Journal of Alloys and Compounds 323–324 (2001) 451–454
www.elsevier.com/locate/jallcom

Local magnetic properties and micromagnetic structure of FeCuNbSiB amorphous microwires

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Abstract

Studies of the local magnetic properties and near-surface micromagnetic structure of as-cast and annealed (550°C for 1 h) $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ amorphous microwires with a magnetic core of 10-μm diameter were carried out employing a magneto-optical micro-magnetometer. The as-cast wires were amorphous. The annealed wires exhibited an ultra-fine structure with a grain size of 10–12 nm. A strong inhomogeneity of the near-surface magnetic properties of the as-cast samples was found. This was explained by the dispersion of the magnetic anisotropy, which is a typical phenomenon for as-cast amorphous materials. Nanocrystalline phase formation in the annealed wires was found to lead to an improvement in their soft magnetic properties and a significant increase in the homogeneity of the magnetic characteristics. The magnetic field behaviour of the near-surface magnetization components allows us to conclude that there is a curling mode of the magnetization reversal in the examined microwires.

Keywords: Amorphous materials; Nanofabrications; Magnetization; Light absorption and reflection

1. Introduction

Amorphous microwires are studied extensively because of the insight that they provide into the fundamental problems of magnetism. The micron dimensions of these materials make them suitable for applications in miniaturized devices of modern microelectronics. $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ amorphous alloys (discovered by Yoshizawa and co-workers in 1988 [1]) have attracted particular interest. Appropriate annealing ($T = 540–550$°C, $t = 1$ h) of amorphous FeCuNbSiB materials was found to lead to a nanocrystalline structure. In consequence, these alloys exhibit a unique combination of properties such as low losses, high permeability, near-zero magnetostriction and high saturation magnetization (see, for example, Refs. [1–3]).

The aim of this work was to study the local magnetic properties and near-surface micromagnetic structure (MMS) of as-cast and annealed (550°C for 1 h) $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ amorphous microwires with a magnetic core of 10-μm diameter. Scanning Kerr microscopy is used to perform these investigations.

2. Experimental

$Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ wires with a magnetic core of 10-μm diameter were obtained using the modified Taylor's technique [4]. The glass coating was removed using fluoric acid solution. The amorphous state of the as-cast wires was confirmed by X-ray diffraction. After annealing at 550°C for 1 h, the microwires exhibited an ultra-fine structure with a grain size of 10–12 nm. The examined wires were cut into pieces 20 mm in length. The inhomogeneity in the diameter of the examined samples was about 5%. Study of the micromagnetic structure (equilibrium distribution of the magnetization) of the $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ microwires was carried out employing a magneto-optical micro-magnetometer with a surface sensitivity of ~10 nm thickness depth and a spatial resolution of up to 0.3 μm [5]. An alternating magnetic field H of frequency $f = 80$ Hz was applied along the axial wire direction. By scanning a light spot of 1 μm-diameter along the wire length L, the distributions of the in-plane magnetization components (both parallel $M_{\parallel}$ and perpendicular $M_{\perp}$ to the applied

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0925-8388/01/$ – see front matter
PII: S0925-8388(01)01091-X

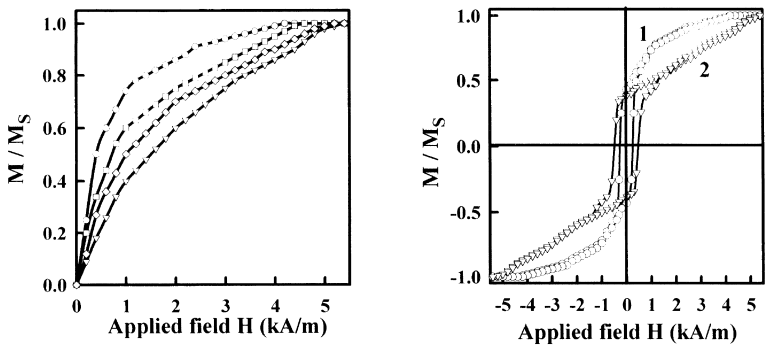

Fig. 1. Local magnetization curves $M_{\parallel}/M_S(H)$ and hysteresis loops observed for various near-surface microparts of an as-cast $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ microwire.

magnetic field) and also the local hysteresis loops were measured using the transverse Kerr effect (TKE), δ. A $\delta(L,H)/\delta_S \propto M(L,H)/M_S$ dependence was found. Here, $\delta = (I - I_0)/I_0$ (I and I_0 are the intensities of the reflected light from the magnetized and nonmagnetized sample, respectively), δ_S is TKE at $M = M_S$, and M_S is the saturation magnetization. The components $M_{\parallel}$ and $M_{\perp}$ are detected by using, respectively, the transverse and longitudinal configurations (the magnetic field H is perpendicular and parallel to the plane of light incidence). All measurements were performed in the central part of the wire in order to reduce the influence of edge effects (in particular, variations of local demagnetizing factors).

3. Results and discussion

Figs. 1 and 2 show typical local magnetization curves $M_{\parallel}/M_S(H)$ and hysteresis loops observed for various near-surface microparts of the as-cast and annealed samples. From Fig. 1 one can see that the local magnetic properties (the saturation field, the coercivity, the initial permeability) of the as-cast wires differ strongly. Analysis of the data obtained for the as-cast sample showed that the local magnitudes of the coercivity H_C and the saturation field H_S vary from 0.26 to 0.36 kA/m and from 4.2 to 5 kA/m, respectively. This is a clear indication of the inhomogeneity of the near-surface local magnetic properties of the as-cast microwires. The obtained data can be explained by the dispersion of the magnetic anisotropy, which is a typical phenomenon for as-cast amorphous materials [6–8].

From Fig. 2 one can see that the nanocrystalline phase formation in the annealed wires leads to an improvement in their soft magnetic properties and a significant increase in the homogeneity of the magnetic characteristics. We found that the coercivity H_C of the annealed sample decreases (about five times) and the initial permeability μ_0 increases (about four times) with respect to the values for the as-cast microwire. The variations in the local values of H_C and μ_0 do not exceed 5%. It should be remarked that, at the present time, there are many reports where the results of investigations of the macroscopic (average) magnetic properties of amorphous glass-covered microwires are presented (see, for example, Refs. [8–12]). It was shown in Refs. [8–12] that the magnetic behaviour of amorphous microwires of fixed diameter and length is mainly determined by the magnetoelastic anisotropy. Its magnitude depends on the internal stresses induced during preparation and the magnetostriction constant, λ_S. The coercivity of the microwires after glass removal was found to decrease, which was ascribed to reduction of the internal stresses [10]. Our investigation allowed us to obtain information about the local magnetic properties of the

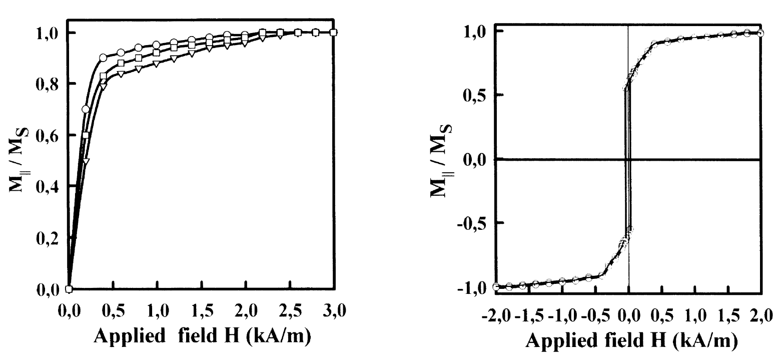

Fig. 2. Local magnetization curves $M_{\parallel}/M_S(H)$ and hysteresis loop observed for various near-surface microparts of an annealed $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ wire.

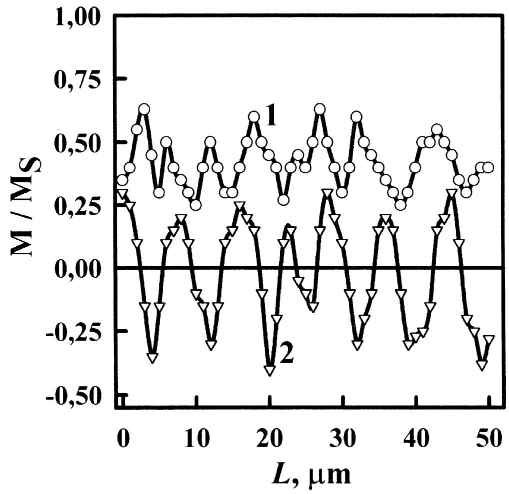

Fig. 3. Typical magnetization distributions of the magnetization components parallel $M_{\parallel}/M_S(L)$ (curve 1) and perpendicular $M_{\perp}/M_S(L)$ (curve 2) to the axial magnetic field observed in the as-cast microwire. The measurements were performed at $H = 0.5$ kA/m.

1-μm diameter near-surface microparts of the examined samples without glass cover. The improvement in the soft magnetic properties of the annealed microwire observed here is caused by a decrease of the magnetoelastic anisotropy due to the reduction of λ_S associated with the appearance of α-FeSi nanosized grains [2].

It was established that, at $H < H_S$, there are in-plane local magnetization components both parallel ($M_{\parallel}$) and perpendicular ($M_{\perp}$) to the applied axial field in the examined microwires. We discovered that the dispersion of the magnetic anisotropy and the nanocrystalline phase formation in the as-cast and annealed wires causes different micromagnetic structures (equilibrium distribution of magnetization) in these samples. For illustration, Figs. 3 and 4 show fragments of the magnetization distributions $M_{\parallel}/M_S(L)$ and $M_{\perp}/M_S(L)$ typical for the as-cast and annealed samples. From Figs. 3 and 4 one can see that, in the as-cast wires, the magnetization distributions along L have an irregular character, while in the annealed samples they are periodic. In both cases the dependence of $M_{\perp}/M_S(L)$ is sign-variable. According to Ref. [13], this indicates that magnetization rotation is the main magnetization process in the examined microwires. Detection of the $M_{\parallel}$ and $M_{\perp}$ components of magnetization allows us to deduce that there is a curling mode of magnetization reversal in these samples.

It is evident that the annealed microwires can be employed as sensing elements in various devices owing to their excellent soft magnetic properties.

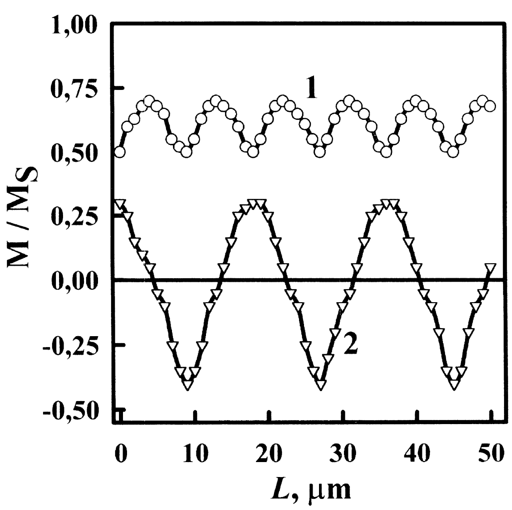

Fig. 4. Typical magnetization distributions of the magnetization components parallel $M_{\parallel}/M_S(L)$ (curve 1) and perpendicular $M_{\perp}/M_S(L)$ (curve 2) to the axial magnetic field observed in the annealed microwire. The measurements were performed at $H = 0.25$ kA/m.

4. Conclusion

We carried out a magneto-optical investigation of the local magnetic properties and micro-magnetic structure of as-cast and annealed (550°C for 1 h) $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ amorphous microwires of 10-μm diameter employing scanning Kerr microscopy. The near-surface local magnetic properties of the as-cast samples were found to be inhomogeneous, which was explained by the dispersion of the magnetic anisotropy. The annealed microwires were found to exhibit superior soft magnetic properties and a high homogeneity of the local magnetic characteristics, which was ascribed to nanocrystalline phase formation in these samples. The distributions of the near-surface magnetization components allowed us to deduce that there is a curling mode of magnetization reversal in the examined microwires.

Acknowledgements

This work was sponsored, in part, by the Korea Institute of Science and Technology Evaluation and Planning under the Korea–Russia Manpower Exchange Program and Russian Fund of Fundamental Investigation (grant No. 99-02-16595).

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