14th Czech and Slovak Conference on Magnetism, Košice, Slovakia, July 6–9, 2010

Directional Ordering in Amorphous $Fe_{43}Ni_{43}Zr_7Cu_1B_6$ Ferromagnetic Alloys

M. Varga[a], R. Varga[a], P. Vojtaník[a,*], B. Hernando[b], V.M. Prida[b], J.D. Santos[b] and M.J. Pérez[b]

[a]Institute of Physics, Faculty of Science, P.J. Šafárik University, Park Angelínum 9, 041 54 Košice, Slovakia

[b]Departamento de Física, Universidad de Oviedo, Calvo Sotelo s/n, 330 07 Oviedo, Spain

Development of the atomic directional ordering in the $Fe_{43}Ni_{43}Zr_7Cu_1B_6$ alloy, during its conventional the same as after transverse magnetic field annealing, was experimentally studied by the amplitude dependence of susceptibility and hysteresis loops measurements, respectively. Diffusion processes of the mobile atoms caused perminvar effect, decrease of the initial susceptibility, increase of the critical field, and linear shape of the hysteresis loop. Uniaxial magnetic anisotropy, created during magnetic field annealing of the FeNiZrCuB alloy, was confirmed also by observation of the surface domain structure.

PACS numbers: 75.50.Kj, 75.60.Nt

1. Introduction

Nanocrystalline alloys of chemical composition Fe–M–B (M = Zr, Hf, Nb), called Nanoperms [1], are perspective group of the soft magnetic materials. They offer higher values of the saturation magnetization in comparision to the Finemet based alloys [2]. As it was shown in [3], the highest Curie temperature of the amorphous matrix, in the $Fe_{86-x}Ni_xZr_7Cu_1B_6$ alloys, belongs to $x = 43$. Such concentration of iron and nickel, respectively, predicts the most intensive influence of the ferromagnetic atom pair reorientation (directional ordering) on the soft magnetic properties of investigated alloys, in accordance with [4, 5].

As an atom pair may occupy two different orientations of its axis towards the direction of a local magnetization, a minimization of the interaction energy is carried out by axis reorientation and occupation of the position with lower interaction energy [6].

So, each atom pair contributes to stabilization of the entire ferromagnetic system. It leads to the formation of a stabilization potential of the domain walls (DWs), to their mobility (susceptibility) decrease, to perminvar critical field increase as well as to induced uniaxial magnetic anisotropy in magnetic domains. Developed potential wells of the DWs have parabolic shape [7], which explains the constant initial susceptibility, χ_0 [8], up to the critical field H_{CR}.

2. Experimental

Directional ordering was experimentally studied by the measurements of the amplitude dependence of the total AC susceptibility and the hysteresis loops, respectively, as well as through the observation of the sample surface domain structure. The $Fe_{43}Ni_{43}Zr_7Cu_1B_6$ amorphous ribbons, in the form of straight pieces, 0.7 mm in width and 30 μm in thickness, were prepared by the rapid melt quenching. The samples were demagnetized by AC magnetic field decreasing from 750 A/m down to zero, before susceptibility measurements. The frequency of the measuring magnetic field was 333 Hz. The hysteresis loops were measured at 12 Hz frequency and high enough amplitude of the applied magnetic field to saturate the samples. The surface domain structure was observed by the Bitter patterns technique. One hour long annealing processes were realized in protective argon atmosphere, to avoid the oxidation of the samples. Heating rate was 10 K/min.

3. Results and discussion

Figure 1 shows amplitude field dependences of the total AC susceptibility, measured on the $Fe_{43}Ni_{43}Zr_7Cu_1B_6$ alloy in the as-cast state, as well as during its annealing at $T = 350\,^{\circ}\mathrm{C}$, after 10 min long stabilization of the sample demagnetized state. The susceptibility increases in a wide range of the applied external magnetic field up to 100 A/m, for the as-cast sample. Contrary to this, constant region of the susceptibility (perminvar effect) appears during annealing of the sample at 350 °C.

The development of the initial susceptibility and the critical field, with annealing temperature, $\chi_0(T)$, respectively $H_{CR}(T)$, obtained from the constituent susceptibility curves, are shown in Fig. 2. The initial susceptibility decreases from the value $\chi_0 = 776$, for the as-cast sample, down to the value $\chi_0 = 329$, for the sample annealed at $T = 150\,^{\circ}\mathrm{C}$. Opposite situation is in the case of the critical field; it increases from room temperature (RT) up to

* corresponding author; e-mail: pavol.vojtanik@upjs.sk

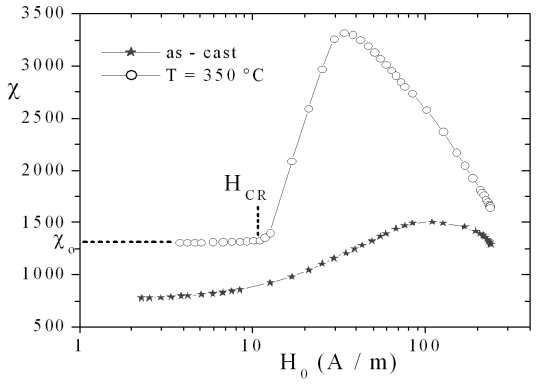

Fig. 1. Amplitude field dependences of the AC susceptibility, measured in the as-cast state, as well as at $T = 350\,^{\circ}$C, after 10 min long stabilization of the sample.

200 ℃, where the maximum value of the $H_{\rm CR} = 30$ A/m was obtained. This behavior of the susceptibility and the critical field can be explained by the directional ordering, at temperatures higher than RT. For $T > 150\,^{\circ}$C, the initial susceptibility increases and it reaches the maximum value $\chi_0 = 1311$ for 350 ℃ annealing. The temperatures higher than 200 ℃ result in the $H_{\rm CR}$ decrease, down to the value 11 A/m for 350 ℃. Homogenization of the structure and destabilization of the previously stabilized domain structure takes place in this temperature range. Finally, annealing at temperature 400 ℃ results in rapid decrease of the initial susceptibility down to the value 121 and increase of the critical field up to the value $H_{\rm CR} = 25$ A/m. It could be explained by the nanocrystallization onset in the sample [3].

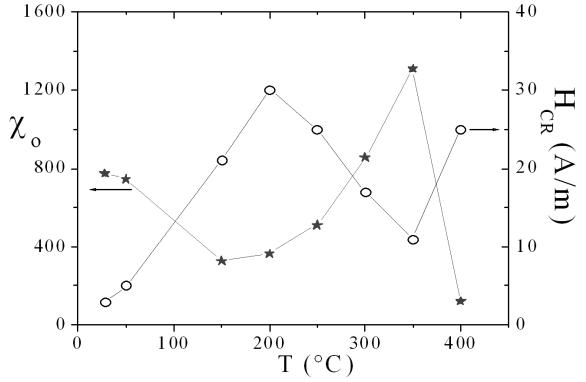

Fig. 2. Temperature dependences of the initial susceptibility, χ_0, and critical field, $H_{\rm CR}$, measured after 10 min long stabilization.

Further macroscopic manifestation of the directional ordering is a linear shape of the hysteresis loop for material, after its annealing in a magnetic field, which is transversally oriented to the ribbon axis [9]. Hysteresis loop, measured on the $Fe_{43}Ni_{43}Zr_7Cu_1B_6$ alloy at RT, after its previous annealing for 1 h at $T = 325\,^{\circ}$C in the transverse magnetic field, is shown in Fig. 3. Linear region of the $M(H)$ curve is observed here, with the anisotropy field, $H_{\rm an} = 900$ A/m. Such result allows us to say that the uniaxial transverse magnetic anisotropy was induced during the magnetic field annealing by the atom pair directional ordering; magnetization processes, during hysteresis loop measurement, are realized by the rotation of the stabilized magnetic moments from their transverse easy axes. Induced transverse anisotropy constant has the value $K_U = 262$ J/m^3.

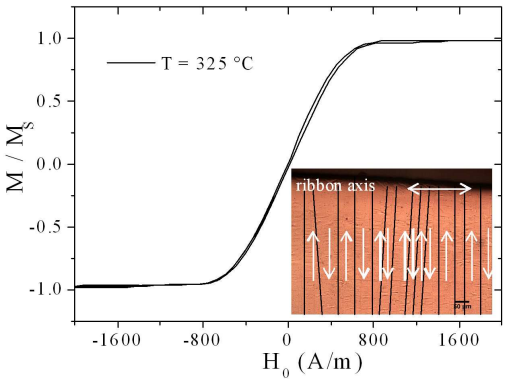

Fig. 3. Hysteresis loop measured at RT, after previous annealing at $T = 325\,^{\circ}$C in the transverse magnetic field. Inset shows the Bitter patterns of the transverse domain structure.

The transverse surface domain structure in the ribbon is observed, as well as confirmed, after its annealing in the transverse magnetic field (inset of Fig. 3). The average domain width is 37.5 μm. It indicates strong uniaxial anisotropy, comparing with the as-cast sample and its 5 μm broad domains.

4. Conclusions

Finally, we have presented in this work the influence of the conventional as well as the transverse magnetic field annealing on the magnetic properties of the $Fe_{43}Ni_{43}Zr_7Cu_1B_6$ alloys. Intensive diffusion processes caused invariability of the susceptibility on the applied external magnetic field (perminvar effect), increase of the critical field from RT up to $T = 200\,^{\circ}$C and decrease of the initial susceptibility down to $T = 150\,^{\circ}$C, too. Directional ordering of the atom pairs, during annealing of the sample at $T = 325\,^{\circ}$C in the external transverse magnetic field, caused linear shape of the hysteresis loop. The anisotropy field has the value $H_{\rm an} = 900$ A/m and the anisotropy constant $K_U = 262$ J/m^3. Induced uniaxial magnetic anisotropy was confirmed also by the observation of the FeNiZrCuB sample surface domain structure; 37.5 μm wide domains, separated by the 180° domain walls, are seen on the ribbon surface.

Acknowledgments

This work was supported by Slovak Ministry of Education under the VEGA grant No. 1/0167/10 and the project NanoCEXmat No. ITMS 26220120019.

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