MODELING OF MAGNETIC PROPERTIES OF HEAT TREATED Dy-DOPED NdFeB PARTICLES BONDED IN ISOTROPIC AND ANISOTROPIC ARRANGEMENTS

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***Abstract*—The effects of compacting methods, heat treatment and chemical additives on the magnetic properties of NdFeB particles have been studied. Five sets of NdFeB powder particles, doped with different amounts of Dy from 0.1-2.9 wt%, were prepared in powder form by gas atomization and annealed at 650-750°C for 600 seconds under an inert argon atmosphere. These were then bonded in epoxy, either in isotropic form, or aligned during fabrication under the action an applied magnetic field. Their magnetic properties were measured using a vibrating sample magnetometer. The results showed that the combined effects of the addition of Dy and heat treatment could dramatically improve the coercive force, remanent magnetization and maximum energy product. The results have been interpreted using a model of hysteresis which takes into account energy losses, anisotropy and texture of a material. The modeling showed that these effects alter the magnetic properties by increasing the hysteresis loss via the loss coefficient and by reducing the reversible component of magnetization through the reversibility coefficient. The compacting process influences the density of the particles in the bonded magnet which alters the magnetic properties through the coupling coefficient. The major influence of particle alignment can be interpreted as a change in the texture which can be described by a texture parameter.**

***Index terms*— hysteresis measurements, model theory of hysteresis, NdFeB, dysprosium, hard magnets.**

I. INTRODUCTION

Permanent magnet materials using light rare earth elements together with iron and boron have revolutionizedthe design of motors and actuators used in machine tools, robots, and computer equipment. Magnets can be manufactured from NdFeB by melt spinning and hot pressing the permanent magnet material, or by powder processing followed either by sintering or bonding. These processes lead to magnets with high values of maximum energy product [1,2] However the applications of REFeB based magnets have been limited by the low Curie temperature of the hard magnetic phase $RE_2Fe_{14}B$, which results in undesirable temperature dependence of magnetic properties such as the coercive field. Partial substitution of Co for Fe and Dy for Nd, or the addition of small amounts of other elements can reduce the temperature sensitivity of the magnetic properties of this material.

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Although some progress has been made improving the magnetic properties of NdFeB, either by changing the chemical composition, modifying the structure through heat treatments or changing the arrangements of the particles, the detailed understanding of the underlying mechanism is still poor because of the complexity of the magnetization processes. Computer modeling of these processes provides one way by which these can be better understood [3]. Previous modeling work has reported the effect of the compacting on the magnetic properties of NdFeB powder, which showed that compaction influences the properties through the coupling coefficient α [4]. In this study, we relate the composition and heat treatment to the magnetic properties using an established thermodynamic model of hysteresis that includes the effects of anisotropy and texture [5].

The high magnetocrystalline anisotropy of the $RE_2Fe_{14}B$ phase at room temperature is one of the factors determining the intrinsic coercivity of these magnets [6]. The coercivity can also be enhanced by increased pinning of domain boundaries through the addition of a small amount (<1wt%) of Al, Nb, Zr, Mo, Ga or other refractory elements. The presence of these can increase the coercivity by up to 30% due to alterations of the microstructure, while the anisotropy only changes slightly. Mixing REFeB with high melting point particles such as TiO_2, Dy_2O_3, Nd_2O_3, La_2O_3, BN, W, Mo, or Ti followed by heat treatment at 500°C to 1200°C in an inert gas atmosphere, removes internal distortion and causes structural modification leading to markedly improved coercive force H_c. Another way to enhance the hard magnetic properties is to inrease the texture by aligning the particles under the action of a magnetic field during fabrication of the magnet [7].

II. EXPERIMENTAL DESCRIPTION AND CHEMICAL ANALYSIS

The technique of high pressure gas atomization was used with a close coupled annular feed atomizer to produce rapidly quenched, equiaxed powder particles of NdFeB. The chemical compositions of the powders are shown in Table 1. Specimens were produced with or without heat treatment from each composition of powder. The heat treatment involved heating the powder from room temperature at a rate of 0.03 degrees per second to the selected temperature of 650-750°C for 600 seconds, and then cooling back to ambient temperature in the furnace.

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The bonded magnets were fabricated either by using fast-cure epoxy or slow-solidification epoxy to form a material in isotropic form in the fast cure epoxy, or ii) in aligned form under the action of an applied magnetic field in the slow cure epoxy. The properties of these magnetic materials were measured and the results were compared with model calculations.

Table 1. Chemical compositions of NdFeB powder specimens showing principally the change in dysprosium content

Sample No.	Nd(wt%)	Fe(wt%)	B(wt%)	Dy(wt%)
1	33.4	65.37	1.13	0.1
2	35.3	63.3	1.10	0.3
3	27.4	66.63	1.17	2.2
4	32.4	63.68	1.12	2.8
5	30.7	65.23	1.14	2.9

III. RESULTS AND DISCUSSION

The magnetic properties of these specimen were measured with a vibrating sample magnetometer. The addition of Dy without heat treatment only caused a small change in coercivity as shown in Fig. 1. However heat treatment with the addition of Dy increased the coercivity dramatically. The addition of Dy, without the heat treatment, seemed to have no apparent influence on the remanence of the samples, as shown in Fig.2, but after heat treatment the remanence increased, with a greater increase occuring in materials with higher Dy content. From Figs. 1 and 2 it is also clear that the anisotropically bonded materials had systematically higher coercivity and remanence than the isotropically bonded materials.

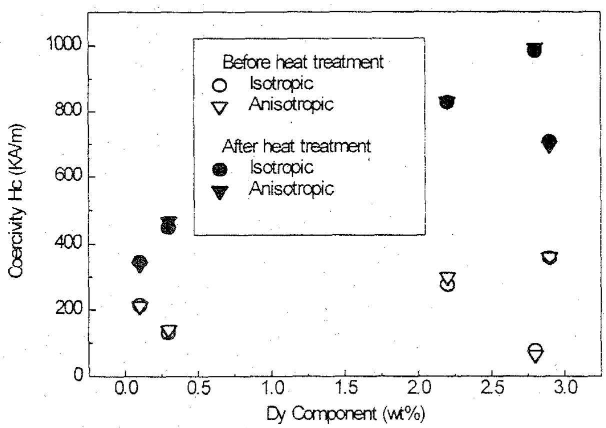

Fig. 1. Measured coercivities H_c of NdFeB materials versus Dy component.

It is concluded therefore that the combination of heat treatment and the addition of Dy plays an important role in changing the magnetic properties of NdFeB materials. In order to obtain higher coercivity and remanence in a magnet, careful selection of the amount of Dy and the heat treatment procedure are required. In the samples studied in this work the optimum properties seem to be obtained by a composition of 2.8% Dy, heat treatment at 750°C and with anisotropic compaction during fabrication under the action of a magnetic field.

In order to understand better the influence of heat treatment, chemical additives and alignment of the particles on the magnetic properties of bonded NdFeB materials, several sets of measured hysteresis curves of these samples were modeled with the generalized anisotropic model of hysteresis developed previously [5]. Two sets of modeled curves are shown in Figs. 3 and 4 as representative of these model calculations which show agreement between the modelled and measured curves. The dependence of the hysteresis model parameters on the Dy content and heat treatment are shown in Fig. 5.

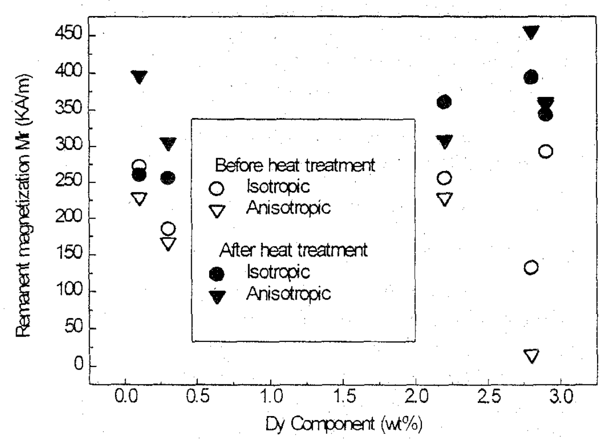

Fig.2. Measured remanent magnetization M_r of NdFeB materials versus Dy component.

The effects of heat treatment and Dy additives enhance the magnetic properties of NdFeB materials mainly through the increase of the hysteresis loss coefficient k and the decrease of the reversibility c as shown in Fig. 5. The introduction of Dy into NdFeB materials forms $Dy_2Fe_{14}B$, giving a two phase material. The lattice parameters change with the Dy content which leads to changes in the strength of the internal exchange interactions and consequently different coercivities of the particles may be expected.

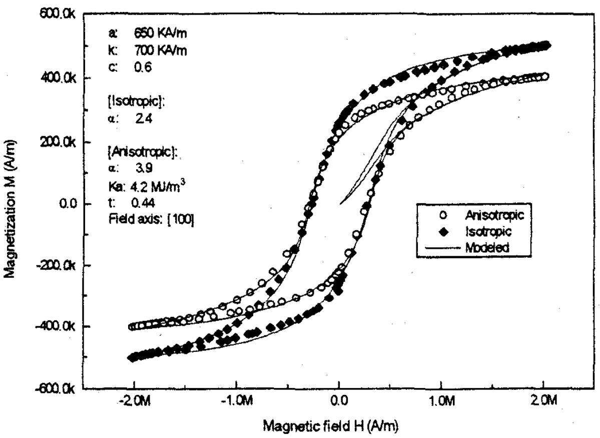

Fig.3. Modeled and measured hysteresis curves of sample 3 without heat treatment

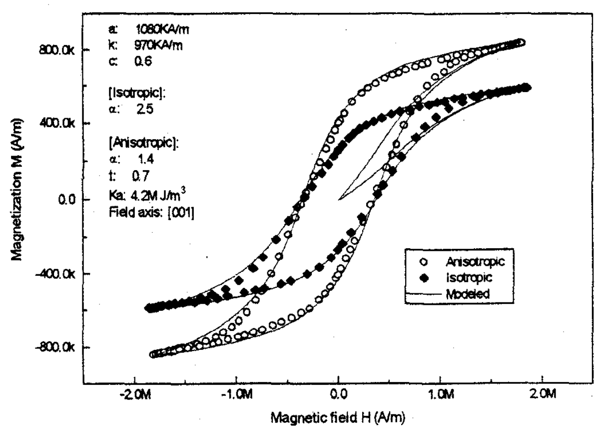

Fig.4. Modeled and measured hysteresis curves of sample 1 after heat treatment

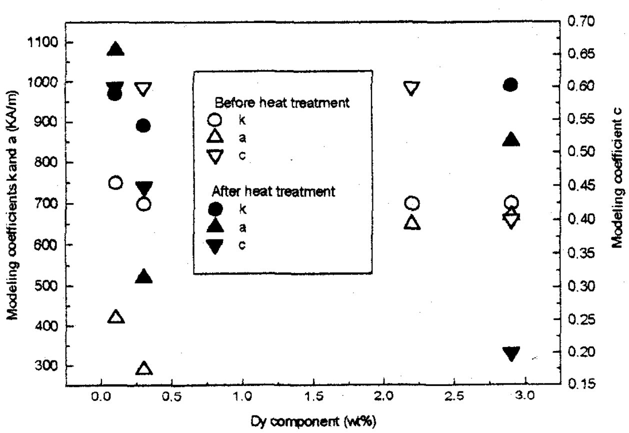

Fig.5. Modeling coefficient versus Dy component of NdFeB materials

The heat treatment, which among other effects alters residual stress in the particles, improves coercivity and remanence. It is also shown from the model calculations that the model parameter a, known as domain density, increased after heat treating, which tends to reduce the coercivity and remanence. From the modeling, it was shown that the interparticle coupling coefficient α did not show any apparent dependence on the additives and heat treatment, which may be a consequence of its strong dependence on compacting processes.

IV. Conclusions

It has been shown that the magnetic properties of bonded NdFeB materials can be improved through a combination of addition of Dy and heat treatment. The addition of Dy leads to higher coercivity but by itself does not influence the remanence significantly. However heat treatment can increase both the coercivity and the remanence of the material, particularly for samples with higher Dy content.

Modeling work on the measured hysteresis data shows that the improvements of the magnetic properties werecaused mainly through the increase in the hysteresis loss and the reduction in reversibility. Different levels of compaction of permanent magnet particles influences the magnetic properties through the coupling coefficient α. The application of a magnetic field during fabrication to align the powder particles alters the texture coefficient t and this also affects the magnetic properties leading to higher coercivity and remanence in the anisotropically aligned materials.

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