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Temperature dependence of the magnetostriction and magnetoelastic coupling in Fe100–xAlx (x = 14.1,16.6,21.5,26.3) and Fe50Co50

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Abstract

In this paper, we report magnetostriction measurements, (λ_{100}) on Fe-rich Fe–Al alloys and $Fe_{50}Co_{50}$ as functions of temperature from 77 K to room temperature (RT). From these measurements and elastic constant (c') measurements, the tetragonal magnetoelastic coupling constants (b_1's) were calculated. Significant differences were found between our RT measurements and earlier magnetostriction measurements for the higher Al concentration alloys (16.6%, 21.5%, 26.3% Al) and the $Fe_{50}Co_{50}$ alloy. Reminiscent of the temperature dependence of λ_{100} for pure Fe, magnetostriction changes with temperature are minimal for Fe–Al alloys having the disordered bcc ($A2$)structure (x<19% Al). In contrast, the alloy possessing the ordered ($D0_3$) structure shows an anomalous decrease in magnetostriction in λ_{100} with decreasing temperature. For the Fe–Al alloy system, the magnetoelastic coupling constant, $|b_1|$, exhibits a peak at room temperature maximizing at 16.6% Al with a value of 12.3 MJ/m^3. For $Fe_{50}Co_{50}$, $|b_1|$ was calculated to be ~ 34 MJ/m^3 at room temperature.

Keywords

aluminium alloys, cobalt alloys, elastic constants, iron alloys, magnetoelastic effects, magnetostriction

Disciplines

Condensed Matter Physics | Metallurgy

Comments

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Temperature dependence of the magnetostriction and magnetoelastic coupling in $Fe_{100-x}Al_x$ ($x=14.1, 16.6, 21.5, 26.3$) and $Fe_{50}Co_{50}$

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In this paper, we report magnetostriction measurements, (λ_{100}) on Fe-rich Fe–Al alloys and $Fe_{50}Co_{50}$ as functions of temperature from 77 K to room temperature (RT). From these measurements and elastic constant (c') measurements, the tetragonal magnetoelastic coupling constants (b_1's) were calculated. Significant differences were found between our RT measurements and earlier magnetostriction measurements for the higher Al concentration alloys (16.6%, 21.5%, 26.3% Al) and the $Fe_{50}Co_{50}$ alloy. Reminiscent of the temperature dependence of λ_{100} for pure Fe, magnetostriction changes with temperature are minimal for Fe–Al alloys having the disordered bcc ($A2$) structure ($x<19\%$ Al). In contrast, the alloy possessing the ordered ($D0_3$) structure shows an anomalous decrease in magnetostriction in λ_{100} with decreasing temperature. For the Fe–Al alloy system, the magnetoelastic coupling constant, $|b_1|$, exhibits a peak at room temperature maximizing at 16.6% Al with a value of 12.3 MJ/m^3. For $Fe_{50}Co_{50}$, $|b_1|$ was calculated to be ~ 34 MJ/m^3 at room temperature. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2831360]

INTRODUCTION

In the iron rich $Fe_{100-x}Al_x$ and $Fe_{100-x}Ga_x$ alloys, the tetragonal distortions, λ_{100}'s, have unusual solute dependences.[1,2] As the nonmagnetic elements are added to iron, λ_{100}'s rise approximately quadratically, exhibiting large magnetostrictive peaks in both alloy systems at $x=\sim 20$. The λ_{100} values decrease sharply beyond this point as the $A2$ structure undergoes chemical ordering. Since the strength of the magnetoelastic coupling b_1 depends upon the product of the magnetostriction and the elastic constants c, $b_1 = -3\lambda_{100}c'$ [$c' = (c_{11} - c_{12})/2$], in order to compare b_1 in Fe-based alloys, e.g., Fe–Al, Fe–Ga, and Fe–Be, knowledge of both the λ_{100} and c's temperature and solute concentration dependence is vital.

Room temperature magnetostriction measurements of Fe–Al alloys indicating a five-fold rise in magnetostriction with Al additions up to 30% Al were made in 1960 by Hall.[1] Measurements at $x=9.1$ and 16.3 by Gersdorf[3] about the same time indicated that the magnetostriction decreases moderately with temperature, and latter measurements by Cook and Pavlovic[4] on alloys near 25% Al reveal an anomaly near 220 K. Not all measurements are in agreement[4] and none have reported values of the magnetoelastic constants. To determine the values of these constants in this paper, we measured the magnetostrictions of $Fe_{100-x}Al_x$ ($x=14.1$, 16.6, 21.5, and 26.3) as functions of temperature and interpolated the elastic constant measurements of Leamy *et al.*[5]

In this paper, the magnetoelasticity of the Fe-rich Fe–Al alloys is compared to those of the similar highly magnetostrictive Fe–Ga alloys (Al and Ga belonging to column IIIB elements) and the Fe–Be alloys (column IIA) whose large magnetostriction and temperature dependent elastic moduli have been recently measured[2,6–8] plus an important highly magnetostrictive alloy $Fe_{50}Co_{50}$.[9]

EXPERIMENT

Single crystal samples (~ 15 mm diam $\times$ 25 mm length) of $Fe_{85.9}Al_{14.1}$, $Fe_{83.4}Al_{16.6}$, $Fe_{78.5}Al_{21.5}$, and $Fe_{73.7}Al_{26.3}$, were prepared using the Bridgman method as described elsewhere.[10] $Fe_{50}Co_{50}$ alloys were prepared using a modified strain annealing procedure, wherein the alloys were first processed using the Bridgman method to produce large crystals of the high temperature fcc phase which in turn resulted into large bcc phases at room temperature. Then, using a conventional strain annealing method (950 °C, 1 week), bcc crystals were grown of sufficient size to extract specimens for strain and elastic constant measurements. Standard strain gauge techniques were used to calculate values of $(3/2)\lambda_{100}$ as functions of temperature between 77 K and room temperature. [The quantity $(3/2)\lambda_{100}$ represents the maximum magnetostriction (sometimes denoted by $\lambda^{\gamma,2}$ or h_1) and is the actual value measured.]

Shown in Fig. 1 are the values of $(3/2)\lambda_{100}$ for samples of Fe–Al from 77 K to room temperature. For the 14.1% and 16.6% Al alloys, the magnetostriction is almost temperature independent, akin to that of Fe.[11] A very large magnetostriction is found for the 16.6% Al alloy. For the 21.5% Al alloy,

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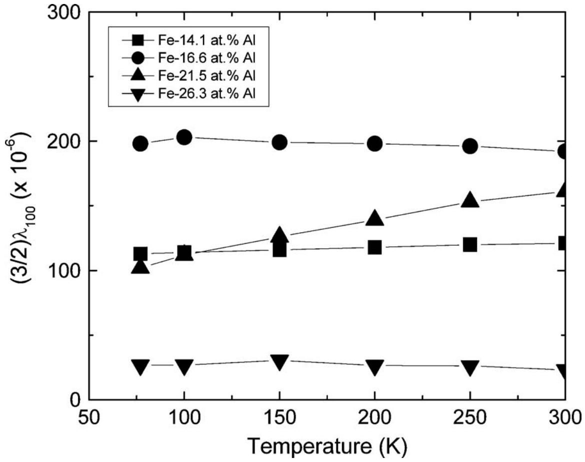

FIG. 1. $(3/2)\lambda_{100}$ for Fe-rich Fe–Al alloys from 77 K to RT.

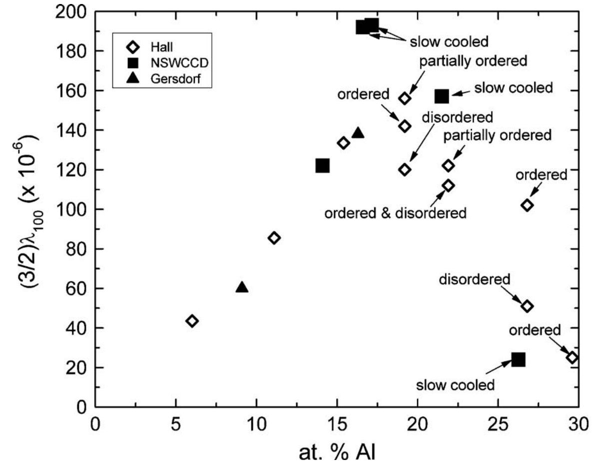

FIG. 3. Comparison of $(3/2)\lambda_{100}$ magnetostriction data of Fe-rich Fe–Al alloys at RT from this paper and those of Hall (Ref. 1), and Gersdorff (Ref. 3).

the magnetostriction temperature dependence is anomalous, with a large (50%) increase in magnitude with temperature. At 26.3% Al, the $(3/2)\lambda_{100}$ remains very small (less than iron) at all temperatures. We found that for the $Fe_{50}Co_{50}$ alloy, $(3/2)\lambda_{100}$ is about 1.5 times that of the largest magnetostrictive Fe–Al alloy and exhibits the anomalous increase in magnetostriction with temperature. See discussion section.

DISCUSSION

Using the magnetostriction data of Fig. 1 and the elastic constants from Leamy *et al.*,[5] the temperature dependences of the tetragonal magnetoelastic constants (b_1's) were calculated for the Fe–Al alloys. Between 77 K and room temperature, only small temperature dependences were found in the c' elastic constants, the elastic constants decreasing ~6% for the 14.1% alloy and ~12% for the 26.3% alloy. Figure 2 shows the b_1's calculated using the relationship $b_1 = -3\lambda_{100}c'$. For the 14.1% alloy, the small rise in $(3/2)\lambda_{100}$ with temperature is offset by the small decrease in c' over this temperature range yielding an almost temperature independent b_1. The magnetoelastic features of the other Fe–Al alloys remain similar to those of the magnetostrictions. The temperature dependent anomaly of the 21.5% alloy still exists. The low magnetostriction values of the 26.3% alloy are consistent with the proximity of this alloy to the Curie temperature.

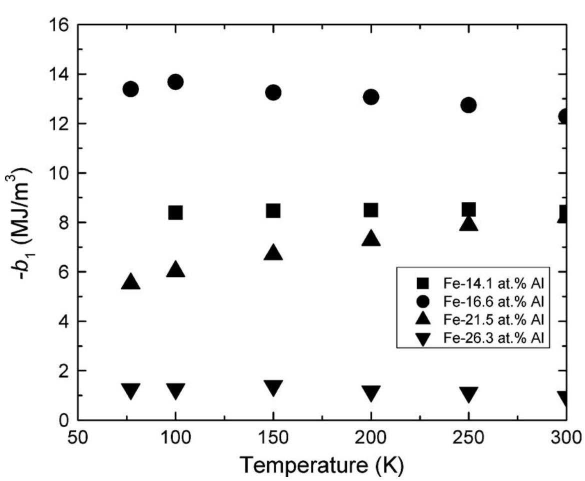

FIG. 2. Magnetoelastic coupling, $-b_1$, for Fe-rich Fe–Al alloys from 77 K to RT.

In Fig. 3, $(3/2)\lambda_{100}$ for the Fe–Al alloys at room temperature are compared to those reported earlier by other authors. A striking disagreement is found in the vicinity of the 16.6% Al sample. The value of $(3/2)\lambda_{100}$ reported in this paper is ~40% higher than indicated by Hall[1] and Gersdorf[3] for similar Al concentrations. This is different from the 14.1% sample where the agreement is excellent. Our samples and those of Gersdorf were both prepared by slow cooling, although the alloys of Gersdorf also included a deoxydizing procedure before single crystal growth.[3] Hall reports furnace cooled alloys, chamber cooled alloys, and water quenched alloys, which he calls ordered, partially ordered, and disordered alloys, respectively.[1] (The exact cooling rates of the Hall and Gersdorf alloys were not reported.) At a concentration of ~19% Al, the magnetostriction reported by Hall was found to be strongly dependent upon atomic ordering, with the *partially* disordered samples having a larger $(3/2)\lambda_{100}$ than both the disordered and ordered samples. The degree of atomic ordering is not believed to be the cause of the large discrepancy in the results near the 16.6% Al alloy. Similarly, ordering apparently cannot account for the large difference (~33%) in our reported measurements and those of Hall near 22% Al, where Hall finds only a minimal effect of ordering on $(3/2)\lambda_{100}$. On the other hand, ordering was again found to have a great effect on $(3/2)\lambda_{100}$ for alloys near 27% Al, with the magnetostriction of the ordered state over a factor of 2 larger than that of the disordered state.[1] Because of the importance of ordering near 27% Al and the rapid drop in Curie temperature near this composition,[12] $(3/2)\lambda_{100}$ at this concentration is likely to be dependent upon the details of alloy preparation. The large values of $(3/2)\lambda_{100}$ for alloys with 16.6% and 21.5% Al, plus the relatively large value of c' for these alloys[5] imply large values for the magnitude of b_1 for these concentrations.

It is possible to compare the solute dependences of b_1 of Fe–Al alloys with those of Fe–Ga alloys for Al and Ga concentrations up to ~30% and Fe–Be alloys for concentrations

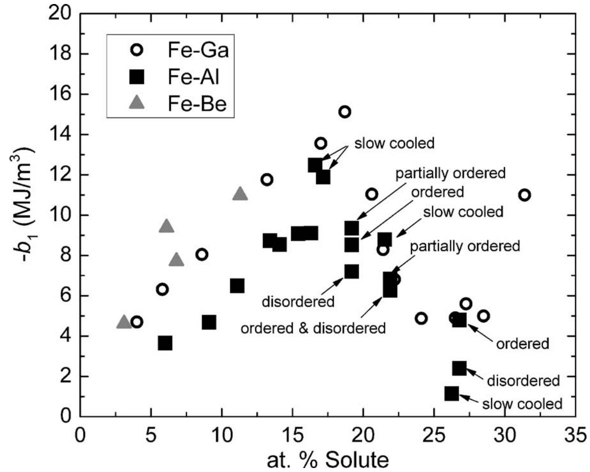

FIG. 4. Comparison of the magnetoelastic coupling, $-b_1$, for Fe-rich Fe–Al, Fe–Ga, and Fe–Be alloys (see text).

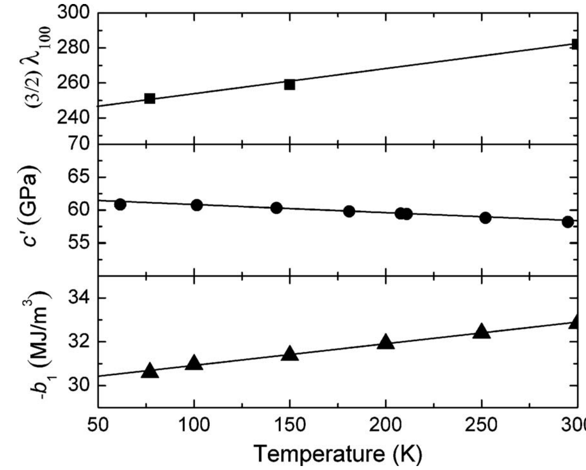

FIG. 5. $(3/2)\lambda_{100}$, c' and $-b_1$ for $Fe_{50}Co_{50}$. The values of $-b_1$ were calculated from interpolation of the $(3/2)\lambda_{100}$ and c' data. c' data courtesy of Dr. Peterson (Ref. 14).

up to ~11% Be. The decrease in value of c' of Fe–Ga alloys with Ga content is similar to that found in the Fe–Al alloys, however, much larger.[2,7,13] The $(3/2)\lambda_{100}$ of the Fe–Ga alloys are well known.[2] For the Fe–Be alloys, the $(3/2)\lambda_{100}$ and the c''s have also been measured.[8] In Fig. 4 are the compared values of $-b_1$ for Fe–Al, Fe–Ga, and Fe–Be at room temperature. Although the c' of the Fe–Al alloys are larger than those of the Fe–Ga alloys, the greatest magnitudes of b_1 are found in the Fe–Ga system. The largest occurs near 19–20% Ga. Because of the larger c' of Fe–Al, the magnitudes of b_1 are larger than expected from comparing only the magnetostriction values. At ~16.6% Al, the magnitude of b_1 is only a few percent lower than those of the Fe–Ga alloy—the stiffer elastic constant is not quite high enough to compensate for the lower magnetostriction. More magnetostriction measurements of alloys at concentrations between 17% and 20% Al would help determine the important details of the coupling in this critical composition region. Falloffs of the couplings for concentrations of Al and Ga above 20% are rapid; however, while the couplings of the Fe–Al alloy approach to zero (because of the lower Curie temperature), those of the Fe–Ga alloy reverse and rise to a second peak. The $-b_1$ values at lower temperatures (not reported here) show that for Fe–Al, the largest measured value of $|b_1|$ (=13.4 MJ/m^3) occurs for the 16.6% Al sample at 77 K. Reported magnetostriction and elastic constant measurements on the Fe–Be system extend only to ~11% Be. Over this composition range, the coupling is somewhat larger than those of the Fe–Ga alloys and about twice as large as those of the Fe–Al alloys.

In Fig. 5, the magnetostrictions $(3/2)\lambda_{100}$, elastic constants (c'), and magnetoelastic couplings ($-b_1$) of $Fe_{50}Co_{50}$ from 77 K to RT are reported. The earlier magnetostriction measures of Hall for $Fe_{51}Co_{49}$ at RT are significantly lower $[(3/2)\lambda_{100}=248\times10^{-6}]$ than our value at $Fe_{50}Co_{50}$, yielding a value of $-b_1$ about 12% lower than those obtained from measurements reported here. Because of the near temperature independence of c', the anomalous positive temperature dependence observed in the magnetostriction still remains in the temperature dependence of $|b_1|$.

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