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A COMPARATIVE STUDY OF Sm-Co AND Nd-Fe-B PERMANENT MAGNETS

BY

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ABSTRACT

The aim of the paper is to review progress made so far in the field of rare earth based permanent magnets. The paper describes the various stages in the development of permanent magnets, origin of ferromagnetism in rare earth transition metal permanent magnets, methods used to produce the Sm-Co and Nd-Fe-B type permanent magnets, and their properties. In the end micro-structures of some important Nd-Fe-B alloys are briefly explained.

INTRODUCTION

Permanent magents play an important role in todays industrial world and are used in many engineerting applications. They are used mainly in devices which convert electrical into mechanical energy or vice versa. Research in permanent magnets has been encouraged by the electrical and electronic industries to produce materials with the necessary properties at a reasonable cost. Many devices such as motors, sensors, computers peripherals, travelling wave guides, cathode ray tubes and loud-speakers incorporate permanent magnets.

The development of permanent magnetic materials started during the latter part of the 19th century with the introduction of C-steel magnets. In 1917 the Japanese introduced Co-steel magnets [1], which were the forerunners of a group of Al-Ni-Co-Fe alloys known generally as Alnicos. The alnicos were developed during the 1930s and became the most widely produced permanent magnets.

In the 1950 the advent of barium or strontium ferrite with high coercivety and low remanance along with much cheaper cost of raw materials than Alnico magnets resulted in the change in the trend of magnet production. Ferrite magnets have been more widely used than Alnico due to the comparable properties and the cheaper raw materials used in the magnets.

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DEVELOPMENT OF RARE EARTH BASED PERMANENT MAGNETS

Rare earth permanent magnets can be defined as a group of permanent magnetic materials containing magnetically active components rare earth transition metals (RTM) where R is one or more of the elements having atomic numbers 57 (La) to 71 (Lu) and the group 3B elements of atomic number 39(Y)

Rare earth-Transition metal (R-TM) permanent magnets first appeared in the late 1960s (2). These magnets were based on Samarium and Cobalt, havcing the hexagonal RT_5 structure. The role of the Rare Earths in these intermetallic compounds is to provide an easy anisotropic axis while coupling to ferromagnetic cobalt. With regard to the R-Co type alloys, the cost of cobalt is important. Cobalt is more expensive than the other two transition elements, nickle (Ni) and iron (Fe). Samarium (Sm) which is more abundant than most rare earths is nevertheless, significantly scracer than the light rare earth elements praseodymium (Pr) and neodymium (Nd) (3). Praseodymium (Pr) and neodymium (Nd) also have the ability to contribute uniaxial anistoropy in a suitable crystal structure. It is therefore, feasible to produces a high performance magnet based upon an iron-rich composition using a light rare-earth, preferably neodymium, to provide the anisotropy.

In November, 1983 Sumitomo Special Metals company of Japan announced a magnet based on a ternary alloy of composition $Nd_{15}Fe_{77}B_8$ showing a maximum energy product of 290 KJ m^{-3}(4) and a Curie temperature of 312°C. The alloy was composed of a new tetragonal crystalline phase, $Nd_2Fe_{14}B$ and Nd-rich grain boundary material. The magnet was given the trade name "Neomax". The main drawback of Neomax is its poor oxidation resistance and a lower Curie temperature when compared with the magnets based on samarium and cobalt. However the attractiveness of this alloy is the large amount of iron present in it, which significantly decreases its cost when compared to the R-Co alloys. Nd is also cheaper than Sm due to its greater concentration in rare earth ores.

ORIGIN OF FERROMAGNETISM IN RARE EARTH-TRANSITION METAL PERMANENT MAGNETS

In the 3d magnetic elements Fe, Co, Ni, large 3d exchange interactions stablize ferromagnetc ordering well above room temperature. Crystal field interactions being much larger than spin-orbit coupling, the orbital moment and thus the magnetic anisotropy are generally very small. However, modern permanent magnet devices require the presence of a large coercive force and in turn this required the presence of magnetocrystalline

anisotropies. Favourable candidates for sufficiently large anisotropies are rare earth base materials, where this property originates from a combinations of the crystal field interaction of 4f electron with the electrostatic charge of the surrounding and the relatively strong spin orbit interactions of the 4f electrons. Rare earth elements exhibit large orbital moments but 4f magnetic interactions are much weaker than 3d ones.

In rare earth-transition metal rich compounds, 3d and 4f magnetism coexist. 3d contributions stablize the ordering temperature above room temperature and the 4f anisotoropy remains faidy strong at room temperature due to the large 4f-3d magnetic interactions. None of the R-Fe binary compounds exhibit at room temperature all of the basic magnetic properties required to obtain large coercivity. However, these properties are encountered in the $R_2Fe_{14}B$ compound (4,5).

DEVELOPMENT OF Sm-Co BASED PERMANENT MAGNETS

Rare earth Co magnets can be divided into four types depending on whether the primary phase is of the R Co_5 or R_2 Co_{17} type and whether a precipitate phase within the grains is present or absent.

Single phase Sm C05 is the most important type of this family of magnets. Magnetization reversal occurs by nucleation and growth of reverse domains in individual grains. Domain walls move easily within the grains but grain boundaries impede their motion from grain to grain (6).

R_2 $C0_{17}$ compound show every desirable combination of high curie temperature and saturation magnetization in excess of R Co_5 series. It is found that with most R_2 Co_{17} binary systems the preferred direction of the magnetization vector is in the plan perpendicular to the hexagonal axis. This prevents the development of coercivety because of the free rotation of magnetization vector with the plane. Easy axis behaviour is only found in the binary system R_2 Co_{17} with R = Sm, Er or Tm. However, the substitution of Co by Fe induces the change from planer preference to axil preference (6).

The main drawback of Sm-Co magnets from a commercial viewpoint is their high cabalt content. Cobalt is more expensive than the other two ferromagnetic transition elements, nickel and iron, by factors of roughly ten and hundred, respectively. Supplies have been erratic over the past decade because of unrest (in 1978) in Zaire, source of about half the world supply of refined Co metal. Samarium, while more abundant in the earth's crust than any of the heavier rare earth elements and more than three times as common as

tin, is nevertheless significantly scarcer than the lighter rare earth elements Pr and Nd which also have the ability to contribute axil anisotropy in a suitable crystal structure. Light rare earths are not really rare elements at all. Neodymium is more abundant in the earth's crust than lead.

Permanent magnets based on FeNdB have received a great deal of attention by design engineers as well as by Material Scientists and Physicists. At the present stage of development NdFeB magnets are superior to R-Co magnets in their B_r and $(BH)_{max}$ values at room temperature (table) but are inferior to them at temperatures higher than approximately 200°C. The important phase for the magnetic properties is $Nd_2Fe_{14}B$. This compound has a tetragonal structure, with uniaxial magnetocrystaline anistropy, and an easy anistropy field of about 7.5T at room temperature (7).

Typical Properties of various Rare-Earth Based Permanent Magnets

Material	Magnetic Properties		
	Br(mT)	H_{cc}(k/A/m)	BH_{max}(kJ/m3)
$SmCo_5$	900	> 1000	150
$Sm_2(Co,Fe,Cu,Zr)_{17}$	1080	> 1400	200
$Nd_{15}Fe_{77}B_8$	1200	950	270

MANUFACTURING TECHNIQUES USED FOR THE PRODUCTION OF Sm-Co AND NDFeB BASED MAGNETS

The material being compared, i.e. the Sm-Co 1:5, - 2 : 17 and Nd-Fe-B magnets, are produced by powder Matallurgy sintering.

To produce the magnets by powder metallurgy, the alloys are first melted from the elements or extracted from the oxides by means of a Co-reduction process(4).

Figure 1 shows an overview of the major process steps involved. Apart from material-specific parameters and treatment times, the procedures are the same. The pre-manufactured alloys are size-reduced and ground to particle size below 10 um in ball or jet mills. Due to the high affinity for oxygen of the rare earth components, grinding takes place submerged in a grinding fluid or in an inert gas atmosphere. The powders are orientated magnetically in fields of 600 to 1200 kA/m and compacted at pressures from 1 to 2 kbar (8).

The compacts are sintered in an inert atmosphere or under vacuum. The sintering temperature for $SmCo_5$ and Nd-Fe-B is around 1100°C, that for Sm-Co - 2 : 17 around 1200°C. The sintering time ranges from 30 to 60 minutes (8).

The difficulty in processing Nd-Fe-B alloys is that of oxygen pick up and this is shown in Fig. 2 where it can be seen that Nd-Fe-B alloy is more reactive than the Sm Co_2 alloys. However by the use of hydrogen decrepitation process (HD), the O_2 pick up can be reduced by an apreciable extent (9).

THE MOCRO-STRUCTURES OF IMPORTANT NdFeB ALLOYS

The optical micrograph of the as cast specimens of the $Nd_2Fe_{14}B$, $Nd_{21}Fe_{14}B$ and $Nd_{15}Fe_{77}B_8$ alloys are shown in fig. Nos. 3 to 5 respectively.

The matrix phase (A) with minor composition differences is common in all of the above alloys. Previous investigations have shown this phase to be tetragonal with composition $Nd_2Fe_{14}B$ (10,11,12). This phase is mainly responsible for the magnetic properties of the alloys. Phase B in the first two alloys is free iron which is due to deviation from the standard "Neomax" composition.

The primary crystals in as cast alloys of composition close to the stoichiometric composition contain free iron. The limit of primary iron lies at 77 at % Fe 15 at % Nd and 8 at % B (10,11,12). These free iron areas are soft magnetic regions and provide sites for the nucleation of reverse domains. This phase i.e., free iron is absent in $Nd_{15}Fe_{77}B_8$ alloy (Fig.5). The phase (C) present in this alloy is the rare earth rich phase (4). The Nd rich grain boundary phase is necessary to provide a barrier to the nucleation of reverse domains. The presence of this phase in sufficient quantity in the standard Neomax composition provides barrier to stop the nucleation of the reverse domains (4).

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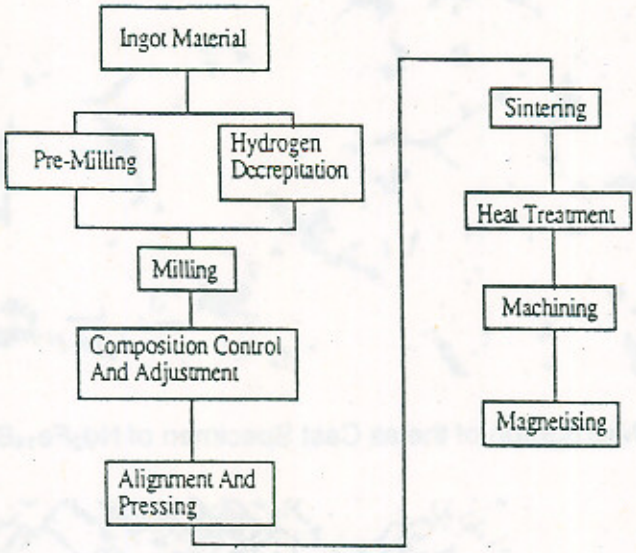


Fig. 1 General Process Steps for the Production of Sintered Rare Earth Permanent Magnets.

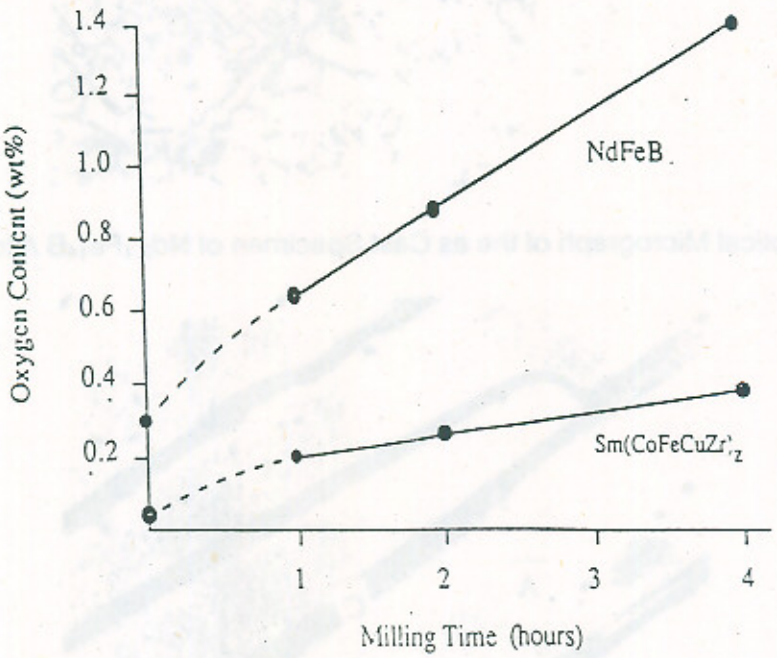


Fig. 2 The Effect of Milling Time on Oxygen "Pick-up".



Fig. 3 Optical Micrograph of the as Cast Specimen of $Nd_2Fe_{14}B$ Alloy Sample.

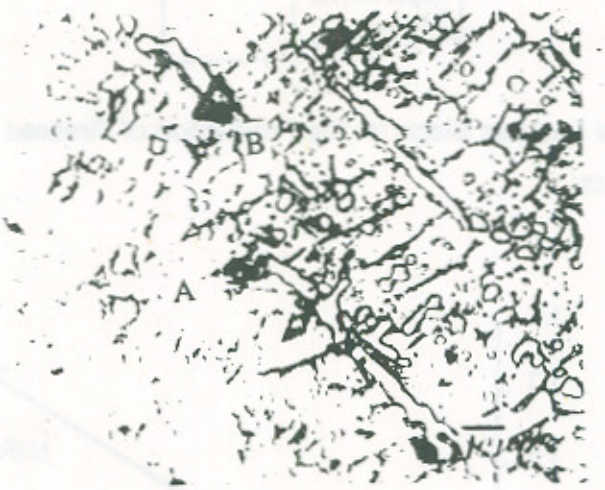


Fig. 4 Cptical Micrograph of the as Cast Specimen of $Nd_{2.1}Fe_{14}B$ Alloy Sample.

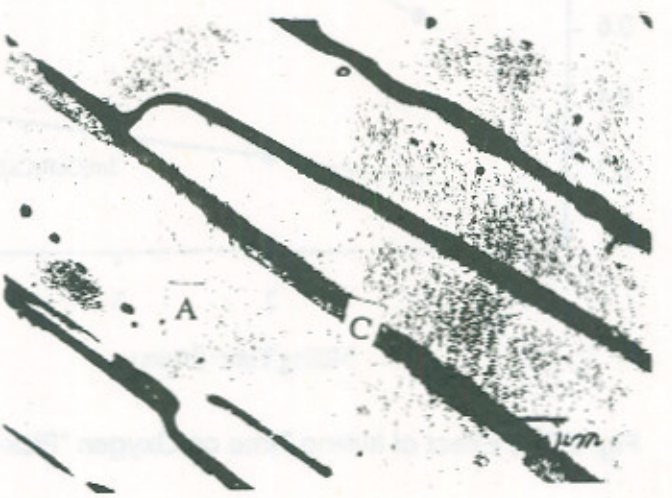


Fig. 5 Optical Micrograph of the as Cast Specimen of $Nd_{15}Fe_{77}B_8$ Alloy Sample.