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Helical Magnetic Anisotropy Induced by Current Annealing Under Torsion in Co-rich Amorphous Wires

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Abstract.- **Helical magnetic anisotropy induced by current annealing under a constant torsional angle of 20π rad/m in two Co-rich amorphous wires with negative and nearly-zero magnetostriction is reported. The measurements were performed using the inverse Wiedemann effect hysteresis loop of the wires. Influence of preannealing on this kind of magnetic anisotropy in both wires is also analysed taking into account the anelastic and plastic contributions to this anisotropy.**

I. INTRODUCTION

Metallic glasses in the form of continuous wire have been a subject of great scientific interest in the last years, due to the remarkable physical properties that these amorphous wires show such as large magnetic permeability and particularly the bistable magnetic behavior for technologically useful applications [1,2].

On the other hand, the circular geometry of these amorphous wires makes them suitable to study the helical magnetic anisotropy which can be induced by thermal treatment such as recently reported on a Fe-rich amorphous wire [3]. From that study, the helical anisotropy induced by torsion annealing, K_{hel}, could be split into two components: the anelastic (K_{an}) one which is recoverable in the sense that it dissapears if the applied torsion strain is removed at elevated temperature, and the plastic component (K_{pl}) non-recoverable in the sense that it remains if the torsion is removed at elevated temperature and it is highly influenced by the thermal hystory (stabilization) of the material. In [3] the influence of the preannealing carried out by means of current density annealing (45.54 A/mm^2 during 2 minutes) on the helical induced anisotropy in the Fe-rich amorphous wire was also studied. It was found that the helical anisotropy behaves in an opposite way to that observed by Nielsen [4] in amorphous ribbons of similar compositions.

The aim of the present paper is to present a systematic study on the helical induced magnetic anisotropy in two Co-based amorphous alloy wires with negative (-3.5×10^{-6}) and nearly-zero (-0.4×10^{-7}) magnetostriction constant in a similar way to that previously reported on a Fe-rich amorphous wire [3] to get a deeper understanding about the mechanisms responsible for this anisotropy in amorphous wires, since it is well kown that these kind of alloys with helical anisotropy could be applied to industrial applications.

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II. EXPERIMENTAL PROCEDURE

Two amorphous wires of nominal composition $(Co_{0.95}Fe_{0.05})_{72.5}Si_{12.5}B_{15}$ and $Co_{72.5}Si_{12.5}B_{15}$ kindly supplied by Unitika Co, Japan, were used in our experiments. The typical diameter of the wires was 125 μm and they were cut in pieces 10 cm long for fitting into the measurement devices.

A conventional experimental set-up has been used in order to obtain M_z-H_ϕ hysteresis loops of the samples (Inverse Wiedemann Effect, (IWE)). This device allowed us to apply a constant torsional strain and to make electric currents flow along the wires. The azimuthal field, H_ϕ, was provided by a 50 Hz ac electric current flowing along the sample. This azimuthal field is inhomogeneous within the wire and is given by the following expression;

$$H_\phi = (1/2)\, jr \qquad (1)$$

where j is the current density and r the distance to the wire axis. The maximum current density, j_{max} = 10 A/mm^2 used for measuring the M_z-H_ϕ loop was not high enough to give rise to the significant heating of the samples. The azimuthal field at the wire surface for such a maximum current density was 250 Am^{-1}.

The heating of the samples was performed by the current annealing technique [4,5]. Helical magnetic anisotropy was induced by annealing with a constant torsional angle $\xi_{ann} = 20\pi$ rad/m applied during the thermal treatment. A large spontaneous value of IWE is observed after the treatment. The measurements of this helical anisotropy were carried out by means of the IWE recording the torsion angle per unit length ξ_{ind} (referred to the free wire after strain annealing) which produces the vanishing of the spontaneous IWE and, therefore, the vanishing of the helical induced anisotropy. The maximum value of such anisotropy occurs at the wire surface and may be written according to ref. [6] as:

$$K_{ind} = -(3/2)\, \lambda_s \mu r \xi_{ind} \qquad (2)$$

where μ is the shear modulus of the material that was determined by means of a torsion pendulus given a value of 6.0 (±0.2) x 10^{10} Nm^{-2}, r is the radius of the wire, λ_s is the magnetostriction constant of the wire. λ_s was determined using the SAMR method [7]. It was obtained that the variations of λ_s with this torsion annealing were less than 10 % of the values corresponding to the as-quenched state (-3.5×10^{-6}) for the Co-Si-B wire. Nevertheless, for the Co-Fe-Si-B wire, magnetostriction takes the value of -0.4×10^{-7} in as-quenched state and the treatments give rise to important changes of λ_s which have been previouly reported in [8]. From that, values of λ_s are taken into account to calculate K_{ind} from equation (2). For ξ_{ind} has been considered positive if it has the same sign as ξ_{ann} and, therefore, the easy axis of helical anisotropy will be perpendicular to the torsional strésses of the wire.

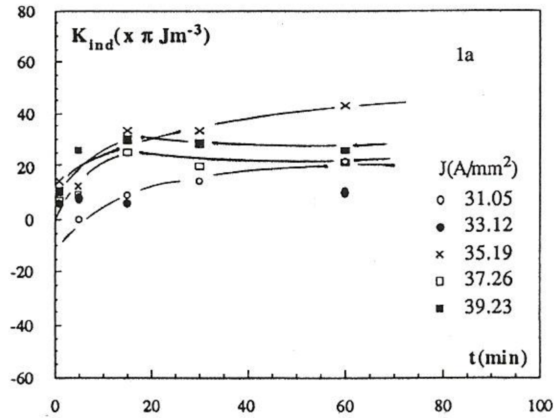
III. EXPERIMENTAL RESULTS AND THEIR ANALYSIS

Figures 1 a and b show the evolution of the helical induced magnetic anisotropy at different values of current densities, j_{ann}, for the Co-Si-B and Co-Fe-Si-B amorphous wires respectively.

According to these results, the behavior of the helical induced anisotropy in the two amorphous wires are clearly different with respect to the sign of such anisotropy. For the Co-Si-B wire the anisotropy is positive and increases with the annealing time up to reach a saturation value which depends on the value of current density annealing. Nevertheless, at high current density the anisotropy behaves in a different way with the annealing time since it increases up to reach a maximum value and then decreases due to the high temperature of the sample with those current annealings could be activated processes in opposition to the induction of anisotropy.

The helical induced anisotropy in the Co-Fe-Si-B wire shows a similar behavior with the annealing time for the different current densities, but in this wire the induced anisotropy can be negative, that is, the easy axis for the magnetization is a helix at 45º with the axis of the wire in opposite direction to the twist applied during the thermal treatment.

Preannealing treatment performed at 45.54 A/mm^2 during 2 minutes without torsional stress applied on the two samples show quantitative changes in the values of subsequent induced anisotropy, although qualitatively the behavior in both wires are the same as that before mentioned even with respect to the sign of K_{ind}. In figures 2 a and b, K_{ind} is plotted as a function of the annealing time for Co-Si-B and Co-Fe-Si-B wires respectively, with the current density annealing as parameter.



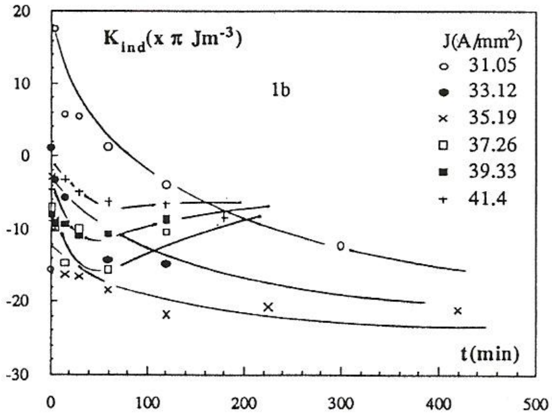


Fig. 1. Helical induced magnetic anisotropy as a function of the annealing time with the density of the current annealing as parameter: a) $Co_{72.5}Si_{12.5}B_{15}$ amorphous wire and b) $(Co_{0.95}Fe_{0.05})_{72.5}Si_{12.5}B_{15}$ amorphous wire.

The saturation or maximum value of K_{ind}, that we have called K_{eq}, obtained in each isothermal treatment has been plotted as a function of the current density annealing in figures 3 a and b, for as-quenched and for preannealed wires respectively. It can be seen that a maximum value is achieved for j_{ann} within the range 34.7 to 37.3 A/mm^2 for both amorphous wires. This behavior is similar to that found in the dependence of the stress induced anisotropy on annealing temperature in amorphous ribbons [9]. These results may indicate that as structiural relaxation proceeds (with preannealing)
annealing temperature in amorphous ribbons [9]. These results may indicate that as structiural relaxation proceeds (with preannealing)
subsequent treatment biased by the action of torsion strain trend to give a helical anisotropy with the same direction of ξ_{ann}.

The difference between the curves of K_{eq} corresponding to the as-quenched and preannealed wires in figures 3 a and b could be interpreted as a consequence of the two contributions already reported of this anisotropy developed during the torsion annealing. Thus, the behavior of K_{eq}-j_{ann} in the Co-Fe-Si-B amorphous wire seems to indicate that the induced anisotropy in preannealed samples at moderated temperature is mainly due to the anelastic contribution with only a small plastic component with opposite direction. Such behavior, in this wire, is similar to that found by Nielsen [9] on the saturation of the anelastic contribution in amorphous ribbons with similar compositions.

Moreover, a reinforcement of the induced anisotropy is observed in the preannealed sample near the maximum of both curves (as-quenched and preanealed wire) around 35.6 A/mm^2 of curent density, practically at the Curie point. At higher current annealing the anelastic contribution to the induced anisotropy in preannealed samples is very much reduced. This can be understood by taking into account that the plastic flow during the annealing under constant strain in this wire almost eliminates the applied stress, and the corresponding saturation value of the anelastic contribution to the anisotropy should be very low.

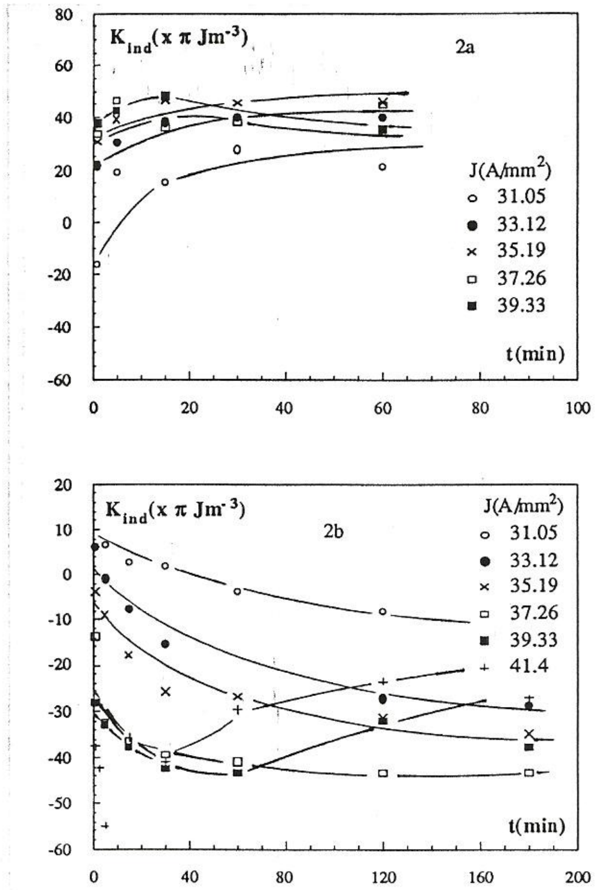


Fig. 2. Helical induced magnetic anisotropy as a function of the annealing time with the density of the current annealing as parameter in : a) $Co_{72.5}Si_{12.5}B_{15}$ and b) $(Co_{0.95}Fe_{0.05})_{72.5}Si_{12.5}B_{15}$ amorphous wire previously treated at 45.54 A/mm^2 during 2 minutes without torsion.

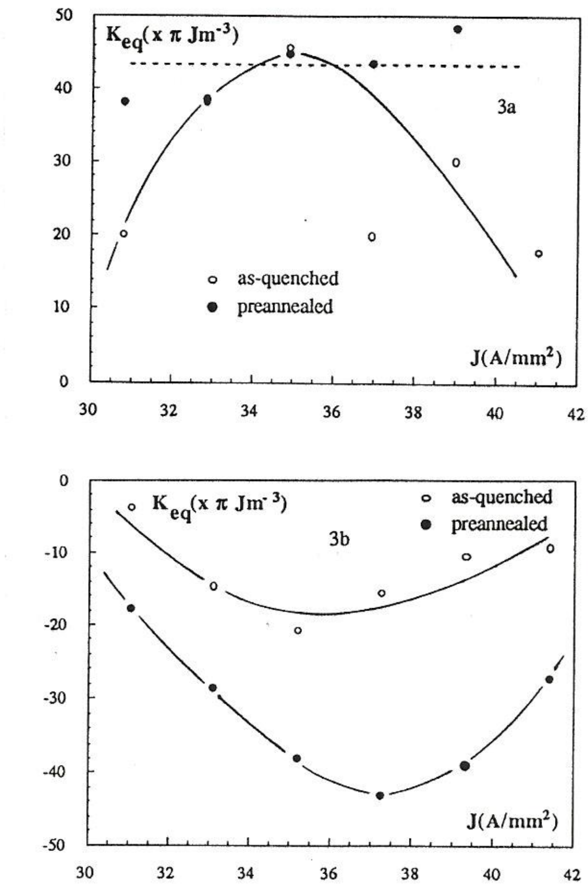


Fig. 3. Saturation value of the helical induced magnetic anisotropy under torsional strain $\xi_{ann} = 20\pi$ rad/m as a function of the annealing current density in as-quenched and preannealed: a) $Co_{72.5}Si_{12.5}B_{15}$ and b) $(Co_{0.95}Fe_{0.05})_{72.5}Si_{12.5}B_{15}$ amorphous wire.

From the curves of K_{eq}-j_{ann} of as-quenched and preannealed Co-Si-B amorphous wire, the two contributions of K_{ind} behave with some significant differences to those reported for the Co-Fe-Si-B wire. The curve of the as-quenched sample shows a maximum around 35.6 A/mm^2, while the induced anisotropy in the preannealed sample is practically constant to that of the maximum of the as-quenched curve in range 30 to 40 A/mm^2 of current density. Differences between the as-quenched and preannealed curves are observed at temperatures above 35.6 A/mm^2, which could be interpreted due to the absence of plastic component at low annealing temperatures .

In conclusion, in this paper has been carried out the characterization of magnetic anisotropy induced in two Co-rich amorphous wires with negative and nearly-zero magnetostriction by torsion annealing in a similar way to that previously reported for a Fe-rich amorphous wire. We have also studied the influence of the preannealing on this anisotropy which appears as a similar behavior to that we have found in amorphous ribbons for the zero-magnetostriction wire, while in the negative magnetostrictive wire it is more complicated. A further study on the influence of the torsion strain applied during the annealing on the helical induced anisotropy in these wires is, at the present, in preparation.

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