

THE RELATION BETWEEN THE DISTRIBUTION BEHAVIOUR OF THE HYSTERESIS LOSS AND MAGNETIZATION REVERSAL MECHANISM IN CoCr FILMS

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The distribution of the hysteresis loss as function of the applied field has been successfully used to investigate the magnetization reversal mechanism in our CoCr films. For high $H_{c\perp}/H_k$ films, the distribution of the hysteresis loss vs. applied field exhibits a monotonically decreasing curve with a single peak, while for low and medium $H_{c\perp}/H_k$ films their curves exhibit double-peak characteristics. On assuming that the magnetization reversal in low $H_{c\perp}/H_k$ films is considered as the superposition of the domain-wall motion with perpendicular and in-plane orientation of the magnetization, then the calculated coercivity vs. angle curve is in good agreement with the measured one. A simple and convenient method for determining the nucleation field is also provided.

1. Introduction

In order to make appropriate use of the perpendicular recording properties of CoCr films, considerable work on its magnetization reversal mechanism has been done [1–7,11–14]. An effective approach to solving the problem is found by combining the microscopic methods of Lorentz electron and Kerr microscopy with the macroscopic method of examining the dependence of the magnetic properties (for example, H_c , H_{cr} , hysteresis loss W_h) on the amplitude and angle of the applied field. In previous papers [7,8] it was found that for CoCr films the magnetization reversal mechanism strongly depends on the amplitude and angle of the applied field. It was concluded from the results of our VSM measurement that a high coercivity is favourable for switching the magnetization in CoCr films by means of the rotation reversal, while the domain-wall reversal acts in the low coercivity films. Experimental data show that the initial growth layer of CoCr films has a rather large influence on the magnetization reversal [8]. For a special CoCr film having very

high coercivity (160 kA/m) with a quite obvious in-plane magnetization component, it was very interesting to find that at a high applied field the magnetization reversal mechanism was mainly controlled by incoherent rotation. However, in the low field range below a certain critical field the magnetization is reversed by domain-wall motion and at the same time the orientation of the magnetization will change from the perpendicular to the in-plane direction.

Comparing the experimental curves of $H_c(\theta)/H_{c\perp}$ with several rotation reversal models for medium and high $H_{c\perp}/H_k$ films, it was discovered that the cos type of incoherent rotation is a relatively better fit with the measured curves than other mathematical models if the influence of the in-plane magnetization component is considered [7].

The observation of the domain structure shows that low coercivity CoCr films present a typical long stripe-domain configuration. On the other hand, the measured domain period vs. the applied field curve is in good agreement with the calculated one, according to the stripe-domain theory [10]. However, it was often found that for low coercivity CoCr films the measured angular de-

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pendence of the coercivity is quite different from the inverse cos law (i.e. the so-called Kondorsky-type angular behaviour). On the contrary, this angular dependence of the coercivity is almost independent of the angle of the applied field. In previous reports [7,8] it has been eloquently proved from the angular dependence of the H_c , remanent coercivity H_{cr} , orientation ratio OR, hysteresis loss W_h that the magnetization reversal mechanism for low coercivity films is quite different from coherent or incoherent rotation. However, at present no strong arguments and satisfactory models can be presented in this case to explain such unique angular dependence of coercivity for low coercivity films.

In order to solve the above-mentioned discrepancy between the measured and calculated angular dependence of coercivity for low coercivity films, in this report we will concentrate our attention on systematically investigating the distribution behaviour of the hysteresis loss for high, medium and low $H_{c\perp}/H_k$ CoCr films and bulk CoCr alloy sample. Combining the observation results on the domain configuration by using a digital enhanced magneto-optical Kerr microscope, the angular dependence of the coercivity for low coercivity films can be modeled on the fact that the magnetization reversal is considered as the superposition of the domain-wall motion with perpendicular and in-plane orientation of the

magnetization. If the dependence of the proportion of the domain-wall motion with perpendicular orientation in the whole reversal as function of the angle, which is the angle between the applied field and the film normal, can be determined, it will be possible to calculate the angular dependence of coercivity for low $H_{c\perp}/H_k$ films.

2. Experimental procedure

The CoCr films used are rf magnetron sputtered on silicon substrates. Their coercivities range from about 8 to 160 kA/m. The bulk CoCr specimen is a circular sample 8 mm in diameter having a thickness of 0.3 mm. The Cr content is about 20–25 at% and 20 at% for sputtered CoCr films and bulk CoCr sample, respectively. The magnetic properties were measured by VSM and Torque magnetometer. X-ray fluorescence was used to check the composition and thickness of the CoCr films. The most relevant properties obtained from the VSM and Torque magnetometer as well as the Kerr microscope are summarized in table 1. The maximum applied field is 800 kA/m.

The observation of domain configuration for low coercivity CoCr films shows that, if starting from saturation, the applied field is gradually decreased to below the nucleation field H_n , the first reversed dot-like domain will appear. However, as

Table 1
The relevant parameters ($H_a = 800$ kA/m)

no.	$H_{c\perp}$ (kA/m)	$H_{c\perp}/H_k$	H_n (kA/m)	H_{cw} (kA/m)	H_1 (kA/m)	H_2 (kA/m)	H_n/H_k	H_{cw}/H_k	H_1/H_k
1	8	0.014	350	312	352	296	0.587	0.52	0.61
2	8	0.015	320	260	325	256	0.615	0.5	0.62
3	8.4	0.017			336	250			0.71
4	32	0.055	432	256	424	256	0.72	0.43	0.68
5	46	0.076	395				0.63		
6	41	0.077			368				0.72
7	49	0.080			380				0.67
8	60	0.09	448				0.66		
9	59.7	0.1			420				0.71
10	59.3	0.095			436				0.7
11	59.7	0.1			432				0.72
12	76	0.14			528				0.83

Note: all the H_n , H_{cw} , H_1 , H_2 values are taken at the angle = 0.

the field is continuously decreased to the field H_{cw} , this kind of dot-like domain will disappear and begin to form the stripe domain. Here the H_n is obtained by extrapolating the dot-like domain density to zero according to the curve of the domain density as function of the applied field, while the H_{cw} is determined by observing the appearance of the first stripe domain in the Kerr-microscopic photograph [9]. The H_1 and H_2 are obtained by plotting the curve of hysteresis loss as function of the applied field. The details will be explained in the ensuing paragraph.

The distribution of the hysteresis loss ΔW_h as function of the applied field is defined as

$$\int_{H_{a1}}^{H_{a2}} d(M_1 - M_2) dH / \int_{-H_m}^{H_m} d(M_1 - M_2) dH, \quad (1)$$

where M_1 and M_2 represent the descending and ascending loops, respectively.

3. Results and discussion

In order to more minutely investigate the relation between the distribution behaviour of the hysteresis loss and magnetization reversal mechanism in CoCr films at a high applied field (800 kA/m), the distribution of the hysteresis loss with respect to the applied fields for high, medium and low coercivity CoCr films was measured. Two typical distribution curves are shown in figs. 1, 2 for high and low coercivity films respectively. It is clearly seen from fig. 1 that for a high $H_{c\perp}/H_k$ film no matter how the direction of the applied field changes, the distribution curves always have a monotonically decreasing form. As the applied field is gradually changed from the film normal to the in-plane direction, the low field peak of the distribution curve of the hysteresis loss, which appears at about zero field, will become more and more obvious. This means that the in-plane magnetization component exerts a tremendous influence on the magnetic behaviour of CoCr films in the vicinity of 90° . It was previously known [8] that the main contribution to this low field peak of the distribution curve is caused by the domain-wall

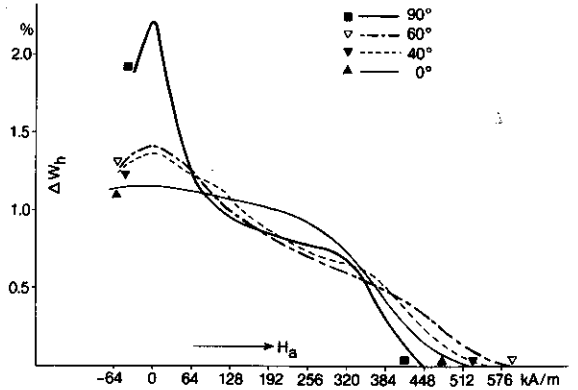


Fig. 1. The dependence of the distribution of hysteresis loss on the applied field for a high $H_{c\perp}/H_k$ film (no. 12).

motion, because it is only possible for a magnetization switch to take place in such a low field by domain-wall motion. However, this kind of influence is only confined to the vicinity of the in-plane direction because even though the angle is equal to 60° , the low field peak of the distribution curve is only slightly raised. When the angle of H_a is lower than 20° , the hysteresis loss vs. applied field curve is almost a flat line in the range of ± 100 kA/m. This fact suggests that the influence of the in-plane magnetization component can be negligible in the vicinity around zero angle. On the contrary, it can be seen from fig. 2 that for low $H_{c\perp}/H_k$ films the height of the low

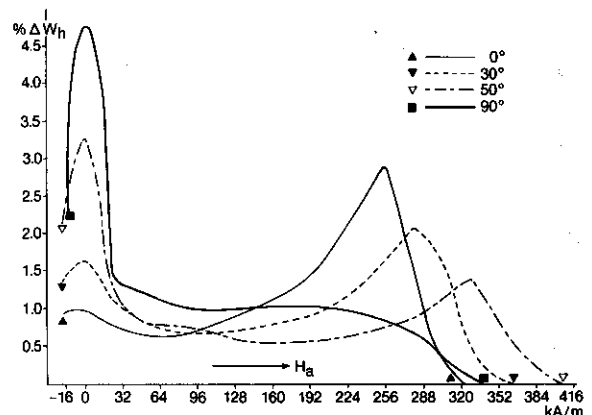


Fig. 2. The dependence of the distribution of hysteresis loss on the applied field for a low $H_{c\perp}/H_k$ film (no. 2).

field peak is not only much higher than that for high $H_{c\perp}/H_k$ films, but also the in-plane magnetization component still exerts quite a large influence on the magnetic behaviour even though the angle = 0. Fortunately it was very interesting to discover that the influence of the in-plane magnetic component for medium coercivity film on the low field peak of the hysteresis loss vs. H_a curve is situated just between those of the low and high coercivity films (including the height of the low field peak and the range of the angle affected by the in-plane magnetic component). This fact indicates that as the $H_{c\perp}/H_k$ of CoCr films decreases, the influence of the in-plane magnetization component strengthens greatly. It may be reasonable to infer that as the $H_{c\perp}/H_k$ of CoCr films decreases, the proportion of the in-plane domain-wall motion, which is switched in a very low field, as a whole will gradually increase. As was expected, when the direction of the applied field is changed from perpendicular to in-plane, the low field peak of the distribution curve increases drastically.

Comparing this with high $H_{c\perp}/H_k$ films, a striking difference of the distribution curve for low $H_{c\perp}/H_k$ films is the presence of a double-peak. Except for the low field peak, the distribution curve also has a high field peak (see fig. 2). The remarkable differences between the high and low field peaks are as follows:

1) As the direction of the applied field is changed from the perpendicular to the in-plane direction, the position of the high field peak will gradually move to a high field region, while the position of low field peak is found to be independent of the field direction. Its peaks always appear at about zero field.

2) As the direction of the applied field is changed from 0 to 90° the amplitudes of a high field peak decrease gradually, while those of the low field peak increase.

H_2 is defined as the field at which the high peak appears, and H_1 as the field at which the hysteresis loss just becomes zero. Comparing H_1 and H_2 with the measured domain nucleation field H_n and domain-wall field H_{cw} by Kerr microscopy, respectively (see table 1), it was unexpectedly found that the H_2 (256 kA/m) is very close to the

H_{cw} (260 kA/m) obtained by Kerr microscopy, while H_1 (325 kA/m) is very close to the H_n (320 kA/m) for a low $H_{c\perp}/H_k$ film (no. 2). For this reason we have further compared other specimens having various coercivities with those with roughly the same $H_{c\perp}/H_k$ value measured by the Kerr microscopy, and found that for our specimens whether they have low, medium or high coercivity, their H_1 and H_2 are in quite good agreement with H_n and H_{cw} , respectively (see table 1). Combining the above experimental data with the results obtained from medium $H_{c\perp}/H_k$ films, it can be concluded that for low and medium $H_{c\perp}/H_k$ CoCr films when the applied field is applied along the film normal, the position of H_2 , where the high field peak of the distribution curve appears, corresponds to the stripe-domain nucleation H_{cw} , while the position of H_1 , where the hysteresis loss just become zero, corresponds to the dot-like domain nucleation H_n . It is quite evident that the H_1 can also be considered as the line of demarcation between the reversible and irreversible magnetization. It is well known that if $H_a > H_1$, the magnetization reversal is rotated reversibly, but if $H_a < H_1$, irreversible magnetization reversal will take place. For the sake of convenience, H_1 and H_2 from now on will be referred to as H_n and H_{cw} .

According to the statistical results on our specimens, it is worth pointing out that for low and medium $H_{c\perp}/H_k$ films the distribution curve of the hysteresis loss seems to have a double-peak characteristic. As the $H_{c\perp}/H_k$ of CoCr films increases, the height of the high field peak gradually decreases. For high coercivity films, the high field peak completely disappears and the distribution curve decreases monotonically. Perhaps this fact may suggest that if the distribution curve has either a double or a single peak, it is an important indication for judging whether the magnetization reversal mechanism belongs to rotation reversal or domain-wall motion.

Based on the related observation results of stripe-domain structure, it is known that H_{cw} represents its stripe-domain nucleation field. Therefore, the high field peak should also exhibit some domain-wall behaviour. In order to confirm this, a bulk CoCr sample ($H_c = 1.37$ kA/m) was also examined. The related results on magnetic mea-

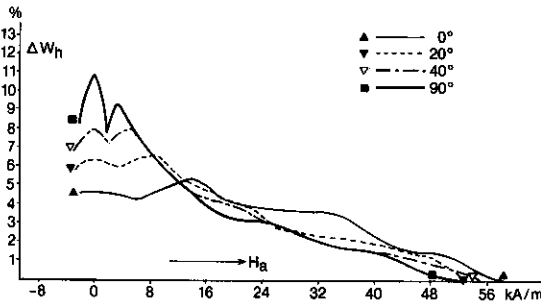


Fig. 3. The dependence of the distribution of hysteresis loss on the field for a bulk CoCr specimen.

surement by VSM (for example the angular dependence of H_c , OR and W_h with respect to H_a) show that the orientation of the magnetization aligns along the in-plane direction of the sample and the magnetization is reversed by domain-wall motion [15]. It is very interesting to see in fig. 3 that its distribution curve of hysteresis loss also exhibits a double-peak characteristic. However, it was found for the bulk CoCr sample, that as the direction of the field is changed from 0 to 90°, the position of the high field peak will move to a lower field direction and the height of the peak will increase. This change pattern is just opposite to that for low and medium $H_{c\perp}/H_k$ CoCr films. Otherwise, the high and low field peaks of the hysteresis loss distribution curve are very close to each other. In figs. 4, 5 the dependence of $H_2(\theta)/H_{2\parallel}$ and $H_2(\theta)/H_{2\perp}$ on the angle are plotted for a bulk CoCr sample and a low coercivity CoCr film (no. 2), respectively. Comparing this

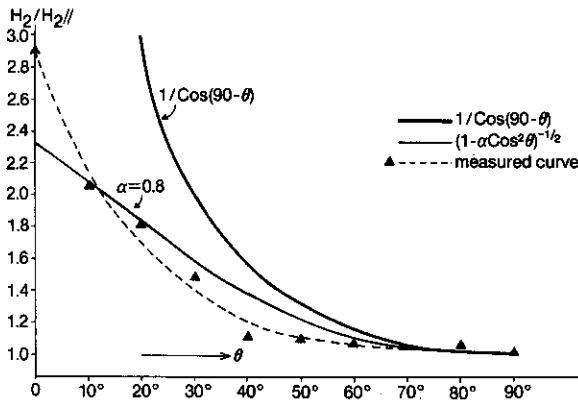


Fig. 4. The angular dependence of H_2 for a bulk CoCr specimen.

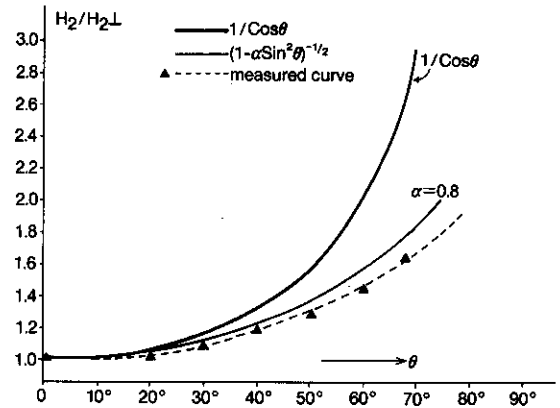


Fig. 5. The angular dependence of H_2 for a low $H_{c\perp}/H_k$ film (no. 2).

with the inverse cos curve from the domain-wall motion theory, it can be seen that the $H_2(\theta)/H_{2\parallel}$ vs. θ curve for a bulk sample basically follows the change pattern of in-plane domain-wall motion $(1-\alpha \cos^2\theta)^{-1/2}$, while the $H_2(\theta)/H_{2\perp}$ vs. θ curve for low coercivity films basically follows the change pattern of domain-wall motion with perpendicular orientation of the magnetization $(1-\alpha \sin^2\theta)^{-1/2}$. It is clearly seen from figs. 4, 5 that if α is taken as 0.8, the calculated curves for both CoCr bulk sample and low $H_{c\perp}/H_k$ film are almost consistent with the measured ones. In view of this argument, it may be reasonable to assume that for low coercivity films the magnetization reversal mechanism can be thought to be the superposition of domain-wall motion with perpendicular and in-plane orientation of the magnetization because its low field peak of the distribution curve of the hysteresis loss shows in-plane domain-wall reversal characteristics. As the direction of the applied field is changed from 0 to 90°, the proportion of domain-wall motion with perpendicular orientation to that with in-plane orientation will decrease. Therefore, it will be possible to calculate the dependence of coercivity on the angle for low $H_{c\perp}/H_k$ films, if the dependence of the proportion of domain-wall with perpendicular orientation to that with in-plane orientation can be determined experimentally.

As a temporary expedient, we assume that the height of the high field peak on the distribution curve of the hysteresis loss for low coercivity films

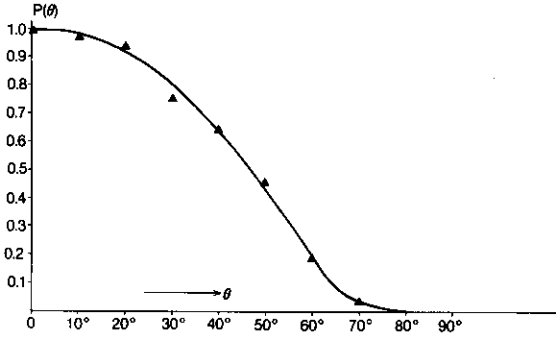


Fig. 6. The measured angular dependence of the proportion of domain-wall motion with perpendicular orientation to that with in-plane orientation.

represents the proportion of domain-wall motion with perpendicular orientation as a whole and the coercivity behaviour follows a modified inverse cos formula: $H_c(\theta)/H_{c\perp} = (1 - \alpha \sin^2\theta)^{-1/2}$ [7], where α is considered to be an adjustable parameter. The measured dependence of the proportion $P(\theta)$ of domain-wall motion with perpendicular orientation as a whole on the angle is shown in fig. 6. Hence, the coercivity as function of the angle can be calculated by formula:

$$\begin{aligned} H_c(\theta)/H_{c\perp} &= (1 - \alpha \sin^2\theta)^{-1/2} P(\theta) + (H_{c\parallel}/H_{c\perp}) \\ &\quad \times (1 - \alpha \cos^2\theta)^{-1/2} (1 - P(\theta)). \end{aligned} \quad (2)$$

Actually, for low coercivity CoCr films there is a more or less constant magnetization component, which is independent of the angle, because the degree of orientation is very poor in the remanent state [7]. If we assume that the $Q\%$ represents the constant magnetic component of total magnetization. The above formula (2) will be changed to:

$$\begin{aligned} H_c(\theta)/H_{c\perp} &= (1 - Q) \left[(1 - \alpha \sin^2\theta)^{-1/2} P(\theta) \right. \\ &\quad \left. + (H_{c\parallel}/H_{c\perp}) (1 - \alpha \cos^2\theta)^{-1/2} \right. \\ &\quad \left. \times (1 - P(\theta)) \right] + Q. \end{aligned} \quad (3)$$

The calculated results for $\alpha = 0.8$ and $Q = 0.2$ are shown in fig. 7 with $P(\theta)$ obtained from fig. 6. It can be clearly seen that the calculated curves are quite consistent with the measured one for low coercivity films drawn with a dashed line. Espe-

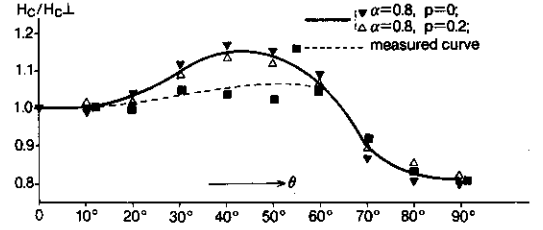


Fig. 7. The calculated and measured angular dependence of the coercivity for a low $H_{c\perp}/H_k$ film (no. 2).

cially in the range of $0-20^\circ$ and $60-90^\circ$, the calculated curve almost coincides with the measured one. However, the constant magnetization component only exhibits a small influence on the coercivity behaviour.

In view of the above-mentioned fact, it may be reasonable to infer that this unique angular dependence of coercivity for low $H_{c\perp}/H_k$ films, i.e. that its coercivity hardly changes with the angle, originates from the superposition property of domain-wall reversal with perpendicular and in-plane orientation of the magnetization. This is applicable if the proportion of domain-wall reversal with perpendicular orientation as a whole is considered to be closely dependent on the angle. There is no harm in supporting the assumption that for low coercivity films the relation between the hysteresis loss behaviour and the magnetization reversal mechanism is presented in fig. 8.

If the applied field is decreased to the nucleation field H_n , starting from saturation, at the same time the first reversed dot-like microdomain will appear and the hysteresis loss will become a little

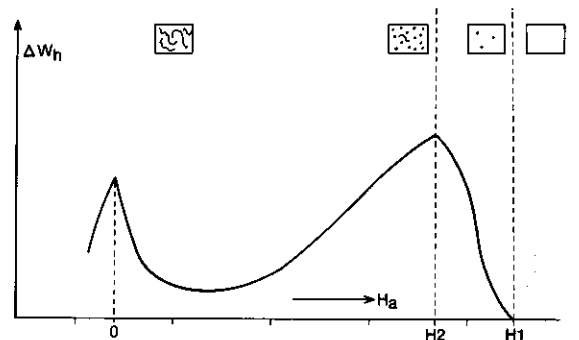


Fig. 8. Schematic drawing of the relation between H_1 , H_2 and H_n , H_{cw} for low $H_{c\perp}/H_k$ films.

more than zero. As the applied field is continuously decreased to the stripe-domain nucleation H_{cw} , the dot-like domain begins to disappear and forms a new stripe-domain while concurrently the high field peak of the distribution of hysteresis loss emerges. With continuously decreasing applied field, more and more dot-like domains disappear as well as more and more stripe domains are generated and grow. As the angle increases from 0 to 90, the proportion of domain-wall reversal with perpendicular orientation to that with in-plane orientation will decrease. It can be assumed that this unique magnetization reversal mechanism shows a series of magnetic parameters (for example, H_c , H_{cr} , OR etc.) that hardly change with the angle for low coercivity films.

Therefore, it can be concluded that domain-wall reversal holds a dominant position in low coercivity films, which is also supported by other arguments: 1) The measured domain period vs. the applied field curves are in good agreement with the calculated one, according to the theory of stripe-domain [9]. 2) The experimental relation between the initial slope of the easy loop [$T = (dM/dH)_{M=0}$] and the thickness is quite consistent with the theoretical curves, which are calculated according to the domain-wall motion [7].

4. Conclusions

The magnetization reversal mechanism in CoCr films is discussed by means of the distribution of hysteresis loss as function of the applied field ($H_a = 800$ kA/m). It can be concluded that:

1) This method can be used as one of the criteria for establishing the magnetization reversal mechanism.
 2) For high $H_{c\perp}/H_k$ CoCr films the dependence of the distribution of hysteresis loss as function of the applied field is a single peak curve. With increasing field, this curve is always a monotonically decreasing one. However, for low and medium $H_{c\perp}/H_k$ films the distribution of hysteresis loss vs. applied field curves exhibit a double peak characteristic. Combining this with the related results on the observation of the dependence of domain configuration on the applied field by

Kerr microscopy it was discovered that the high field peak of the distribution curve of hysteresis loss corresponds to the stripe-domain field H_{cw} , while the field where the hysteresis loss just become zero corresponds to the domain nucleation field. With regard to our specimens, these have already proven useful and easy for determining the nucleation field.

3) On assuming that for low $H_{c\perp}/H_k$ CoCr films the magnetization reversal mechanism is considered as the superposition of domain wall reversal with perpendicular and in-plane orientation of the magnetization, the coercivity vs. angle curve was calculated. It was found that the measured curve is quite consistent with the calculated one predicted by the above-mentioned model.

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