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# Magnetostriction enhancement of $Fe_{73}Ga_{27}$ alloy by magnetic field annealing

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ABSTRACT

In this work, on the basis of multiphase characterics of near Ga-27 at.% alloy, magnetic field annealing was applied in a directional solidification (DS) ⟨001⟩ oriented $Fe_{73}Ga_{27}$ polycrystalline alloy, and the saturation magnetostriction of 370 ppm under low magnetic field has been achieved. Large numbers of multiphase nanoparticles are precipitated in this process; also the magnetic heterogeneities are used to enhance magnetostriction. Meanwhile, this method provides an approach for developing excellent magnetostrictive materials.



Magnetostrictive materials are playing an increasingly important role in actuators, transducers, and torque sensors, among others [1]. Terfenol-D materials possess giant magnetostriction, but they are extremely brittle and their saturation magnetic fields are too high, limiting practical applications [2]. Meanwhile, Fe-Ga alloys are promising magnetostrictive materials since they show high magnetostriction under low magnetic field [3], high mechanical properties [4], and a high Curie temperature ($Tc > 650$ °C) [5]. The introduction of Ga into the body-centered cubic (bcc) α-Fe may result in several crystal structures such as disordered bcc A2, ordered bcc B2 and $D0_3$, ordered fcc $L1_2$ and hcp $D0_{19}$ [6,7]. So the magnetostriction of Fe-Ga alloys varies with Ga concentration. There are two peaks in the curve of magnetostriction vs Ga concentration in Fe-Ga alloys [8]. The first peak at near Ga-19% is thought to be attributed to the short range order of Ga atoms pairs along the [100] axis of the A2 structure [3], and the second peak at Ga-27% due to the softness of shear elastic constant $\frac{1}{2}(C_{11}-C_{12})$ [8,9]. Previous investigations were mainly focused on the near Ga-19 at.% alloy [10–15]. The magnetostriction of near 27 at.% Ga alloys sharply decreases when the large-area fcc ordered phase appears in the A2 matrix [16]. However, the researches show that the heterogeneities resulted from the nanoscale precipitations can result in local strain in the surrounding of A2 matrix and is thought to be helpful to magnetostrictive property [17–21]. This indicates that the magnetostriction of Fe-Ga alloys is sensitive to structure and heterogeneity of phases. These facts give us clues for reviewing the important role of nanoprecipitations in Fe-Ga magnetostrictive materials. Given that nanoparticles are generally precipitated by aging or annealing for a relatively long time, in this work, numerous multiphase nanoparticles precipitated when magnetic field annealing was applied to the $Fe_{73}Ga_{27}$ alloy in a very short time. Moreover, the saturation magnetostriction λs ($\lambda s = \lambda_{//} - \lambda_{\perp}$) of 370 ppm under a low magnetic field has been achieved in DS ⟨001⟩ oriented $Fe_{73}Ga_{27}$ polycrystalline alloy.

The directional solidification (DS) ⟨001⟩ $Fe_{73}Ga_{27}$ alloy was prepared from high pure Fe (99.9 wt%), Ga (99.99 wt%) by induction melting under the protection of argon gas and grown by the DS processes at a growth rate of 720 mm/h. The ingot was annealed at 1100 °C for 3 h in an argon atmosphere. Samples were cut from the ingot. Each sample was cut into 5 mm length and 4 mm wide for the strain gauge and magnetic field annealing, and its thickness was about 0.3 mm. The length direction (LD) of all samples was along the ⟨001⟩ direction of columnar crystals. The specific heat treatments methods of samples (shown in Table 1) were based on the differential scanning calorimetry (DSC) curve, as shown in Fig. 1(a). The sample was rapidly heated to 720 °C, and held for 2 min under a magnetic field of 1200 Oe along LD, which was higher than the value of saturation magnetic field measured from the magnetostriction curves of the $Fe_{73}Ga_{27}$ alloy (shown in Fig. 4). Finally, the sample was cooled at a rate of 100 °C/min under a magnetic field. Fig. 1(b) showed the crystal orientation information of the DS $Fe_{73}Ga_{27}$ alloy. As can be seen, the DS $Fe_{73}Ga_{27}$ sample consisted of several large columnar grains with a ⟨100⟩ preferred orientation. Electron backscatter diffraction (EBSD, Zeiss, z5) was implemented to obtain the grain orientation information, and FEI Tecnai $G^2$ F30 equipment was employed to get TEM images free of oxidation. The magnetostrictions were measured using a standard strain gauge technique.

Fig. 2 shows the selected area electron diffraction (SAED) patterns of samples in different states with the beam direction parallel to the [110] direction of A2 and B2 phases. The SAED patterns of samples a1, a2, a3

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**Table 1**
The specific heat treatments methods of samples.

| Sample | Treatment | Sample | Treatment |
|---|---|---|---|
| a1 | 860 °C/2 h | b1 | 700 °C/20 h |
| a2 | 860 °C/2 h + 720 °C/2 min | b2 | 700 °C/20 h + 720 °C/2 min |
| a3 | 860 °C/2 h + 720 °C/1200 Oe/2 min | b3 | 700 °C/20 h + 720 °C/1200 Oe/2 min |

are shown in Fig. 2(a1), (a2), (a3), respectively. As can be seen in Fig. 2(a1) and (a2), diffraction spots indexed to $(01\bar{1})$, $(\bar{2}00)$ and $(\bar{2}1\bar{1})$ planes correspond to bcc A2 phase indicated with white lines, and $(\bar{1}\bar{1}1)$, $(\bar{1}1\bar{1})$ and $(\bar{2}00)$ planes correspond to bcc $D0_3$ phase indicated with red lines. In Fig. 2(a1) and (a2), there are also two uncalibrated light spots pointed by two black arrows in Fig. 2(a2) symmetrically distributing on both sides of the $[\bar{1}00]$ direction of A2 matrix, and this fact indicates that the matrix lattice is not that purity. In Fig. 2(a3), besides A2 and weakened $D0_3$ phases, the diffraction spots indexed to (100), $(01\bar{1})$ and $(11\bar{1})$ planes correspond to fcc $L1_2$ phase indicated with blue lines, and $(\bar{1}1\bar{1})$, $(\bar{3}1\bar{1})$ and $(\bar{2}00)$ planes correspond to fcc A1 phase indicated with yellow lines (referring to fcc Aluminum phase, group number: 225, a = b = c = 4.0494 Å). Furthermore, a variant of $L1_2$ phase appears in Fig. 2(a3) indicated with blue lines, which is symmetrical to itself along the [100] direction. Meanwhile, two uncalibrated

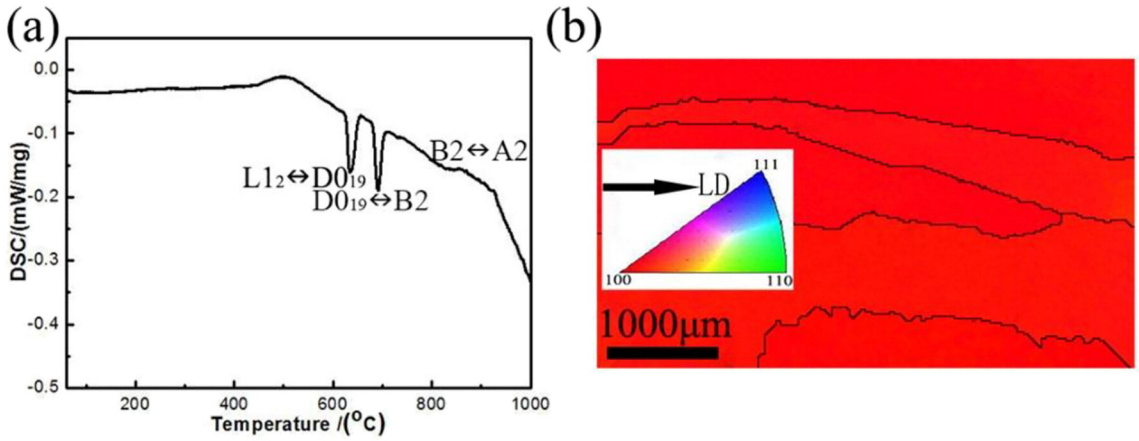


**Fig. 1.** (a) DSC curve of the DS $Fe_{73}Ga_{27}$ polycrystalline alloy with a ⟨001⟩ preferred direction, (b) Crystal orientation information along LD.

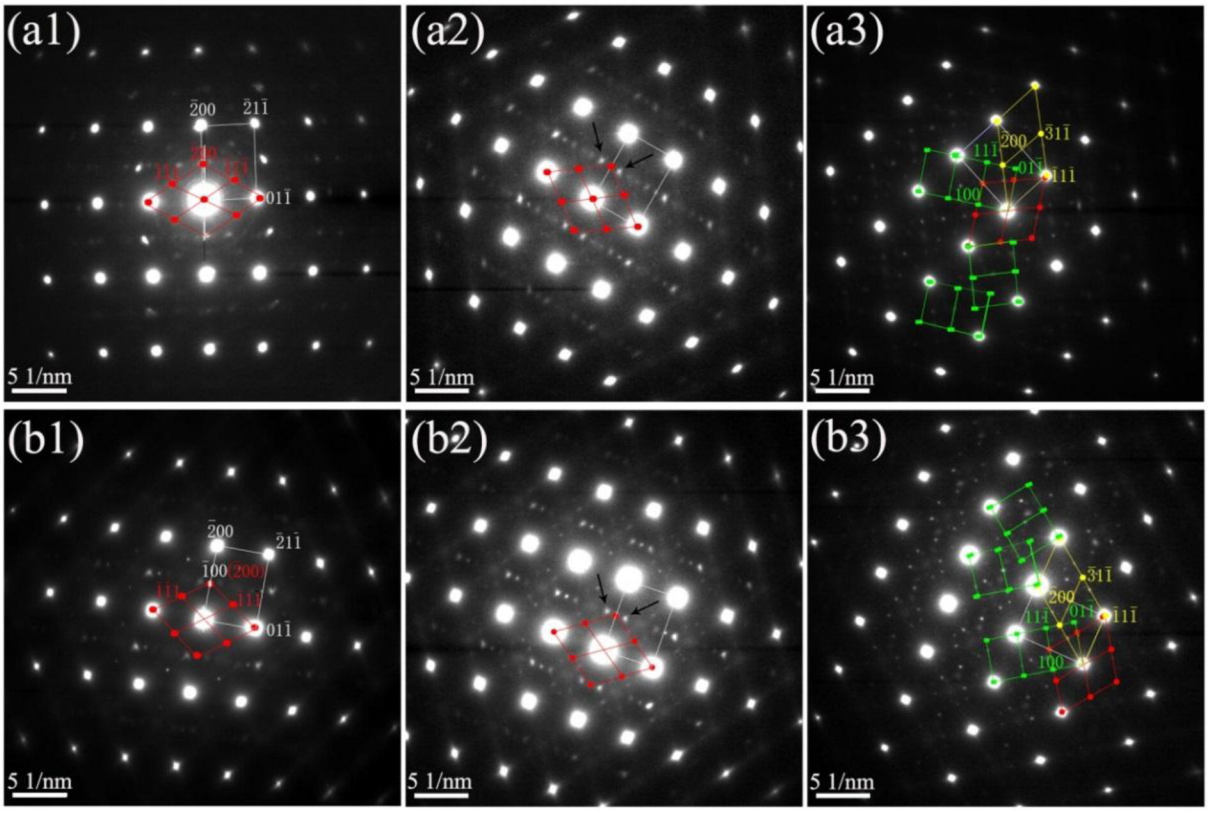


**Fig. 2.** SAED patterns of samples in different states with the beam parallel to the [110] direction of A2 and B2 phases. Images of (a1), (a2), (a3), (b1), (b2), (b3) represent the SAED image of corresponding state sample.