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Domain Structure of 'Thick' Amorphous Microwires with Nearly Zero Magnetostriction

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ABSTRACT

Nearly zero magnetostrictive glass-coated amorphous microwires are suitable materials for sensor applications. Samples with metallic core diameters below 20 μm exhibit almost nonhysteretic BH loop, related to the existence of a domain structure with azimuthal easy axis. The magnetic behavior of these microwires is changing drastically when the metallic core diameter increases over 25 μm, i.e. they display a bistable magnetic behavior at low fields, that is a one step magnetization reversal at a certain value of the applied field, called switching field. Results on the direct domain observation in nearly zero magnetostrictive $Co_{68.25}Fe_{4.5}Si_{12.25}B_{15}$ glass-coated amorphous microwires by means of Kerr microscopy are reported for the first time. The effect of glass removal on the domain structure has been also studied. AC hysteresis loop measurements have been employed to establish a correlation between domain structure and magnetic behavior.

Glass-coated microwires exhibit a single domain configuration with the magnetization pointing mostly to the wire axis. The domain structure does not change qualitatively after glass removal, but the parameters of the squared hysteresis loops are modified. The remanence to saturation ratio increases after glass removal, while the switching field decreases.

The obtained results are of interest for sensor applications, and show that the metallic core diameter is a dimensional factor that contributes to important changes in the domain structure and magnetization process of such microwires.

INTRODUCTION

Ferromagnetic amorphous glass-coated wires, also called microwires, represent a new class of materials, very suitable for sensors applications [1, 2]. Such microwires are usually prepared from three ferromagnetic alloy categories: (i) Fe-based with large and positive magnetostriction (e.g., $Fe_{77.5}Si_{7.5}B_{15}$ with $\lambda_S = 25 \times 10^{-6}$), (ii) Co-based with negative magnetostriction (e.g., $Co_{80}Si_{10}B_{10}$ with $\lambda_S = -4 \times 10^{-6}$), and (iii) Co-based with small amounts of Fe or Mn with nearly zero magnetostriction (e.g., $Co_{68.25}Fe_{4.5}Si_{12.25}B_{15}$ with $\lambda_S = -1 \times 10^{-7}$). Nearly zero magnetostrictive microwires are mostly employed as sensing elements for magnetic sensors based on the giant magneto-impedance effect [3], due to their high azimuthal permeability and favorable domain structure.

CoFeSiB microwires with typical dimensions - diameters of the metallic core below 20 μm and glass coating thickness up to 15 μm - exhibit a domain structure with azimuthal easy axis of magnetization that results in an almost nonhysteretic axial BH loop [4].

The aim of this paper is to report for the first time results on the magnetic behavior of CoFeSiB amorphous microwires with the metallic core diameter over 25 μm and large total diameter (over 60 μm). In order to make a difference between such samples and microwires with typical dimensions, we called them 'thick' amorphous microwires.

EXPERIMENT

CoFeSiB amorphous microwires cut to 7 cm long samples have been investigated. Axial hysteresis loops were determined by an inductive method, using an AC axial field with a frequency of 60 Hz and a maximum amplitude of 4 Oe. Direct domain observations were performed based on longitudinal Kerr effect optical microscopy using an image processor.

Two sets of samples were studied: sample A with a total diameter of 101 μm, the metallic core diameter being 34 μm, and sample B with a total diameter of 63 μm, the metallic core diameter being 27 μm. Both sample A and B were measured before and after glass removal by chemical etching. The samples after glass removal were denominated as sample A1 and B1, respectively.

Figure 1 shows the low and high field axial hysteresis loops for sample A. The low field loop corresponds to a maximum applied field of 0.08 Oe, while the high field one is obtained for a maximum applied field of 4 Oe. One observes that the sample displays a bistable axial magnetization process, i.e. a single and large Barkhausen jump that occurs at a switching field value, H*, of 31.5 mOe.

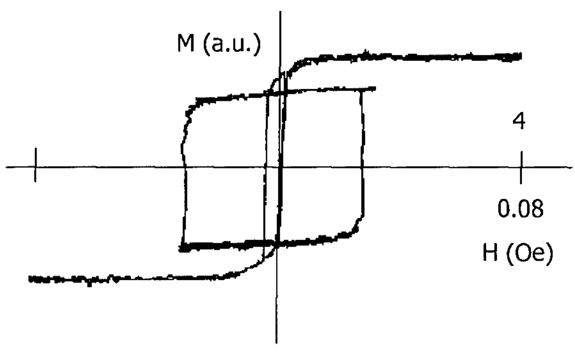


Figure 1. Low and high field axial hysteresis loops for a glass-coated CoFeSiB amorphous microwire with the metallic core diameter of 34 μm and a total diameter of 101 μm (sample A).

This magnetic behavior is different from that of microwires with the same composition, but with typical dimensions. Thus, the axial direction is a hard axis for typical microwires with this composition, while in this case it is an easy axis of magnetization. The explanation for this fact is related to the dominant energy terms from the expression of the total free energy, whose minimization decides the formation of domain structure.

In the case of typical microwires with nearly zero magnetostriction, it has been shown that the magnetoelastic energy minimization is responsible for the formation of a domain structure with transverse easy axis of magnetization, i.e. azimuthal in cylindrical coordinates, which are the most appropriate for the geometry of such materials [5]. In this way, the coupling between negative magnetostriction and large axial tensile stresses in the wire's inner region, and large compressive azimuthal ones at the surface, results in both cases in an easy axis of magnetization perpendicular to the axial direction. However, in the case of 'thick' microwires, it seems that the magnetoelastic energy is no longer the term whose minimization mainly decides the domain structure formation, but rather the magnetostatic energy plays this role. This hypothesis is supported by internal stress calculations. For example, the maximum value of the axial tensile stress within the microwire's inner region is about 1.5 GPa, and the maximum value of the compressive azimuthal stress at its surface is about -2.8 GPa for a microwire with a metallic core diameter of 7 μm and a glass coating thickness of 5 μm (total diameter 17 μm), while for the microwire with the metallic core diameter of 34 μm and the glass coating thickness of 33.5 μm (sample A) these values decrease to 450 MPa and -1.75 GPa respectively. Thus, it is expected to have a less important role of the magnetoelastic term in 'thick' microwires. The magnetoelastic term should count mostly near the surface of the metallic core, were the azimuthal compressive stresses are still large. Consequently, the magnetostatic energy minimization would result in an axial easy axis of magnetization, mainly due to the sample's shape.

Figure 2 shows the domain structure of sample A, before and after magnetization reversal. One observes a single domain configuration, that explains the measured hysteresis loops and sustains the above hypothesis.

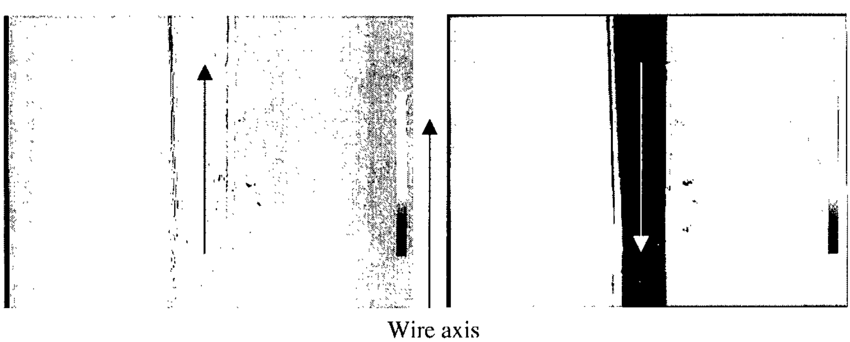


Figure 2. Kerr microscopy image showing the domain pattern of a glass-coated CoFeSiB amorphous microwire with the metallic core diameter of 34 μm and a total diameter of 101 μm (sample A).

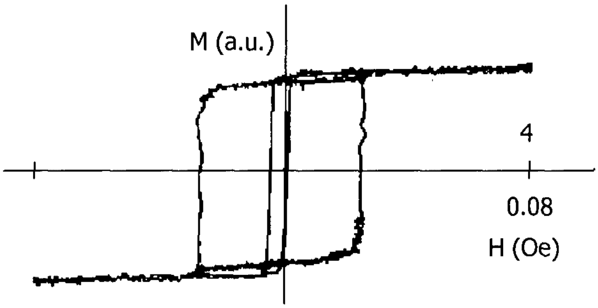


Figure 3. Low and high field axial hysteresis loops for a CoFeSiB amorphous microwire with the glass coating removed, having the metallic core diameter of 34 μm (sample A1).

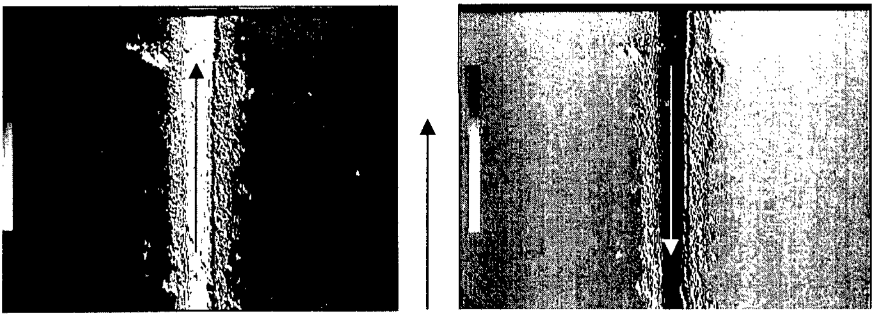
By analyzing the domain structure and the value of M_r/M_s (0.68), correlated with the quite large values of the azimuthal stresses towards the surface of the metallic core, one can state that near the surface the easy axis of magnetization has some inclination with respect to the axial direction as a result of the local importance of the magnetoelastic term.

Figure 3 shows the axial hysteresis loop for sample A1 (sample A after glass removal). One observes that the magnetic bistability is maintained (the large Barkhausen jump occurs at a somewhat lower value of H*: 27.7 mOe). On the other hand, the remanence to saturation ratio increases after glass removal, being 0.88.

These changes in the magnetic behavior are in agreement with the transformations suffered by typical microwires with the same composition at glass removal [5]. Hence, typical microwires become bistable after glass removal, mainly due to stress relief that accompanies glass removal. In the case of 'thick' microwires after glass removal, stress relief improves bistability, i.e. the switching field decreases while the remanence to saturation ratio increases. Thus, stress relief is expected to reduce the influence of the magnetoelastic term even near the surface of the metallic core, and consequently the inclination of the easy axis in this region, and the microwire becomes magnetically softer on the axial direction.

Results of direct domain observation by Kerr microscopy, illustrated in figure 4, for the case of sample A1 show that the single domain configuration with the magnetization pointing to the wire axis is maintained.

Similar magnetic behavior and domain configurations have been observed for samples B and B1. For sample B, H* is 66.8 mOe and M_r/M_s is 0.82, while after glass removal H* decreases to 46.3 mOe and M_r/M_s increases slightly to 0.88. In this case, the maximum value of axial tensile stress reaches to 750 MPa, while the maximum azimuthal compressive one is -1.5 GPa. The larger value of H* for sample B, with respect to the value obtained for sample A, is related to the differences in the shape anisotropy and other contributions like smaller demagnetization. The larger value of M_r/M_s originates in the even weaker contribution of magnetoelastic energy near the surface of the metallic core as compared to the case of sample A, which is perfectly explainable if we refer to the ratio between glass thickness and metallic radius. Thus, it has been previously shown that the magnetoelastic term's contribution is larger in

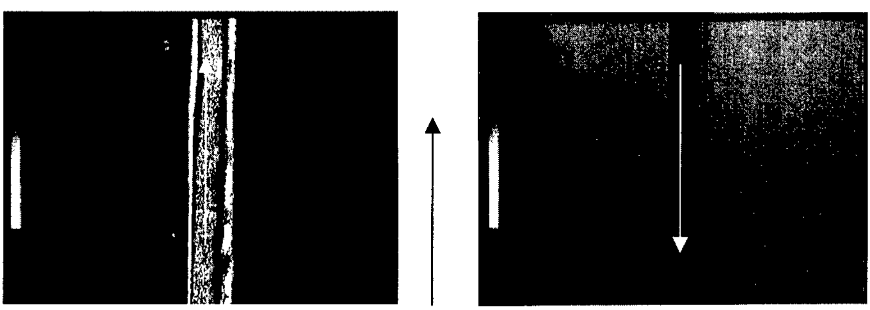


Wire axis

Figure 4. Kerr microscopy image illustrating the domain configuration of a CoFeSiB amorphous microwire with the glass coating removed; the metallic core diameter is 34 μm (sample A1).

microwires with larger ratios between glass coating thickness and metallic core radius [6]. In the case of sample A, this ratio is 1.97, while in the case of sample B it is 1.33.

Glass removal induces similar changes in the characteristics of the magnetic behavior of sample B as in the case of sample A. The fact that M_r/M_s reaches to the same value (0.88), indicates some kind of 'saturation' of the remanence to saturation ratio, that should originate in the local action of the magnetoelastic term that is always important near the surface of the metallic core. Results of direct domain observation by Kerr microscopy show for both samples B and B1 the single domain configuration with axial magnetization. The domain configuration for sample B is illustrated in figure 5.



Wire axis

Figure 5. Kerr microscopy image of the domain configuration of a glass-coated CoFeSiB amorphous microwire with a metallic core diameter of 27 μm and a total diameter of 63 μm (sample B).

CONCLUSIONS

Results on the magnetic behavior and domain structure of 'thick' amorphous microwires with nearly zero magnetostriction were presented for the first time.

We observed that such samples display single domain configuration with the magnetization direction pointing mostly to the wire axis. In addition, the low field axial magnetization process of the investigated samples is achieved by a single and large Barkhausen jump that occurs at a certain value of the axially applied magnetic field. The domain configuration and magnetization process do not change after glass removal, but an enhancement of the soft magnetic properties on the axial direction was observed.

The obtained results show that the microwire dimensions are a critical parameter that can determine abrupt changes in the magnetic behavior of microwires with the same composition, i.e. changes in the mechanism of magnetization.

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