MODULATED MAGNETIC STRUCTURE OF AN INHOMOGENEOUSLY STRESSED SINGLE CRYSTAL $FeBO_3$

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With the help of low-symmetry mechanical stresses, we induced an additional spatially inhomogeneous anisotropy in the basal plane of a single crystal $FeBO_3$. By the magnetooptical method, we study the effect of an inhomogeneous magnetic anisotropy on the magnetic state of this easy-plane weak ferromagnetic. It is established that, at the magnetization of inhomogeneously stressed $FeBO_3$ in the basal plane near some separated direction, the crystal transits from the homogeneous state into a spatially modulated magnetic state. The latter can be represented in the form of a static spin wave, in which a local vector of ferromagnetism oscillates near the direction of the mean magnetization of a crystal, by remaining in the basal plane.

1. Introduction

Ferric borate ($FeBO_3$) is an easy-plane weak ferromagnetic with the Neel temperature $T_N \approx 350$ K, and it is practically a single crystal from the available crystals magnetically ordered at room temperature which is transparent in the visible spectrum. Below T_N, a stable domain structure (DS) is realized in $FeBO_3$. Due to the optical transparency of a crystal, this structure is easily registered with the use of magnetooptical methods [1–5]. The last fact makes $FeBO_3$ to be a convenient model object for visual studies of the magnetic structure and the process of magnetization of magnetics of this class.

Recently, it was reported in [2, 3] about the observation of an orientation phase transition of $FeBO_3$ from the state with a homogeneous magnetization in a spatially modulated magnetic state arising at the introduction of a small amount of diamagnetic Mg ions into the crystal composition. In this case, a modulated magnetic structure (MMS) of a crystal $FeBO_3$: Mg is formed. Its model proposed in [2, 3] assumes the presence of an additional magnetic anisotropy related to local elastic deformations of the crystal lattice in the basal plane near impurities. These deformations are caused by the difference of the atomic radii of the impurity and the matrix. In other words, it was assumed in [2, 3] that the easy magnetization plane in $FeBO_3$: Mg is characterized by a spatially inhomogeneous magnetic anisotropy induced by mechanical stresses. The contribution of this anisotropy to the thermodynamical potential of the crystal makes the state with a long-period modulation of the magnetic order to be energy-gained (at the switching-on of an external magnetic field).

With the purpose to verify the model [2, 3] of the appearance of MMS in magnetics of this class, we carried out the studies of the influence of inhomogeneous mechanical stresses on the magnetic structure of $FeBO_3$, whose results are presented in what follows.

2. Specimens and the Method of Experiments

In our experiments, we used a nominally pure (without impurities) single crystal of $FeBO_3$ in the form of a plane-parallel plate ~ 50 μm in thickness with a transverse size of ~ 3 mm. The developed faces of the crystal coincided with the basal plane (with the easy magnetization plane), and their shape was close to a regular hexagon. In order to induce mechanical stresses in the crystal, the specimen under study was glued (by glue BF-2) at its four corners (see Fig. 1) to a copper washer (~ 0.5 mm in thickness) so that its center coincides with the washer hole center. Then the whole construction was placed on the cold-pipe of a nitrogen optical cryostat. As the temperature decreases from room one to the liquid nitrogen temperature, a washer is deformed (its diameter decreases) together with the specimen. In this case, elastic stresses appeared in the latter. According to the results of measurements presented in [4], a crystal is compressed in the basal plane along the radii of a washer.

In Fig. 1, we show the direction of forces compressing the crystal and a distribution of longitudinal (compressive) components of the tensor of stresses induced in the central region of a "glued" specimen. As seen, the compressing forces create a field of elastic stresses in the specimen which are inhomogeneous in its plane. These stresses induce an additional spatially inhomogeneous magnetic anisotropy in the basal plane of $FeBO_3$. This anisotropy is characterized by a constant $K_A \propto \Lambda\sigma(x, y)$ (where Λ is the constant of magnetostriction, and $\sigma(x, y) = f(\sigma_{xx}, \sigma_{yy}, \sigma_{xy})$ is the effective plane stress at a point on the basal plane with coordinates (x, y) and the axis azimuth $\Theta_A(x, y)$. Since the stress-free crystal of $FeBO_3$ is practically isotropic in the basal plane as for the magnetization (at T =77 K, the effective intraplane hexagonal anisotropy field $H_a < 1$ Oe and decreases with increase in T [6]), we may expect that the anisotropy induced by stresses will play a significant role in the process of magnetization of a glued specimen.

The influence of inhomogeneous mechanical stresses on a magnetic state of $FeBO_3$ was studied with the use of a magnetooptical method analogous to that described in [5]: with a polarization microscope, we observed visually the evolution of DS of the specimen caused by stresses induced in the crystal and by variations of the magnitude and the direction of the external magnetic field applied in the basal plane of the crystal. The observation of DS was realized "by looking through" at wavelengths $\lambda \sim 0.5$ μm (in the optical transparency window of $FeBO_3$) under normal incidence of light on the specimen plane. The system of magnetization included two pairs of Helmholtz crossed coils and allowed us to create a homogeneous magnetic field with the strength $H < 70$ Oe in the specimen and to orient the vector $\mathbf{H}$ along any direction in crystal plane to within $\sim \pm 1^\circ$ at $|\mathbf{H}| = \text{const}$.

3. Experimental Results

As follows from Fig. 2,*a*, the studied specimen at room temperature had a regular two-layer 180-degree DS which is typical of sufficiently thin crystals of $FeBO_3$ free from mechanical stresses [1–4]. This DS was visualized in the form of rectangular strips with clearly outlined boundaries. In the course of cooling of the specimen, its DS remained to be two-layer, but significantly varied: below $T \sim 200$ K, the domains gradually acquired a shape of complicated figures with different areas. As an example, Fig. 2,*b* shows a typical form of DS of a glued specimen which was observed without a magnetic field at $T = 80$ K. In the region of sufficiently high temperatures, the process of technical magnetization of a glued crystal was running usually as follows: irrespective of the orientation of $\mathbf{H}$ in the basal plane, the areas of domains, whose vectors of ferromagnetism $\mathbf{m}$ formed acute angles with $\mathbf{H}$, increased at the expense of adjacent domains with less favorable orientations of $\mathbf{m}$ until no domain boundaries (Fig. 2,*c*)[1] remained on the image of the crystal (in the field H $\sim$ 7 – 10 Oe), i.e., its magnetization became saturated. The further increase in the field strength (up to a value maximally attainable in the experiment) did not cause any remarkable changes in images of the specimen.

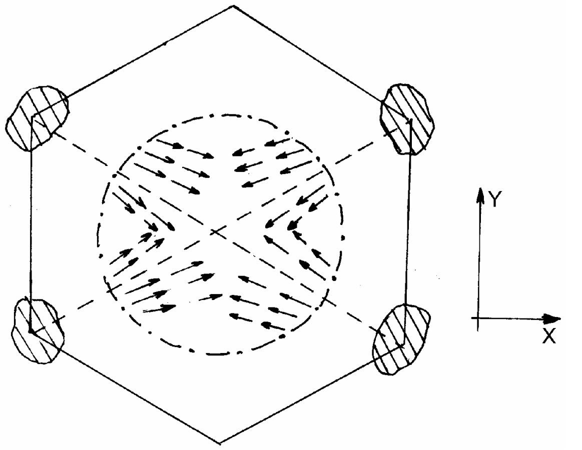

Fig. 1. Schematic image of the crystal under study. Hatched regions show the drops of glue which fix the crystal on a copper washer. Dotted lines indicate the directions of the forces compressing the crystal, and the dash-dotted line points out the washer hole contour. Arrows indicate the compressive components of the stress tensor (the length of arrows is proportional to the magnitude of local compressing forces)

However, below $T \approx 125$ K at the magnetization of a specimen near the direction of the X axis (the orientation of axes of the laboratory coordinate system is shown in Fig. 1), the domains in the basal plane disappeared at the field $H_c \approx 10$ Oe. Then, as H increases, we observe the appearance of quasiperiodic systems of alternating "light" and "dark" strips in the specimen image. Moreover, as $\mathbf{H}$ deviated from this direction separated in the basal plane of the glued crystal by the angle $-5 \leq \phi \geq +5^\circ$, we observed simultaneously two systems of strips (arising in different domain layers). But if $5 \leq |\phi| \geq 10^\circ$, we saw only the system, for which the angle between the vector $\mathbf{H}$ and the mean direction of strips was the greatest one (Fig. 2,*d–g*). We note that the variation of the field strength and its orientation in

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[1] A certain inhomogeneity of color observed on the image of the specimen shown in Fig. 2,*c* is probably related to the birefringence induced by deformations of the crystal lattice of a stressed specimen.

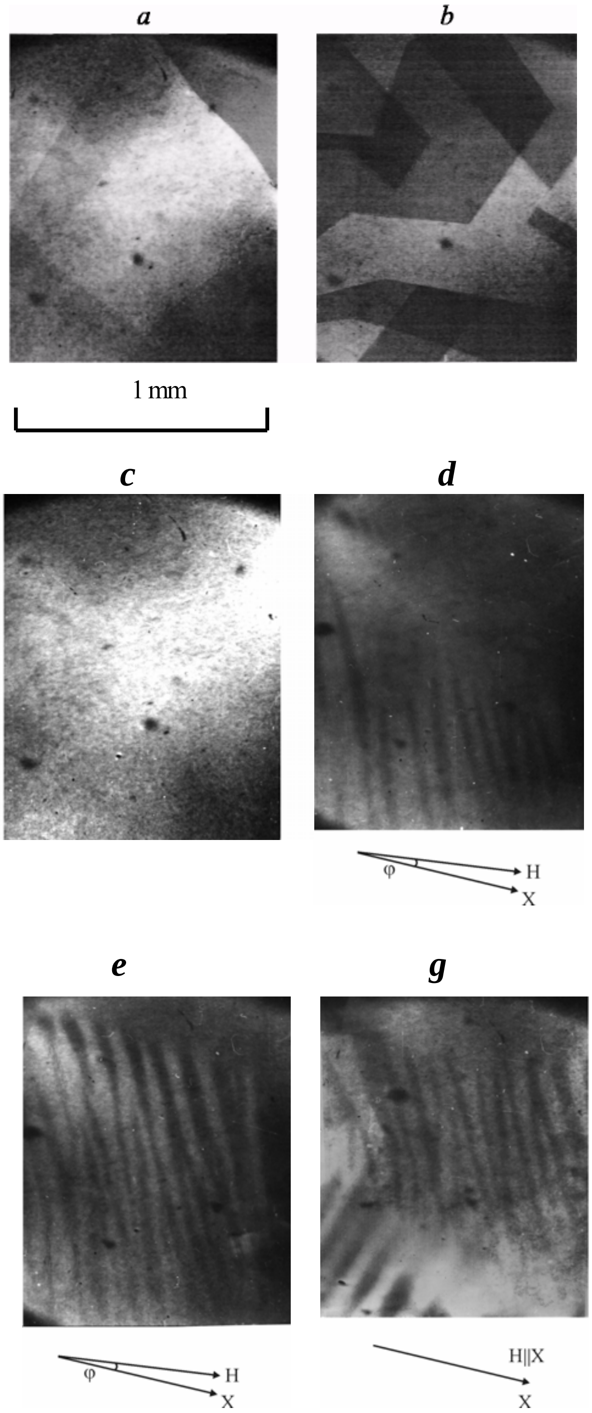

Fig. 2. Images of glued $FeBO_3$ obtained in a polirized light at $T = 290$ K (a) and at $T = 80$ K ($b - g$) for various strengths and orientations of a magnetic field in the basal plane of the crystal: a, b – $H = 0$; c – $H = 10$ Oe; d – $H = 12$ Oe; e–g – $H = 13$ Oe. Arrows indicate the directions of the X axis and the vector $\mathbf{H}$, $\varphi \approx 10°$ is the angle between the X axis and the direction of magnetization

the basal plane did not cause the appearance of analogous strips on images of the same specimen without any stresses in the whole involved temperature region (in our experiments, the specimen is positioned in a special holder which reduces the influence of temperature-induced deformations of metallic details of the cryostat to a minimum value [7]). It is worth also noting that we observed no appearance of strips analogous to the above-discussed ones at the visual observation of the process of magnetization of a single crystal $FeBO_3$ subjected to a uniform compression in the basal plane [1].

We have established experimentally that, at the normal incidence of light on the plane of the stressed specimen, the maximum contrast of the image of a system of strips was observed in the case where the transmission axis of an analyzer slightly deviated from the position "crossed" relative to the transmission axis of a polarizer (the images of strips presented in Fig. 2,d–g were obtained at the angle between the axes of a polarizer and an analyzer $\Delta \approx 95°$). Moreover, at a synchronous rotation of a polarizer and an analyzer around the light propagation direction by an angle of $\sim 20 - 25°$ (depending on the magnitude of H), we can obtain the inverse image of strips. In other words, after such a rotation of a polarizer and an analyzer, the "light" strips become "dark" ones and *vice versa*.[2]

The arising systems of strips existed in some temperature-dependent interval of fields ΔH (for the systems of strips, the values of ΔH differ somewhat from each other) and disappeared with increase in $H$by means of a gradual deterioration of the contrast between the adjacent "light" and "dark" strips. As seen from Fig. 2,d–g, the mean direction of strips takes an angle of $\sim \pm 60°$ with the X axis. According to the observations, this angle was practically invariable in the whole regions of the fields and the temperatures, where the strips were present.

It turns out that though the spatial periods D (mean distances between the "light" and "dark" strips) of two systems of strips are considerably different (Fig. 2,d–g), nevertheless, the dependences of D on T and H are similar for both systems: the period D is practically independent of T but monotonously varies with change in H. Moreover, at the remagnetization of the crystal, we observed no noticeable hysteresis of D. The variation in D occurred by means of the simultaneous decrease

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[2] Unfortunately (apparently, due to the above-mentioned effect of the birefringence induced by stresses in the plane of the crystal on the polarization of light), the contrast of obtained strips was significantly worse than that shown in Fig. 2,d–g. Therefore, we omitted these images.

(increase) in the widths of “light” and “dark” strips. In other words, an increase (decrease) in H was accompanied by a growth (diminution) of the number of strips per unit area of the specimen surface. Figure 3 illustrates a variation of the period of the system of strips shown in Fig. 2,*d*,*e* in a magnetic field.

4. Discussion of Experimental Results

While interpreting the results obtained, we take into account that a compression of $FeBO_3$ in the basal plane does not lead to the outcome of the vector **m** from the specimen plane [1]. Hence, at the normal incidence of light on the plane of the crystal under study, the main magnetooptical effects are the magnetic linear birefringence and the magnetic linear dichroism (MLD). The results of measurements executed in [3] imply that the contribution of magnetic linear birefringence at the chosen geometry of the experiment in the spectral region $\lambda \sim 0.5$ μm to the intensity of light forming the image of the crystal is insignificant. Hence, the contrast of observed systems of strips arises mainly due to the difference in values of MLD on the adjacent parts of the specimen in the direction which is normal to the direction of strips. As was noted above, the best contrast of strips was observed in a slightly less “crossed” geometry of the axes of transmission of a polarizer and an analyzer. In this case, the intensity of light passed the polarizer – specimen – analyzer system at a point on the specimen plane with coordinates x and y can be presented in the form

$$I(x,y) = I_0 \cos^2[\Delta + \alpha(x,y)] \approx$$

$$\approx I_0\,[1 + \cos 2\Delta - 2\alpha(x,y)\sin 2\Delta]/2, \qquad (1)$$

where I_0 is the intensity of light at the output from the specimen, $\Delta = \pi/2 + \delta$ is the angle between the axes of transmission of a polarizer and an analyzer ($\delta \ll \pi/2$), and $\alpha(x,y)$ is the angle of rotation of a light polarization plane due to MLD in the specimen.

In view of (1), the contrast of an image of the system of strips in the direction normal to the mean direction of strips is given as

$$\Delta I = I(r_1) - I(r_2) = I_0 \sin 2\Delta[\alpha(r_2) - \alpha(r_1)], \qquad (2)$$

where $\alpha(r_1)$ and $\alpha(r_2)$ are the values of MLD at points r_1 and r_2 (the r axis lies in the specimen plane and is perpendicular to the mean direction of strips).

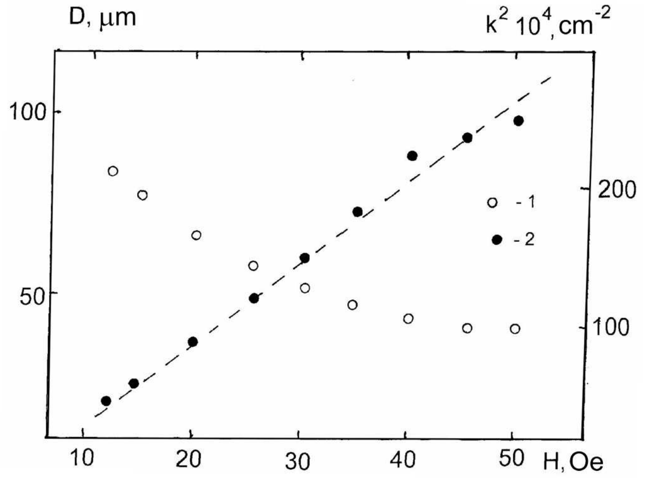

Fig. 3. Field dependences of both the spatial period of a system of strips (1) and the square of the modulus of a wave vector of the modulated magnetic structure (2) obtained at the orientation of the vector **H** at an angle of 10° to the X axis ($T = 80$ K). The dashed line presents the dependence $k^2 \propto H$

As known [8], MLD in $FeBO_3$ is determined by the plane component of the vector of antiferromagnetism **l** $= (\mathbf{M}_1 - \mathbf{M}_2)$, where $\mathbf{M}_1$ and $\mathbf{M}_2$ are the sublattice magnetic moments (respectively, $\mathbf{m} = (\mathbf{M}_1 + \mathbf{M}_2)$, $\mathbf{m} \perp \mathbf{l}$). In view of the dependence of MLD on the orientation of the vector **l** relative to the polarization plane of light incident on the crystal [8], we present relation (2) in the form

$$\Delta I = \alpha I_0 \sin 2\Delta\{\sin 2[\vartheta - \beta(r_2)] - \sin 2[\vartheta - \beta(r_1)]\} =$$

$$= 2\alpha I_0 \sin 2\Delta \sin[\beta(r_2) -$$

$$-\beta(r_1)] \cos 2\{\vartheta - [\beta(r_1) - \beta(r_2)]/2\}, \qquad (3)$$

where α is the maximum magnetooptical rotation of the polarization plane of light passed through the crystal (by our data, $\alpha \approx 0.5°$), ϑ is the angle between the axis of transmission of a polarizer and the r axis, and $\beta(r_1)$ and $\beta(r_2)$ are the azimuths (relative to the same axis) of the local vector **l** at the points r_1 and r_2.

Let r_1 and r_2 be the coordinates of the centers of adjacent “light” and “dark” strips. Then relation (3) implies that the maximum contrast of the system of strips will be observed under the condition $\vartheta = [\beta(r_1) - \beta(r_2)]/2$. Hence, at a synchronous rotation of a polarizer and an analyzer around the light propagation direction (at $\Delta =$ const) by the angle $[\beta(r_2) - \beta(r_1)]/2$, the inverse image of strips must appear, which was experimentally observed. It is obvious that the difference of angles of two positions of a polarizer, at which we observed the maximum contrast of the direct and inverse images of strips, will be exactly equal to the difference of azimuths of the vector **l** at the centers of adjacent strips.

Thus, we may conclude that the systems of strips arising on the images of inhomogeneously stressed FeBO_3 are caused by variations of the azimuth angle of a local vector **l** in the basal plane of the crystal along the $r$axis. The absence of clear boundaries between "light" and "dark" strips and their periodicity allow us, on the basis of relation (3), to describe the spatial distribution of the azimuth of a vector **m** in the plane of a glued specimen at $T < 125$ K in the region of fields, where the systems of strips are observed, by a periodic function of the type

$$\beta = \beta_0 \cos kr + \gamma,$$

where $k = 2\pi/D$ is the modulus of the wave vector of the systems of strips (**k** is parallel to the r axis), $\gamma \approx \pm 30^\circ$ is the angle between the X axis and the direction of the vector **k** , and β_0 is the amplitude of deviations of **m** from the direction of **k**. In this case, according to a decrease in the period of the system of strips and the weakening of the contrast between "light" and "dark" strips which are observed at an increase of the magnetic field, we should consider k and β_0 to be functions of H. In Fig. 3, we present the function $k^2(H)$ for the systems of strips shown in Fig. 2,*d*,*e*.

The above-presented consideration indicates the following. Let **H** be oriented near the separated direction in the basal plane of inhomogeneously stressed FeBO_3 (near the bisectrix of the less of the angles between the directions of the forces compressing the crystal). During the rotation of the vector of mean magnetization of the specimen to the direction of **H**, a field $H \geq H_c$ induces the transition of the crystal from the homogeneous state to a spatially modulated magnetic one. The appeared modulated magnetic phase can be represented in the form of a static transverse spin wave linearly polarized in the basal plane of the crystal, where the azimuth of the vector of weak ferromagnetism oscillates near the direction of a mean magnetization. An analogous structure (except for the difference in the angle between the vectors **k** and **H**) is characteristic of the noncollinear magnetic phase of the crystal FeBO_3: Mg [2, 3].

The theoretical consideration of the transition of an easy-plane weak ferromagnetic from the homogeneous magnetic state to a modulated one [2] implies, in particular, that the field dependence of the wave vector of a modulation of the magnetic order can be represented as

$$k = \sqrt{A + BH},$$

where A and B are some phenomenological constants. Namely such a dependence $k(H)$ for the systems of strips arising on images of the specimen under study was experimentally observed (Fig. 3). In view of the orientation of strips in the plane of the glued specimen (Fig. 2,*c*–*g*), we can conclude that the vectors **k** of the observed MMS are approximately collinear to one of the two directions of forces compressing the crystal. Hence, as distinct from modulated magnetic structures which are realized in an external field H in FeBO_3: Mg [2, 3], for which the symmetry of wave vectors corresponds to the hexagonal symmetry of the crystal in the basal plane, the magnetic superstructure is related to the symmetry of stresses arising in a crystal.

5. Conclusion

Thus, despite some minor differences between modulated magnetic phases of inhomogeneously stressed FeBO_3 and crystal FeBO_3: Mg, the executed studies have confirmed, on the whole, the model of appearance of MMS in easy-plane weak ferromagnetics which was proposed in [2, 3].

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МОДУЛЬОВАНА МАГНІТНА СТРУКТУРА НЕОДНОРІДНО НАПРУЖЕНОГО МОНОКРИСТАЛА $FeBO_3$

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Резюме

За допомогою низькосиметричних механічних напружень індукована додаткова просторово неоднорідна магнітна анізотропія в базисній площині монокристала $FeBO_3$. Магнітооптичним методом досліджено вплив неоднорідної магнітної анізотропії на магнітний стан цього легкоплощинного слабкого феромагнетика. Виявлено, що при намагнічуванні неоднорідно напруженого $FeBO_3$ у базисній площині поблизу деякого виділеного напрямку відбувається перехід кристала із однорідного в просторово модульований магнітний стан, який може бути представлено у вигляді статичної спінової хвилі, в якій локальний вектор феромагнетизму, залишаючись в базисній площині, осцилює поблизу напрямку середньої намагніченості кристала.