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# Piezomagnetism in Cr doped Fe65Co35 alloy.

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## Abstract

Fe-Co alloys have the highest magnetizations among all existing magnetic materials, 2.45 T for the alloy with 35% Co (% by mass). Regarding magnetostriction, the highest magnetostrictions occurs in Co rich Fe-Co alloys. The piezomagnetic behavior of Fe-Co alloys rich in Fe, that is, the variation of the material's magnetic induction as a function of applied force, was not found in the literature. In the present work, the Fe65Co35 alloy (% by mass) was doped with 0.5% Cr (% by mass) to inhibit the formation of the bcc cubic ordered phase with B2 structure. The purpose is to retain only the disordered bcc phase with A2 structure, as the ordered phase turn out the material brittle. The saturation magnetostriction was determined  $3/2\lambda_s = 61 \times 10^{-6}$  for the doped alloy and  $3/2\lambda_s = 26 \times 10^{-6}$  for the undoped. The enhancement of the magnetostriction imply in an improvement on the magneto mechanical coupling. The magnetic induction as a function of the applied magnetic field was determined for the doped alloy for tensile and compressive stresses ( $\sigma$ ) in the range of  $-100 \text{ MPa} \leq \sigma \leq 100 \text{ MPa}$  and magnetic fields (H) of  $0 < H \leq 5.5 \text{ kA/m}$ . From B vs  $\sigma$  curves a sensitivity as high as  $6 \text{ kA m}^{-1}/\text{MPa}$  was achieved for an applied field of only 3 kA/m.

## Index Terms

Magnetomechanical effects, Magnetostriction, Ferromagnetic materials, Iron alloys.

## **INTRODUCTION**

Force sensors and energy harvesting are applications of ferromagnetic materials that demand the material to have high magnetostriction, consequently a strong magnetoelastic coupling. Due to the magnetoelastic coupling, when a mechanical stress is applied to a ferromagnetic material, its internal strain causes a change in magnetic permeability and this behavior can be used, for example to build a piezomagnetic force sensor. Materials that exhibit positive magnetostriction are more sensitive to compressive forces. Among the materials with high and positive magnetostriction are Terfenol-D ( $\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_2$ ) [1][2], Galfenol ( $\text{Fe}_{81}\text{Ga}_{19}$ ) [3] [4] alloys and Fe-Co alloys. In [5] the authors affirm that " Fe-Co alloys are good candidates for sensors, actuators, and energy harvesters due to their low cost and abundance compared to those of Terfenol-D and Galfenol". Usually the Fe-Co alloys studied for piezomagnetic applications are those with compositions with %Co > 50 %, because they have high magnetostriction than alloys with %Co < 50% [6],[7],[8]. However, Co is also very expensive compared to Fe and the reduction of the Co quantity is also interesting to reduce costs. The Fe65Co35 alloy (% by mass) has the highest magnetization among all existing magnetic materials, namely 2.45 T. Therefore, studies of piezomagnetic behavior have not been accomplished in Fe-Co alloys rich in Fe. In the present work, 0.5% Cr was added to the

Fe65Co35 polycrystalline alloy (% by mass) to inhibit the formation of the bcc cubic ordered phase with B2 structure. The purpose is to retain only the disordered bcc phase with A2 structure, as the ordered phase turns out to be brittle. The magnetostriction ( $\lambda$ ) as a function of the magnetic field (H) was determined for both alloys, Fe65Co35 and (Fe65Co35)99.5Cr0.5. Whereas the magnetic induction (B) as a function of the magnetic field (H) was determined for the doped alloy for tensile and compressive stresses ( $\sigma$ ) in the range of  $-100 \text{ MPa} \leq \sigma \leq 100 \text{ MPa}$  and magnetic fields (H) in the interval of  $0 < H \leq 5.5 \text{ kA/m}$ .

## EXPERIMENTAL PROCEDURE

Ingots of the alloys of approximately 40 g were manufactured using iron (99.8%), cobalt (99.9%) and chromium (99.99%). An arc furnace with a non-consumable tungsten electrode in a water-cooled copper crucible, under an inert argon atmosphere was used in the manufacturing. After melting, the ingots were encapsulated in quartz tubes under an argon atmosphere. Subsequently, the samples underwent a heat treatment in a muffle furnace at a temperature of 1200 °C for a period of 6 hours followed by water cooling to eliminate the segregations produced during solidification of the ingots as well as to reduce the crystalline structure ordering before rolling steps. For the hot rolling process, the ingots were encapsulated under argon in a stainless-steel tube. The hot rolling took place in a FENN 4, model 105 rolling mill, at a temperature of 1100°C. Afterwards, specimens were cut with width  $\times$  length of  $\sim 8 \times 70 \text{ mm}^2$  and the thicknesses were 1.5 mm for Fe65Co35 alloy (61% of thickness reduction) and of 2.5 mm for (Fe65Co35)99.5Cr0.5 alloy (80% of thickness reduction).

Longitudinal and transverse magnetostrictions ( $\lambda_{\text{long}}$  and  $\lambda_{\text{trans}}$ ) of the specimens were measured using strain gages in an SST- type device, a closed magnetic circuit. In this apparatus, a cylindrical primary coil is used to apply the magnetic field (H) along the length plate and the magnetic circuit is closed using two U-type ferrite yokes. The strain gauges are glued to the central region of the specimen, one in the longitudinal direction, parallel to the H direction, and the other transversal to the H direction. The saturation magnetostriction ( $\lambda_s$ ) is obtained through the relations  $\lambda_{\text{total}} = 3/2 \lambda_s = (\lambda_{\text{long}} - \lambda_{\text{trans}})$ .

The magnetomechanical experiment consisted of measuring the magnetic induction of the specimens as a function of the applied magnetic field, for fixed value either tractive or compressive stress. The uniaxial stress was applied to the specimen using a servo hydraulic MTS machine. An external cylindrical bobbin was placed surrounding the specimen for applying the magnetic field and a secondary coil was wound around the material to measure the magnetic induction as the magnetic field was varied as a function of time.

## RESULTS AND DISCUSSION

Fig. 1 depicts the  $\lambda_{\text{long}}$  and  $\lambda_{\text{trans}}$  magnetostriction curves as a function of the applied magnetic field. The values obtained of  $3/2\lambda_s$  is  $23 \times 10^{-6}$  for the Fe65Co35 alloy and  $61 \times 10^{-6}$  for the (Fe65Co35)99.5Cr0.5. In [9] are reported values of  $\sim 80 \times 10^{-6}$  for the Fe65Co35, and the difference compared to the material of the present work is probably due to the material processing. In [9] they observed nano-heterogeneities which were supposed to be responsible for the macroscopically observed enhancement of the magnetostriction. In the

present case the thermomechanical process used to produce the sheets could have increased the size of these nano-heterogeneities, decreasing their efficiency on causing tetragonal distortions in the lattice and consequently the magnetostriction is not so high. However, the Cr addition made up for the lack of the nano-precipitates and the magnetostriction was improved.

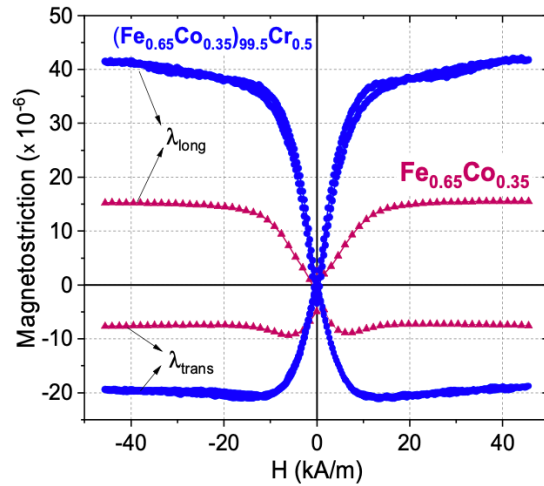


Fig. 1. Longitudinal and transverse magnetostriction as a function of applied field of the  $\text{Fe}_{65}\text{Co}_{35}$  and  $(\text{Fe}_{65}\text{Co}_{35})_{99.5}\text{Cr}_{0.5}$  alloys.

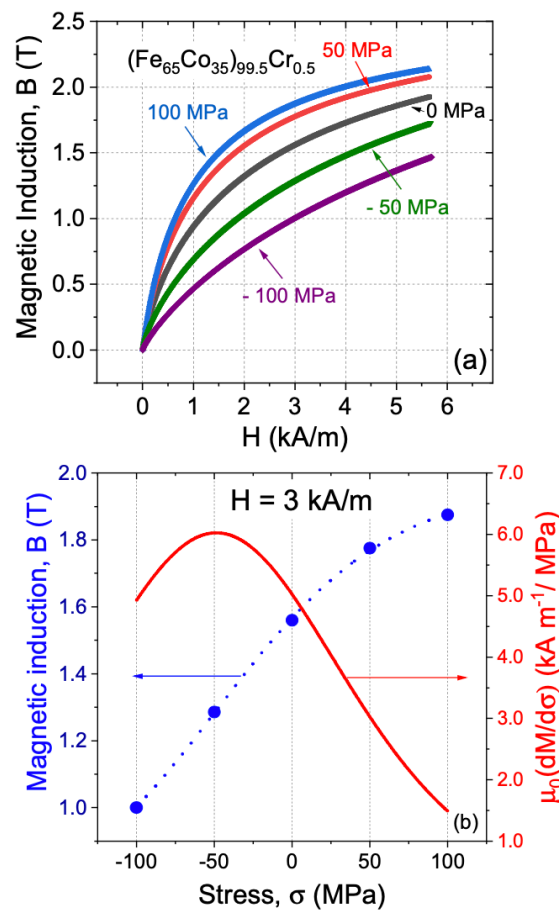


Fig. 2.  $(\text{Fe}_{65}\text{Co}_{35})_{99.5}\text{Cr}_{0.5}$  alloy's curves: (a)  $B$  vs  $H$  for fixed values of applied stresses in the range of  $-100 \text{ MPa} \leq \sigma \leq 100 \text{ MPa}$  and in (b)  $B$  vs  $\sigma$  and  $dM/d\sigma$  vs  $\sigma$  for  $H = 3 \text{ kA/m}$ .

In Fig. 1,  $\lambda_{\text{trans}} \cong -\lambda_{\text{long}}/2$  for both alloys, then the magnetostriction is isotropic and the influence of texture in these magnetostriction values are negligible. The addition of Cr to the Fe<sub>65</sub>Co<sub>35</sub> alloy caused an increase of the magnetostriction of the order of 2.65 times. Somehow the magnetoelastic coupling was enhanced by the presence of Cr in the bcc lattice.

Fig. 2 (a) shows the magnetic induction as a function of the applied magnetic field, for fixed stresses, tensile ( $\sigma > 0$ ) and compression ( $\sigma < 0$ ). Then, from this Fig. 2 (a) it was taken the data of  $B$  vs  $\sigma$  for an applied field of  $H=3\text{kA/m}$ , and the  $B$  vs  $\sigma$  curve was obtained using a Hill type fitting, dotted line in Fig. 2(b). The derivative  $dB/d\sigma$  obtained ( $B \cong \mu_0 M$ ), corresponds to the solid line in Fig. 2(b).

A high rate of change  $d(\mu_0 M)/d\sigma$  is needed for adequate sensitivity of a force sensor, and this should be typically greater than  $1 \text{ kA m}^{-1}/\text{MPa}$ , in giant magnetostrictive materials [9]. From Fig. 2 (b), the sensitivity for  $\sigma < 0$  is in the range of  $5 - 6 \text{ kA m}^{-1}/\text{MPa}$ . This result is interesting, since the material is a polycrystal and could have this sensitivity improved by introducing some texture to the alloy, as it is usually done in the case of the Galfenol [3].

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