Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 17
ISSUE 1-2
July-August
2006

Materials with specific magnetic properties

L.A. Dobrzański*, M. Drak, B. Ziębowicz
Division of, Materials Processing Technology and Computer Techniques in Materials Science, Institute of Engineering Materials and Biomaterials, Silesian University of Technology, ul. Konarskiego 18a, 44-100 Gliwice, Poland
* Corresponding author: E-mail address: leszek.dobrzanski@polsl.pl

Received 15.03.2006; accepted in revised form 30.04.2006

Materials

ABSTRACT

Purpose: The purpose of the paper is characterization of properties and application possibilities of modern, soft and hard magnetic materials. Another aspect involved in the paper is to compare these materials with classical magnetic materials and to show their influence on the development of modern technology connected with miniaturization of devices in different branches of techniques.

Design/methodology/approach: The main base of the paper is to compare the properties and possibilities of application of soft and hard magnetic materials with taking into consideration the development of manufacturing technology of these materials which by obtaining the maximum possible values of properties allows for simplification of machines and devices construction with use of magnetic elements.

Findings: In comparison to classical magnets modern magnetic materials have optimum technology of production with properties that allow for miniaturizing, simplification and lowering the costs of devices.

Practical implications: Further examination to obtain improved properties of magnetic materials and investigations of constructions of new machines and devices with these materials elements are still needed.

Originality/value: The paper is the review of modern magnetic materials development.

Keywords: Metallic alloy; Manufacturing and processing; Magnetic materials; Application

1. Introduction

Most of materials show magnetic properties. A great deal of information of magnetic material can be learnt by studying its hysteresis loop which shows the relationship between the induced magnetic flux density B and the magnetizing force H. It is often referred to as the B-H loop.

Some well known materials that exhibit easily detectable magnetic properties are iron, some steels, and the mineral lodestone; however, almost every material is influenced to one degree or another by the presence of a magnetic field, although in most cases the influence is too small to detect it without special equipment. Magnetic forces are fundamental forces that arise from the movement of electrical charge. When a material is placed within a magnetic field, the magnetic forces of the material's electrons will be affected.

Magnetic materials may be classified according to some of their basic magnetic properties: remanence (B_r), coercive force (H_c), Curie temperature (T_c). Based on the value of these features materials can be divided into soft or hard magnetic materials. For soft magnetic materials the value of coercive force is very low (in the ideal material coercive force is equal zero). That means material previously strongly magnetized by extrinsic magnetic field undergoes demagnetization when the magnetic field is removed. While in hard magnetic materials, after removing of magnetic field, the materials stay strongly magnetized and become to be permanent magnets. The product of coercive force (H_c) and remanence (B_r) is called maximum energy product (BH_{max}). The higher value of maximum energy product the stronger field can make the permanent magnet [1].

2. Evolution of magnetic materials

Hard magnetic materials are characteristic for their good magnetic properties such as remanence, coercive force and maximum energy product. Depending on the hard magnetic material type magnets are split into the following groups: Co, W steels; AlNiCo magnets; ferrite magnets; magnets from the cobalt alloys with the rare earth group elements; magnets from the Nd-Fe-B alloys.

The progress in the field of permanent magnets rapidly grow in the last fifty years (Fig 1.). Understanding of physical phenomena responsible for hard magnetic properties led to discovery of new families of permanent magnets based on rare earth – transition metal compounds. The search for new materials with superior properties focuses on materials with high values of Curie temperature, magnetic saturation and coercive force.

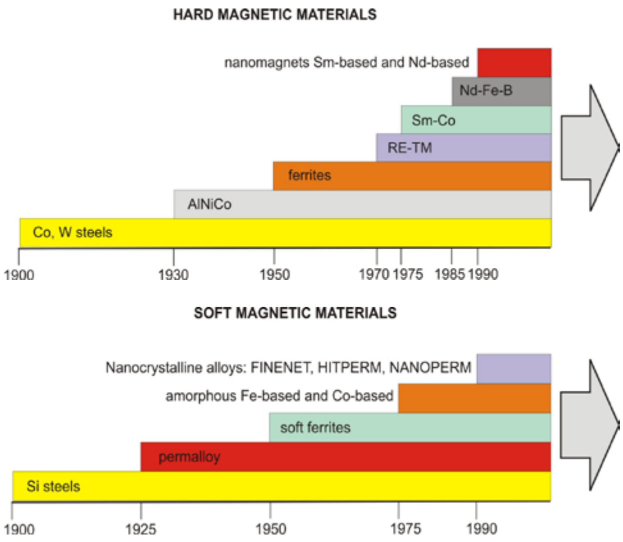

Fig. 1. Development of magnetic materials

The first hard magnetic material was carbon steel which was later modified; in 1885 in Australia a tungsten steel and in United Kingdom and USA a chromium steel were developed. In 1917 in Japan cobalt steel, called Honda's steel, was found. In 1932 Y. Mishima in Japan has worked out a new alloy – AlNiCo with iron, nickel and aluminum. In the fifties of the last century it was also found that oxides with general formula $MO{\cdot}Fe_{12}O_{18}$ called ferrites have magnetic properties. Intermetallic phases of rare earth metals with 3d-metals have been found out recently, in the seventies of the last century. First materials based on Sm-Co were phases $SmCo_5$ and Sm_2Co_{17}. These materials have excellent magnetic properties but their price is high because of the presence of samarium and cobalt. The turning point was founding out in 1984 the hard magnetic material based on $Nd_2Fe_{14}B$ phase simultaneously by Sumitomo Special Metals in Japan and General Motors in USA. Currently the investigations are being made on new hard magnetic materials like: tetragonal $RE_2Fe_{14}C$ phase (where RE – rare earth metal), isomorphic $RE_2Fe_{14}B$ phase and hexagonal or rhombohedral $RE_2Fe_{17}C_x$ and $RE_2Fe_{17}N_x$ phases. The addition of nitrogen results in growth of Curie temperature and coercive force [1-4].

Soft magnetic materials are those materials that are easily magnetised and demagnetised. They typicallly have coercive force less than 1000A/m and high magnetic permeability. Depending on the type soft magnetic materials are split into the following groups: Si steels, permalloys, Mn-Zn soft ferrites, amorphous Fe-based and Co-based. Understanding of physical phenomena responsible for soft magnetic properties led to discovery of new families of nanocrystalline ferromagnetics (Fig. 1). The progress in the field of soft magnetic materials rapidly has grown in the last thirty years. The search for new materials with superior properties focuses on materials with high value of magnetic permeability and low coercive force.

In the early 1900s the first major improvement in soft magnetic materials took place when R. Hadfield introduced steels with silicon which gave higher permeabilities and appereciably less loss than earlier developed steels. In 1914 Permalloy was discovered (alloy with about 20% Fe and 80% Ni content) by Gustav Elmen of Bell Laboratories, who found out it has higher permeability than silicon steel. In 1923, he discovered that its permeability could be greatly enhanced by heat treatment. At the end of the forties of XX century in the laboratories of the Dutch Philips firm were made soft ferrites (compound of iron oxide and oxides of others metals: zinc, manganese) which have low cost. The next step in the development of soft magnetic materials was the beginning of the commercial scale production of the amorphous alloys (metallic glasses) in the seventies of XX century by the Allied Chemical concern in USA. These alloys called Metglass are manufactured as thin tapes. The main components of these materials are iron and cobalt. In 1988 Y. Yoshizawa and co-workers from Hitachi have published surprising examination results, which state that generation of about 70% of crystalline phase in the originally amorphous alloy rich in Fe, leads to obtain material with specific magnetic properties with improved properties in comparison with amorphous precursors. Obtained this way materials are called nanocrystalline ferromagnetics and are the newest generation of soft magnetic materials. The best known commercial nanocrystalline ferromagnetics are FINEMET, HITPERM, NANOPERM. [2-6].

2.1. Traditional hard and soft materials

The traditional permanent magnets based on AlNiCo alloys and ferrites are still substantial commercial importance because of their low cost, although some of their magnetic properties are much lower than those of rare earth magnets. AlNiCo alloys contain mainly ferromagnetic iron, cobalt and nickel and various types of additivies such as aluminum, titanium, cooper. Alnico magnets can be obtained through casting or sintering methods. AlNiCo magnets can be characterized as fine-particle alloys in which elongated ferromagnetic particle are dispersed in a basically nonmagnetic matrix. Magnetic hardness of this alloys comes from shape anisotropy. Advantages of AlNiCo are high Curie temperature 850°C which results from cobalt presence, good temperature stability – ability for working up to 550°C and remanence comparable to Nd-Fe-B magnets. The drawbacks of AlNiCo alloys are their low coercive force in comparison to rare earth-based magnet, limit in attainable energy product, brittleness and hardness [3,7].

Hard ferrites still play dominant role in permanent magnets marked owing to the low price per unit of available energy, the wide availability of raw materials and high chemical stability. Magnetic properties of ferrites come from anisotropic properties of iron oxides and barium, strontium or lead oxides ($MeO{\cdot}Fe_{12}O_{18}$ where Me = Ba, Sr, Pb). Ferrites can be made by powder metallurgy method. They are produced as sintered magnets or composite materials bonded with polymer matrix. Ferrites, because of low remanence and coercive force better than AlNiCo, are resistant to demagnetizing field, high electrical resistivity allows to work in variable fields. These materials have also good corrosion resistance and high chemical stability. The best prominent disadvantage of magnets made of hard ferrites is their low maximum energy product, high shrinkage after sintering process (15 – 25%) and sensivity of remanence and coercive force on temperature changes [2].

The traditional soft magnetic materials like: Si steels, Permalloys, Ferrites, amorphous alloys are widely used in spite of lower magnetic properties in comparison with nanocrystalline ferromagnetics. Si steels known as electrical steels are used for transformer cores. In the power industry electrical voltage is almost always AC and at low frequency, 50÷60Hz. At these frequencies eddy currents are generated in the transformer core. Alloying the Fe with Si has a large marked effect on the electric resistivity of the material, with an increase of a factor of 4÷3%Si. Silicon also has the benefit of reducing the magnetostriction (i.e. length change on magnetization) and the magnetocrystalline anisotropy. In addition, the material is used in the form of laminations, typically 0.3÷0.7mm thick. The addition of too much silicon makes the material extremely brittle and difficult to produce, giving a practical limitation of 4% to the amount of Si that can be added. Recently, a technique has been developed to produce laminations with >6% Si, by a $SiCl_4$ chemical vapor deposition treatment to enrich the laminations with Si after forming the laminations. Typically most electrical steels will contain between 3÷4% Si [5].

Permalloys, are extremely versatile and are used over a wide range of compositions, from 30÷80% Ni. Over this composition range the properties vary and the optimum composition must be selected for a particular application. The high Ni content alloys have high permeability; around 50%Ni have high saturation magnetisation. Low Ni content have a high electrical resistance. There are special grades of Ni-Fe alloys that have zero magnetostriction and zero magnetic anisotropy, such as mumetal which is produced by a careful heat treatment and minor additions of Cu and Cr. These alloys have extremely high permeable, up to $5 \cdot 10^5$ and intrinsic coercivity as low as 0.5 A/m [2, 3].

At high frequency metallic soft magnetic materials simply cannot be used due to the eddy current losses. Therefore, soft ferrites, which are ceramic insulators, become the most desirable material. These materials are ferrimagnetic with a cubic crystal structure and the general composition $MO \cdot Fe_2O_3$, where M is a transition metal such as nickel, manganese or zinc. MnZn ferrite, sold commercially as ferroxcube, can be used at frequencies up to 10MHz, for example in telephone signal transmitters and receivers and in switch mode power supplies (also referred to as DC-DC converters). For these types of application the driving force to increase frequency is to allow miniaturization. Additionally, part of the family of soft ferrites, are the microwave ferrites, e.g. yttrium iron garnet. These ferrites is used in the frequency range from 100MHz to 500GHz, for waveguides for electromagnetic radiation and in microwave devices such as phase shifters.

2.2. Modern hard and soft magnetic materials

Rare earth permanent magnets RE-TM are based on the intermetallic compounds of rare earth metals (RE) and transition metal (TM) iron or cobalt. The combination of properties of the rare earth sublattice and the 3d sublattice of transition metal lead to the spectacular development in hard magnetic materials. Higher magnetic anisotropy, Curie temperature, coercive force and magnetization were obtained. The two most relevant classes of RE-TM magnets are based on samarium and cobalt exhibit very high coercive force, low temperature coefficients, and neodymium, iron boron which are unrivalled in terms of its maximum energy product.

The intermetallic phases of the rare earth metals (RE) and transition metals (TM) RE-TM type, since years, are very interesting materials for the permanent magnets. The samarium-cobalt magnets based on the $SmCo_5$ and Sm_2Co_{17} intermetallic phases are the materials meeting the requirements of many modern applications. These materials are characteristic for their significant magnetocrystalline anisotropy and saturation induction; therefore, they are very useful for fabrication of magnets with very high magnetic energy density. Magnets based on $SmCo_5$ phase can be obtained by powder metallurgy method, sintered or bonded with polymers. The main advantage of Sm-Co magnets is their high Curie temperature making them suitable for use in application in elevated temperatures. These magnets show also high coercive force, exellent corrosion resistance and can work in demagnetizing fields but they are very brittle and expensive – because of the high concentration of costly samarium [2, 3, 7-10].

The limited availability of samarium and high price of cobalt have contributed to the search for new magnetic hard materials. The first experiments consisted in fabricating the NdFe compound; however, it does not meet the requirements posed to magnetic hard materials. Introducing boron has made possible to improve the magnetic properties of the material. The magnetic hard material based on the $Nd_2Fe_{14}B$ intermetallic phase was developed in 1984 by Sumitomo Special Materials in Japan with the powder metallurgy technology and by General Motors in USA with the melt quenching method used for making metallic glasses. The magnetic properties of this phase result from the ferromagnetic coupling of magnetic moments of sublattices of the rare earth metals group and iron [7].

The hard magnetic powders can be obtained, among others, with the HD (Hydrogenation Disproportionation) technologies, with the HDDR (Hydrogenation, Disproportionation, Desorption, Recombination) method, by Mechanical Alloying (MA), and by Melt Quenching (MQ). The neodymium magnets may be made by sintering, bonding with polymer materials – compacting with the chemically-setting or thermosetting resins, bonding with the low-melting glass or metal, injection moulding, hot compacting, upsetting, casting or explosive consolidation. They have various properties and prices depending on technology [1,9].

Modern soft magnetic materials – nanocrystalline ferromagnetics mostly are obtained by melt quenching combined with controlled crystallization and mechanical synthesis. To examples can be included FINEMET alloys Fe-Si-B-Cu-Nb discovered in 1988 by Yoshizwa, NANOPERM alloys Fe-M-B-Cu (M=Zr, Nb, Hf) patented in 1994 by Kojami and HITPERM alloys (Fe,Co)-M-B-Cu (M=Zr, Nb, Hf).

They are characteristic of very low value of coercive force, very high magnetic permeability, high magnetic moment of saturation and low magnetostriction.

The most commonly used nanocrystalline ferromagnetic is FINEMET. As opposed to traditional soft magnetic materials nanocrystalline ferromagnetic are two phases materials and shows grains of about10÷15 nm.

The main disadvantage of ther manufacturing methods is their limitations pertaining to the geometrical form of the manufactured nanomaterials (powder or thin strip), which limit their range of applications to a great extent. Therefore, to extend their potential applications it is necessary to connect the nanocrystalline magnetic materials with other materials – creating thus the composite materials. The thermosetting or chemically cured polymers are used most often to manufacture composites, which volume portion in the composite does not exceed 20 % and the low-melting metals, e.g., zinc in the amount of about 15 % mass [4-6, 11-16].

3. Application of magnetic materials

The range of magnetic materials application grows with the improvement of their magnetic, mechanical, electrical and thermal properties. They are used among others in motorization in driving motors, starters, ventilators, speed indicators, current generators; in electro technique in sensors, switches, converters; in aviation and cosmic industry in frictionless bearings, couplings, magnetrons; in loudspeakers, motors for household equipments, clocks, earphones, magnetic locks; in medicine in magnetic dentures, separators of cancer cells, artificial hearts, nuclear magnetic resonance devices, audiovisual and telecommunications equipments. Table 1 shows possibilities of hard and soft magnetic composite materials applications. The application of magnetic composite materials allows to miniaturizing magnetic elements, construction simplification and lowering both manufacturing and material costs (Fig. 2) [4-6, 10, 17].

Table 1.
Application of hard and soft magnetic composite materials

Hard magnetic composite materials
brushless direct current motors, ABS sensors, couplings, voice coil motors, loudspeaker, insertion devices, stepper motors, generators, air cores, sensors, bearings, transmitters, magnetic separators which allows to remove very tiny parts of materials containing iron, separators for cleaning coffee, tea, flour, in ceramic, chemical industry, in medicine in computer-assisted tomography, apparatuses for testing of tissues cancer
Soft magnetic composite materials
magnetic cores in high frequency transformers, transformers impedance coils, sensors, instruments for power measurements, frequency converters, signal transformers, read-write head of digital devices, magnetic screen, magnetostriction converters, computers power packs, telephone exchange power packs, magnetostriction transducers, telecommunication engineering

Fig. 2. The main direction of miniaturization in modern world

4. Conclusions

The dynamical development of the technical civilisation causes greater and greater progress in magnetic materials. It is the result of the fact that modern civilsation is based on converting electric current devices and there is the need to extent the possibilities of their application. Contemporary civilization needs also materials with better properties. Nanocrystalline ferromagnets and neodymium magnets are the examples of these materials. Their dynamical development is observed from the eighties of XX century.

Modern magnetic materials, with exellent magnetic properties allow to miniaturizing of machines and devices. That influence also on our common life because most of devices till now consider to be stationary ones can be now replaced in any places (Fig. 2).

References

[1] C. Kuhrt, Processing of permament magnet materials based on rare earth transition metal intermetallics, Intermetallics, 3 (1995) 255-263.

[2] J.M.D. Coey, Magnetic materials, Journal of Alloys and Compounds, 326 (2001) 2-6.

[3] H.J. Fastenau, E.J. Loenen, Aplication of rare earth permament magnets, Journal of Magnetism and Magnetic Materials, 1570158 (1996) 1-6.

[4] M. Soiński, Magnetic materials in engineering. NOSiW SEP, Warsaw, 2001 (in Polish).

[5] M.E. McHenry, M.A. Willard, David E. Lauglin, Amorphous and nanocrystaliine materials for applications as soft magnets, Progress in Materials Science, 44 (1999) 291-433.

[6] L.A. Dobrzański, M. Drak, B. Ziębowicz, New possibilities of composite materials application – materials of specific magnetic properties, Proceedings of Conference AMPT, Las Vegas, USA, (in print).

[7] L.A. Dobrzański, M. Drak, Hard magnetic composite materials Nd-Fe-B with additions of iron and X2CrNiMo-17-12-2 steel, Journal of Alloys and Compounds (2006) (in print).

[8] L.A. Dobrzański M. Drak, Structure and properties of composite materials with polymer matrix reinforced NdFeB hard magnetic nanostructured particles. Journal of Materials Processing Technology 157-158 (2004) 650-657.

[9] L.A. Dobrzański, M. Drak, Properties of composite materials with polimer matrix reiforced with Nd-Fe-B hard magnetic particles, Journal of Materials Processing Technology (2006) (in print).

[10] D.C. Jiles, Recent advances and future direction in magnetic materials, Acta Materialia, 51 (2003) 5907-5939.

[11] L.A. Dobrzański, M. Drak, Permament Magnets Nd-Fe-B, Proceedings of Conference CAM3S'2005, Gliwice-Zakopane, 2005, 193-201.

[12] D. Szewieczek, L.A. Dobrzański, B. Ziębowicz, Structure and magnetic properties of nanocomposites of nanocrystalline powder - polymer type, Journal of Materials Processing Technology, 157-158 (2004) 765-770.

[13] B. Ziębowicz, D. Szewieczek, L.A. Dobrzański, Magnetic properties and structure of nanocomposites of powder $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ alloy – polymer type, Journal of Materials Processing Technology, 157-158 (2004) 776-780.

[14] B. Ziębowicz, D. Szewieczek, L.A. Dobrzański, J.J. Wysłocki and A. Przybył, Structure and properties of the composite materials consisting of the nanocrystalline $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ alloy powders and polyethylene, Journal of Materials Processing Technology, 162-163 (2005) 149-155.

[15] B. Ziębowicz, D. Szewieczek, L.A. Dobrzański, A. Przybył G. Matula, Magnetic properties and structure of the Finemet alloy powders bound with polyethylene, Proceedings of Conference PFAM XIII, Singapore, 2005, Vol. I, 394-402.

[16] B. Ziębowicz, D. Szewieczek, L.A. Dobrzański, Manufacturing technology of the composite materials: nanocrystalline material-polymer type, Proceedings of Conference CAM3S'2005, Gliwice-Zakopane, 2005, 1080-1085.

[17] M. Leonowicz, Nanocrystalline magnetic materials, WNT, 1998 (in Polish).