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Magnetic-field-dependent microstructure evolution and magnetic properties of $Tb_{0.27}Dy_{0.73}Fe_{1.95}$ alloy during solidification

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ABSTRACT

We report on the influence of magnetic field strength on the alloy $Tb_{0.27}Dy_{0.73}Fe_{1.95}$ during slow-cooling solidification. We examined the effect of magnetic field strength on microstructure, magnetization, and magnetostrictive properties of this giant magnetostrictive alloy. We found that after field-treated solidification, the microstructure of specimens had a distinct grain arrangement and displayed magnetic anisotropy. The crystal orientation changed from random in the field-free treatment to aligned along the ⟨110⟩ direction in flux densities of 1 and 2.2 T, and along the easy magnetization axis ⟨111⟩ at a flux density of 4.4 T. In consequence, the magnetostrictive coefficient of the samples under various stresses improved with increasing magnetic flux density. Both the d_{33} and k_{33} values and the energy transformation efficiency of the field-treated specimens showed strong enhancements.

1. Introduction

Since the 1980s, the rare-earth giant magnetostrictive alloy $Tb_{0.27}Dy_{0.73}Fe_{1.95}$ has been an important functional material known for its efficient conversion between electromagnetic and mechanical energy [1,2]. In practical applications, it displays superior properties over piezoceramic materials (such as PZT). It has advantages of large magnetostriction strain, high energy conversion efficiency, and rapid response rate [3–6]. This material is used widely in high technology devices, such as magnetomechanical transducers, actuators, and adaptive vibration control systems [7–9].

The $Tb_{0.27}Dy_{0.73}Fe_{1.95}$ alloy has a typical $MgCu_2$-type cubic Laves phase structure and exhibits different magnetostrictive properties along different crystal orientations. The ⟨111⟩ orientation of this alloy is the easy magnetization axis, along which the linear magnetostriction is higher than in other directions when the magnetostriction is unsaturated. However, this alloy has no preferred orientation in normal casting conditions. Generally, the directional solidification method is used to prepare this alloy. The crystal is always oriented along the ⟨110⟩ or ⟨112⟩ direction [10,11]. The ⟨111⟩ preferred growth orientation can be acquired using seed crystal technology. However, the relatively small size and high brittleness induced by the appearance of the linear $(Tb,Dy)Fe_3$ phase does not suit industrial applications [12,13]. Therefore, new methods to prepare $Tb_{0.27}Dy_{0.73}Fe_{1.95}$ products with high ⟨111⟩ orientation are of great importance.

Researchers have resorted to applying high magnetic fields to this material under extreme conditions [14–19]. Experiments and theoretical analyses demonstrate that structures associated with preferred orientations can be obtained during solidification under such magnetic field conditions. Rango et al. obtained the crystal-oriented $YBa_2Cu_3O_7$ alloy by solidification and confirmed the possibility of establishing crystal orientation at high temperatures in magnetic fields [20]. Al–35Cu, Cd–60Zn, and Al–10Ni alloys solidified under magnetic fields with a magnetic flux density of 0.5–1.5 T could yield structures with a preferred orientation [21]. Wang et al. reported such an instance with the MnBi phase of the Mn–Bi alloy [22]. Magnetic fields can also alter the solidification structure of Al_3Ni in the Al–Ni alloy and the Al_3Ni phase [23]. Liu et al. found that the MnSb phase of the Mn–Sb alloy generated a texture when it was remelted under magnetic fields up to 11.5 T [24]. The magnetostriction of the $Tb_{0.27}Dy_{0.73}Fe_{1.95}$ alloy can be improved through solidification under magnetic field conditions, because the magnetic field can induce rotations of its magnetic crystal domains and align the easy magnetization axis in the direction of the magnetic field. In our study reported here, the crystal orientation and magnetostriction change of the $Tb_{0.27}Dy_{0.73}Fe_{1.95}$ alloy were investigated using specimens prepared in different magnetic flux densities during slow-cooling solidification.

2. Experimental procedure

The master $Tb_{0.27}Dy_{0.73}Fe_{1.95}$ alloy was prepared under vacuum from Fe, Tb, and Dy (purity 99.9%) by induction melting. The ingot

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was cut into cylindrical samples 10 mm in diameter and 15 mm in length and placed into quartz tubes. Set in the middle of a superconducting magnet, the axial direction of the sample was parallel to the magnetic field direction, and opposite to the direction of gravity. Further details of the experimental apparatus are given elsewhere [25]. With magnetic field flux densities set at 0, 1, 2.2, and 4.4 T, the samples were then heated to 1350 °C in an argon atmosphere, which was approximately 50–80 °C above its melting point. After being held at the same temperature for 5 min, each sample was cooled to 700 °C at a rate of approximately 1.5 °C/min. Finally, with the power to the furnace switched off, the samples were allowed to cool to room temperature.

The treated samples were sectioned both longitudinally and transversely, polished and etched with natal solution (HNO_3 (5 vol %)/C_2H_5OH). The microstructures of each specimen were observed using optical and scanning electron microscopes. The crystal orientation of phases was checked using the transverse sections by X-ray diffraction (XRD), (Ultima IV, Cu $K\alpha$ radiation, Rigaku, Japan). The magnetization was measured using a vibrating sample magnetometer (VSM), (Lakeshore Cryotronic, Westerville, OH, USA) at room temperature. A standard resistant strain gauge was used to measure the magnetostrictive properties in the longitudinal sections of the specimens under different stresses.

3. Results and discussion

To observe the grain arrangements, the longitudinal section of the sample microstructure was examined. Fig. 1 shows metallographic micrographs of the specimens during solidification with the magnetic field direction as marked and parallel to the section. In Fig. 1(a)–(d), some grains with cellular and columnar-like shapes separate out from the substrate. According to the results of the energy spectrum analysis, the substrate corresponds to the (Tb,Dy)Fe_2 phase and the slender grains are the (Tb,Dy)Fe_3 phase. There is no distinct grain arrangement in Fig. 1(a). In Fig. 1(b), the (Tb,Dy)Fe_3 grains tend to orient along the magnetic field direction, with a deviation of 30–45° from the magnetic field direction, but the matrix has no preferred orientation. This is because the magnetic flux density of 1 T is not high enough to affect the (Tb,Dy)Fe_2 matrix. At a flux density of 2.2 T, both the (Tb,Dy)Fe_2 and (Tb,Dy)Fe_3 matrices are oriented in the magnetic field direction and the angle between the preferred orientation and the magnetic field direction ranges from 5 to 15°. At 4.4 T, with angles ranging from 5 to 10°, the structure shows effects of the magnetic field during solidification with grain alignment. When the magnetic field direction is parallel to the direction of gravity, the fields can dampen the perpendicular convection and thereby columnar grains can grow along the field direction.

XRD measurements were performed on sections perpendicular to the magnetic field direction with the results shown in Fig. 2. The major phase was the (Tb,Dy)Fe_2 phase and some diffraction peaks of the (Tb,Dy)Fe_3 phase were also present. Fig. 2 illustrates the crystal orientation of $Tb_{0.27}Dy_{0.73}Fe_{1.95}$ in the transverse section under different magnetic field conditions. For the field-free sample, the highest diffraction peak of the (Tb,Dy)Fe_2 phase is along the (113) and (220) planes and the entire sample has no obvious preferred orientation. With a 1-T flux density, the diffraction peak intensity of (220) and (333) has increased and the (113) peak intensity has decreased compared with the field-free sample. The crystal tends to grow along the easy growth direction of ⟨110⟩ and easy magnetization direction of ⟨111⟩ with the former being dominant. With a 2.2-T flux density, the diffraction peaks of the (220) and (440) planes continue to increase. Similarly, the diffraction peak intensities of (111), (222), and (333) are also enhanced. The remaining diffraction peaks weaken. This means that the ⟨110⟩ and ⟨111⟩ textures parallel to the magnetic field direction compete with one another under this condition. However, with a 4.4-T flux density, the (333) plane is enhanced, becoming the highest diffraction peak in the sample. The diffraction peak intensity of (111) and (222) continues to increase, and the diffraction peak intensities of (220) and (440) are reduced. The ⟨111⟩ direction is dominant and the preferred orientation forms along its easy magnetization axis parallel to the magnetic field direction.

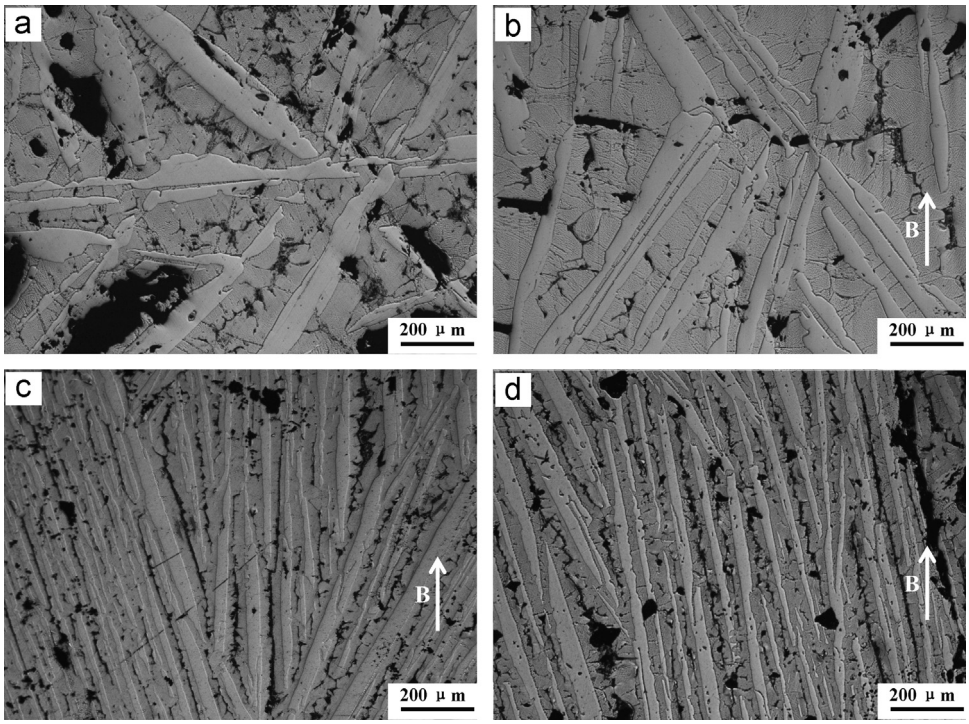

Fig. 1. Longitudinal section showing metallography of $Tb_{0.27}Dy_{0.73}Fe_{1.95}$ alloy under different magnetic field conditions (a) 0 T, (b) 1 T, (c) 2.2 T and (d) 4.4 T.