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The magnetostriction of Fe–(18 − x) at% Ga–x at% Al ($3 \leq x \leq 13.5$) alloys

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ABSTRACT

The ingot of Fe–(18 − x) at% Ga–x at% Al ($3 \leq x \leq 13.5$) alloys was prepared from high purity elements using a high vacuum arc melting system. The X-ray diffraction patterns indicated that the alloys were disordered bcc A2 structure. The magnetostriction of the alloys was measured and the effect of partial substitution of Ga with Al on the magnetostriction of the alloys was investigated. Fe–9 at% Ga–9 at% Al alloy, the optimizing magnetostrictive alloy was found in Fe–(18 − x) at% Ga–x at% Al ($3 \leq x \leq 13.5$) alloys. The saturated magnetostriction of the directional solidification Fe–9 at% Ga–9 at% Al rod is up to 135 ppm for 0 MPa and 221 ppm for 53 MPa. It was found that the alloy has the high linearity of the magnetostriction curve, the low hysteresis and saturated magnetic field, which suggests the directional solidification Fe–9 at% Ga–9 at% Al alloy is a potential candidate for magnetostrictive actuator and transducer applications.

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1. Introduction

Fe alloys with nonmagnetic elements in which there are no d-shell electrons (Be, Al) or the d-shell is full (Ga) are known to have appreciable low field magnetostriction, good mechanical properties and relatively low cost [1–4]. Clark and co-authors [2,3] have found two peaks, which occurred near x=18 and 28 in the magnetostriction of $Fe_{100-x}Ga_x$ single-crystals. Magnetostriction constants $(3/2)\lambda_{100}$ for $Fe_{81.8}Ga_{18.2}$ and $Fe_{71.5}Ga_{28.5}$ are up to 350×10^{-6} and 380×10^{-6} in the low magnetic field, respectively. It is commonly believed that the increase in magnetostriction for Fe–Ga alloys with increasing Ga content is the result of preferential (1 0 0) Ga–Ga pairing in the disordered bcc structure [5]. Recently, Basumatary et al. [6] have investigated the magnetostriction of arc-melted $Fe_{100-x}Ga_x$ (x=17 − 30) alloys and found that the $Fe_{83}Ga_{17}$ alloy possesses the greatest saturation magnetostriction due to the presence of a single disordered A2 phase.

Fe–Al alloys have some advantages over Fe–Ga alloys in large-scale applications and greater durability. Some work on Fe–Ga–Al alloys [2] has indicated a roughly linear decrease in magnetostriction with increasing Al content. However, Ref. [7] has reported that the replacement of a small fraction of Fe atoms by the nonmagnetic element Al enhances the magnetostriction of the Fe-based alloys. Furthermore, the magnetostriction of $Fe_{87}Ga_4Al_9$ $\langle 1\,0\,0 \rangle$ single crystal increases from 250×10^{-6} at 10.3 MPa applied compressive stress to 290×10^{-6} at 96.5 MPa [2].

In this work, the influence of partially substituting Ga in Fe–Ga alloys with Al on the magnetostrictive behavior of Fe–Ga–Al alloys is observed. It is shown that Fe–Ga–Al alloys have large low field magnetostriction. We also show the stress dependencies of the magnetostrictive properties of the Fe–Ga–Al alloys.

2. Experimental methods

Appropriate quantities of pure Fe (99.9 wt%), Ga (99.99 wt%) and Al (99.99 wt%) were cleaned and arc melted together 3 or 4 times under an argon atmosphere. The weight of each sample was 10 g and the weight loss of each sample was controlled below 1 wt%. The resulting ingots, wrapped by molybdenum foil separately, were sealed in quartz capsules and homogenized. After heat-treatment, the samples were quenched in water. Table 1 shows heat treatment condition of $Fe_{82}Ga_{18-x}Al_x$ ($3 \leq x \leq 13.5$) alloys.

The directional solidification alloy was prepared from high purity Fe (99.9 wt%), Ga (99.99 wt%) and Al (99.99 wt%) using a directional solidification furnace specially designed for the "one-step" process [8]. The raw materials were placed in a crucible and melted under Ar atmosphere at an intermediate frequency. The melted alloy was cast into a flat bottomed quartz tube that was completely within the hot zone. Then the quartz tube was drawn vertically downwards at a desired rate (125 mm/h), causing the

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Table 1
The composition and heat treatment condition of $Fe_{82}Ga_{18-x}Al_x$ ($3 \leq x \leq 13.5$) alloys.

Alloys	Heat-treatment condition
$Fe_{82}Ga_{15}Al_3$	1100 °C for 3 h, 1000 °C for 120 h and then 730 °C for 168 h, water cooling
$Fe_{82}Ga_{13.5}Al_{4.5}$	1100 °C for 3 h, 1000 °C for 120 h and then 730 °C for 168 h, water cooling
$Fe_{82}Ga_{12}Al_6$	1100° C for 3 h, 1000 °C for 120 h and then 730 °C for 168 h, water cooling
$Fe_{82}Ga_9Al_9$	1100 °C for 3 h, 1000 °C for 120 h and then 730 °C for 168 h, water cooling (DS) 1150 °C for 1 hour and 850 °C for 3 h, wind cooling
$Fe_{82}Ga_6Al_{12}$	1100 °C for 3 h, 1000 °C for 120 h and then 730 °C for 168 h, water cooling
$Fe_{82}Ga_{4.5}Al_{13.5}$	1100 °C for 3 h, 1000 °C for 120 h and then 730 °C for 168 h, water cooling

melt to solidify slowly. After the directional solidification has finished, the sample rod in the quartz tube was homogenized at 1150 °C for 11 h and 850 °C for 3 h.

X-ray diffraction analysis was carried out in a Philips X'Pert MPD diffractometer. Cu-K_α radiation was used. After being burnished and etched the microstructure of the sample was observed using an XJX-300 optical microscope. The etchant used was $FeCl_3$ solution. The magnetostriction was measured using a NIM-2000 magnetic measurement system.

3. Results and discussion

Nonmagnetic elements Ga and Al have filled d-shell and no d-shell, respectively. And the outer shell configurations of Ga ($4s^2 4p^1$) and Al ($3s^2 3p^1$) are similar. Both Ga and Al can enhance the magnetostriction of the b.c.c. Fe. The influence of partially substituting Ga in Fe–Ga alloys with Al on the microstructure and the magnetostrictive behavior of Fe–Ga–Al alloys is observed in the vacuum arc melting Fe–$(18-x)$ at% Ga–x at% Al (x=3, 4.5, 6, 9, 12 and 13.5) alloys and the directional solidification Fe–9 at% Ga–9 at% Al rod.

3.1. Microstructure of polycrystalline Fe–Ga–Al alloys

The XRD was used to analyze the structure of the Fe–$(18-x)$ at% Ga–x at% Al (x=3, 4.5, 6, 9, 12 and 13.5) alloys. The result indicates that the samples are disordered α-Fe structures (A2). Fig. 1(a) shows the XRD pattern of Fe–9 at% Ga–9 at% Al alloy, homogenized at 1100 °C for 3 h, 1000 °C for 120 h and then 730 °C for 168 h. The metallographic examination confirms that the microstructure of the Fe–9 at% Ga–9 at% Al alloy is nearly a disordered A2 phase as shown in Fig. 2.

According to the Fe–Ga [9,10], Fe–Al [9,11] and Ga–Al [9] binary phase diagrams, the dot-shaped phase is confirmed to a $L1_2$ phase, which separates out from A2 base phase during the cooling process from 730 °C to room temperature.

3.2. Magnetostriction of polycrystalline Fe–Ga–Al alloys

Fig. 3 illustrates the Al concentration dependence of saturated magnetostriction of Fe–$(18-x)$ at% Ga–x at% Al (x=3, 3.6, 4.5, 6, 9, 12 and 13.5) alloys. From Fig. 3, we can find that the saturated magnetostriction of the alloys increases with the increasing Al concentration in the range of $3 \leq x \leq 9$. However, the saturated magnetostriction decreases with the increasing Al concentration when $9 \leq x \leq 13.5$. Clearly, the Al concentration dependence of the saturated magnetostriction of Fe–$(18-x)$ at% Ga$-x$ at% Al alloys is intricate, especially in the range of $3 \leq x < 6$, which is similar to the variation of magnetostriction with Al substitution for Ga in Fe–$(20-y)$ at% Ga$-y$ at% Al alloys in Ref. [12].

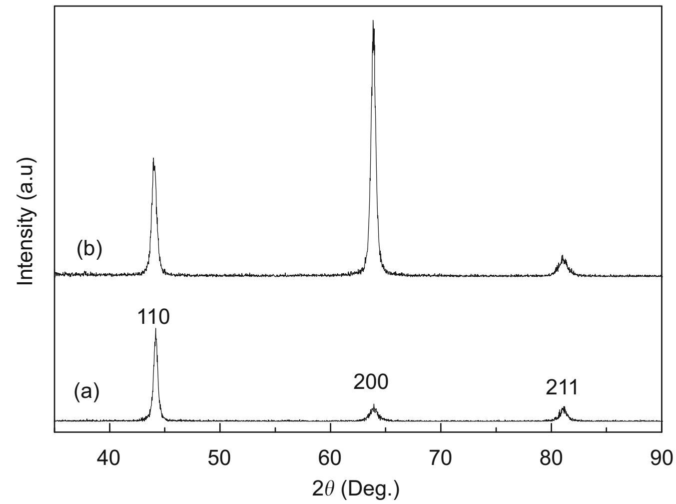

Fig. 1. XRD patterns of (a) the vacuum arc melted Fe–9 at% Ga–9 at% Al alloy and (b) the directional solidification Fe–9 at% Ga–9 at% Al rod after annealing treatments.

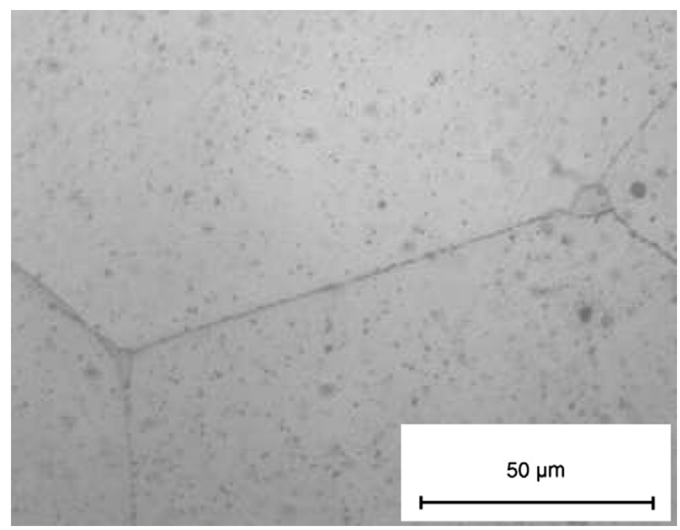

Fig. 2. Optical micrograph of the vacuum arc melted Fe–9 at% Ga–9 at% Al alloy.

The values of the ratio of Ga to Al, saturated magnetostriction and magnetic field for the Fe–$(18-x)$ at% Ga$-x$ at% Al as well as Fe–20 at% Ga [13,14] alloys are listed in Table 2. The maximum magnetostriction of Fe–9 at% Ga–9 at% Al alloy is 88 ppm, which is higher than that of polycrystalline Fe–20 at% Ga alloy. It can be found that the substitution of Fe with an appropriate amount of Al and Ga can obviously enhance the magnetostriction of Fe–Ga–Al alloys in certain composition range. However, high substitution amount of Al tends to decrease magnetostriction of the Fe–Ga–Al alloys.

It can also be observed that the maximum magnetostriction of Fe–9 at% Ga–9 at% Al alloy is nearly 4 times of the magnetostriction of the Fe–4.5 at% Ga–13.5 at% Al alloy when the ratio of Ga to Al content is 1/1. In fact, Ref. [5] has found that the magnetostriction of Fe–Al or Fe–Ga alloys increases with the increasing x (x is content of Ga or Al) when $x < 19$ due to Ga–Ga and Al–Al pairings. Whereafter, Wutting et al. [15] have proposed the

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