Journal of Alloys and Compounds 408–412 (2006) 130–132

Journal of ALLOYS AND COMPOUNDS

www.elsevier.com/locate/jallcom

Magnetostriction of $Pr_{0.1}Tb_{0.3}Dy_{0.6}Fe_{2-x}Mn_x$ alloys ($0.0 \leqslant x \leqslant 0.2$)

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Available online 23 May 2005

Abstract

Magnetic properties of single-phase $Pr_{0.1}Tb_{0.3}Dy_{0.6}Fe_{2-x}Mn_x$ alloys have been investigated using X-ray diffraction, A.C. susceptibility, Vibrating Sample Magnetometer and standard strain gauge techniques. The lattice parameter increases and Curie temperature decreases with increasing Mn content. The magnetostriction of $Pr_{0.1}Tb_{0.3}Dy_{0.6}Fe_{2-x}Mn_x$ alloys exhibits the maximum value at $x = 0.10$ in applied magnetic field. The magnetostriction of $Pr_{0.1}Tb_{0.3}Dy_{0.6}Fe_{1.9}Mn_{0.1}$ alloy was measured under compressive stress up to 31 MPa. The experimental results indicate the $Pr_{0.1}Tb_{0.3}Dy_{0.6}Fe_{1.9}Mn_{0.1}$ alloy shows good magnetostrictive properties in low magnetic fields under the compressive stress of 2–16 MPa.

Keywords: Laves phase; Rare earth iron compounds; $Pr_{0.1}Tb_{0.3}Dy_{0.6}Fe_{2-x}Mn_x$ alloys; Magnetic properties; Magnetostriction

1. Introduction

In 1974, Clark found the pseudobinary compound Terfenol-D [1], which has $MgCu_2$-type Laves phase structure and shows great potentials for application in actuators and transducers. Since then, other pseudobinary compounds have been studied intensively [2,3]. According to the single-ion model, the $PrFe_2$ compound has larger magnetostriction than $TbFe_2$ and $DyFe_2$ at 0 K. So, Pr-based compounds may be the candidate materials for magnetostriction application. But the $PrFe_2$ compound cannot be fabricated at ambient pressure because of the bigger atomic radius of Pr. It was found that the $Pr_{0.1}Tb_{0.3}Dy_{0.6}Fe_2$ alloy has larger magnetostriction and low magnetocrystalline anisotropy energy [4]. It has been reported that Mn substitution for Fe can obtain a larger magnetostriction [5], and the magnetic properties of $R(TMn)_2$ (R: rare earth and T: transitional metal) are sensitive to external parameters such as the applied pressure, applied magnetic field and so on [6–8]. In this paper, the magnetic properties and magnetostriction of $Pr_{0.1}Tb_{0.3}Dy_{0.6}Fe_{2-x}Mn_x$ alloys were investigated.

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doi:10.1016/j.jallcom.2005.04.095

2. Experiment

The $Pr_{0.1}Tb_{0.3}Dy_{0.6}Fe_{2-x}Mn_x$ ($0.00 \leqslant x \leqslant 0.20$) alloys were prepared by arc melting under a high purified-argon atmosphere. The purities of rare earth, Fe and Mn were 99.9, 99.99 and 99.8%, respectively. Five and 10% excess rare-earth and metal Mn relative to the ideal composition were added to compensate for the volatility of rare-earth and metal Mn. The constituent metals were remelted four times. Then the samples were wrapped in a stainless steel foil and vacuum annealed in a sealed quartz capsule at 850°C for 72 h.

The phase purity was performed by X-ray diffraction (Philips X'Pert MPD) using Cu Kα radiation at room temperature. The lattice parameters were determined by least-squares fitting to X-ray pattern, and the accuracy is estimated to be ±0.002 Å. Curie temperatures were determined by measuring the temperature dependence on A.C. susceptibility. A Vibrating Sample Magnetometer measured the magnetization at room temperature. The anisotropic magnetostriction was measured using a standard strain gauge in directions of parallel ($\lambda_{//}$) and perpendicular ($\lambda_{\perp}$) to the magnetic field up to 11 kOe at room temperature. A bar of 1.5 mm × 1.5 mm × 3 mm was cut from $Pr_{0.1}Tb_{0.3}Dy_{0.6}Fe_{1.9}Mn_{0.1}$ alloy, and compressive stress up to 31 MPa was applied to the bar in direction parallel to magnetic field. The magnetostriction λ of the bar was measured in direction parallel to magnetic field.

3. Results and discussion

X-ray diffraction patterns shows that all the $Pr_{0.1}Tb_{0.3}Dy_{0.6}Fe_{2-x}Mn_x$ alloys are single Laves phase with $MgCu_2$-type structure. The values of lattice parameter (a) and Curie temperature (T_C) of $Pr_{0.1}Tb_{0.3}Dy_{0.6}Fe_{2-x}Mn_x$ alloys are listed in Table 1. The lattice parameter increases linearly with increasing Mn content because the atomic radius of Mn is larger than that of Fe. The substitution of Mn for Fe results in a linear decrease of Curie temperature from 651 to 553 K. The decrease of T_C presumably results from antiferromagnetic Fe–Mn interactions [9].

The magnetization isotherms of $Pr_{0.1}Tb_{0.3}Dy_{0.6}Fe_{2-x}Mn_x$ alloys are shown in Fig. 1. The saturation magnetization M_s was taken as the value of magnetization at the magnetic field of 10 kOe and the values of M_s are listed in Table 1. It can be seen that M_s shows a decreasing tendency while increases slightly at $x = 0.10$.

The dependence of anisotropic magnetostriction ($\Delta\lambda = \lambda_{//} - \lambda_{\perp}$) on magnetic field for $Pr_{0.1}Tb_{0.3}Dy_{0.6}Fe_{2-x}Mn_x$ alloys is represented in Fig. 2. It can be clearly seen that the magnetostriction of $Pr_{0.1}Tb_{0.3}Dy_{0.6}Fe_{2-x}Mn_x$ alloys increases from $x = 0.00$ to 0.10, while decreases when $0.10 \leqslant x \leqslant 0.20$. It should be noted that the alloys with $0.05 \leqslant x \leqslant 0.15$ show larger magnetostriction than $Pr_{0.1}Tb_{0.3}Dy_{0.6}Fe_2$ alloy in low magnetic fields. A maximum magnetostriction of 1521 ppm is obtained under the magnetic field of 11 kOe at $x = 0.1$. The magnetostriction of low Mn content alloys does not reach saturation, while for high Mn content alloys it reaches saturation.

The dependence of magnetostriction on magnetic field for $Pr_{0.1}Tb_{0.3}Dy_{0.6}Fe_{1.9}Mn_{0.1}$ alloy under different compressive stress is shown Fig. 3. It can be obviously seen that the magnetostriction increases a lot when pre-stress was applied. At the magnetic field of 10 kOe, the magnetostriction increases from 1037 to 1754 ppm with the compressive stress increasing from 0 to 31 MPa. The $Pr_{0.1}Tb_{0.3}Dy_{0.6}Fe_{1.9}Mn_{0.1}$ alloy shows larger magnetostriction in low magnetic fields under the compressive stress of 2–16 MPa. At the magnetic field of 2.5 kOe, the magnetostriction is 945 ppm at 4 MPa, and much larger than 587 ppm at 0 MPa. When the compressive stress is more than 25 MPa, the magnetostriction at low magnetic fields drops. The $Pr_{0.1}Tb_{0.3}Dy_{0.6}Fe_{1.9}Mn_{0.1}$ alloy shows good magnetostrictive properties under compressive stress.

Table 1
The lattice parameter (a), Curie temperature (T_C) and saturation magnetization (M_s) of $Pr_{0.1}Tb_{0.3}Dy_{0.6}Fe_{2-x}Mn_x$ alloys

x	a (Å)	T_C (K)	M_s (emu/g)
0.00	7.309	651	83.01
0.05	7.321	627	73.53
0.10	7.333	596	76.37
0.15	7.339	570	65.28
0.20	7.347	553	65.22

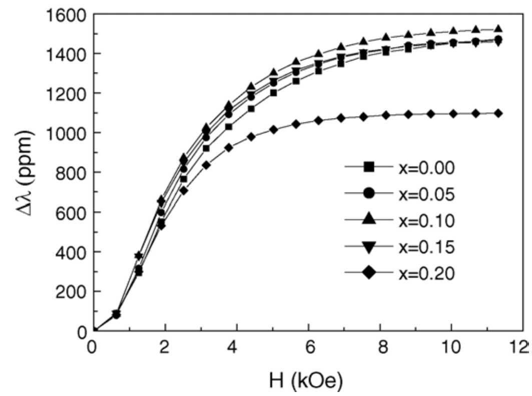

Fig. 2. The dependence of magnetostriction on magnetic field for $Pr_{0.1}Tb_{0.3}Dy_{0.6}Fe_{2-x}Mn_x$ alloys at room temperature.

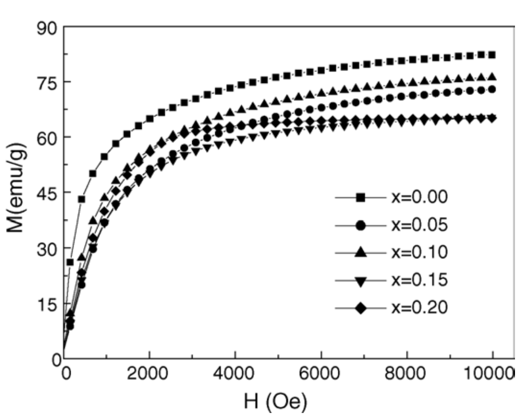

Fig. 1. Magnetization isotherms of $Pr_{0.1}Tb_{0.3}Dy_{0.6}Fe_{2-x}Mn_x$ alloys at room temperature.

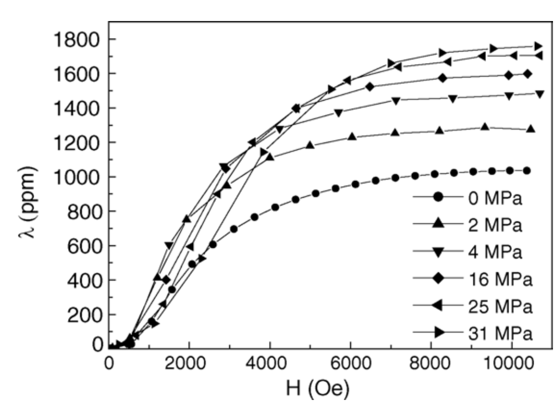

Fig. 3. The dependence of magnetostriction on magnetic field for $Pr_{0.1}Tb_{0.3}Dy_{0.6}Fe_{1.9}Mn_{0.1}$ alloy under different compressive stresses.

4. Conclusion

The single-phase $Pr_{0.1}Tb_{0.3}Dy_{0.6}Fe_{2-x}Mn_x$ alloys were fabricated in this paper. With Mn content increasing, the lattice parameter increases and Curie temperature decreases. The magnetostriction shows the maximum value at $x = 0.1$ in applied magnetic field. Compressive stress up to 31 MPa is applied to a bar cut from $Pr_{0.1}Tb_{0.3}Dy_{0.6}Fe_{1.9}Mn_{0.1}$ alloy. Magnetostriction of the bar at the magnetic field of 10 kOe increases with compressive stress increasing. The bar shows good magnetostrictive properties in low magnetic fields under compressive stress of 2–16 MPa. The $Pr_{0.1}Tb_{0.3}Dy_{0.6}Fe_{1.9}Mn_{0.1}$ alloy has great potential for application.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. 50271023), the Natural Science Foundation of Hebei province and the Key Foundation of Education Ministry (No. 02017).

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