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Abstract
Low coercivity is the main disadvantage of RE-Fe-B permanent magnets containing highly abundant rare earths (RE: La, Ce) from the application point of view, even though they exhibit many cost and resource advantages. In this work, an industrial mixed rare earth alloy (RE 100 = La 30.6 Ce 50.2 Pr 6.4 Nd 12.8 ) with a high amount of the more abundant elements was adopted to fabricate RE-Fe-B permanent magnets by means of mechanical alloying accompanied by post-annealing. A synergetic effect towards enhancing the coercivity was observed after co-doping with Dy 2 O 3 and Ca, with the coercivity increasing from 2.44 kOe to 11.43 kOe for co-dopant percentages of 7 wt.% Dy 2 O 3 + 2.3 wt.% Ca. Through analysis of the phase constituents and microstructure, it was determined that part of the Dy atoms entered the matrix of RE 2 Fe 14 B phase to enhance the magnetocrystalline anisotropy; due to the reductive effect of Ca on Dy 2 O 3 , nanocrystals of Dy-rich RE 2 Fe 14 B were present throughout the matrix, which could increase the resistance to domain wall movement. These are the dominant factors behind the improvement of the coercivity of the RE-Fe-B magnets with highly abundant RE elements.

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Synergetic Effect of Dy$_2$O$_3$ and Ca Co-Dopants towards Enhanced Coercivity of Rare Earth Abundant RE-Fe-B Magnets

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Abstract
Low coercivity is the main disadvantage of RE-Fe-B permanent magnets containing highly abundant rare earths (RE: La, Ce) from the application point of view, even though they exhibit many cost and resource advantages. In this work, an industrial mixed rare earth alloy (RE$_{100} = \text{La}_{30.6}\text{Ce}_{50.2}\text{Pr}_{6.4}\text{Nd}_{12.8}$) with a high amount of the more abundant elements was adopted to fabricate RE-Fe-B permanent magnets by means of mechanical alloying accompanied by post-annealing. A synergetic effect towards enhancing the coercivity was observed after co-doping with Dy$_2$O$_3$ and Ca, with the coercivity increasing from 2.44 kOe to 11.43 kOe for co-dopant percentages of 7 wt.% Dy$_2$O$_3$ + 2.3 wt.% Ca. Through analysis of the phase constituents and microstructure, it was determined that part of the Dy atoms entered the matrix of RE$_2$Fe$_{14}$B phase to enhance the magnetocrystalline anisotropy; due to the reductive effect of Ca on Dy$_2$O$_3$, nanocrystals of Dy-rich RE$_2$Fe$_{14}$B were present throughout the matrix, which could increase the resistance to domain wall movement. These are the dominant factors behind the improvement of the coercivity of the RE-Fe-B magnets with highly abundant RE elements.

Keywords: Abundant RE-Fe-B magnets, Coercivity, Dy$_2$O$_3$ and Ca co-dopants, Synergetic effect

Background
Highly abundant rare earth elements, such as La and Ce, have been used to fabricate rare earth permanent magnets for the purposes of reducing costs and conserving usage of rare earth resources [1–5]. Nevertheless, the permanent magnets with high concentrations of La and Ce exhibit significantly degraded performance because the magnetocrystalline anisotropy of the 2:14:1 phases La$_3$Fe$_{14}$B and Ce$_3$Fe$_{14}$B is much lower than for their Nd$_2$Fe$_{14}$B counterpart [6]. So far, most work has been focused on the substitution of La and Ce for Nd in Nd-Fe-B-based magnets [7–14]. The performance of these permanent magnets can be much enhanced through adjusting the microstructure. In addition, it has been widely reported that doping with heavy rare earth elements (Dy or Tb) is a highly useful way to improve the magnetic performance [15, 16], by enhancing the coercivity and thermal stability. It was reported that both the coercivity and the thermal stability of Nd$_2$Fe$_{14}$B-type magnets can be enhanced through doping with Dy$_{70}$Cu$_{30}$ [17, 18] or Dy$_{80}$Al$_{20}$ [19]. The increase in the coercivity was 4.4 kOe and 9.0 kOe for the 2 wt.% Dy$_{70}$Cu$_{30}$ [18] and 4 wt.% Dy$_{80}$Al$_{20}$ [19] samples, respectively. As is well known, these heavy rare earth alloys are much more expensive. Thus, the cost advantages of La-Ce-Fe-B-based permanent magnets could be diminished if pure heavy rare earth metals or alloys were selected as dopants. Therefore, it would be worthwhile to find a route to match the enhancing effects of the pure heavy rare earth metals or alloys by using low-price compounds of heavy rare earth elements (Dy or Tb), for example, in the form of oxides. In fact, the addition of oxides could be helpful for improving the high frequency behavior of the magnets due to their high resistivity.

Recently, the reduction-diffusion process through Ca reduction of the rare earth oxides has been widely investigated to fabricate high-performance rare earth permanent magnets, such as Nd$_2$Fe$_{14}$B- and Sm$_2$Fe$_{17}$N$_x$-based magnets [20, 21]. In this work, a cheap industrial rare earth alloy (RE$_{100} = \text{La}_{30.6}\text{Ce}_{50.2}\text{Pr}_{6.4}\text{Nd}_{12.8}$) with a high amount...
of the abundant elements was adopted as the source material. Dy$_2$O$_3$ was utilized as the precursor of the heavy rare earth element Dy to improve the magnetic performance rather than the expensive pure heavy rare earths or their metallic alloys [15–19]. Furthermore, Ca was also co-doped to promote the beneficial effects of Dy$_2$O$_3$ through the reducing reaction between Dy$_2$O$_3$ and Ca. A coercivity as high as 11.43 kOe was achieved for the magnets with a concentration of the abundant rare earth elements La and Ce that was higher than 80 at.%. This work suggests a facile way of making use of the Ca-reducing effect to strengthen the enhancement of the magnetic properties of rare earth permanent magnets by the use of rare earth oxides.

Methods
An industrial rare earth (RE) alloy with abundant La and Ce (RE$_{100}$ = La$_{30.6}$Ce$_{50.2}$Pr$_{6.4}$Nd$_{12.8}$, 99.5 wt.%), denoted as RE in this work), iron (99.9 wt.%), and iron-boron alloy (99.5 wt.%) with the nominal composition of RE$_{13.6}$Fe$_{78.4}$B$_8$ were arc melted. The melted alloy was smashed into powder. In a high-purity argon-filled glove box, the powders were sealed in a hardened steel vial containing steel balls 12 mm diameter, with the powder-ball mass ratio of 1:16. Dy$_2$O$_3$ and Ca powders with a particle size of about 100 μm were added. Ball milling was performed using a high-energy ball mill with a rotation speed of 700 rpm for 5 h. In order to investigate the effects of the Dy$_2$O$_3$ and Ca dopants on the magnetic properties, 2.3 wt.% Ca (sample denoted as MC), 3 wt.% Dy$_2$O$_3$ (sample denoted as M3D), 7 wt.% Dy$_2$O$_3$ (sample denoted as M7D), and the co-dopants 2.3 wt.% Ca and 7 wt.% Dy$_2$O$_3$ (sample denoted as M7 DC) were, respectively, added before milling. The pure RE-Fe-B sample without the dopant was denoted as RM. Subsequently, the milled powders were annealed at 620–780 °C for 10 min in a vacuum environment (better than 1.3 × 10$^{-3}$ Pa). The phase components were analyzed with an MSAL-XD2 mode X-ray diffraction instrument (Cu-Kα, λ = 0.15406 nm). Hysteresis loops were measured using a LakeShore 7404 Model vibrating sample magnetometer (VSM) at room temperature, for which the sample powder was solidified into a cylinder 2 mm in diameter and 4 mm in length with epoxy resin, and the results were corrected by using an experimentally determined demagnetization factor of 0.28 [22]. Magnetic performances at low and high temperature were characterized by a Quantum Design Versa-lab and DynaCool physical properties measurement system (PPMS). A JEM-2100F transmission electron microscope (TEM) was used to carry out the microstructural observations.

Results and Discussion
The samples annealed at 700 °C were selected to characterize the phase constituents. Figure 1 presents the X-ray diffraction (XRD) patterns of the annealed samples. All the samples mainly consisted of RE$_2$Fe$_{14}$B matrix phases [5, 6]. Slow scanning from 37° to 45° was performed to study the lattice variations after doping with Dy$_2$O$_3$ and Ca, as shown in Fig. 1b. The lattice parameters, a and c, and the cell volume (Fig. 1c) were evaluated by Jade software in terms of the XRD patterns of Fig. 1b. The results indicated that the Ca, as a single dopant, caused obvious shrinkage of the 2:14:1 phase crystal cell, indicating the substitution of Ca for the rare earth elements, since the Ca metallic radius is much larger than the value for Fe [23]. The Dy$_2$O$_3$ dopant caused shrinkage of the crystal cells, too, suggesting Dy entrance into the 2:14:1 phase. With increasing Dy$_2$O$_3$ content, the cell shrinkage became serious, presenting lower values of the lattice parameters. Regarding the sample with Dy$_2$O$_3$ and Ca as co-dopants, the total volume shrinkage of about 0.0048 (nm$^3$) was above the sum of the values for 2 wt% Ca (0.0008 nm$^3$) and 7 wt.% Dy$_2$O$_3$ (0.0032 nm$^3$) as single dopants, implying that the Ca promoted the shrinkage due to more Dy entrance into 2:14:1 phase.

The thermal magnetic behavior of the samples was investigated to further clarify the dopant occupation in the 2:14:1 matrix phase. Figure 2 shows the
variation in magnetization of samples annealed at 700 °C as a function of temperature from 300 to 700 K, in which the magnetic field of 2 T was applied to saturate the magnetic moment. On heating the samples, the ferromagnetic-paramagnetic phase transition of 2:14:1 phase took place at the Curie temperature ($T_C$). As indicated in Fig. 2, $T_C$ was slightly increased from 551.5 to 557.3 K after doping with Dy$_2$O$_3$, but it exhibited a significant increase from 551.5 to 564.5 K with Ca dopant. There is a slight further increase in $T_C$ from 564.5 to 566.1 K after co-doping with Ca and Dy$_2$O$_3$. These features are consistent with the XRD results, indicating the entrance of Dy or Ca into the lattice of 2:14:1 phase. It was also observed that the temperature of the spin re-orientation varied consistently with the dopants (data not shown here).

Figure 3 presents typical magnetic hysteresis loops of the samples annealed at 700 °C. The coercivity increased, and the saturation magnetization decreased in the presence of the dopants. The dependence of the coercivity on the annealing temperature is shown in Fig. 4. With Ca doping, the coercivity of all the samples was slightly enhanced. Dy$_2$O$_3$ dopant was also helpful for improving the coercivity. On doping with 7 wt.% Dy$_2$O$_3$, the coercivity increased from 2.44 to 7.65 kOe when the sample was annealed at 700 °C. Although the 2.3 wt.% Ca as a single dopant did not contribute a large enhancement of coercivity (about 1.2 kOe), Dy$_2$O$_3$ and Ca as co-dopants caused more significant enhancement of coercivity (about 9.1 kOe) than the total effect of each individual dop-ant (about 6.3 kOe), as shown in Fig. 4.

The co-doped sample annealed at 700 °C, which presented the highest coercivity, was selected for the
microstructural observations, as shown in Figs. 5 and 6. Figure 5a presents a bright field TEM image, which exhibits a nanocrystalline structure (inset: corresponding selected area diffraction pattern). In addition, there are some coarse grains embedded within the matrix. Scanning TEM (STEM) mode was selected to detect the chemical information. Figure 5 presents the STEM image, in which dark coarse grains appear, dotting the sample. Through energy dispersive spectroscopy (EDS) analyses, it could be shown that the dark coarse grains contain high fractions of Dy and Ca compared with the other regions, as listed in Table 1. Note that the contents of oxygen and boron are not included in Table 1 because there is less EDS accuracy for the light elements. A further characterization of the elemental chemistry was carried out by point detection in EDS along one coarse grain, as shown in Fig. 6. Figure 6b presents the elemental concentrations at each detected site. It is clear that there is a Dy-rich region containing less Ce and La.

As shown in Fig. 5, the coercivity can be enhanced by doping with Ca or Dy$_2$O$_3$. The co-dopants Ca and Dy$_2$O$_3$ give a strong improvement in comparison to each single dopant alone. It can be seen that the initial magnetic curve of the co-doped sample exhibits a mixed mechanism of nucleation and domain wall pinning, as indicated by the arrow in Fig. 3. When the applied field is under 5 kOe, the initial magnetic curve of the co-doped sample presents the features of the nucleation mode; after the external field is higher than 5 kOe, the reversal of magnetic domains becomes difficult, showing the feature of domain wall pinning. In terms of the microstructural observations, there were some coarse grains with a high concentration of Dy element (Figs. 5 and 6), which could act as pinning sites due to the high magnetocrystalline anisotropy.

XRD analysis shows that doping with Ca shrank the $a$-axis parameter and expanded the $c$-axis parameter, while doping with Dy$_2$O$_3$ shrank both the $a$ and the $c$ axis parameters (Fig. 1c). Shrinkage of both the $a$ and the $c$ axis parameters occurred for the sample with the co-dopants. The Pearson’s metallic radius of Dy (0.1773 nm) is smaller than for La (0.1877 nm), Nd (0.1821 nm), and Pr (0.1828 nm) [23]. Thus, shrinkage of the unit cell of RE$_2$Fe$_{14}$B takes place with increasing amounts of Dy. The Ca prefers to replace the RE atoms due to its large metallic radius (0.1773 nm) [23], causing the expansion of the $c$-axis parameter. Nevertheless, the cell volume of RE$_2$Fe$_{14}$B was reduced due to the shrinkage of the $a$-axis parameter after doping with Ca. In contrast to the sample with 7 wt.% Dy$_2$O$_3$, the shrinkage of both $a$ and $c$ appeared after additional doping with Ca, rather than the shrinkage of the $a$ parameter alone, as in the case of Ca single doping.
As reported previously, the high energy mechanical milling caused a partially amorphous alloy, and recrystallization behavior took place in the milled alloys during the post-annealing at relatively low temperature [22]. According to the Standard Electrode Potentials [24], Ca (−2.868 V) has a lower potential than the rare earth elements involved in this work, while Dy (−2.295 V) has the highest potential among the rare earth elements. Making use of the chemical potential differentials, a reduction-diffusion process between Ca and the rare earth oxides took place in the fabrication of the rare earth permanent magnets [20, 21]. Thus, a reductive reaction would occur between the Ca and Dy₂O₃ during the mechanical milling and post-annealing. The reduced Dy atoms can take part in the recrystallization of RE₂Fe₁₄B phase, suggesting that the Ca could enhance the entrance of Dy into the 2:14:1 matrix rather than its own entrance. In addition, this local reductive reaction could promote elemental diffusion and mobility, resulting in the formation of some coarse grains, as shown in Figs. 5 and 6, which contain high amount of Ca and Dy. Therefore, the coercivity was significantly enhanced for the co-dopants due to the significant increase in magnetocrystalline anisotropy originating from more Dy in the 2:14:1 phase. A better magnetic performance could also be expected if the trace CaO could be removed.

Table 1 EDS results from points 001 and 002 in Fig. 5b of RE₁₃.₆Fe₇₈.₄B₈ with 7wt.%Dy₂O₃ and 2.₃wt.%Ca co-dopants

| Element | Ca  | Fe  | La  | Ce  | Pr  | Nd  | Dy  | Point |
|---------|-----|-----|-----|-----|-----|-----|-----|-------|
| Point 001 | 12.47 | 72.70 | 3.40 | 5.96 | 1.06 | 1.85 | 2.56 |       |
| Point 002 | 7.32 | 77.68 | 3.73 | 6.92 | 0.81 | 2.12 | 1.42 |       |

Note that the concentrations of oxygen and boron are not included because there is less EDS accuracy for the light elements.

Conclusions

The coercivity of a RE₂Fe₁₄B-based permanent magnet, with the RE content coming from an industrial mixed alloy of highly abundant rare earth elements (RE₁₀₀ = La₃₀.₆Ce₅₀.₂Pr₆.₄Nd₁₂.₈), was significantly enhanced from 2.₄₄ kOe to 11.₄₃ kOe through doping with Dy₂O₃ and Ca. Based on the variations in the lattice parameters, it could be deduced that Ca promotes the entrance of Dy into 2:14:1 phase due to its reducing effect on Dy₂O₃. This work proposes a way to fabricate high-coercivity permanent magnets with a high concentration of highly abundant rare earth elements.

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Authors’ Contributions

YFL carried out the experiments and drafted the manuscript. XDF and WLP participated in the measurements and performed the analysis. NT, CYY, and ZXC supervised the overall study and polished the manuscript. All the authors read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests.

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References

1. Yamasaki J, Soeda H, Yanagida M, Mohri K, Teshima N, Kohnoto O, Yoneyama T, Yamaguchi N (1986) Misch metal-Fe-B melt spun magnets with 8 MGOe energy product. IEEE Trans Magn MAG-22:763–765

2. Popov O, Skumryev V, Mikhailov M (1987) Magnetic properties of as-spun $\text{Mn}_x\text{Fe}_{92-x}\text{B}_8$ ribbons. J Magn Magn Mater 71:17–19

3. Zhang M, Li ZB, Shen BG, FX, Sun JR (2015) Permanent magnetic properties of rapidly quenched ($\text{La}_x\text{Ce}_{1-x})_2\text{Fe}_{14}\text{B}_6$ nanomaterials based on $\text{La-Ce}$ mischmetal. J Alloys Compd 651:144–148

4. Fan XD, Guo S, Chen K, Chen RJ, Dee D, You CY, Yan AR (2016) Tuning Ce distribution for high performance Nd-Fe-B sintered magnets. J Magn Magn Mater 419:394–399

5. Pei K, Lin M, Yan AR, Zhang X (2016) Effects of annealing process on magnetic properties of Nd-Pr-Ce-Fe-B melt-spin powders. J Magn Magn Mater 406:239–243

6. Herbst JF (1991) $\text{R}_2\text{Fe}_{14}\text{B}$ materials: intrinsic properties and technological aspects. Rev Mod Phys 63:819–898

7. Li ZB, Wang LC, Geng XP, FX H, Sun JR, Shen BG (2017) Variation of magnetic properties with mischmetal content in the resource saving magnets of $\text{MM-Fe-B}$ ribbons. J Magn Magn Mater 426:70–73

8. Zuo WL, Zuo SL, Li R, Zhao TY, FX H, Sun JR, Zhang XF, Liu JP, Shen BG (2017) High performance misch-metal (MM)-Fe-B magnets prepared by melt spinning. J Alloys Compd 695:1786–1792

9. Pathak AK, Khan M, Gschneidner KA Jr, McCallum RW, Zhou L, Sun KW, Dennis KW, Zhou C, Pinkerton FE, Kramer MJ, Pecharsky VK (2015) Cerium: an unlikely replacement of dysprosium in high performance Nd-Fe-B permanent magnets. Adv Mater 27:2663–2667

10. Pathak AK, Khan M, Gschneidner KA Jr, McCallum RW, Zhou L, Sun KW, Kramer MJ, Pecharsky VK (2016) Magnetic properties of bulk, and rapidly solidified nanostructured (Nd$_{1-x}$Ce$_x$)$_2$Fe$_{14}$-CoyB ribbons. Acta Mater 103:211–216

11. Niu E, Chen ZA, Chen GA, Zhao YG, Zhang J, Rao XL, BP H, Wang ZX (2014) Achievement of high coercivity in sintered R-Fe-B magnets based on mischmetal by dual alloy method. J Appl Phys 115:113912

12. Colin CV, Ito M, Yano M, Dempsey NM, Suard E, Givord D (2016) Solid-solution stability and preferential site-occupancy in ($\text{R-R'}$)$_2\text{Fe}_{14}\text{B}$ compounds. Appl Phys Lett 108:242415

13. Hussain M, Liu J, Zhao LZ, Zhong ZC, Zhang GQ, Liu ZW (2016) Composition related magnetic properties and coercivity mechanism for melt spun ($\text{La}_x\text{Ce}_{1-x})_2\text{Fe}_{14}\text{B}_6$ ($\text{RE}=$Nd or Dy) nanocomposite alloys. J Magn Magn Mater 399:26–31

14. XQ Y, Yue M, Liu WQ, Li Z, Zhu MG, Dong SZ (2016) Structure and intrinsic magnetic properties of MM-Fe-B (MM=La, Ce, Pr, Nd) alloys. J Rare Earths 34:614–617

15. Löwe K, Brombacher C, Katter M, Gutfleisch O (2015) Temperature-dependent Dy diffusion processes in Nd-Fe-B permanent magnets. Acta Mater 83:248–255

16. Li WF, Sepehri-Amin H, Ohkubo T, Hase N, Hono K (2011) Distribution of Dy in high-coercivity (Nd,Dy)-Fe-B sintered magnet. Acta Mater 59:3061–3069

17. Lee YI, Huang GY, Shih CW, Chang WC, Chang HW, You JS (2017) Coercivity enhancement in hot deformed Nd$_2$Fe$_{14}$B-type magnets by doping low-melting $\text{RCu}$ alloys ($\text{R}=$Nd, Dy, $\text{Nd}_2$). J Magn Magn Mater 399:26–31

18. Li WF, Sepehri-Amin H, Ohkubo T, Hase N, Hono K (2011) Distribution of Dy in high-coercivity (Nd,Dy)-Fe-B sintered magnet. Acta Mater 59:3061–3069

19. Lee YI, Huang GY, Shih CW, Chang WC, Chang HW, You JS (2017) Coercivity enhancement in hot deformed Nd$_2$Fe$_{14}$B-type magnets by doping low-melting $\text{RCu}$ alloys ($\text{R}=$Nd, Dy, $\text{Nd}_2$). J Magn Magn Mater 439:1–5

20. Lee YI, Chang HW, Huang GY, Shih CW, Chang WC (2017) Comparison on the coercivity enhancement of hot-deformed Nd$_2$Fe$_{14}$B-type magnets by doping $\text{R}_2\text{Cu}_3$ ($\text{R}=$Nd, Dy, and Tb) alloy powders. IEEE Trans Magn 53(11):2100704

21. Zhou BB, Li XB, Liang XL, Yan GL, Chen K, Yan AR (2017) Improvement of the magnetic property, thermal stability and corrosion resistance of the sintered Nd-Fe-B magnets with $\text{Dy}_2\text{Al}_{12}$ addition. J Magn Magn Mater 429:257–262

22. You CY, Sun XK, Xiong LY, Liu W, Cui BZ, Zhao XG, Geng DY, Zhang ZD (2004) Effects of the precursor ingot for Nd$_2$Fe$_{14}$B/Cu-Fe nanocomposite magnets prepared by mechanical milling. J Magn Magn Mater 268:403–409

23. Pearson WB (1967) A handbook of lattice Spacings and structures of metals and alloys. Pergamon Press, Oxford

24. Bratsch SC (1989) Standard electrode potentials and temperature coefficients in water at 298.15 K. J Phys Chem Ref Data 18:1–21