5-15-2003

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Abstract

It is known that the substitution of Co for Fe gives rise to increases in magnetization and Curie temperature, not only in the bcc metals, but also in intermetallic compounds and alloys as well. With the expectation that this is the case in Co-substituted FeGa, we measured magnetization, Curie temperature, magnetostriction and elastic constants of a series of polycrystalline FeCoGa ternary alloys with up to 17% Ga and up to 10% Co. The magnetostriction at saturation for $Fe_{0.93-x}Co_{.07}Ga_x$ increases to 90 ppm for x=0.17. For larger percentages of Co, the rise in magnetostriction is not as sharp as it is in the 7% case. The shear elastic modulus decreases with Ga, again in keeping with the results for FeGa. The magnetostriction and the elastic constants are sensitive to sample preparation for the high-Ga material. We conclude that the substitution of small (<0.10)percentages of Co for Fe in bcc FeCoGa alloys enhances the magnetic and magnetostrictive properties of the parent FeGa material.

Keywords

iron alloys, cobalt alloys, gallium alloys, magnetisation, Curie temperature, magnetostriction, ferromagnetic materials, elastic constants, shear modulus

Disciplines

Condensed Matter Physics | Metallurgy

Comments

The following article appeared in *Journal of Applied Physics* 93 (2003): 8627 and may be found at http://dx.doi.org/10.1063/1.1555980.

Magnetism, elasticity, and magnetostriction of FeCoGa alloys

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(Presented on 15 November 2002)

It is known that the substitution of Co for Fe gives rise to increases in magnetization and Curie temperature, not only in the bcc metals, but also in intermetallic compounds and alloys as well. With the expectation that this is the case in Co-substituted FeGa, we measured magnetization, Curie temperature, magnetostriction and elastic constants of a series of polycrystalline FeCoGa ternary alloys with up to 17% Ga and up to 10% Co. The magnetostriction at saturation for $Fe_{0.93-x}Co_{.07}Ga_x$ increases to 90 ppm for $x=0.17$. For larger percentages of Co, the rise in magnetostriction is not as sharp as it is in the 7% case. The shear elastic modulus decreases with Ga, again in keeping with the results for FeGa. The magnetostriction and the elastic constants are sensitive to sample preparation for the high-Ga material. We conclude that the substitution of small (<0.10) percentages of Co for Fe in bcc FeCoGa alloys enhances the magnetic and magnetostrictive properties of the parent FeGa material. [DOI: 10.1063/1.1555980]

I. INTRODUCTION

Recently, it was shown that FeGa alloys exhibit an extraordinary increase in magnetostriction as the Ga content increases; up to about 20% Ga substituted for Fe.[1] At room temperature, λ_{100} peaks at about 230 ppm for $Fe_{81}Ga_{19}$.[2] The FeGa solid solution is thus a candidate for an inexpensive ductile, highly magnetostrictive alloy.

The magnetostriction of body centered cubic (bcc) Fe is known for its nearly compensating constants ($\lambda_{100}=20$ ppm, $\lambda_{111}=-16$ ppm) at room temperature[3] and anomalous temperature dependence. The addition of some nonmagnetic elements strongly alters this anisotropy and enhances the magnetostriction. The replacement of a small fraction of Fe atoms by these nonmagnetic elements is found to both lower the magneto-crystalline anisotropy and reduce the temperature anomalies. In the case of a small decrease in the magnitude of λ_{111}, a large increase in λ_{100} occurs.[4] FeGa alloys exhibit an even greater increase in magnetostriction as the Ga content increases, up to about 20% Ga substituted for Fe.[1] It is known that the substitution of Co for Fe gives rise to increases in magnetization and Curie temperature, not only in the bcc metals, but also in intermetallic compounds and alloys. The influence of the substitution of cobalt for Fe was thus expected to enhance the magnetostrictive properties of the parent FeGa alloys.

Accordingly, the purpose of this work is to investigate the influence of Co substituted for iron in FeGa alloy. Based on this purpose, the elastic constants, magnetization, Curie temperature and magnetostriction of a series of polycrystalline FeCoGa ternary alloys were measured that contain up to 17% Ga and up to 10% Co.

II. RESULTS AND DISCUSSION

Pursuant to the purpose of this work, a series of polycrystalline FeCoGa ternary alloys were prepared and the shear modulus, magnetostriction and Curie temperature of each were measured. The moduli were measured by the continuous wave method. The Curie temperatures were measured using the superconducting quantum interference device. The magnetostriction was measured using Micro Measurement EA-06-062AP-120 strain gauges bonded to the specimens with M-Bond 200 glue. All polycrystalline samples were quenched in ice water from 900 °C before magnetostriction measurements were attempted.

The Curie temperatures were determined from the magnetization curves at high temperature. It was found that T_c increases with the substitution of Co for Fe as expected. For fixed Co concentration, T_c decreases with Ga substitution, as it does in FeGa.[6] The general trends are depicted in a three-dimensional plot in Fig. 1. Figure 2 demonstrates how the shear elastic modulus changes with the composition of these polycrystalline FeCoGa alloys. The modulus decreases with the substitution of Co for fixed Ga content. Finally, the saturation magnetostrictions[5] (λ_s) are plotted in Fig. 3. The general trend is a monotonic increase in λ_s with Ga for fixed Co concentrations. However, as shown more precisely in Fig. 4, there is a marked difference in the rate of increase between low-cobalt alloys and those with cobalt concentrations greater than 7%. For the former, the dependence on Ga concentration is similar to what is found in $Fe_{1-x}Ga_x$; while in the later, the increase with Ga is less pronounced. One result of this difference is the striking decline in λ_s for 17% Ga

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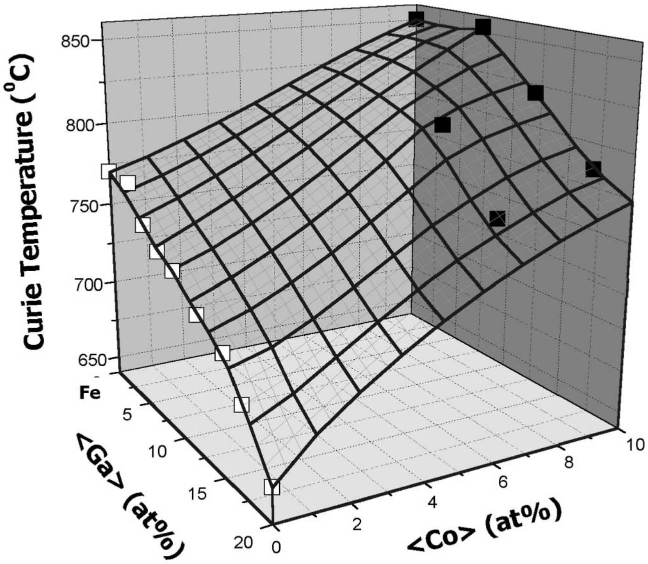

FIG. 1. Three-dimensional plot of the Curie temperature of the polycrystalline FeCoGa alloys. The solid squares are the experimental data. For comparing to the experimental data, the open squares are taken from the Fe–Ga phase diagram (see Ref. 6). The three-dimensional plot was fitted by both the experimental data and the calculated results.

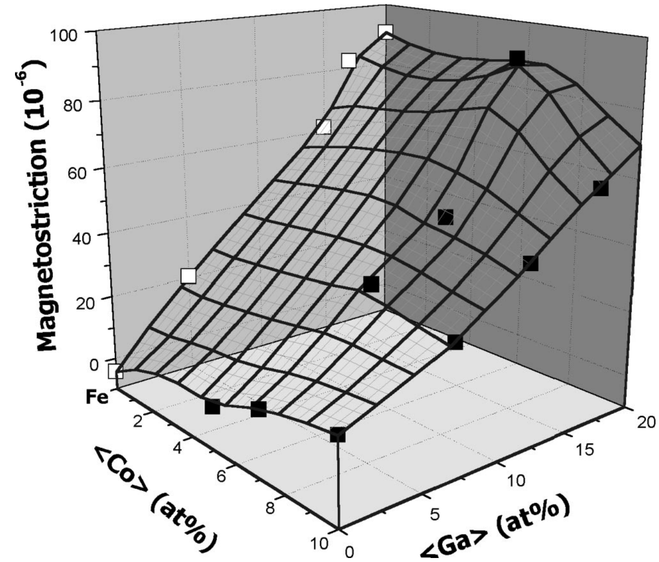

FIG. 3. Three-dimensional plot of the magnetostriction of the polycrystalline FeCoGa alloys. The solid squares are the experimental data. For comparing to the experimental data, the open squares are calculated results from the magnetostriction constants of FeGa single crystal,[2] i.e., $\lambda_s = 2\lambda_{100}/5 + 3\lambda_{111}/5$.

alloy created by a small increase in Co (7%–10%). Magnetostriction measurements on two FeCoGa single crystals were made available to us, as shown in Table I.[5] Both contain about 17% Ga, one with 10% and the other 15% Co. The single crystal results bear out the fact that including more than about 10% Co in FeCoGa has a detrimental effect on λ_s. Specifically, it shows that λ_{100} is most affected. It is almost a factor of 5 smaller in $Fe_{68}Co_{15}Ga_{17}$ than it is in $Fe_{83}Ga_{17}$.

As mentioned in the introduction, FeGa alloys exhibit an extraordinary increase in magnetostriction as the Ga content increases up to about 20% Ga.[1] It has also been demonstrated that the $(C_{11}-C_{12})$ for $Fe_{1-x}Ga_x$ decreases rapidly with x, extrapolating to zero for $x \approx 0.25$.[6] Figure 2 shows that in polycrystalline FeCoGa alloys, increasing the Ga content results in a decreasing shear elastic modulus. The moduli for zero Co are in agreement with those obtained by averaging

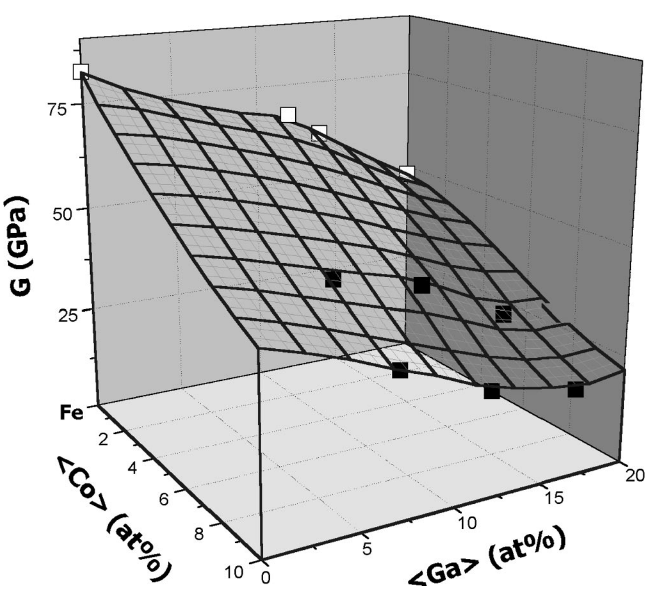

FIG. 2. The shear elastic moduli of the polycrystalline FeCoGa ternary alloys are schematically shown in a three-dimensional graph. The solid squares are the experimental data of these polycrystals. The opened squares are calculated results, which are data converted from the elastic constants of FeGa single crystals (see Ref. 7) by averaging the Reuss and Voigt approximations.

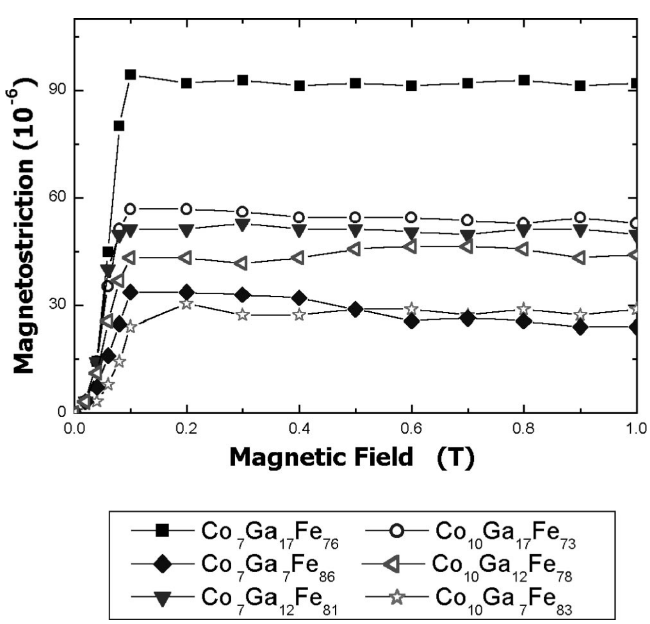

FIG. 4. Schematic of the magnetostriction changing with the magnetic field. The solid spots (square, triangle and circle) are the series of alloys with 7% cobalt; on the other hand, the open spots are the series of alloys with 10% cobalt. For larger percentages of cobalt, the magnetostriction actually decreases with Ga concentration.

TABLE I. FeCoGa single crystal magnetostrictions from the Naval Surface Warfare Center with Ga∼17 at. % (see Ref. 7).

Co at. %	$\frac{3}{2}\lambda_{100}$ (10^{-6})	$\frac{3}{2}\lambda_{111}$ (10^{-6})	$\frac{3}{2}\left(\frac{2}{5}\lambda_{100}+\frac{3}{5}\lambda_{100}\right)$ (10^{-6})
10	118	10	54
15	43	29	48

the C_{44} and $(C_{11}-C_{12})$ values measured in single crystal $Fe_{1-x}Ga_x$.

Increasing the Co content decreases the Ga effect in the property of magnetostriction. Figure 4 depicts clearly that the magnetostriction rises more efficiently with increasing Ga content in the series of 7 at. % cobalt alloys $(Co_{0.07}Fe_{(0.93-x)}Ga_x)$ as compared to the 10% case $(Co_{0.1}Fe_{(0.9-x)}Ga_x)$. However, a larger percentage of Co gives rise to a smaller increase in the magnetostriction.

III. CONCLUSION

In summary, despite the increase in Curie temperature and the slight decrease in shear modulus, adding Co to FeGa has little or no effect on the magnetostriction of FeCoGa, for low Ga concentrations. It has a detrimental effect on samples that have Ga concentrations near the ‘‘critical’’ concentration of about 19% Ga.

ACKNOWLEDGMENTS

This work is supported by the Office of Naval Research, Contract Nos. N000149910837, N000140010849 and MURI N000140110761. It also benefits from the support of the National Science Foundation, Grant No. DMR 0095166. One of the authors (T.L.) acknowledges the support of the Office of Basic Energy Sciences, Materials Sciences Division, of the U.S. Department of Energy under Contract No. W-7405-ENG-82.

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