Effect of Ce on phase formation and magnetic properties of (Nd–Pr)_{2.28}Fe_{13.58}B_{1.14} melt-spun ribbons

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Abstract
The phase formation of the (Nd_{0.70}Pr_{0.30–y}Ce_{y})_{2.28}Fe_{13.58}B_{1.14} (x = 0.10, 0.15, and 0.20; hereafter defined as Pr_{20}Ce_{10}, Pr_{15}Ce_{15} and Pr_{10}Ce_{20}, respectively) and (Nd_{0.60}Pr_{0.40–y}Ce_{y})_{2.28}Fe_{13.58}B_{1.14} (y = 0.10, 0.20, and 0.30; hereafter defined as Pr_{30}Ce_{10}, Pr_{20}Ce_{20} and Pr_{10}Ce_{30}, respectively) alloys that were prepared via the arc-melting method was investigated experimentally. The x-ray diffraction results revealed that all alloys annealed at 1173 K for 360 h consisted of a Nd_{2}Fe_{14}B main phase with a tetragonal Nd_{2}Fe_{14}B-type structure (space group P4_{2}/mmm) and an α-Fe minor phase, except for the Pr_{10}Ce_{30} alloy, which contained an additional CeFe_{2} phase. The magnetic properties of the (Nd_{0.70}Pr_{0.30–y}Ce_{y})_{2.28}Fe_{13.58}B_{1.14} and (Nd_{0.60}Pr_{0.40–y}Ce_{y})_{2.28}Fe_{13.58}B_{1.14} ribbons that were prepared by melt spinning were examined. The remanence (B_r) and maximum magnetic energy product ((BH)_{max}) of the (Nd_{0.70}Pr_{0.30–y}Ce_{y})_{2.28}Fe_{13.58}B_{1.14} ribbons increased first and then decreased, whereas the coercivity (H_c) of the ribbons increased with an increase in Ce content. The B_r and (BH)_{max} of the (Nd_{0.60}Pr_{0.40–y}Ce_{y})_{2.28}Fe_{13.58}B_{1.14} ribbons increased, whereas the H_c of the ribbons decreased gradually with an increase in Ce content. This changed behavior of magnetic properties is attributed to the variation of volume fraction of the α-Fe phase and different phase formations in the melt-spin ribbons. The Curie temperatures (T_c) of all alloys decreased slightly with Ce substitution, which results from the lower Curie temperatures of Pr_{2}Fe_{14}B and Ce_{2}Fe_{14}B. The Pr_{10}Ce_{30} ribbon with a higher Ce content exhibited optimal magnetic properties (B_r = 9.71 kGs, H_c = 13.09 kOe, (BH)_{max} = 18.78 MGOe), which indicates that suitable magnetic properties of the Nd–Pr–Ce–Fe–B melt-spin ribbons can be achieved by alloy-composition and phase-formation design.

1. Introduction

Nd–Fe–B sintered permanent magnets with excellent magnetic properties have been used extensively in the applications of modern electronic industry, such as in motors for hybrid/electric vehicles and magnetic resonance imaging devices [1–5]. The development of Nd–Fe–B permanent magnets that contain high abundant rare-earth metals (e.g., La, Ce and Y) is an effective and promising approach to balance the rare-earth-metal use and the reduced costs of magnets [6–27]. Zhu et al [17] reported that (Nd_{1−x}Ce_{x})_{3}Fel,TM BM Fe_{1} sintered magnets that were prepared via the double main-phase-alloy method exhibited good magnetic properties, although the saturation magnetization (11.7 kGs) and magnetocrystalline anisotropy field (26 kOe) of CeFe_{14}B were lower than those of Nd_{2}Fe_{14}B [28]. Especially, the sintered magnet that contains 30% Ce content of total amount of all the rare earth metals retained a maximum magnetic energy product ((BH)_{max}) of 43 MGOe [17]. The phase constitution, microstructure and magnetic properties of Nd–Fe–B permanent magnets with high abundant rare-earth metals (i.e. La, Ce and Y) prepared by different methods (e.g., dual-alloy method, hot-deformed method, grain-boundary diffusion) have been studied extensively by many researchers [6–27, 29–35]. Pathak et al [19, 20], Yang et al [21] and Wang et al [22] found that the coercivity of the
Nd0.8Ce0.2–Fe–B alloy increased abnormally because of the phase segregation of Ce2Fe14B and Nd2Fe14B and the mixed valence of Ce in Ce2Fe14B compared with trivalent Nd in the Nd2Fe14B phase. Zhang et al [31, 32] found that the coercivity of the (PrNd)11Ce4Fe77B8 alloy that had been prepared by the dual-alloy method was highest in (PrNd)15-xCexFe77B8 (x = 0–10) alloys. Pei et al [33, 34] investigated the magnetic properties and microstructure of [(Nd4Pr)1-xCex]27Fe72B melt-spun ribbons. Even though the remanence (Br) and maximum magnetic energy product ((BH)max) of the Nd–Pr–Fe–B melt-spun ribbons decreased with an increase in Ce content, the coercivity (Hcj = 9.49 kOe) of the [(Nd4Pr)0.76Ce0.24]27Fe72B ribbon was relatively high.

To understand the effect of Ce substitution on the phase constitution, microstructure and magnetic properties of Nd–Pr–Fe–B alloys, the phase structure and magnetic properties of (Nd0.70Pr0.30−xCex)2.28Fe13.58B1.14 and (Nd0.60Pr0.40−yCey)2.28Fe13.58B1.14 alloys were investigated experimentally.

2. Experiments

(Nd0.70Pr0.30−xCex)2.28Fe13.58B1.14 (x = 0.10, 0.15, and 0.20; hereafter defined as Pr20Ce10, Pr15Ce15 and Pr10Ce20, respectively) and (Nd0.60Pr0.40−yCey)2.28Fe13.58B1.14 (y = 0.10, 0.20, and 0.30; hereafter defined as Pr20Ce10, Pr30Ce10, Pr20Ce20, and Pr10Ce30, respectively) alloys were prepared by an arc-melting method using bulk Nd, Pr, Ce, B and Fe (99.99% purity) as the starting materials. Each alloy sample was melted at least three times. Alloy samples that were sealed in an evacuated quartz tube were annealed at 1173 K for 360 h and quenched in ice water. The melt-spin ribbons were obtained by induction melting annealed alloys and ejecting the melt onto a copper wheel surface with various wheel speeds of 20–30 m s⁻¹.

The phase structure of the annealed alloys was examined by x-ray powder diffraction (XRD, PLXcel 3D, Co Kα radiation). The crystal structure was refined by the Rietveld technique using Fullprof software. Magnetic measurements of the melt-spin ribbons at room temperature were performed by a physical property measurement system (PPMS-9, Quantum Design). The Curie temperatures of the melt-spin ribbons were determined by thermogravimetric experiments under a constant magnetic field using differential thermal analysis (DTA, TA Instruments SDT/Q-600) at heating rate of 20 K min⁻¹.

3. Results and discussion

3.1. Phase structure

Figure 1 shows the XRD powder patterns of (Nd0.70Pr0.30−xCex)2.28Fe13.58B1.14 (x = 0.10, 0.15, 0.20) and (Nd0.60Pr0.40−yCey)2.28Fe13.58B1.14 (y = 0.10, 0.20, 0.30) alloys annealed at 1173 K for 360 h. The diffraction peaks of all alloys display the characteristics of a tetragonal Nd2Fe14B-typed structure phase (space group P42/mnm), which is termed the (NdPrCe)2Fe8B main phase and α-Fe minor phase (space group Im 3 m). Compared with the phase constitutions of the (NdPrCe)2Fe8B and α-Fe phases in other annealed alloys, the Pr10Ce30 alloy contains an additional CeFe2 phase (space group Fd 3 m).
Figure 2 shows the Rietveld refinements of the XRD powder patterns of \((\text{Nd}_{0.70}\text{Pr}_{0.30}-x\text{Ce}_x)_{2.28}\text{Fe}_{13.58}\text{B}_{1.14}\) and \((\text{Nd}_{0.60}\text{Pr}_{0.40}-y\text{Ce}_y)_{2.28}\text{Fe}_{13.58}\text{B}_{1.14}\) annealed alloys. The red points show the experimental data and the solid lines represent the calculated results. The vertical bars in different colors indicate the Bragg positions of the \((\text{NdPrCe})_2\text{Fe}_4\text{B}, \alpha-\text{Fe}\) and CeFe2 phases, respectively. The black lines show the differences between the experimental data and the calculated results. The calculated patterns agree well with the experimental data. Table 1 shows the structure parameters and volume fractions of the \((\text{NdPrCe})_2\text{Fe}_4\text{B}, \alpha-\text{Fe}\) and CeFe2 phases in the \((\text{Nd}_{0.70}\text{Pr}_{0.30}-x\text{Ce}_x)_{2.28}\text{Fe}_{13.58}\text{B}_{1.14}\) and \((\text{Nd}_{0.60}\text{Pr}_{0.40}-y\text{Ce}_y)_{2.28}\text{Fe}_{13.58}\text{B}_{1.14}\) annealed alloys obtained by Rietveld refinement. According to the Rietveld refinement results, Nd, Pr and Ce atoms occupy two \((4g, 4f)\) positions in the tetragonal Nd2Fe14B-type structure, whereas Fe atoms are located at five sites \((4c, 4e, 8j, 16k_1, 16k_2)\) and B atoms occupy one \((4g)\) sublattice. An increase in Ce content results in a decrease in the lattice parameters and cell volumes of the \((\text{NdPrCe})_2\text{Fe}_4\text{B}\) main phase in the \((\text{Nd}_{0.70}\text{Pr}_{0.30}-x\text{Ce}_x)_{2.28}\text{Fe}_{13.58}\text{B}_{1.14}\) and \((\text{Nd}_{0.60}\text{Pr}_{0.40}-y\text{Ce}_y)_{2.28}\text{Fe}_{13.58}\text{B}_{1.14}\) annealed alloys because of the smaller atomic radius of Ce than that of Pr and Nd. These results suggest that Ce and Pr atoms enter the structure lattice of Nd2Fe14B to replace Nd atoms in both annealed alloys.

3.2. Magnetic properties

Figure 3 shows the initial magnetization and demagnetization curves of the \((\text{Nd}_{0.70}\text{Pr}_{0.30}-x\text{Ce}_x)_{2.28}\text{Fe}_{13.58}\text{B}_{1.14}\) \((x = 0.10, 0.15, 0.20)\) melt-spun ribbons at room temperature. The magnetic properties, including the coercivity \((H_c)\), remanence \((B_r)\) and maximum magnetic energy product \((\text{(BH)}_{\text{max}})\) of the ribbons, were determined, as shown in table 2. The initial magnetization curves in figure 3(a) reveal that the coercivity mechanism of the ribbons is based on domain wall pinning [14]. With an increase in Ce content, the \(B_r\) and \((\text{BH)}_{\text{max}}\) of the ribbons increased initially and then decreased, whereas the \(H_c\) of the ribbons increased gradually.
Table 1. Lattice parameters and volume fractions of identified phases in \((\text{Nd}_{0.70}\text{Pr}_{0.30-x}\text{Ce}_x)_{2.28}\text{Fe}_{13.58}\text{B}_{1.14}\) and \((\text{Nd}_{0.60}\text{Pr}_{0.40-y}\text{Ce}_y)_{2.28}\text{Fe}_{13.58}\text{B}_{1.14}\) annealed alloys by Rietveld refinements.

| Sample alloys | \(a\) (Å) | \(c\) (Å) | Cell volume (Å\(^3\)) | \(\alpha\)-Fe | \(\alpha\)-Fe \(a\) (Å) | CeFe\(_2\) | CeFe\(_2\) (%) | Remanent ratio | \(R_{wp}\) | \(R_{exp}\) | \(\chi^2\) |
|---------------|----------|----------|------------------------|-------------|----------------|--------|-----------|-----------------|---------|---------|---|
| Pr\(_{20}\)Ce\(_{10}\) | 8.806 | 12.209 | 946.755 | 2.852 | — | 2.2 | 13.6 | 9.15 | 2.21 |
| Pr\(_{15}\)Ce\(_{15}\) | 8.804 | 12.203 | 945.861 | 2.859 | — | 1.5 | 13.8 | 8.36 | 2.74 |
| Pr\(_{10}\)Ce\(_{20}\) | 8.804 | 12.201 | 945.705 | 2.859 | — | 1.9 | 14.7 | 9.68 | 2.32 |
| Pr\(_{30}\)Ce\(_{10}\) | 8.807 | 12.213 | 947.279 | 2.859 | — | 3.2 | 14.3 | 9.68 | 2.18 |
| Pr\(_{20}\)Ce\(_{20}\) | 8.803 | 12.203 | 945.451 | 2.860 | — | 3.0 | 13.7 | 9.00 | 2.33 |
| Pr\(_{10}\)Ce\(_{30}\) | 8.799 | 12.193 | 944.012 | 2.858 | 7.317 | 6.4 | 14.5 | 9.77 | 2.20 |

Figure 3. Initial magnetization curves (a) and demagnetization curves (b) of \((\text{Nd}_{0.70}\text{Pr}_{0.30-x}\text{Ce}_x)_{2.28}\text{Fe}_{13.58}\text{B}_{1.14}\) \((x = 0.10, 0.15, 0.20)\) melt-spun ribbons at room temperature.

Table 2. Magnetic properties of \((\text{Nd}_{0.70}\text{Pr}_{0.30-x}\text{Ce}_x)_{2.28}\text{Fe}_{13.58}\text{B}_{1.14}\) and \((\text{Nd}_{0.60}\text{Pr}_{0.40-y}\text{Ce}_y)_{2.28}\text{Fe}_{13.58}\text{B}_{1.14}\) melt-spun ribbons at room temperature.

| Melt-spun ribbons | \(T_c\) (K) | \(B_i\) (kG) | \(H_{cj}\) (kOe) | \(\text{BH}_{\text{max}}\) (MGOe) | \(M_r\) (emu/g) | Remanent ratio \((M_r/M_s)\) |
|-------------------|----------|----------|--------|-----------------|--------|--------|
| Pr\(_{20}\)Ce\(_{10}\) | 570.2 | 5.89 | 13.05 | 7.18 | 44.12 | 0.62 |
| Pr\(_{15}\)Ce\(_{15}\) | 567.1 | 7.73 | 13.24 | 12.31 | 75.55 | 0.74 |
| Pr\(_{10}\)Ce\(_{20}\) | 563.1 | 7.19 | 14.29 | 11.44 | 65.79 | 0.72 |
| Pr\(_{30}\)Ce\(_{10}\) | 567.6 | 8.57 | 15.17 | 15.01 | 79.08 | 0.72 |
| Pr\(_{20}\)Ce\(_{20}\) | 562.9 | 9.04 | 14.82 | 15.81 | 81.94 | 0.66 |
| Pr\(_{10}\)Ce\(_{30}\) | 552.2 | 9.71 | 13.09 | 18.78 | 90.81 | 0.73 |
The Pr$_{15}$Ce$_{15}$ ribbon shows an optimal remanence ($B_r = 7.73$ kGs) and maximum magnetic energy product ($\mu_0 BH_{\text{max}} = 12.31$ MGOe) due to better squareness and higher remanence of the hysteresis loop in figure 3(b), although the $H_{cj}$ of the ribbon is not highest. Kinks in the demagnetization curves of the ribbons (except for the Pr$_{10}$Ce$_{20}$ ribbon) in figure 3(b) are attributed to the existence and non-uniform distribution of the $\alpha$-Fe phase in the ribbons because of smaller volume fractions (less than 3%) of $\alpha$-Fe phase as shown in table 1. The region of the $\alpha$-Fe soft magnetic phase would partially exchange-couple to the adjacent (NdPrCe)$_2$Fe$_{14}$B hard magnetic main phase, which reverse incongruously to show a kink in the demagnetization curves. In addition, it should be noted in table 1 that the volume fractions of $\alpha$-Fe phase in the ribbons increased initially and then decreased with an increase in Ce content, which is consistent with the changed tendency for the $B_r$ and ($\mu_0 BH_{\text{max}}$) of the ribbons.

Figure 4 shows the initial magnetization and demagnetization curves of the (Nd$_{0.60}$Pr$_{0.40-y}$Ce$_y$)$_{2.28}$Fe$_{13.58}$B$_{1.14}$ melt-spun ribbons at room temperature. Figure 4(a) shows that the coercivity mechanism of the ribbons is dominant to domain wall pinning [14], which is similar to that of the (Nd$_{0.70}$Pr$_{0.30-x}$Ce$_x$)$_{2.28}$Fe$_{13.58}$B$_{1.14}$ ribbons. With an increase in Ce content, the $B_r$ and ($\mu_0 BH_{\text{max}}$) of the (Nd$_{0.70}$Pr$_{0.30-x}$Ce$_x$)$_{2.28}$Fe$_{13.58}$B$_{1.14}$ ribbons increase, whereas the $H_{cj}$ decreases gradually. It is evidently found in table 2 that the magnetic properties ($B_r$, $H_{cj}$ and ($\mu_0 BH_{\text{max}}$)) of (Nd$_{0.60}$Pr$_{0.40-y}$Ce$_y$)$_{2.28}$Fe$_{13.58}$B$_{1.14}$ ribbons are better than those of (Nd$_{0.70}$Pr$_{0.30-x}$Ce$_x$)$_{2.28}$Fe$_{13.58}$B$_{1.14}$ ribbons, although kinks in demagnetization curves were observed due to higher volume fractions of $\alpha$-Fe phase in the ribbons. In particular, the Pr$_{10}$Ce$_{30}$ ribbon with a higher Ce content shows optimal magnetic properties ($H_{cj} = 13.09$ kOe, $B_r = 9.71$ kGs, ($\mu_0 BH_{\text{max}}$) = 18.78 MGOe), which is attributed to the higher remanence and better squareness of the hysteresis loop. The reason could be that the Pr$_{10}$Ce$_{30}$ ribbon shows a different phase constitution from the other ribbons, which consists of an additional CeFe$_2$ phase, except for the (NdPrCe)$_2$Fe$_{14}$B main phase and the $\alpha$-Fe minor phase. According to the experimental results reported by Zhang et al [36] and Jin et al [37], the REFe$_2$ phase tends to form as the grain boundary phase in Nd–Ce–Fe–B magnets with a high Ce content. The formation of the REFe$_2$ phase is

![Figure 4. Initial magnetization curves (a) and demagnetization curves (b) of (Nd$_{0.60}$Pr$_{0.40-y}$Ce$_y$)$_{2.28}$Fe$_{13.58}$B$_{1.14}$ ($y = 0.10, 0.20, 0.30$) melt-spun ribbons at room temperature.](image-url)
considered harmful to the magnetic properties of Nd–Ce–Fe–B magnets because of its intrinsic magnetic properties. However, its lower melting temperature favors liquid-phase sintering of magnets. Therefore, the REFe₂ phase formation is vital to promote the formation of a continuous intergranular phase along the grain boundary, which can explain the good magnetic properties of the Nd–Ce–Fe–B magnets with the RE₂Fe phase [36, 37].

As shown in table 2, the remanent ratios between the remanent magnetization (\(M_r\)) and saturation magnetization (\(M_s\)) of the \((\text{Nd}_{0.70}\text{Pr}_{0.30-x}\text{Ce}_x)_{2.28}\text{Fe}_{13.58}\text{B}_{1.14}\) and \((\text{Nd}_{0.60}\text{Pr}_{0.40-y}\text{Ce}_y)_{2.28}\text{Fe}_{13.58}\text{B}_{1.14}\) ribbons are larger than 0.5, which suggests the existence of intergranular exchange coupling in the ribbons [14]. The magnetic performance, including the coercivity (\(H_c\)), remanence (\(B_r\)) and maximum magnetic energy product \((BH)_{max}\) of the \(\alpha\)-Fe/(NdPrCe) \(\text{Fe}_{14}\) alloys, are dependent on the phase formation (e.g., \((\text{NdPrCe})_{2-x}\text{Fe}_{14}\) main phase and \(\alpha\)-Fe/Ce₂Fe minor phases as grain boundary phases) in the melt-spun ribbons [14]. As shown in table 1, both \((\text{Nd}_{0.70}\text{Pr}_{0.30-x}\text{Ce}_x)_{2.28}\text{Fe}_{13.58}\text{B}_{1.14}\) and \((\text{Nd}_{0.60}\text{Pr}_{0.40-y}\text{Ce}_y)_{2.28}\text{Fe}_{13.58}\text{B}_{1.14}\) ribbons show smaller volume fractions of \(\alpha\)-Fe phase (less than 3.5%), except for the \(\text{Pr}_{10}\text{Ce}_{30}\) ribbon, which shows the volume fraction of \(\alpha\)-Fe phase to be 6.4%. It indicates that all ribbons process strong intergranular exchange coupling, which could be the reason for the improvement of magnetic properties.

Thermogravimetric experiments under a constant magnetic field were performed to determine the Curie temperatures of the ribbons using differential thermal analysis (DTA) for 300–800 K. Figure 5(a) presents thermogravimetric curves of the \((\text{Nd}_{0.70}\text{Ce}_{x}\text{Pr}_{0.30-x})_{2.28}\text{Fe}_{13.58}\text{B}_{1.14}\) \((x = 0.10, 0.15, 0.20)\) and \((\text{Nd}_{0.60}\text{Ce}_{y}\text{Pr}_{0.40-y})_{2.28}\text{Fe}_{13.58}\text{B}_{1.14}\) \((y = 0.10, 0.20, 0.30)\) ribbons. During heating, thermogravimetric curves of the ribbons show a sudden mass change because of a magnetic phase transition from the ferromagnetic to paramagnetic state. The Curie temperatures \((T_c)\) of the ribbons are the minimum temperatures from the derivative thermogravimetric curves \((dW/dT)\), as shown in figure 5(b) and table 2. The Curie temperatures \((T_c)\)
of the Pr$_{30}$Ce$_{10}$, Pr$_{20}$Ce$_{20}$ and Pr$_{10}$Ce$_{30}$ ribbons are 567.6 K, 562.9 K and 552.2 K, respectively, whereas those of the Pr$_{20}$Ce$_{10}$, Pr$_{30}$Ce$_{15}$ and Pr$_{10}$Ce$_{20}$ ribbons are 570.2 K, 567.1 K and 563.1 K, respectively. It is expected that the Curie temperatures of the (Nd$_{0.70}$Pr$_{0.30}$–x)Ce$_{x}$2.28Fe$_{13.58}$B$_{1.14}$ and (Nd$_{0.60}$Pr$_{0.40}$–y)Ce$_{y}$2.28Fe$_{13.58}$B$_{1.14}$ ribbons decrease slightly compared with that (583 K) of Nd$_2$Fe$_{14}$B [28]. The Curie temperatures of the ribbons (except for Pr$_{10}$Ce$_{30}$ Ribbon) are higher than the lower Curie temperatures (557 K and 423 K) of Pr$_2$Fe$_{14}$B and Ce$_2$Fe$_{14}$B [28], which could favor the thermal stability of Nd–Pr–Ce–Fe–B magnets at high operating temperatures.

4. Conclusions

Based on experimental investigations of the phase formation and magnetic properties of (Nd$_{0.70}$Pr$_{0.30}$–x)Ce$_{x}$2.28Fe$_{13.58}$B$_{1.14}$ and (Nd$_{0.60}$Pr$_{0.40}$–y)Ce$_{y}$2.28Fe$_{13.58}$B$_{1.14}$ alloys, the following conclusions were drawn:

1. The XRD results reveal all alloys annealed at 1173 K for 360 h contain both (NdPrCe)$_2$Fe$_{14}$B main phase with a tetragonal Nd$_2$Fe$_{14}$B-type structure and α-Fe minor phase, except for the Pr$_{10}$Ce$_{30}$ alloy, which consists of an additional CeFe$_2$ phase.

2. Magnetic measurements show that the $H_J$ of the (Nd$_{0.70}$Pr$_{0.30}$–x)Ce$_{x}$2.28Fe$_{13.58}$B$_{1.14}$ ribbons increases gradually with an increase in Ce content, whereas $B_B$ and $(BH)_{max}$ increase first and then decrease. The $B_H$ and $(BH)_{max}$ of the (Nd$_{0.60}$Pr$_{0.40}$–y)Ce$_{y}$2.28Fe$_{13.58}$B$_{1.14}$ ribbons increase, whereas the $H_J$ decreases with an increase in Ce content. The Curie temperatures of all ribbons decrease slightly with an increase in Ce substitution, which results from the lower Curie temperatures of Pr$_2$Fe$_{14}$B and Ce$_2$Fe$_{14}$B.

3. Optimal magnetic properties ($H_J = 13.09$ kOe, $B_B = 9.71$ kGs and $(BH)_{max} = 18.78$ MGOe) of the Pr$_{10}$Ce$_{30}$ ribbon with a higher Ce content were achieved. Therefore, the optimization of alloy composition and phase formation of the Nd–Pr–Ce–Fe–B melt-spun ribbons could improve their magnetic properties.

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