MAGNETIC MATERIALS

I.R. Harris and A.J. Williams

School of Metallurgy and Materials, University of Birmingham, Birmingham, UK

Keywords: Magnetism, magnetic materials, hard magnets, permanent magnets, soft magnets, recording media, magnetic domains

Contents

1. Introduction
2. The Origin of Magnetism
3. Magnetic Terminology and Units
4. Types of Magnetic Materials
5. Intrinsic Properties of Magnetic Materials
6. Magnetic Domains
7. Magnetic Hysteresis
8. Observation of Magnetic Domains
9. Hard Magnetic Materials
10. Applications of Hard Magnetic Materials
11. Soft Magnetic Materials
12. Applications of Soft Magnetic Materials
13. Magnetic Recording
14. Other Magnetic Materials
Glossary
Bibliography
Biographical Sketches

Summary

This chapter begins by outlining in basic terms the origin of magnetism and the terminology used to describe magnetic effects and properties. The various types of magnetic behaviors, diamagnetism, paramagnetism, ferromagnetism, antiferromagnetism, and ferrimagnetism are discussed. The main intrinsic properties of ferromagnetic and ferrimagnetic materials, saturation magnetization, and magnetocrystalline anisotropy are described. The nature of magnetic domains is discussed, the control of which is one of the key aspects in generating good magnetic properties for both hard and soft magnets and recording media. The extrinsic properties, dependent on microstructure and control of domains, are introduced by consideration of the magnetic hysteresis loop. Then each of the main classes of magnetic material, hard and soft magnetic materials and recording media, are described in terms of development, processing, and applications of hard and soft magnetic materials. Finally, other types of important magnetic materials are briefly discussed.

1. Introduction

Magnetic materials encompass a wide variety of materials, which are used in a diverse range of applications. Magnetic materials are utilized in the creation and distribution of

electricity, and, in most cases, in the appliances that use that electricity. They are used for the storage of data on audiotape and videotape and on computer disks. In the world of medicine, they are used in body scanners and in a range of applications where they are attached to or implanted into the body. The home entertainment market relies on magnetic materials in applications such as PCs, CD players, televisions, games consoles, and loudspeakers.

It is difficult to imagine a world without magnetic materials, and they are becoming more important in the development of modern society. The need for efficient generation and use of electricity is dependent on improved magnetic materials and designs. Nonpolluting electric vehicles will rely on efficient motors utilizing advanced magnetic materials. The telecommunications industry is always striving for faster data transmission and miniaturization of devices, both of which require development of improved magnetic materials.

Magnetic materials are classified in terms of their magnetic properties and their uses. If a material is easily magnetized and demagnetized then it is referred to as a soft magnetic material, whereas if it is difficult to demagnetize then it is referred to as a hard (or permanent) magnetic material. Materials in between hard and soft are almost exclusively used as recording media and have no other general term to describe them. Other classifications for types of magnetic materials are subsets of soft or hard materials, such as magnetostrictive and magnetoresistive materials.

This chapter will start by describing in basic terms the origin of magnetism and the terminology used to describe magnetic effects and properties. The various types of magnetic behaviors and materials will be discussed. The nature of magnetic domains, the control of which is one of the key aspects to generating good magnetic properties, both hard and soft, will be explained. The development, processing, and applications of hard and soft magnetic materials and recording media will then be described in detail.

2. The Origin of Magnetism

Almost everyone is familiar with what a magnetic material can do but very few know how a magnet works. To understand this phenomenon one must first grasp the inextricable connection that exists between magnetism and electricity.

A simple electromagnet can be produced by wrapping copper wire into the form of a coil and connecting the wire to a battery. A magnetic field is created in the coil, but it remains there only while electricity flows through the wire.

An ordinary bar magnet does not have an obvious connection with electricity, so how does it work? The field created by the magnet is associated with the motions and interactions of its electrons, the minute charged particles which orbit the nucleus of each atom.

Electricity is the movement of electrons, whether in a wire or in an atom, so each atom represents a tiny permanent magnet in its own right. The circulating electron produces its own orbital magnetic moment, and there is also a spin magnetic moment because the

electron itself spins, like the earth, on its own axis (illustrated in Figure 1). In most materials these magnetic moments, measured in Bohr magnetons (μ_B), cancel each other out with each electronic magnet negating the field produced by another.

In certain magnetic materials the magnetic moments of a large proportion of the electrons align, producing a unified magnetic field. The field produced in the material (or by an electromagnet) has a direction of flow, and any magnet will experience a force trying to align it with an externally applied field, just like a compass needle. These forces are used to drive electric motors, produce sounds in a speaker system, control the voice coil in a CD player, and so on.

The interactions between magnetism and electricity are therefore an essential aspect of many devices we use every day (see Structural and Functional Materials).
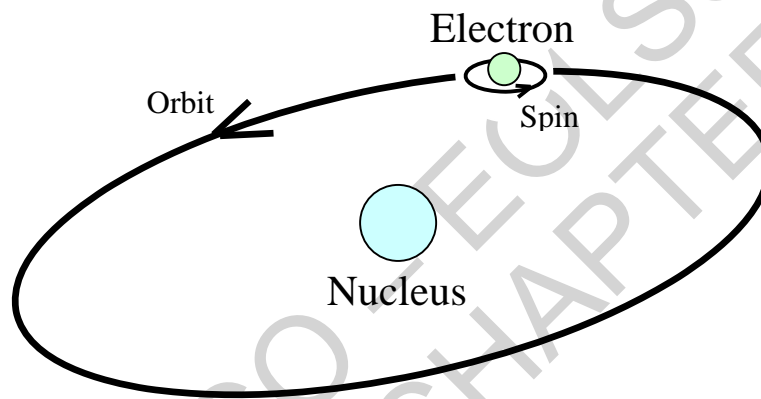
Figure 1. The orbit of a spinning electron about the nucleus of an atom

3. Magnetic Terminology and Units

In the study of magnetism there are two systems of units currently in use: the mks (metres-kilograms-seconds) system, which has been adopted as the S.I. units and the cgs (centimeters-grams-seconds) system, which is also known as the Gaussian system. The cgs system is used by many magnets experts because of the numerical equivalence of the magnetic induction (B) and the applied field (H).

When a field is applied to a material then it responds by producing a magnetic field, the magnetization (M). This magnetization is a measure of the magnetic moment per unit volume of material, but can also be expressed per unit mass and is called the specific magnetization (σ). The field that is applied to the material is called the applied field (H) and is the total field that would be present if the field were applied to a vacuum. Another important parameter is the magnetic induction (B), which is the total flux of magnetic field lines through a unit cross sectional area of the material, considering both lines of force from the applied field and from the magnetization of the material. *B*, *H,* and *M* are related by Eq. (1a) in S.I. units and by Eq. (1b) in cgs units.

$$B = \mu_o(H + M)$$ (1a)

$$B = H + 4\pi M \tag{1b}$$

In Eq. (1a), the constant μ_o is the permeability of free space ($4\pi \times 10^{-7}\,\mathrm{Hm^{-1}}$), which is the ratio of B/H measured in a vacuum. In cgs units the permeability of free space is unity and so does not appear in Eq. (1b). The units of B, H, and M for both S.I. and cgs systems are given in Table 1. Note that in the cgs system $4\pi M$ is usually quoted as it has units of Gauss and is numerically equivalent to B and H.

Quantity	Gaussian (cgs units)	S.I. Units	Conversion factor (cgs to S.I.)
Magnetic Induction (B)	G	T	10^{-4}
Applied Field (H)	Oe	A m^{-1}	$10^3 / 4\pi$
Magnetization (M)	emu cm^{-3}	A m^{-1}	10^3
Magnetization ($4\pi M$)	G	–	–
Magnetic Polarization (J)	–	T	–
Specific Magnetization (σ)	emu g^{-1}	J T^{-1} kg^{-1}	1
Permeability (μ)	Dimensionless	H m^{-1}	$4\pi . 10^{-7}$
Relative Permeability (μ_r)	–	Dimensionless	–
Susceptibility (χ)	emu cm^{-3} Oe^{-1}	Dimensionless	4π
Product of $B \times H$	M G Oe	k J m^{-3}	$10^2 / 4\pi$

G = Gauss, Oe = Oersted, T = Tesla

Table 1. The relationship between some magnetic parameters in cgs and S.I. units

Another equation (Eq. (2), the same for S.I. and cgs units) to consider at this stage is that concerning the magnetic susceptibility (χ), which is a parameter that demonstrates the type of magnetic material and the strength of that type of magnetic effect.

$$\chi = \frac{M}{H} \tag{2}$$

Sometimes the mass susceptibility (χ_m) is quoted and this has the units of m^{3}kg^{-1} and can be calculated by dividing the susceptibility of the material by the density.

Another parameter that demonstrates the type of magnetic material and the strength of that type of magnetic effect is the permeability (μ) of a material, which is defined in Eq. (3) (the same for S.I. and cgs units).

$$\mu = \frac{B}{H} \tag{3}$$

In the S.I. system of units, the permeability is related to the susceptibility, as shown in Eq. (4) and can also be broken down into μ_o and the relative permeability (μ_r), as shown in Eq. (5).

$$\mu = \chi + 1 \tag{4}$$

$$\mu = \mu_o \cdot \mu_r \tag{5}$$

Finally, an important parameter (in S.I. units) to know is the magnetic polarization (*J*), sometimes referred to as the intensity of magnetization (*I*). This value is effectively the magnetization of a sample expressed in Tesla, and can be calculated as shown in Eq. (6).

$$J = \mu_o \cdot M \tag{6}$$

4. Types of Magnetic Materials

Type of Magnetism	Susceptibility	Example	
Diamagnetism	Small and negative	Au,	-2.74×10^{-6}
		Cu,	-0.77×10^{-6}
Paramagnetism	Small and positive	β-Sn,	0.19×10^{-6}
		Pt,	21.04×10^{-6}
		Mn,	66.10×10^{-6}
Ferromagnetism	Large and positive, function of applied field, microstructure dependent	Fe,	Up to ~100,000
Antiferromagnetism	Small and positive	Cr,	
Ferrimagnetism	Large and positive, function of applied field, microstructure dependent	Ba Ferrite,	Up to ~3

Table 2. Susceptibility at room temperature for each type of magnetic material

All materials can be classified in terms of their magnetic behavior. The two most common types of magnetism are diamagnetism and paramagnetism, which account for the magnetic properties of most of the periodic table of elements at room temperature (see Figure 2). These elements are usually referred to as nonmagnetic, whereas those which are referred to as magnetic are actually classified as ferromagnetic. The only other type of magnetism observed in pure elements at room temperature is antiferromagnetism. Finally, magnetic materials can also be classified as ferromagnetic, although this is not observed in any pure element but can only be found in compounds, such as the mixed oxides, known as ferrites, from which ferrimagnetism derives its name. The value of magnetic susceptibility falls into a particular range for each type of material and this is shown in Table 2 with some examples. The various types of behavior are illustrated in Figure 3.

4.1. Diamagnetism

In a diamagnetic material the atoms have no magnetic moment when there is no applied field. Under the influence of an applied field (*H*) the spinning electrons precess, and this motion, which is a type of electric current, produces a magnetization (*M*) in the opposite

direction to that of the applied field. All materials have a diamagnetic effect. However, in nondiamagnetic material another effect makes the diamagnetic contribution insignificant. The value of susceptibility is independent of temperature.

4.2. Paramagnetism

There are several theories of paramagnetism, which are valid for specific types of material. The Langevin model, which is true for materials with noninteracting localized electrons, states that each atom has a magnetic moment which is randomly oriented as a result of thermal agitation. The application of a magnetic field creates a slight alignment of these moments and hence a low magnetization in the same direction as the applied field. As the temperature increases, then the thermal agitation will increase and it will become harder to align the atomic magnetic moments and hence the susceptibility will decrease. This behavior is known as the Curie law and is shown below in Eq. (7), where C is a material constant called the Curie constant.

$$\chi = \frac{C}{T} \tag{7}$$

Materials that obey this law are materials in which the magnetic moments are localized at the atomic or ionic sites and where there is no interaction between neighboring magnetic moments. The hydrated salts of the transition metals, e.g., $CuSO_4 \cdot 5H_2O$, are examples of this type of behavior as the transition metal ions, which have a magnetic moment, are surrounded by a number of nonmagnetic ions / atoms, which prevent interaction between neighboring magnetic moments.

In fact the Curie law is a special case of the more general Curie-Weiss law, Eq. (8), which incorporates a temperature constant (θ) and derives from Weiss theory which incorporates the interaction between magnetic moments.

$$\chi = \frac{C}{T - \theta} \tag{8}$$

In this equation, θ can either be positive, negative, or zero. Clearly when $\theta = 0$ then the Curie-Weiss law equates to the Curie law. When θ is nonzero then there is an interaction between neighboring magnetic moments, and the material is only paramagnetic above a certain transition temperature. If θ is positive, then the material is ferromagnetic below the transition temperature, and the value of θ corresponds to the transition temperature (Curie temperature, T_C). If θ is negative then the material is antiferromagnetic below the transition temperature (Néel temperature, T_N). However the value of θ does not relate to T_N. It is important to note that this equation is only valid when the material is in a paramagnetic state. It is also not valid for many metals, as the electrons contributing to the magnetic moment are not localized. However, the law does apply to some metals, e.g. the rare-earths, where the 4f electrons, which create the magnetic moment, are closely bound.

The Pauli model of paramagnetism is true for materials where the electrons are free and

interact to form a conduction band and is valid for most paramagnetic metals. In this model the conduction electrons are considered essentially to be free, and under an applied field an imbalance between electrons with opposite spin is set up leading to a low magnetization in the same direction as the applied field. The susceptibility is independent of temperature, although the electronic band structure may be affected, which will then have an effect on the susceptibility.
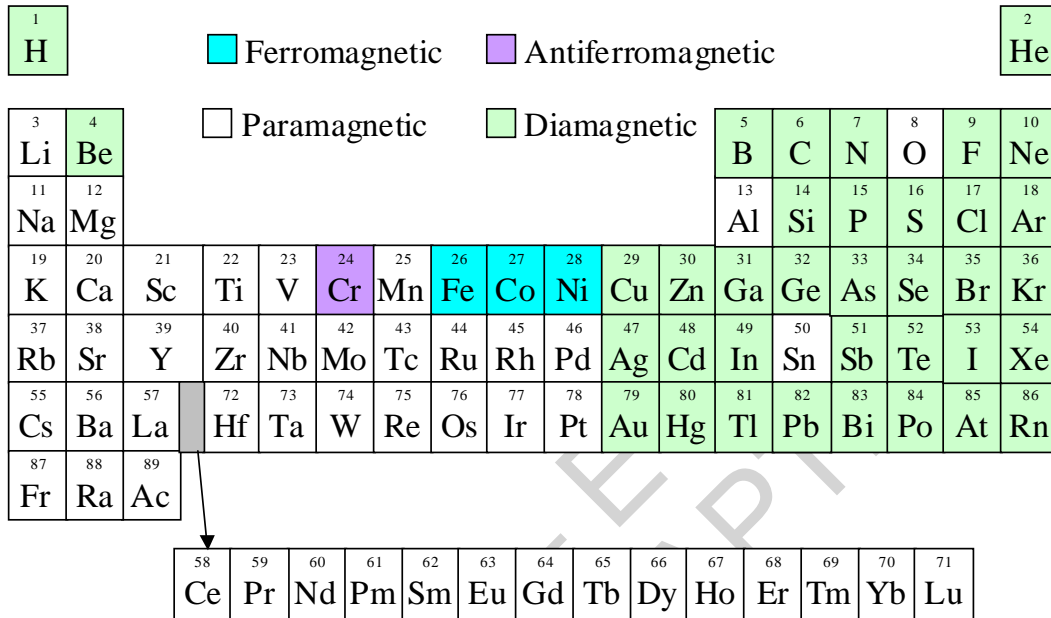
1 H		■ Ferromagnetic				■ Antiferromagnetic											2 He
3 Li	4 Be	□ Paramagnetic				□ Diamagnetic						5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac															

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu

Figure 2. A periodic table showing the type of magnetic behavior of each element at room temperature

4.3. Ferromagnetism

Ferromagnetism is only possible when atoms are arranged in a lattice and the atomic magnetic moments can interact to align parallel to each other. This effect is explained in classical theory by the presence of a molecular field within the ferromagnetic material, which was first postulated by Weiss in 1907. This field is sufficient to magnetize the material to saturation. In quantum mechanics, the Heisenberg model of ferromagnetism describes the parallel alignment of magnetic moments in terms of an exchange interaction between neighboring moments.

Weiss postulated the presence of magnetic domains (considered later) within the material, which are regions where the atomic magnetic moments are aligned. The movement of these domains determines how the material responds to a magnetic field and as a consequence the susceptibility is a function of applied magnetic field. Therefore, ferromagnetic materials are usually compared in terms of saturation magnetization (magnetization when all domains are aligned) rather than susceptibility.

In the periodic table of elements only Fe, Co, and Ni are ferromagnetic at and above room temperature. As ferromagnetic materials are heated, the thermal agitation of the atoms means that the degree of alignment of the atomic magnetic moments decreases

and hence the saturation magnetization also decreases. Eventually the thermal agitation becomes so great that the material becomes paramagnetic; the temperature of this transition is the Curie temperature, T_C (Fe: $T_C = 770$ °C, Co: $T_C = 1131$ °C and Ni: $T_C = 358$ °C). Above T_C the susceptibility varies according to the Curie-Weiss law.
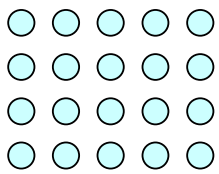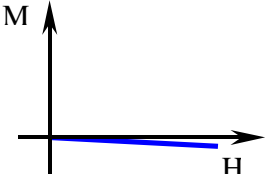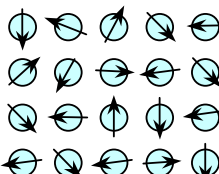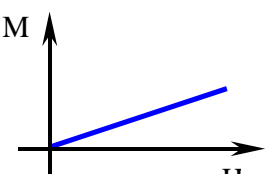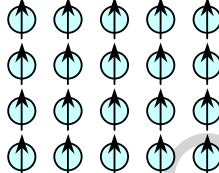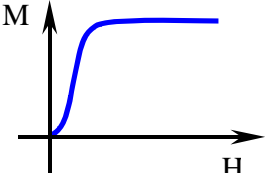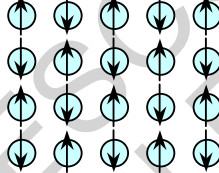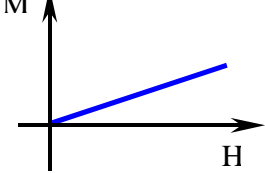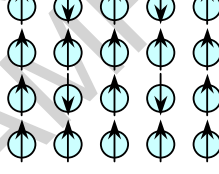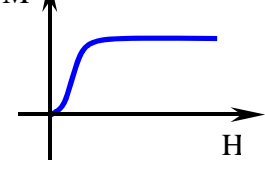
Type	Atomic / Magnetic Behaviour	
Dia-magnetism	Atoms have no magnetic moment	M / H
Para-magnetism	Atoms have randomly oriented magnetic moments	M / H
Ferro-magnetism	Atoms have parallel aligned magnetic moments	M / H
Antiferro-magnetism	Atoms have anti-parallel aligned magnetic moments	M / H
Ferri-magnetism	Atoms have mixed parallel and anti-parallel aligned magnetic moments	M / H

Figure 3. A summary of the different types of magnetic behavior

4.4. Antiferromagnetism

In the periodic table the only element exhibiting antiferromagnetism at room temperature is chromium. Antiferromagnetic materials are similar to ferromagnetic materials, but the exchange interaction between neighboring atoms leads to the antiparallel alignment of the atomic magnetic moments. Therefore, the magnetic field cancels out, and the material appears to behave in the same way as a paramagnetic material. Like ferromagnetic materials these materials become paramagnetic above a transition temperature, known as the Néel temperature, T_N. (Cr: $T_N = 37$ °C).

4.5. Ferrimagnetism

Ferrimagnetism is only observed in compounds, which have more complex crystal structures than pure elements. Within these materials the exchange interactions lead to parallel alignment of atoms in some of the crystal sites and antiparallel alignment of others. The material breaks down into magnetic domains, just like a ferromagnetic material, and the magnetic behavior is also similar, although ferrimagnetic materials usually have lower saturation magnetizations. For example, in barium ferrite ($BaO.6Fe_2O_3$), the unit cell contains 64 ions of which the barium and oxygen ions have no magnetic moment, 16 Fe^{3+} ions have moments aligned parallel and 8 Fe^{3+} aligned antiparallel, giving a net magnetization parallel to the applied field, but with a relatively low magnitude as only 1/8 of the ions contribute to the magnetization of the material.

5. Intrinsic Properties of Magnetic Materials

The intrinsic properties of a magnetic material are those properties that are characteristic of the material and are unaffected by the microstructure (e.g., grain size, crystal orientation of grains). These properties include the Curie temperature, the saturation magnetization, and the magnetocrystalline anisotropy.

5.1. Saturation Magnetization

Material	Magnetic Structure	J_S at 298K (T)	T_C (ºC)
Fe	Ferro-	2.15	770
Co	Ferro-	1.76	1131
Ni	Ferro-	0.60	358
$Nd_2Fe_{14}B$	Ferro-	1.59	585
$SmCo_5$	Ferro-	1.14	720
Sm_2Co_{17}	Ferro-	1.25	820
$BaO.6Fe_2O_3$	Ferri-	0.48	450
$SrO.6Fe_2O_3$	Ferri-	0.48	450
Fe 3wt% Si	Ferro-	2.00	740
Fe 4wt% Si	Ferro-	1.97	690
Fe 35wt% Co	Ferro-	2.45	970
Fe 78wt% Ni	Ferro-	0.70	580
Fe 50wt% Ni	Ferro-	1.55	500
$MnO.Fe_2O_3$	Ferri-	0.51	300

Table 3. The saturation polarization (J_S) and Curie temperature
of a range of magnetic materials

The saturation magnetization (M_S) is a measure of the maximum amount of field that can be generated by a material. It will depend on the strength of the dipole moments on

the atoms that make up the material and how densely they are packed together. The atomic dipole moment will be affected by the nature of the atom and the overall electronic structure within the compound. The packing density of the atomic moments will be determined by the crystal structure (i.e. the spacing of the moments) and the presence of any nonmagnetic elements within the structure.

For ferromagnetic materials, at finite temperatures, M_S will also depend on how well these moments are aligned, as thermal vibration of the atoms causes misalignment of the moments and a reduction in M_S. For ferrimagnetic materials not all of the moments align parallel, even at zero Kelvin and hence M_S will depend on the relative alignment of the moments as well as on the temperature.

The saturation magnetization is also referred to as the spontaneous magnetization, although this term is usually used to describe the magnetization within a single magnetic domain. Table 3 gives some examples of the saturation polarization and Curie temperature of materials commonly used in magnetic applications.

-
-
-

TO ACCESS ALL THE **35 PAGES** OF THIS CHAPTER,
Visit: http://www.eolss.net/Eolss-sampleAllChapter.aspx

Bibliography

Coey J.M.D., ed.. *Rare-earth Iron Permanent Magnets*. Clarendon Press. [This book covers the principles of permanent magnetism, magnet processing, and applications in a series of interlocking chapters written by experts in each area.]

Gutfleisch O. (2000). Controlling the properties of high energy density permanent magnetic materials by different processing routes. *Journal of Physics D−Applied Physics* **Vol. 33**, Iss. 17, 157–172. [Review of advances in permanent magnet processing.]

Jiles David C. (1998). *Introduction to Magnetism and Magnetic Materials,* 576 pp. Stanley Thorne Publishing. [Aimed to be used as an introductory course for scientists and engineers who wish to develop an understanding of magnetism and magnetic materials.]

Livingston James D. (1997). *Driving Force***,** 336 pp. Harvard University Press. [Describes the properties of magnetic forces, the history of their applications, and the future uses being developed for them.]

McHenry M.E. (1999). Amorphous and nanocrystalline materials for applications as soft magnets. *Progress in Materials Science* **Vol. 44**, Iss. 4, 291–433. [Review of recent developments in soft magnet processing and applications.]

Zhu Z.Q. and Howe D. (2001). Halbach permanent magnet machines and applications: a review. *Electric Power Applications* (Proceedings of the IEE, **Vol. 148**, Iss. 4, 299–308). [Review of recent developments in motor design.]

Biographical Sketches

Professor Ivor Rex Harris was appointed Professor of Materials Science in 1988 and has been at the forefront of the development of new magnetic materials for the past thirty years. He leads the Applied Alloy Chemistry Group (AACG) of the School of Metallurgy and Materials. A major innovation that originated from this group is the hydrogen decrepitation (HD) process that has been adopted worldwide as a standard production route for sintered Nd-Fe-B magnets. It has been estimated that reductions in processing costs of up to 25% are achieved through this route. In recognition of his work in this and other areas of hydrogen technology, Professor Harris was awarded a fellowship of the Royal Academy of Engineering in 1994. He was the joint prize winner of the Secretary of State University/Industry Partnership Prize, and in 2000 he was awarded a Marie Curie individual fellowship and he was elected a foreign member of the National Academy of Science, Ukraine. Professor Harris has been head of the School of Metallurgy and Materials since 1994 and has published more than 475 scientific papers, has 5 patents, and has published 3 books.

Dr. Andrew John Williams joined the Applied Alloy Chemistry Group (AACG) of the School of Metallurgy and Materials in 1988 and has been a lecturer since January 1998. He is studying the use of hydrogen in the processing of permanent magnets and has coordinated several research programs within the group. These include the production of fully dense magnets by powder processing and hot deformation of cast ingots and the production of resin and PTFE-bonded magnets by conventional pressing, rotary forging, and hot pressing.