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Effect of thermomagnetic treatments on the domain structure of Finemet amorphous films

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Thermomagnetic processing of films of the Finemet type with an easy magnetization axis in the plane under the action of a constant and rotating magnetic field was carried out in order to obtain an isotropic state. After heat treatment in a constant field, the easy magnetization axis was reoriented along the line of action of the field, as a result of which the domain walls were oriented along the new axis. After thermomagnetic treatment in a rotating field, regions with different anisotropy patterns, including isotropic regions, were revealed.

Keywords: domain structure, thermomagnetic treatment, rotating magnetic field.

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Magnetic metal films may become suitable sensors for magneto–optical visualization and mapping of inhomogeneous magnetic fields [1] due to their high functionality: they enable visualization of three components of the inhomogeeous field. The presence of magnetic anisotropy and coercive force in indicating films inhibits appropriate reflection of inhomogeneous fields [2]. Finement amorphous films possess soft magnetic properties sufficiently good for visualizing and mapping inhomogeneous medium–intensity fields [3]. Heat treatment of the Finemet–type films at proper temperatures leads to improvement of its soft magnetic properties, likely due to stress relaxation [4]. Application of a rotating magnetic field during heat treatment of amorphous ribbons prevents arising of the so–called M-induced anisotropy along the magnetization orientation in cooling to the annealing temperature. Such a thermomagnetic treatment resulted in obtaining almost fully isotropic state [5].

In this work, the domain structure (DS) properties were studied, which are defined by the magnetic anisotropy pattern varying due to thermomagnetic treatments. The objective of the work was obtaining the isotropic state of Finemet films. This problem is both of the research and practical interest.

The thin film samples 100 nm thick were fabricated by high–frequency ion–plasma sputtering of a $Fe_{72.5}Cu_{1.1}Nb_{1.5}Mo_2Si_{14.2}B_{8.7}$ target 50 mm in diameter in the argon atmosphere using setup URMZ-013. The argon operating pressure was 10^{-} mm Hg. The films were deposited on glass substrates in the presence of the constant technological magnetic field of 100 Oe applied in the substrate plane. Direction of this field defines orientation of the easy magnetization axis (EA). In the absence of the technological field, anisotropy with varying EA direction is induced. Formation of the anisotropy homogeneous over the plane made it possible to reveal a tendency for its variation under thermomagnetic treatment.

As the results of the X–ray diffraction analysis showed, the structural state of films not subjected to heat treatment may be characterized as X–ray amorphous. The observed halo is formed mainly by the coherent scattering regions 1.1 ± 0.1 nm in size. Further the films were covered with a ZrO_2 layer in order to improve the magneto–optical images quality and protect the film against oxidation. For heat treatment, samples about 10×10 mm in size were cut from the initial–size films.

The heat treatment was performed for an hour in air in the presence of homogeneous constant external field and in rotating magnetic field at the temperatures of 300, 350 and 400°C. The constant and rotating magnetic fields of 200 Oe in the film planes were created by a pair of magnets. The rotation frequency was 40 Hz. The field magnitude varied over the film within 50%. This inhomogeneity is insignificant since the effect of this field consists in orienting the film magnetization in the specified direction.

The heat treatment results were controlled by observing the DS rearrangement in differently oriented magnetic fields and by measuring the coercive force. Thereat, the following considerations were taken into account. Domain walls in the equilibrium (EA-demagnetized) state are oriented along EA thus indicating its orientation. In the case of demagnetization perpendicular to the easy magnetization axis, the domain walls get oriented along the easy magnetization axis with significantly closer packing, which is caused by the anisotropy dispersion (the so–called blocked structures) [6]. The packing density depends on the anisotropy dispersion magnitude. The domain structure regularity depends on the domain walls coercivity that is also a structural–sensitive parameter. At present, there is no experimental data on the domain structure in isotropic macrosize films; however, specific features of properties arising under the action of various fields are known, for instance, easy orientation of demagnetization by field in any direction and the absence of domain walls perpendicular to the film edges. In the presence of homogeneous anisotropy, EA can be easily identified by demagnetization with an alternating field in different directions. The presence of directionally inhomogeneous anisotropy after demagnetization is identified by different orientations of the domain walls, which indicate local orientations of the easy axes.

DSs were observed via the magneto−optical longitudinal Kerr effect. The field of vision almost fully coincided with the film dimensions. The films were demagnetized by an alternating power−frequency field with the amplitude decreasing to zero. The measured coercive force of the studied films was 2 Oe, the anisotropy field was 15 Oe, the Curie temperature was 300°C.

In the initial state after demagnetization in an alternating magnetic field oriented along EA, the DS shape is typical for films with EA laying in the film plane (Fig. 1, *a*). The domain walls are preferably oriented along EA. Demagnetization perpendicularly to EA led also to orientation of the domain walls parallel to EA and their closer packing. Such a behavior is typically caused by a slight deviation of nanocrystallite easy axes from the average direction (by the mechanisms of blocked structures [6]).

After heat treatment in a constant magnetic field oriented perpendicular to EA induced during deposition, demagnetization by the alternating field resulted in the domain walls orientation parallel to the newly induced axis (Fig. 1, *b*). Our observations showed that perpendicular demagnetization makes the packing of domain walls oriented along the new EA even closer than that in the initial state. That experiment showed that the temperature of 300°C is sufficient for thermal activation of relaxation of anisotropy induced during deposition. In addition, the used field was sufficient for establishing magnetization in the preset direction during heat treatment, which resulted in inducing EA in the direction of this field. Probably, the coercive force reduction from 2.2 to 1.6 Oe and more regular shape of the domain structure after heat treatment evidence for the removal of nonuniform residual stresses. At the same time, the closer domain wall packing taking place during demagnetization perpendicular to the easy axis evidences probably for the onset of the crystallites growth causing the domain structure blocking.

The results of heat treatment in the rotating magnetic field at 300°C showed that this temperature is insufficient for relaxation of both the initial and induced anisotropy.

After heat treatment in the rotating magnetic field at 350°C, the domain structure properties change qualitatively. Similarly to the above−described method, demagnetization by the alternating field of different directions has not revealed a pronounced EA. The DS configurations after demagnetization by the alternating field in two mutually perpendicular directions (parallel and perpendicular to the initial easy magnetization axis) differ only slightly. An example of such a configuration is presented in Fig. 2, *a*.

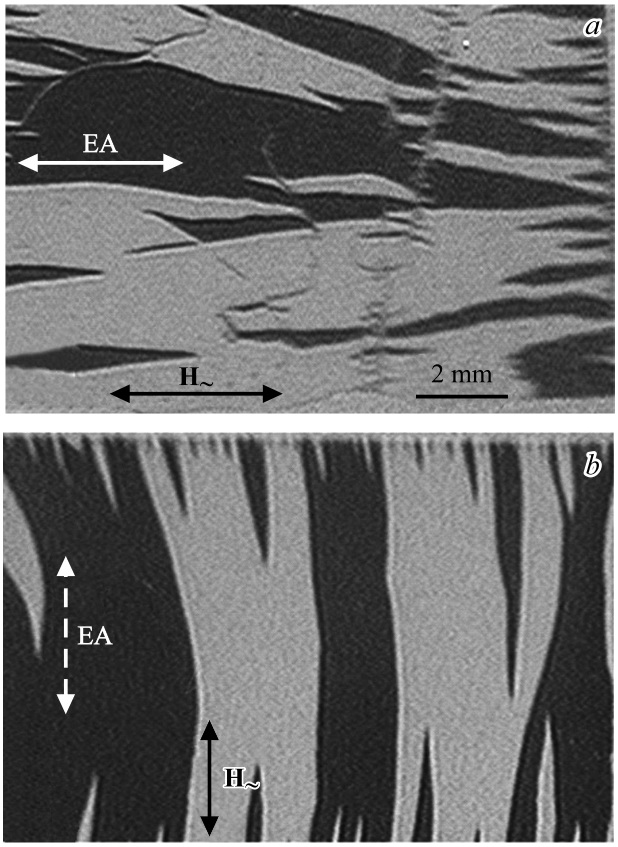

Figure 1. Domain structure of the demagnetized Finemet film prior to thermomagnetic treatment (a) and after thermomagnetic treatment in the presence of constant field (b). The demagnetization field ($H_\sim$) orientation is indicated by dark solid arrows. The easy axis induced during thermomagnetic treatment is indicated by an unfilled dashed arrow.

The distinguishing feature is formation of dagger−shaped domains near the film edges, while the central part is free of pointedly pronounced domain walls (Fig. 2, *a*). In this region, the alternating field of several intermediate orientations exerts an orienting effect on the magnetization and domain walls: they line up with the field action line (Fig. 2, *b*). Such a behavior of the domain structure evidences for total relaxation of the M-induced anisotropy in the film middle part.

Formation of the dagger−shaped domains near the film edges during demagnetization in any direction indicates the presence of anisotropy; thereat, orientation of the easy axes varies along the film perimeter. Probably, this „residual" anisotropy is connected with stresses that have not relaxed during the thermomagnetic treatment (or have arisen due to the difference in the film and substrate thermal−expansion coefficients). Excluding these regions from consideration, one can conclude that heat treatment in the rotating magnetic field at 350°C exhibits a tendency for formation of the isotropic state.

An increase in the annealing temperature to 400°C in the rotating field gives rise to the pseudo−isotropic state. After

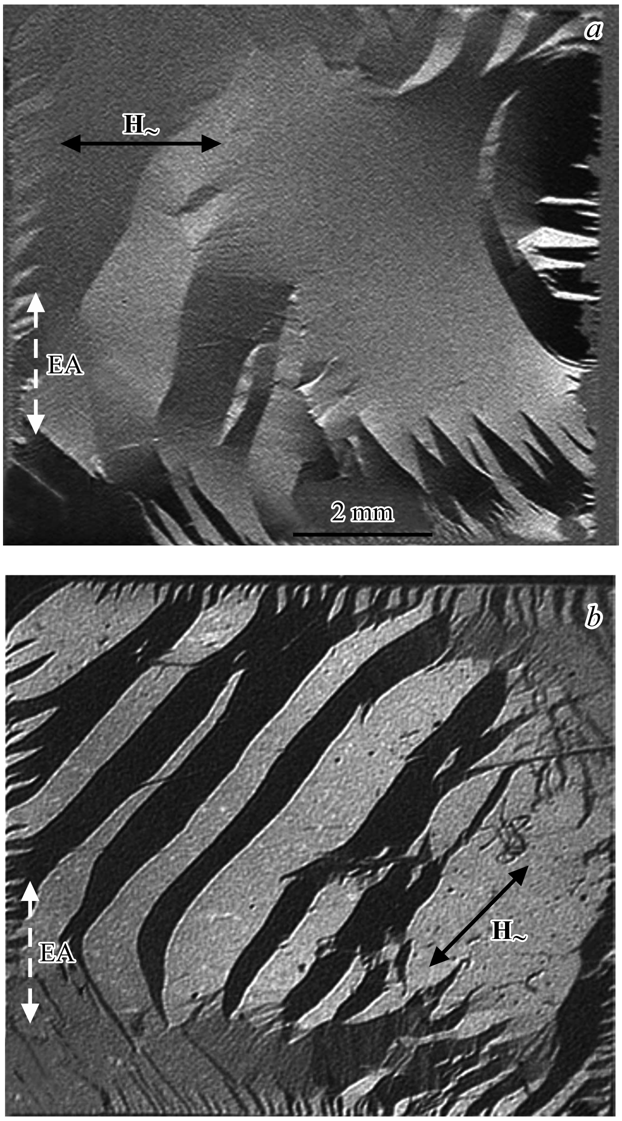

Figure 2. Domain structure of the demagnetized Finemet film after thermomagnetic treatment in a rotating magnetic field at 350°C. The easy magnetization axis direction in the initial state is indicated by unfilled dashed arrows, orientation of the alternating demagnetization field is indicated by dark solid arrows.

the alternating–field demagnetization, domain walls are in average oriented along the line of action of the alternating demagnetizing field. However, attention is attracted by a considerable curvedness of the domain walls and the presence of finely dispersed island–type domain structure, which is evidently connected with arising of the domain wall pinning centers. A significant (to 6 Oe) increase in the coercive force confirms this fact. An increase in the heat treatment temperature probably results in formation of crystalline phases [4] that play the role of nucleation centers of remagnetization along the field action line.

The positive effect of approaching the isotropic state was demonstrated by example of visualizing the planar component of magnetic field of the four–pole magnetic system (Fig. 3). This system was designed for creating magnetic field of a preset configuration.

The experimental magneto–optical image of the system field revealed by using the magnetic indicating film not subjected to thermomagnetic treatment does not provide conclusions on the planar field configuration and magnitude (Fig. 3, *a*) since the anisotropy prevents orientation of the indicating film magnetization along the field action line. In addition, there is presented a magneto–optical image of the field of this system, which was revealed by the „isotropic" film region heat–treated in the rotating magnetic field at the temperature of 350°C. This magneto–optical image pronouncedly exhibit the planar field singular points. Continuous variation in the contrast evidences that the magnetization is oriented along the direction of the inhomogeneous field of the system (Fig. 3, *b*).

Thus, based on the results of previous studies and on our results, we assume that the proposed way of obtaining

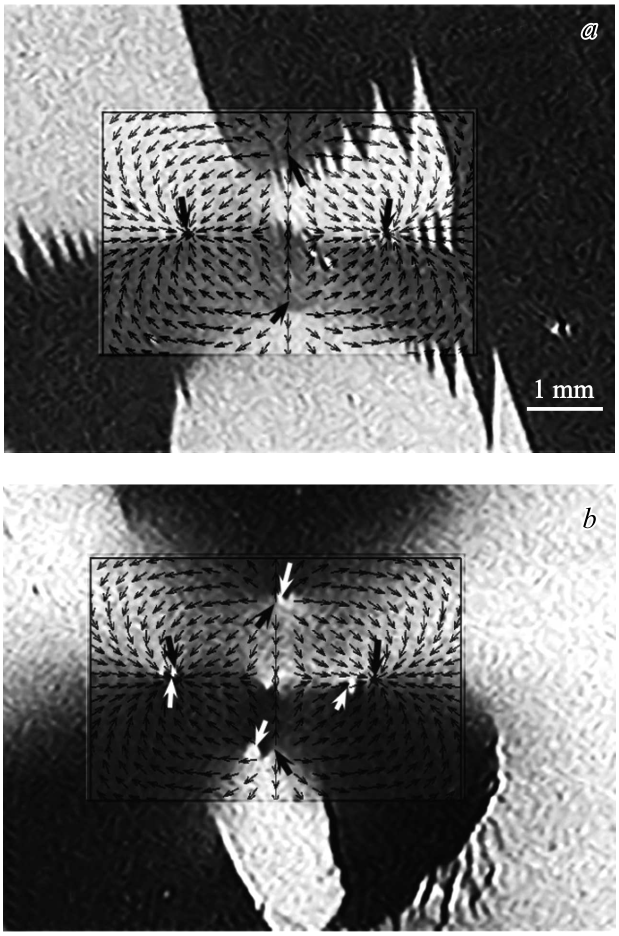

Figure 3. Magneto–optical images of distribution of the planar component of the four–pole micromagnet magnetic field obtained by using the Finemet film prior to thermomagnetic treatment (*a*) and after thermomagnetic treatment in the rotating field (*b*). The magneto–optical image is superimposed by the vector field map calculated for the magnetic system. Dark arrows indicate singular points of the calculated field, unfilled arrows show those of the magnet field.

isotropic films for magneto–optical visualization is defined by the following factors.

Heat treatment in the field oriented perpendicular to the induced axis results in reorientation of the easy axis and decrease in the coercive force, which is probably connected with a partial stress relaxation.

The rotating magnetic field suppresses the M-induced anisotropy. Heat treatment in the rotating magnetic field at 350°C revealed positive tendencies for obtaining isotropic films. Isotropic regions may be distinguished in the film middle part. Along the film perimeter, anisotropic regions are observed; orientation of their axes are close to that perpendicular to the film edges. The existence of regions with pronounced anisotropy is probably caused by residual stresses.

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Conflict of interests

The authors declare that they have no conflict of interests.

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