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Magnetostrictive properties of directional solidification Fe₈₂Ga₉Al₉ alloy

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 135×10^{-6} at 2.3 MPa to 221×10^{-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

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Magnetostrictive properties of directional solidification $\text{Fe}_{82}\text{Ga}_9\text{Al}_9$ alloy

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$\text{Fe}_{82}\text{Ga}_9\text{Al}_9$ 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 135×10^{-6} at 2.3 MPa to 221×10^{-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 λ 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 ($4s^24p^1$) and Al ($3s^23p^1$) are also similar. Gallium (Fe-Ga) alloys are known to have appreciable low field magnetostriction, good mechanical properties, and relatively low cost.^{1–4} Clark *et al.*^{3,5} have found that the magnetostriction of Fe-Ga alloys exhibits a complicated dependence on Ga concentration. Two magnetostriction peaks occur near $\text{Fe}_{82}\text{Ga}_{18}$ and $\text{Fe}_{72}\text{Ga}_{28}$, 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 alloys³ 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 $\text{Fe}_{87}\text{Ga}_4\text{Al}_9$ {100} single crystals was found to increase from 250×10^{-6} at applied compressive stress of 10.3 MPa to 290×10^{-6} at 96.5 MPa.³

In this work we report the effects of compressive stress on the magnetostrictive properties of directional solidification (DS) $\text{Fe}_{82}\text{Ga}_9\text{Al}_9$ 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 magnetostric-

tion, 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 α 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 techniques¹⁰ 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 $\text{Fe}_{82}\text{Ga}_{18-x}\text{Al}_x$ ($x = 1.5, 3, 3.6, 4.5, 6, 7.5, 9, 10.5, 12, 13.5, \text{ and } 15$) 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 $\text{Fe}_{82}\text{Ga}_9\text{Al}_9$ alloy, homogenized at 1100 °C for

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FIG. 1. (Color online) Measured (dots) and calculated (line) XRD patterns of $\text{Fe}_{82}\text{Ga}_9\text{Al}_9$ alloy, with the bottom spectrum marking the standardline positions. Inset shows the unit cell.

3 h, 1000 °C for 120 h, and then 730 °C for 168 h. The results indicate that the sample is single phase, crystallizing in the disordered α -Fe structure (A2) with space group $Im\bar{3}m$ and lattice parameter $a = 2.848(8)$ Å.

The effects of Al concentration on the saturated magnetostriction of $\text{Fe}_{82}\text{Ga}_{18-x}\text{Al}_x$ alloys are shown in Fig. 2. It can be found that the saturated magnetostriction of the alloys increases with increasing Al concentration in the range of $x < 9$, and then it decreases for $9 \leq x \leq 15$. Clearly, the $\text{Fe}_{82}\text{Ga}_9\text{Al}_9$ alloy has the maximum magnetostriction, up to 88×10^{-6} , which is higher than that of polycrystalline $\text{Fe}_{80}\text{Ga}_{20}$ alloy.¹¹ However, high substitution amounts of Al tend to decrease magnetostriction of the Fe-Ga-Al alloys.

It was reported that the magnetostriction of $\text{Fe}_{100-x}\text{Al}_x$ or $\text{Fe}_{100-x}\text{Ga}_x$ alloys increases with increasing x for $x < 19$ due to Ga-Ga and Al-Al pairings.⁶ Wutting *et al.*⁷ have proposed a magnetostriction model based on Ga pairs along the $\langle 100 \rangle$ direction. $\langle 100 \rangle$ next-nearest Ga substitutional pairs in bcc alloys cause short range order, and these pairs create a local tetragonal stress that results in a cubic-to-tetragonal transformation. Therefore, the magnetostriction of the Fe-Ga alloys is proportional to the concentration of Ga pairs.

FIG. 2. Al concentration x dependence of the magnetostriction of $\text{Fe}_{82}\text{Ga}_{18-x}\text{Al}_x$ ($x = 1.5, 3, 3.6, 4.5, 6, 7.5, 9, 10.5, 12, 13.5$, and 15) alloys at a saturation magnetic field. The samples were prepared using the arc melting method, and magnetostrictive 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,¹² $\text{Fe}_{82}\text{Ga}_9\text{Al}_9$ 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 $\langle 100 \rangle$ induce changes in the internal stress, resulting in the enhancement of the magnetostriction of $\text{Fe}_{82}\text{Ga}_9\text{Al}_9$.

The XRD patterns of the alloys prepared by the DS method suggest a $\langle 100 \rangle$ 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 $\text{Fe}_{82}\text{Ga}_9\text{Al}_9$ rod is shown in Fig. 3. It can be seen that the maximum magnetostriction increases with increasing compressive stress from 135×10^{-6} for 0 MPa to 221×10^{-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 magnetostriction reaches saturation. Thus, the magnetostriction increases with increasing applied uniaxial compressive stress, as is shown in inset of Fig. 3. It also can be found that the magnetostriction 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 magnetostriction begins to decrease as the applied magnetic field exceeds the saturated field. The existence of the magnetostrictive peaks may be related to internal texture, which is similar to a phenomenon reported in [110] texture iron single crystals.¹⁰ Initially, the magnetostriction arises from the wall motion of [100] and [010] domains.

FIG. 3. (Color online) Applied magnetic field dependence of magnetostriction for the DS $\text{Fe}_{82}\text{Ga}_9\text{Al}_9$ 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 magnetostriction 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 $[00\bar{1}]$ domains and expansion in the $[110]$ direction. With further increase in field, the rotation of $[100]$ and $[010]$ domains causes an additional strain of λ_{111} along $[110]$. Because λ_{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 $\text{Fe}_{82}\text{Ga}_9\text{Al}_9$ alloy is a potential candidate for magnetostrictive actuator and transducer applications. To investigate the temperature dependence of the magnetostriction of the DS $\text{Fe}_{82}\text{Ga}_9\text{Al}_9$ alloy 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 $\text{Fe}_{0.81}\text{Ga}_{0.19}$ at 45.3 MPa for various temperatures.¹³ This indicates that no abnormal changes in the λ_{100} or λ_{111} magnetostriction are occurring. Figure 5 shows the maximum magnetostriction values at various temperatures and 18.8 kA/m applied field for 0 MPa 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 $-0.16 \times 10^{-6}/^\circ\text{C}$. 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 $-0.31 \times 10^{-6}/^\circ\text{C}$ when the stress is 15 MPa. These temperature dependencies of maximum magnetostriction are similar to the trends for $\text{Fe}_{83}\text{Ga}_{17}$.⁸ 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 $\text{Fe}_{0.81}\text{Ga}_{0.19}$ for a 45.3 MPa compressive stress.¹³ At the moment, the

FIG. 4. (Color online) Applied magnetic field dependence of magnetostriction of the DS $\text{Fe}_{82}\text{Ga}_9\text{Al}_9$ rod at various temperatures for 0 MPa applied stress.

FIG. 5. (Color online) Temperature dependence of magnetostriction of the DS $\text{Fe}_{82}\text{Ga}_9\text{Al}_9$ rod at 25–120 °C for 0 MPa and 25–100 °C for 15 MPa stress.

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 $\text{Fe}_{82}\text{Ga}_9\text{Al}_9$ alloy and the temperature dependence of the magnetostriction. The results indicate that DS $\text{Fe}_{82}\text{Ga}_9\text{Al}_9$ alloy has stable magnetostriction of about 221×10^{-6} under high compressive stress (53 MPa–90 MPa). The $\text{Fe}_{82}\text{Ga}_9\text{Al}_9$ alloy also shows weak temperature dependence ($\geq -0.31 \times 10^{-6}/^\circ\text{C}$) 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.

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