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Effect of Current Annealing on Domain Structure in Amorphous and Nanocrystalline FeCoMoB Microwires

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The influence of current annealing on the complex domain structure in amorphous and nanocrystalline FeCoMoB microwire has been studied. The thickness of radial domain structure together with the switching field of single domain wall change as a consequence of variation of complex internal stress distribution inside metallic core. Firstly, radial domain structure thickness monotonously increases with increasing annealing DC current density for amorphous state. Switching field exhibits local minimum in nanocrystalline sample annealed at 500 MA/m^2 for 10 min when the lowest thickness of outer shell (182 nm) was observed. Such annealed sample (which magnetic properties exhibit excellent temperature stability) is suitable candidate for miniaturized sensor construction for sensing the magnetic field or mechanical stress.

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1. Introduction

Amorphous ferromagnetic glass-coated microwires are very attractive materials as sensing element in modern microsensors (temperature, magnetic field, stress, position, or etc.) [1, 2] magnetic coding, automotive and biomedical applications. They are prepared by the modified Taylor–Ulitovsky method by drawing and quenching of molten master alloy. Peculiar domain structure of such prepared microwires is characterized an internal axial monodomain that is surrounded by radial multi-domain structure (see Fig. 1). As a result, static magnetization has only two stable states: $+M_S$ or $-M_S$. Switching between these two stable states is driven by the domain wall propagation inside axial domain at the field called switching field.

However, disadvantage of amorphous microwires is their unstability or change of magnetic properties with time (ageing) and temperature [3]. One possible solution is to use nanocrystalline materials [4], which are prepared by controlled annealing from the amorphous precursors. They consist of nanocrystalline grains embedded in the residual amorphous matrix. Nanocrystalline microwires are characterized by high temperature stability of the magnetic properties [5, 6].

In the given contribution, we present the influence of current annealing on domain structure of FeCoMoB microwire. Such a composition is characteristic with high Curie temperature and low crystallization temperature. Hence, it allows inducing anisotropies by magnetic annealing (e.g. by current annealing) even at high temperatures. Current annealing is very effective method of thermal treatment (it was shown that 10 min of current annealing corresponds to 1 h of classical annealing in furnace). Moreover, current annealing leads to the more homogeneous final nanocrystalline microstructure in comparison to the classical annealing. Additionally, electrical current flowing through microwire produces Oersted circular magnetic field and therefore circular magnetic anisotropy is induced during annealing. Induced circular anisotropy prefers vortex domain walls with much faster velocities. As a result of current annealing, complex distribution of internal stresses is changed and therefore the values of the thickness of axial monodomain and switching field of single domain wall were strongly affected.

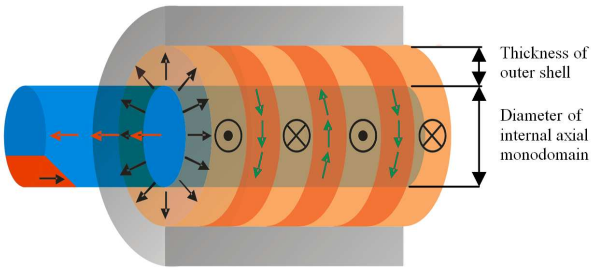

Fig. 1. Schematic internal core-outer shell domain structure of amorphous or nanocrystalline microwire with positive magnetostriction.

2. Experimental methods

Amorphous glass-coated microwires with nominal composition of $Fe_{40}Co_{38}Mo_4B_{18}$ were selected for our study. The diameter of metal core was 16 μm and total diameter was 34 μm. The studied microwires were annealed at various DC current densities starting from 150 MA/m^2 up to 520 MA/m^2 for 10 min.

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In order to estimate the value of crystallization current density, the dependence of the resistance on the applied electrical current density has been measured at the rate of 0.1 MA/(m^{2}min).

Quasistatic hysteresis loops were measured at room temperature by the static induction method [7]. The length of samples used in the hysteresis loops measurements was 8 cm.

The switching field has been measured by induction method using triangular waveform to feed primary coils at two different frequencies: 20 and 2000 Hz. The maximum amplitude of exciting magnetic field was kept constant (1000 A/m). All measurements of the switching field were performed at room temperature and length of selected samples was 10 cm. For more details see [8].

The remanent and saturation magnetization was measured using a SQUID magnetometer (Quantum Design) within the temperature range of 10–390 K. The saturation magnetization has been measured in a field of 1 T. The length of all studied samples used in the SQUID measurements was 1.5 cm.

3. Results and discussion

Temperature dependence of resistance can help to determine the structural changes which occurred during annealing in materials [9].

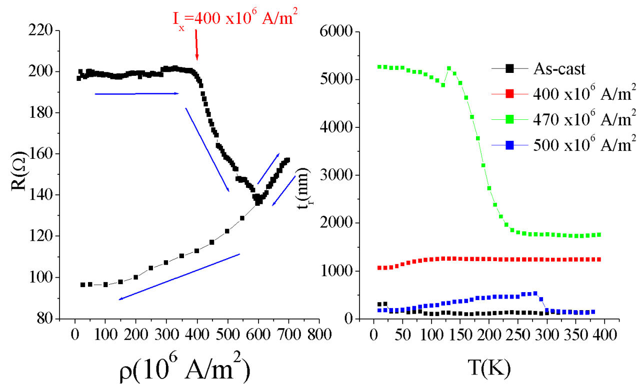

Fig. 2. (left) Dependence of resistance on the annealing DC current density, (right) Temperature dependence of the thickness of outer shell for 4 samples after different thermal treatment.

Therefore, measurements of dependence of resistance on the annealing DC current density was firstly performed (Fig. 2, left). Small variations of resistance at current density below 400 MA/m^2 reflect the structural relaxation (stress relief and homogenization) of the amorphous structure. Above 400 MA/m^2, the resistance steeply decreased as a result of crystallization of bcc-(Fe,Co) crystalline grains [10]. It is worth to note that crystallization current density ≈ 400 MA/m^2 corresponds to the crystallization temperature ≈ 420 °C estimated from temperature dependence of resistance [11]. Decrease of resistance due to nanocrystallization process with increasing annealing DC current density was observed up to 600 MA/m^2. Resistance increases again at higher values of applied annealing DC current density most probably due to thermal activation of atomic structure.

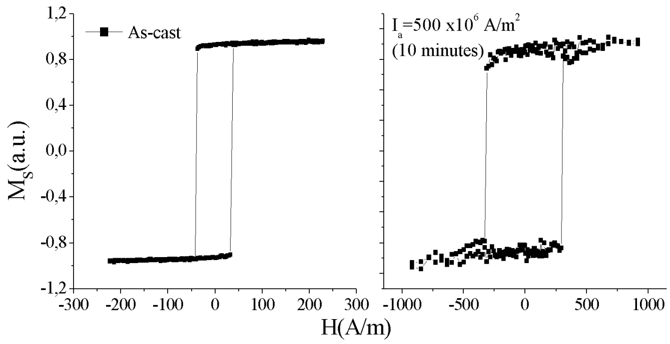

Fig. 3. Quasistatic hysteresis loops for (left) amorphous as-cast microwire and (right) nanocrystalline microwire annealed at 500 MA/m^2 for 10 min.

Finally, the resistance is much lower in nanocrystalline microwire after crystallization process in comparison to initial amorphous state of sample. To conclude, microwires annealed by current density up to 400 MA/m^2 are in amorphous state after stress relaxation while microwires annealed at higher current densities are nanocrystalline.

Fig. 3 shows perfectly bistable quasistatic hysteresis loops of the FeCoMoB microwires in the initial as-prepared state and in nanocrystalline sample after annealing by current density of 500 MA/m^2 for 10 min. It is worth to note that studied FeCoMoB-based microwire does not lose its bistability even after annealing at very high temperatures (or current densities) [12].

Measurements of temperature dependences of saturation and remanent magnetization were performed in order to study the effect of current annealing on domain structure. The thickness of outer shell covering internal axial monodomain was estimated using the relationship [12]:

$$\frac{M_R}{M_S} \approx \frac{V_a}{V_t} \approx \frac{r_a^2}{r_t^2}, \tag{1}$$

where V_a and V_t are the volume of the axial monodomain and total volume of metallic core, respectively, and r_a and r_t are their respective radii.

Temperature dependences of outer shell thickness for 4 samples after various thermal treatments are shown in Fig. 2, right. Sample annealed at 470 MA/m^2 for 10 min is the most sensitive on temperature (variation is more than 250%). In contrary, as-prepared sample and sample annealed at 400 MA/m^2 are extremely stable and exhibit almost no change of domain structure with temperature. Moreover, nanocrystalline sample annealed at 500 MA/m^2 is also very stable and exhibits very low variation of the radial domain structure thickness with temperature.

Annealing at low current density below crystallization current density (up to 400 MA/m^2) leads to the stress relaxation. As a result, strongest axial magnetoelastic anisotropy from production process decreases which leads to

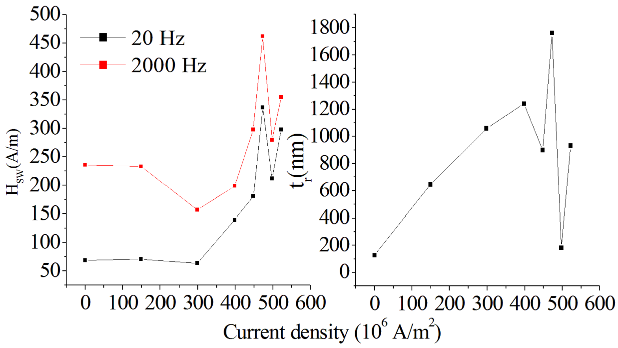

Fig. 4. (left) Dependence of the switching field on annealing DC current density, (right) dependence of thickness of outer shell on annealing DC current density.

the increase of the thickness of outer shell. Additionally, strong circular anisotropy is induced during current annealing which also leads to the increase of thickness of outer shell that consists of many adjacent strips with different orientation of magnetization (radial and circular ones) as is schematically depicted in Fig. 1, which has been experimentally observed in amorphous microwires, see for example in [13, 14]. As a result of such annealing thickness of outer shell almost linearly increases while values of the switching field exhibit slightly decreasing tendency.

In contrary, more complex situation was observed in sample annealed at 400 MA/m^2 for 10 min. At least three reasons are responsible for increase of the switching field together with thickness of outer shell: 1. crystallization process of bcc-(Fe,Co) nanograins, 2. annealing at high temperatures leads to the inducing strong stresses applied by glass-coating during cooling after thermal treatment or 3. most probably, a strong circular anisotropy is induced by the Oersted field during thermal treatment.

Another situation was observed in nanocrystalline microwires annealed above crystallization current density $\approx$ 400 MA/m^2. Such annealing leads to the appearance of bcc-(Fe,Co) grains with very small diameter 12–13 nm embedded in the residual amorphous matrix [10]. Created grains are too small and well separated to interact between them through exchange interaction. Instead, they acts as pinning centers for the domain wall propagation. Therefore, maximum switching field (361 A/m) together with maximum thickness of outer shell (1763 nm) was observed in sample annealed at 470 MA/m^2.

Annealing at higher current density $\approx$ 500 MA/m^2 leads to the grain growth that are exchangeably coupled through the amorphous matrix, in which they are embedded. Therefore, magnetocrystalline anisotropy is averaged out more effectively in comparison to the sample annealed at 470 MA/m^2. Particularly, minimum switching field (227 A/m) together with minimum thickness of outer shell (182 nm) was observed in such annealed sample. Therefore annealing current density of 500 MA/m^2 is optimum current density for achievement of soft and stable nanocrystalline microstructure of metallic core.

Annealing at higher current density $\approx$ 520 MA/m^2 leads to the introducing of strong stresses by glass-coating during cooling after thermal treatment and the switching field increases.

The switching field is in good accordance with the thickness of outer shell (Fig. 4). The switching field increases with decreasing diameter of the internal axial monodomain or with increase of the thickness of outer shell.

4. Conclusions

Effect of current annealing on domain structure and switching field below and above crystallization temperature has been studied. It is shown that there is a strong influence between the switching field and outer shell domain structure in bistable microwires. Current annealing below 400 MA/m^2 and above 500 MA/m^2 for 10 min leads to the stable domain structure in a wide range of temperature, which can be used for miniaturized sensor construction for sensing the magnetic field or mechanical stress.

Acknowledgments

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