On direction of spontaneous magnetization in a "cubic" ferromagnet

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Abstract

The magnetic properties of anisotropic films have been studied using 3D-neutron polarization analysis. The experimental facts refer to essential distinction of the sample states, magnetized in opposite directions. For an explanation of asymmetrical effects the model is offered, in which the fundamental theoretical principles of structural phase transitions are used.

Key words: ferromagnet, crystal symmetry, twinning, texture, anisotropy, polarized neutrons, asymmetrical effects

1. Introduction

The central point of the present work is the hypothesis about the quite certain direction of a vector of the spontaneous magnetization $\mathbf{M}_s$ in a single crystal of a magnetic phase $G_m$ [1]. In the case under study the orientation $\mathbf{M}_s\parallel[110]$ takes place. Hence, the phase $G_m$ should have the monoclinic symmetry $2/m$ (Neumann principle), and bcc cell should be deformed along the directions of the types [001], [110] and [111]. In a crystal lattice of a paramagnetic phase $G_p$ after structural phase transition $G_p \rightarrow G_m$ the twins of a magnetic phase will be formed. The number of various orientations $n$ of such twins is equal to the number of equivalent directions $[hkl]$ of a phase $G_p$, which the direction of $\mathbf{M}_s$ coincides with. For example, for a cubic phase and with $\mathbf{M}_s\parallel[110]$ this number is $n = 12$. The component of the spontaneous deformation of a bcc cell along a direction of the type [111] results in formation of the twins (fig. 1). The atoms are located in the corners and centers of a parallelograms disposed in a (110) plane. Such twins are transformed into each other by a halfturn around $z$-axis. Thus, the directions of all magnetic moments of atoms (spins) change also. The following assumption, therefore, seems quite natural: the spontaneous magnetization in the considered twins has opposite directions. Thus, the problem arises of definition of a "correct" direction of $\mathbf{M}_s$.

The study of the possibilities of vector analysis of polarized neutrons for the solution of this problem was the initial purpose of the present work.

2. The samples and the method of measurements

The choice of samples in our case plays a crucial role. The optimum way would be to use a single
crystal of a monoclinic phase. We worked with the more complex system: anisotropic polycrystalline Co-Fe films, in which uniaxial texture of the twins is formed by the asymmetry of the fluxes of deposited particles [2]. In particular, the ideal model of this texture is given on fig. 1. The films 3 \( \mu \)m thick were manufactured by magnetron sputtering on glass substrates. During the films deposition the metastable states of the crystalline structure are formed which stabilize themselves at annealing temperatures of the order 150\(^\circ\)C [1]. On hysteresis loops (fig. 2), measured in a magnetic field of the frequency 50 Hz, the strong distinction of magnetic properties along easy and hard axes (EA and HA) is observed. For the initial treatment of the films the permanent magnet with \( H = 1500 \) Oe is used.

The diagram of the setup for 3D analysis of polarized neutrons and the general concept of measurements are given in [3], therefore, here we shall note only the basic moments regarding the present work. The neutron beam directed along the x-axis falls on a film, initially lying in yz-plane (z - vertical direction) and EA coincides with z-axis. The measurements are performed at constant \( \vartheta \) for a number of orientations as the sample is rotated around z-axis up to \( \vartheta = 80^\circ \). Because the coercive force \( H_c \) for our films is about 40 Oe, the external magnetic field \( H < 0.05 \) Oe in the region of the sample can be neglected. The primary polarization \( \mathbf{P}_0 \) is fixed along the coordinate axes in turn. After passing the sample for each directions of the primary polarization three components \( P_{ij} \) of the vectors \( \mathbf{P}_i(\mathbf{P}_x, \mathbf{P}_y, \mathbf{P}_z) \) are measured. In model calculations the normalized values \( P_{ij} \) are used.

With homogeneous distribution of a magnetic field \( \mathbf{B} \) in a sample the magnitude of \( B \) is calculated according to the expressions:

\[
\begin{align*}
P_{xx} &= P_{yy} = \cos \psi , \\
P_{xy} &= -P_{yx} = \sin \psi , \\
\psi (\text{radn}) &= 0.106 \cdot B \cdot (G) \cdot L (\text{cm}) ,
\end{align*}
\]

where \( L = d/\cos \vartheta \) is the effective thickness of a sample in the direction of a neutron beam. In this case there is no depolarization of the beam at all, i.e. \( M_i \equiv |\mathbf{P}_i| = 1 \). The main results of the studies of asymmetrical effects are presented below.

3. Results and discussions

The characteristic dependencies \( P_{ij}(L) \) and \( M_i(L) \) for the uniformly magnetized samples are presented in fig. 3. The initial state of the sput-
tered films appears to be uniformly magnetized also. The possible spatial distribution of vectors $\mathbf{B}$ around EA- direction results in the small distinctions of $B$ values, calculated from the different components $P_{ij}(L)$. For example, for an initial state they are $B(P_{xx}) = 11730(170)G$ and $B(P_{xy}) = 12220(210)G$. Therefore, the average $<B>$ will be employed below.

After the annealing of the sample at $t \approx 200^\circ C$ there is a small increase of the induction $<B>$ up to $12840(200)$ G only. After the sample is being dragged between the poles of a magnet, in such a way that $\mathbf{H} \parallel \mathbf{B}$, $<B>$ does not change. But after the similar operation with the opposite direction $\mathbf{H}$ the change of the direction $\mathbf{B}$ and its reduction to $<B> = 10400(300)G$ has been observed, that leads to a conclusion on the distinction of the states of the film magnetized in opposite directions.

The qualitative effects have been observed in another measurements. The magnetic field was applied on the film at the angle $\varphi$ to EA-direction. One can assume, that at $\varphi = 90^\circ$ and after extracting of the film from the magnet a multi-domain structure is generated, that can be registered easily by the occurrence of strong depolarization of the neutron beam (fig. 4). It turned out, that for $\varphi = 90^\circ$ one can obtain such a state for one direction of the initial magnetization only and after a number of trials. Usually, after such operation either the initial state of magnetization restores or it turns by $180^\circ$. For the opposite initial magnetization the change of the $\mathbf{B}$ direction occurs in an interval of angles from $100^\circ$ up to $110^\circ$. Besides, the values $<B_1(\varphi = 100^\circ)> = 13120(240)G$ and $<B_2(\varphi = 110^\circ)> = 10600(280)G$ coincide with the values measured in the first experiment. These facts indicate the different stabilities of the magnetized film states.

The asymmetrical effects are in contrast to the results of the magnetic measurements (fig. 2): the residual magnetization $M_r$ is equal to $-M_r$. So far, the reason of these contradictions has not been properly understood. But on the basis of the considerable evidences one can put forward a tentative model for an explanation of the asymmetrical effects.

In the films, under certain crystallization conditions, the different concentrations of the twins of the monoclinic phase form. It is reasonable to call the ”correct” direction of $\mathbf{B} \parallel \mathbf{M}_s$, as the ground
state of the magnetized crystal. The change of the direction $\mathbf{B} \rightarrow -\mathbf{B}$ in an external magnetic field can result in different states of the crystal structure of the twin because of the essential difference between the spontaneous deformation and magnetostriction (MS). The MS distortion can change, in principle, the orientation of the twin that is equivalent to its turn. Then the two states of the film, which differ by the opposite magnetizations, will have the same energy and in this case the asymmetrical effects should not be observed. But the external magnetic field can result in the small distortions of parallelograms represented in fig.1. The reset of the magnetization to the “normal” condition is prevented by the crystal anisotropy and the metastable state retains without the external field.

It is worth to note that the different stability of the opposite magnetized states can be connected with the elastic strains. But it is difficult to explain the measured difference between $<B_1>$ and $<B_2>$ by this reason.

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