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I. Nedkov

Institute of Electronics, Bulgarian Academy of Sciences, 72 Tzarigradsko Chaussee blvd, Sofia 1784, Bulgaria

Abstract. An attempt was made to adapt the domain-wall size model to the explanation of magnetization mechanisms in real polycrystalline hard ferrites (SrFe$_{12}$O$_{19}$). Some new data concerning the total anisotropy specifically for polycrystals were discussed and its value deduced from natural spin resonance measurements. It was observed that samples with different $H_{	ext{eff}}$ grain size and shape, can present different hysteresis loops. To explain these differences, we applied the theoretical expressions for the magnetization curve and the hysteresis loop developed earlier.

In spite of the quickly broadening area of application of polycrystalline highly anisotropic ferrites, the theory still lags behind in explaining their specific magnetization behavior [1]. A good description of the magnetization processes from the viewpoint of the grain size in isotropic ferrite structures is provided by the Globus-Guyot model [2], which considers the single crystallite as a sphere divided by a Bloch domain wall (DW) moving under the action of an external magnetic field. Magana et al. [3] made the first attempt to apply this model to structures with non-spherical grains.

The present work reports on studies of the magnetization processes in real highly anisotropic polycrystalline Sr-hexaferrites with various size of the grains (crystallites) and aims at applying the DW-size theory to explain the discrepancies observed.

We investigated the magnetization processes, the hysteresis BH-curves and the variation of the effective anisotropy field $H_{	ext{eff}}$ as functions of the grain shape and size in the case of a highly anisotropic polycrystalline Sr hexaferrite (SrFe$_{12}$O$_{19}$). The samples were prepared by following the ceramic technology of “wet” pressing in an external magnetic field. The crystallite size was controlled by means of choosing appropriate temperatures and final isothermic delay. Using systematic optical microscopy observations and statistical analysis, we selected a series of samples with different grain sizes and a maximal degree of texturing.

Since the most energetically favorable location of the DW in texturized hexaferrites is along the weak magnetization axis, which we assume to be parallel to the texturing axis (c), all further discussion will imply a (c) sample cross-section. Thus, the crystallite can be approximated by an ellipsoid of revolution with semi-axes $(a)$ and $(c)$, and the ratio $\beta = a/c$ be defined. The samples studied had a quasi-constant $\beta$ $(\beta = 0.6 \pm 0.25)$ and average grain size as follows $(a/c, \mu\text{m})$ (see Fig. 2b): Sample S1 - 1.1/1.86; S2 - 1.2/2; S3 - 5/8; S4 - 8/13; and S5 - 40/65.

The size variance did not exceed 25 %, while the degree of texturing was more than 95 % in samples S1, S2 and S3, and less than 78 % in samples with advanced recrystallization (S4 and S5).

The magnetic measurements were carried out using a computerized BH - tracer developed at Laboratoire de Magnetisme et Materiaux Magnetiques - CNRS, France. It allowed us to perform the hysteresis-curve evolution at external magnetic fields of up to 30 kOe. The $H_{	ext{eff}}$ measurements were performed by means of an MW technique described in [4].

Based on the results obtained on the magnetization process and on the BH-curves of the series of Sr-ferrite samples investigated, we calculated the data for the pinning force $f$ and DW energy per unit area $\gamma$ from the experimental curves making use of the following expression [2]:

$$E_{\text{BH}}D \frac{1}{8} m_s = f + \frac{n\gamma}{3m_s}$$

where $E_{\text{BH}}$ are the losses per unit volume (BH - loop surface) and $D = 2a^2c$ reflects the averaged data for the grain size in cross-section $c$. Following the classical model, we plotted the BH-energy as a function of $m_s$ for all five samples (Fig. 1a). This reduced line is independent of the grain size so that it is possible to determine the parameter $f = 2.85 \times 10^2$ erg/cm$^2$.

Magana et al. [3] adopted the condition of the DW-size model, namely, that the value of $\gamma$ is independent of the applied magnetic field, and derived an expression for the reduced magnetization:

$$m_s = M / M_s = 2\lambda(0.25 - \varepsilon^2) + \lambda^2 / \beta^2$$
where \( M \) and \( M_s \) are the produced and saturation magnetization of a single grain, and \( \lambda = \beta (x^2 / 2a) \); \( \xi = y / 2c \); \( \beta = a / c \), with \( x \) and \( y \) being the coordinates of the DW bowing and displacement with respect to equilibrium, respectively (Fig. 2.b). Using mathematical transformations related to the ellipsoid geometry, dependences were derived in [3] that can be employed to construct a universal hysteresis curve, where the coercive field \( H_c \), and the remanence \( B_r \), are functions of \( \beta = a / c \) (which accounts for the grain shape) and \( \eta = f / y \), the latter reflecting the material's properties.

Fig. 1.b. shows a sequence of loops for two typical samples from the series - S2 (small grains) and S4 (recrystallized grains). The theoretical values for the same samples are represented by the dashed lines. The discrepancy is easily seen between the experimental and theoretical curves for \( H_c \), which we relate to the fact that calculating \( \eta \) from (1) leaves out the specific characteristics of the highly anisotropic material, namely, the role of the crystallite shape.

One can calculate the DW energy from the formula \( \gamma = 2 (A K)^{1/4} \), where \( K \) and \( A \) are the anisotropy and exchange DW energy interaction constants. A number of studies [e.g., 5] on cubic polycrystal ferrites have shown that the DW energy depends on the so-called "spontaneous anisotropy" - a stress factor specific for the polycrystalline state and related to the magnetostriction; this relation, however, is not well studied for the case of highly anisotropic structures. One of the best ways to deduce the total anisotropy is to use the Larmor relation \( \alpha (H_{eff}) \), \( H_{eff} \) being the effective anisotropy field. Starting out from classical theory for the case of an ellipsoidal crystallite that is smaller than the wavelength and whose axis of symmetry either coincides with the axis of hexagonal symmetry \( c \) or forms an angle \( \theta \) with it (see Fig. 2.a), one can write the following expression for the energy of magnetic anisotropy:

\[
E_a = K_x \sin^2 \theta + K_y \sin^4 \theta + \frac{1}{2} N_{eff} M_s^2 \sin^2 \theta
\]

(3)

Here \( K_x \) and \( K_y \) are the first- and second-order uniaxial magnetic anisotropy constants, and \( N_{eff} \) is the demagnetization factor. In the case of uniaxial anisotropy \( N_{eff} = N_a - N_c \), where \( N_a \) and \( N_c \) are the demagnetization factors perpendicular and parallel to the ellipsoid rotation axis. \( E_a \) is identical to the crystal anisotropy energy, which includes the first- and second-order anisotropy constant. If one considers the motion of the static magnetization vector \( (M = M_s) \) for small induced vibrations, one obtains the following expressions for the \( H_{eff} \) components in a Cartesian coordinate system:

\[
H'_{eff} = 2 K_x / \mu_0 M_s + N_{eff} M_s \quad (3a), \quad H''_{eff} = 4 K_x / \mu_0 M_s \quad (3b)
\]

The role of \( N_{eff} \) is connected exclusively with \( H'_{eff} \) and \( K_1 \), so that formula (3a) reflects the influence of the demagnetization factor. The results of our measurements of \( H_{eff} \) in the 50 - 70 GHz range are presented in Table 1.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Single Crystal</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H_{eff} ), kOe</td>
<td>18.7</td>
<td>21.2</td>
<td>21.2</td>
<td>21.5</td>
<td>22.0</td>
<td>23</td>
</tr>
</tbody>
</table>

In conclusion, the salient points of our investigation can be summarized as follows: Following [3] we made an attempt to apply the modified DW-size model to highly anisotropic structures when the crystallite shape can be approximated by an ellipsoid. We calculated the pinning force in a Sr-hexaferrite - the accuracy of its determination is hindered by the recrystallization processes. The strong dependence of \( H_{eff} \) on the polycrystalline state led us to the conclusion that the model is not adequate in reflecting the grain-shape effect on the DW energy - this is most probably the cause of the discrepancies observed in the comparison of the experimental and theoretical data.

References