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Angular Dependence of Torque in Anisotropic Permalloy Films*

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Torque curves in thin permalloy films have been studied using a high sensitivity (10^{-3} dyne-cm) continuous recording torque magnetometer. The behavior of the torque curves was found to depend on h_c, the ratio of the coercive force to the anisotropy field. Results reported here are for the range $h_c<0.5$. These experimental results are compared with three models of magnetization processes in ferromagnets: a) coherent rotations, b) 180° wall motion in a uniaxial single crystal, c) non-coherent reversal in an infinite circular cylinder. It is found, that while agreement with the first model is good for fields larger than the anisotropy field and with the second model only for fields small compared with the anisotropy field, agreement with the last model is good over the entire range of field.

Torque curves in thin permalloy films have been studied using a high sensitivity (10^{-3} dyne-cm) continuous recording torque magnetometer[1]. The results reported here are for a 1500 Å, 77% Ni film, prepared by vacuum deposition in a magnetic field[2]. The hysteresis loop taken at 1000 cycles, was rectangular in the easy direction with a coercive force H_c=1.0 Oe. In the hard direction, it was reversible with an anisotropy field H_k= 5.8 Oe.

The experimental results are summarized in Figs. 1-3. Examples of the recorded torque curves[3], all of which had a period of 180°, are shown in Fig. 1. For applied fields $H<H_c$, or in the more convenient reduced field notation, $h<h_c$ where $h=H/H_k$ and $h_c=H_c/H_k$, the torque was essentially zero. For $h_c<h<1$, the curves were irreversible, i.e., showed rotational hysteresis and were of the type shown in Fig. 1(a). For $h>1$, the hysteresis vanished and curves similar to Fig. 1(b) were observed. This last result is in disagreement with the earlier work of Mayfield[4] who, using a different technique, reported a non-zero value of rotational hysteresis even for fields as large as h=15.

The anisotropy constant K was 2.5×10^3 ergs/cc. It was determined from the magnitude of the high field torque curves which became field independent for $h>.9$. For $h>6$, the curves assumed a nearly pure sine dependence.

The rotational hysteresis loss per unit volume[5] was computed from the torque curves and is plotted versus the reduced field in Fig. 2.

Fig. 3 shows the component of the reduced

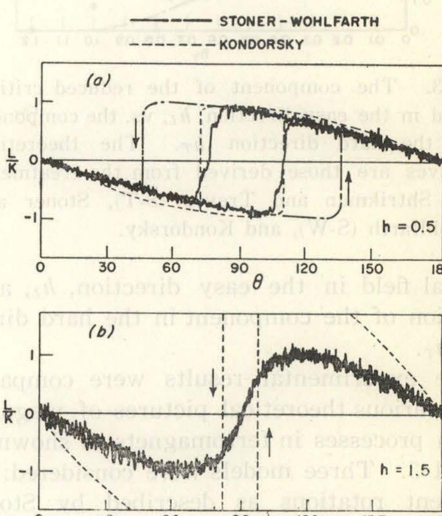

Fig. 1. Angular dependence of the torque L, plotted in reduced units, for two values of the reduced applied field; (a) h=0.5, (b) h=1.5. The broken curves are those calculated from the Stoner-Wohlfarth (S-W) and Kondorsky models. Reversible portions of the (S-W) curves are not shown in both (a) and (b), since they fall on the experimental curves. Arrows indicate the direction of rotation of h.

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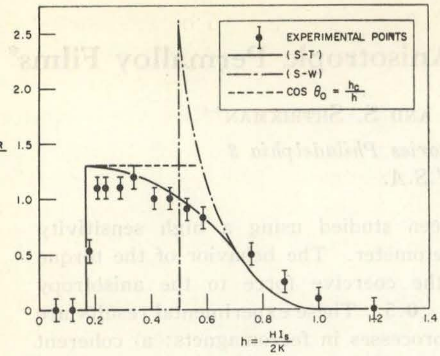

Fig. 2. Rotational hysteresis W_r, plotted in reduced units, vs. reduced applied field. The theoretical curves are those derived from the treatments by Shtrikman and Treves (S-T), Stoner and Wohlfarth (S-W), and Kondorsky.

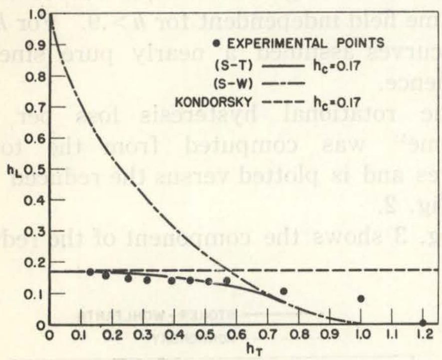

Fig. 3. The component of the reduced critical field in the easy direction, h_L, vs. the component in the hard direction h_T. The theoretical curves are those derived from the treatments by Shtrikman and Treves (S-T), Stoner and Wohlfarth (S-W), and Kondorsky.

critical field in the easy direction, h_L, as a function of the component in the hard direction h_T.

The experimental results were compared with various theoretical pictures of magnetization processes in ferromagnets as shown in Fig. 1-3. Three models were considered: (a) coherent rotations as described by Stoner and Wohlfarth[6]; (b) 180° wall motion in a uniaxial single crystal as discussed by Kondorsky[7]; (c) an adaptation of the results of the calculations by Shtrikman and Treves[8] on non-coherent reversal in an infinite circular cylinder.

(a) Coherent Rotation: Here the film is considered to be a single domain particle with uniaxial anisotropy. The saturation magnetization I_s is given by $I_s=2K/H_k$. Using the experimental value of H_k and K, I_s was calculated to be 860 emu/cc, which is in close agreement with the bulk value[9]. As shown in Fig. 1, the reversible parts of the experimental torque curves are in very good agreement with the calculated ones. The onset of irreversible torque reversal as well as the magnitude of the rotational hysteresis are, however, in wide disagreement with this model except in fields approaching $h=1$.

(b) 180° Wall Motion: Here it is assumed that the hysteresis loop is rectangular and that only the component of the field parallel to the easy axis is effective. This should be a good approximation as long as the magnetization is parallel to the easy axis i.e. for $h \ll 1$. It follows accordingly that the rotational hysteresis, W_r, is field independent, with a value

$$W_r=4H_cI_s \tag{1}$$

The critical angle θ_c is given by

$$\cos\theta_c=\frac{-h_c}{h} \tag{2}$$

Since the magnetization is parallel to the easy axis, the torque L, is simply

$$\begin{aligned} L&=-HI_s\sin\theta, \quad \theta<\theta_c \\ L&=HI_s\sin\theta, \quad \theta>\theta_c \end{aligned} \tag{3}$$

Examination of Figs. 1-3 shows that for $h \ll 1$, the predictions based on this model are in good agreement with experiment. However, as h approaches 1, discrepancies appear which grow as h increases.

(3) Non-Coherent Rotation: Here the torque curves are identical to those calculated from the Stoner-Wohlfarth model except when

$$h^2<1-3h_c+3h_c^2. \tag{4}$$

When Equation (4) is satisfied, the critical angle is given by

$$\cos\theta_c=\frac{-h_c}{(1-2h_c)^{1/2}}\left[\left(\frac{1-h_c}{h}\right)^2-1\right]^{1/2} \tag{5}$$

although in the regions where the curves are reversible, they are the same as the Stoner-Wohlfarth curves, calculated for corresponding regions.

The hysteresis losses are computed as described by Shtrikman and Treves. Comparison with experiment, Fig. 2, show that this model fits the experimental results reasonably well over the entire field range.

In order to obtain the critical switching curves in the usual form, it is convenient to rewrite Eq. 5 in terms of h_L and h_T. It then becomes

$$\left(\frac{h_L}{h_c}\right)^2+\left(\frac{h_T}{1-h_c}\right)^2=1 \qquad (6)$$

Fig. 4 shows a plot of this function for several values of h_c.

In Fig. 3, the experimental switching curve is shown for the particular case discussed and the agreement with the Shtrikman-Treves model is again seen to be reasonably good.

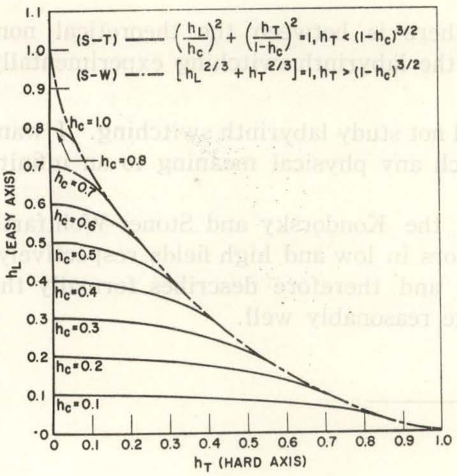

Fig. 4. Theoretical critical switching curves, for several values of the reduced coercive force h_c, derived from the Shtrikman and Treves (S-T) model. Also the critical curve derived from the Stoner and Wohlfarth (S-W) model to which the (S-T) model reduces when $h_T=(1-h_c)^{3/2}$.

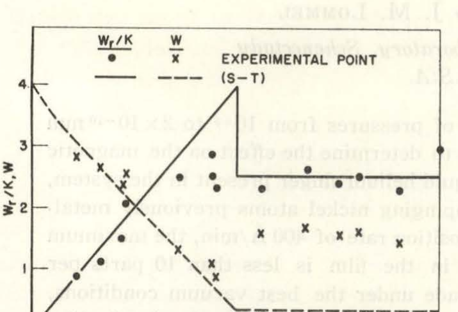

Fig. 5. The dependence of the maximum reduced rotational hysteresis W_r/K and the rotational hysteresis integral W on the reduced coercive force h_c. The theoretical curves are derived from the Shtrikman and Treves (S-T) model which reduces to the Stoner and Wohlfarth (S-W) model for $h_c>0.5$.

These favorable results are in fact no surprise. For cases where $h_c<1$, as for this film ($h_c=.17$), the model is equivalent to the Stoner-Wohlfarth one in the region $h\gtrsim 1$ and to the Kondorsky one for $h\ll 1$. As it is hard to attach physical meaning to the picture assumed in the derivation of equation (5), i.e., an infinite cylinder describing a thin film, it is perhaps best to regard it an interpolation scheme between the limits of the Stoner-Wohlfarth and the Kondorsky models.

As a further check on the validity of the Shtrikman-Treves model in thin films an experimental study of the dependence of the hysteretic properties on the parameter h_c was undertaken. Fig. 5 shows the results[11] for the maximum reduced rotational hysteresis $W_{r/K}$ and the rotational hysteresis integral[12] W. For $h_c<0.5$ the agreement between theory and experiment is satisfactory. For $h_c>0.5$ the experimental value of W is too large. Thus, the range of applicability of the model is limited to $h_c<0.5$. The situation in the range $h_c>0.5$ is much more complex[13] and does not lend itself to a simple quantitative description at present.

The authors would like to thank Dr. Ami Berkowitz, I.B.M. Corporation, formerly of this laboratory, who originally suggested the study of rotational hysteresis in thin films.

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10 The authors are indebted to Dr. E. P. Wohlforth for suggesting the presentation of the critical switching curve in this form.

11 The composition of the films measured generally about a 1000 Å thick, varied between 77 and 83% Ni. This includes several films kindly provided by A. Noreika, Philco Corp. D. O. Smith, Lincoln Laboratory and M. Prutton, I. C. T.
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DISCUSSION

E. P. WOHLFARTH: For the specimen you describe the rotational hysteresis W_r vanishes below h about 0.16. This leads to a reduced cylinder radius $S=2.6$. The rotational hysteresis integral for this specimen is quoted as 2.6 which, on using the Shtrikman-Treves' results, leads to $S=2.5$. Hence the quantitative agreement is here excellent.

D. O. SMITH: What relation do you think there is between the theoretical noncoherent switching of an infinite cylinder and the labyrinth switching experimentally observed in thin films?

S. SHTRIKMAN: I really do not know. We did not study labyrinth switching. I want to stress, however, that I do not claim to attach any physical meaning to an infinite cylinder in connection with a thin film.

I think however that it is clear enough why the Kondorsky and Stoner-Wohlfarth models yield good approximation to the behaviors in low and high fields respectively. The infinite cylinder behaves in a similar way and therefore describes formally the experimental behavior for the whole field range reasonably well.

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Effect of Pressure During Evaporation on the Magnetic Properties of Nickel Films

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Nickel films have been evaporated over a range of pressures from 10^{-5} to 2×10^{-10} mm Hg and at two widely different evaporation rates to determine the effect on the magnetic properties. Under the best conditions, with a liquid helium finger present in the system, all the glass surfaces which are exposed to impinging nickel atoms previously metal-coated, a pressure of 2×10^{-10} mm Hg and a deposition rate of 400 Å/min, the maximum calculated concentration of trapped gas atoms in the film is less than 10 parts per million. All the films tested, including those made under the best vacuum conditions, show a uniaxial anisotropy of 1 to 3×10^{3} erg/cm^3 which can be reoriented by annealing in a field. We therefore conclude that trapped impurity atoms such as oxygen are not responsible for the uniaxial anisotropy in nickel films.

Introduction

A major unsolved problem in the behavior of ferromagnetic thin films is the origin of the uniaxial anisotropy (usually denoted by K_u) which occurs in films evaporated or electrodeposited in a magnetic field. Similar phenomena in bulk alloys are generally attributed to directional ordering[1], but this explana-

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