing techniques are available for the fabrication of $Nd_2Fe_{14}B$ magnets: powder metallurgy (sintering) and rapid solidification (melt spinning). The powder metallurgical approach is similar to that used for the $SmCo_5$ materials. For rapid solidification, the alloy, in molten form, is quenched very rapidly such that either an amorphous or very fine grained and thin solid ribbon is produced. This ribbon material is then pulverized, compacted into the desired shape, and subsequently heat treated. Rapid solidification is the more involved of the two fabrication processes; nevertheless, it is continuous, whereas powder metallurgy is a batch process, which has its inherent disadvantages.

These high-energy hard magnetic materials are employed in a host of different devices in a variety of technological fields. One common application is in motors. Permanent magnets are far superior to electromagnets in that their magnetic fields are continuously maintained and without the necessity of expending electrical power; furthermore, no heat is generated during operation. Motors using permanent magnets are much smaller than their electromagnet counterparts and are utilized extensively in fractional horsepower units. Familiar motor applications include the following: in cordless drills and screw drivers; in automobiles (starting, window winder, wiper, washer, and fan motors); in audio and video recorders; and in clocks. Other common devices that employ these magnetic materials are speakers in audio systems, lightweight earphones, hearing aids, and computer peripherals.

20.11 MAGNETIC STORAGE

Within the past few years, magnetic materials have become increasingly important in the area of information storage; in fact, magnetic recording has become virtually the universal technology for the storage of electronic information. This is evidenced by the preponderance of audio tapes, VCRs, disk storage media, credit cards, and so on. Whereas in computers, semiconductor elements serve as primary memory, magnetic disks are used for secondary memory because they are capable of storing larger quantities of information and at a lower cost. Furthermore, the recording and television industries rely heavily on magnetic tapes for the storage and reproduction of audio and video sequences.

In essence, computer bytes, sound, or visual images in the form of electrical signals are recorded on very small segments of the magnetic storage medium—a tape or disk. Transference to and retrieval from the tape or disk is accomplished by means of an inductive read–write head, which consists basically of a wire coil wound around a magnetic material core into which a gap is cut. Data are introduced (or "written") by the electrical signal within the coil, which generates a magnetic field across the gap. This field in turn magnetizes a very small area of the disk or tape within the proximity of the head. Upon removal of the field, the magnetization remains; that is, the signal has been stored. The essential features of this recording process are shown in Figure 20.23.

Furthermore, the same head may be utilized to retrieve (or "read") the stored information. A voltage is induced when there is a change in the magnetic field as