MAGNETIC MATERIALS AND MAGNETIC TECHNIQUES

Andrew Nafalski
University of South Australia, Adelaide, Australia

Keywords: Magnetic properties of materials, magnetic characteristics, soft magnetic materials, hard magnetic materials, applications of magnetic materials and techniques, environmental considerations

Contents

Summary

The developments in the field of magnetic materials along with a better understanding of electromagnetic phenomena and their practical applications in daily and industrial life have been shaping the human civilization in the 19th, 20th and the 21st centuries. This chapter reviews different categories of magnetic materials and their applications, with an emphasis on electrical power that dominates the energy market, where more effective magnetic materials can bring the most spectacular benefits to society. Materials are characterized by their magnetic behavior, that includes ferromagnetic, diamagnetic, paramagnetic, antiferromagnetic or ferrimagnetic, as well as their composition, production methods and their macroscopic properties – crystalline, ferrites, metallic glasses, permanent magnets and nanocrystalline materials. The importance of energy saving by using more efficient magnetic materials and design methods of

electromagnetic devices are highlighted to help create more environmentally sustainable economies. What else could be more sustainable than using the Earth' magnetic field for space energy supply? In addition, the concept and implementation of electrodynamic tethers for space applications are also described. The chapter concludes with promises for the future of magnetic materials and technologies as important as ever for humanity.

1. Introduction

The fascination with electricity and magnetism began in ancient China and Greece, however it was not until the nineteenth century when the first experiments in electricity resulted in the advancement of theory that produced the future applications of electrical engineering. Such advances included historic and significant discoveries by Alessandro Volta in 1800, who produced an electric current; Hans Christian Oersted in 1820 that discovered that changeable magnetic fields produced electric currents to discoveries by Michael Faraday in 1831, which linked magnetism and electricity in his experiments. Although the list of names of theoretical contributors to electrical engineering is long, at least three names stand out with the first being James Clerk Maxwell, who merged electrical and magnetic phenomena into epochal electromagnetic waves as described in *Treatise on Electricity and Magnetism* (1873). The second was Olivier Heaviside who greatly advanced the practical understanding of electrical engineering concepts and finally Charles Proteus Steinmetz, who introduced alternating circuit analysis techniques that are now taken for granted in early years of electrical engineering education.

It is hard to imagine the current civilization without magnetic materials. Some 98% of all electricity in the world is generated by synchronous generators with stators and rotors made of soft magnetic materials. All generated electricity needs voltage transformation in power transformers, often more than once; again their cores are made of soft magnetic materials, where the majority of electrical appliances such as motors also use either soft or hard or both magnetic materials. The improvement of device efficiency by developing more efficient magnetic materials and improved design methodologies has greatly impacted on society both economically and environmentally. The reduction of cost of electricity generation and subsequent use can be translated in the reduction of emissions of greenhouse gases and other harmful pollutants into the environment.

The application of magnetic materials in consumer goods is vast by the quantity of sales: the majority of data storage devices (tapes, CD players, TV sets, stereo systems, magnetic identification stripes on bank and credit cards) rely on magnetic materials and technologies; a single computer contains dozens of magnetic circuits, often on a miniature scale. Moving toys and house appliances have almost always contained magnetic materials. Telecommunication devices from mobile phones through satellite modems to military communications rely heavily on magnetic materials. Medicine also uses magnetic materials extensively that include magnetic shielding used in body and organ scanning, electromagnetic tomographic imaging, automatic - often intravascular drug dosing devices to hyperthermic cancer treatment which involves inducing eddy currents in magnetic particles within a patient's body.

The field of magnetic materials and technologies does not show any signs of slowing down from the developments in the 19^{th} and 20^{th} centuries, where the basics of electromagnetism were formulated. The prestigious publication of the Institute of Electrical and Electronic Engineers (IEEE) in the U.S.A. - IEEE Transactions on Magnetics is still the thickest of dozens of the existing IEEE Transactions, not only by the sheer volume but predominately by its scientific and engineering content and innovation. Magnetics is thriving in the 21^{st} century.

The following sections of the chapter discuss necessary basics of magnetism including terminology, followed by the magnetic behavior of materials, their classification and applications, with an emphasis given to electrical power. Finally, some new developments including nanocrystalline materials are highlighted.

2. Basics of Magnetism

Magnetism and electricity are closely related to each other. Electric fields are associated only with the presence of electric charge that is a fundamental property of matter. Examples of electric charges are electrons (elementary negative electric charge), protons (elementary positive electric charge) and ions flowing in a fluid. Properties of electric fields depend on the distribution of positive and negative charges. An electric field, $\boldsymbol{E}$, (more precisely called electric field strength) expressed in volts per meter (Vm^{-1}), can exert a physical force on an electric charge. Magnetic fields can also be produced in the vicinity of magnetized bodies, however ultimately all magnetism results from the physical movement of electric charge that constitutes electric current. Magnetic charges do not exist, but are often used for visualizing magnetic field phenomena using a concept of a magnetic dipole (see *Magnetic Measurements*).

Electric and magnetic fields are represented as vectors; a vector is characterized by both magnitude and direction. A magnetic field can be described by using magnetic field density, $\boldsymbol{B}$ (known also as magnetic induction), expressed in Tesla (T) or by magnetic field strength, $\boldsymbol{H}$, expressed in Ampere per meter (Am^{-1}). At low frequencies, electric and magnetic fields are often treated separately, at higher frequencies; the concept of electromagnetic waves is used. One of the most common models of electromagnetic waves is the plane-wave, where $\boldsymbol{E}$, $\boldsymbol{B}$ and the direction of the wave movement (propagation) are mutually perpendicular and the electric and magnetic fields are inseparable.

The magnetic field strength, $\boldsymbol{H}$, in a free space (vacuum) produces magnetic flux density $\boldsymbol{B}$, where $\boldsymbol{B}$ is defined by the following equation:

$$\boldsymbol{B} = \mu_0 \boldsymbol{H} \quad (1)$$

The constant μ_0 is called the permeability of free space where $\mu_0 = 4\pi \times 10^{-7}$ Henry per meter (Hm^{-1}). If the space in which $\boldsymbol{H}$ is acting contains any material substance in addition to the free space component of Eq. (1), there will also be a component due to the substance itself called the magnetization (or induced magnetization):

$$\boldsymbol{B} = \mu_0(\boldsymbol{H} + \boldsymbol{M}) \quad (2)$$

After introducing a parameter that links the magnetization and the magnetic field strength, the material's magnetic susceptibility χ, an equation is obtained:

$$\boldsymbol{B} = \mu_0(1 + \chi)\boldsymbol{H} = \mu_0\mu_r\boldsymbol{H} = \mu\boldsymbol{H} \qquad (3)$$

where μ_r is the relative permeability of the material (dimensionless), i.e. the permeability of a material is related to the permeability of free space and μ is the absolute permeability of a material in Hm^{-1} . The relative permeability can be less than unity for diamagnetic materials and much greater than unity for ferromagnetic materials. In general, vectors of $\boldsymbol{B}$ and $\boldsymbol{H}$ are not aligned and the permeability and susceptibility are functions of $\boldsymbol{H}$. For anisotropic materials, μ and χ become tensors, i.e. three by three matrices. In a simple situation where there is no permanent magnetization and the material is isotropic, μ and χ become scalars and $\boldsymbol{B}$ and $\boldsymbol{H}$ have the same direction.

Finally, the magnetization of an object or sample (magnetization can be induced in magnetic materials by nonmagnetic impurities or chemical treatment) can be expressed in Tesla by using the vector of polarization, $\boldsymbol{J}$, where $\boldsymbol{J}$ is defined by the following equation:

$$\boldsymbol{J} = \mu_0\boldsymbol{M} \qquad (4)$$

The International System of Units SI, based on meters-kilogram-second (the mks system) was introduced in 1960 and will be used in this chapter unless otherwise stated, although in physics of magnetics the cgs (centimeters-grams-seconds) system is still applied mainly due the numerical equivalence of H and M.

3. Magnetic Behavior of Materials

According to the classical Bohr's model of the atom, electrons orbit about a nucleus; in addition they also have gyroscopic spin (precession). As stated previously a moving electric charge, i.e. electric current produces a magnetic field commonly represented by a magnetic moment that is linked to the magnetization, $\boldsymbol{M}$. In some substances, the net magnetic moment of atoms in an applied field is zero, due to the mutual cancellation of the orbital and spin components. These are predominantly diamagnetic materials where atoms do not exhibit magnetic moment. All materials are inherently diamagnetic. In remaining materials, some magnetic behavior of atoms is present, however their bulk of magnetic properties depends on the orientation of atoms, and thus the resulting macroscopic magnetic moment is dependant on temperature, and in solid-state materials, dependant on interatomic forces.

Depending on their magnetic behavior resulting from the above factors, all materials can be classified into five categories: ferromagnetic, antiferromagnetic, ferrimagnetic, diamagnetic and paramagnetic. The two latter categories constitute the majority of materials and are usually called nonmagnetic materials.

The characteristics of magnetic materials are expressed by their magnetization curves, which illustrate the magnetic response of the material to an applied magnetic field. As the majority of practically applied magnetic materials exhibit nonlinear behavior, curves of flux density (*B*), induced magnetization (*M*) or magnetic polarization (*J*), permeability (μ) or susceptibility (χ) are plotted or tabulated as a function of the externally applied magnetic field strength (*H*), rather than given as single constants.

Ferromagnetic and ferrimagnetic materials show nonlinearity of *B*-*H* curve and they also have hysteresis behavior (Figure 1). When a magnetic field, *H*, is applied to an unmagnetized sample of magnetic material, the induction (flux density) *B*, increases from zero along the bold solid curve, both *B* and *H* are in the same direction. The reversal of the applied magnetic field at the point 1 (*H* is becoming smaller) delivers the magnetic remanence, (remanent induction or remanent flux density) B_r, at $H = 0$, as the induction lags behind the applied field. B_r means that with no external magnetic field, some magnetic induction exists in the magnetic material. This is of particular importance in case of permanent magnets as this defines the field produced by the magnet after the magnetizing field has been removed. Further continuing decreases of *H* leads to the point where the magnetic induction is zero; this defines another material parameter – the coercive field strength (coercivity) H_c. Both B_r and H_c are especially important for characterization of both soft and hard magnetic materials. On a major loop, minor or subsidiary loops can exist (see point A in Figure 1) responding to the temporary change of the applied field – in this case the minor increase of *H*. The other parameter of significance is the saturation induction B_s or $-B_s$ with further increases or decreases of the applied field *H* bringing virtually no increase of *B*. Soft and hard magnetic materials have comparable saturable inductions, but have greatly different coercivity: 0.1-100Am^{-1} and 200-2000 kAm^{-1} respectively, for the majority of commercial products.

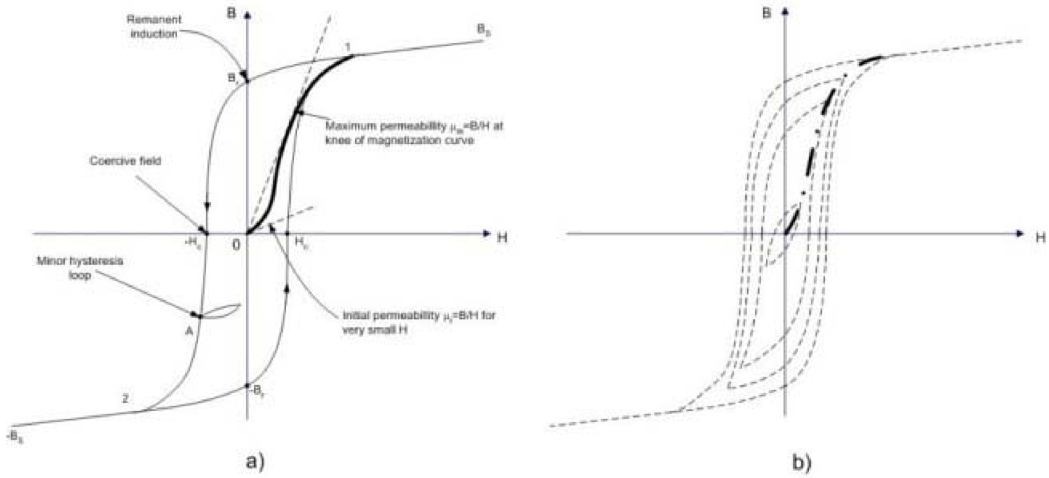

Figure 1: (a) Hysteresis loop basics and (b) construction of the commutation curve

The hysteresis loop of Figure 1a also provides other useful information about the properties of a material. It gives the indication of the static magnetic permeability as a tangent to the initial magnetization curve. In many practical cases, a single-valued magnetization curve is used rather than the hysteresis loop as it can be constructed as an average between the ascending and the descending hysteresis branches for different values of *H*, and can be extended symmetrically about the origin into the third quadrant (see Figure 1b). The initial (called also virgin) magnetization curve of Figure 1 is very close to the 'averaged' magnetization curve, which is also called the commutation curve. The area of the loop (Figure 1) between points 1 and 2 is a measure of energy losses induced in a sample or device. If the rate of change of the magnetic field strength is low (dc or up to several Hz) – the loss is predominantly hysteresis loss. If the frequency of excitation increases the hysteresis loop becomes wider (Figure 2) as it represents other types of losses, for example eddy current loss and anomalous loss. For permanent magnet materials, the magnetic hysteresis loop also provides information about the merit of performance, i.e. the maximum value of the product of B and H, $(BH)_{max}$ where the larger the value of $(BH)_{max}$, the better the permanent magnet material.

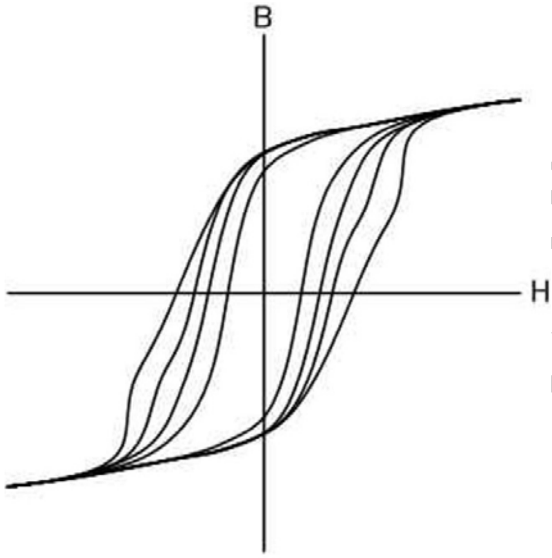

Figure 2: Hysteresis loops become wider with increasing frequencies

Magnetic domains are clusters of atoms (10^{12}-10^{18} atoms) where atomic moments are aligned. Their typical size is between 0.001 and 0.1 mm^{-3}. Domains can be observed by experiments using a variety of techniques such as magneto-optic, Kerr and Faraday effects, or electromagnetic imaging.

Their configuration is also linked to the shape of hysteresis loop and can be expressed by the loop squareness factor, which is the ratio of B_r to B_s. Domain structure represents the equilibrium of magnetostatic energy within the bulk magnetic material, where the number of domains depends on the size and the shape of the specimen and magnetic properties of the material.

Domains are aligned in a way that reduces the energy of the system. The borderline between domains of different magnetic orientation is defined by the concept of a domain wall (called also Bloch wall), which represents the magnetostatic energy that depends on the material structure and the energy relationship between the atom neighbors. An example of a domain structure where the adjacent domains have both the 90° and 180°orientation is shown in Figure 3a and the atom's magnetic moment orientation of the 180° domain wall in Figure 3b.

As the dipole moments of atoms within the wall are not aligned with the easy magnetization direction, they represent higher energy. The domain wall energy is an intrinsic property of a material that depends on the magnetocrystalline anisotropy and the exchange interactions between neighboring atoms.

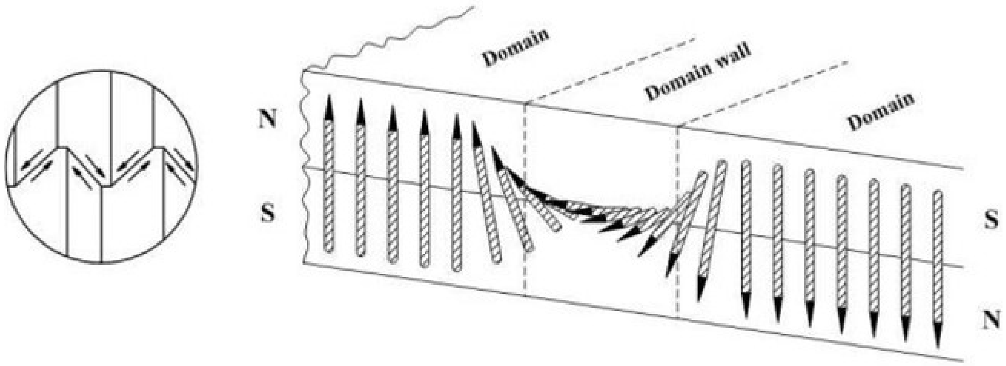

Figure 3: (a) Magnetic domain configuration with 90° and 180° orientation of magnetic moments in adjacent domains and (b) schematic representation of 180° domain wall of a magnetic material

When an external magnetic field is applied to a magnetic material, the whole structure of domain walls begins to move, firstly by small domain wall shifts and secondly with the increasing field in larger jumps, called Barkhausen jumps. These jumps are the strongest in the medium area of a magnetization curve. Domain wall shifts are also accompanied by the rotation of atom magnets in the whole domain to align with the direction of the applied field. The rotational processes become dominant for high-applied fields when the material is close to saturation. In the case where saturation represents the highest possible magnetization, all atom magnets of the material are aligned parallel to the applied field, and the only atomic movement is the thermal noise.

For the purpose of modeling electromagnetic devices and systems, magnetic materials need to be analytically described. Magnetic behavior of materials can be modeled at various levels of resolution. The highest and most detailed level is the atomic level where quantum mechanic tools are needed to have insight into basic processes involved. An intermediate level is at the micromagnetic level, where material is divided into uniformly magnetized domains separated by domain walls (e.g. Stone-Wohlfarth model). Finally the macromagnetic level or the lower level represents the lowest resolution and basically handles input-output relationships of the nonlinear medium. As in the two higher resolution levels, the macro level can be based on physical principles (Preisach and Jiles-Atherton models fit here); it can also be detached from the physical phenomena and rely on the mathematical curve fitting of observed data (approximation theory models and neural networks fall into this category).

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Biographical Sketch

Andrew Nafalski's career spans over 30 years in academic and research institutions in Poland, Austria, the UK, Germany, Japan and Australia. He holds BEng(Hons), GradDipEd, MEng, PhD and DSc degrees. He is a Chartered Professional Engineer and Fellow of the Institution of Engineers, Australia, Fellow of the Institution of Electrical Engineers (UK) and Senior Member of the Institute of Electrical and Electronic Engineers (USA). He is currently a Professor and Head of School of Electrical and Information Engineering at the University of South Australia in Adelaide. His major research areas include: applications of modern magnetic materials and electromagnetic technologies, computer aided testing of magnetic materials and magnetic measurements, computer aided analysis and design of electromagnetic devices, electromagnetic compatibility, and innovative methods in engineering education. His teaching areas cover: Fundamental Electrical Engineering, Network Theory, Electrical Design, Electromagnetic Compatibility, Electromagnetic Energy Conversion, Information Technology, Programming Techniques and Numerical Methods in Electrical Engineering. He has published some 250 articles, books, textbooks and software sets in the above fields. He has received numerous university, national, and international prizes for excellence in research and education.