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Domain structure of Fe-based microwires

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Abstract

Some magnetic characteristics of the Fe-based cast amorphous glass-coated microwires with positive magnetostriction constant are investigated. The residual stress distributions in this type of microwires determine the domain structures and the switching field behavior; in particular, we present a phenomenological law of its temperature dependence, which has a very good agreement with the experimental data.

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Keywords: Domain structure; Switching field

1. Introduction

The cast glass-coated amorphous microwires are of practical interest because of their application for magnetic sensors and magnetic memory components. The fabrication of cast glass-coated amorphous microwires by Ulitovsky–Taylor method and the study of its magnetic properties have been reported in Ref. [1]. The cast amorphous microwires produced by the method of the "in rotating water quenching" has distinctive magnetic properties since they have different magnetic domain structures [2].

The orientation of the magnetization vector for wires made of materials with positive magnetostriction is determined by the maximal component of the stress tensor, which is along the axis of the wire [3]. Therefore the cast Fe-based microwires with a positive magnetostriction constant show a rectangular hysteresis loop with a single and large Barkhausen jump between two stable magnetization states and exhibit the phenomenon of natural ferromagnetic resonance [4].

In the present work, a theory of domain structure of cast glass-coated amorphous microwires with positive magnetostriction [5] allows us to theoretically estimate the thickness and the energy density of the domain wall for the considered wires and also, to formulate a phenomenological expression for the temperature dependence of the switching field, which is in very good agreement with the experimental result in Ref. [6]. The article is arranged in the following way: in the Section 2 the residual stresses in microwires are presented, in the Section 3 the domain wall structure is analyzed, in the Section 4 the magnetic structure of cast amorphous microwires is studied, in the Section 5 we state a phenomenological expression of switching field as function as temperature. Finally, conclusions are stated in the Section 6.

2. Residual stresses in microwires

The residual stresses are the result of differences in the coefficients of thermal expansion of the metal and of the glass. A simple theory for the distribution of residual thermoelastic stresses was presented in [4]. In terms of

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cylindrical coordinates, the residual thermoelastic tension is characterized by axial, radial and tangential components which are independent of the radial coordinate:

$$\sigma_{0r} = \sigma_{0\phi} = \sigma_{\mathrm{m}} kx/((1 + k/3)x + 4/3), \quad (1a)$$

$$\sigma_{0z} = \sigma_{0\phi}((k + 1)x + 2)/(kx + 1), \quad (1b)$$

where $x = (R_{\mathrm{m}}/R)^2 - 1$, with R the radius of the metallic core of the microwire and R_{m} the radius of the microwire; also $\sigma_{\mathrm{m}} = \varepsilon Y_{\mathrm{m}}$, with Y_{m} the Young modulus of metal and $\varepsilon = (\alpha_{\mathrm{m}} - \alpha_{\mathrm{g}})(T - T^{*})$, where α_{m} and α_{g} are the thermal expansion coefficients of the metal and the glass, respectively; T^* is the solidification temperature of the composite microwire (when both metallic nucleus and glass-coating solidify) and T is the experiment's temperature; besides $k = Y_{\mathrm{g}}/Y_{\mathrm{m}}$, where Y_{g} is the Young modulus of the glass.

The model that we use for the stress formation in the microwire considers that the microwire strand from its axis up to an internal radius, b, preserves liquid status, while from b up to in metallic core radius, R, freezes earlier and only elastic residual stresses persist. So, if $b<r<R$ (region 1) this model gives

$$\sigma_{1r}(r) = \sigma_{0r} + P(1 - (b/r)^2), \quad (2a)$$

$$\sigma_{1\phi}(r) = \sigma_{0\phi} + P(1 + (b/r)^2), \quad (2b)$$

$$\sigma_{1z}(r) \approx v(\sigma_{1r}(r) + \sigma_{1\phi}(r)), \quad (2c)$$

where v is Poisson's coefficient. Besides, if $r<b$ (region 2) this model gives

$$\sigma_{2r}(r) = 2k\ \ln(b/r) + \sigma_{0r}, \quad (3a)$$

$$\sigma_{2\phi}(r) = 2k(1 + \ln(b/r)) + \sigma_{0\phi}, \quad (3b)$$

$$\sigma_{2z}(r) \approx v(\sigma_{2r}(r) + \sigma_{2\phi}(r)), \quad (3c)$$

where k is the anisotropy constant. We remark that, a rigorous solution should be obtained by lacing the Eqs. (2) and (3) at $r = b$ and taking into consideration that they are unacceptable at $r = 0$; also we note that $\sigma_r < \sigma_\phi$ for any r.

3. Domain wall of microwires

We have found that, the domain structure of the Fe-based cast amorphous microwire consists of two cylindrical domains [5]. The domain wall (DW) can arise in the region of cylinder where $r<b$, because the anisotropy energy in this region is smaller. One minimizes the sum of the exchange and anisotropy energies:

$$E = -A\Delta^{-1} - \lambda(2k\ \ln(\Delta/b) + \sigma_r) \quad (4)$$

where A is the exchange energy constant, λ is the magnetostriction constant and Δ is the DW thickness, which we will calculate. So the energy minimization, $\delta_\Delta E = 0$, gives the following expresion for the DW thickness Δ_1:

$$\Delta_1 = A/(2\lambda kb). \quad (5)$$

By using the following empirical order of magnitude values $A\sim10^{-11}$ J/m, $b\sim10^{-6}$ m, $\lambda\sim10^{-6}$, $k\sim10^{8}$ Pa, we obtain $\Delta_1\sim0,1$ μm. In addition, we estimate the density energy W_1 of the DW by $W_1 \approx \sigma\lambda\Delta_1$. In this approximation, W_1 is independent of the magnetostriction and it is determined by the exchange interaction and the parameter b; also by using the given experimental values, we find $W_1\sim10^{-5}$ J/m^2.

On the other hand, when the DW is located in the region where $r\sim R$ we can use a method similar to the one proposed in Ref. [7]. Thus, the DW thickness Δ_2 is determined by $\Delta_2 = \sqrt[3]{AR/(\lambda P)}$ and its numerical value is of the order of 0.01 μm. Moreover, the energy density in this case is given by $W_2 = \sqrt[3]{A^2\lambda P/R}$; we note that, it is determined by the magnetostriction, the residual thermoelastic tension, the exchange interaction and the radius , R, of the metallic core of the microwire. Besides, using the previous experimental values we find that $W_2\sim10^{-4}$ J/m^2. Additionally, in the formation of the domain structures it is energetically advantageous for a large part of the DW to be in states close to metastable states.

4. Magnetic structure cast amorphous microwire

With allowance for the suggested model of thermoplastic relaxation, we assume that a microwire with positive magnetostriction in a zero external magnetic field should possess a magnetized state. In order to prove this, we will consider a microwire consisting of two domains, with counter magnetization parallel to the microwire axis, which are separated by a coaxial cylindrical domain wall. If we neglect the energy of the DW, the radius Δr of the internal domain should be determinable from the condition that the variation of the magnetic energy be equal to zero, i.e. that the domains have equal volumes. In this case $\Delta r^2 = R^2/2$ and the domain wall goes into the region with the higher anisotropy energy. The anisotropy energy densities, $\varpi_{\mathrm{a}j}$, are given by $\varpi_{\mathrm{a}j}(r) = -\lambda\sigma_{jr}(r)$, where $j = 1, 2$. In addition, the relative magnetization energy density ϖ_{m} of the internal domain is given by $\varpi_{\mathrm{m}}(r) = 2\pi M^2(r/R)^2$, where M is the magnetization. The size of the internal domain, for compensating the magnetic energy of the external domain, is limited by a growth of the anisotropy energy. The energy density minimization can be obtained by $\delta_{\Delta r}(\varpi_{\mathrm{m}} + \varpi_{\mathrm{a}j}) = 0$. Therefore, for region 1 and 2, we have

$$4\pi M^2\,\Delta r_1/R^2 - 2\lambda Pb^2/\Delta r_1^3 = 0, \quad (6a)$$

$$4\pi M^2\,\Delta r_2/R^2 - 2\lambda k/\Delta r_2 = 0, \quad (6b)$$

implying that

$$\Delta r_1^2 = \eta_1\, bR, \quad (7a)$$

$$\Delta r_2^2 = \eta_2 R^2, \quad (7b)$$

where $\eta_1 = \sqrt{\lambda P/2\pi M^2}$ and $\eta_2 = \lambda k/\pi M^2$. Since in a soft magnetic material these η have values smaller than one, $\eta_i<1$, the minimum of the total energy is not, in general,

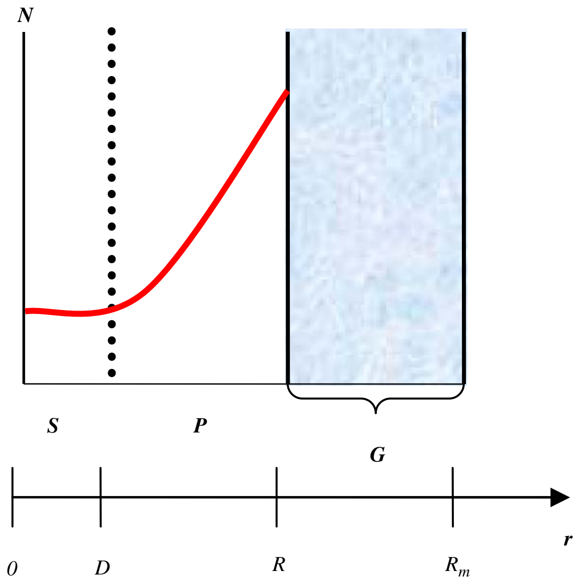

Fig. 1. Qualitative pattern of relative tensile stresses of cast amorphous microwire.

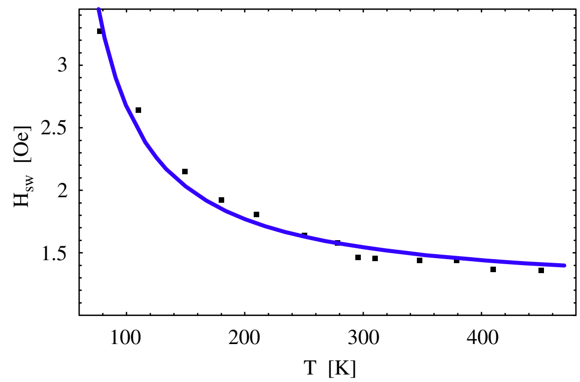

Fig. 2. The most probable switching field as function of temperature. The continuous line is the theoretical model and the points are experimental data.

conducive to a compensation of the magnetostatic energy. Therefore the microwire may have a magnetized state, which has been experimentally detected for amorphous microwires. Nanocrystalline soft magnetic microwires do not possess this property, because the strain anisotropy does not play a substantial role in the formation of their domain structures.

Fig. 1 shows a pattern of relative tensile stresses resulting from the previous model, where R is the metallic core radius and R_m the microwire radius. The dotted line at D represents the presumed position of the DW separating two oppositely magnetized regions, the magnetizations being parallel to the microwire axis. The region G corresponds to the glass shell bonded to the metal core. The region S corresponds to that part of the metallic core which is subjected to elastic stresses. The region P corresponds to that part of the metallic core with substantial processes of thermoplastic relaxation. Furthermore, the region N is the inner zone of the metallic core which is not describable by the given model. The DW lies in region P or in the beginning of the region S, depending where the system energy is minimal. Therefore, the internal domain does not compensate the magnetization; this implies the existence of residual magnetization.

5. Temperature dependence of the switching field

As an application of the previous analysis of the domain structure characteristics, in this section we present a phenomenological approach for the temperature dependence of the switching field of the considered wires. A magnetization reversal involves motions of DWs which produce energy changes. So from our model of stress distribution, we obtain that the energy levels are $E_j = -\lambda V \sigma_{jr}$, where V is the DW micro-effective volume and $j = 1, 2$. Then the energy jump, ΔE, is determined approximately by

$$\Delta E \approx cV(T^* - T), \tag{8}$$

where $c \approx \lambda Y_m(\alpha_m - \alpha_g)$ and T^* is the solidification temperature of the composite microwire.

At this point we refer to an analogy with various physical chemical processes, for which the relative probability density for reaction among states with energy difference, ΔE, is:

$$\rho(1,2) \propto \exp(-|\Delta E_{12}|/k_B T) \tag{9}$$

where k_B is the Boltzmann's constant. Since we have determined the energy differences in the motion of the domain wall, for the switching field, H_{sw}, we propose the following temperature dependence:

$$\langle H_{sw}/H_{sw}^{max} \rangle = \exp(cV(T^* - T)/k_B T), \tag{10}$$

where H_{sw}^{max} is the maximum switching field. We remark that, Eq. (10) is a phenomenological and simple structure giving the switching field dependence on the temperature, which just requires only one parameter, V, for fitting the experimental results. Fig. 2 shows the switching field as a function of the temperature at $T^* = 10^3[K]$; the continuous line represents this theoretical model and the points are the experimental data. Note that, the model has very good agreement with the empirical results. Furthermore, with that fitting of the experimental data we can estimate that $V \approx 1.13 \times 10^{-24}\,m^3$ and so, the DW thickness is approximately $\Delta \approx 0.01\,\mu m$, its equivalence with Δ_2 can be considered to represent a validation of the proposed model for the domain structure.

6. Final remarks

In the fabrication of cast amorphous glass-coated microwires, the residual stresses increase from the axis attaining their maximum values on its surface. The theory of thermoplastic relaxation can be used to show that residual stresses will increase on the surface of a microwire, which corresponds to the earlier obtained experimental data. The cast glass-coated amorphous microwires possess residual magnetization due the specific distribution of the residual stresses. This property of these considered microwires can be used for producing long-term magnetic storage elements and for improving the behavior of some sensor electronic devices. We have stated a simple analytic expression for the switching field dependence on the residual stresses, the radius of the metallic core of the microwire, the magnetostriction constant and the temperature, which has been experimentally verified. The macroscopic mechanism of DW activation qualitatively explains the main switching field dependence as a decreasing exponential function of the temperature.

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References

[1] M. Vazquez, Physica B 229 (2001) 302.
[2] S.A. Baranov, V.S. Larin, A.V. Torcunov, A. Zhukov, M. Vazquez, in: Proceedings of the Fourth International Workshop on Noncrystalline Solids, World Scientific, Singapore, 1995, p. 425.
[3] S.A. Baranov, V.S. Larin, A.V. Torkunov, A.N. Antonenko, J. Phys. IV 8 (1998) 2.
[4] S.A. Baranov, S.K. Zotov, V.S. Larin, A.V. Torcunov, Fizika Met. Metalloved (Russian) 67 (1989) 73.
[5] S.A. Baranov, Surf. Eng. Appl. Electrochem. 3 (2002) 84.
[6] M. Vázquez, A. Zhukov, K.R. Pirota, R. Varga, K.L. García, C. Luna, M. Provencio, D. Navas, J.L. Martínez, M. Hernández-Vélez, J. Non-Cryst. Solids 329 (2003) 123.
[7] A. Antonov, A. Dykhne, A. Lagarkov, N. Usov, Structure of 90° domain wall in Co-based amorphous wire, Physica A 241 (1997) 425.