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Structure and magnetostriction of $(Dy_{0.65}Tb_{0.25}Pr_{0.1})(Fe_{1-x}Al_x)_3$ alloys

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Abstract

The structure, Curie temperature and magnetostriction of $(Dy_{0.65}Tb_{0.25}Pr_{0.1})(Fe_{1-x}Al_x)_3$ ($0 \leqslant x \leqslant 0.30$) alloys were investigated using optical microscopy, X-ray diffraction, electron probe microanalysis, vibrating sample magnetometer and standard strain gauge techniques. It was found that these alloys are multiphase. When $x \leqslant 0.10$, the main phase possesses the $PuNi_3$-type rhombohedral structure and becomes $CeNi_3$-type hexagonal when $x > 0.25$. When $0.10 < x \leqslant 0.25$, both structures coexist. A minor phase $(Dy,Tb,Pr)_6(Fe,Al)_{23}$ exists in all alloys, which increases with increasing Al content. The Curie temperature and the room-temperature magnetostriction of the $(Dy_{0.65}Tb_{0.25}Pr_{0.1})(Fe_{1-x}Al_x)_3$ alloys decrease with increasing Al substitution for Fe.

Keywords: Magnetostriction; Aluminium; Iron

1. Introduction

Since the giant magnetostrictive rare earth–iron compounds were found in 1972, extensive investigations have been performed in this field. Clark and co-workers [1,2] systematically investigated the magnetic properties and the magnetostriction of RFe_2 and RFe_3 compounds. Oesterreicher and McNeely [3,4] studied the structural behaviour, phase relationships and low-temperature magnetic properties of $Dy(Fe_{1-x}Al_x)_3$. Oesterreicher [5] also reported the structural behaviour and the phase relationships of $Tb(Fe_{1-x}Al_x)_3$ pseudobinary compounds. In the present investigation, we studied the structure and the magnetostriction of $(Dy_{0.65}Tb_{0.25}Pr_{0.1})(Fe_{1-x}Al_x)_3$ alloys.

2. Experimental procedure

All samples of $(Dy_{0.65}Tb_{0.25}Pr_{0.1})(Fe_{1-x}Al_x)_3$ ($x = 0$, 0.025, 0.05, 0.075, 0.10, 0.15, 0.20, 0.25 and 0.30) were prepared by melting the appropriate amount of the constituent metals in a magneto-controlled arc furnace under a high-purity argon atmosphere. The purities of the metals were Dy, Tb and Pr 99.9%, Fe 99.8% and Al 99.99%. The as-cast button samples were sealed in an evacuated silica tube and homogenized at 1000 °C for 15 days.

X-ray diffraction analysis was performed in a D/max-rA diffractometer with a pyrolytic graphite monochromator using Cu Kα radiation. Electron probe microanalysis (EPMA) was carried out in a Camebax-Micro analyser. The Curie temperature was measured in a vibrating sample magnetometer. The magnetostriction was measured using the standard strain gauge technique in applied fields up to 20 kOe at room temperature. For magnetostriction measurements, cylindrical samples (15 mm × 10 mm diameter) were produced by arc casting in an arc furnace under a high-purity argon atmosphere and homogenized at 1000 °C for 50 h.

3. Results and discussion

The metallographic examination and X-ray diffraction analysis indicate that all annealed samples of $(Dy_{0.65}Tb_{0.25}Pr_{0.1})(Fe_{1-x}Al_x)_3$ alloys contain the R_6M_{23} phase [R = (Dy,Tb,Pr), M = (Fe,Al)], with a Th_6Mn_{23}-type cubic structure. Its amount increases with increasing Al content up to $x = 0.30$. The matrix of the alloys is

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of a $PuNi_3$-type rhombohedral structure for $x \leqslant 0.10$ (7.5 at.% Al), and of $CeNi_3$-type hexagonal structure for $x > 0.25$ (18.75 at.% Al). In the range of $0.10 < x \leqslant 0.25$, both structures coexist. EPMA data (average values) of the phases in $(Dy_{0.65}Tb_{0.25}Pr_{0.1})Fe_3$ alloy are shown in Table 1. It reveals that the homogeneity region of the RFe_3 pseudobinary compound is slightly shifted to the rare earth-rich side of the stoichiometric composition and, consequently, the stoichiometric $(Dy_{0.65}Tb_{0.25}Pr_{0.1})Fe_3$ alloy contains some R_6Fe_{23} phase. Van der Goot and Buschow [6] reported that the as-cast sample of 75 at.% Fe in the Dy–Fe binary system was single phase and $DyFe_3$ was a congruently melting compound. Oesterreicher [5] investigated the structural behaviour of the $TbFe_3$–$TbAl_3$ pseudobinary section and reported that the annealed $TbFe_3$ sample was of $PuNi_3$-type structure with small amounts of a second phase. The second phase was identified as Tb_6Fe_{23} with Th_6Mn_{23}-type cubic structure. The amount of Th_6Mn_{23}-type phase increased with increasing substitution of Al for Fe. The matrix of alloys with 10–25 at.% Al contained small amounts of the $PuNi_3$-type $Tb(Fe,Al)_3$ phase and a $CeNi_3$-type hexagonal phase or one with a closely related structure. The present result is essentially consistent with that of Oesterreicher [5]. It is evident that this structural change arose from the partial substitution of Tb and Pr for Dy. Table 2 shows the structure of the principal phase in $(Dy_{0.65}Tb_{0.25}Pr_{0.1})(Fe_{1-x}Al_x)_3$ alloys. All these alloys contain small amount of minor phase R_6Mn_{23}. The radius of the Pr atom is larger than either that of Tb or Dy. Substitution of Pr and Tb for Dy will increase the lattice parameters of RFe_3. The lattice parameter a of the rhombohedral phase in $DyFe_3$ and $TbFe_3$ alloys is 0.5118 and 0.5135 nm, respectively. The lattice parameter a for the rhombohedral phase $(Dy_{0.65}Tb_{0.25}Pr_{0.1})Fe_3$ is 0.5133 nm, which is larger than that of $DyFe_3$ and close to that of the $TbFe_3$.

The effect of Al substitution for Fe on the Curie temperature of $(Dy_{0.65}Tb_{0.25}Pr_{0.1})(Fe_{1-x}Al_x)_3$ alloys is shown in Fig. 1. It decreases steadily with increasing Al substitution when $x \leqslant 0.15$ and its decrease becomes slower when $x > 0.15$. The magnetostriction of $(Dy_{0.65}Tb_{0.25}Pr_{0.1})(Fe_{1-x}Al_x)_3$ alloys has been measured along directions parallel ($\lambda_{\parallel}$) and perpendicular ($\lambda_{\perp}$) to the applied magnetic field. The composition dependence and the magnetic field dependence of magnetostriction are shown in Figs. 2 and 3, respectively. It is evident that the magnetostriction of $(Dy_{0.65}Tb_{0.25}Pr_{0.1})(Fe_{1-x}Al_x)_3$ alloys with $x \leqslant 0.10$ slowly

Table 1
Phases of $(Dy_{0.65}Tb_{0.25}Pr_{0.1})Fe_3$ alloy identified by EPMA

Feature	Composition (at.%)				Phase identified
	Dy	Tb	Pr	Fe	
Matrix	16.48	6.46	2.77	74.29	RFe_3
Dark phase	13.74	5.63	2.50	78.13	R_6Fe_{23}

Table 2
Structure and lattice parameters of the main phase in $(Dy_{0.65}Tb_{0.25}Pr_{0.1})(Fe_{1-x}Al_x)_3$ alloys homogenized at 1000 °C for 15 days

x (at.%)	Structure of main phase(s)	Lattice parameter	
		a (nm)	c (nm)
0 (0.00)	$PuNi_3$-type rhombohedral	0.5133	2.4575
0.05 (3.75)	$PuNi_3$-type rhombohedral	0.5148	2.4665
0.10 (7.50)	$PuNi_3$-type rhombohedral	0.5166	2.4757
0.15 (11.25)	Coexistence of $PuNi_3$-type rhombohedral and $CeNi_3$-type hexagonal phases		
0.20 (15.00)			
0.25 (18.75)			
0.30 (22.50)	$CeNi_3$-type hexagonal	0.5229	1.6738

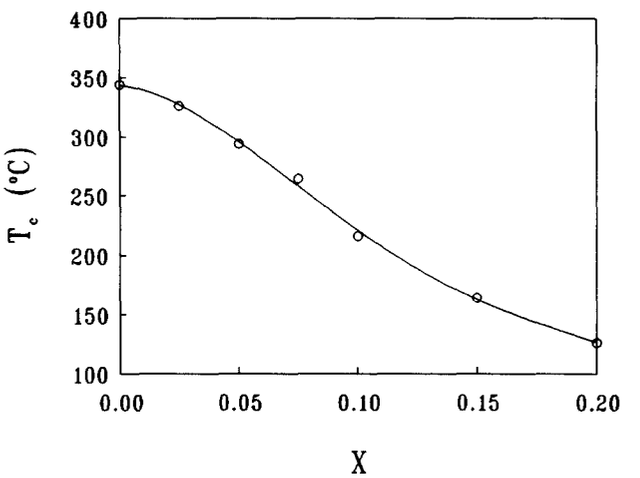

Fig. 1. Curie temperature T_c vs. Al content x of $(Dy_{0.65}Tb_{0.25}Pr_{0.1})(Fe_{1-x}Al_x)_3$ alloys.

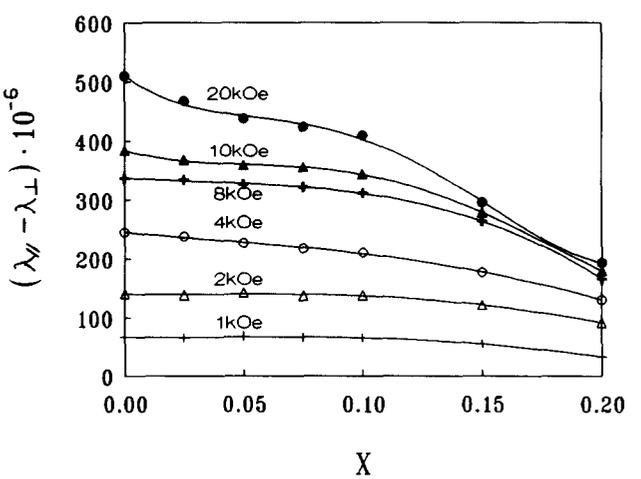

Fig. 2. Composition dependence of magnetostriction for annealed $(Dy_{0.65}Tb_{0.25}Pr_{0.1})(Fe_{1-x}Al_x)_3$ alloys.

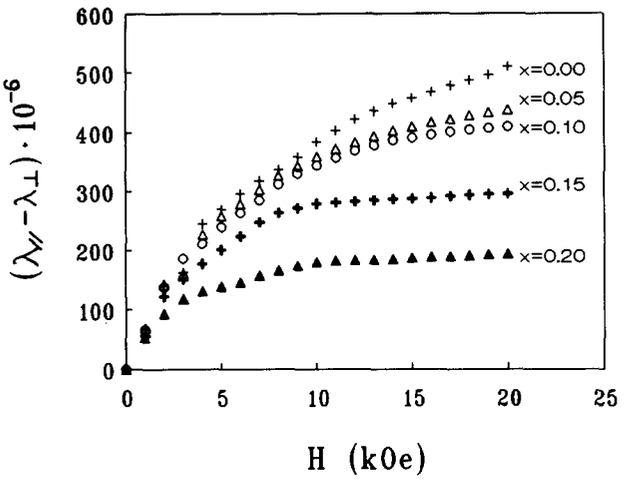

Fig. 3. Magnetic field dependence of magnetostriction for annealed $(Dy_{0.65}Tb_{0.25}Pr_{0.1})(Fe_{1-x}Al_x)_3$ alloys.

decreases or remains almost unchanged with increasing Al content at applied fields larger or lower than 3.0 kOe, respectively. However, the magnetostriction of these alloys with $x > 0.10$ decreases considerably with increasing Al concentration at all applied fields. The magnitude of the room-temperature magnetostriction in the R_6Fe_{23} compounds is smaller than that in the RFe_3 compounds [1,2]. Metallographic examination and X-ray diffraction analysis indicate that the amount of the minor phase $(Dy,Tb,Pr)_6(Fe,Al)_{23}$ increases with increasing Al concentration, and the $PuNi_3$-type rhombohedral structure of the major phase $(Dy,Tb,Pr)(Fe,Al)_3$ becomes unstable and another phase with a $CeNi_3$-type hexagonal structure emerges when $x > 0.10$. Therefore, the samples with $x > 0.10$ consist of three phases, and their magnetostriction is reduced owing to the hindrance of rotation of domains and motion of domain walls by the existing minor phases, phase boundaries and grain boundaries [7]. In the present investigation the magnetostriction of the $(Dy,Tb,Pr)Fe_3$ is 500.0×10^{-6} at 20 kOe. This value is in agreement with that reported for $DyFe_3$ [1,2].

4. Concluding remarks

The matrix of $(Dy_{0.65}Tb_{0.25}Pr_{0.1})(Fe_{1-x}Al_x)_3$ alloys with $x \leqslant 0.10$ possesses a $PuNi_3$-type rhombohedral structure, and is of a $CeNi_3$-type hexagonal structure when $x > 0.25$. With $0.10 < x \leqslant 0.25$, both structures coexist. The common minor phase in these alloys is R_6Mn_{23}. It possesses a Th_6Mn_{23}-type cubic structure, the amount of which increases with increasing Al content. The Curie temperature and the high magnetic field magnetostriction behave in the opposite way with respect to Al content. The magnetostriction in a low magnetic field ($H < 3$ kOe) remains almost unchanged, however, with increasing Al content when $x \leqslant 0.10$.

Acknowledgment

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