The Science and Engineering of Materials, 4th ed

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Chapter 19 – Magnetic Materials

Objectives of Chapter 19

- To study the fundamental basis for responses of certain materials to the presence of magnetic fields.
- To examine the properties and applications of different types of magnetic materials.

Chapter Outline

Section 19.1
Classification of Magnetic Materials

- Ferromagnetism
- Ferrimagnetism
- Diamagnetism
- Antiferromagnetism
- Hard magnet

Section 19.2
Magnetic Dipoles and Magnetic Moments

- The magnetic behavior of materials can be traced to the structure of atoms.
- Bohr magneton - The strength of a magnetic moment of an electron (μ_B) due to electron spin.

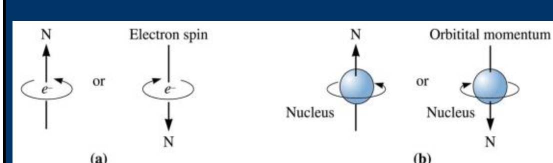

Figure 19.1 Origin of magnetic dipoles: (a) The spin of the electron produces a magnetic field with a direction dependent on the quantum number m_s. (b) Electrons Electrons orbiting around the nucleus create a magnetic field around the atom.

TABLE 19-1 ■ *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	↑↓	↑↓	↑↓	↑↓	↑↓	↑

Section 19.3 Magnetization, Permeability, and the Magnetic Field

- 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.
- Magnetization - The total magnetic moment per unit volume.
- Magnetic susceptibility - The ratio between magnetization and the applied field.

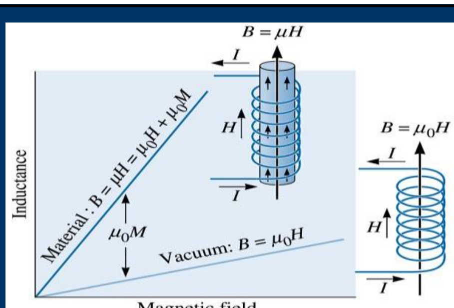

Figure 19.2 A current passing through a coil sets up a magnetic field *H* with a flux density *B*. The flux density is higher when a magnetic core is placed within the coil.

TABLE 19-2 ■ *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 1 Wb-m/kg = $(1/4\pi) \times 10^7$ emu/g
Magnetic moment (m)	emu, erg/G	A-m^2, Joules (J) 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 (value)	
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

Example 19.1 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.)

Example 19.1 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:

$$\text{Number of Fe atoms/m}^3 = \frac{2 \text{ atoms/cell}}{(2.866 \times 10^{-10} \text{ m})^3} = 8.48 \times 10^{28}$$

Example 19.1 SOLUTION (Continued)

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

$$M_{sat} = \left[8.48 \times 10^{28} \frac{\text{atoms}}{\text{m}^3}\right]\left[9.27 \times 10^{-24} \text{ Am}^2\right]\left[4 \frac{\text{Bohr magnetons}}{\text{atom}}\right]$$

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

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 $\mu_0 M >> \mu_0 H$ and therefore, $B \cong \mu_0 M$.

Saturation induction in tesla = $B_{sat} = \mu_0 M_{sat}$.

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

$$B_{sat} = 3.95 \frac{\text{Wb}}{\text{m}^2} = 3.95 \text{ tesla}$$

Section 19.4
Diamagnetic, Paramagnetic, Ferromagnetic, Ferrimagnetic, and Superparamagnetic Materials

- Ferromagnetism - Alignment of the magnetic moments of atoms in the same direction so that a net magnetization remains after the magnetic field is removed.
- 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.
- Diamagnetism - The effect caused by the magnetic moment due to the orbiting electrons, which produces a slight opposition to the imposed magnetic field.

Section 19.4 (Continued)

- Antiferromagnetism - Arrangement of magnetic moments such that the magnetic moments of atoms or ions cancel out causing zero net magnetization.
- Hard magnet - Ferromagnetic or ferrimagnetic material that has a coercivity > 10^4 A . m^{-1}.

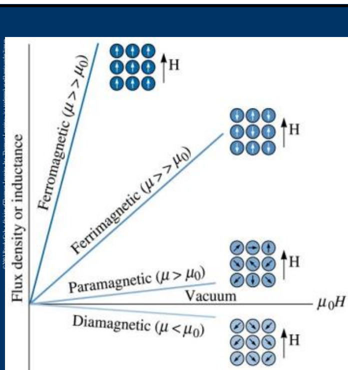

Figure 19.3 The effect of the core material on the flux density. The magnetic moment opposes the field in diamagnetic materials. Progressively stronger moments are present in paramagnetic, ferrimagnetic, and ferromagnetic materials for the same applied field.

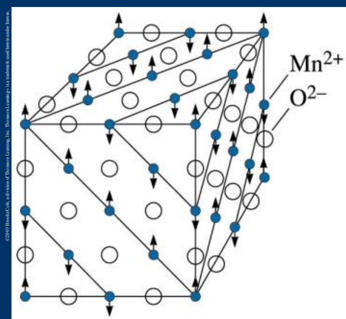

Figure 19.4 The crystal structure of Mn0 consists of alternating layers of {111} type planes of oxygen and manganese ions. The magnetic moments of the manganese ions in every other (111) plane are oppositely aligned. Consequently, Mn0 is antiferromagnetic.

Example 19.2
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.

TABLE 19-4 ■ *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*
(Source: 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.)*

Example 19.2 SOLUTION

The magnetic field *H* produced by the coil.

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

$$H = (10\ \text{A/m})(4\pi \times 10^{-3}\ \text{oersted/A/m}) = 0.126\ \text{oersted}$$

The permeability of the core material must be:

$$\mu = \frac{B}{H} = \frac{2000}{0.126} = 15{,}873\ \text{gauss/oersted}$$

The relative permeability of the core material must be at least:

$$\mu_r = \frac{\mu}{\mu_0} = \frac{15{,}873}{1} = 15{,}873$$

From Table 19-4, we find that 4-79 permalloy has a maximum relative permeability of 80,000 and might be a good selection for the core material.

Section 19.5 Domain Structure and the Hysteresis Loop

- Domains - Small regions within a single or polycrystalline material in which all of the magnetization directions are aligned.
- Bloch walls - The boundaries between magnetic domains.
- Saturation magnetization - When all of the dipoles have been aligned by the field, producing the maximum magnetization.
- Remanance - The polarization or magnetization that remains in a material after it has been removed from the field.
- Hysteresis loop - The loop traced out by magnetization in a ferromagnetic or ferrimagnetic material as the magnetic field is cycled.

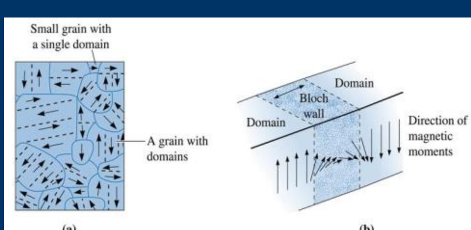

Figure 19.5 (a) A qualitative sketch of magnetic domains in a polycrystalline material. The dashed lines show demarcation between different magnetic domains; the dark curves show the grain boundaries. (b) The magnetic moments in adjoining atoms change direction continuously across the boundary between domains.

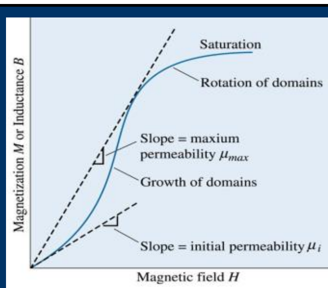

Figure 19.6 When a magnetic field is first applied to a magnetic material, magnetization initially increases slowly, then more rapidly as the domains begin to grow. Later, magnetization slows, as domains must eventually rotate to reach saturation. Notice the permeability values depend upon the magnitude of *H*.

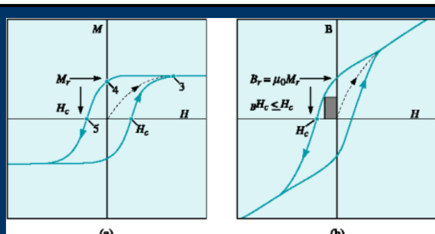

Figure 19.7 (a) The ferromagnetic hysteresis M-H loop showing the effect of the magnetic field on inductance or magnetization. The dipole alignment leads to saturation magnetization (point 3), a remanance (point 4), and a coercive field (point 5). (b) The corresponding B-H loop. Notice the end of the B-H loop, the B value does not saturate since B = $\mu_0 H + \mu_0 M$. (*Source: 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.*)

Section 19.6
The Curie Temperature

- Curie temperature - The temperature above (T_c) which ferromagnetic or ferrimagnetic materials become paramagnetic.

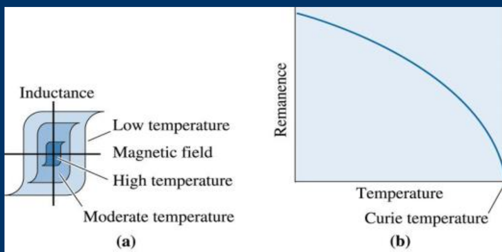

Figure 19.8 The effect of temperature on (a) the hysteresis loop and (b) the remanance. Ferromagnetic behavior disappears above the Curie temperature.

TABLE 19-3 ■ ***Curie temperatures for selected materials***

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

Example 19.3 Design/Materials Selection for a High-Temperature Magnet

Select a permanent magnet for an application in an aerospace vehicle that must re-enter Earth's atmosphere. During re-entry, the magnet may be exposed to magnetic fields as high as 600 oersted and may briefly reach temperatures as high as 500°C. We want the material to have the highest power possible and to maintain its magnetization after re-entry.

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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
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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*
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(Source: 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.)*

Example 19.3 SOLUTION

It is first necessary to select potential materials having sufficient coercive field H_c and Curie temperature that re-entry will not demagnetize them.

The Co_5Sm has four times the power of the Alnico 5 and, based on performance, might be our best choice.

Section 19.7 Applications of 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. Applications include cores for electromagnets, electric motors, transformers, generators, and other electrical equipment.
- Data Storage Materials - Magnetic materials are used for data storage.
- Permanent Magnets - Magnetic materials are used to make strong permanent magnets
- Power - The strength of a permanent magnet as expressed by the maximum product of the inductance and magnetic field.

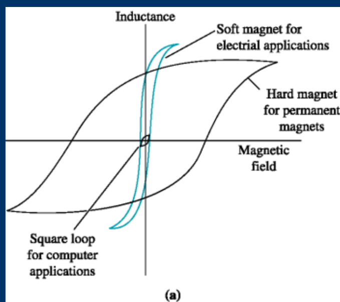

Figure 19.9 (a) Comparison of the hysteresis loops for three applications of ferromagnetic and ferrimagnetic materials.

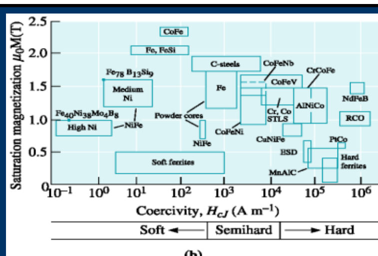

Figure 19.9 (b) Saturation magnetization and coercivity values for different magnetic materials. (*Source: Adapted from* "Magnetic Materials: An Overview, Basic Concepts, Magnetic Measurements, Magnetostrictive Materials," *by G.Y. Chin et al. In D. Bloor, M. Flemings, and S. Mahajan (Eds.), Encyclopedia of Advanced Materials, Vol. 1, 1994, p. 1423, Fig. 1. Copyright © 1994 Pergamon Press. Reprinted by permission of the editor*.)

TABLE 19-4 ■ *Soft magnetic materials*

Name	Composition	Permeability (μ_r)		Coercivity (H_c) (A · m^{-1})	Retentivity (B_r) (*T*)	B_{max} (*T*)	Resistivity ($\mu\Omega \cdot m$)
		Initial	Maximum				
Ingot Iron	99.8% Fe	150	5000	80	0.77	2.14	0.10
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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}

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TABLE 19-5 ■ *Typical magnetic recording materials*[16]

	Particle Length μm	Aspect Ratio	Magnetization (B_r) Wb/m²	Magnetization (B_r) emu/cc	Coercivity (H_c) kA/m	Coercivity (H_c) Oe	Surface Area m²/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*

(Source: From The Complete Handbook of Magnetic Recording, Fourth Edition, *by F. Jorgensen, p. 324, Table 11-1. Copyright © 1996 Reprinted by permission of The McGraw-Hill Companies.)*

TABLE 19-6 ■ *Selected properties of hard, 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

(Source: 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.)*

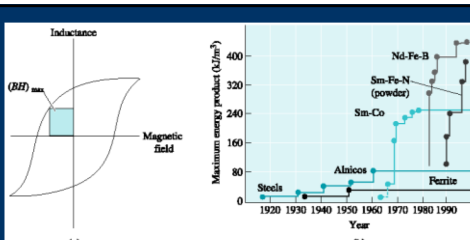

Figure 19.10 (a) The largest rectangle drawn in the second or fourth quadrant of the *B-H* curve gives the maximum *BH* product. $(BH)_{max}$ is related to the power, or energy, required to demagnetize the permanent magnet. (b) Development of permanent magnet materials, maximum energy product is shown on the y -axis. (*Source: 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.*)

Example 19.4
Energy Product for Permanent Magnets

Determine the power, or *BH* product, for the magnetic material whose properties are shown in Figure 19.11.

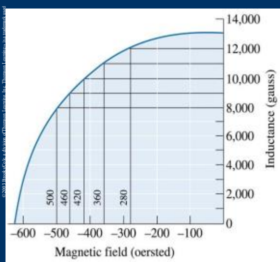

Figure 19.11 The fourth quadrant of the *B-H* curve for a permanent magnetic material (for Example 19.4)

Example 19.4 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 19.5
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.

Example 19.5 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.

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.

Example 19.5 SOLUTION (Continued)

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, assuring 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 made using superconductors.

Example 19.6
Lifting Power of a Magnet

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

Example 19.6 SOLUTION

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.

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

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

Section 19.8
Metallic and Ceramic Magnetic Materials

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

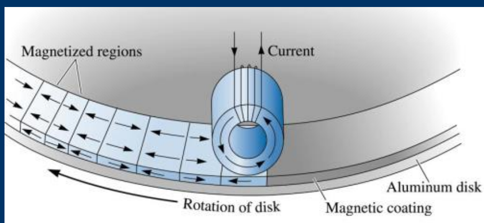

Figure 19.12 Information can be stored or retrieved from a magnetic disk by use of an electromagnetic head. A current in the head magnetizes domains in the disk during storage; the domains in the disk induce a current in the head during retrieval.

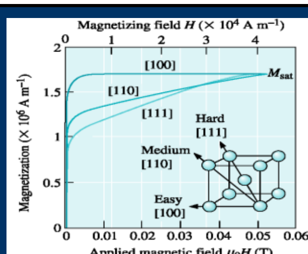

Figure 19.13 The initial magnetization curve for iron is highly anisotropic; magnetization is easiest when the ⟨100⟩ directions are aligned with the field and hardest along [111]. (*Source: From* Principles of Electrical Engineering Materials and Devices, *by S.O. Kasap, p. 623, Fig. 8-24. Copyright © 1997 Irwin. Reprinted by permission of The McGraw-Hill Companies.*)

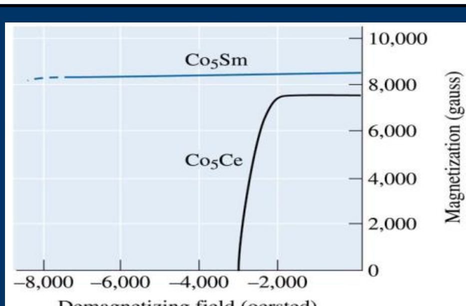

Figure 19.14 Demagnetizing curves for Co_5Sm and Co_5Ce, representing a portion of the hysteresis loop.

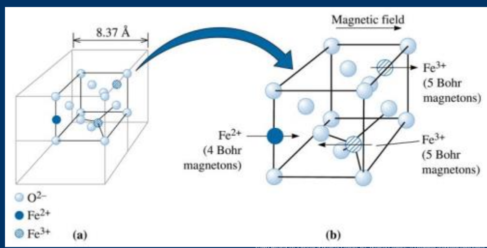

Figure 19.15 (a) The structure of magnetite, Fe_3O_4. (b) The subcell of magnetite. The magnetic moments of ions in the octahedral sites line up with the magnetic field, but the magnetic moments of ions in tetrahedral sites oppose the field. A net magnetic moment is produced by this ionic arrangement.

Example 19.7
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.

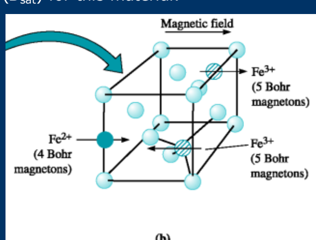

Figure 19.15 (b) The subcell of magnetite.

Example 19.7 SOLUTION

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:

$$\text{Total moment} = \frac{32\ \text{Bohr magnetons/cell}}{5.86 \times 10^{-22}\ \text{cm}^3\text{/cell}} = 5.46 \times 10^{22}\ \text{magnetons/cm}^3$$

$$= (5.46 \times 10^{22})(9.27 \times 10^{-24}\ \text{A} \cdot \text{m}^2\text{/magneton})$$

$$= 0.51\ \text{A} \cdot \text{m}^2/\text{cm}^3 = 5.1 \times 10^5\ \text{A/m}^2/\text{m}^3 = 5.1 \times 10^5\ \text{A/m}$$

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

TABLE 19-7 Magnetic moments for ions in the spinel structure

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

Example 19.8 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.

TABLE 19-7 Magnetic moments for ions in the spinel structure

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

Example 19.8 SOLUTION

Assuming that the addition of Mn ions does not appreciably affect the size of the unit cell, we find from Example 19-7 that: $V_{cell} = 5.86 \times 10^{-22}\ cm^3 = 5.86 \times 10^{-28}\ m^3$

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

$$= \frac{(8\ \text{subcells})[(x)(5\ \text{magnetons}) + (1-x)(4\ \text{magnetons})](9.27 \times 10^{-24}\ A \cdot m^2)}{5.86 \times 10^{-28}\ m^3}$$

$$= \frac{(8)(5x + 4 - 4x)(9.27 \times 10^{-24})}{5.86 \times 10^{-28}} = 5.5 \times 10^5$$

$$x = -4 + 4.346 = 0.346$$

Therefore we need to replace 34.6 at% of the Fe^{2+} ions with Mn^{2+} ions to obtain the desired magnetization.

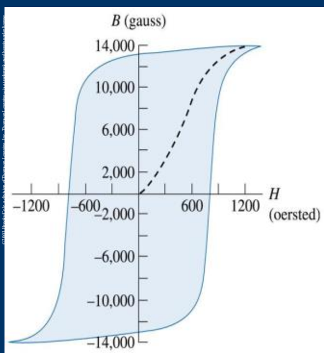

Figure 19.16 Hysteresis curve for a hard magnetic material (for Problem 19.19).

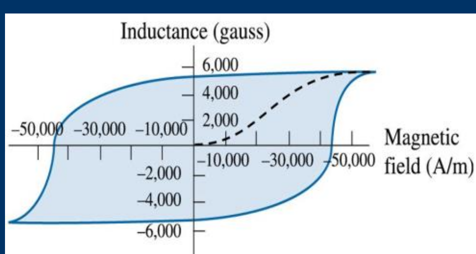

Figure 19.17 Hysteresis curve for a hard magnetic material (for Problem 19.30).

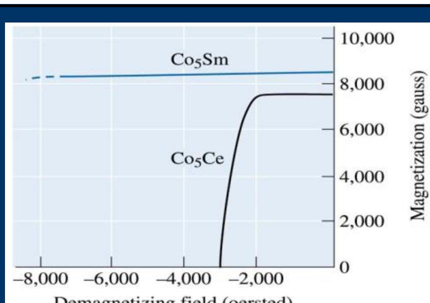

Figure 19.14 (Repeated for Problem 19.36.) Demagnetizing curves for Co_5Sm and Co_5Ce, representing a portion of the hysteresis loop.