2012

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Publication Details
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Abstract
"Fe82Ga9Al9 alloy rod was prepared by the directional solidification (DS) method. The effects of uniaxial compressive stress on magnetostriction of the alloy and the temperature dependence of magnetostriction were investigated. The results show that the magnetostriction increases from $135 \times 10^{-6}$ at 2.3 MPa to $221 \times 10^{-6}$ at 53 MPa and then remains at this value between 53 MPa and 90 MPa. This enhancement results from domain rotation under the compressive stress. The temperature dependence results show that the saturated magnetostriction decreases by 11% (25 degrees C-120 degrees C) and 13% (25 degrees C-100 degrees C) for samples with 0 MPa and 15 MPa compressive stress applied, respectively. This decrease is due to reduced magnetic crystalline anisotropy as the temperature increases. Under the compressive stress conditions, the magnetostriction decreases more notably. (C) 2012 American Institute of Physics. [doi:10.1063/1.3679152]"

Keywords
magnetostrictive, alloy, properties, directional, solidification, fe82ga9al9

Disciplines
Engineering | Physical Sciences and Mathematics

Publication Details

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This journal article is available at Research Online: http://ro.uow.edu.au/aiimpapers/565
Magnetostrictive properties of directional solidification Fe$_{82}$Ga$_{9}$Al$_{9}$ alloy

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(Presented 3 November 2011; received 21 September 2011; accepted 5 December 2011; published online 17 February 2012)

Fe$_{82}$Ga$_{9}$Al$_{9}$ alloy rod was prepared by the directional solidification (DS) method. The effects of uniaxial compressive stress on magnetostriction of the alloy and the temperature dependence of magnetostriction were investigated. The results show that the magnetostriction increases from $135 \times 10^{-6}$ at 2.3 MPa to $221 \times 10^{-6}$ at 53 MPa and then remains at this value between 53 MPa and 90 MPa. This enhancement results from domain rotation under the compressive stress. The temperature dependence results show that the saturated magnetostriction decreases by 11% (25°C–120°C) and 13% (25°C–100°C) for samples with 0 MPa and 15 MPa compressive stress applied, respectively. This decrease is due to reduced magnetic crystalline anisotropy as the temperature increases. Under the compressive stress conditions, the magnetostriction decreases more notably. © 2012 American Institute of Physics. [doi:10.1063/1.3679152]

I. INTRODUCTION

Both of the non-magnetic elements Ga and Al can enhance the magnetostriction $\lambda$ of body-centered cubic (bcc) Fe in the [100] direction. The two elements have a filled $d$-shell and no $d$-shell, respectively. The outer shell configurations of Ga (4s$^2$4p$^1$) and Al (3s$^2$3p$^1$) are also similar. Gallenol (Fe-Ga) alloys are known to have appreciable low field magnetostriction, good mechanical properties, and relatively low cost.¹–⁴ Clark et al.⁵,⁶ have found that the magnetostriction of Fe-Ga alloys exhibits a complicated dependence on Ga concentration. Two magnetostriction peaks occur near Fe$_{82}$Ga$_{18}$ and Fe$_{72}$Ga$_{28}$, respectively. It is commonly believed that the first magnetostrictive peak is the result of preferential (100) Ga-Ga pairing in the disordered bcc structure,⁶ and the second peak appears because the drop in the elastic constant $C$ enhances the magnetostriction.⁷

Fe-Al alloys have some advantages over Fe-Ga alloys in large-scale applications and have greater durability. As combinations of both alloys, Fe-Ga-Al alloys⁸ have shown a roughly linear decrease in magnetostriction with increasing Al content. However, the replacement of a small fraction of Fe atoms by Al enhances the magnetostriction of the Fe-based alloys.⁸ Furthermore, the magnetostriction of Fe$_{82}$Ga$_{9}$Al$_{9}$ (100) single crystals was found to increase from $250 \times 10^{-6}$ at applied compressive stress of 10.3 MPa to $290 \times 10^{-6}$ at 96.5 MPa.³

In this work we report the effects of compressive stress on the magnetostrictive properties of directional solidification (DS) Fe$_{82}$Ga$_{9}$Al$_{9}$ alloy and the temperature dependence of the magnetostriction. It is shown that Fe-Ga-Al alloys have large low field magnetostriction, and that uniaxial compressive stress can significantly enhance the magnetostriction, while the magnetostriction decreases slightly with increasing temperature.

II. EXPERIMENTAL METHODS

Appropriate quantities of pure Fe (99.9 wt. %), Ga (99.99 wt. %), and Al (99.99 wt. %) were well mixed and arc-melted together 3 or three or four times under an argon atmosphere. The weight of each sample was 10 g and the weight loss of each sample was controlled to below 1 wt. %. The resulting ingots, separately wrapped in molybdenum foil, were sealed in quartz capsules and heat-treated at 1100°C for 3 h, 1000°C for 120 h, and then 730°C for 168 h to achieve homogeneity. Some alloys were also prepared using a directional solidification (DS) furnace that was specially designed for the one-step process.⁹ After the directional solidification was finished, the sample rod in the quartz tube was homogenized at 1150°C for 1 h and 850°C for 3 h before wind cooling. The DS rod for measurements has a diameter of 10 mm and length of 25 mm.

X-ray diffraction (XRD) analysis was carried out in a Philips X’Pert MPD diffractometer with Cu-K$_\alpha$ radiation. The lattice parameters and the crystal structure were refined using the Rietica software package (VISION 1.7.7). The magnetostriction was measured by standard strain gauge techniques using a NIM-2000 magnetic measurement system and SDY2202 static digital strain gauge apparatus with sensitive area of 3 mm $\times$ 2 mm.

III. RESULTS AND DISCUSSION

The XRD results for the Fe$_{82}$Ga$_{18}$–$\alpha$Al$_x$ ($x = 1.5, 3, 3.6, 4.5, 6, 7.5, 9, 10.5, 12, 13.5, and 15$) alloys indicate that all the alloys in this series have the same crystal structure. As an example, Fig. 1 shows the XRD pattern and refinement results for Fe$_{82}$Ga$_{9}$Al$_{9}$ alloy, homogenized at 1100°C for

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0021-8979/2012/111(7)/07A332/3/$30.00 111, 07A332-1 © 2012 American Institute of Physics.
to a saturation magnetic field. The samples were prepared using the arc melting method, and magnetostriuctive measurements were carried out at room temperature for 0 MPa stress.

Our results also provide experimental support to this model of Ga or Al pairs. According to the phase diagram, Fe$_{82}$Ga$_{18}$Al$_{0}$ alloy has disordered A2 structure after heat treatment. However, it seems that this alloy composition is beneficial to the formation of more Ga or Al pairs. The Ga-Ga or Al-Al pairings along (100) induce changes in the internal stress, resulting in the enhancement of the magnetostriction of Fe$_{82}$Ga$_{9}$Al$_{9}$.

The XRD patterns of the alloys prepared by the DS method suggest a (100) preferred orientation along the rod axis. It is well known that magnetostrictive devices usually are used under stress conditions because an applied mechanical stress can alter the domain structure of the magnetostrictive material and create a new source of magnetic anisotropy. The effect of stress on the magnetomechanical response of the DS Fe$_{82}$Ga$_{9}$Al$_{9}$ rod is shown in Fig. 3. It can be seen that the maximum magnetostriiction increases with increasing compressive stress from $135 \times 10^{-6}$ for 0 MPa to $221 \times 10^{-6}$ for 53 MPa.

When a uniaxial compressive stress is applied along the axis of the rod, in response to the magnetoelastic energy the saturation magnetization, $M_S$, vectors of the domains rotate to perpendicular to the axis. Here, magnetic field parallel to the axis of the rod was applied, and the stress axis becomes a hard axis, because the field now has to supply energy that is equal to the magnetoelastic energy for rotating the $M_S$ vectors of the domains into the field direction. When the rotation is complete, the magnetostriiction reaches saturation. Thus, the magnetostriiction increases with increasing applied uniaxial compressive stress, as is shown in inset of Fig. 3. It also can be found that the magnetostriiction hardly changes from 53 MPa to 90 MPa due to the saturated state. From Fig. 3, we can see that for loading conditions over 10 MPa, the magnetostriiction begins to decrease as the applied magnetic field exceeds the saturated field. The existence of the magnetostriiction peaks may be related to internal texture, which is similar to a phenomenon reported in [110] texture iron single crystals. Initially, the magnetostriiction arises from the wall motion of [100] and [010] domains.

FIG. 1. (Color online) Measured (dots) and calculated (line) XRD patterns of Fe$_{82}$Ga$_{9}$Al$_{9}$ alloy, with the bottom spectrum marking the standardline positions. Inset shows the unit cell.

FIG. 2. Al concentration $x$ dependence of the magnetostriiction of Fe$_{82}$Ga$_{18-x}$Al$_{x}$ ($x = 1.5, 3, 6, 4.5, 6, 7.5, 9, 10.5, 12, 13.5, and 15$) alloys at a saturation magnetic field. The samples were prepared using the arc melting method, and magnetostrictic measurements were carried out at room temperature for 0 MPa stress.

FIG. 3. (Color online) Applied magnetic field dependence of magnetostriiction for the DS Fe$_{82}$Ga$_{9}$Al$_{9}$ rod, which was heat-treated at 1150 °C for 1 h and 850 °C for 3 h at 2.3–90 MPa. Inset shows that the compressive stress dependence of saturated magnetostriiction of the sample.
When an applied field $H$ is along the [110] direction, in response to the applied field, 90° and 180° wall motion will take place, which causes the disappearance of [001] and [100] domains and expansion in the [110] direction. With further increase in field, the rotation of [100] and [010] domains causes an additional strain of $\lambda_{111}$ along [110]. Because $\lambda_{111}$ is negative, the strain is a contraction at high field. Therefore, peaks in the magnetostriction can be observed.

The improvement in the magnetostriction performance indicates that DS Fe$_{82}$Ga$_{9}$Al$_{9}$ alloy is a potential candidate for magnetostrictive actuator and transducer applications. To investigate the temperature dependence of the magnetostriction of the DS Fe$_{82}$Ga$_{9}$Al$_{9}$ rod, the magnetostriction versus applied magnetic field relationship was measured under 0 MPa and 15 MPa compressive stress conditions. Figure 4 shows magnetostriction curves at 0 MPa for various temperatures. The results indicate that the alloy has a highly linear magnetostriction curve and low hysteresis, while the saturated field hardly changes. However, the magnetostriction experiences only a little constriction with increasing temperature for applied fields above 10 kA/m. The performance is similar to that of Fe$_{0.81}$Ga$_{0.19}$ at 45.3 MPa for various temperatures. This indicates that no abnormal changes in the $\lambda_{100}$ or $\lambda_{111}$ magnetostriction are occurring. Figure 5 shows the maximum magnetostriction values at various temperatures and 18.8 kA/m applied field and 15 MPa stress. When the compressive stress is 0 MPa, the maximum magnetostriction declines only 11% from 25°C to 120°C, and the temperature dependence ($\Delta \lambda / \Delta T$) is only $-0.16 \times 10^{-6}/^\circ C$. The relatively slight decrease suggests that the anisotropy constants $K_1$ or $K_2$ are subject to no abnormal changes with increasing temperature. However, the magnetostriction declines more significantly, but still slowly up to 13%, from 25°C to 100°C, and the temperature dependence is $-0.51 \times 10^{-6}/^\circ C$ when the stress is 15 MPa. These temperature dependencies of maximum magnetostriction are similar to the trends for Fe$_{0.81}$Ga$_{0.19}$. It is also observed that there is a discontinuous decline in the magnetostriction around 70°C at 15 MPa. A similar change at about 70°C has also been observed in the temperature dependence of the maximum magnetostriction of Fe$_{0.81}$Ga$_{0.19}$ for a 45.3 MPa compressive stress. At the moment, the underlying physics is not understood. However, it might be a result of compressive stress inducing a structural transition in the alloy at some high temperature.

**IV. CONCLUSIONS**

In summary, we have studied the effects of uniaxial compressive stress on the magnetostriction of Fe$_{82}$Ga$_{9}$Al$_{9}$ alloy and the temperature dependence of the magnetostriction. The results indicate that DS Fe$_{82}$Ga$_{9}$Al$_{9}$ alloy has stable magnetostriction of about $22.1 \times 10^{-6}$ under high compressive stress (53 MPa–90 MPa). The Fe$_{82}$Ga$_{9}$Al$_{9}$ alloy also shows weak temperature dependence $(\geq -0.31 \times 10^{-6}/^\circ C)$ over a wide temperature range (25–120°C). The stability under compressive stress and the weak temperature dependence indicate that this alloy might be a potential candidate for industrial or military applications in smart actuators and transducers.

**ACKNOWLEDGMENTS**

This project is supported by the National Natural Science Foundation of China (50971056, 51171057), Tianjin Municipal Education Commission of China (21000314) and the Australian Research Council through two Discovery projects (DP0987190 and DP1094073).

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**FIG. 4.** (Color online) Applied magnetic field dependence of magnetostriction of the DS Fe$_{82}$Ga$_{9}$Al$_{9}$ rod at various temperatures for 0 MPa applied stress.

**FIG. 5.** (Color online) Temperature dependence of magnetostriction of the DS Fe$_{82}$Ga$_{9}$Al$_{9}$ rod at 25–120°C for 0 MPa and 25–100°C for 15 MPa stress.