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Regular Article

Magnetostriction of a $Fe_{83}Ga_{17}$ single crystal slightly doped with Tb

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ABSTRACT

A novel strategy of sub-rapid directional solidification is developed for preparing doped FeGa single crystals. Crystals of nominal composition $Fe_{83}Ga_{17}Tb_x$ ($x = 0, 0.05$) have been grown with [100] preferred orientation at a high growth rate of 3000 mm/h. Using this method, trace amounts of normally-insoluble Tb can be incorporated into the A2 $Fe_{83}Ga_{17}$ matrix. A large magnetostriction (λ_{100}) of 310 ppm is achieved in the [100] oriented $Fe_{83}Ga_{17}Tb_{0.05}$ single crystal, ~50% higher than that of a similar undoped crystal.

The past few decades have witnessed extensive applications of magnetostrictive materials in different fields such as sensors, actuators and transducers [1,2]. The giant room-temperature magnetostriction of Terfenol-D ($Tb_{1-x}Dy_xFe_2$) alloys has been widely used in these fields. However, Terfenol-D is limited by its mechanical brittleness, heavy use of rare earth elements and high magnetic saturation field [3]. Galfenol ($Fe_{1-x}Ga_x$) alloys have the advantages of excellent ductility, low cost and low magnetic saturation field [4]. Magnetostriction or iron is enhanced tenfold when a fraction of the iron atoms are replaced by nonmagnetic Ga [5–8], although it is still much lower than that of Terfenol-D. Great efforts have been made to further improve the magnetostriction by adding 3*d* and 4*d* transition elements such as Ni, V, Cr, Mn, Co, Mo, and Rh [9–12], or interstitial elements such as C, B and N [13–15]. Despite all that, there was no significant enhancement in the magnetostriction. However, it was recently reported that the magnetostriction of $Fe_{83}Ga_{17}$ alloys could be remarkably increased by melt spinning with small amount of rare earth elements such as Tb, Dy and Ce [16–18], although the perpendicularly grown grains in the melt-spun ribbons make it very difficult to measure the magnetostriction directly. Moreover, due to the large demagnetizing field, the shape anisotropy of the ribbons also leads to a high magnetic saturation field. Enhanced magnetostriction with lower applied field is expected in bulk FeGa slightly doped with rare earth elements, but it is hard to obtain such materials by conventional methods.

Very recently, bulk $Fe_{83}Ga_{17}Tb_x$ has been prepared by a directional casting process and magnetostriction of up to 160 ppm was obtained in polycrystalline $Fe_{83}Ga_{17}Tb_{0.2}$ alloys [19,20]. However, the relatively slow cooling rate limits the solid solubility of Tb in the A2 matrix of the FeGa alloy, and a sound magnetostriction could not be obtained by this method. Therefore, a novel strategy combining rapid solidification with directional solidification, is urgently required to achieve magnetostriction in Tb-doped $Fe_{83}Ga_{17}$ crystals.

In this report, we develop a sub-rapid directional solidification procedure. [100] oriented $Fe_{83}Ga_{17}$ single crystals slightly doped with Tb have been prepared, and their magnetostriction (λ_{100}) of up to 310 ppm is approximately 50% higher than that of undoped $Fe_{83}Ga_{17}$ crystals, and almost twice as high as previously reported for $Fe_{83}Ga_{17}Tb_{0.2}$ prepared by directional casting [19].

The nominal $Fe_{83}Ga_{17}Tb_x$ ($x = 0, 0.05$) master alloys were prepared by arc melting from high purity starting elements Fe, Ga and Tb (99.99%). Each ingot was re-melted four times under an argon atmosphere and cast in a chilled copper mold to obtain master rods. The crystals were grown in a sub-rapid directional solidification furnace. Master rods were first entirely melted and then moved downwards into cooling medium at velocities of 1000 mm/h, 3000 mm/h or 6000 mm/h. Afterwards, the directional microstructure and the magnetostriction of the polycrystalline specimens were measured. Following that, $x = 0.05$ Tb-doped $Fe_{83}Ga_{17}$ and $x = 0$ undoped $Fe_{83}Ga_{17}$ single crystals were grown at a velocity of 3000 mm/h based on a [100] oriented $Fe_{83}Ga_{17}$ seed crystal as shown in Fig. 1. The crystals were then cut into sheets 3 mm × 4 mm × 1.3 mm with six [100] faces. The crystallographic structure was identified by X-ray diffraction (XRD, D/MAX 2200 PC) with Cu-K_α radiation ($\lambda = 154.18$ pm) and scanning speed of 6°/min. The microscopic morphology of the crystals was determined by using a JEOL JXA-8100 electron probe micro-analyzer (EPMA). The preferred orientation of the single crystals was determined by the Lauë back-reflection X-ray technique. Magnetostriction was measured by the standard strain gauge method, and magnetization hysteresis loops (M–H) were measured with a Quantum Design physical property measurement system (PPMS-9).

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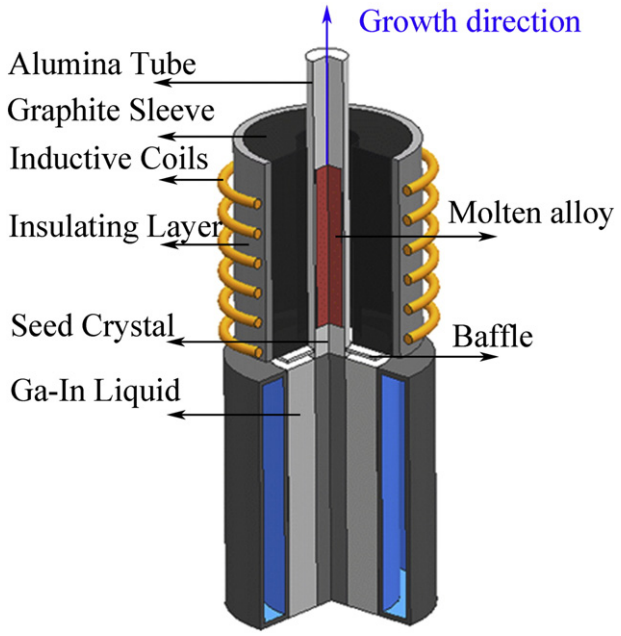

Fig. 1. Schematic illustration of sub-rapid directional solidification equipment.

It has been found that rapid solidification (melt spinning) can be used to prepare rare-earth doped FeGa solid solutions, resulting in a significant increase of magnetostriction [16–18]. It has also been proved that the directional solidification method can enhance the magnetostriction of FeGa alloys by realizing [100] orientation which has the highest value of anisotropic magnetostriction [6]. In order to incorporate the advantages of both rapid solidification and directional solidification concurrently, an optimal cooling rate ($R = G_L \times V$) is required, where G_L is the liquid temperature gradient in front of the solid–liquid interface and V is the growth velocity. This can be realized with a large G_L and V. We develop a novel strategy to achieve sub-rapid solidification, as shown in Fig. 1. In this equipment, high-frequency induction coils and graphite sleeves are employed to melt the master rods. The liquid metal cooling medium (Ga–In) combined with a floating ceramic baffle (BN) was adopted in order to achieve large G_L; V can be manipulated over a range of 1000–10,000 mm/h.

Fig. 2(a) shows the granular morphology of polycrystalline $Fe_{83}Ga_{17}Tb_{0.05}$ in longitudinal sections of specimens prepared at different velocities. Columnar grains can be clearly observed along the growth direction in the 1000 mm/h and 3000 mm/h specimens, while lateral grains are found in the 6000 mm/h specimen. It appears that a growth velocity less than 3000 mm/h is beneficial for directional solidification. Furthermore, back-scattered electron (BSE) imaging has been employed to analyze the phase composition in $Fe_{83}Ga_{17}Tb_{0.05}$ specimens. In Fig. 2(b), there are obvious bright spheres and rods distributed in a dark background in the 1000 mm/h specimen, suggesting that a second phase precipitates from the matrix along grain boundaries. The 3000 mm/h and 6000 mm/h specimens observed are single phase. Energy-dispersive X-ray spectroscopy (EDS) analysis confirms that the precipitates in the 1000 mm/h specimen are Tb-rich, possessing the rhombohedral Th_2Zn_{17} structure (2:17R), consistent with our previous work [21]. This indicates that the solid solution of a trace amount of Tb can be achieved at a growth velocity of 3000 mm/h or more. Fig. 2(c) shows the XRD patterns of $Fe_{83}Ga_{17}Tb_{0.05}$ specimens prepared at 1000 mm/h, 3000 mm/h and 6000 mm/h. All diffraction peaks are indexed as (110), (200) and (211) on the body-centered cubic (bcc) structure, demonstrating that the matrix of all the Tb-doped $Fe_{83}Ga_{17}$ alloys possesses the same bcc structure as the binary $Fe_{83}Ga_{17}$ alloy. Meanwhile, the intensity of the (200) diffraction peak increases with growth velocities up to a maximum at 3000 mm/h, suggesting that this velocity is beneficial for [100] preferred oriented growth. The magnetostriction of a $Fe_{83}Ga_{17}Tb_{0.05}$ specimen (Φ 7 mm × 20 mm) is summarized in Fig. 2(d). With the increase of growth velocity, the magnetostriction changes significantly, to a maximum of 200 ppm at a growth velocity of 3000 mm/h, which can be attributed to the [100] orientation and the solid solution of Tb. Therefore, rapid solidification and directional solidification are concurrently achieved at 3000 mm/h in a sub-rapid directional solidification process. The solid solution of Tb was suppressed below a velocity of 3000 mm/h, whereas directional growth was impeded above a velocity of 3000 mm/h. Thus, we

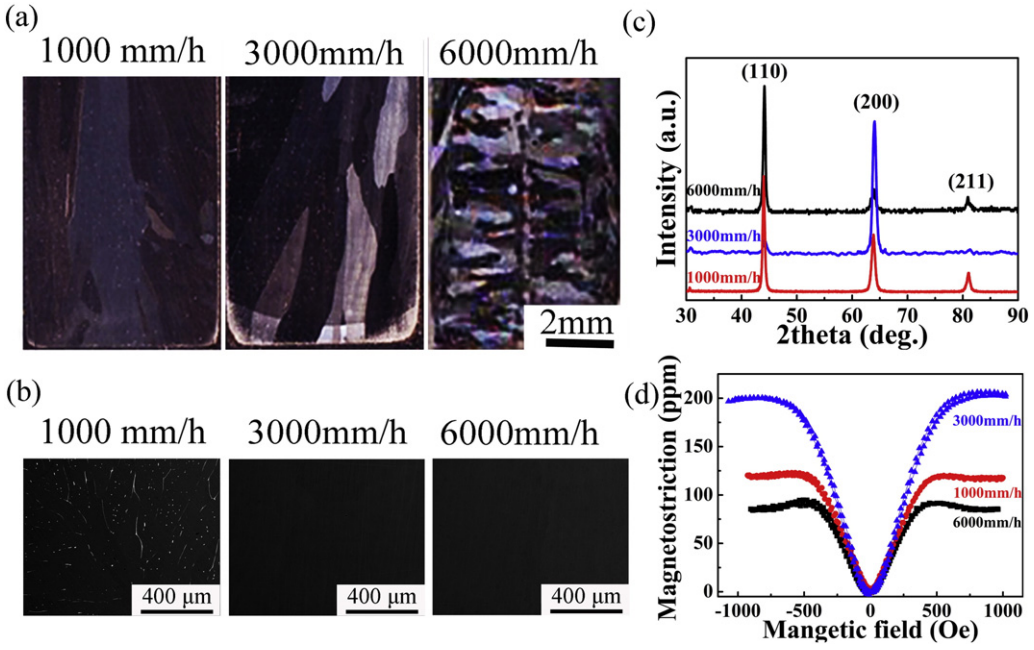

Fig. 2. Characterization of $Fe_{83}Ga_{17}Tb_{0.05}$ crystals prepared at different growth velocities of 1000 mm/h, 3000 mm/h or 6000 mm/h: (a) optical metallographic graphs of $Fe_{83}Ga_{17}Tb_{0.05}$ crystals; (b) BSE images of the $Fe_{83}Ga_{17}Tb_{0.05}$ crystals; (c) XRD patterns of $Fe_{83}Ga_{17}Tb_{0.05}$ crystals; (d) magnetostriction of $Fe_{83}Ga_{17}Tb_{0.05}$ crystals.