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Magnetostriction in Co-rich bcc CoFe Solid Solutions

Liyang Dai and Manfred Wuttig
Dept. of Mat. Sci. & Eng., University of Maryland, College Park, MD 20472

Abstract

The maximum of the magnetostriction in polycrystalline Co-rich CoFe solid solution, first reported in 1932, was investigated. It was found that the magnitude of the magnetostriction depends on the state of the alloy and reaches a maximum, 150 ppm in homogenized arcmelted $Co_{70}Fe_{30}$, when annealed close to the bcc/(hcp+bcc) phase boundary. It is proposed that, similar to FeGa, magnetically induced nano-twinning of martensitic embryos is responsible for the effect.

Keywords; magnetostriction, cobalt-iron alloys, bcc solid solution, coherent precipitate, martensite

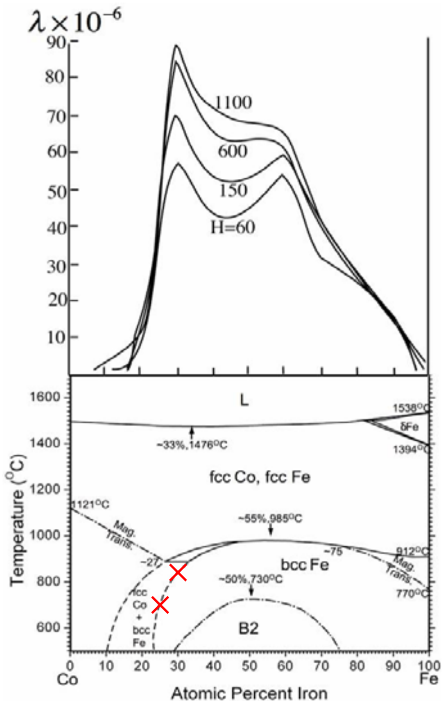

Fig. 1: Top, Joule magnetostriction of slowly cooled CoFe solid solutions according to Masuyama. [8] Bottom, CoFe Phase Diagram.

The large magnetostriction of Iron-Gallium solid solutions has attracted much attention since it was discovered in 2000.[1] The most attractive feature of this alloy is the combination of a technologically interesting magnetostriction with good tensile properties.[2] The values of the magnetostriction depend on the thermal history of the particular FeGa alloy, especially near the bcc/DO_3 and DO_{22}/DO_{19}/$L1_2$//bcc boundaries where the striction rises to two maxima.[3] Both features have recently been interpreted in terms of coarsening resistant metastable martensitic clusters.[4,5] These clusters form when DO_3 precipitates equilibrate by undergoing a displacive transition.[6] This transition is enabled by vacancies that relieve the accompanying volume change. The key prerequisite of this metallurgical reaction is a bcc/fcc or bcc/hcp boundary in a phase diagram where all participating phases are ferromagnetic. Furthermore, vacancies are crucial participants in the reaction. It is thus of interest to inquire into the existence of other ferromagnetic solid solutions in which the above metallurgical reaction might occur.

The large values of the magnetostriction in near stoichiometric CoFe bcc solid solutions have found their way into reference and textbooks.[7,8] The same applies to the old data of the magnetostriction in off-stoichiometric CoFe solid solutions,[9] see Fig. 1. Based on the scenario described in the first paragraph it may be suspected that the peak of the magnetostriction in CoFe solid solutions around the composition $Co_{75}Fe_{25}$ is of similar origin as the one in FeGa. This peak almost certainly pertains to polycrystalline material which, if $\lambda_{111} << \lambda_{100}$ would signal $\lambda_{100} \approx 225 \cdot 10^{-6}$, a respectable value especially since the related commercial alloy, Permedur, is workable. If of similar origin as in FeGa, the above value of λ_{100} in $Co_{75}Fe_{25}$ must be thermal history dependent which is what this letter will report.

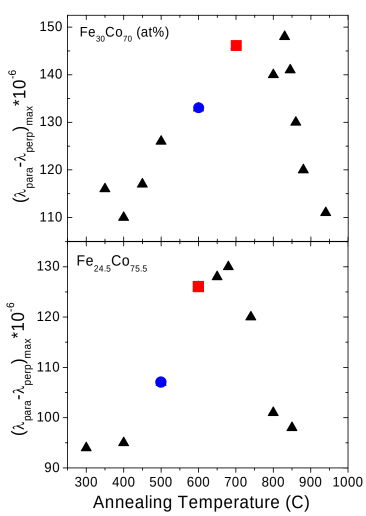

Fig. 2, above: Saturation Joule magnetostriction λ of $Co_{70}Fe_{30}$ (above) and $Co_{75.5}Fe_{24.5}$ (below) as a function of the annealing temperature.

Two CoFe alloys, nominal composition $Co_{75.5}Fe_{24.5}$ and $Co_{70}Fe_{30}$ (at%), were prepared at Ames Laboratory by arc-melting under argon. The buttons were repeatedly remolten and subsequently annealed for 3 days at 1000 ^{0}C to assure homogeneity. Their solidification/annealing microstructure was columnar. The saturation Joule magnetostriction was determined at 0.2 Tesla after annealing the samples at various temperatures via biaxial gauges placed per-

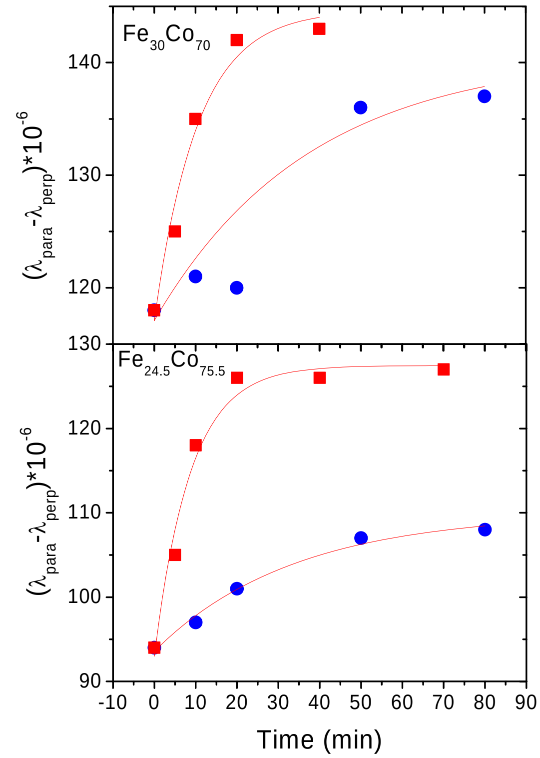

Fig. 3: Time evolution of the Joule magnetostriction.
Above, $Co_{70}Fe_{30}$ annealed at 600^0C, ●●●, and 700^0C, ●●●.
Below, $Co_{75.5}Fe_{24.5}$ annealed at 500^0C, ●●●, and 600^0C, ●●●.
The solid curves represent simple exponential fits, see text.

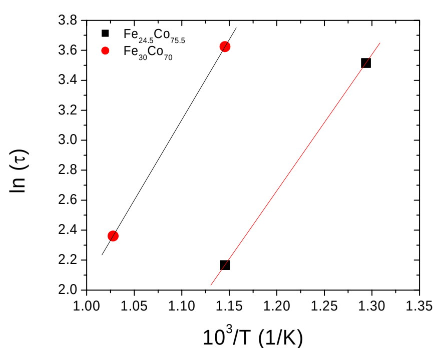

Fig. 4: Arrhenius plot of the characteristic times of the evolution of the magnetostriction in $Co_{70}Fe_{30}$ and $Co_{75.5}Fe_{24.5}$ alloys when annealed at 500^0C, 600^0C and 700^0C.

pendicularly to the columns. All anneals were performed in a tube furnace under argon.

Figure 2 displays the saturation magnetostriction of the two alloys measured as described above as a function of the annealing temperature. For this determination the isothermal anneals were continued until the striction approached an asymptotic value. The two figures indicate that the magnetostriction initially increased up to a maximum only to decay precipitously after traversing this maximum. The maximum magnetostriction attained depends on the alloy composition and annealing temperature. The coordinates of the maxima, composition and annealing temperature, $(c_{max,1};T_{max,1})$ = ($Co_{70}Fe_{30}$;840^0C) and $(c_{max,2};T_{max,2})$ = ($Co_{75.5}Fe_{24.5}$/680^0C), are marked in the Co-Fe phase diagram in Fig. 1, bottom, by crosses, ×. It can be seen that the high values occur when the pairs $(c_{max};T_{max})$ are located just inside the bcc phase field, very similar to the situation for FeGa for which the saturation magnetostriction also drops drastically when the anneals are performed in the equilibrium DO_3 phase field adjacent to the solid solution.

The isothermal annealing behavior of the magnetostriction of the two alloys determined at two temperatures is displayed in Fig. 3. The solid lines in both figures represent a least squares exponential fit of the form $\lambda(t) = [\lambda(\infty) - \lambda(0)][1- \exp(t/\tau)]$ and the data points are color-keyed to Fig. 2. The quantities $\lambda(\infty)$, $\lambda(0)$ and τ denote the asymptotic magnetostriction at long annealing times, the initial magnetostriction and the characteristic time in which the magnetostriction evolves. This time is given by $\tau=\tau_0\exp(\Delta Q/kT)$ where ΔQ and k represent the activation energy of the evolution process and Boltzman's constant, respectively. The Arrhenius plots that can be seen in Fig. 4 yield an average activation energy of (0.85 ±0.15) eV/atom.

The data presented in this letter do demonstrate that the magnitude of the magnetostriction in bcc CoFe alloys around the 75/25 (at%) composition is history dependent. At any one composition it reaches a maximum when annealed at temperatures that are close to the bcc/(hcp+bcc) phase boundary, see the crosses, ×, in the phase diagram, Fig. 2, bottom. The kinetics of the process that give rise to the increase of the magnetostriction are characterized by an activation energy of (0.85 ±0.15) eV/atom.

There are strong resemblances between the high magnetostriction in these two CoFe and the well known FeGa alloys. The location of the maximum of the magteostriction in the bcc CoFe phase diagram mirrors the condition for achieving a high magnetostriction in FeGa alloys. In addition, the reaction giving rise to the high striction is thermally activated. It is thus tempting to suggest that the magnetostriction in the present alloys is, at least in part, extrinsic in origin as has been proposed for FeGa [4,6]. The displacive $DO_3 \rightarrow$ fct ($L1_2$) transition proposed to take place in FeGa would be replaced by the equivalent bcc' $\rightarrow$ fct (fcc) reaction taking place in Co-rich FeCo solid solutions. The formation of the coherent nano-precipitate phase bcc' as well as the needed relief of the bcc'/fct transformation volume would be accomplished by a thermally activated process as demonstrated in this letter. It is possible that the bcc' phase consists of coherently stabilized DO_3. [10] The magnitude of the measured activation energy, (0.85 ±0.15) eV/atom, could represent the activation energy of vacancy motion [11] as expected. The enhanced magnetostriction of bcc Co-rich CoFe alloys would then be the result of the reorientation of martensitically transformed bcc' embryos by nano-twinning.

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