Improved magnetostriction in Fe$_{83}$Ga$_{17}$ alloy by tensile-stress annealing treatment

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Abstract

For optimizing the magnetostriction in Fe–Ga alloys, a novel tensile-stress heat-treatment method has been used for textured polycrystalline rods. Utilizing the consistency between the intrinsic magnetocrystalline anisotropy and the shape anisotropy in the textured structure, a large magnetostriction up to 200 ppm has been obtained in an alloy with composition Fe$_{83}$Ga$_{17}$ without application of pre-stress. Such samples also exhibit large pre-stress adjustable magnitude, about 90% for total magnetostriction. Due to the complete alignment of the magnetic moments, a magnetostriction contribution of the bcc (A2) phase can be ruled out and the magnetostrictive behavior of the Fe$_3$Ga (DO$_3$) phase has been investigated in detail.

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1. Introduction

In the last few years, Fe–Ga alloys have attracted great attention due to their superior properties, such as magnetostriction with a low saturation field, high mechanical strength, good ductility, negligible magnetic hysteresis and low cost [1–6]. In view of applications, proper alignment of the magnetic moments is very important. For getting full strain performance, a post-growth treatment process is indispensable. Furthermore, an additional external pre-stress usually is required for further aligning the moments. In previous work, compressive-stress annealing of Fe–Ga alloys [7] and tensile-stress-annealing of Fe–Al alloys [8], an alloy system quite similar to Fe–Ga, were commonly used. However, treatment under tensile stress for Fe–Ga alloys has rarely been reported.

In this work, the effects of annealing under tensile stress on textured polycrystalline Fe$_{83}$Ga$_{17}$ rods have been investigated. Due to the longitudinally solidified crystal grains in the textured rod, the magnetocrystalline anisotropy and the shape anisotropy are both in the growth direction. Thus, an optimal treatment should use tensile stress during the post-growth process to align the magnetic moments in this direction. We report improved magnetostrictive behavior and the influence from traces of DO$_3$ phase, found by using different measuring configurations.

2. Experimental

Textured samples were prepared by means of the Czochralski method at a pulling rate of 5 mm/min from the pure metals iron (99.99% pure) and gallium (99.99% pure) with composition Fe$_{83}$Ga$_{17}$. The purpose to select this composition is to have a stable composition dependence of magnetostriction to avoid discrepancies caused by composition variation. Chemical analysis was carried out to confirm that the Ga content of the as-grown rods is close to the starting composition. The as-grown rods were annealed at 640°C under a tensile stress of 100 MPa for 2 h and then were cooled down slowly in the furnace. The rods were examined by X-ray diffraction (XRD) with Cu Kα radiation and a highly (0 0 1)-textured structure along the growth direction was established. The sample dimensions for magnetostrictive measurement are of 10 mm × 6 mm × 6 mm cut from as-grown and annealed rods. The magnetostriction was measured by carefully using the standard strain-gauge technique to ensure the reliability of the measured data. Combined parallel and perpendicular magnetic fields were used to achieve the measuring configurations shown in Fig. 1(a) and (b). The magnetostrictive measurement direction was always in the growth direction of...
the textured rods. In this open magnetic circuit measurement, the demagnetizing effect has not been deducted, because it does not significantly affect the related experimental observation.

3. Results and discussion

Fig. 2 illustrates the magnetostriction measured in the configuration of parallel magnetic field under external compressive stress, as shown in Fig. 1(a). The magnetostriction, denoted by $\lambda_{||}$, has a saturation value of +115 ppm under zero pre-stress, which reflects the high quality of the sample where the magnetostriction contribution from non-180° domains in a free sample. With the compressive pre-stress increasing to 40 MPa, the saturation magnetostriction increases monotonically to a maximum value of +200 ppm, an increase of 85 ppm. This quite large increase of the magnetostriction suggests that the proportion of the moments aligned in the growth direction is more than 1/3, which can be attributed to mutual effect from the magnetocrystalline anisotropy in the ⟨001⟩ orientation and the shape anisotropy of the textured structure. In order to turn these moments out of the 180° state, such large stress is needed.

Fig. 3 illustrates the magnetostriction in the Fe$_{83}$Ga$_{17}$ sample after undergoing a tensile-stressed annealing procedure. When the magnetostriction is measured in a perpendicular magnetic field, in the configuration shown in Fig. 1(b), the largest magnetostriction up to $-\lambda_{||}$ is obtained under zero-stress condition, as shown in Fig. 3(a). This stress dependent magnetostriction behavior is very different from the behavior of samples annealed under compressive stress [7]. With increasing the compressive stress to 44 MPa, the saturation magnetostriction decreased from $-200$ ppm to $-20$ ppm. Compared with the change of about 85 ppm shown in Fig. 2, it shows a quite large adjustable magnitude of 180 ppm, i.e. 90% for the total magnetostriction by pre-stress.

This “anomalous” magnetostrictive behavior should be attributed to a perfect moments alignment in the growth direction achieved by the annealing under tensile stress. The tensile stress trends to align the moments along the growth direction in which the intrinsic magnetocrystalline anisotropy and the shape anisotropy are consistent in a (001)-textured rod. Thus, such a sample shows the largest magnetostriction of $-200$ ppm without the help of pre-stress. Compared with the largest value for the as-grown rod, this observation also strongly suggests that the moments are almost completely aligned in the grown direction. Furthermore, this kind of sample allows a large stress-adjustable magnitude for magnetostriction.
As shown in Fig. 3(b), when the magnetic field is applied in the parallel direction, the saturation magnetostriction $\lambda_{||}$ shows a negative value of $-36$ ppm under zero pre-stress. With increase of the pre-stress, the magnetostriction increases to $144$ ppm. This seems to be an interesting ability of Fe–Ga alloys of which the magnetostriction can be tuned from negative to positive by applying a small pre-stress.

The negative magnetostriction of $\lambda_{||} = -36$ ppm shown in Fig. 3(b) has not been reported before and it cannot be explained by any possible configuration of the moments in an A2 phase. It implies that a second phase may be present, DO3 structure embedded in the A2 structure of the sample [9]. The calculation expected that a negative magnetostriction might arise from DO3 [10], although it is lack of the experimental evidence [11]. In our case, the DO3 structure is a byproduct unwantedly obtained during the process of slowly cooling down. Although, due to the similar atomic scattering factors of Fe and Ga, the Fe$_3$Ga (DO3) structure is difficult to determine with XRD [12], we observe it in the present work by magnetic measurements because, as mentioned above, in this direction the magnetostriction contribution from A2 moments has been effectively ruled out by the tensile treated method.

A detailed look at the Fe–Ga phase diagram [9] indicates that the ordered Fe$_3$Ga (DO3) phase may precipitate if an Fe–Ga alloy is slowly cooled from a temperature above the A2/DO3 transition temperature. In our annealing process, the sample was annealed at a temperature of $640$ °C and cooled down slowly. However, based on the phase diagram, the composition Fe$_{83}$Ga$_{17}$ has a A2/DO3 transition temperature of about $400$ °C, which seems too low, in a relatively short cooling time at temperatures where diffusion is very limited, to precipitate enough amount of DO3 phase to exhibit such large negative magnetostriction. On the other hand, a pre-annealing at a high temperature, even up to $850$ °C, before the tensile-annealing did not show any significant decrease of the negative magnetostriction.

A reasonable explanation for this conflict may be that the A2 structure is not completely disordered and that some DO3 exists locally. Under tensile-stress-annealing conditions, the magnetic moments of the DO3 phase can also be aligned, but in an opposite way from the A2 phase in which the moments of DO3 are perpendicular to the sample-growth direction [13]. Thus, when the magnetic field is applied along the measuring direction, the A2 phase contributes very little magnetostriction, but the DO3 phase exhibits a negative magnetostriction at zero compressive pre-stress, as shown in Fig. 3(b). Under compressive pre-stress, the moments of both the A2 and the DO3 phase will leave their original directions and the contribution from A2 becomes dominant, which results in a shift from a negative to a positive magnetostriction.

Furthermore, one can see that there is a dip shown in some magnetostriction curves. They reflect a combinative effect from both of the positive magnetostriction in A2 phase and the negative magnetostriction in DO3 phase. Under this stressed configuration, the negative magnetostriction decreased and the positive magnetostriction increased with the increase of the stress strength. So we can see that the dips disappeared when the applied stress is above $26$ MPa. This observation also indicates that the DO3 phase has an opposite magnetoelastic relation to that of A2 phase.

We changed the compressive pre-stress to the perpendicular direction, as shown in the inset of Fig. 4, to further investigate the magnetostriction behavior of the DO3 phase. This stress arrangement tends to further align the residual moments of both phases, shielding the A2 influence and highlighting the DO3 magnetostriction. It can be seen that, in a very large stress range, the negative magnetostriction does not change significantly, keeping a value around $\lambda_{||} = -36$ ppm. This result indicates that the negative magnetostriction is purely from the DO3 phase and that the moments in both phases are all aligned effectively by the tensile-stress annealing treatment. However, the present work indicates that, like has been pointed by others, the DO3 is not good for the overall magnetostriction of the sample. The present results suggest that fast cooling in the tensile-stress-treatment process or a higher annealing temperature, maybe above $1000$ °C, is required for obtaining homogeneous alloys. It may be expected that the process of tensile-stress heat treatment will be very useful for material preparation and devices design.

4. Conclusions

In summary, a novel method for effectively aligning magnetic moments and improving the magnetostriction has been applied to Fe$_{83}$Ga$_{17}$ by annealing textured polycrystalline rods under tensile stress. Because of the consistency between the intrinsic magnetostrictive anisotropy and the shape anisotropy in the textured structure, the magnetic moments can be completely aligned in the growth direction. A largest magnetostriction up to $200$ ppm was found in a perpendicular magnetic field without application of pre-stress. It also makes that as much as about $90\%$ of the total magnetostriction can be adjusted by stress. Because a magnetostriction contribution of the A2 phase can be ruled out by the built-in internal tensile stress, the DO3 phase is responsible for the observed magnetostrictive behavior.
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References