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Journal of Alloys and Compounds 414 (2006) 276–281

Journal of ALLOYS AND COMPOUNDS

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# Magnetostriction of $Tb_{0.36}Dy_{0.64}(Fe_{1-x}Co_x)_2$ ($x = 0$–$0.20$) ⟨1 1 2⟩-oriented crystals

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Received 15 March 2005; received in revised form 14 July 2005; accepted 18 July 2005
Available online 26 August 2005

**Abstract**

⟨1 1 2⟩-Oriented crystals of the highly magnetostrictive alloys $Tb_{0.36}Dy_{0.64}(Fe_{1-x}Co_x)_2$ ($x = 0$–$0.20$) and $Tb_{0.3}Dy_{0.7}Fe_2$ have been prepared by zone melting directional solidification method with growth velocities of 240 and 600 mm/h. It is found that ⟨1 1 2⟩-oriented crystals were formed with dendritic-solidified morphologies. Narrower lamellar spacing is observed in samples obtained with higher growth velocity. Magnetostrictive properties were measured under various compressive pre-stresses at room temperature (20 °C), elevated temperature (100 °C) and cryogenic temperature (−80 °C). Magnetostriction "jump" effect is less obvious in all $Tb_{0.36}Dy_{0.64}(Fe_{1-x}Co_x)_2$ ⟨1 1 2⟩-oriented crystals at −80 °C than at 20 and 100 °C. The measurement results reveal that large magnetostriction in the ⟨1 1 2⟩-oriented polycrystalline materials of $Tb_{0.36}Dy_{0.64}(Fe_{1-x}Co_x)_2$ can be retained in a wide temperature range from −80 to 100 °C.


*PACS:* 75.80.+q; 74.25.Ha; 75.30.Gw

*Keywords:* Magnetostriction; X-ray diffraction; Oriented crystal; Magnetic measurements

## 1. Introduction

In the last decades, Terfenol-D ($Tb_{0.3}Dy_{0.7}Fe_2$) has attracted much attention due to its giant magnetostriction and low magnetocrystalline anisotropy at room temperature [1]. The easy magnetization direction is ⟨1 1 1⟩ for temperatures above the spin reorientation temperature $T_r$, and turns to the ⟨1 0 0⟩ direction when the temperature is below $T_r$ [2]. Giant magnetostriction only occurs for temperatures higher than $T_r$ because $\lambda_{111}$ is far larger than $\lambda_{100}$ [1]. Some research has been reported on the substitution of other 3d metals such as Ni, Co, and Mn for Fe in $Tb_xDy_{1-x}Fe_2$ compounds in order to improve their magnetostrictive properties [2–4]. It was found that small amounts of Co substitution can increase the Curie temperature $T_C$, while Mn or Ni substitution cause a decrease of $T_C$ in $Tb_xDy_{1-x}(Fe_{1-y}T_y)_2$ (T = Co, Ni, Mn) compounds. It is possible to tailor an improved system of Laves compounds, $Tb_xDy_{1-x}(Fe_{1-y}Co_y)_2$ to obtain optimum magnetostrictive properties over a wide temperature range, because an increase of $x$ causes a drastic decrease of the spin reorientation temperature $T_r$ [4].

Because of the strongly magnetostrictive anisotropy, ⟨1 1 1⟩-oriented rods should exhibit excellent magnetostriction in $Tb_xDy_{1-x}(Fe_{1-y}Co_y)_2$ compounds. Previous studies have established that it is fairly easy to prepare ⟨1 1 2⟩-oriented $Tb_{0.3}Dy_{0.7}Fe_2$ rods that exhibit satisfactory magnetostrictive properties by means of float zone technique [5] and zone melting technique [6]. Verhoeven et al. found that the dendrites of $Tb_{0.3}Dy_{0.7}Fe_2$ rods are thin parallel sheets, which grow with a primary direction of ⟨1 1 2⟩ and sheet planes of {1 1 1} [5]. Our previous work has shown that ⟨1 1 0⟩-oriented crystals of $Tb_{0.36}Dy_{0.64}(Fe_{1-y}Co_y)_2$ can be obtained by means of zone melting with high growth velocities and exhibit giant magnetostriction over a wide temperature range [7].

In this paper, we have prepared ⟨1 1 2⟩-oriented $Tb_{0.36}Dy_{0.64}(Fe_{1-x}Co_x)_2$ ($x = 0$–$0.20$) compounds with high

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doi:10.1016/j.jallcom.2005.07.033

growth velocities of 240 and 600 mm/h. The microstructures and magnetostrictive properties of $Tb_{0.36}Dy_{0.64}(Fe_{1-x}Co_x)_2$-oriented crystals were investigated and compared with $Tb_{0.3}Dy_{0.7}Fe_2$ ⟨1 1 2⟩-oriented crystals grown with 720 mm/h. The relations between magnetostrictive properties and ⟨1 1 2⟩ orientation degree, lamellar spacing and temperature are discussed.

## 2. Experiments

The starting materials of the objective composition $Tb_{0.36}Dy_{0.64}(Fe_{1-x}Co_x)_2$ ($x = 0$–0.20) and $Tb_{0.3}Dy_{0.7}Fe_2$ were prepared from Tb, Dy, Fe with a purity of 99.9% and Co with a purity of 99.8%. The metals were alloyed directly by means of arc melting under a high-purity argon atmosphere then arc cast into rods with a diameter of 6.8 mm. Grain aligned rods with a length of about 100 mm were grown in an $Al_2O_3$ crucible by a self-made zone melting crystal growth device. A super high temperature gradient about 500 °C/cm can be obtained at the solidification front by using Ga–In liquid metal in the furnace to cool the sample. The oriented rods with a diameter of 7.2 mm were prepared with velocities of 240, 600 and 720 mm/h. Sections with 5 mm thickness were cut from the oriented rods for metallographic examination and analyzed with a Regaku D/max 2200 pc X-ray diffractometer with Cu kα radiation to check their axial grain orientations. Microstructures of the samples etched with 4% Nital's (4% nitric in ethanol) were observed by optical microscopy. The magnetostrictive properties were measured with a strain gauge under compressive pre-stress up to 15 MPa and magnetic field up to 5 kOe over a wide temperature range from −80 to 100 °C.

## 3. Results and discussion

### 3.1. ⟨1 1 2⟩-preferred orientation formation

Fig. 1 shows the X-ray diffraction (XRD) spectra of the transverse sections of directional-solidified $Tb_{0.36}Dy_{0.64}(Fe_{1-x}Co_x)_2$ ($x = 0$–0.20) and $Tb_{0.3}Dy_{0.7}Fe_2$ samples. No oxides and $RFe_3$ phases can be seen from the XRD patterns. The strongest peak of all the five samples is (2 2 4), compared

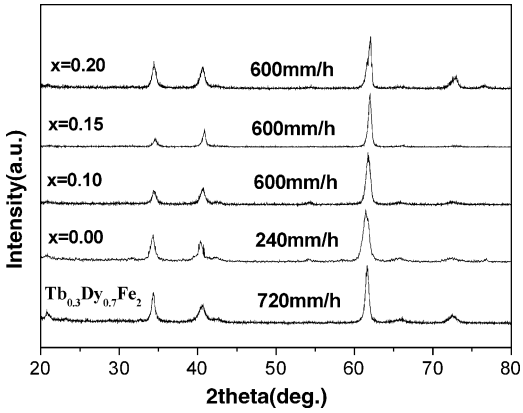


Fig. 1. X-Ray diffraction patterns from the transverse sections of oriented $Tb_{0.3}Dy_{0.7}Fe_2$ and $Tb_{0.36}Dy_{0.64}(Fe_{1-x}Co_x)_2$ samples prepared with growth velocities of 720, 240 or 600 mm/h.

with XRD patterns of (Tb, Dy)$Fe_2$ Laves phase in powder form, where the (1 1 3) peak is the strongest one, indicates that samples grown with 240, 600 and 720 mm/h possess ⟨1 1 2⟩-preferred orientation. Approximately, the orientation degree can be expressed as:

$$\eta = (I_{224} : I_{113})/(I^0_{224} : I^0_{113}) \quad (1)$$

where $I_{224}$ and $I_{113}$ represent the intensity of (2 2 4) and (1 1 3) peak of directional-solidified $Tb_{0.36}Dy_{0.64}(Fe_{1-x}Co_x)_2$ ($x = 0$–0.20) and $Tb_{0.3}Dy_{0.7}Fe_2$ samples; $I^0_{224}$ and $I^0_{113}$ are intensities of (2 2 4) and (1 1 3) peak for samples in powder form. Values of $\eta$ for $Tb_{0.36}Dy_{0.64}(Fe_{1-x}Co_x)_2$ ($x = 0$–0.20) and $Tb_{0.3}Dy_{0.7}Fe_2$-oriented crystals are summarized in Table 1. It can be seen that the orientation degree is different though among samples grown with the same velocity, due to different temperature gradient in the solidification front during the real crystal growth process besides the composition difference.

Typical optical morphologies from the transverse sections of $Tb_{0.36}Dy_{0.64}(Fe_{1-x}Co_x)_2$ ($x = 0$–0.20) and $Tb_{0.3}Dy_{0.7}Fe_2$ ⟨1 1 2⟩-oriented crystals are shown in Fig. 2. Clear dendritic morphologies can be seen in all the five ⟨1 1 2⟩-oriented crystals, and the phases were arranged uniformly and regularly. Individual grains of each ⟨1 1 2⟩-oriented crystal contain a dark second phase arranged in parallel arrays. More than 95% rare earth Tb + Dy metals were found in this second phase

Table 1
Room temperature magnetostriction in 5 kOe magnetic field, orientation degree, lamellar spacing, magnetostriction increase ratio and $\lambda_{111}$ of ⟨1 1 2⟩-oriented crystals in $Tb_{0.3}Dy_{0.7}Fe_2$ and $Tb_{0.36}Dy_{0.64}(Fe_{1-x}Co_x)_2$ samples

| Samples | Magnetostriction ($10^{-6}$) | | | Orientation degree, $\eta$ | Lamellar spacing (μm) | $(\lambda_{10} - \lambda_0)/\lambda_0$ (%) | $\lambda_{111}$ ($10^{-6}$) |
|---|---|---|---|---|---|---|---|
| | 0 MPa | 10 MPa | 15 MPa | | | | |
| $Tb_{0.3}Dy_{0.7}Fe_2$ | 1042 | 1538 | 1910 | 15.96 | 60 | 47.60 | 1640 [1] |
| $x = 0.00$ | 1201 | 1441 | 1487 | 11.07 | 120 | 19.98 | 1720 |
| $x = 0.10$ | 863 | 1424 | 1614 | 13.32 | 80 | 65.01 | 1580 |
| $x = 0.15$ | 1325 | 1746 | 1847 | 14.22 | 80 | 31.77 | 1530 |
| $x = 0.20$ | 1308 | 1544 | 1632 | 10.20 | 80 | 18.04 | 1460 |