Structure and magnetic properties of melt-spun Tb$_{0.27}$Dy$_{0.73}$Fe$_x$ ribbons

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Abstract

The structure and magnetic properties of the melt-spun ribbons of Tb$_{0.27}$Dy$_{0.73}$Fe$_x$ alloy are investigated as a function of various wheel speeds during melt-quenching using a single-roll technique. It is found that Tb$_{0.27}$Dy$_{0.73}$Fe$_x$ alloy is difficult to be fabricated as an amorphous state by using the melt-quenching method. X-ray diffractions show that all these ribbons for $x = 1.7-2.0$ are the MgCu$_2$-type phase at the wheel speed of $45 \text{ m s}^{-1}$. For Tb$_{0.27}$Dy$_{0.73}$Fe$_x$ alloy, the high wheel speed is beneficial to eliminate the RFe$_3$ phase and form the perfect MgCu$_2$-type phase. Compared with the bulk of Tb$_{0.27}$Dy$_{0.73}$Fe$_{1.95}$, these ribbons exhibit higher intrinsic coercivity value and their saturation magnetizations increase as well. The magnetostriction of Tb$_{0.27}$Dy$_{0.73}$Fe$_{1.95}$ composite with 4% epoxy resin is $640 \times 10^{-6}$ at 900 kA m$^{-1}$.

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1. Introduction

The RFe$_2$ ($R =$ rare earth) compounds crystallize in the cubic Laves phase and the room-temperature magnetostriictions of some of them are very large. For example, polycrystalline TbFe$_2$ compound exhibits a magnetostriction of $1760 \times 10^{-6}$ at room temperature [1]. However, the magnetocrystalline anisotropy of RFe$_2$ compound is very large due to the highly aspherical 4f orbitals remaining oriented by the strong coupling between the rare earth and iron moments. A large magnetic field is required to obtain a large strain, which may cause a serious problem in the practical applications of the compound. In order to solve this problem, Clark tried to minimize the magnetocrystalline anisotropy by alloying two different RFe$_2$ compounds, exhibiting anisotropy coefficient of different signs. He succeeded in finding a ternary alloy Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ with a large magnetostriction at room temperature, but a magnetocrystalline anisotropy strongly reduced [1]. This discovery opened the era of technical applications for the large magnetoelasticity of rare earth metals. Since then, much research has been done to improve the magnetostriction and magnetic properties of this commercial compound to make it more suitable for applications [2–7]. Many researchers have paid attention to prepare the oriented Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ alloy and substitute other atoms for Fe in Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ alloy [8–10]. But there are few reports concerning the magnetic properties of the ribbons of Tb$_{0.27}$Dy$_{0.73}$Fe$_x$ alloys. To shed some light on this area, some magnetic properties of the melt-spun ribbons of Tb$_{0.27}$Dy$_{0.73}$Fe$_x$ alloys fabricated at different wheel speeds are reported in this paper.

2. Experiment

Elemental Tb (99.9 wt% purity), Dy (99.9 wt% purity) and Fe (99.9 wt% purity) were used to prepare the alloys of Tb$_{0.27}$Dy$_{0.73}$Fe$_x$. Pre-alloyed ingots were arc-melted in a high-purity Ar atmosphere and then melt-spinning was carried out also under a high-purity Ar atmosphere. The wheel speed was varied over a wide range from 25 to $45 \text{ m s}^{-1}$. The orifice diameter of the quartz tubes that were used to eject the melt alloy onto a copper roller were about 0.5–0.8 mm and the chamber and ejecting Ar pressures were 0.05 and 0.15 MPa, respectively. The structure was mainly examined by both a D/max-2500
X-ray diffractometer with a Cu Kα radiation at room temperature and, in some cases, by scanning electron microscopy (SEM). Magnetic properties of the ribbons were measured at room temperature by a vibrating sample magnetometer (VSM). The magnetostriiction of specimens was measured at room temperature by using a standard strain gauge up to 900 kA m⁻¹.

3. Results and discussion

X-ray diffraction patterns of melt-spun Tb₀.₂₇Dy₀.₇₃Feᵧ alloys for \( x = 1.7–2.1 \) quenched at wheel speeds of 45 m s⁻¹ are shown in Fig. 1. It can be seen from Fig. 1 that all these Tb₀.₂₇Dy₀.₇₃Feᵧ ribbons for \( x = 1.7–2.0 \) crystallize in the cubic Laves MgCu₂-type phase. For \( x = 2.1 \), the ribbon is predominantly the Laves phase with a small amount of the second phase RFe₃ (R = Tb, Dy) phase. In order to make a further study of some properties of melt-spun Tb₀.₂₇Dy₀.₇₃Fe₁.₉₅ as a function of wheel speeds, Tb₀.₂₇Dy₀.₇₃Fe₁.₉₅ alloy was chosen.

Fig. 2 shows the X-ray diffraction patterns of Tb₀.₂₇Dy₀.₇₃Fe₁.₉₅ ribbons quenched at various wheel speeds. From Fig. 2, it can be seen that all the ribbons fabricated at different wheel speeds show a sharp crystalline peak. It is difficult to be fabricated as amorphous state by using our melt-spinning method unlike the other alloys [11,12]. There is a small amount of RFe₃ (R = Tb, Dy) phase in ribbons that were fabricated at low wheel speeds (< 40 m s⁻¹) and especially obvious at the wheel speed of 35 m s⁻¹, but disappears at high wheel speeds (≥ 40 m s⁻¹).

It is a fact that rapid solidification can improve some elements’ solid solubility in certain alloys. During the process of crystallization of Tb₀.₂₇Dy₀.₇₃Fe₁.₉₅ alloy, the ability of formation of cubic Laves phase is prior to the RFe₃ phase. As a consequence, the melt-quenching method improved the solid solubility of iron in Tb₀.₂₇Dy₀.₇₃Fe₁.₉₅ alloy; moreover, the high wheel speed is beneficial to eliminate the RFe₃ phase and to form the perfect Laves phase for Tb₀.₂₇Dy₀.₇₃Fe₁.₉₅ alloy.

Magnetization versus applied field loops for Tb₀.₂₇Dy₀.₇₃Fe₁.₉₅ ribbons of various wheel speeds at room temperature are shown in Fig. 3. It can be found that all the ribbons are very difficult to be saturated along the ribbon normal, which is obviously different from the loop measured along the plane. This result is attributed to two reasons: (1) the strong self-demagnetization effect and (2) the stress produced during melt-spinning. The stress in the ribbons is along the ribbon plane and it will hold back the movement of magnetic domain as applying field along the normal direction. So the magnetic moment of ribbons is easier saturated along its plane direction than the normal direction.

Magnetization versus applied field loops for powdered samples from ribbons are shown in Fig. 3(b). The magnetic hysteresis loops at the wheel speeds of 25 and 40 m s⁻¹ are similar with those at 30 and 45 m s⁻¹, respectively, so only the hysteresis curves at the wheel speeds of 25, 35 and 45 m s⁻¹ and the arc-melted Tb₀.₂₇Dy₀.₇₃Fe₁.₉₅ alloy are shown in Fig. 3(b). Compared with the bulk of Tb₀.₂₇Dy₀.₇₃Fe₁.₉₅ alloy, the melt-spin samples possess larger intrinsic coercivity and saturation magnetization. The same behavior was also obtained in Pr(Fe₀.₆Co₀.₄)₂ ribbons [13]. The previous studies indicated that the large
coercivity may be attributed to the large magnetocrystalline anisotropy of the Pr(Fe,Co)$_2$ phase and ultrafine grain size. The melt-spun samples at the wheel speeds of 40 and 45 m s$^{-1}$ had higher saturation magnetization, while the low-saturation magnetization at the wheel speed of 35 m s$^{-1}$ is due to the appearance of RFe$_3$ phase, which can be confirmed in X-ray diffraction pattern.

The microstructure of the quench surface and the free surface of the ribbons were observed. It was found that the microstructure varies through the thickness as well as inhomogeneities caused by airflow on the wheel surface. Because there are some traces of airflow, we did not find the grain on the quench surface. But the X-ray diffraction patterns on the quench surface and the free surface is uniform. SEM examinations of Tb$_{0.27}$Dy$_{0.73}$Fe$_{1.95}$ ribbons are shown in Fig. 4. It can be observed that the grain size of these ribbons decreases and becomes uniform with increasing wheel surface speed. The grain size of ribbons with the wheel speed of 45 m s$^{-1}$ is about 1 µm.

The powder obtained from the arc-melt ingot and ribbons of Tb$_{0.27}$Dy$_{0.73}$Fe$_{1.95}$ alloy at the wheel speeds of 25 and 45 m s$^{-1}$ is blended with about 4% epoxy resin, and then compacted at pressure of 80 MPa. The magnetostriction of Tb$_{0.27}$Dy$_{0.73}$Fe$_{1.95}$ composites as a function of the applied field is shown in Fig. 5. It can be found that the largest magnetostriction of 645 × 10$^{-6}$ was obtained in the composite made from Tb$_{0.27}$Dy$_{0.73}$Fe$_{1.95}$ ribbon at the wheel speed of 45 m s$^{-1}$. The magnetostriction of the composite made from arc-melt ingot and melt-spun ribbon at the wheel speed of 25 m s$^{-1}$ is 540 and 510 × 10$^{-6}$.

Fig. 3. Magnetization versus applied field. (a) Ribbon sample at the wheel speed of 35 m s$^{-1}$; (b) powder samples at different speeds. The numbers at the curves denote wheel speed in m s$^{-1}$.

Fig. 5. Magnetostriction curves for Tb$_{0.27}$Dy$_{0.73}$Fe$_{1.95}$ composites at room temperature.

Fig. 4. SEM examination of Tb$_{0.27}$Dy$_{0.73}$Fe$_{1.95}$ ribbons: (a) the quench surface at the speed of 45 m s$^{-1}$; (b) the free surface at the speed of 25 m s$^{-1}$; (c) the free surface at the speed of 45 m s$^{-1}$.
respectively. This result of magntostriction is consistent with that of X-ray diffraction and magnetization. It is known in X-ray diffraction patterns that there is a small amount of RFe$_3$ phase in ribbons at low wheel speeds \((< 40 \text{ m s}^{-1})\); it is also confirmed that arc-melt Tb$_{0.27}$Dy$_{0.73}$Fe$_{1.95}$ ingot possesses a small amount of rare-earth-rich phase and Fe. The low magnetization and magnetostrction of arc-melt ingot and melt-spun ribbon at the wheel speed of 25 m s$^{-1}$ is ascribed to the second phase. In order to study the intrinsic magnetostriction \(\lambda_{111}\), we have measured the splitting of the (400) reflection by the step-scanned way. X-ray diffraction pattern of Tb$_{0.27}$Dy$_{0.73}$Fe$_{1.95}$ melt-spun and arc-melt alloy for (440) splitting is shown in Fig. 6. The results show that the (440) peaks of the ribbon are different from that of the bulk compound and do not exhibit obvious split, which can be attributed to the strain and lattice distortion during the melt-quenching process.

4. Conclusions

Tb$_{0.27}$Dy$_{0.73}$Fe$_{x}$ \((x = 1.7–2.0)\) melt-spun ribbons are the MgCu$_2$-type phase at the wheel speed of 45 m s$^{-1}$. For Tb$_{0.27}$Dy$_{0.73}$Fe$_{x}$ alloy, the high wheel speed is beneficial to eliminate the RFe$_3$ phase and form the perfect MgCu$_2$-type phase. Compared with the bulk of Tb$_{0.27}$Dy$_{0.73}$Fe$_{x}$ alloy, the ribbons exhibit larger intrinsic coercivity and saturation magnetization. The grain size of these ribbons decreases with increasing the wheel surface speed. The largest magnetostriction of Tb$_{0.27}$Dy$_{0.73}$Fe$_{1.95}$ composite obtained from the ribbon at the wheel speed of 45 m s$^{-1}$ with 4% epoxy resin is about \(640 \times 10^{-6}\) near saturation.

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