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Magnetic anisotropy and magnetostriction in nanocrystalline Fe–Al alloys obtained by melt spinning technique

J.A. García [a], J. Carrizo [a], L. Elbaile [a,*], D. Lago-Cachón [a], M. Rivas [a], D. Castrillo [b], A.R. Pierna [c]

[a] Depto. de Física de la Universidad de Oviedo, c/Calvo Sotelo s/n, 33007 Oviedo, Spain
[b] Depto. de Ciencias de los Materiales de la Universidad de Oviedo, c/Independencia, 33004 Oviedo, Spain
[c] Depto. de Ingeniería Química y Medio Ambiente, EUPSS, UPV/EHU, San Sebastián, Spain

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ABSTRACT

A study about the magnetic anisotropy and magnetostriction in ribbons of composition $Fe_{81}Al_{19}$ and $Fe_{70}Al_{30}$ obtained by the melt spinning technique is presented. The hysteresis loops indicate that the easy magnetization direction lies in both cases on the plane of the ribbon. Torque magnetometry measurements show that the in-plane magnetic anisotropy constant results $10100\ \mathrm{J\,m^{-3}}$ and $490\ \mathrm{J\,m^{-3}}$ for the $Fe_{81}Al_{19}$ and $Fe_{70}Al_{30}$ respectively. After a thermal treatment of 2 h at 473 K to remove the residual stresses, the in-plane magnetic anisotropy constants falls down to $2500\ \mathrm{J\,m^{-3}}$ in the first composition and remains the same in the second one, while the easy direction remains the same.

Measurements of the magnetostriction and the residual stresses of both ribbons allow us to explain the above mentioned results about the magnetic anisotropy and to conclude that the residual stresses via magnetostriction are the main source of magnetic anisotropy in the case of $Fe_{81}Al_{19}$ ribbon but they do not influence this property in the ribbon of composition $Fe_{70}Al_{30}$.

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1. Introduction

Magnetostrictive materials attract a great interest for their use in engineering applications as acoustic sensors, torque sensors, positioning devices, actuators and level devices, among others.

So far, the research developed has been focused on obtaining magnetostrictive materials with low cost, high magnetostriction, low magnetic anisotropy, good mechanical properties and high corrosion resistance.

Special attention has been paid to $Fe_{100-x}Al_x$ and $Fe_{100-x}Ga_x$ alloys due to their low cost and high magnetostriction. Different studies have been performed about the magnetoelasticity [1], magnetostriction [2–5], mechanical properties [6,7] and corrosion resistance [8,9] of Fe–Al and Fe–Ga alloys obtained by different methods. The objective of these studies was the obtaining of materials based in these elements that fit with the above mentioned properties related to their use as sensor elements in low cost sensor devices.

The dependence of the magnetostriction constant λ_{100} on x is similar in both kinds of alloys: it increases with x^2 [10] reaching a maximum value and then, for higher values of x, the magnetostriction decreases because it is impossible to keep the disordered bcc structure that becomes totally or partially a DO_3 structure [11]. Nevertheless, rapid cooling increases the magnetostriction but also creates undesirable internal stresses that results in a magnetic anisotropy.

Recently, the melt spinning technique has been used to successfully produce Fe–Al and Fe–Ga alloys with remarkably high values of the magnetostriction [12–15] and the authors report giant values of the magnetostriction in these materials, reaching values as high as 2000 ppm. Nevertheless, these results have been questioned by Grössinger et al. [16,17] because the magnetostriction had been measured by the strain-gauge technique and the bending of the ribbons would influence strongly its measured value. In addition, the enhancement of magnetostriction in melt spun ribbons has been attributed to the appearance of a short-range preferential ordering of the Al or Ga atoms. The experimental evidence for this hypothesized short-range ordering has been provided by X-ray diffraction patterns of the structural transformation in quenched Fe–Ga alloys [18]. Nevertheles, Sato Turtelli et al. [20] have recently studied melt-spun $Fe_{85}Ga_{15}$ ribbons by extended X-ray Absorption Fine Structure (EXAFS) and X-ray Absorption Near Edge Structure (XANES) and concluded that no Ga–Ga bonds are detected, excluding the tendency to form clusters of Ga atoms. They attributed the increase of the magnetostriction to a local strain originated by Ga substitutes Fe.

From these different results it can be concluded that there is not an agreement about the value and origin of the magnetostriction in these alloys which seem to be dependent on their history.

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* Corresponding author.
E-mail address: elbaile@uniovi.es (L. Elbaile).

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Many magnetostrictive sensors relay on controlling the magnitude of the magnetic anisotropy and the easy magnetization direction [19,20]. In general, the best magnetostrictive material for sensing applications should have low magnetic anisotropy to allow easy rotation of magnetic domain to generate magnetostrictive deformation.

In spite of the fact that the magnetostriction of Fe–Al alloys has been extensively studied, only few articles are devoted to study their magnetic anisotropy. Hall [21,22] has studied this property in single crystals of FeAl and concluded that the anisotropy K_1 for ordered and disordered FeAl alloys reduces sharply with increasing Al content, goes through zero at some composition and then changes sign. The composition of zero anisotropy alloys varies between 22 and 27 at% Al depending of the degree of ordering which in turn depends on the thermal treatment. In addition, Morita [23] has studied the variation of the magnetocrystalline anisotropy with annealing and has also induced magnetic anisotropy in these materials by magnetic annealing. Nevertheless, the magnetic anisotropy of Fe–Al ribbons obtained by melt-spinning has not been studied to date.

In this work, a study about the magnetic anisotropy and its origin in two FeAl ribbons obtained by melt spinning technique, one with high magnetostriction and composition $Fe_{81}Al_{19}$ and the other with composition $Fe_{70}Al_{30}$ which is near the limit of Fe content, that makes the ribbon magnetic, is presented. The magnetostriction of these alloys combined with their residual stresses provides a coherent understanding of their magnetic anisotropy.

2. Experimental procedure

Master alloy ingots of $Fe_{81}Al_{19}$ and $Fe_{70}Al_{30}$ were prepared by arc-melting the constituent elements in argon atmosphere. From these ingots pieces of about 6 g were melt spun to ribbons of 5 mm width and 25 μm and 30 μm thick for $Fe_{81}Al_{19}$ and $Fe_{70}Al_{30}$ respectively. The chemical composition of the ribbons was determined by inductive coupled plasma.

The structural characterization of the samples was performed by X-ray diffraction on a Seifert XRD 3000 with Cu $K\alpha$ radiation.

The magnetic characterization of the samples at room temperature was performed using a Vibrating Sample Magnetometer (EV9 VSM).

The magnetic anisotropy was determined by torque magnetometry, using a very sensitive torque magnetometer developed in our laboratory. A detailed description of the device can be found elsewhere [24]. This technique requires the use of circular samples to avoid any shape effect. Disks from different part of the ribbons, to ensure reproducibility, were cut using a method developed in our laboratory [25].

Magnetostriction was measured using the strain-gauge technique. To avoid any flexion of the ribbon which can induce spurious deformation of the sample, a holder similar to that developed by Takahashi el al. [14] represented schematically in Fig. 1 has been used. The measurements were performed under a tensile pre-stress of 8 MPa. This pre-stress was applied along the longitudinal direction of the ribbon by using a dead weight. The magnetostriction was measured in the plane of the ribbon parallel to the direction of the applied magnetic field.

The residual stress distribution of the ribbons was obtained by an adaptation of the surface layer removing method to this kind of materials. In this technique, the stresses in the sample are obtained by measuring its deformation after the removal of uniform layers of the material from the surfaces. Different procedures can be used for the measurement of the deformation. In this work the measurement of the change of curvature of the sample has been chosen. The details of the method and the calculation of the relationship between stress and curvature have been shown elsewhere [26]. The removal of the surface layers were performed by electrolytic polishing according to the conventional method described by Chikazumi [27].

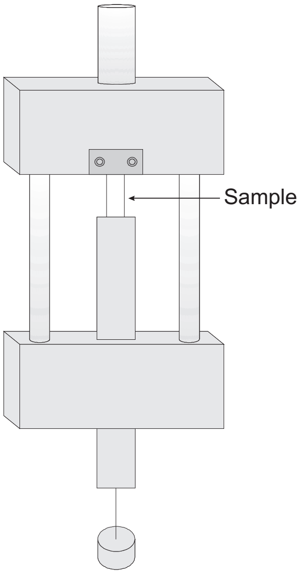

Fig. 1. Schematic representation of the holder for magnetostriction measurements.

Thermogravimetric measurements were performed using a DS Mettler instrument, from which the Curie temperature of the samples was obtained. The selected thermal treatments to remove the residual stresses originated by the manufacturing process were chosen well below the Curie temperature. The thermal treatments were carried out in argon atmosphere flowing through a tube furnace in order to avoid oxidation of the samples.

3. Results and discussion

Fig. 2 shows the XRD patterns of the air side of the ribbons. In the case of the $Fe_{81}Al_{19}$ alloy the three peaks (1 1 0), (2 0 0) and (2 1 1) indicating that the phase of the samples has a pure disordered bcc structure can be observed, showing the same characteristic peaks as that of α-Fe (A2 phase). In the X-ray diffraction pattern of the $Fe_{70}Al_{30}$ alloy a new peak emerges at 31° which indicates the presence of at least partial DO_3 long range order. After a thermal treatment of 2 h at 473 K, the X-ray diffraction patterns of the $Fe_{81}Al_{19}$ showed no change, but in the case of $Fe_{70}Al_{30}$ the disappearance of the reflection at 31° could be observed indicating that the DO_3 ordering is suppressed. A similar result has been obtained in Fe–Ga alloys [11].

The dimensions of the ribbons obtained by melt-spinning causes a shape magnetic anisotropy that in general makes the magnetization lie in the plane of the ribbon. The existence of a strong anisotropy in our ribbons can be seen in Fig. 3 in which the magnetization curves of the as-quenched ribbons in the longitudinal direction and perpendicular to the plane of the ribbon is presented. In the case of $Fe_{81}Al_{19}$, the magnetization in the longitudinal direction increases rapidly with the applied magnetic field and reaches the saturation value at an applied magnetic field of about 2.5 kOe, meanwhile in the perpendicular direction, the saturation is not reached even at an applied magnetic field of 1 T. The coercive field and the saturation magnetization obtained from the hysteresis loops result in $H_C = 5$ Oe and $M_S = 214$ emu g^{-1}, these results are similar for the ribbon of composition $Fe_{70}Al_{30}$ in which the saturation magnetization is reached for an applied

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