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$Dy_{1-x}Pr_x(Fe_{0.35}Co_{0.55}B_{0.1})_2$ ($0 \leqslant x \leqslant 1$) Laves compounds with a cubic $MgCu_2$-type structure were synthesized by arc melting and subsequent annealing. The lattice parameter of the Laves compounds linearly increases, while the Curie temperature T_C decreases with increasing Pr content. The saturation magnetization M_s at 5 K or 295 K for the $Dy_{1-x}Pr_x(Fe_{0.35}Co_{0.55}B_{0.1})_2$ alloys decreases to reach a minimum, then increases with increasing Pr content. The composition for magnetic moment compensation is about $x=0.55$ at 295 K and $x=0.65$ at 5 K, respectively. The magnetostriction $\lambda_\parallel$ or $\lambda_\perp$ at room temperature was investigated either parallel or perpendicular to the applied field using a standard strain gauge technique. © *2006 American Institute of Physics*.
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I. INTRODUCTION

RFe_2 ($R \equiv$ rare earth) magnetostrictive Laves compounds possess good characteristics such as large magnetostriction, high magnetomechanical coupling coefficient, very short response time (from applying a magnetic field to getting a strain), and so on. $TbFe_2$ is an example, which has the largest room-temperature magnetostriction of any known material. $TbFe_2$ also has a large anisotropy, which is a hindrance to its technical usefulness because a large field is required to obtain the large magnetostriction.[1] $PrFe_2$ should have a larger magnetostriction than $TbFe_2$ based on the prediction of the single-ion model.[1] Moreover, the magnetocrystalline anisotropy of $PrFe_2$ is much smaller than that of $TbFe_2$.[2] But because of the large radius of Pr^{3+}, a pure $PrFe_2$ compound with a Laves phase structure cannot be formed at ambient pressure.[3] Only a partial Pr substitution in stable RFe_2 compounds is possible. However, when the Pr content is over 20 at. % for rare earths, a single phase cannot be obtained in $(R,Pr)Fe_2$ systems.[1] Wang *et al.*[4] and Guo *et al.*[5] found that the partial substitution of Co for Fe can stabilize the Pr content in the Laves phase. Ren *et al.* reported that the introduction of a small amount of B is beneficial to the formation of the Laves phase with a high Pr content.[6–8] Recently, Ren *et al.* proved phenomenologically that the anisotropy of Pr^{3+} may be compensated by that of Dy^{3+} using a single-ion approach.[9] In this paper, the structural and magnetic properties of magnetostrictive compounds $Dy_{1-x}Pr_x(Fe_{0.35}Co_{0.55}B_{0.1})_2$ ($0 \leqslant x \leqslant 1$) have been investigated.

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II. EXPERIMENTAL PROCEDURE

All polycrystalline samples of $Dy_{1-x}Pr_x(Fe_{0.35}Co_{0.55}B_{0.1})_2$ alloys with $x=0$, 0.4, 0.6, 0.7, 0.8, 0.9, and 1.0 were prepared by arc melting the appropriate constituent metals in a high-purity argon atmosphere. The purities of the constituents are 99.9% for Dy, Pr, and B and 99.8% for Fe and Co. The ingots were homogenized at 700 °C for 7 days in a high-purity argon atmosphere. X-ray-diffraction (XRD) data were recorded at room temperature with Cu K_α radiation in a D/max-2500pc diffractrometer. Temperature dependencies of ac initial susceptibility χ_{ac} were recorded at $H=2$ Oe. The magnetization at 5 and 295 K of the compounds was measured using a superconducting quantum interference device magnetometer at fields of up to 50 kOe. The magnetostriction $\lambda_\parallel$ or $\lambda_\perp$ was measured at room temperature either parallel or perpendicular to the applied fields of up to 12 kOe using a standard strain gauge technique.

III. RESULTS AND DISCUSSION

XRD patterns of homogenized $Dy_{1-x}Pr_x(Fe_{0.35}Co_{0.55}B_{0.1})_2$ alloys are shown in Fig. 1. All the homogenized alloys consist predominantly of the cubic Laves phase with a $MgCu_2$-type structure, with minor impurity phases. The (h,k,l) of the Laves phase was also indexed in Fig. 1. The formation of the Laves phase with a high Pr content is ascribed to the substitution of Co or B for Fe.[4–8]

The dependence of the lattice parameter a on the nominal Pr content for the Laves phases in $Dy_{1-x}Pr_x(Fe_{0.35}Co_{0.55}B_{0.1})_2$ alloys is shown in Fig. 2(a). The lattice parameter linearly increases from 0.7275 nm for the

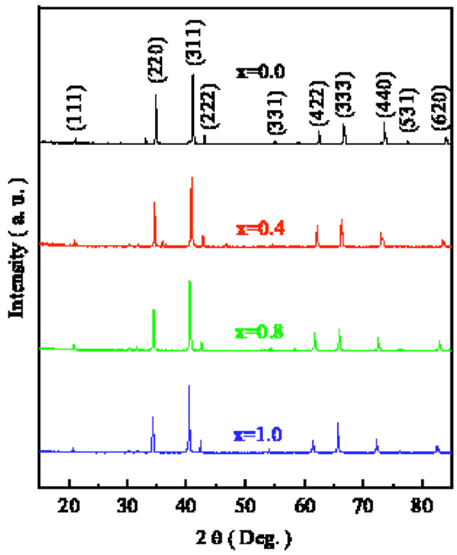

FIG. 1. XRD patterns of homogenized $Dy_{1-x}Pr_x(Fe_{0.35}Co_{0.55}B_{0.1})_2$ alloys.

Pr-free compound to 0.7383 nm for the Dy-free one with increasing Pr content. The linear regularity suggests that the amount of the impurities is very small and may be neglected. The composition dependence of Curie temperature of the $Dy_{1-x}Pr_x(Fe_{0.35}Co_{0.55}B_{0.1})_2$ Laves compounds is given in Fig. 2(b). The Curie temperature T_C of the Pr-free $Dy(Fe_{0.35}Co_{0.55}B_{0.1})_2$ compound is 546 K. This value is consistent with the Curie temperature T_C of the Laves compound with the close composition.[10] When $0.6 \leqslant x \leqslant 1$, T_C linearly decreases with increasing x. The T_C of the Pr-free compound is not in the line, which may be ascribed to some different nature between Pr and other rare-earth ions.[11,12] It is a pity that the T_C of $Dy_{0.6}Pr_{0.4}(Fe_{0.35}Co_{0.55}B_{0.1})_2$ is not detectable within the accuracy of the present work. The possible reason is that the magnetization at T_C is very small due to the moment compensation.

The magnetization curves at 5 K for all the $Dy_{1-x}Pr_x(Fe_{0.35}Co_{0.55}B_{0.1})_2$ alloys are presented in Fig. 3. A

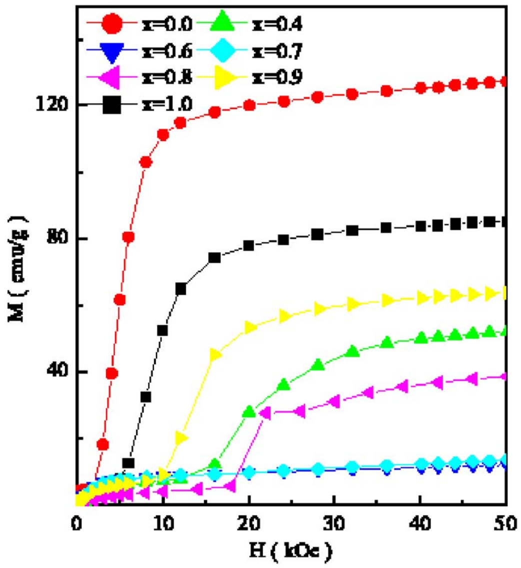

FIG. 3. Magnetization curves of the $Dy_{1-x}Pr_x(Fe_{0.35}Co_{0.55}B_{0.1})_2$ alloys at 5 K.

jump is observed in every magnetization except the ones for the compounds with $x=0.6$ and 0.7, which have a low saturation magnetization M_s. This can be reduced to the large anisotropy of the compounds at low temperatures.[13] The composition dependences of M_s at 5 and 295 K for $Dy_{1-x}Pr_x(Fe_{0.35}Co_{0.55}B_{0.1})_2$ alloys are shown in Fig. 4. M_s at either 5 or 295 K decreases with increasing Pr content and reaches a minimum value. After that, further increasing Pr content increases M_s. This can be understood by the magnetic-moment compensation: the moment of Pr (or Dy) ions aligns parallel (or antiparallel) with the moment of Fe/Co. The composition for magnetic-moment compensation is about $x=0.55$ at 295 K and $x=0.65$ at 5 K, respectively.

Figure 5 shows the room-temperature magnetostriction $\lambda_{\parallel}$ of the $Dy_{1-x}Pr_x(Fe_{0.35}Co_{0.55}B_{0.1})_2$ alloys. The $\lambda_{\parallel}$ for the

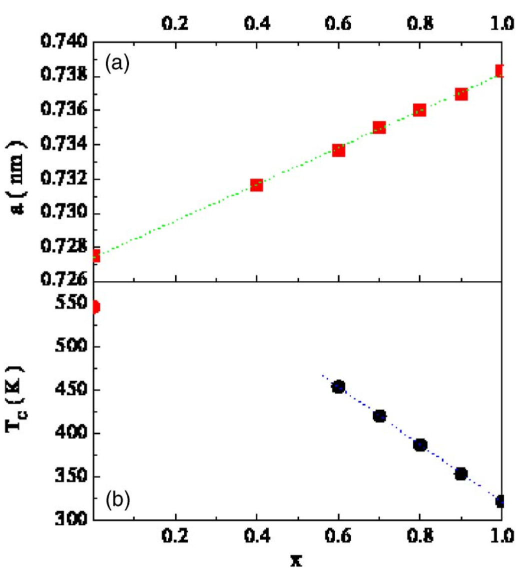

FIG. 2. Composition dependences of (a) lattice parameter a and (b) Curie temperature T_C of $Dy_{1-x}Pr_x(Fe_{0.35}Co_{0.55}B_{0.1})_2$ Laves compounds.

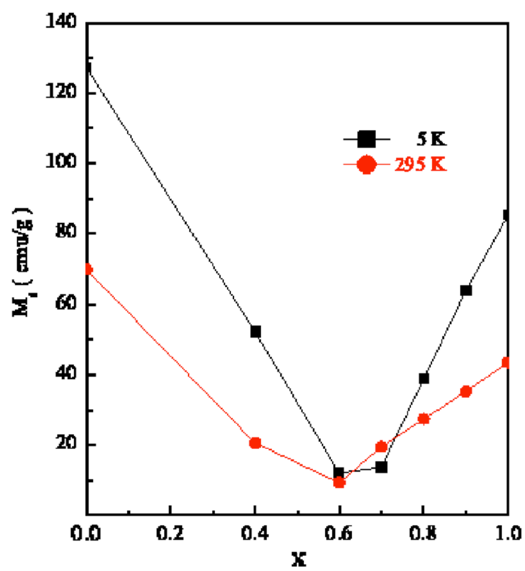

FIG. 4. Composition dependences of saturation magnetization M_s at 5 and 295 K for $Dy_{1-x}Pr_x(Fe_{0.35}Co_{0.55}B_{0.1})_2$ alloys.

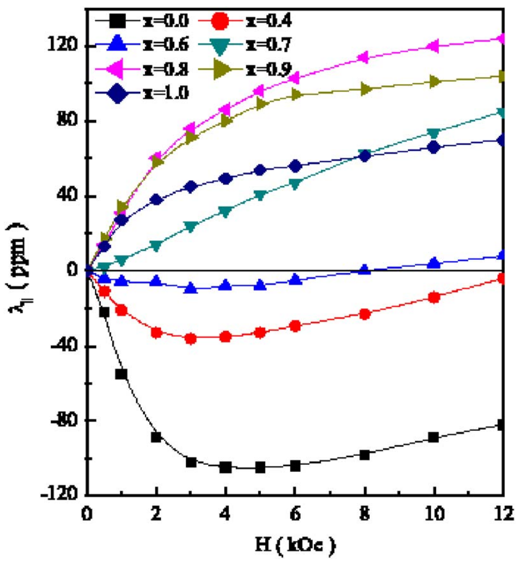

FIG. 5. Magnetic field dependence of $\lambda_{\parallel}$ at room temperature for polycrystalline $Dy_{1-x}Pr_x(Fe_{0.35}Co_{0.55}B_{0.1})_2$ alloys.

alloys with $0 \leqslant x \leqslant 0.6$ is negative and initially goes to a negative maximum, then increases with increasing H. This character is in agreement with the abnormal magnetostriction of $DyFe_2$ and $DyCo_2$.[1,14] The $\lambda_{\parallel}$ for the $Dy_{0.4}Pr_{0.6}(Fe_{0.35}Co_{0.55}B_{0.1})_2$ alloy changes its sign when $H \geqslant 10$ kOe. It can be understood by the competition between the normal magnetostriction for $PrFe_2$ and $PrCo_2$ and the abnormal magnetostriction for $DyFe_2$ and $DyCo_2$. The $\lambda_{\parallel}$ for the alloys with $x \geqslant 0.7$ is positive and increases with increasing H. $\lambda_{\parallel}$ decreases with increasing Pr content when $0.8 \leqslant x \leqslant 1$ and $Pr(Fe_{0.35}Co_{0.55}B_{0.1})_2$ alloys donot possess large magnetostriction. It may be ascribed to the decrease of the Curie temperature. For instance, T_C is only 322 K for $Pr(Fe_{0.35}Co_{0.55}B_{0.1})_2$. The features of $\lambda_{\perp}$ are opposite to those of $\lambda_{\parallel}$ for all the alloys (not shown).

IV. CONCLUSION

In conclusion, the structural and magnetic properties of magnetostrictive compounds $Dy_{1-x}Pr_x(Fe_{0.35}Co_{0.55}B_{0.1})_2$ $(0 \leqslant x \leqslant 1)$ have been investigated. The lattice parameter of the Laves compounds linearly increases with increasing Pr content. The Curie temperature T_C decreases when x is increased from 0 to 1. In the range of $0.6 \leqslant x \leqslant 1$, the decrement is linearly dependent of the Pr content. The saturation magnetization M_s at 5 K for the $Dy_{1-x}Pr_x(Fe_{0.35}Co_{0.55}B_{0.1})_2$ compounds decreases and reaches a minimum, then increases with increasing x. The saturation magnetization M_s at 295 K has a similar variation to that at 5 K. The composition for magnetic-moment compensation is about $x=0.54$ at 295 K and $x=0.65$ at 5 K, respectively. The abnormal magnetostriction of the $Dy_{1-x}Pr_x(Fe_{0.35}Co_{0.55}B_{0.1})_2$ alloys with $0 \leqslant x \leqslant 0.6$ originates mainly from that of $DyCo_2$.

ACKNOWLEDGMENTS

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