INVESTIGATIONS ON THE MAGNETIC DOMAIN STRUCTURE OF THIN UNIAXIAL COBALT CRYSTALS*

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Experimental investigations of some properties of magnetic domain structures in thin uniaxial hcp cobalt films are presented. The technology of the specimen preparation for the transmission electron microscope is described. A good agreement was found between the experimental values of domain widths as well as domain wall widths and the theory of Jakubovics. Some deviations from the theory are pointed out.

1. Introduction

Many papers have been published in the last two decades on thin ferromagnetic films. The use of these films as the computer memories stimulate a number of investigations. The problems in technology and proper applications involve also basic research. Of special interest is the domain magnetic structure of such films. Several theoretical models with different stages of complexity have been developed. The stripe domain structure in uniaxial thin films was first studied by Kittel [1] (Fig. 1a, b, c). It was assumed that the easy axis of magnetization was perpendicular to the film surface. Two of his models were found to exist for different film thicknesses, when material constants were introduced. Kittel's work was continued and revised by Málek and Kamberský [2] for thin MnBi films. Structures d for smaller and b for greater thicknesses of the foil were possible (Fig. 1). In the paper of Kaczér et al. [3] a ratio, $\kappa = 2\pi M_s^2/K_1$, where M_s is the saturation magnetization and K_1 is the anisotropy constant of the film, was introduced. For $\kappa > 1$ (e.g., cobalt) the structure, b, changes to c, for $\kappa < 1$ (e.g., MnBi), structure, b, changes to d when the foil thickness decreases as predicted in [1, 2]. Silcox [4, 5] used the experimental results for policrystalline films and proposed a model with the angle between the direction perpendicular to the foil plane and the easy axis of magnetization (Fig. 2). The same model was studied by Jakubovics [6] in greater detail. In his work another parameter was in-

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troduced, namely the domain wall width, b. The magnetization distribution in the wall was proposed as it was for the bulk uniaxial material [7]. This model was the most general for stripe domain structure in cobalt films and the results of (1–3, 5] are special cases of

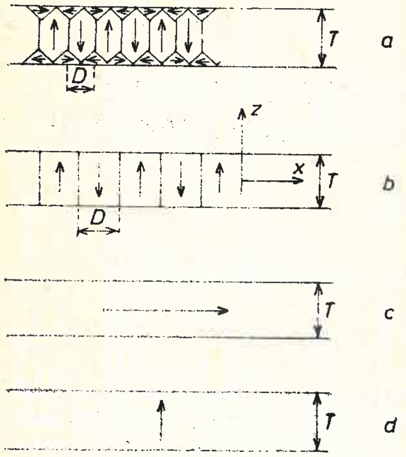


Fig. 1

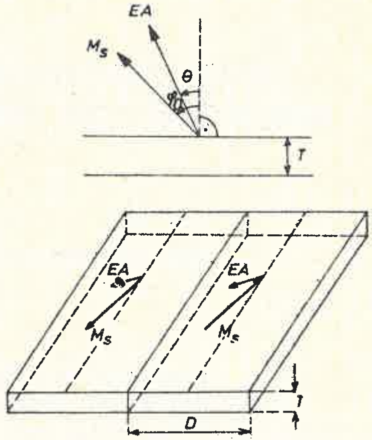


Fig. 2

Fig. 1. The domain structure of thin uniaxial films proposed by Kittel [1] (a, b, c) and Málek, Kamberský [2] (a, b, c, d).

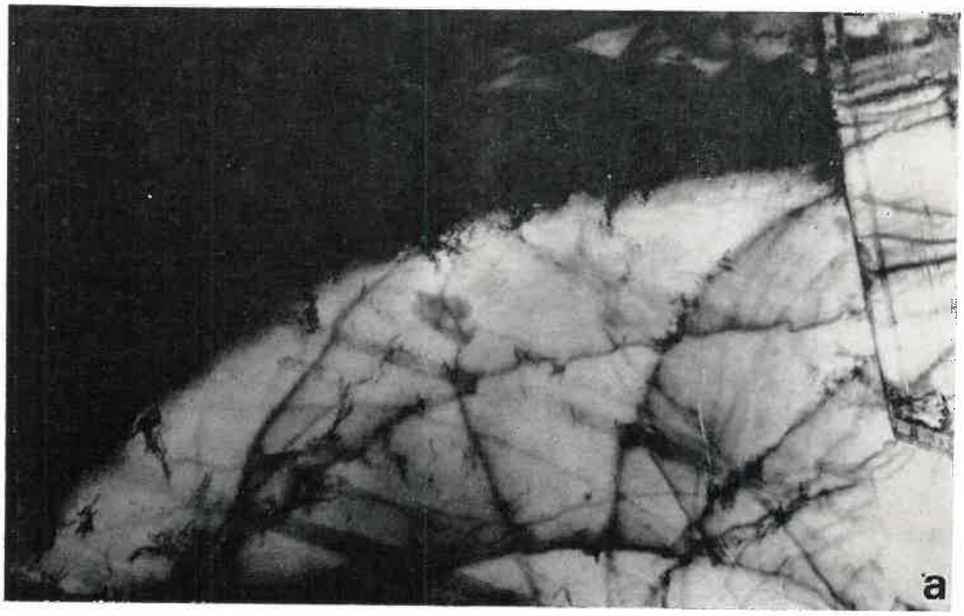
Fig. 2. The model of domain structure according to Silcox [4, 5] and Jakubovics [6]: EA is the easy axis direction, θ is the angle between the EA and perpendicular to the foil surface, M_s is the magnetization direction in the domain, φ_0 is the angle between M_s and the direction perpendicular to the foil surface, D is the domain width and T is the foil thickness.

this. Detailed numerical calculations were made for cobalt hexagonal close-packed (hcp) crystals.

In the last years the bubbles became the most pronounced problem in the thin film domain structure. However, there are still a number of problems in the stripe domain structures that should be investigated in greater detail and this was one of the reasons of presenting this paper.

2. *Experimental procedure*

In this paper an experimental verification of the Jakubovics theory for cobalt hcp thin films was undertaken. The spectral purity attested policrystalline cobalt rods of Johnson Matthey (JMC 873) and of Hoboken 0.2 mm sheets (0.01% impurity) were used. Thinned plates, about 0.15 mm thick were electropolished using the jet machining technique [8, 9] in a special solution. The process parameters such as the proper solution, temperature of the solution, voltage, current density and the speed of the jet were chosen experimentally. The process was stopped automatically when perforation occurred. The very thin regions for the electron microscope observations were found near the perforation point on the sample. A five-lens transmission electron microscope with an accelerating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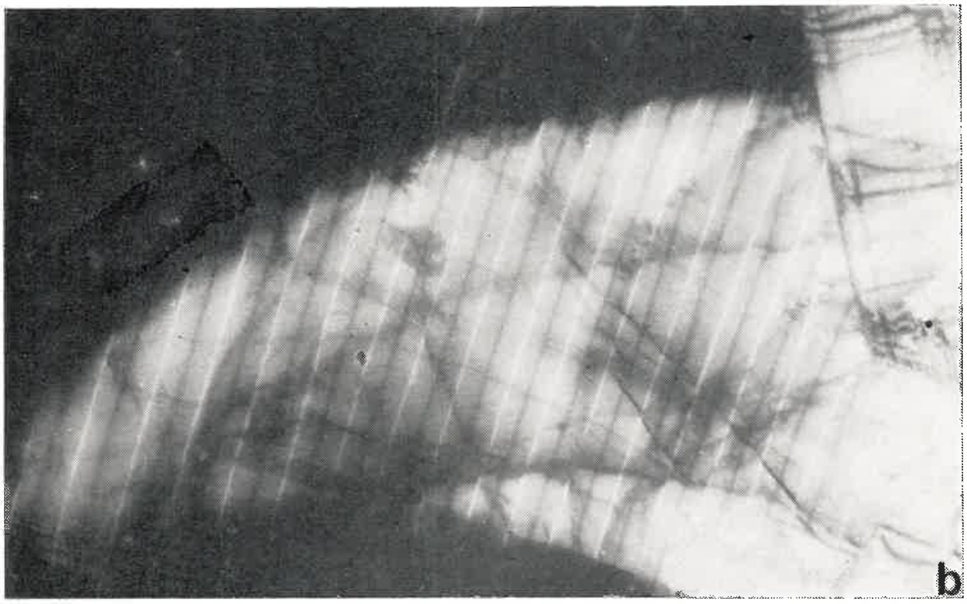
b

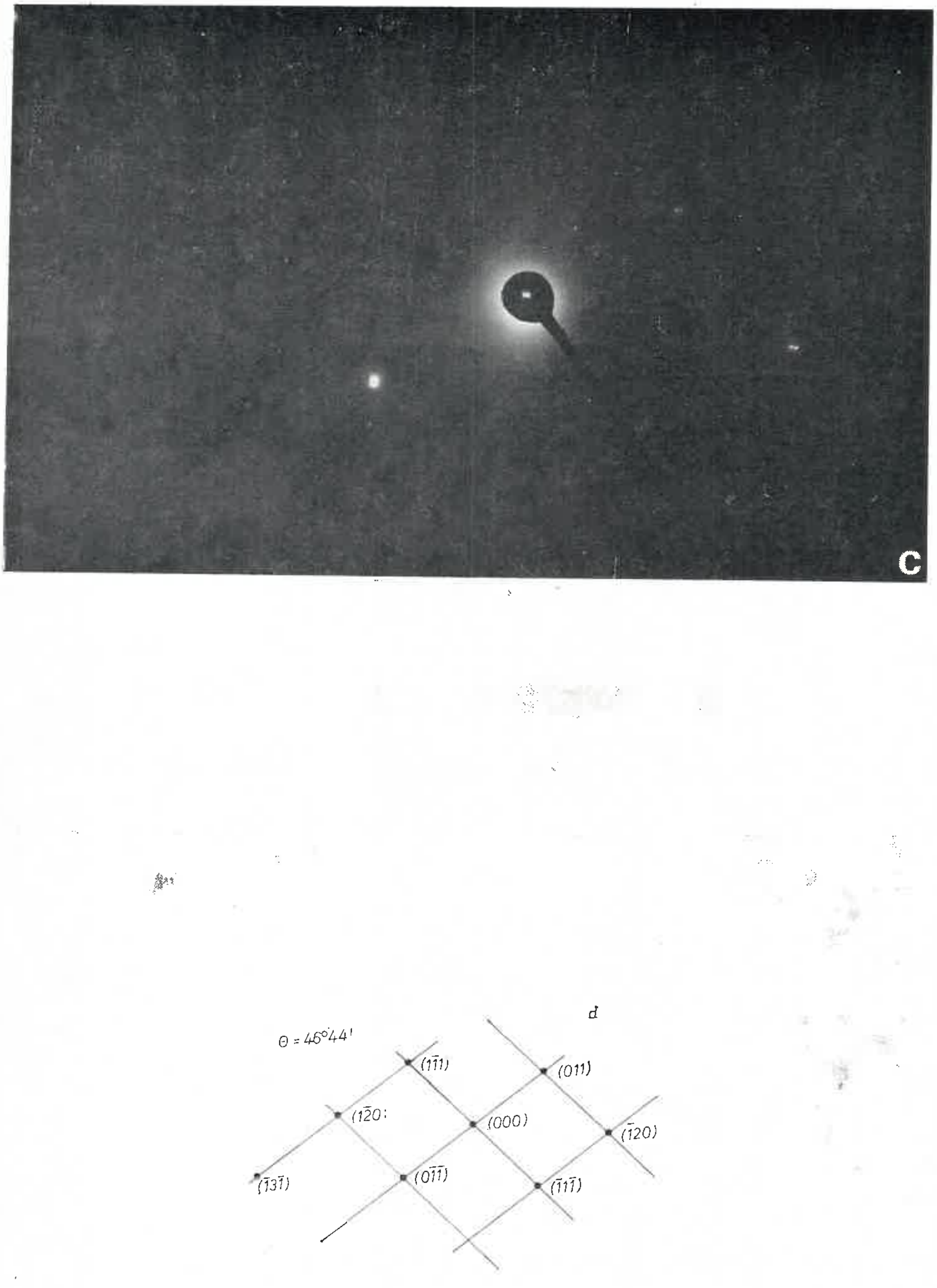

Fig. 3. The representative set of photographs $\theta = 46°44'$: a) in focus, b) out of focus — magnetic structure, c) selected area diffraction, d) the easy axis direction determination from the diffraction pattern

voltage of 100 kV was used in the experiments. The specimen holder was 4.2 mm higher than in the normal position for the objective lens magnetic field reduction.

When the intermediate lens projected the back focal plane of the objective lens, the diffraction pattern (Fig. 3c) of the thin crystal (area selecting aperture) was obtained. Then the determination of crystal orientation was possible. The fine policrystalline gold films were used for camera constant control. The diffraction spot notation was made according to [10] (Fig. 3d).

When the intermediate lens projected the image plane of the objective lens, the final image on the screen or the photographic plate (Fig. 3a) was obtained. Then the crystal thickness could be calculated from the stacking faults which occured in the (001) planes in the hcp cobalt crystals. When the stacking fault could not be seen (for $\theta = 0°$ or $90°$) the extinction contours were useful.

For observations of the domain magnetic structures of thin crystals the out of focus [11] Lorentz microscopy was chosen (Fresnel mode). In this method a good domain wall contrast was obtained (Fig. 3b). The microdensitometer curves with a magnification of 20 or 50 times were useful to determine the domain width, D, and the domain wall width, b. The wall width was calculated from the simple Wade method [12]. Other, more exact methods [13] were found to be too complicated when a great number of specimens were investigated. The diffraction split-spot (Fig. 3d) permitted the determination of the mean magnetization direction in the domain [14].

At room temperatures both hcp and face-cube centered (fcc) cobalt structures exist simultaneously [16]. For choosing the proper hcp grain the shape of the stacking fault and domain structure stripes were useful. A number of crystals had to be rejected because of the fcc to hcp transition.

3. Results and discussion

A large number of photographs of the magnetic domains in cobalt were examined. They corresponded to the following crystal orientations: 0°, 17°28′, 31°32′, 46°44′, 58°22′ 70°25′, 90°. Only the photographs for $\theta = 46°44'$, as representative example, are shown in Figs. 3a–d. The results of the experiments are given in Figs. 4–6. The points relating to the same crystal are joined by solid lines. These are compared with the theoretical curves of Jakubovics (the dashed lines).

The results for the domain width, D, versus the foil thickness, T, with the crystal orientation, θ, as the parameter are presented in Figs. 4a, b. When the foil thickness decreases the domain width also decreases. For thinner films a minimum and later an increase in D, is observed. This leads asymptotically to a uniformly magnetized state. For the foil thickness constant we found also that D increases when θ increases. The curves are similar to those of the Jakubovics theory. However, in most cases the experimental domain widths appear to be higher than the theoretical widths. One could expect that the local energy barriers (i.e., material impurities) may be the reason for this. But no significant differences in the experimental curves were found when the purity of one material was 10^2 higher than of the other. It was also suggested [5, 15] that the higher value of the angle, φ_0, near the foil surface may explain such discrepancies. A comparison of our results with [15] (dot-dash line) for $\theta = 0°$ seems to confirm this supposition (Fig. 4a). Another reason might be also connected with this finding. The temperature of the specimen can rise to 35–50°C what is caused by the electron bombardment of the probe. The temperature influence on the anisotropy constants in thin hcp cobalt foils indeed may involve an increase in the

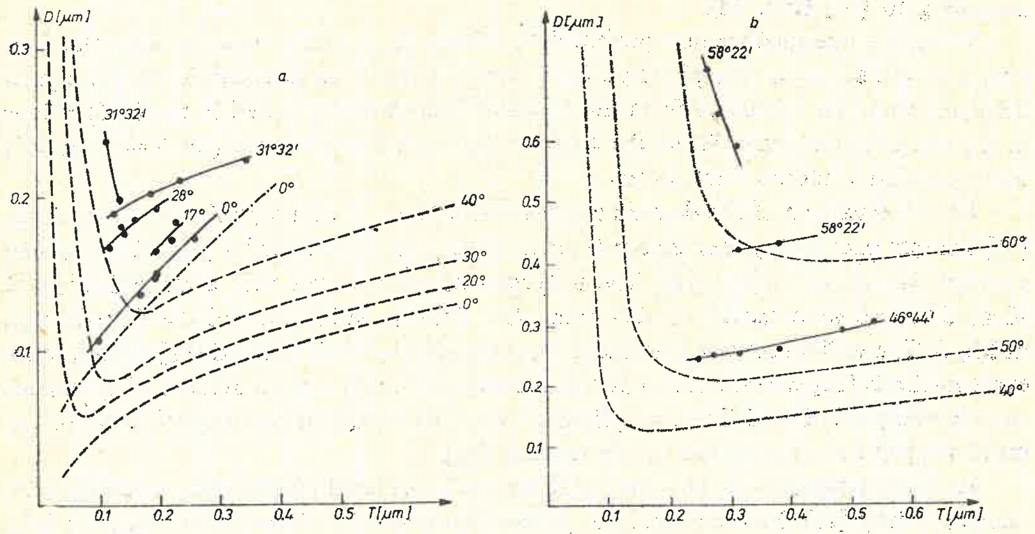

Fig. 4. The domain width, D, versus the foil thickness, T, with the crystal orientation, θ, as the parameter. The dashed lines represent the theory of Jakubovics, the dot-dashed line is the result of Gemperle [15], points and solid lines are our experiments. We also obtained: $\theta = 70°25'$, $D = 1.43$–1.47 μm when $T = 0.247$–0.337 μm and for $\theta = 90°$, $D = 2.23$–3.38 μm when $T = 0.1$–0.18 μm.

domain widths of approximately 30% [16]. The other problem concerns the finite grain size in our experiments. One grain can influence the other and the domain structure of one crystal can affect the structure of the other (i.e., Fig. 3b). The single domain structure near the perforation hole was calculated to exist for different θ for the film thicknesses

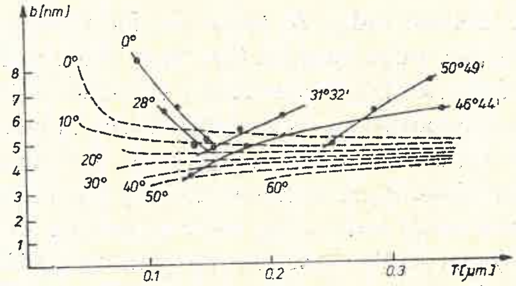

Fig. 5. The domain wall width, b, versus the foil thickness, T, with the crystal orientation, θ, as the parameter. The dashed lines are the theory of Jakubovics, the points and solid lines are our experiments

lower than 0.1–0.2 μm. These results differ from the Jakubovics theory, but we should remember that the structural inhomogeneities can also change the results.

From te same photographs the domain wall width was also measured. The variations of the domain wall width, b, with the crystal thickness, T, for different orientations, θ, are presented in Fig. 5. When the foil thickness decreases the wall width for greater values of θ decreases but for smaller θ it increases. For high values of T the wall width tends to 7–8 nm. In the paper of Jakubovics this value was 4.3 nm and was calculated for the bulk material

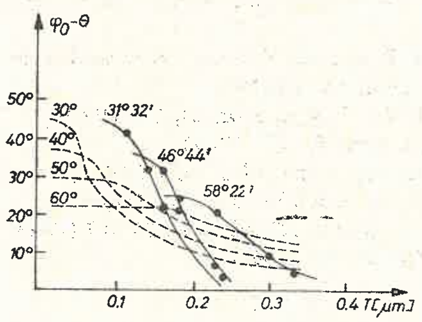

Fig. 6. The magnetization deviation from the easy axis direction φ_0–θ, versus film thickness, T, with the crystal orientation as the parameter. The dashed lines represent the theory of Jakubovics, the points and solid lines are our experiments

constants. It should be noted at this point that our results on the wall widths can have significant errors due to the low difference between the widths of the divergent and convergent wall images. In view of this, the agreement between our results and Jakubovics's theory may be treated as quite satisfactory.

The dependence of the magnetization deviation, $\varphi_0-\theta$, from the easy axis direction on film thickness, T, is given in Fig. 6. The small disagreement with the theory can be induced, i.e., by the differences in the magnetostatic energy as was suggested previously [15]. The weak magnetic field of the objective lens can also influence the results. It was not possible to confirm the stable solution for $\theta = \varphi_0 = 0°$ in the measured range of the foil thicknesses. Probably the orientation, θ, was never exactly to 0° (i.e., for $T = 0.164$ μm, we obtained $\varphi_0 = 47°$).

4. *Conclusions*

The experimental material suggests the reality of the model of Jakubovics with some restrictions which were pointed out above. A good agreement was found between the idealised model and the real crystal. Some results suggest that material constants in this films may be different from those in the bulk. The variation of the magnetization direction across the film possibly could make the theory and experiment agree more closely.

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