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Magnetostriction of ternary Fe–Ga–X alloys (X=Ni,Mo,Sn,Al)

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Abstract

Investigations were made into the effect of small additions of Ni, Mo, Sn, as well as larger additions of Al on the magnetostriction of single crystal $Fe_{100-x}Ga_x$ alloys ($x \cong 13$). The Fe–Ga and Fe–Al systems are seemingly unique among the Fe-based alloys in having very large magnetostrictions in spite of Ga and Al being nonmagnetic. In this paper, we show how additions of Ni, Mo, Sn, and Al affect λ_{100} and λ_{111} of the binary Fe–Ga alloys. We substituted small amounts of Ni into a binary Fe–Ga alloy in an attempt to reduce the magnitude of the negative λ_{111}, as Ni does in Fe, in order to improve the magnetostriction of polycrystals. The measured λ_{111}'s were reduced to a very small value, ~3 ppm, butλ_{100} fell dramatically to +67 ppm for $Fe_{86}Ga_{11}Ni_3$. Mo was substituted for Ga to determine the effect of a partially filled 4*d* shell on the magnetostriction. Here $|\lambda_{111}|$ is affected the most, increasing to a value greater than all known α-Fe-based alloys ($\lambda_{111}=-22$ ppm for $Fe_{85}Ga_{10.2}Mo_{4.8}$). We find that the addition of Sn, with its very large atomic radius, makes only small changes in both λ_{100} and λ_{111}. For $Fe_{86.1}Ga_{12.4}Sn_{1.5}$ at room temperature, $\lambda_{100}=+161$ ppm and for $Fe_{86.7}Ga_{12.0}Sn_{1.3}$, $\lambda_{111}=-15$ ppm. The decrease ofλ_{100} in $Fe_{87}(Ga_yAl_{1-y})_{13}$ was approximately linear, going from 67 ppm at y=0 to 154 ppm at y=1.

Keywords

iron alloys, gallium alloys, nickel alloys, molybdenum alloys, tin alloys, aluminium alloys, alloying additions, magnetostriction, crystal structure, magnetic impurities, ferromagnetic materials

Disciplines

Condensed Matter Physics | Metallurgy

Comments

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Investigations were made into the effect of small additions of Ni, Mo, Sn, as well as larger additions of Al on the magnetostriction of single crystal $Fe_{100-x}Ga_x$ alloys ($x \cong 13$). The Fe–Ga and Fe–Al systems are seemingly unique among the Fe-based alloys in having very large magnetostrictions in spite of Ga and Al being nonmagnetic. In this paper, we show how additions of Ni, Mo, Sn, and Al affect λ_{100} and λ_{111} of the binary Fe–Ga alloys. We substituted small amounts of Ni into a binary Fe–Ga alloy in an attempt to reduce the magnitude of the negative λ_{111}, as Ni does in Fe, in order to improve the magnetostriction of polycrystals. The measured λ_{111}'s were reduced to a very small value, ~3 ppm, but λ_{100} fell dramatically to +67 ppm for $Fe_{86}Ga_{11}Ni_3$. Mo was substituted for Ga to determine the effect of a partially filled 4d shell on the magnetostriction. Here $|\lambda_{111}|$ is affected the most, increasing to a value greater than all known α-Fe-based alloys ($\lambda_{111}=-22$ ppm for $Fe_{85}Ga_{10.2}Mo_{4.8}$). We find that the addition of Sn, with its very large atomic radius, makes only small changes in both λ_{100} and λ_{111}. For $Fe_{86.1}Ga_{12.4}Sn_{1.5}$ at room temperature, $\lambda_{100}=+161$ ppm and for $Fe_{86.7}Ga_{12.0}Sn_{1.3}$, $\lambda_{111}=-15$ ppm. The decrease of λ_{100} in $Fe_{87}(Ga_yAl_{1-y})_{13}$ was approximately linear, going from 67 ppm at $y=0$ to 154 ppm at $y=1$. [DOI: 10.1063/1.1452220]

I. INTRODUCTION

The addition of the nonmagnetic elements Al and Ga to bcc Fe greatly increases the magnetostriction in the [100] direction. For Al, the maximum λ_{100} is ~100 ppm at room temperature;[1] for $Fe_{81}Ga_{19}$ samples that are quenched from 800 °C, λ_{100} reaches an astonishing 260 ppm.[2] The available strains (3/2 λ_{100}) for the Fe–Ga alloy are comparable to those of PZT ceramics. At stresses up to 100 MPa, saturation values of the magnetostriction can be reached at fields less than 400 Oe. $Fe_{100-x}Ga_x$($x \cong 17$) alloys show great promise as actuator materials. In addition to their high magnetostriction, they can be machined, welded, and are strong enough to be used as load-bearing members.

This paper reports the results of adding small (<4%) amounts of Ni, Mo, Sn, and larger amounts of Al to these highly magnetostrictive Fe–Ga alloys. The rationale for choosing Ni as an additive follows from the fact that in the Fe–Ga alloys λ_{111} is negative, necessitating the use of single crystal or highly textured polycrystals in order to achieve maximum performance. Bozorth[3] suggested that the addition of Ni to Fe reduces the magnitude of the negative λ_{111}. Mo was chosen to examine the effect of a partially filled 3d electron shell. (Ga has a filled 3d shell and the 3d shell of Al is empty.) The atomic radius of Ga is ~12% larger than Fe; Sn, whose atomic radius is about 30% larger than Fe, was selected as an addition to examine the effects of an even larger atom. Finally, Al was chosen for a ternary addition since $Fe_{100-x}Al_x$ ($x \cong 15$) alloys also have large magnetostrictions.[1]

II. EXPERIMENT

Samples were single crystal disks 6.4 mm in diameter and about 2 mm thick. Two orientations were used for Ni, Mo, and Sn containing alloys, with either [100] or [110] perpendicular to the disk. The Al samples had [100] perpendicular to the disk. The samples were grown by a Bridgman technique using a growth rate of about 2 mm/h. Following crystal growth, all of the samples were annealed at 1000 °C for 168 h and furnace cooled at 10 °C/min. It was difficult to maintain the desired Fe–Ga–X (X=Ni,Mo,Sn,Al) ratios during the growth process. Thus the ratios varied slightly from sample to sample. Magnetostriction data were taken at room temperature on the samples utilizing strain gages glued parallel to the [100] or [111] direction. The samples were placed in a large iron electromagnet and rotated relative to the magnetic field. The resulting data were fit to $S=c+a\cos^2(\theta+\phi)+b\cos^4(\theta+\phi)$, where S is the strain, θ is the rotation angle, a and b are strain amplitudes, and c and ϕ are used to shift the curve. The measured data were a good fit to the function and a was used as the value for (3/2) λ_{100} or (3/2) λ_{111}; b varied from 3% to 12% of a. Measurements were taken at 15 kOe, which was sufficient to saturate the samples. Some difficulties were encountered in the λ_{111} measurements of the Ni alloys due to the very small valves of λ_{111} zones.

III. RESULTS

A. Ni additions

The magnetostriction of four samples containing Ni was measured: $Fe_{86}Ga_{11}Ni_3$ [(100) disk], $Fe_{81.4}Ga_{16.0}Ni_{2.6}$ [(100)

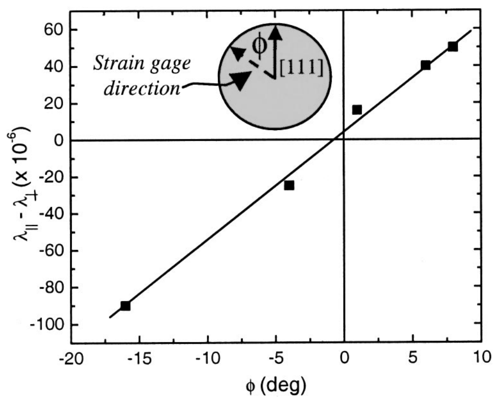

FIG. 1. Magnetostriction ($\lambda_{\parallel}-\lambda_{\perp}$) as a function of offset angle ϕ of strain gage mounting relative to the [111] crystal axis for the $Fe_{81.1}Ga_{16.2}Ni_{2.7}$ [(110) disk] sample.

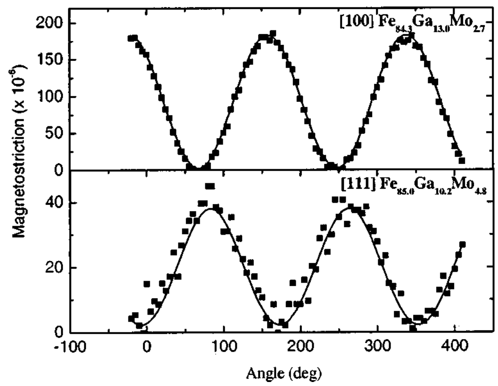

FIG. 2. Magnetostriction at 15 kOe of the $Fe_{84.3}Ga_{13.0}Mo_{2.7}$ [(100) disk] sample and the $Fe_{85.0}Ga_{10.2}Mo_{4.8}$ [(110) disk] sample. The solid lines represent fits to the data using the equation in the text.

disk], $Fe_{87.3}Ga_{10.2}Ni_{2.5}$ [(110) disk], and $Fe_{81.1}Ga_{16.2}Ni_{2.7}$ [(110) disk]. As predicted, the addition of Ni lowered the negative value of λ_{111} substantially. However, the value of λ_{100} also decreased. In the $Fe_{86}Ga_{11}Ni_3$ sample, λ_{100} decreased to 67 ppm or about 60% of the expected value of 109 ppm (assuming Ni replaces Fe substitutionally). In the $Fe_{81.4}Ga_{16.0}Ni_{2.6}$ alloy λ_{100} decreased to 165 ppm, or about 80% of the expected value of 207 ppm.

Difficulty was encountered during the λ_{111} measurements because of the low value of λ_{111}. To lowest order, the measured strain is given by

$$S=\frac{3\lambda_{100}}{2}\left(\sum_i (\alpha_i^2\beta_i^2)-\frac{1}{3}\right)+3\lambda_{111}\sum_{j>i}\alpha_i\alpha_j\beta_i\beta_j, \quad (1)$$

where S is the strain and the α_i and β_i are the direction cosines of the moment and strain measurement relative to the principle axes, respectively. If λ_{111} is small compared to λ_{100} and the strain gage is not precisely oriented parallel to the [111] direction, some of the λ_{100} "leaks" into the measurement. The error is about 2.6% of λ_{100} per degree of misalignment. To obtain the correct value of λ_{111}, strain gages were intentionally mounted off axis and a straight line fit to the results was made; see Fig. 1. The zero offset value was interpolated from the fit. Very low values of -1.3 ppm and $+3.3$ ppm for the $Fe_{87.3}Ga_{10.2}Ni_{2.5}$ and $Fe_{81.1}Ga_{16.2}Ni_{2.7}$ samples, respectively, were obtained.

B. Mo additions

Figure 2 shows λ_{100} for the $Fe_{84.3}Ga_{13.0}Mo_{2.7}$ [(100) disk] sample and λ_{111} for the $Fe_{85}Ga_{10.2}Mo_{4.8}$ [(110) disk] sample. The addition of Mo made λ_{111} more negative (-22 ppm) and reduced λ_{100} about 40% from the expected 202 ppm (assuming Mo substitutes for Ga) to 117 ppm.

C. Sn additions

Figure 3 shows λ_{100} for the $Fe_{86.1}Ga_{12.4}Sn_{1.5}$ [(100) disk] sample and λ_{111} for the $Fe_{86.7}Ga_{12.0}Sn_{1.3}$ [(110) disk] sample. Because Sn is not very soluble in Fe, we were only able to obtain samples with ~1.5% Sn content, which is about half the ternary content of the Ni, Mo, and Al alloys. Both λ_{100} (161 ppm) and λ_{111} (-15 ppm) were nearly unchanged relative to the binary alloy.

D. Al additions

λ_{100} was measured on $Fe_{86.6}Ga_{8.7}Al_{4.7}$ and $Fe_{87.1}Ga_{3.8}Al_{9.1}$ [(100) disk] samples. The sample containing 4.7% Al had a λ_{100} of 123 ppm and the sample containing 9.1% Al had a λ_{100} of 105 ppm. These values indicate an approximately linear decrease in λ_{100} as Al concentration is increased in $Fe_{87}(Ga_yAl_{1-y})_{13}$. See Fig. 4.

IV. DISCUSSION

Figure 5 shows a summary of the results of this study. λ_{100} decreased substantially with the addition of Ni and Mo to the Fe–Ga alloys. The addition of small amounts of Ni to Fe–Ga reduced $|\lambda_{111}|$ to near 0 but also reduced λ_{100} to about 60% of its expected value with a Ni/Ga ratio of 0.27 and to about 80% of its expected value with a Ni/Ga ratio of 0.16. Mo additions to Fe–Ga alloys made λ_{111} more negative and reduced λ_{100}. The addition of Sn left λ_{100} nearly unchanged and the replacement of Ga by Al decreased λ_{100}

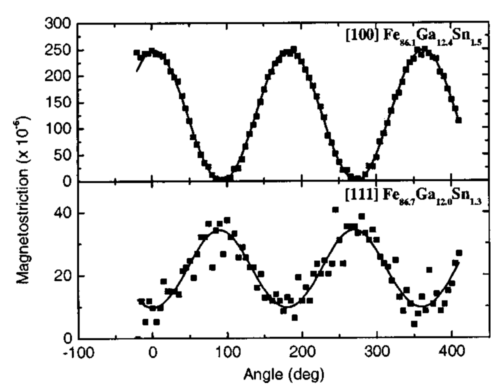

FIG. 3. Magnetostriction at 15 kOe of the $Fe_{86.1}Ga_{12.4}Sn_{1.5}$ [(100) disk] sample and the $Fe_{86.7}Ga_{12.0}Sn_{1.3}$ [(110) disk] sample. The solid lines represent fits to the data using the equation in the text.

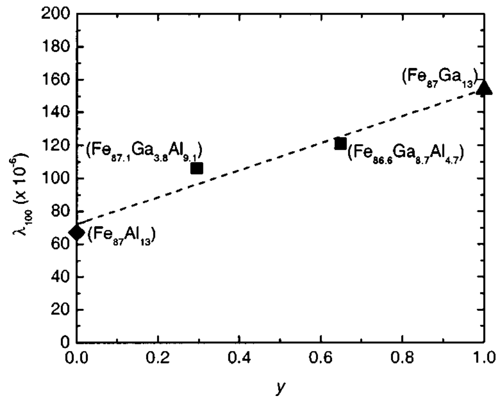

FIG. 4. Nearly linear relationship of λ_{100} vs y for $Fe_{87}(Ga_yAl_{1-y})_{13}$. (◆) taken from Ref. 1; (▲) taken from Ref. 4.

almost linearly. The dashed lines are parabolic fits to the furnace cooled binary Fe–Al (Ref. 1) and Fe–Ga (Ref. 4) systems. The lower left corner of the figure shows the results of adding Sn and Mo to pure Fe.[5]

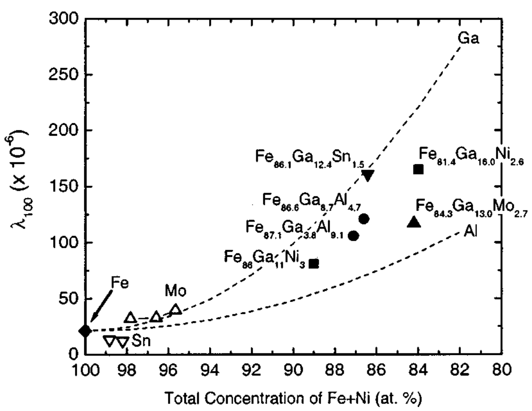

FIG. 5. λ_{100} vs the total Fe+Ni concentration. The results for Sn (▽) and Mo (△) additions to Fe are taken from Hall (Ref. 5). The concentration of Fe–Ga–X alloys [Ni (■); Mo (▲); Sn (▼); Al (●)] is plotted assuming Mo, Sn, and Al replace Ga and Ni replaces Fe. The dashed lines are parabolic fits to the binary Fe–Al and Fe–Ga alloys. The Fe–Al data are taken from Hall (Ref. 1).

After the reductions in λ_{100} caused by the addition of Ni, Mo, and Al, the essentially zero change in magnetostriction with the addition of Sn was unexpected; Sn added to pure Fe decreases the magnetostriction.[5] It was reported in previous studies[2,4] that the magnetostriction of the Fe–Ga alloys peaks at a Ga concentration that is between the α-Fe structure and the DO_3 structure and the magnetostriction appears to depend on a certain amount of disorder.[6] For the case of the Sn addition, it may be that the large size of the Sn atom maintains the required disorder. The details of the magnetostriction in the bcc Fe-based alloys, however, are not well understood.

With the exception of the Sn addition, all ternary additions show a drop in λ_{100}. Ga may be unique in its ability to greatly increase the magnetostriction of Fe.

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