ANGULAR DEPENDENCE OF THE COERCIVE FORCE IN MAGNETICALLY UNIAXIAL FERROMAGNETIC SINGLE CRYSTALS

Ya. S. SHUR, G. S. KANDAUROVA, and L. G. ONOPRIENKO

Institute of the Physics of Metals, Academy of Sciences, U.S.S.R.

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The authors calculate the angular dependence of the coercive force in magnetically uniaxial ferromagnetic single crystals. The calculation takes account of the process of rotation of the spontaneous-magnetization vectors in the domains. Experimental data obtained on a single-crystal disk of cobalt are in agreement with the theoretical dependence.

As is known[1], the angular dependence of the coercive force in multidomain magnetically uniaxial ferromagnetic single crystals can be described in the form

$$H_c = H_c^0 / \cos\psi, \tag{1}$$

where ψ is the angle between the direction of the external magnetic field and the axis of easy magnetization, and H_c^0 is the coercive force for $\psi = 0°$. In the derivation of the relation (1) it is assumed that displacement of a domain wall occurs under the influence of the component of the external magnetic field parallel to the axis of easy magnetization. From this formula it follows that at large angles ψ ($\psi \sim 90°$), H_c tends to infinity. This is in contradiction to experimental data. Evidently the observed discrepancy is due to the fact that in the relation (1) no account was taken of the rotations of the spontaneous-magnetization vectors under the influence of the component of the external field perpendicular to the axis of easy magnetization, and that the effect of the demagnetizing fields of the specimen was also neglected.

In the present work, the dependence $H_c(\psi)$ is calculated with a more complete treatment of the effective magnetic fields that determine that dependence; the dependence $H_c(\psi)$ is studied experimentally on a single crystal of cobalt; and a comparison is made between the experimental results obtained and the theoretical formula.

1. We consider a magnetically uniaxial single-crystal specimen, possessing a domain structure and having the form of an ellipsoid. We superpose a rectangular system of coordinates XYZ on the principal semiaxes of the ellipsoid. We orient the Z axis along the axis of easy magnetization. We apply an external magnetic field H in the ZY plane at angle ψ to the Z axis. As the value of the coercive force we take that value of the external magnetic field at which the resultant component of magnetization in the direction of the field,

$$J_H = J_s(\sin\theta\sin\psi - \nu\cos\theta\cos\psi) \tag{2}$$

is zero. Here J_s is the saturation magnetization; θ is the angle of deviation of the vector J_s from the Z axis under the influence of the component of the external field perpendicular to the axis of easy magnetization[2]; and ν is the relative change of volume of one of the magnetic phases. The value of ν can be determined from the condition that the Z component of the internal effective magnetic field must vanish,

$$H\cos\psi + \nu N_Z J_s \cos\theta = H_c^0. \tag{3}$$

In references[2] it was shown that

$$\sin\theta = \frac{H\sin\psi}{H_A + N_Y J_s},$$

$$H < \left\{\frac{\sin^2\psi}{(H_A + N_Y J_s)^2} + \frac{\cos^2\psi}{(N_Z J_s)^2}\right\}^{-1/2}, \tag{4}$$

where N_Y and N_Z are the effective demagnetizing factors of the ellipsoidal specimen, $H_A = 2K/J_s$ is the anisotropy field, and K is the magnetocrystalline anisotropy constant of the uniaxial ferromagnet. On using the expressions (3) and (4), we get for the angular dependence of H_c

$$H_C = \frac{H_C{}^0\cos\psi}{\lambda\sin^2\psi + \cos^2\psi}, \tag{5}$$

where

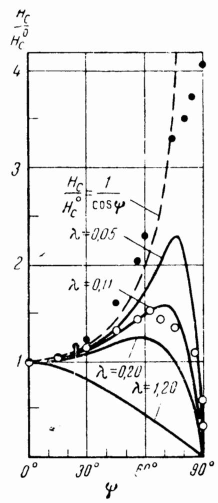
$$\lambda = N_Z J_s / (H_A + N_Y J_s). \tag{6}$$

The value of the angle ψ at which H_c reaches its greatest value is

$$\psi_h = \arccos \sqrt{\frac{N_Z J_s}{H_A - (N_Z - N_Y) J_s}},$$

$$H_A - (N_Z - N_Y) J_s > N_Z J_s;$$

$$\psi_h = 0, \quad H_A - (N_Z - N_Y) J_s < N_Z J_s. \qquad (7)$$



Theoretical and experimental dependence of H_c/H_c^0 on angle ψ.

By way of illustration, the figure presents the theoretical dependence $H_c(\psi)$ for various values of the parameter λ. Also shown, for comparison, is the dependence given by the relation (1) (the dashed curve).

2. The angular dependence of H_c was studied on a single-crystal disk of cobalt. A specimen of diameter 9.8 mm and height 1.4 mm was prepared from a coarse-grained bar of cobalt by anodic-mechanical cutting. The surfaces of the disk were very carefully ground on thin emery paper and polished mechanically. To remove the hardened surface layer, the specimen was polished electrolytically in a 10-% solution of orthophosphoric acid, at a current density of about 2A/mm^2. Finally, after such treatment the domain structure was observed on both surfaces of the disk; it consisted of 180-degree walls of basic domains, wedge-shaped closure domains at the edge of the specimen, and a small quantity of subregions near surface defects. To judge from the powder-pattern picture, the hexagonal axis [0001] of the crystal made an angle of no more than 4° with the specimen surface.

The measurement of the coercive force was carried out by the ballistic throw method, with the aid of a type F-18 photocompensated microvolt-ampere-weber meter. The specimen was placed in the magnetic field in such a way that the surfaces of the disk were parallel to the lines of force. The orientation of the axis of easy magnetization was established on the basis of the form of the powder patterns.

3. For comparison of the experimental results with formula (5), it was necessary to carry out the measurement of H_c in such a way that the state of residual magnetization of the specimen was identical. For this purpose, in all the measurements of H_c, at various angles ψ, the specimen was first magnetized along the hexagonal axis only. Experimental data according to this method of measuring the coercive force are shown in the figure by circles. These results agree with the theoretical dependence (5) with λ = 0.11. If we assume that the specimen studied is an oblate ellipsoid of revolution, and if we calculate the demagnetizing factors N_Y and N_Z according to the formulas of reference[3], we get the value λ ~ 0.2.

Thus we may assume that formula (5) takes sufficiently complete account of all fundamental factors that determine the angular dependence of the coercive force in a multidomain, magnetically uniaxial single crystal.

It must be mentioned that if we carry out the measurement of $H_c(\psi)$ in the usual way, i.e., if we first magnetize the specimen at angle ψ and then measure H_c in the opposite direction (ψ + 180°), then we get a different angular dependence $H_c(\psi)$ (the dark circles in the figure). With such a method of measuring the coercive force, the state of residual magnetization of the specimen is different for different angles ψ. In fact, it follows from the results of an earlier study of the domain structure of cobalt[4,5] that after magnetization of a specimen in a magnetic field oriented parallel or perpendicular to the hexagonal axis, a domain structure of a different type forms in it. Furthermore, in actual crystals there is a nonuniformity of magnetization in the domain boundaries[6], and this will have different effects on the state of residual magnetization as it depends on the angle ψ.

As is evident from the figure, at small angles ψ the experimental values of $H_c(\psi)$ measured by the different methods practically coincide. This is due to the fact that at small angles the state of residual magnetization is almost identical.

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