RARE-EARTH PERMANENT MAGNETS: NEW MAGNET MATERIALS AND APPLICATIONS

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Abstract: The introduction of rare-earth permanent magnets based on samarium-cobalt in about 1970, and neodymium-iron-boron magnets in the mid-nineteen eighties, has ushered in a new era in hard magnetic materials. This has resulted in a dramatic improvement in permanent magnet performance, with neodymium-iron-boron ($Nd_2Fe_{14}B$) magnets having a magnetic energy product up to an order of magnitude greater than those of Alnico and ferrite magnets, with high remanence and coercive force. The search for new permanent magnet materials has led to further interest in rare-earth-iron intermetallic compounds modified by the introduction of interstitial atoms such as nitrogen or carbon.

We discuss `What makes a good permanent magnet', in the context of the crystal structure and the magnetic properties of rare-earth-iron intermetallic alloys that are candidates for new permanent magnet materials. The methods for producing these new candidate magnet materials, including arc-melting under an atmosphere of argon, high-energy ball-milling (HEBM), mechanical alloying, melt-spinning and HDDR (hydrogenation, disproportionation, desorption, recombination) are reviewed. Examples of high efficiency electric motors, which use rare-earth permanent magnets, developed by the School of Electrical Engineering, University of Technology, Sydney, and the CSIRO Division of Telecommunications and Industrial Physics are given.

Keywords: rare-earth magnets, rare-earth--iron intermetallic alloys, new phases, electric motors

1. INTRODUCTION

The first practical application of a permanent magnet material was probably the use of lodestone in a compass for navigation, by the Chinese some 2000 years ago. The most spectacular advances in permanent magnet materials have occurred over the past 100 years, as the magnetic steels of the late nineteenth century were replaced by intermetallic compounds and oxides of the twentieth century. The AlNiCo alloy was discovered in Japan during the 1930's and the ceramic hexaferrites in Holland by Philips in the 1950's. These permanent magnet materials made it practical to replace electromagnets in many applications, and ushered in the era of the widespread use of permanent magnets in electric motors, generators and loudspeakers. A major advance in permanent magnets occurred about 25 years ago with development of magnets based on rare-earth intermetallic alloys. The first of the new rare-earth magnets was samarium-cobalt ($SmCo_5$), which became available in the 1970's, followed by neodymium-iron-boron magnets (NdFeB) in the mid-1980's. The improvement in permanent magnet materials over the past 100 years can be tracked by the maximum energy product, ($(BH)_{max}$), the most common figure of merit for a permanent magnet. ($(BH)_{max}$ is the maximum product of the magnetic induction, B, and magnetising field strength, H, in the second quadrant of the magnetic hysteresis curve, and represents twice the maximum energy that can be stored in the magnetic field created in space around a magnet of optimum shape.) Figure 1, a semilogarithimic plot, shows the improvement in $(BH)_{max}$ since 1900. Compared to SmCo, NdFeB has the advantages of lower cost and a higher magnetic energy product. These favourable features have made NdFeB, for many applications, the magnet of first choice, resulting in its widespread use and the rapid expansion of the world rare-earth permanent magnet market.

Compared to their predecessors, Alnico and ferrites, rare-earth permanent magnets (REPM) have a magnetic energy product up to a magnitude larger, high remanence and high intrinsic coercivity. These attributes are important in permanent magnet machines, and when combined with recent developments in electromagnetic design, using finite-element methods, new compact power and control electronics, and improvements in soft magnetic materials, result in a new generation of electric motors. Advantages of REPM motors are high-efficiency, high-torque and high-power in a compact size, with low noise, low temperature rise, improved dynamic response, and in brushlesss electronically commutated motors high reliability [1]. Motors that benefit from these features may

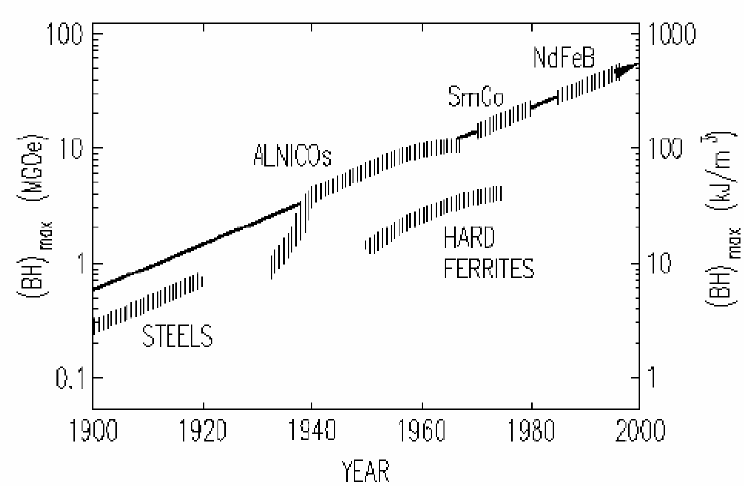

Figure 1. Improvements in $(BH)_{max}$ for permanent magnets since 1900.

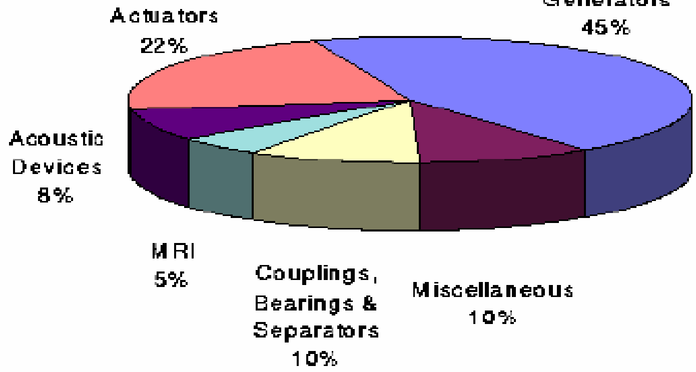

Figure 2. Share of applications of NdFeB in Europe.

be found in hand-operated tools, servomotors in machine tools and robotics, computer disk drives, CD players, video recorders and camcorders, solar powered vehicles, medical devices, aerospace, high-speed turbines and low-speed direct drive wind generators. The industrial and commercial applications of REPM are broader than just electric motors, and the breakdown of the use of NdFeB by application is shown in figure 2 [2]. World production of rare-earth magnets in 1994 was estimated at US$1.16 billion, and is expected to grow to US$5.4 billion by 2004 [3].

2. RARE-EARTH MAGNETS

A permanent magnet is characterised by its hysteresis loop. The hard magnetic properties of technological importance are the remanent induction (or remanence), B_R, intrinsic coercivity, H_C^M, which is a measure of the magnet's resistance to demagnetisation, and $(BH)_{max}$. These are extrinsic properties, being dependent on the processing method used to produce the magnet, and are closely linked to the size, crystallographic perfection and alignment of the constituent grains. Intrinsic properties, e.g. saturation magnetisation, Curie temperature, and anisotropy field, are dictated by the crystal structure and composition of the intermetallic phase. The development of a high-strength technologically useful permanent magnet requires both an intermetallic phase with suitable intrinsic magnetic properties and a processing method to induce desirable extrinsic (hard) magnetic properties. Magnets are usually subject to an internal demagnetising field which is in a direction opposite to the magnetisation. The magnitude of the demagnetising field is dependent on the shape of the magnet and the form of any external magnetic circuit. If the demagnetising field is larger than the intrinsic coercivity of the magnet it will reduce the magnetisation. The high-intrinsic coercivity of REPMs is particularly important for their use in electric motors as magnets of any shape can be used and it enables the motor to withstand high armature currents, which could lead to demagnetisation of the magnets, under conditions of high overload torque. The usefulness of Alnico magnets in many applications is limited by its relatively low intrinsic coercivity. Typical properties of commercially available permanent magnets are given in table 1.

Table 1. Typical properties of commercially available permanent magnets.

Material	Remanent Induction (T)	Intrinsic Coercivity (MA/m)	Energy Product (kJ/m^3)
Sr Ferrite	0.43	0.20	34
Alnico 5	1.27	0.05	44
Alnico 9	1.05	0.12	84
$SmCo_5$	0.95	1.3	176
Sm_2Co_{17}	1.05	1.3	208
$Nd_2Fe_{14}B$	1.36	1.03	350

2.1 What makes a good permanent magnet ?

Requirements for a permanent magnet are twofold; a suitable intermetallic phase that has desirable intrinsic magnetic properties and a method to grain refine or process the intermetallic phase to produce useful extrinsic magnetic properties. When certain rare-earth metals, such as Nd, Sm, Dy and Pr, are alloyed with Co or Fe, a range of intermetallic structures are formed with suitable intrinsic magnetic properties . These are:

- high saturation magnetisation - the use of Fe, to take advantage of its high saturation magnetisation, and a light rare-earth (La to Gd) eg. Nd or Sm, whose magnetic moment couples parallel to that of the Fe;
- magneto-crystalline anisotropy (large anisotropy field) and a uniaxial crystal structure, with the easy direction of magnetisation along the unique axis; and
- a high Curie temperature.

2.2 New Intermetallic Phases

New candidate intermetallics include:-

- 1:12 phase with the tetragonal $ThMn_{12}$-type structure [4], eg. $RE(Fe,TM)_{12}$ (RE = rare-earth, TM = transition metal) ternary alloys, including $Nd(Fe,Mo)_{12}$, $Nd(Fe,Ti)_{12}$ and $Sm(Fe,Mo)_{12}$,
- 2:17 phase with the rhombohedral Th_2Zn_{17}-type structure [5], including RE_2Fe_{17} binary alloys eg. Sm_2Fe_{17}, and $RE_2(Fe,TM)_{17}$ ternary alloys, and

- 3:29 phase with a monoclinic structure related to that of hexagonal $TbCu_7$ [6], examples include $RE_3(Fe,TM)_{29}$ RE = Pr, Nd, Sm, Gd, and Tb, and TM = Ti, Re and V.

Of particular interest is that the intrinsic properties of these binary and ternary alloys can be changed markedly by the absorption of nitrogen or carbon onto the interstitial sites surrounding the rare-earth ion [7-8]. Interstitial modification results in an increase in the Curie temperature, an expansion in the lattice, and it may induce hard magnetic properties, eg. coercivity. For example on nitriding Sm_2Fe_{17} to obtain $Sm_2Fe_{17}N_x$ there is an increase in the Curie temperature from 116^{o}C to 476^{o}C, expansion of the lattice (about 6 vol%) and the magnetic easy axis changes from being in the basal plane to the c-axis, inducing coercivity.

2.3 Material Processing

Commercial sintered $Nd_2Fe_{14}B$ magnets are produced by one of two methods, a powder metallurgy liquid-phase sintering method (a process also used to manufacture $SmCo_5$ magnets) or a rapid-solidification method, similar to the melt-spinning process used to produce glassy metals [9]. Rapid solidification produces an isotropic magnet material, which may be hot-pressed and die upset in subsequent processing stages to produce anisotropic material. These high-temperature processing methods are not suitable for the production of many of the new phases and their nitrides and carbides. Rare-earth iron nitride alloys are metastable, and if heated to around 600^{o}C separate into a stable rare-earth nitride phase and α-Fe, destroying any useful hard magnetic properties. New processing methods have been developed for preparation of powders suitable for magnets, and include mechanical alloying (MA) (or high-energy ball milling where the starting material is an alloy of the desired composition), where the kinetic energy of colliding balls is used to deform, mill, cold weld or alloy powders [10], and HDDR (hydrogenation, disproportionation, desorption, recombination) [11]. The HDDR process involves hydrogenation of the alloy at relatively low temperatures (less than 500^{o}C) and disproportionation of the alloy into a fine-scaled mixture of a rare-earth hydride and α-Fe. The fine-scaled mixture is heated under vacuum (typically at 700-800^{o}C) to desorb the hydrogen and recombine the rare-earth and α-Fe, to form an intermetallic with sub-micron grain structure. Most often HDDR processing produces an isotropic magnet powder, but through elemental additions it is possible to produce an anisotropic powder. It is the HDDR process that is being used to produce anisotropic $Nd_2Fe_{14}B$ powders for use in polymer bonded magnets.

Figure 3. Aurora solar car.

3. RARE-EARTH PERMANENT MAGNET MOTORS

In applications where the prime requirements are compactness, high-efficiency and a high-torque to volume ratio, REPM motors are fast becoming the motor of choice. These motors are usually brushless and electronic switches are used for commutation. For motors of the highest-performance the motor designer will use the very best sintered NdFeB magnets, as the energy product may be as high as 400kJ/m^3, combined with a high-remanence and high-intrinsic coercivity. Where compactness is not so critical, NdFeB polymer-bonded magnets are popular as they have an energy product 2 to 4 times that of ferrite, and the advantage that the magnet shape can be formed by either injection or compression moulding, enabling the use of low-cost mass production methods. The trend to polymer-bonded magnets is increasing with the availability of anisotropic powders. CSIRO-UTS Electrical Machines has developed a number of REPM motors for a variety of applications. The most efficient motor developed is a in-wheel motor for the Aurora Vehicle Association solar car. Another motor of interest is for a oil well MULE (motorised utility logging equipment). The MULE is a tractor that tows data-logging equipment along `horizontal' sections of oil wells.

The most recent World Solar Challenge from Darwin to Adelaide was held in 1996. The rules of the race limit the solar array area to 8 m^2 for a single seat car. It is important to maximise the drive system efficiency to make the very best use of the available energy, and minimise the mass of the motor so it can be incorporated in the front drive wheel of the car, without the front wheel of the car starting to lift on rough roads at high-speed. The Aurora solar car is shown in figure 3. The specification for the motor called for at least 3.24 Nm/kg of active mass (magnets and winding), a figure which is double that achieved by direct-drive motors used in solar cars in previous World Solar Challenges. An axial flux design with an ironless air-gap winding and rotating magnet rings was chosen. This has the advantages that the two magnet rotors are mounted on the wheel side walls; the stator winding is mounted centrally on the axle; the losses associated with an air gap winding are lower than with toothed structures; and stranded Litz wire is used in the winding to minimise the eddy current losses. The stator has no backing iron and magnets are arranged in a

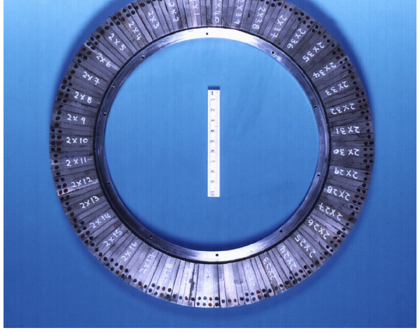

Figure 4a. Magnet ring for Aurora solar car motor.

Figure 4b. Stator winding for Aurora solar car.

Halbach array, each group of four magnets forming a pole, with 40 poles in all. A magnet ring and stator winding are shown in figures 4a and 4b. Selected details of the motor are given in table 2. On January 21, 1998, Aurora claimed the world record for their car, using the CSIRO-UTS motor, for the distance travelled by a solar car in one hour. The record of 100.9 km was set between Hay and Balranald in NSW.

Table 2. Selected parameters of Aurora solar car motor.

Power	1800W
Motor speed at 100 km/hr	1060 rev/min
Motor speed at 130 km/hr	1380 rev/min
Continuous torque	16.2 Nm
Peak torque (hill climb)	50.2 Nm
Outer diameter	360 mm
Axial length	43 mm
Active mass	5 kg
Efficiency	97.9%

An oil well mule motor has been developed for ORAD Pty Ltd in Perth, Western Australia, who conduct surveys of oil wells using a variety of data logging equipment. The motor has to operate in the hostile environment of the oil well, and have a high-efficiency, as it may be at the end of a 10 km long cable. The motor is a slotless design, rated at 500 W at 10000 rev/min, and has a 2-pole cylindrical rotor. The rotor is made from Sm_2Co_{17}, as the motor is required to operate at temperatures of 150^{o}C, and it is oil filled to withstand pressures up to 500 atmospheres. Physically, the motor is 275 mm long and 46 mm in diameter. The motor in its disassembled state is shown in figure 5. The motor forms part of a logging string that is typically 23.6 m long and weighs 155 kg, and in a recent survey of three Mobil off-shore oil wells travelled more than 8 km.

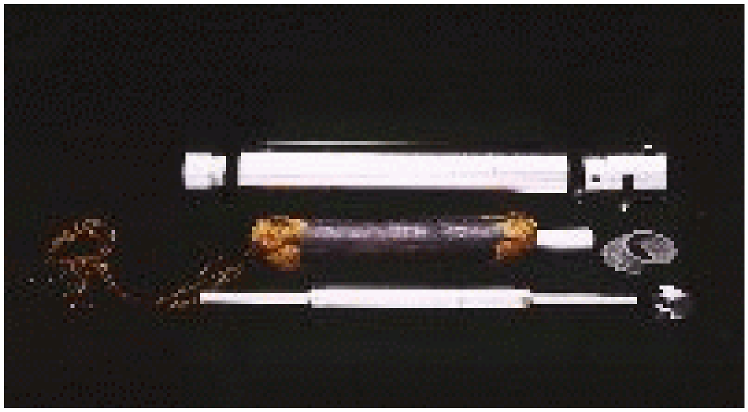

Figure 5. ORAD motor diassembled.

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