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Characterization of stress-annealed amorphous CoFeBSi ribbons by GMI and inductance spectroscopy

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Abstract

The effect of tension annealing on $Co_{66}Fe_4Si_{12}B_{18}$ amorphous alloys was studied by means of magnetoinductance measurements. Samples annealed under stress manifested a strong decrease in transverse permeability and relaxation frequency, as compared with their as-cast alloy counterpart. Samples subsequently subjected to a further relaxation regime showed moderate improvements on both parameters. These results are interpreted on the basis of the axial anisotropy induced by the stress-annealing conditions and its influence on the low-frequency magnetization processes of the alloys.

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Keywords: Magnetoimpedance; Magnetoinductance; Stress annealing; Anisotropy field

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1. Introduction

The magnetoimpedance (MI) effect in soft magnetic materials carrying an AC current, consists of a considerable change of material's impedance when submitted to a static magnetic field. Although the phenomenon was first described several decades ago in basic ferromagnetism reports [1], it reappeared in the early 90s [2–4] and since then, has attracted considerable interest both from the basic theoretical viewpoint and from its wide technological applicability, e.g., for magnetic sensing or as an additional tool to investigate soft magnetic materials properties [5].

The rapid solidification process usually induces a significant magnetoelastic anisotropy, which in turn results in a remarkable material's sensitivity to torsion and tension stress [6], and to heat treatments or to a combination of both [7]. In this report, we studied the effect of tension annealing on the magnetoinductance response of Co-based amorphous ribbons at low frequencies,

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as well as the effects of a subsequent relaxation annealing.

2. Experimental techniques

Amorphous alloy ribbons of nominal composition $Co_{66}Fe_4Si_{12}B_{18}$ were prepared by the conventional melt-spinning technique. Samples with a cross-section of $0.5 \times 0.0198\,mm^2$ with lengths of 82 and 101 mm, were subjected to the following stress-annealing conditions: 400 °C for 1 h with an applied tensile stress of 350 MPa (alloy sample denoted as “M1”); another group of samples were subjected to 400 °C with an applied tensile stress of 300 MPa for 1 h, followed by a relaxation treatment of 400 °C for 1 h (sample “M2”). An as-cast sample (labeled as “M0”) with a cross-section $1.0 \times 0.020\,mm^2$, and 98 mm in length was used for comparison. Magnetoinductance measurements were carried out by means of an HP 4192. A impedance analyzer, which enables the application of AC currents i_{rms} within the 0.15–17 mA range (rms) on alloy samples at variable frequencies between 100 Hz–13 MHz. A 200-turn solenoid powered by a DC source provides magnetic H_{DC} fields up to 40 Oe.

3. Experimental results

Most reports concerning MI studies are based on the complex impedance formalism $\mathbf{Z} = Z_{re} + jZ_{im}$, for which the MI ratio is defined as $\Delta Z/Z = 100 \times (Z(H) - Z(H_{max}))/Z(H_{max})$ (where $Z = |\mathbf{Z}|$ and H_{max} is the maximum applied field, typically enough to saturate the sample). According to this approach, MI ratios for M0, M1 and M2 measured at a frequency of 10 MHz and $i_{rms} = 17$ mA are shown in Fig. 1. Peak values of $\Delta Z/Z\%$ plots are associated with the anisotropy field H_k of each alloy. For M0 this H_k has a vanishing value (around 0.6 Oe), whilst for its heat-treated counter-parts, M1 and M2, H_k exhibits a noticeable enhancement (up to around 7 Oe). This H_k improvement reflects an axial anisotropy induced by the stress-annealing conditions, as it is discussed in the following paragraphs.

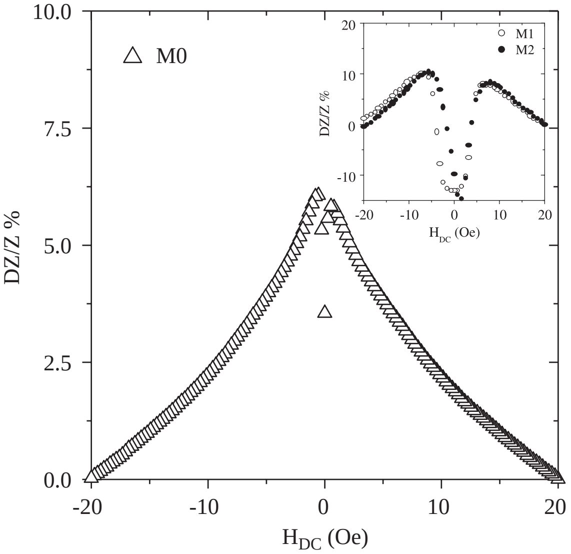

Fig. 1. MI ratio as a function of H_{DC} for M0, M1 and M2 alloys.

The magnetoinductance response of the material is described by means of the complex inductance formalism $\mathbf{L} = L_{re} + jL_{im}$, which in turn, affords the calculation of the complex permeability $\boldsymbol{\mu} = \mu_{re} + j\mu_{im}$ via a simple transformation [8], at frequencies low enough to neglect the skin-depth effect:

$$\boldsymbol{\mu} = G\mathbf{L} = G(jZ/\omega), \tag{1}$$

where G is a geometrical factor and ω is the angular frequency $\omega = 2\pi f$ of the i_{rms} flowing through the sample. Cole–Cole plots for M0, M1 and M2, measured at $i_{rms} = 0.15$ mA along the whole frequency range are displayed in Fig. 2. For M0 the transverse permeability, taken as the low frequency μ_{re} at the intersection with the real axis, is 13,000 whilst a strong decrease is observed for M1 and M2 (1800 and 2000, respectively). This reduction in μ_{re} can be explained on the basis of the effect of the stress annealing on the anisotropy, since this kind of heat treatment in Co-based amorphous alloys results in an induced anisotropy $K_{in} = K_{an} + K_{pl}$ [9], where the anelastic K_{an} component makes the ribbon axis a hard magnetization direction, while the plastic K_{pl} component

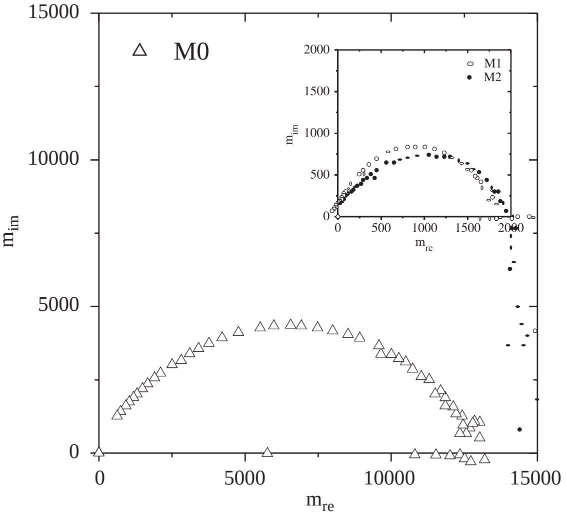

Fig. 2. Cole–cole plots for M0, M1 and M2 alloys. Each point (μ_{re}, μ_{im}) is measured at a fixed frequency, which increases from right to left.

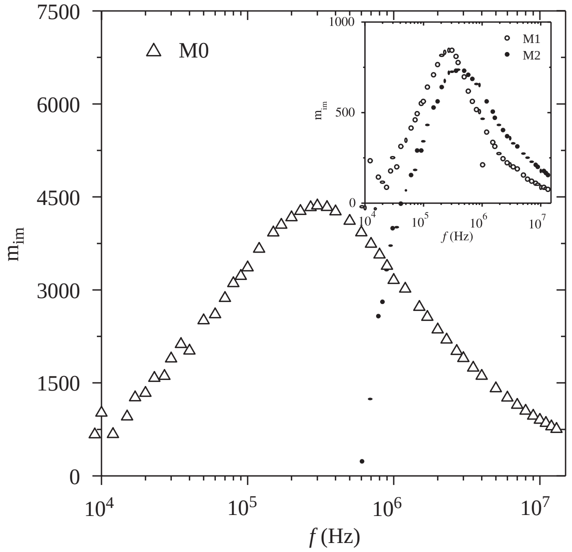

Fig. 3. Spectroscopic μ_{im} (*f*) plots for M0, M1 and M2 alloys.

tends to preserve the ribbon axis as an easy magnetization direction. In addition, $K_{an} > K_{pl}$. Thus, a stress-annealing process results in a hard direction along ribbons axis. The reduction observed in μ_{re} for M1 and M2 is then a consequence of the hindering of transverse domain wall movements caused by K_{in}. Since the AC field amplitude is very small, μ_{re} depends essentially on the reversible bulging of pinned domain walls, as it is shown below. The shallow enhancement of μ_{re} for M2 is a result of the relaxation treatment, which has a deleterious effect on K_{an}, facilitating a predominant effect of K_{pl} [7] and thus, improving μ_{re}.

Spectroscopic plots of the imaginary part of permeability, μ_{im} (*f*), for M0, M1 and M2 are exhibited in Fig. 3. The maximum observed in this curves corresponds to the relaxation frequency f_x [10], and represents the limit for which the reversible domain wall bulging becomes unable to follow the excitation field h_{AC}. Beyond this f_x, the spin rotation is the only magnetization mechanism active. f_x is around 300 kHz for M0; it shows a decrease for M1 (267 kHz) and a considerable improvement for M2 (400 kHz). Again, this variations can be attributed to the stress-annealing conditions, since this treatment should favor the domain wall viscous damping parameter β (through the hindering of domain wall bulging and the increase of pinning centers [7]), which in turn, is inversely proportional to f_x [11]. On the other hand, the relaxation treatment applied to M2 diminishes the number of pinning centers together with the attenuation of the component K_{an} and thus, decreases β. The improved f_x value for M2 reflects this reduced β.

Real permeability plots as a function of h_{AC}, measured at $f = 100$ kHz (well below f_x) for M0, M1 and M2 alloy samples are shown in Fig. 4. M1 and M2 data display a general trend which matches a typical magnetization process: an initial constant tendency associated with reversible domain wall bulging of pinned domain walls, followed by a sudden increase ascribed to irreversible domain wall displacements and a further roughly hyperbolic decrease, reflecting the approach to magnetization saturation. This $\mu_{re}(h_{AC})$ behavior is truncated for M0, for which only the reversible initial trend for μ_{re} is observed even at the maximum applied field (i.e., at the limiting i_{rms} which is possible to apply with our system). μ_{re} values are considerably higher for M0 due to the absence of K_{in}, while the marked decrease exhibited by M1 and M2 is a consequence of K_{in},

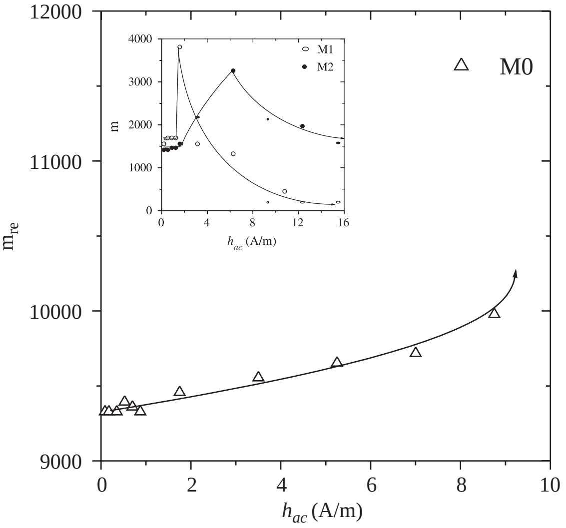

Fig. 4. Transverse permeability μ_{re} as a function of h_{AC} for M0, M1 and M2 alloys. (Solid lines are for eye guidance only.)

which precludes the reversible bulging and displacement of the transverse domain walls.

4. Conclusions

The effect of induced anisotropy K_{in} attained by stress-annealing conditions on Co-based amorphous alloys was studied by means of their magnetoinductance response. Stress-only heat treated samples manifested a strong decrease in μ_{re} and f_x as compared with its as-cast alloy counterpart, due to the hindering from reversible deformation of pinned transverse domain walls caused by K_{in}. On the other hand, the relaxed alloy showed a moderated recovery on both parameters as a consequence of an attenuation of K_{in}, which led to an enhancement of reversible magnetization processes.

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