Role of Rare Earth Content on Microstructure and Coercivity of Sintered Nd-Fe-B Magnets

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May 03, 2024
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The sintered Nd-Fe-B magnets with various rare earth (RE) contents were prepared using strip casting technique, and the dependence of the microstructures and coercivity on rare earth content was investigated. It is found that an appropriate higher rare earth content in magnets is beneficial to the formation of uniform distribution of the RE-rich phases in grain boundaries, which leads to a rapid growth in the coercivity of magnets with increasing the rare earth content from the range of 29 wt.% to 32 wt.%. Moreover, continuous thin layers of RE-rich phase were confirmed by scanning electron microscopy in details. We further demonstrate that the coercivity of magnets becomes stronger with an appropriate higher RE content using micromagnetic simulation.

Index Terms—Nd-Fe-B magnets, rare earth content, microstructure, coercivity, micromagnetic simulation, OOMMF

I. INTRODUCTION

SINTERED Nd-Fe-B magnets have been widely applied for electric motors, wind turbines, and magnetic resonance imaging scanners due to their exceptional magnetic properties [1]–[9]. Since their discovery in the 1980s, Nd-Fe-B magnets have been extensively studied by optimizing the composition of the alloy to achieve maximum magnetic performance [10]–[12]. Different combinations of neodymium (Nd), iron (Fe), and boron (B) were explored, as well as the addition of some minor elements such as aluminum (Al), cobalt (Co), and terbium (Te) to enhance specific properties, such as coercivity enhancement, resistance to demagnetization, and temperature stability [13]–[16]. With the rapidly growing demand for Nd-Fe-B magnets in extensive applications, there has been increasing interest in understanding the fundamental relationship between the microstructure and magnetic properties of Nd-Fe-B magnets [17]–[20]. Microstructural features, such as phase composition, grain size, distribution of rare earth elements, etc., play a vital role in affecting the overall magnetic performance [21]–[24]. However, comprehensive microstructure characterizations and their relationship to magnetic performance were not completely clarified for the effect of rare earth content. In this paper, we show that increasing the RE content in magnets can improve the coercivity considerably, which is substantiated based on detailed structural studies on the Nd-Fe-B magnets with various RE contents using scanning electron microscopy (SEM). We also present simulated results of the magnetic properties of Nd-Fe-B magnets with various grain boundary (GB) thicknesses using micromagnetic simulation.

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II. EXPERIMENTAL

A. Preparation of Nd-Fe-B magnets

The original alloys with nominal composition of \((\text{Pr}_{0.25}\text{Nd}_{0.75})_x\text{Fe}_{0.98}\text{B}_{0.02}\) \((\text{wt.}\%\), \(x = 29, 30, 31, 32\), \(M = \text{Cu}, \text{Al}, \text{Ga}, \text{Zr}, \text{Co}\) were prepared by strip casting technique, using high-purity constituent elements. The alloy strips were processed into coarse powders with particle size about 10–100 \(\mu\text{m}\) by hydrogen decrepitation technique. Then, the powders were jet-milled to an average particle size of 3 \(\mu\text{m}\) in nitrogen atmosphere. The green compacts by powders were compressed in a perpendicular magnetic field of 1800 kA/m. Then, they were subjected to cold isostatic compacting under a pressure of 200 MPa. The green compacts were sintered at the temperature ranged from 1050 \(^\circ\text{C}\) to 1150 \(^\circ\text{C}\) for 8 h in vacuum followed by gas quenching and then tempered at 940 \(^\circ\text{C}\) and 520 \(^\circ\text{C}\), respectively, for 2 h. The final samples were machined to \(\phi 10\text{mm} \times 10\text{mm}\) cylinders for testing.

B. Characterization and analysis

The demagnetization curves of samples were obtained using a magnetic measurement device NIM-6500C. The morphology and elemental composition of samples were investigated by scanning electron microscopy (SEM, Apreo S HiVac) in back-scattered electron (BSE) mode with energy dispersive spectrometer (EDS).

C. Micromagnetic simulation

To study the influence of RE content on the coercivity of Nd-Fe-B magnets, the micromagnetic simulations were constructed using OOMMF software [25]. The simulation models consisted of \(20 \times 20 \times 20 \text{nm}^3\) grains, and a mesh size of \(2 \times 2 \times 2 \text{nm}^3\) due to the accuracy of the calculations [26]. The anisotropy constant \((K_1)\), saturation magnetization \((M_s)\), and exchange stiffness \((A)\) of \(\text{RE}_2\text{Fe}_{14}\text{B}\) were obtained by
linear interpolation based on the values of Pr$_2$Fe$_{14}$B and Nd$_2$Fe$_{14}$B collected from previous work [27], [28].

III. RESULTS AND DISCUSSION

A. Magnetic properties

![Demagnetization curves of Nd-Fe-B magnets with RE content of (a) 29 wt.%, (b) 30 wt.%, (c) 31 wt.% and (d) 32 wt.%, respectively.](image1)

Figure 1(a) shows demagnetization curves of Nd-Fe-B magnets with various RE contents at 20 °C. It can be seen that the RE content has a crucial effect on magnetic properties of these samples. With increasing the RE content, the coercivity increases dramatically, especially from 29 wt.% to 30 wt.%. The highest coercivity, up to 15.14 kOe, can be obtained with 32 wt.% RE content, showing an amplification of 43.78% compared with that with 29 wt.% RE content. Simultaneously, in Fig. 1(b), the remanence shows a small decrease of 4%, from 14.96 kGs to 14.36 kGs. The variation of magnetic properties among the samples mainly results from the difference of RE content in the samples, so the effect of RE content on microstructure and coercivity of Nd-Fe-B magnets will be fully discussed below.

B. Microstructure and chemical composition

As discussed earlier that with changing the RE content in the sintered Nd-Fe-B magnets, significant variation in coercivity was shown, which inspires our interest to investigate the role that RE content plays in the microstructure and phase composition. Figure 2 shows the BSE-SEM images of the sintered Nd-Fe-B magnets with RE content of 29 wt.%, 30 wt.%, 31 wt.% and 32 wt.%, respectively. The gray regions in the figures represent RE$_2$Fe$_{14}$B, while brighter regions stand for the RE-rich phase, i.e., the GB phase. It can be clearly seen that, with increasing the RE content, grain boundaries are becoming more visible. A great majority of RE$_2$Fe$_{14}$B phases (gray regions) are isolated by thin and continuous intergranular RE-rich phases (brighter regions), which is beneficial to improve the coercivity of magnets, due to the weaker exchange coupling. Moreover, the area of RE-rich phases is also becoming larger. By calculating the pixel number of gray region and brighter region in these SEM images, the percentages of RE-rich phases (brighter regions) are 3.63%, 4.85%, 6.38% and 9.50%, respectively (more details in Supplementary Information Fig. S1), which is also consistent with the theoretical RE content in these four samples.

To further clarify the relation between varying magnetic properties and microstructure evolution, detailed Energy Dispersive Spectrometer (EDS) investigation was carried out. Based on the EDS line scan results illustrated in Fig. 3, it can be inferred that Pr and Nd elements are mainly distributed in brighter regions (RE-rich phase), while Fe element is mainly distributed in gray regions (RE$_2$Fe$_{14}$B phase). Moreover, the EDS point scan and mapping scan results also indicate that higher RE content in the magnets is helpful to form more GB phases between the RE$_2$Fe$_{14}$B phases, which are shown in the Supplementary Information (Fig. S2–S9).

C. Micromagnetic simulations of Nd-Fe-B magnets

For a better understanding of the underlying mechanism of the role of RE Content on microstructure and magnetic properties of sintered Nd-Fe-B Magnets, micromagnetic simulations by OOMMF software were carried out. As shown in Fig. 4(a), basic simulation models of eight cubic grains with a size of $20 \times 20 \times 20$ nm$^3$ were set up, due to the
Fig. 3. (Color online) BSE-SEM images and the corresponding EDS line scan profiles of the sintered Nd-Fe-B magnets with RE content of (a, b) 29 wt.%, (c, d) 30 wt.%, (e, f) 31 wt.% and (g, h) 32 wt.%, respectively.

Fig. 4. (Color online) (a) The micromagnetic model and (b) simulated demagnetization curves for sintered Nd-Fe-B magnets with various GB phase thicknesses (2 nm, 6 nm, 10 nm and 12 nm).

IV. CONCLUSIONS

In summary, the sintered Nd-Fe-B magnets with various RE contents can be achieved by strip casting technique. The influence of microstructure of magnets on their magnetic properties using SEM technique was discussed in details. Thin RE grain boundaries are formed with higher RE content, which rapidly enhances the coercivity of magnets. Furthermore, the results from micromagnetic simulation also demonstrate the importance of grain boundaries for improving the coercivity of Nd-Fe-B magnets.

ACKNOWLEDGEMENTS

This work at Jiangxi Copper Technology Institute Co., Ltd. was supported by National Key R&D Program of China...
REFERENCES


