REVERSAL BEHAVIOUR IN PERPENDICULAR IRON PARTICLE ARRAYS (ALUMITE MEDIA)

J.C. Lodder and Li Cheng-Zhang
University of Twente, P.O.Box 217, 7500 AE Enschede, The Netherlands.

Abstract: Alumite was chosen as an ideal material to investigate the influence of particle interaction on the magnetic behaviour of a perpendicular anisotropic particle array. It was found that the measured reduced coercivity versus the reduced diameter curves fits the theoretical curling mode. However, the magnetic behaviour will no longer obey curling if the applied field deviates from the film normal. This is due to the presence of magnetic charge next to iron single-domain cylinders, which completely destroys the validity for curling. Their reversal can be interpreted from the superposition of Cos-type incoherent rotation and the magnetization reversal switched by the demagnetizing field and the dipole-dipole field.

Introduction

High-density recording media with a columnar morphology and a perpendicular magnetic orientation are well known. Up to now the reversal mechanism has not always been completely understood and depends on the dimensions of the columns and their interaction. By complete magnetical isolation of the single-domain columns the magnetization will be rotated by one of the rotational mechanisms. Here the magnetostatic interaction is important. The stray fields of the surrounding columns will cause a difference between the applied field and the actual field at the site of the column. To understand this, Alumite was used [1]. It consists of well-defined Fe-needles positioned perpendicular to the film-plane in a regular array. The pores are separated by nonmagnetic Al_2O_3. The dimensions and magnetic properties are given in table 1.

Table 1: Dimensions and magnetic properties of Alumite used

no	cell size Å	pore size Å	thick -ness µm	P	Nz	Ms kA/m	Hc⊥ kA/m	Ms/Mst	Rs	Hc/Ha	sample
1	618	300	3.3	0.214	0.019	166	125	0.096	0.56	0.146	TU7
2	618	300	1.6	0.213	0.049	182	125	0.106	0.45	0.146	TU1
3	618	360	3.0	0.307	0.039	184	106	0.107	0.39	0.124	TU8
4	618	425	3.2	0.429	0.042	230	74	0.134	0.25	0.086	TU9
5	907	360	1.2	0.143	0.099	109	113	0.064	0.55	0.132	TU6
6	907	360	3.5	0.143	0.02	184	110	0.107	0.51	0.128	TU10
7	907	425	0.9	0.200	0.162	231	77	0.135	0.30	0.089	TU3
8	907	480	2.0	0.254	0.069	359	64	0.209	0.20	0.074	TU2
9	1130	425	4.7	0.128	0.016	223	80	0.130	0.38	0.094	YS625
10	907	425	4.6	0.200	0.019	340	70	0.198	0.22	0.082	YS619
11	618	425	4.3	0.429	0.02	357	73	0.208	0.20	0.085	YS623
12	618	425	1.0	0.429	0.146	736	72	0.420	0.10	0.084	YS624
13	1170	450	1.0	0.13	0.147	247	77	0.144		0.09	A-1-1
14	745	450	0.7	0.33	0.213	571	75	0.333		0.088	B-3-3
15	1170	720	1.1	0.34	0.228	651	31	0.380		0.035	A-3-2
16	1130	580	0.8	0.304	0.302	303	41	0.177	0.11	0.047	FDTU5

Specimens 9-12 and 13-15 are hard-disk media with respectively Aluminium and glass substrates, the rest were made as floppies. In table 1 the packing density P is given, being the ratio of the iron needles to the whole volume. Rs is the squareness ratio along the perpendicular direction (Mr⊥/Ms). The demagnetizing factor of a needle along the easy axis is expressed by Nz. The anisotropy field (Ha = 0.5 Mst) is calculated by formula of the shape anisotropy [2,3]. Here Mst is the theoretical value of the magnetization for Fe. For an infinitely elongated single-domain particle without any interaction several models like S-W, curling, buckling and fanning were proposed. An angular dependence of the coercivity as a function of the diameter can be found in [2-6]. In realistic media, magnetostatic interaction between the particles is inevitable. At present most of the typical theory about the reversal cannot be directly used to illustrate their magnetic behaviour. Alumite is favoured as there is only a magnetostatic but no exchange interaction between the needles.

Reversal mode of single-domain particles

As the basic cell is an Fe cylinder, the magnetization will preferably lie along the major axis, where the demagnetizing factor is minimum. The calculated Bloch wall has a thickness ≈ 835 Å for Fe, if the exchange constant is $1.1*10^{-11}$ J/m [7]. In table 1 the Fe diameters for all samples used are smaller than the thickness of the Bloch wall. Therefore the basic unit is a single-domain cylinder [8], and only two reversal modes are important, viz. curling and coherent rotation. Based on the latter, the major consequences will be: 1) The extremely high coercivity of 856 kA/m for an infinitely long Fe cylinder. 2) A coercivity, independent of the size of the single-domain needle. 3) A sharply decreasing angular dependence of Hc. The nucleation field for the coherent rotation is given by [5,14]:

$$Hn = -2Ki/\mu_o Ms - Nx^*Ms \qquad (1)$$

The calculated crystalline anisotropy field of 40 kA/m for an aligned array of this ideal cylinder, is at least 20 times less than the shape anisotropy field of 856 kA/m. Hence, the perpendicular anisotropy is mainly determined by the shape instead of the crystalline anisotropy. Table 1 shows that Hc is much less than the calculated values. In addition, the experimental data show that Hc strongly depends on the size of the cylinder and the change pattern of angular dependence of Hc is quite different from that expected for a S-W mode. Therefore curling was proposed to explain the reversal. If the applied field lies parallel to the longer axis of the cylinder, Hn for the curling mode is given by [5,14].

$$Hn = (-2Ki/\mu_o Ms) + (Nz^*Ms) - (2\pi K^*A/\mu_o Ms) * (1/R^2) \qquad (2)$$

Where Nz is the demagnetizing factor in the direction of easy axis and R is the radius. The constant K depends on the length/diameter. For a infinite cylinder K ≈ 1.08. As previously pointed out, Hk can be neglected. Nz for a cylindrical particle can be calculated by the formula [9]. In table 1, Nz is somewhat smaller if the length/diameter is large enough. If Nz becomes very small, formula (2) can be reduced to:

$$Hn = (-2\pi K^*A/\mu_o Ms) * (1/R^2) + (-2Ki/\mu_o Ms) \qquad (3)$$

This means that Hc will be inversely propositional to R^2 if the applied field is large enough to saturate and lies in the film normal. Fortunately, for the low packing fraction [7] the relation between Hc⊥ and $1/R^2$ obeys a linear relation, except in the case of radii less than 150 Å. It is reasonable to conclude from this relation that the reversal is curling. On the other hand, the calculated critical diameter d_0, which is the delimitation for transition from the coherent rotation to curling, is about 120 Å. The reduced coercivity vs the reduced diameter (d/d_0) for d's from 300 Å to 720 Å is plotted in Fig. 1.

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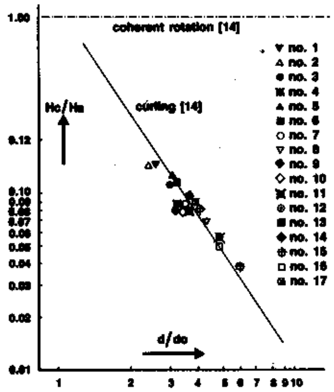

Fig. 1 The relation between the measured and calculated reduced coercivity vs. the reduced diameter.

An unexpected identity between the theoretical and the measured curve proves that curling certainly takes place. It is apparent that for a long cylinder the lowest energy mechanism of the reversal is curling, until d_0 is reached, below which, coherent rotation will occur. Hc is mainly controlled by its d/d_0 i.e. the size of the needle and the magnetization. In [10] it was shown that Hc is almost independent of P if the diameter was kept constant. In principle, no free magnetic charge is formed during curling hence there is no magnetostatic interaction because, the average value of magnetic charge on the side of the needles should be zero. Consequently, no decrease in Hc on P is predicted [2]. The experimental results are opposite. In Fig.2 Hc decreases with increasing P and it basically follows:

$$Hc(P) = Hc\ (0) * (1-\alpha P) \qquad (4)$$

where Hc(0) is the Hc for the Fe cylinders at infinite dilution i.e. no magnetostatic interaction and α depends on the size and magnetization.

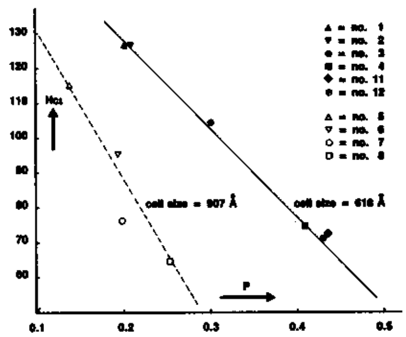

Fig. 2 The relation between the coercivity and the packing density (P) for two different cell sizes.

The results are in contrast with the independent behaviour of packing density expected by curling. This also proves the influence of the interaction between the cylinders on the magnetic behaviour. Based on the influence of the interaction on its total field in a needle the calculation of the effect of the number of needles on the angular dependence of Hc revealed that the curve for one cylinder is the same as that expected by curling. With increasing numbers of cylinders the peak height will gradually decrease and shift to small angles until it vanishes [7], i.e. with increasing P, the transition angle from curling to rotation will decrease.

<u>Angle-dependent measurements</u>

In view of the above, it may be reasonable to infer that reversal is no longer controlled by curling if the direction of the applied field deviates from the normal, even though the Hc values are a good fit for theoretical curling when the applied field is normal to the plane.

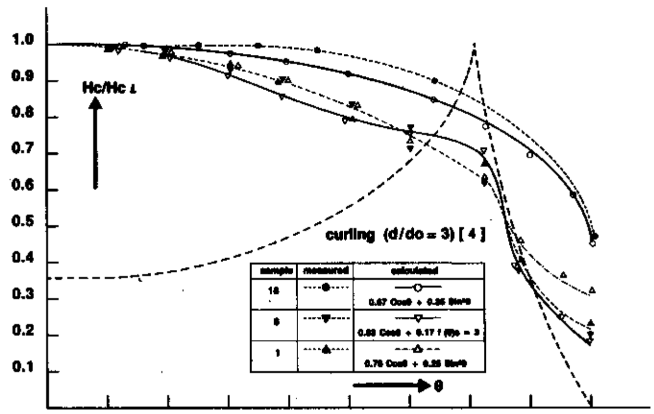

Fig.3. The measured and calculated Hc/Hc⊥ vs. θ for low (#16) and high coercivity samples. The calculated curling line (S=3) is also given.

In Fig. 3, the in-plane component of the magnetization will be induced if the applied field is at an angle with the easy axis. Its presence will cause a magnetic charge next to the cylinders, resulting in deviation of the curling behaviour. Obviously, the larger the angle, the larger the deviation. As a result of this magnetostatic dipole-dipole interaction between the needles, the demagnetizing field (Hd), which includes the local Hd for the Fe cylinders and the macroscopic Hd for whole film, will exert a great influence on the reversal mechanism. It is evident that the larger the deviation of the applied field from the easy axis, the stronger the influence of Hd will be. It is known that Hd strongly depends on Nz and Ms. Ms/Mst is a reflection of the real P if all pores are completely filled. In [7] the initial slope of the perpendicular loop is almost equal to 1 for hard-disc samples i.e. Mr=Hc. On the other hand, (Hn) can be calculated by [5]:

$$Hn=Hc = -(6.78 * A/\mu0\ Ms * R^2) \qquad (5)$$

Therefore the squarness ratio can be written as:

$$Rs= (6.78 * A/\mu0\ R^2\ Ms^2) \qquad (6)$$

In table 1 the measured Rs values qualitively follow the same change tendency. Generally, the decrease in Rs along the film normal will cause an increase along the film plane. The experimental results show that the orientation ratio OR⊥ and HC// are controlled by the demagnetizing factor of the cylinders.

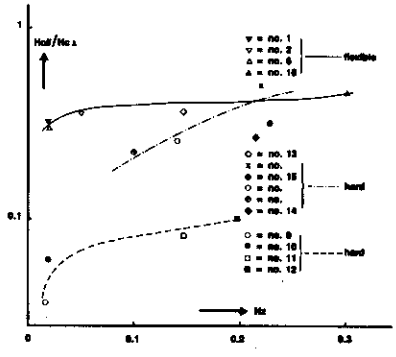

Fig.4. The dependance of Hc//Hc⊥ on the calculated demagnetizing factor (Nz) for 3 series of samples.

In Fig.4, Hc∥ increases with increasing local N. This means that any increase in Hd along the easy axis will result in an increase of Hc∥ i.e. an increase of Hc∥/Hc⊥. The angular dependence of the orientation OR with different Nz are plotted in Fig. 5.

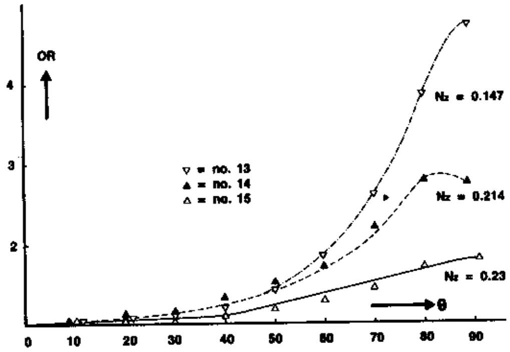

Fig.5. The angular dependance of the orientation ratio (OR) for 3 samples with different Nz.

Obviously smaller Nz will be advantageous for the improvement of the OR, i.e. it is favourable for producing superior perpendicular anisotropy. It has been shown [10] that Hc⊥ direction increases with increasing particle length until it reaches a constant value. As already known [11], the decrease in the OR⊥ and the increase in the Hc∥/Hc⊥ will definitely lead to an increase of the in-plane component of the magnetization. This suggests that it originates from the magnetostatic interaction between the basic units for perpendicular anisotropy. The initial slope of one is caused by the macroscopic Hd=Ms. For this reason, Alumite, can be seen as a continuous film having mean magnetization. Thus, the magnetic behaviour is subject to both the local Hd of the single-domain cylinder and the macroscopic Hd of the film, which are attributed to the inevitable outcome of the interaction between the single-domain cylinders [10]. It was found for CoCr and Ba ferrite media [12] that the Cos-type rotation [11] plays a leading role in the reversal. The cos mode [13] was used as a mathematical explanation to describe the special magnetic behaviour. A weak point is the unknown physical meaning. In addition, the reversal along the easy axis for Alumite belongs to curling, but this is not so for a deviating applied field. The greater the deviation, the larger the discrepancy between the magnetic behaviour and the change pattern due to curling. It can be assumed that the reversal is still the superposition of Cos-type with perpendicular orientation and a curling mode. Hence, Hc/Hc⊥ as function of the angle can be modified as:

$$Hc/Hc_{\perp} = \alpha * \cos\theta + (1 - \alpha)\, f(\theta)\, s$$

Here α represents the proportion of Cos-type with perpendicular orientation as a whole, $f(\theta)$ is the reduced coercivity calculated by curling [3,15] for Alumite with S(d/do) and can be described by:

$$f(\theta) = Hc/0.5Ms = 1.08\,(1-1.08S^{-2}) \,/\, (S^2((1-1.08S^{-2})^2 \sin^2(\theta) * (1-2.16S^{-2}))^{1/2} \qquad (8)$$

The angular dependence Hc is plotted in Fig. 3. It can be seen that for high-coercivity no. 6(S=3) the measured Hc(θ)/Hc⊥ vs. θ curve basically follows the calculated one expected from the curling mode (S=3) in the range of 0-60°, if α=0.83. The major discrepancy is an obvious "elbow" on the calculated curve appearing at 70°, but the measured one decreases monotonically. In an attempt to explain this phenomenon, the following model has been proposed if we consider that the magnetostatic interaction between needles leads to magnetic charge at the side if the applied field deviates from the normal. The presence of the charge will result in mutual attraction between the needles along the film plane. This magnetic attraction, which depends on the amount of charge and the shape of the needles, will change the characteristic of Hd. Therefore, the magnetization reversal is closely related to the Hd. This tends to orientate the Ms along the film plane, because the demagnetizing energy in this direction is minimum. If the angular dependence of the demagnetizing field is assumed to obey the $\sin^2\theta$ law [11] then a modified angular dependence of Hc is:

$$Hc/Hc_{\perp} = \alpha * \cos\theta + (1-\alpha)\sin^2\theta \qquad (9)$$

Results for α = 0.75 are shown in Fig. 3. It is suprising that the calculated curve fits the measured one well, except in the range of 80-90°. Accordingly this is valid for low Hc film no. 16, which has a much higher Hc∥/Hc⊥ value (0.47) than for most of the samples. It is interesting to find that for this sample the calculated curve is almost consistent with the measured one, if α 1=0.67. It appears that the proportion of Hd exerts a great influence on the change characteristic of angular dependence of Hc. A slight increase of the proportion of Hd will cause a rather large increase of Hc∥. For example, it will increase from 0.248 for sample 6 to 0.47 for sample 16, if their proportion of Hd increases from 0.25 to 0.33 respectively. The change tendencies of Hc for high- and low-coercivity do not have anything in common, but it can be successfully expounded by the same mode proposed above. The only difference lies in the different proportions of Cos-type rotation to the reversal caused by Hd and dipole-dipole field.

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