Journal of Optoelectronics and Advanced Materials Vol. 4, No. 2, June 2002, p. 367 - 371

A MODEL FOR MAGNETIZATION REVERSAL IN POSITIVE MAGNETOSTRICTIVE AMORPHOUS MICROWIRES

H. Chiriac, T. A. Óvári

National Institute of R&D for Technical Physics, 47 Mangeron Blvd., 6600 Iasi, Romania

A new method for the calculation of switching field values in $Fe_{77.5}Si_{7.5}B_{15}$ amorphous microwires with large and positive magnetostriction is presented. The approach used is based on the nucleation at coercivity process. The anisotropy constants that enter the energy balance are calculated starting from internal stresses induced during preparation. Experimental values of the switching field are used to validate the theoretical results.

(Received February 14, 2002; accepted June 13, 2002)

Keywords: Amorphous microwires, Magnetization reversal, Switching field

1. Introduction

Ferromagnetic amorphous glass-covered wires, also called amorphous microwires, consist of a metallic core with diameters ranging from several micrometers to 30 μm covered by a glass insulator with a thickness of several micrometers up to 25 μm. They are prepared from magnetostrictive alloys (e.g. $Fe_{77.5}Si_{7.5}B_{15}$ with $\lambda_S = 25 \times 10^{-6}$, $Co_{80}Si_{10}B_{10}$ with $\lambda_S = -4 \times 10^{-6}$, and $Co_{68.15}Fe_{4.35}Si_{12.5}B_{15}$ with $\lambda_S = -1 \times 10^{-7}$) in a one step process called glass-coated melt spinning, an improved method of the original Taylor technique. The high quenching rates involved in this process along with the presence of the glass coating are responsible for large internal stresses induced during preparation.

The magnetoelastic anisotropy that arises from the coupling between internal stresses and magnetostriction is the anisotropy that determines the magnetic behavior of these materials. It has been previously shown that the magnetic behavior of microwires is strongly dependent on their dimensions - metallic core diameter, Φ_m, glass coating thickness, t_g, and their ratio [1].

Amorphous microwires with large and positive magnetostriction display a bistable magnetic behavior, i.e. the magnetization jumps from negative to positive remanent state when the sample is subjected to a positive applied field larger than a certain value called switching field, and usually denoted H^*.

2. Model and discussion

The aim of this paper is to propose a general method for the calculation of switching field values in positive magnetostrictive microwires having different dimensions of the metallic core and glass coating. The calculated values of the switching field are then checked against experimentally determined ones.

Axial magnetoelastic anisotropy, K_Z, characterizes most of the volume of amorphous microwires with large and positive magnetostriction, like $Fe_{77.5}Si_{7.5}B_{15}$ ones. Only a small volume towards the surface displays a different anisotropy direction, i.e. radial. This is the reason for the bistable behavior at low fields.

Let us denote the volume of the microwire's metallic core characterized by axial anisotropy as axial core (AC). Magnetization switching should be treated as a nucleation at coercivity process, since the most suitable approach is to consider magnetization reversal as the formation of some region of reversed magnetization, which can then expand in the volume of the AC. Thus, nucleation implies the formation of a domain wall. The reversal process is in this way controlled by the balance of three energy terms: wall energy, magnetostatic energy variation, and Zeeman energy, since the whole process is caused by an applied field. This energy balance results in the following expression for the nucleation field [2], which in this case is the actual switching field:

$$H^* \cong \alpha \frac{\gamma_W}{\mu_0 M_S V^{1/3}} - N_{eff} M_S \tag{1}$$

where γ_W is the wall surface tension, μ_0 the magnetic permeability of vacuum, M_S the saturation magnetization, V the volume of the reversed nucleus driving the reversal process, and N_{eff} a phenomenological coefficient which contains the effect of local magnetostatic fields over the space occupied by the nucleus. α is another phenomenological parameter, that reflects the existence of an anisotropy distribution instead of constant anisotropy.

Estimations of N_{eff} for 'conventional' amorphous wires showed that its values for samples with different diameters are almost equal to N, the demagnetizing factor of the samples, calculated at remanence or for reverse applied fields smaller than the switching field [3]. Using the same method for the calculation of N, i.e. by approximating the cylindrical metallic core of the microwire with a prolate spheroid whose major axis is much larger than the minor one, for a 1 cm long typical microwire with the diameter of the metallic core of 7 μm, we found $N = 2.56 \times 10^{-6}$ and a corresponding demagnetizing field of 3.3 A/m. The value of N is one order of magnitude smaller than in 'conventional' amorphous wires, and the resulting demagnetizing field is very small as well, allowing us to neglect in a first approximation the second term of (1).

The wall surface tension is expressed as:

$$\gamma_W = \beta \sqrt{A \langle K_Z \rangle} \tag{2}$$

where β is a coefficient that depends on the wall shape, A is the exchange constant, and $\langle K_Z \rangle$ is the mean axial magnetoelastic anisotropy constant. We will use $\beta = 2$, a reasonable value that has been also employed for 'conventional' wires [3]. For A we employed the value of the exchange constant for Fe, i.e. $A = 1.5 \times 10^{-11}$ J/m.

In order to evaluate $\langle K_Z \rangle$, it is necessary to know the magnetoelastic anisotropy distribution, that requires first the calculation of internal stress distribution. Calculation of internal stress distributions for microwires with different dimensions were performed by considering only the diagonal components of the stress tensor. The fully developed mathematical formulation of stress calculation is presented in a previous work [4].

We have calculated the radial distribution of internal stresses for $Fe_{77.5}Si_{7.5}B_{15}$ microwires with the metallic core diameter ranging between 7 and 41 μm and the glass coating thickness of 5 to 20.6 μm. All the obtained stress distributions are qualitatively similar. The values of stresses display large variations with the microwire dimensions. The maximum axial tensile stress - that dominates on over 90% of the microwire's radius starting from its center - decreases from 1.66 GPa for a microwire with $\Phi_m = 7$ μm and $t_g = 15$ μm to 0.58 GPa for one with $\Phi_m = 25$ μm and $t_g = 5.5$ μm. The maximum circumferential compressive stress - that dominates toward the surface - decreases from 2.79 GPa for a microwire with $\Phi_m = 7$ μm and $t_g = 5$ μm to 1.51 GPa for one with $\Phi_m = 25$ μm and $t_g = 15$ μm.

After the stress distribution is known, the next step is to see which component is dominant in each point on the microwire radius (radial, axial, or circumferential). This is because of the tensorial character of stresses, which determines the formation of an easy axis of anisotropy as a result of the coupling between magnetostriction and the largest component of the stress tensor [5]. It is also important to know the radial distribution of smaller stress components, since they play an important role in establishing the anisotropy axis when the dominant component and magnetostriction constant have different signs.

Fig. 1 illustrates the radial distribution of the dominant stress components for the microwire with Φ_m = 25 μm and t_g = 5.5 μm. The existence of two main regions of stress dominance - one in the microwire's inner part, in which axial tensile stresses are dominating, and another one near the surface, in which circumferential compressive stresses are dominating - is a general feature for all the calculated cases.

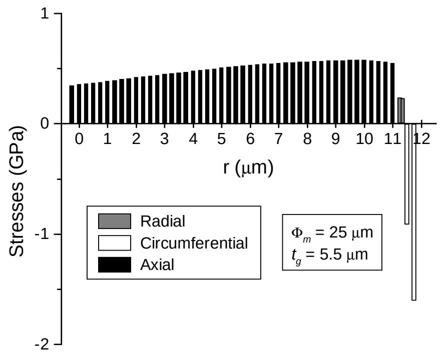

Fig. 1. Distribution of dominant stresses in an FeSiB microwire.

Between these regions, there is a small intermediate one in which radial tensile stresses are dominating. Once the dominant stress components have been identified, we can proceed to the next step, and to calculate the magnetoelastic anisotropy distribution on the radial direction. The magnetoelastic anisotropy constant is given by:

$$K = \frac{3}{2}\lambda_S \sigma_{ii} \tag{3}$$

where σ_{ii} is the dominant stress component and λ_S the saturation magnetostriction constant.

Fig. 2 shows the radial distribution of the magnetoelastic anisotropy constants for the $Fe_{77.5}Si_{7.5}B_{15}$ microwire with Φ_m = 25 μm and t_g = 5.5 μm, having $\lambda_S = 25 \times 10^{-6}$. One observes a large region of axial anisotropy in the inner region, which occupies about 95% of the metallic core radius. The axial easy axis of anisotropy results from the coupling between axial tensile stresses and positive magnetostriction. Immediately near the region with axial anisotropy, there is a small region of radial anisotropy that originates in the coupling between radial tensile stresses (positive) and the positive magnetostriction. In the remaining part, near the surface of the microwire, the easy axis of anisotropy is radial as well, but it results from the coupling between circumferential compressive stresses (negative) and positive magnetostriction. Here, the resulting anisotropy axis has to be perpendicular to the circumferential direction, so it will be either axial or radial. Since axial stresses in this region are also compressive and large, but radial ones are the smallest and positive (tensile), the resulting direction of the anisotropy axis is radial. We have to emphasize the rather large values of the anisotropy constants (the axial one, K_Z, reaches a maximum of about 2.2×10^4 J/m^3 in the inner region of the microwire, while the radial one, K_r, reaches to 6×10^4 J/m^3 near the surface).

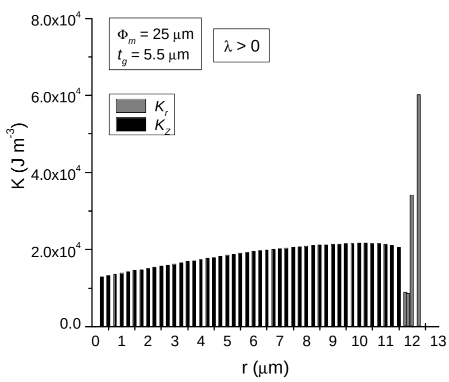

Fig. 2. Anisotropy distribution in an FeSiB microwire.

As concerns the axial magnetization process of microwires with $\lambda_S > 0$, the anisotropy distribution from Fig. 2 is consistent with the bistable behavior at low fields. The degree in which remanence reaches close to saturation is proportional to the volume of the region with axial anisotropy.

Since stresses display a radial distribution, the axial magnetoelastic anisotropy constant K_Z also exhibits a radial distribution. Thus, in (2) it is necessary to employ a weighted mean of K_Z's in order to characterize the axial magnetoelastic anisotropy of the microwire.

Let us evaluate next the volume of the reversed nucleus, V. One should not limit the transverse dimensions of the nucleus to the cross section area of the AC only, since it is reasonable to consider nucleation as starting in regions with lower and even not axial anisotropy, which are located outside the AC. Obviously, the propagation following nucleation is a different aspect. Therefore, it is plausible to consider in a first approximation that V is given by an axial dimension of the order of the wall thickness, δ_W, and by transverse dimensions proportional to the cross section area of the microwire's metallic core, πR_m^2. Thus, V should be proportional to $\pi R_m^2 \delta_W$. On the other hand, the volume of the nucleus should depend on the anisotropy distribution. The most important parameter related to the anisotropy distribution is the ratio between the radius of the microwire's metallic core, R_m, and the glass coating thickness, t_g, denoted in the following as $\eta = R_m/t_g$. Thus, we can consider that the radial dimension of the nucleus is ηR_m, its cross section area being $\pi\eta^2 R_m^2$. It is difficult to estimate the actual shape of the reversed nucleus, but since for $\eta > 1$ the cross section of a cylindrical nucleus would exceed the cross section of the metallic core, one should imagine the nucleus as having a different shape, i.e. its margin being either as an ellipse that is oblique to the core's cross section under different inclination angles (larger for larger values of η), or as a paraboloid with a large enough surface. Even so, for simplicity, the volume of the reversed nucleus can be expressed as an equivalent cylindrical volume: $V = \pi\delta_W \eta^2 R_m^2$. $V^{1/3}$ becomes:

$$V^{1/3} = \eta^{2/3}\left(\pi\delta_W R_m^2\right)^{1/3} \tag{4}$$

Here, the factor containing η reflects the contribution of the anisotropy distribution, so it can be assimilated to α from (1). By taking $\alpha = 1/\eta^{2/3}$, $\delta_W = \pi\sqrt{A/\langle K_Z\rangle}$, and considering (2), (4), and the above made assumptions, expression (1) for the switching field becomes:

$$H^* = C \cdot \frac{1}{\eta^{2/3}} \cdot \left(\frac{\langle K_Z\rangle}{R_m}\right)^{2/3} \tag{5}$$

with:

$$C = \frac{2}{\mu_0 M_S} \cdot \frac{A^{1/3}}{\pi^{2/3}} \tag{6}$$

that includes all the constant parameters. With $\mu_0 M_S = 1.6$ T one obtain the value of the constant C: $C = 1.44 \times 10^{-4}$.

Thus, we achieved a general method for the calculation of switching field values for microwires with positive magnetostriction having different dimensions.

Table 1 illustrates the measured and calculated values of the switching field for several $Fe_{77.5}Si_{7.5}B_{15}$ samples with different dimensions. The calculations were performed using (5).

Table 1. Measured and calculated switching field values for FeSiB microwires.

Sample no.	Φ_m [μm]	t_g [μm]	$\langle K_Z \rangle$ [$\times 10^4$ J/m^3]	H^*_{measured} [Oe]	$H^*_{\text{calculated}}$ [Oe]
1.	7.2	13.4	4.233	22.17	22.47
2.	10.8	20.6	3.594	15.52	15.63
3.	17.0	8.5	2.770	4.43	3.98
4.	25.0	5.5	2.196	2.00	1.52
5.	41.0	10.5	2.076	1.44	1.17
6.	32.6	5.3	1.687	0.38	0.87

One observes a quite reasonable agreement between the calculated and measured values of the switching field. The differences are due to the deviations of the real samples from the ideal calculated cases, that assume perfectly cylindrical microwires.

3. Conclusion

Summarizing, a general method that allows the calculation of the switching field as function of the sample dimensions has been achieved. Although the agreement between calculated and measured switching field values is far from perfect, the method could find use in selecting samples with appropriate dimensions for sensor applications based on the bistable magnetic behavior of amorphous microwires with positive magnetostriction.

References

[1] H. Chiriac, T. A. Óvári, Gh. Pop, F. Barariu, IEEE Trans. Magn. **33**, 782 (1997).
[2] G. Bertotti, Hysteresis in Magnetism (Academic Press, San Diego), 379 (1998).
[3] A. M. Severino, C. Gómez-Polo, P. Marín, M. Vázquez, J. Magn. Magn. Mater. **103**, 117(1992).
[4] H. Chiriac, T. A. Óvári, Gh. Pop, Phys. Rev. **B 52,** 10104(1995).
[5] P. T. Squire, D. Atkinson, M. R. J. Gibbs, S. Atalay, J. Magn. Magn. Mater. **132**, 10 (1994).