Vol. A57 (1980) ACTA PHYSICA POLONICA No 6

THE INFLUENCE OF DOMAIN STRUCTURES ON THE MAGNETIC TORQUE IN Fe-3.25%Si SINGLE CRYSTAL WITH (001) PLANES

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(Received October 5, 1979)

The effect of domain structure on the shape and the shift of torque curves in weak magnetic fields has been studied in Fe-3.25% Si single crystals cut in the form of discs with surfaces parallel to the plane (001). The results show that the shape of torque curves is described by the equation sin 2φ if in the single crystal the presence of 180° Bloch walls is observed. The shift of torque curves in the [100] direction in weak fields is, however, associated with the presence of 90° Bloch walls, which occupy a small volume of the sample (approximately 1%).

1. Introduction

In magnetic fields of great magnitude, when the domain structure (in the sample) is no longer present, the shape of torque curves is determined by crystallographic anisotropy of the ferromagnetic material [1].

In fields of low magnetic intensity the magnitude of the torque acting upon the sample, placed in a homogeneous magnetic field, depends on the domain structure [2–4]. In all these works the interpretation of experimental results has been based on the theories of Néel [5], as well as Lawton and Stewart [6] concerning the magnetization of ferromagnetic materials which have a domain structure.

The influence of a domain structure on torque curves, in samples with a single easy magnetization direction, has been studied in [2] and in samples featuring an entirely hexagonal symmetry in [3]. In [4], the influence of domains on torque curves in a magnetic field was examined in Fe-3.4% Si spherically shaped single crystals in the (001) plane.

The prime objective of this work has been the determination of the influence of 180° Bloch wall domain structure on the shape of torque curves in Fe-3.25% Si disc-shaped single crystals with faces parallel to the (001) plane. The second aim has been to explain the shift of torque curves in the [100] direction in magnetic fields of low magnitude.

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2. *Experimental procedure, preparation of samples*

Measurements were performed on Fe-3.25% Si single-crystal samples having the form of discs of 13 mm in diameter and 0.15 mm thickness, with the surface parallel to the plane (001). After polishing, samples were soaked for 3 hrs at the temperature of 1073 K in $13 \cdot 10^{-4}$ Pa vacuum. Subsequently, an interference layer of ZnS of $13.6 \cdot 10^{-8}$ m in thickness, was deposited on samples by vacuum evaporation technique. Torque and magnetization curves measurements were performed, and observation of domain structure was made by means of polarized light (Kerr effect).

3. *Experimental results*

3.1. Torque curves

In external fields of magnetic intensity up to $H_z = 6400$ A/m ($I/I_s = 0.32$), the shape of torque curves $M(\varphi)$ is described by the equation $\sin 2\varphi$ (Fig. 1), where I is a magnetization, I_s — saturation magnetization, φ — the angle which forms the magnetic field with the axis of an easy magnetization direction. An increase in magnetic field to $H_z = 12800$ A/m ($I/I_s = 0.62$) brings about a marked change in torque curves, which occurs under the

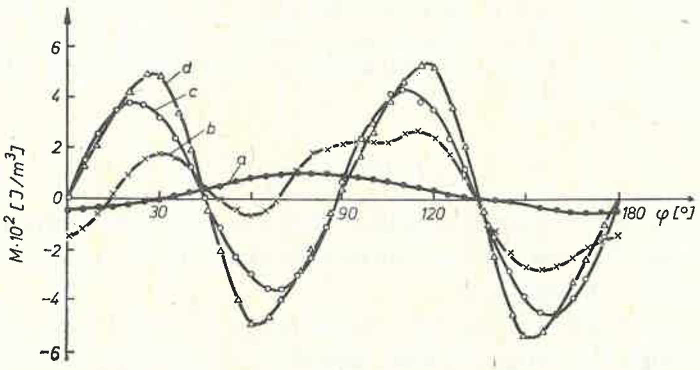

Fig. 1. Magnetic torque curves $M(\varphi)$ of the Fe-3.25% Si single crystal sample of planar orientation (001) for various magnitudes of the external magnetic field H_z(in 10^4 A/m): a — 0.64, b — 1.28, c — 1.92, d — 2.24

influence of magnetocrystalline anisotropy. In fields of greater magnitude than $H_z =$ 19200 A/m ($I/I_s = 0.84$), $M(\varphi)$ curves become similar in shape to torque curves for single crystals of (001) planar orientation.

Moreover, it was also observed that below $H_z < 19200$ A/m torque curves are displaced with respect to the easy magnetization direction (along the crystal direction [100] ($\varphi = 0$) the magnitude of torque is not zero). Initially, the torque in the [100] direction is increasing with the field, and later it decreases, falling to zero when the field is $H_z = 19200$ A/m (Fig. 1).

3.2. Observation of the structure

In weak magnetic fields (up to $H_z = 6400$ A/m), which are directed at an angle $\varphi = 0$, in the plane (001) of a single crystal, only traces of 180° domain walls are observed (Fig. 2a).

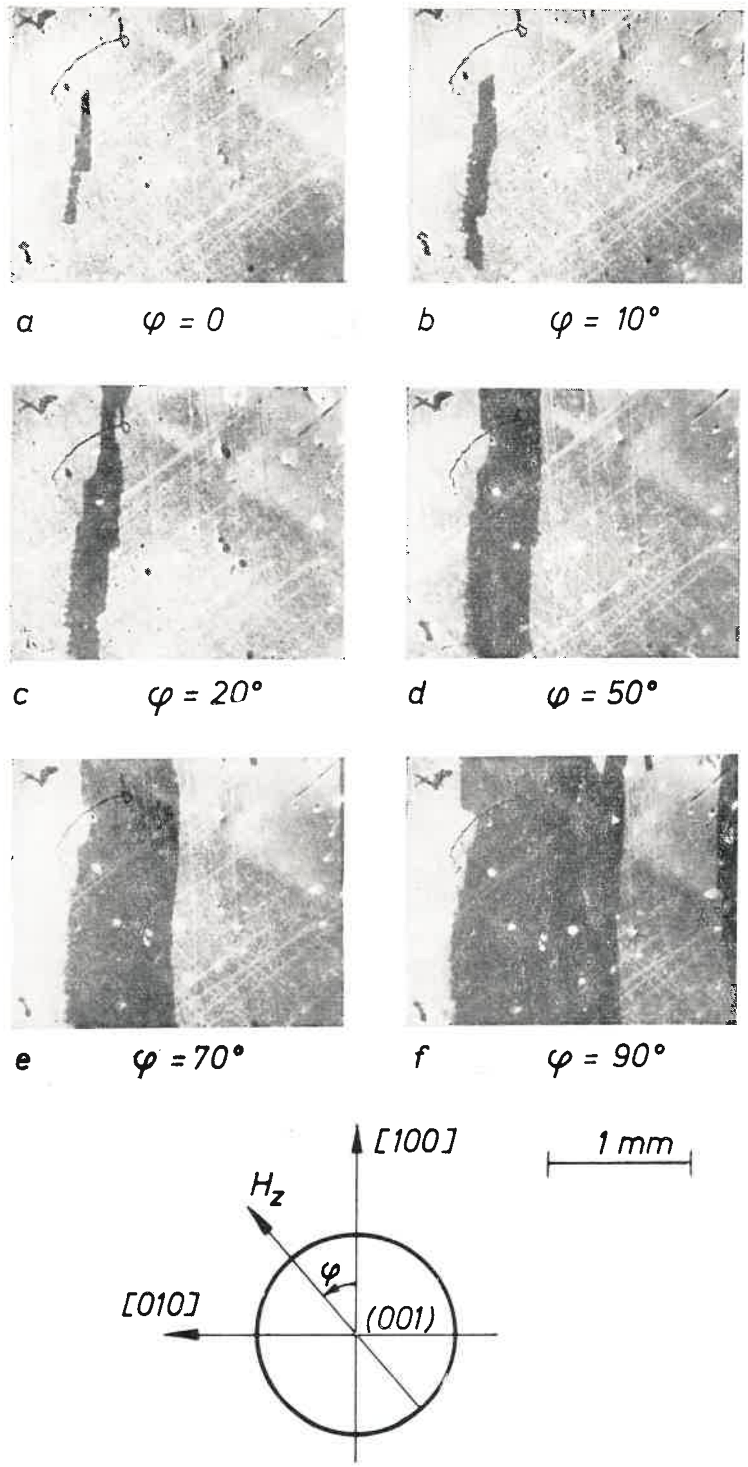

Fig. 2. Changes of domain structure on the surface Fe-3.25% Si crystal parallel to (001) plane, under the influence of a weak magnetic field (H_z = 6400 A/m), which forms an angle φ with the direction [100]

However, with the rotation of the field, of that magnitude, an expansion of domains and the build-up of a domain pattern of antiparallel magnetization direction is taking place (Fig. 2 b–f).

In fields of greater magnitude the existence of complex domains with 90° Bloch walls is observed and their influence on torque curves is also more complex. The interpretation of this problem will be the object of further investigations.

4. *Discussion of results*

4.1. Torque curves

The problem of interpreting the shape of torque curves in weak magnetic fields must take account of the domain structure [2–4]. As can be deduced from Fig. 1 and observation of the domain structure (Fig. 2), the shape of torque curves $M(\varphi)$ is described by the equation $\sin 2\varphi$ when in the sample only 180° domains are present, what has not resulted from the theory [4]. On the surface of the sample are known to exist two equivalent and oriented at right angle to each other easy magnetization directions, thus, in a demagnetized condition two domain sets of 180° walls can be present with magnetization vectors along two easy directions of magnetization. This type of pattern persists in very weak fields when $H_z \ll NI_s$ (Fig. 3a). The sample is as if it were two different samples with uniaxial anisotropy. In this case, the torque acting on the sample is equal to the sum of torque from spaces having the volumes V_1 and V_2 ($M = M_1 + M_2$). In order to calculate M_1 and M_2 torques, it may be assumed that components $H_z \cos\varphi$ and $H_z \sin\varphi$ of the field in volumes V_1 and V_2 are being compensated by the demagnetizing fields $N_1 I_1$ and $N_2 I_2$; where N_1 and N_2 are demagnetizing coefficients of V_1 and V_2 respectively. Neglecting the deflection of the magnetization vector from the easy direction, the torque acting on the sample is described by the equation [2, 3]

$$M = H_z^2 \left(\frac{V_1}{2N_1} - \frac{V_2}{2N_2}\right) \sin 2\varphi. \tag{1}$$

Thus, if the volumes V_1 and V_2 do not vary with the movement of 180° walls during the rotation of fields of that magnitude, the torque is proportional to $\sin 2\varphi$ and the second power of the fields intensity.

With the aid of the described model, which takes into consideration two invariable areas of domain structures, the shape of the observed torque curves (Fig. 1) in very weak fields ($I/I_s = 0.31$) can be explained.

In fields of greater magnitude, the volumes V_1 and V_2 are varying with the rotation of the magnetic field. In this case, calculation of the torque M by equation (1) is practically impossible.

If $NI_s/\sqrt{2} \leqslant H_z < NI_s \cos^{-1} 22°30'$, the structure of the sample is as in Fig. 3b. The calculation of the torque M becomes again possible [4]. If $H_z \geqslant NI_s \cos^{-1} 22°30'$, the sample is magnetized up to magnetic saturation. In this case the torque is defined by

$$M = \frac{\partial E_K}{\partial \theta},$$

where $E_K = \frac{K}{8}(1-\cos 4\theta)$ is the energy of magnetic anisotropy in (001) plane, and θ is the angle between the magnetization vector I_s and the [100] direction. Thus the torque is

$$M = \tfrac{1}{2} K \sin 4\theta. \tag{2}$$

The deflexion of the magnetization vector θ from the [100] direction (for a specified magnitude of the external magnetic field H_z and the angle φ) is determined in accordance with conditions minimizing the anisotropic E_K and the magnetostatic $E_m = H_z I_s \cos(\varphi-\theta)$

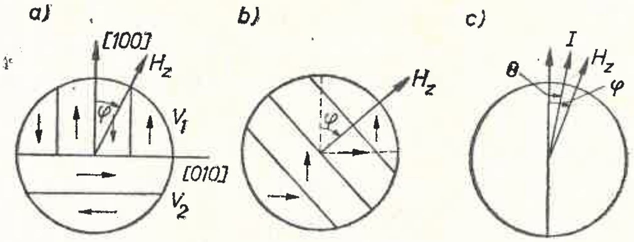

Fig. 3. Models of domain structure in the (001) plane with two easy magnetization directions for three magnitudes of the external magnetic field: a) $H_z \ll NI_s$, b) $\frac{NI_s}{\sqrt{2}} \leqslant H_z < NI_s \cos^{-1} 22°30'$, c) $H_z \gg NI_s \cos^{-1} 22°30'$

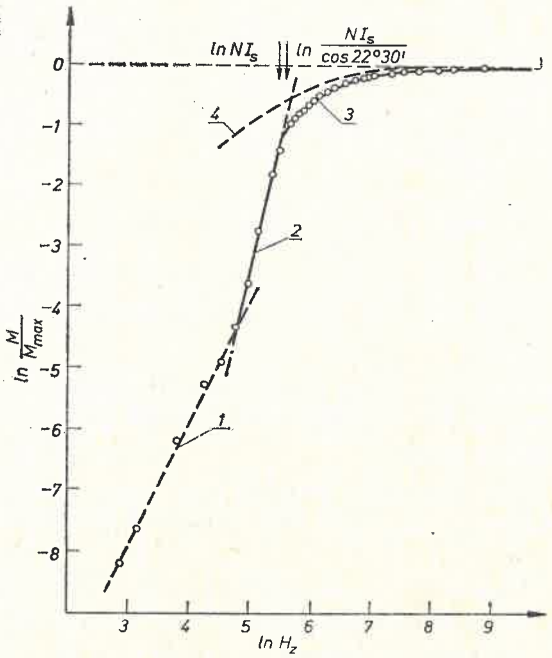

Fig. 4. The dependence of the magnitude of maximal torque for $\varphi = 22°30'$ (given by $\ln M/M_{max}$) on the intensity of the external magnetic field (given by $\ln H_z$) for Fe–3.25% Si single crystal of planar orientation (001): ○ ○ ○ experimental results, ——— data obtained by calculations

energies. The equation obtained by minimization can be written as

$$\frac{1}{2} K \sin 4\theta = H_z I_s \sin(\varphi - \theta),$$

therefrom θ can be calculated and its value substituted into equation (2).

Thus, the values of torque M, according to the magnitude of the external magnetic field, are described by equations (1), (2). The data obtained by calculations as well as the experimental results, for $\varphi = 22°30'$, are shown in Fig. 4. The values obtained by experiments confirm fully the dependence of $M_{22°30'}$ on the intensity of the magnetic field ($\ln H_z < 5$) described by equation (1) when the structure shown in Fig. 3a is retained in the sample. The inclination coefficient of the straight line 1 is equal to 2, which means, that the magnitude of the torque amplitude $M_{22°30'}$ is proportional to H_z^2, which is in agreement with equation (1). The above inference is valid only if the volumes V_1 and V_2 (Fig. 3a) remain unchanged. A sudden increase of $M_{22°30'}$ (straight line 2) is related to the change in volumes of V_1 and V_2 and the occurrence of the domain structures with 90° walls [4] within the field range $5 < \ln H_z < 5.5$. The inclination coefficient of the straight line 2 is then equal about 4, which means, that the magnitude of $M_{22°30'}$ is proportional to H_z^4. In fields, in which the samples are magnetized up to saturation, the experimentally determined magnitude of $M_{22°30'}$ (curve 3) falls below the theoretically calculated one (curve 4). This fact can be explained by the presence of a boundary domain structure.

4.2. The shift of torque curves

An interesting phenomenon is the observed shift of magnetic torque curves with respect to the easy direction in weak fields $I/I_s < 0.8$ (Fig. 1). In some samples the amount of this shift is considerable and attains the magnitude of about 30°. This shift can not be

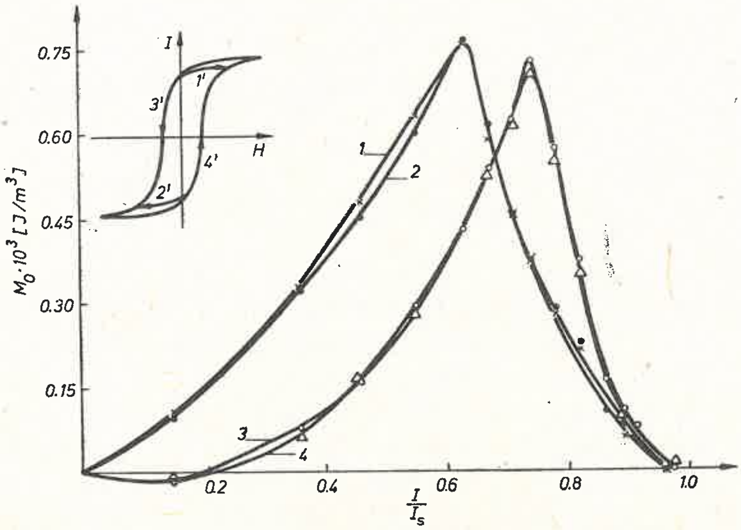

Fig. 5. The dependence of the torque M_0 in the easy direction on I/I_s for Fe-3.25% Si of planar orientation (001). The curves *1*, *2*, *3* and *4* correspond with different methods of magnetization (compare respective designations *1'*, *2'*, *3'* and *4'* on the hysteresis loop)

exclusively ascribed to the movement of 180° walls in the rotating field. In order to explain this shift, the additional measurements were made, which consisted in determining the torque M_0 in the field fixed in the easy direction, i.e. corresponding to the direction of the field when in fields of high strength M_0 was zero. The measurements were performed on samples in the state of remanence. The results of measurements of $M_0(I/I_s)$ are shown in Fig. 5. Various curves in the upper left diagram of this figure correspond to respective magnetizing curves described in the diagram, representing the hysteresis loop.

The diagram in Fig. 5 shows that: 1. the sign of the torque M_0 is not dependent on the reversal of the magnetizing fields; 2. the shift occurs in this range of fields when $I/I_s < 0.95$; 3. curves *3*, *4*, which correspond to the magnetization reversal following a fully formed hysteresis loop, are displaced in the direction of higher fields with respect to curves corresponding to a partially formed hysteresis loop. The independence of the M_0 sign from the field reversal indicates that this phenomenon is not related with heterogenity of the field generated by the electromagnet and the anisotropy of the shape of the sample. The most likely explanation of that phenomenon is a presence of 90° domain walls in the sample.

Consider a certain part of a sample of planar orientation (001) to be occupied by four equivalent structures of 90° domains, as shown in Fig. 6. If all four structures would occupy

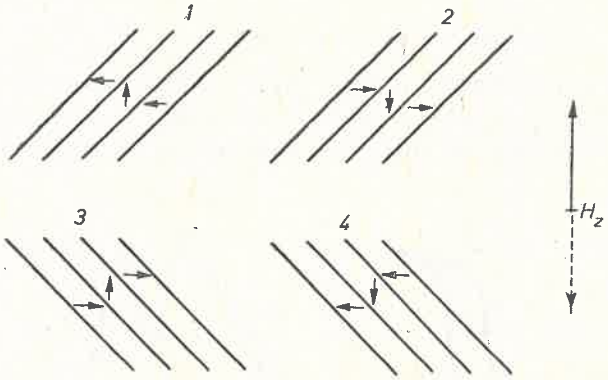

Fig. 6. The models of 90° domain wall structure

equal volumes, the torque, associated with these volumes, in the magnetic field H_z parallel to the easy direction would be zero. Actually there is little probability of all four volumes being equal, thus, taking that inequality for granted, in the field parallel to the easy direction, the sample is subjected to the action of a resultant torque. For simplicity, it can be assumed that $V_3 = V_4 = 0$ (V_3 and V_4 — volumes occupied by structures 3 and 4). Assuming that the field H_z is directed as shown in Fig. 6, then with the increase in this field, an increase in the volume occupied by the domains magnetized in accordance with the reversal of the field (structure 1), and decrease in the volume occupied by the domains magnetized in the opposite direction (structure 2) would take place. Thus, the volume with domains magnetized at right angles to the field will decrease in the case of structure 1, and this volume will increase in structure 2, in consequence, the resultant of magnetization will be directed to the right. Changing the magnetic field reversal, the movement of 90° walls will cause the resulting magnetization to be directed to the left. Hence it follows that the reversal of the torque does not depend on the reversal of the field, which agrees well with the results of the experiment. Thus, the difference in the volumes of magnetic material occupied respectively by the structures 1, 2, 3 and 4 is responsible for the phenomenon observed in the course of this work. In order to explain this phenomenon in the case of a sample characterized by the relation M_0 (I/I_s), which is represented graphically in Fig. 5, suffices the difference in volumes $(V_1+V_2)-(V_3+V_4)$ of about 1%. Such a low volumetric percentage of 90° wall structure is very likely to be found in actual samples, e.g. domains in inclusions or on the surface of a sample.

The decrease in the magnitude of the torque M_0, with the increase in I/I_s, can also be explained with the aid of an adopted model of the domain structure. This behavior is associated with the annihilation of the 90° domain structure with the increase in the magnetic field in the easy direction. In strong magnetic fields $I/I_s \geqslant 0.95$ the 90° domain structure does not exist and M_0 is equal to zero. The observed shift of curves 3, 4 with respect to 1 and 2 curves is most likely associated with the hysteresis of 1, 2, 3 and 4 structures.

5. *Conclusions*

A close association has been found to exist between the domain structure and magnetic torque curves in Fe-3.25% Si single crystal discs of (001) planar orientation. If during the process of magnetization a movement of 180° Bloch walls takes place, torque curves are described by the function $\sin 2\varphi$. The observed shift of M curves along the easy magnetization direction is associated with the presence in Fe-3.25% Si single crystals in addition to 180° domains of 90° Bloch walls.

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