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Study of Stress-Annealing Enhancement of Magnetoimpedance Effect in $Fe_{89.8}Ni_{1.5}Si_{5.2}B_3C_{0.5}$ Metallic Glass Ribbons

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In this study, the magnetoimpedance effect in magnetically soft $Fe_{89.8}Ni_{1.5}Si_{5.2}B_3C_{0.5}$ metallic glass ribbon samples with significant decrease in atomic percentage of metalloids content (less than 10 at.%) was investigated. Thermal treatments were performed by stress-annealing technique of up to 693 K/475 MPa/30 min. The critical frequency of about 600 kHz was observed as the point with the initial increase in magnetoimpedance ratio. Significant improvement of magnetoimpedance-response reaching the value $\Delta Z/Z = 25\%$ after stress-annealing at 693 K/130 MPa/30 min was recorded in samples with still amorphous structure at driving frequency of 4 MHz. The highest magnetoimpedance-element sensitivity was found for low magnetic field intensity ($H \leq 1$ kA/m), where values of about 12%/kA/m were attained.

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1. Introduction

One of the most interesting phenomena observed in amorphous ribbons and wires of soft magnetic alloys is magnetoimpedance (MI) effect. MI refers to the change in impedance of magnetic material sample that is exposed to the influence of external magnetic field (H). MI effect can be tailored by the changes of electrical resistivity (ρ) and magnetic permeability (μ), i.e. two material properties that in classical skin effect determine the penetration depth (δ_m), i.e. $\delta_m = [(\rho/\pi)\mu f]^{1/2}$ [1]. For ribbon geometry the improvement of transverse magnetic anisotropy is crucial for obtaining large MI effect [1–3]. In order to induce suitable magnetic anisotropy it is possible to perform few different experimental techniques: field--annealing, current-annealing [4], stress-annealing, as well as combinations of these techniques. Therefore, this paper studies the MI changes in Fe-based alloy with very low metalloid content ($Fe_{89.8}Ni_{1.5}Si_{5.2}B_3C_{0.5}$ ribbons), previously exposed to simultaneous effects of stress and isothermal annealing.

2. Experimental

Ribbon shaped samples of $Fe_{89.8}Ni_{1.5}Si_{5.2}B_3C_{0.5}$ amorphous alloy were obtained using the procedure of rapid quenching (melt-spinning technique). The crystallization process was investigated in a nitrogen atmosphere by the differential scanning calorimetry (DSC) method using SHIMADZU DSC-50 analyzer. X-ray investigations were performed using Cu K_α radiation lines on a Phillips PW1710 device. Samples were treated by stress-annealing (SA) technique of up to 693 K/475 MPa/30 min. The MI measurements of the 65 mm long, 2 mm wide and 35 μm thick samples were performed by four-point method in the longitudinal direction. The MI ratio, defined as $\Delta Z/Z = [Z(H) - Z(H_{\max})]/Z(H_{\max})$, was explored in a dc axial magnetic field, produced by the Helmholtz coils generating a maximum field of $H_{\max} = 5$ kA/m. The frequency of the MI measurements ranged from 100 kHz to 10 MHz and amplitude of sinusoidal current was fixed at 8 mA.

3. Results and discussions

Figure 1(I) shows a constant rate DSC trace for the investigated alloy. DSC thermogram shows that intensive exothermic reaction occurs in two separate stages with temperature peaks of $T_{\mathrm{k1}} = 812$ K and $T_{\mathrm{k2}} = 833$ K. Therefore, the region used for annealing was chosen to be about 100 K lower than the temperature of devitrification process. The X-ray diffraction (XRD) patterns shown in Fig. 1(II), of the samples annealed at 693 K and exposed to strain degrees of $\sigma_1 = 130$ MPa, $\sigma_2 = 300$ MPa and $\sigma_3 = 475$ MPa, revealed that the ribbons are mainly amorphous with a very small amount of crystalline α-Fe phase. The presence of α-Fe is due to the alloy composition with significant decrease in atomic percentage of the metalloids content (less than 10 at.%). Perusal of Fig. 1(II) implies that annealing and mechanical strain had no significant influence on the formation of crystal phases, however there was induced relaxation of the amorphous structure.

MI effect depends on the ratio between electrical resistivity and magnetic permeability (ρ/μ). Sample annealing enables amorphous structure relaxation, which brings about a decrease in electrical resistivity and an increase in magnetic permeability [5]. The critical frequency of about 600 kHz (when $\delta_{\mathrm{m}} \approx d/2$) was observed as the point with the initial increase in the MI (Fig. 2). The maximal values of relative change in annealed samples impedance module were registered

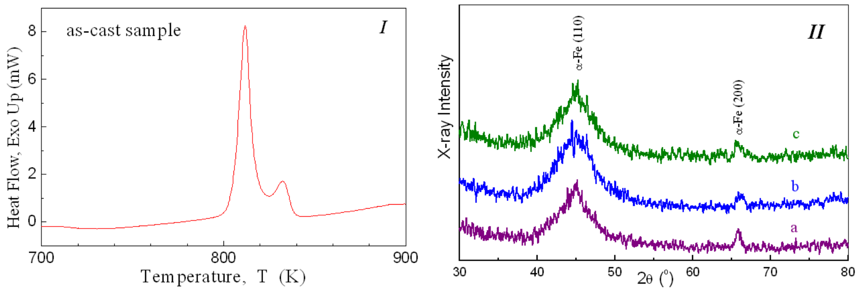

Fig. 1. (I) DSC thermogram of $Fe_{89.8}Ni_{1.5}Si_{5.2}B_3C_{0.5}$ amorphous alloy for the as-cast sample obtained at heating rate of 20 K/min; (II) X-ray patterns for the samples isothermally annealed for 30 min at temperature $T = 693$ K under different stresses: (a) $\sigma_1 = 130$ MPa, (b) $\sigma_2 = 300$ MPa and (c) $\sigma_3 = 475$ MPa.

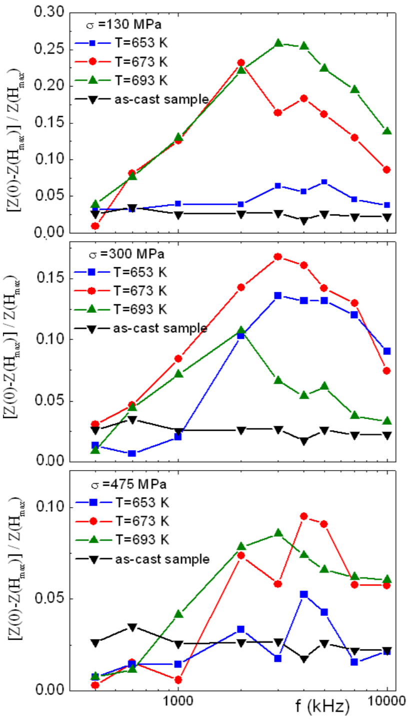

Fig. 2

Fig. 3

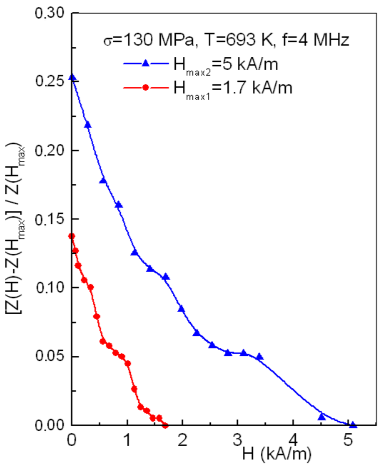

Fig. 2. Frequency dependence of MI ratio $\Delta Z/Z$ for the samples annealed at various temperatures and different stresses ($H_{\max} = 5$ kA/m).

Fig. 3. Magnetoimpedance as a function of external magnetic field, for two different intensity maxima $H_{\max 1} = 1.7$ kA/m and $H_{\max 2} = 5$ kA/m.

at driving frequencies of 3–4 MHz. Such maximal values were caused by decrease in magnetic permeability at higher frequencies [6].

Curves representing the MI dependence of external magnetic field show the ever-decreasing trend (see Fig. 3), while the domain walls moving mechanism is predominant in the magnetization process. However, for values, which are near to the anisotropy field H_{k}, the magnetization process is defined by rotation mechanism, thus at values of external magnetic field of approximately 1 to 1.25 kA/m, a curves knee accompanied by decrease in sensitivity was observed. The enhancement of the MI-ratio is not proportional to the applied stress intensity (σ). Similar results have been observed for FeNbCuSiB [7] and FeZrNbB [8] ribbons as a consequence of non-uniform anisotropy induced by stress-annealing. As soft magnetic amorphous materials are usually random anisotropy materials they exhibit dispersion of the local anisotropy axes with respect to the induced anisotropy axes. The largest MI magnitude is associated with small induced anisotropy, i.e. with low strain degree (it is also predicted by the MI model proposed by Kraus [9]). Further experiments deduced to the assessment of anisotropy attained by performed tensile stress-annealing are in progress. Degree of structural relaxation, followed by decrease in electrical resistivity [5], is the most intensive at the highest performed annealing temperature (693 K). Therefore, the highest changes in impedance module were detected on the sample annealed at 693 K, under strain degree of 130 MPa, amounting to 25% (Fig. 3). The highest MI-element sensitivity $(\Delta Z/Z)/H$ of about 12%/kA/m was found for low field intensity ($H \leq 1$ kA/m) where linear response was observed.

Acknowledgments

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References

[1] R.L. Sommer, C.L. Chien, *Appl. Phys. Lett.* **67**, 857 (1995).

[2] K. Mohri, K. Bushida, M. Noda, L.V. Panina, T. Uchiyama, *IEEE Trans. Magn.* **MAG-31**, 2455 (1995).

[3] N. Mitrović, S. Roth, S. Kane, *Mater. Sci. Forum* **518**, 313 (2006).

[4] N. Mitrović, *Sci. Sintering Spec. Issue* **30**, 85 (1998).

[5] A. Kalezić-Glišović, L. Novaković, A. Maričić, D. Minić, N. Mitrović, *Mater. Sci. Eng. B* **131**, 45 (2006).

[6] J.M. Barandiaran, A. Garcia-Aribes, J.L. Muza, G.V. Kurlyandskaya, *IEEE Trans. Magn.* **MAG-38**, 3051 (2002).

[7] M. Vàzquez, G.V. Kurlyandskaya, J.M. Garcia-Beneytez, J.P. Sinnecker, J.M. Barandiaran, V.A. Lukshina, A.P. Potatova, *IEEE Trans. Magn.* **MAG-35**, 3358 (1999).

[8] M.N. Gona, S. Yanase, S. Hashi, Y. Okozaki, *J. Magn. Magn. Mater.* **254-255**, 466 (2003).

[9] L. Kraus, *Sensors Actuators A* **106**, 187 (2003).