MAGNETOSTRICTION OF A SINGLE CRYSTAL OF HEXAGONAL FERRITE $BaFe_{18}O_{27}$

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The magnetostriction of a single crystal of hexagonal ferrite $BaFe_{18}O_{27}$ was studied at room temperature using wire strain gauges. The anisotropic part of the magnetostriction is described by a phenomenological formula with four constants. The values of these constants, determined experimentally, are: $\lambda_A = 13 \times 10^{-6}$, $\lambda_B = 3 \times 10^{-6}$, $\lambda_C = -23 \times 10^{-6}$, and $\lambda_D = 3 \times 10^{-6}$.

IN contrast to cubic ferromagnets, the magnetostriction of hexagonal ferromagnetic crystals has not yet been studied sufficiently. Among the latter, those which have been investigated most are cobalt [1] and some rare-earth metals.[2,3] The magnetostriction of a large group of hexagonal oxide ferromagnets (barium ferrites) has not been investigated so far.

The purpose of the present work was to study experimentally the magnetostriction of a single crystal of barium ferrite of the composition $BaFe_2^{2+}Fe_{16}^{3+}O_{27}$ (W structure).

The investigated crystal was magnetically uniaxial; the anisotropic part of its magnetostriction, due to the rotation of the magnetization vector, is described by the following formula [4]:

$$\lambda = \lambda_A[(\alpha_1\beta_1 + \alpha_2\beta_2)^2 - (\alpha_1\beta_1 + \alpha_2\beta_2)\alpha_3\beta_3] + \lambda_B[(1-\alpha_3^2)(1-\beta_3^2) - (\alpha_1\beta_1 + \alpha_2\beta_2)^2] + \lambda_C[(1-\alpha_3^2)\beta_3^2 - (\alpha_1\beta_1 + \alpha_2\beta_2)\alpha_3\beta_3] + 4\lambda_D(\alpha_1\beta_1 + \alpha_2\beta_2)\alpha_3\beta_3,$$

where α_1, α_2, α_3 and β_1, β_2, β_3 are, respectively, the direction cosines of the magnetization vector and of the direction of measurement of the magnetostriction with respect to the crystallographic axes x_1, x_2, x_3. The axes x_1 and x_2 lie in the basal plane [their selection is arbitrary, since the expression (1) does not allow for the anisotropy in the basal plane]; the x_3-axis coincides with the hexagonal c-axis. The constants λ_A, λ_B, λ_C, λ_D are determined experimentally for the following orientations of the magnetization and direction of measurement of the magnetostriction:

$$\lambda_A(\alpha_2 = \beta_2 = 1), \quad \lambda_B(\alpha_1 = \beta_2 = 1), \quad \lambda_C(\alpha_2 = \beta_3 = 1),$$

$$\lambda_D(\alpha_2 = \beta_2 = \alpha_3 = \beta_3 = 1/\sqrt{2}).$$

For brevity, we shall denote the various special cases which follow from the general formula (1) by the values of the angles θ, φ and γ which determine, respectively, the position of the magnetization vector I_s in saturation fields with respect to the axes x_3 (or c), x_1, and the direction of measurement of the magnetostriction with respect to the c-axis in the x_2x_3 plane (cf. Fig. 1). In considering the dependence of the magnetostriction on the angle between an external magnetic field H and the c-axis, we shall introduce the angle ψ (Fig. 1) instead of the angle θ.

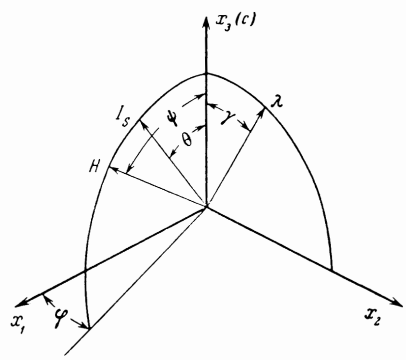

FIG. 1. Orientation of the direction of measurement of the magnetostriction λ, of the magnetic field H, and of the magnetization vector I_s with respect to the coordinate axes.

Using this notation, constants λ_A, λ_B, λ_C, and λ_D correspond to the following effects:

λ_A—90.90.90 (longitudinal effect in the basal plane),

λ_B—90.0.90 (transverse effect in the basal plane),

λ_C—90.90.0 (magnetostriction along the c-axis with magnetization in the basal plane),

λ_D—45.90.45 (longitudinal effect at 45° to the c-axis).

It follows that to determine the magnetostriction constants it is necessary to have samples of at least two different cuts: parallel to the basal plane (sample No. 1) and parallel to the plane with the c-axis (sample No. 2). In our measurements, we used samples in the form of disks having diameters 6.4 and 6.15 mm and thicknesses 2.75 and 2.36 mm for cuts No. 1 and No. 2, respectively.

The crystals were prepared by the Verneuil method. The magnetostriction was measured with wire strain gauges using a bridge method with an unloaded gauge as one of the arms in series with a loaded gauge, in order to compensate the effect of the magnetic field on the electrical resistance of the constantan wire. The single-crystal disks were placed between the poles of an electromagnet where fields of up to 26 000 Oe could be obtained in a 10 mm gap. By means of a special device, the disks could be rotated with respect to the magnetic field direction.

Figures 2a and 2b show the results of measuring the magnetostriction of disk No. 1. Curves 90.90.90 and 90.0.90 illustrate, respectively, the dependence of the longitudinal and transverse magnetostriction in the basal plane on the external field. The magnetostriction reaches saturation in fields of about 18 000 Oe, corresponding to saturation magnetization of the test crystal at right angles to the c-axis.

Curve 0—90 represents the change in the magnetostriction in the basal plane when the sample is magnetized along the c-axis (at right angles to the plane of the disk). In the absence of domains with boundaries not parallel to the c-axis in the initial demagnetized state of the disk, the magnetization along the "easy" axis c should give either zero magnetostriction (since there is no rotation) or a linear dependence of λ on H, due to a change in the intrinsic magnetization. However, the shape of the 0—90 curve in Fig. 2a indicates the presence of the rotation process. This is due to the presence of domains with boundaries not parallel to the c-axis. The appearance of domains of this orientation may be explained by the shape of the sample since the c-axis coincides with the direction of the highest demagnetization factor.

The indeterminacy of the initial state of sample No. 1 prevents us from determining the values of the constants λ_A and λ_B. From the data in Fig. 2, we can determine only the difference $\lambda_A - \lambda_B$, which is equal to 10×10^{-6}. Figure 2b shows the dependence of the $90.\psi.90$ magnetostriction in the basal plane on the angle φ, obtained by rotating the crystal in a magnetic field of 21 000 Oe. The continuous curve is plotted in accordance with the law $A + B \sin^2\varphi$, with the amplitude $B = \lambda_A - \lambda_B = 10 \times 10^{-6}$. The value of the magnetostriction for $\varphi = 0$ represents the transverse effect in the basal plane and the longitudinal effect is given by $\varphi = 90°$.

Figures 3a and 3b show the results of measuring the magnetostriction for disk No. 2 having its planes parallel to the c-axis (the x_3x_2 plane in Fig. 1). The dashed curves passing through the open circles in Fig. 3a, represent the experimentally determined dependences of the magnetostriction along the directions x_3 and x_2 (curves $\psi.90.0$ and $\psi.90.90$, respectively) on the angle between the external magnetic field H = 21 000 Oe and the c-axis in the plane of rotation x_3x_2 ($\varphi = 90°$). It is easily seen that the $\varphi.90.90$ and $\psi.90.0$ curves do not obey a simple sinusoidal dependence: at $\psi = 0$, they have a flat maximum, while at $\psi = 90°$, they have a sharper maximum. This is related to the "lag" of the magnetization vector, for $0 < \psi < 90°$, behind the external field direction by the angle $\psi - \theta$. Since, for comparison with theory, we need to know the dependence of λ on the angle θ, it is necessary to introduce a correction for the angle of the "lag" of I_S behind H. This correction was found from additional measurements of the torque L of disk No. 2 at the same field intensity at which the magnetostriction was measured; then the angle $\psi - \theta$

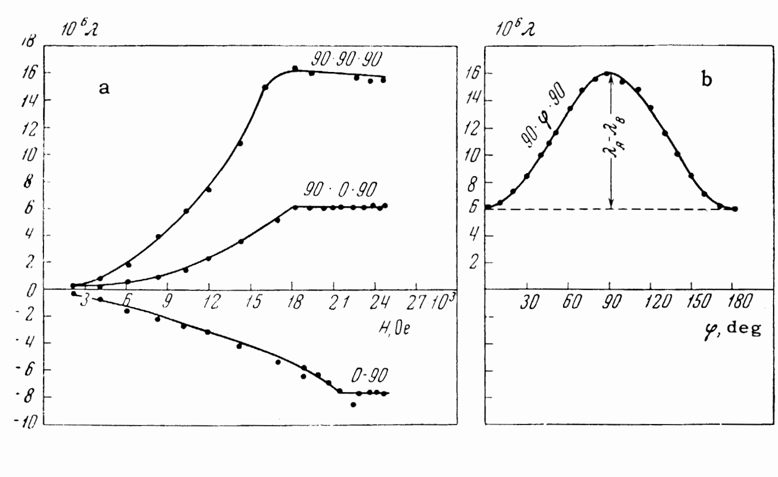

FIG. 2. Magnetostriction of disk No. 1 cut parallel to the basal plane: a) dependence of the magnetostriction λ in the basal plane on the external field intensity H; the numbers by the curves denote the angles θ, φ and γ which give the orientation of the magnetization in fields H > 19 000 Oe and the direction of measurement of the magnetostriction (cf. Fig. 1); curve 0—90 represents the magnetostriction along the direction $\gamma = 90°$ for magnetization along the c-axis; b) dependence of the magnetostriction along the direction x_2 on the orientation of the magnetization vector in the basal plane; the curve was recorded in a field of 21 000 Oe.

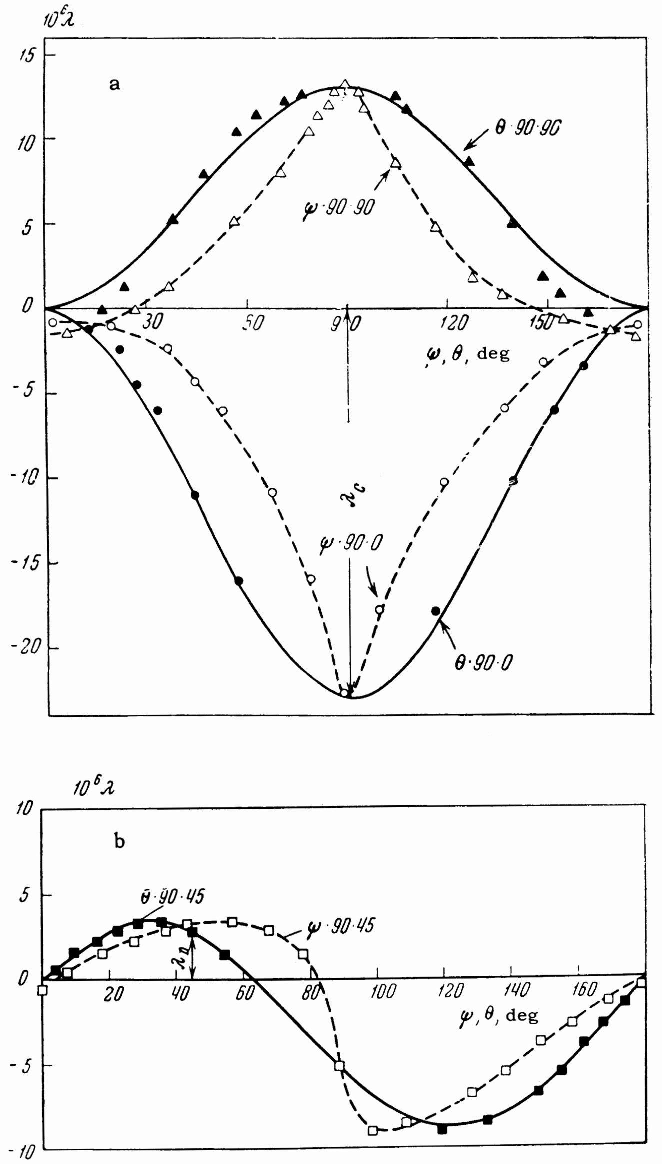

FIG. 3. Dependence of the magnetostriction in the x_3x_2 plane on the angles φ and θ which give, respectively, the orientation of the external field H = 21 000 Oe (dashed curves) and of the magnetization vector (continuous curves) on rotation of disk No. 2 about the x_1 axis: a) the magnetostriction along the directions x_3 (curves θ.90.0 and φ.90.0) and x_2 (curves θ.90.90 and φ.90.90); b) the magnetostriction at 45° to the c-axis.

was found from the well-known relationship $L = -HI_S \sin(\psi - \theta)$.

Using the experimental values of L, we can find the dependence of the "lag" angle $\psi - \theta$ on ψ from the known values of I_S and H, and then we can shift the experimental points by the corresponding angles. The values of λ denoted by black dots in Fig. 3a were obtained in this way.

The magnetostriction of sample No. 2 was close to zero for H ∥ c ($\theta = \psi = 0$). Small negative values of λ at $\theta = 0$ could be explained either by the influence of the intrinsic saturation magnetization or by the inaccurate orientation of the sample.

Thus, for this disk, there were no difficulties related to the indeterminacy of the initial domain structure. The continuous curves in Fig. 3a were plotted using formulas which follow from Eq. (1) for the effects θ.90.90 and θ.90.0, respectively:

$$\lambda = \lambda_A(1 - \cos 2\theta)/2, \qquad \lambda = \lambda_C(1 - \cos 2\theta)/2$$

for the values $\lambda_A = 13 \times 10^{-6}$ and $\lambda_C = -23 \times 10^{-6}$.

Figure 3b shows the dependence of the magnetostriction at 45° to the c-axis on the angles ψ and θ in the x_3x_2 plane (curves ψ.90.45 and θ.90.45, respectively). The continuous curve passing through the "corrected" points (black circles) is plotted from the formula

$$\lambda = (\lambda_C + \lambda_A)/4 + [\lambda_D - (\lambda_A - \lambda_C)/4] \sin 2\theta - (\lambda_A - \lambda_C) \cos 2\theta / 4,$$

which follows from Eq. (1) applied to the present case with the following values of the constants

$$\lambda_A = 13 \cdot 10^{-6}, \ \lambda_C = -23 \cdot 10^{-6} \text{ and } \lambda_D = 3 \cdot 10^{-6}.$$

It follows from curves in Fig. 3b that in order to rotate the magnetization vector by $\theta = 45°$ to the c-axis, a field H = 21 000 Oe should be applied at an angle $\psi = 67°$. Therefore, to obtain the correct value of λ_D by recording the dependence of λ on H for the longitudinal effect at 45° to the c-axis (45.90.45), the field should be directed at the angle $\psi = 67°$ to the c-axis. The 45.90.45 curve in Fig. 4, which shows the dependence of λ on H for disk No. 2, was obtained in precisely this way.

The 90.90.90 curve in Fig. 4 corresponds to the 90.90.90 curve in Fig. 2. The difference in the saturation magnetization in these two cases is due to the different initial states of the samples. The values denoted by 0—90, 0—45 and 0—0 in Fig. 4, which represent magnetostriction along the directions $\gamma = 90°$, $\gamma = 45°$ and $\gamma = 0°$ for the magnetization along the c-axis, indicate that the initial state of disk No. 2 remained the same and was "normal" for a magnetically uniaxial crystal.

Thus, using the values $\lambda_A - \lambda_B = 10 \times 10^{-6}$ and the constants λ_A, λ_C and λ_D found for disk No. 2, we find the following values of the magnetostriction constants for the $BaFe_{18}O_{27}$ crystal:

$$\lambda_A = 13 \cdot 10^{-6}, \quad \lambda_B = 3 \cdot 10^{-6},$$
$$\lambda_C = -23 \cdot 10^{-6}, \quad \lambda_D = 3 \cdot 10^{-6}.$$

It is interesting to note that these constants are opposite in sign to the analogous constants

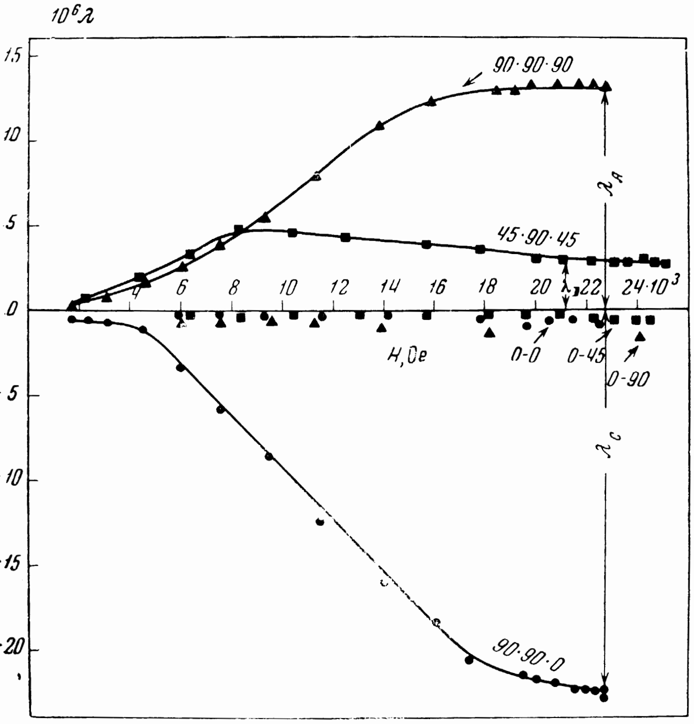

FIG. 4. Dependence of the magnetostriction λ on the external field intensity for disk No. 2. Numbers by the curves denote the angle θ, φ and γ which give the orientation of the magnetization vector in fields H > 19 000 Oe and the direction of the measurement of the magnetostriction (cf. Fig. 1). The values 0 – 0, 0 – 45, and 0 – 90 were obtained for the magnetostriction along the directions $\gamma = 0°$, $\gamma = 45°$ and $\gamma = 90°$ for magnetization along the c-axis; in recording the 45.90.45 curve the field was directed at the angle $\varphi = 67°$.

for a cobalt crystal [1] (the absolute values of our constants are about an order of magnitude smaller). The characteristic shape of the 45.90.45 curve in Fig. 4 can be understood by the comparison of our results with those obtained by Bozorth for cobalt.[1] Bozorth discovered that, when a cobalt crystal was magnetized along the directions $0 < \psi < 90°$, a contraction of the linear dimensions of the samples was first observed, followed by elongation and saturation on further increase of the field. Bozorth showed that this feature may be explained by calculating the dependence of λ on H for the $0 < \psi < 90°$ case taking into account the various forms of energy responsible for the magnetization processes and using experimentally determined parameters. Since, as mentioned earlier, the magnetostriction constants for the $BaFe_{18}O_{27}$ crystal are opposite in sign to the constants for cobalt, then instead of the initial contraction of the linear dimensions, which occurs in the case of cobalt, $BaFe_{18}O_{27}$ exhibits first elongation and then contraction of the linear dimensions of the sample, as indicated by the form of the 45.90.45 curve in Fig. 4.

[1] R. M. Bozorth, Phys. Rev, **96**, 311 (1954).

[2] R. M. Bozorth and T. Wakiyama, J. Appl. Phys. 34, 1351 (1963).

[3] Legvold, Alstad, and Rhyne, Phys. Rev. Letters **10**, 509 (1963).

[4] W. P. Mason, Phys. Rev. **96**, 302 (1954).

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