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Helical anisotropy and magnetoimpedance of CoFeSiB wires under torsional stress

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Abstract

Recent measurements of the magnetoimpedance (at a fixed frequency of 1 MHz) of cobalt-rich wires subjected to torsion stress show an asymmetry as a function of torsion angle stemming from residual anisotropies induced during wire fabrication. We interpret these measurements with a simple model based on the competition between a circumferential magnetic anisotropy and another one induced by torsional or residual stress. This allows extraction of the physical parameters of the wire and explains the positive and negative torsion cases. The agreement between theoretical and experimental results provides a firm support for the model describing the behavior of the anisotropy field versus static magnetic field for all torsion angles.

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Keywords: Amorphous magnetic wires; Giant magnetoimpedance; Magnetic anisotropy; Magnetostriction

1. Introduction

The giant magnetoimpedance effect (GMI) in amorphous ribbons, wires and thin films has become a topic of growing interest for a wide variety of prospective applications in storage information technology and sensors possessing high sensitivity and fast response [1,2].

Magnetoimpedance effect (MI) consists in the change of impedance introduced by a low-amplitude AC current I_{AC} flowing through a magnetic conductor under application of a static magnetic field H_{DC} (usually parallel to the direction of the AC current). The origin of this behavior is related to the relative magnetic permeability μ_r and the direction of the magnetic anisotropy field H_K. When MI measurements are performed on wires, injecting an AC current in the wire and applying a DC magnetic field H_{DC} along the wire axis, one probes the wire rotational permeability wire that controls the behavior of the MI.

Ordinarily, the MI curve is symmetric with respect to the DC magnetic field H_{DC} with a single (at $H_{DC} = 0$) or a double peak (when $H_{DC} = \pm H_{max}$), the anisotropy field of the wire being considered as the value of H_{max}. Applying a torsion stress to the wire alters its MI behavior versus field H_{DC} in a way such that one observes, for instance, a single peak only for positive stress and a double peak for negative stress.

Recent work by Betancourt and Valenzuela (BV) [3] tackled MI measurements of CoFeBSi wires subjected to torsion stress [4,5], at a fixed frequency of 1 MHz, obtaining the aforementioned asymmetry [6,7] of the MI profile with respect to torsion stress. Interpreting the asymmetry in terms of residual anisotropies induced during wire fabrication [3] leads to an effect that, respectively, counterbalances or enhances the wire circumferential anisotropy with positive or negative torsional stress.

The wires were prepared by the in-rotating water-quenching technique and have the nominal composition $(Co_{94}Fe_6)_{72.5}Si_{12.5}B_{15}$. Their typical dimensions are 10 cm in length and 120 μm for diameter. They possess a characteristic domain structure dictated by the sign of the

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magnetostriction coefficient λ_s^R which is expected to have a small value ($|\lambda_s^R| \sim 10^{-7}$ in these Cobalt-rich alloys). When λ_s^R is negative, an axially oriented magnetization core exists surrounded by circular domains [1,2], whereas in the opposite case, radially oriented magnetization states exist such as those observed in Fe-rich alloys [7]. After performing several measurements such as Barkhausen jump and magnetization reversal measurements [3], BV favor the negative sign for the λ_s^R coefficient and presence of helical anisotropy [4].

In this paper, a simple model for the anisotropy field, based on the competition between a fabrication-induced circumferential anisotropy and a torsion-induced one with presence of fabrication-induced residual torsional stress, is proposed. This model allows the extraction of the relevant physical parameters of the wire and explains the observed behavior in the cited work [3] as a function of the static magnetic field for all torsion angles.

2. Theory

In order to reveal the residual stress within the wires, positive and negative torsion stress [4] are applied and the effect is analyzed with MI response. Following the work of Favieres et al. [8] on cylindrical CoP amorphous multilayers electrodeposited on copper wires, we use a stress-induced easy axis making an arbitrary angle δ_T [4] with the circumferential direction (see Fig. 1). We extend this model to include the presence of residual torsion stress induced by fabrication. The total magnetoelastic energy in presence of applied and residual torsional stress (σ_r) is

$$E = K_c \sin^2(\theta) + \frac{3}{2}\lambda_s^R(\sigma + \sigma_r)\sin^2(\delta_T - \theta), \quad (1)$$

where K_c is the fabrication-induced circumferential anisotropy of the wire and λ_s^R the rotational saturation magnetostriction constant [9] (see Fig. 1). We are in the linear case where the magnetoelastic energy is proportional to stress σ. Our energy functional does not include demagnetization nor Zeeman terms originating from the DC field H_{DC} applied along the wire axis. Energy due to the AC circular field H_{AC} created by the injected AC current I_{AC} is neglected. The anisotropy field as a function of stress is determined by identifying it, experimentally, with the value of the DC field H_{max} where the MI curve displays a peak. Previously Makhnovskiy et al. [10] introduced explicitly these terms in the energy functional with a single helical anisotropy [4] term in contrast with our work dealing with several competing (fabrication and torsion-induced) anisotropies. The stress σ (on the surface of the wire) is related to the torsion angle δ through:

$$\sigma = (Ga\delta)/l, \quad (2)$$

where G is the shear modulus, a is the radius of the wire and l the length (see Fig. 2). In general, σ has a radial dependence since the wire has an inner core with an axial magnetization surrounded by circular domains [1,2] when λ_s^R is small and negative. We neglect such dependence and consider, for simplicity, the value of stress on the surface [11] of the wire. Introducing the saturation magnetization of the samples M_s (measured with a vibrating sample magnetometer [3] as $\mu_0 M_s = 0.8\,\mathrm{T}$), the energy may be rewritten as

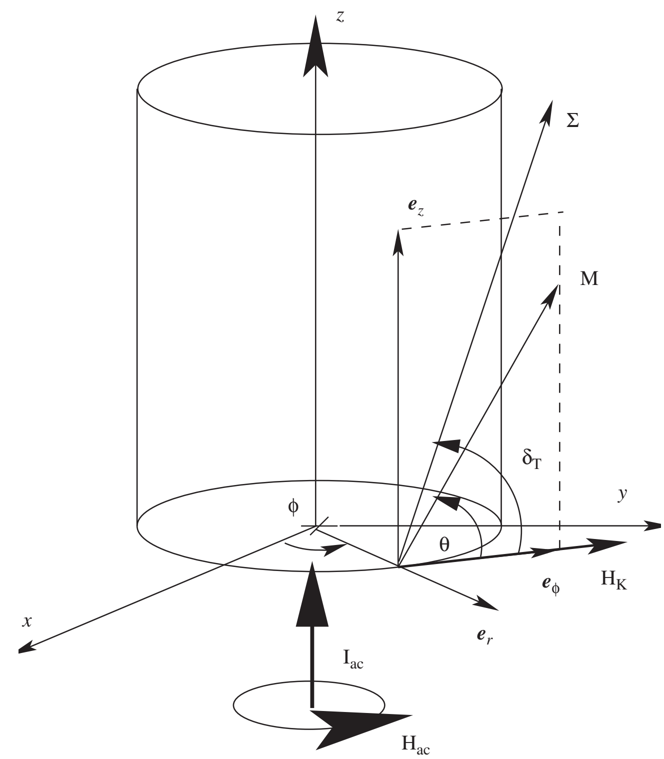

Fig. 1. Geometry of the anisotropy and stress-induced easy axis. The circumferential anisotropy axis induced by fabrication is along $\mathbf{e}_\phi$ and the torsion stress-induced easy axis $\mathbf{\Sigma}$ makes an angle δ_T with $\mathbf{e}_\phi$. The zero-stress circular anisotropy field H_K is along $\mathbf{e}_\phi$. In the helical anisotropy case, the magnetization $\mathbf{M}$ lies in the $\mathbf{e}_\phi$, $\mathbf{e}_z$ plane making a non-zero angle θ with the circumferential basis vector $\mathbf{e}_\phi$, otherwise, both the magnetization $\mathbf{M}$ and anisotropy axis lie in the $\mathbf{e}_r$, $\mathbf{e}_\phi$ plane.

$$E = (M_s/2)[H_K \sin^2(\theta) + H_\sigma \sin^2(\theta - \delta_T)]. \quad (3)$$

This shows that we have a competition between a circumferential anisotropy field $H_K = 2K_c/M_s$ and a torsion stress-induced one (called henceforth twist field including the residual stress) $H_\sigma = 3\lambda_s^R(\sigma + \sigma_r)/M_s$. Using a Stoner–Wohlfarth approach [12,13], this amounts to rotate the astroid equation from a set of perpendicular fields H_x, H_y:

$$H_x^{2/3} + H_y^{2/3} = H_K^{2/3} \quad (4)$$

to another by an angle θ^* resulting in another astroid. This angle is the same that gives the new equilibrium orientation of the magnetization and is simply obtained from the condition minimizing the energy, i.e. $[\partial E/\partial\theta]_{\theta=\theta^*} = 0$. We obtain

$$\tan(2\theta^*) = \frac{H_\sigma \sin(2\delta_T)}{H_K + H_\sigma \cos(2\delta_T)}. \quad (5)$$