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Investigation of the properties of Co-rich amorphous ferromagnetic microwires by means of small angle magnetization rotation method

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ABSTRACT

The amplitude of the second harmonic of the electro-motive force occurring in the receiving pick-up coil when alternating electrical current is flowing through the microwire is measured as a function of applied external magnetic field, at different mechanical tensile stresses. In addition, an analytical expression for the amplitude of the second harmonic of the electro-motive force is derived. Comparing the experimental and theoretical data the saturation magnetization, the magnetostriction constant and the amplitude of the residual quenching stress have been determined for a family of Co-rich glass-coated microwires.

1. Introduction

Accurate measurement of the magnetostriction constants and other parameters of magnetic amorphous ferromagnetic ribbons and wires are essential in the study of their magnetic properties. The latter have great potential for use in a variety of technical devices such as sensors of weak magnetic field, sensitive tensile and torsional stress sensors, etc. [1,2] Indirect evaluation of the magnetostriction constant of amorphous magnetic material can be performed by means of the hysteresis loop measurement. An estimate of the magnetostriction constants for amorphous ferromagnetic ribbons [3] and wires [4] was carried out analyzing the stress dependence of the wire initial magnetic susceptibility. For the same purposes the small-angle magnetization rotation (SAMR) method was developed some years ago [5–7]. In [8] the SAMR method has been successfully used to measure the magnetostriction constants of a set of amorphous glass-coated ferromagnetic microwires. Meanwhile, the full potential of the SAMR method appears to be revealed only if the nature of magnetic anisotropy of the amorphous ferromagnetic microwire is taken into consideration. The latter is mainly related to the distribution of the residual quenching stresses within the metallic nucleus and glass envelope of the microwire.

In this paper, the amplitude of the second harmonic of the electro-motive force (EMF) occurring in the receiving pick-up coil when alternating electrical current is flowing through the wire is measured as a function of the applied external magnetic field, at different mechanical tensile stresses. Moreover, an expression for the amplitude of the second EMF harmonic is obtained analytically. It holds in applied magnetic field higher than the effective anisotropy field of the microwire. It is shown that the comparison of experimental and theoretical data enables one to determine simultaneously a number of important parameters of Co-rich amorphous ferromagnetic microwire, such as the saturation magnetization, the magnetostriction constant and the amplitude of the residual quenching stress.

2. Magnetic anisotropy of amorphous glass-coated microwire

It is well known [9–13], that the distribution of the easy anisotropy axes in amorphous ferromagnetic ribbons and wires is determined mainly by magnetoelastic interactions. The latter are significant in amorphous alloys due to the presence of appreciable residual quenching stresses which occur during the rapid solidification process of the material. For amorphous Co-rich microwire with a negative magnetostriction constant, $\lambda_s < 0$, the magneto-elastic energy density can be written in cylindrical coordinates (ρ, φ,z) as a diagonal quadratic form [12]

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$$w_{m-el} = K\left[\tilde{\sigma}_{\rho\rho}\,\alpha_\rho^2 + \tilde{\sigma}_{\phi\phi}\,\alpha_\phi^2 + \left(\tilde{\sigma}_{zz} + \tilde{\sigma}_{zz}^{(a)}\right)\alpha_z^2\right],\ K = \frac{3}{2}|\lambda_s|\sigma_0 \tag{1}$$

where K is the nominal anisotropy constant of the wire, $\sigma_0 = 100$ MPa is a characteristic amplitude of the residual quenching stresses, $\tilde{\sigma}_{ij} = \sigma_{ij}/\sigma_0$ $(i,j = \rho,\varphi,z)$ are the reduced tensor components of the residual stress in cylindrical coordinates, and $\tilde{\sigma}_{zz}^{(a)} = \sigma_{zz}^{(a)}/\sigma_0$ is the reduced applied tensile stress.

Note that Eq. (1) is a consequence of almost perfect axial symmetry of amorphous glass-coated microwire. For simplicity, we neglect in Eq. (1) small off-diagonal correction [14], which can describe the properties of a microwire with weak helical anisotropy. The calculations [12,13] of the residual quenching stresses in glass-coated microwires show that, as a rule, the azimuthal component of the residual stress tensor has the lowest value, $\tilde{\sigma}_{\phi\phi} << \tilde{\sigma}_{\rho\rho}, \tilde{\sigma}_{zz}$, within the ferromagnetic nucleus. Therefore, the magneto-elastic energy density (1) has a minimum when the unit magnetization vector points in azimuthal direction, $\vec{\alpha} = (0, \pm 1, 0)$. In other words, the azimuthal direction is the easy anisotropy axis for microwires with negative magnetostriction constant. It is clear that a deviation of the unit magnetization vector in the radial direction is energetically unfavorable, as it leads to the appearance of the demagnetizing fields and appreciable magnetostatic energy. On the other hand, a rotation of the unit magnetization vector in the longitudinal direction leads to a relation $\alpha_\phi^2 = 1 - \alpha_z^2$. For such magnetization process the magneto-elastic energy density (1) takes the form

$$w_{m-el} = K\left[\tilde{\sigma}_{\phi\phi} + \left(\tilde{\sigma}_{zz} - \tilde{\sigma}_{\phi\phi} + \tilde{\sigma}_{zz}^{(a)}\right)\alpha_z^2\right].$$

Therefore, the axial direction is a hard magnetization axis for this type of microwire. The corresponding effective magnetic anisotropy constant is given by $K_{ef} = K\left(\tilde{\sigma}_{zz} - \tilde{\sigma}_{\phi\phi} + \tilde{\sigma}_{zz}^{(a)}\right)$. This expression implies that the magnetic properties of amorphous glass-coated microwires are determined mainly by three physical parameters, namely, the saturation magnetization M_s, the magnetostriction constant λ_s and characteristic amplitude of the residual quenching stress, $\Delta\tilde{\sigma} = \tilde{\sigma}_{zz} - \tilde{\sigma}_{\phi\phi}$.

In this paper we study experimentally the magnetic parameters of amorphous glass-coated Co-rich microwires with inner and outer diameters listed in Table 1.

The microwires 1 and 3 have the same metallic nucleus composition $Co_{67}Fe_{3.85}Ni_{1.45}B_{11.5}Si_{14.5}Mo_{1.7}$; the composition of the microwire 2 is $Co_{65}Fe_4Ni_2B_{13.5}Si_{14}Mo_1C_{0.5}$.

The calculation of the residual quenching stresses in these microwires on the basis of the theory of visco-elastic medium [12,13] shows that the average amplitude of the reduced residual stress for the first microwire varies in the range $\Delta\tilde{\sigma}_{th} = 0.5$–$0.75$, depending on the ratio of the bulk elastic modulus, $k_2/k_1 = 0.5-0.6$, and the ratio of the linear expansion coefficients, $\alpha_2/\alpha_1 = 0.3$–0.4, of the glass shell and ferromagnetic nucleus, respectively. For the second microwire with a thicker glass shell, the average amplitude of the residual stress increases to $\Delta\tilde{\sigma}_{th} = 0.7$–$1.0$ for the same range of changes of the ratios k_2/k_1 and α_2/α_1. Finally, for the third microwire with a very thin glass shell the residual stress, although having a significant dependence on the radial coordinate, is small enough, $\Delta\tilde{\sigma}_{th} \approx 0.1$.

3. SAMR theory for Co-rich microwire

Let amorphous Co-rich microwire with a metallic nucleus radius R is placed in an external longitudinal magnetic field H_{0z} sufficiently large compared to the wire effective anisotropy field, $H_{a,ef} = 2K_{ef}/M_s$, so that $H_{0z} \gg H_{a,ef}$. Then the wire magnetization is almost parallel to the wire axis so that the unit magnetization vector in cylindrical coordinates is given by $\vec{\alpha} = (0, 0, 1)$. Let now an alternating current of frequency f and amplitude I_0, $I(t) = I_0\sin(\omega t)$, is flowing through the wire, where $\omega = 2\pi f$ is the angular frequency. Under the influence of circular magnetic field of the ac current the circular component of the unit magnetization vector undergoes small oscillations with a frequency ω

$$\alpha_\phi = A(\rho)\sin(\omega t),\ a_\varphi << 1. \tag{2}$$

Note that the appearance of the radial component of the unit magnetization vector in this situation is energetically unfavorable, since its presence would lead to arising of demagnetizing field associated with the volume and surface magnetic charges.

The oscillation amplitude $A(\rho)$ of the α_φ component will be determined below. First, let us estimate the EMF that occurs in the receiving pick-up coil wound on the amorphous wire. The total magnetic flux through the coil is

$$\Phi = 4\pi M_s N \int \alpha_z\, ds, \tag{3}$$

where N is the number of coil turns and the integral is taken over the cross section of the metallic nucleus. Therefore, the EMF induced in the coil is given by

$$E = -\frac{1}{c}\frac{\partial\Phi}{\partial t} = -\frac{4\pi M_s N}{c}\int\frac{\partial\alpha_z}{\partial t}ds. \tag{4}$$

Given the smallness of the α_φ component and absence of the α_ρ component, to the lowest order in α_φ the longitudinal component of the unit magnetization vector is given by $\alpha_z = \sqrt{1-\alpha_\phi^2} \approx 1 - \alpha_\phi^2/2$. Taking into account the relation

$$\frac{\partial\alpha_z}{\partial t} = -\frac{\omega}{2}\sin(2\omega t)A^2(\rho),$$

one obtains

$$E = \frac{4\pi^2 M_s N\omega}{c}\sin(2\omega t)\int_0^R A^2(\rho)\rho\, d\rho, \tag{5}$$

where R is the radius of the metallic nucleus of the wire. Thus, the electrical signal in the receiving coil oscillates at twice of the angular frequency. It is proportional to the square of the amplitude $A(\rho)$. To determine the function $A(\rho)$ it is necessary to consider the equilibrium conditions for the unit magnetization vector of the microwire under the influence of the external longitudinal magnetic field $H_{0z} \gg H_{a,ef}$ and quasistatically varying magnetic field of the ac current

$$H_\phi(\rho) = \frac{2I_0}{cR^2}\rho\sin(\omega t), \tag{6}$$

where c is the speed of light. The equilibrium equation for unit magnetization vector, $\left[\vec{\alpha}, \vec{H}_{ef}\right] = 0$, in the given case reduces to the

Table 1
Co-rich amorphous glass-coated ferromagnetic microwires.

No.	Metallic nucleus diameter (μm)	Total wire diameter (μm)	d/D	M_s (emu/cm^3)	Magnetostriction constant	Reduced residual stress
1	$d = 21.4$	$D = 26.2$	0.816	500 ± 10	$\lambda_s = -1.45 \times 10^{-7}$	$\Delta\tilde{\sigma} = 1.03$
2	$d = 11.8$	$D = 15.8$	0.747	530 ± 10	$\lambda_s = -2.01 \times 10^{-7}$	$\Delta\tilde{\sigma} = 1.82$
3	$d = 22.4$	$D = 22.8$	0.982	500 ± 10	$\lambda_s = -1.02 \times 10^{-7}$	$\Delta\tilde{\sigma} = 0.04$