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Magnetic viscosity of recording media (alumite) with perpendicular anisotropy

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Abstract

In this paper, we will present a study on magnetic viscosity of alumite perpendicular media at different thicknesses. Viscosity as a function of applied field (viscosity curve) exhibits a short plateau at low field and then decreases monotonously with increasing field. After correcting for the demagnetizing field, the shape of the intrinsic viscosity curves changes to the well-known shape of viscosity curve of in-plane media, i.e. they have a peak near H_c. The intrinsic viscosity curves obtained from experiments were fitted to an analytical model of Chantrell et al. [1], from which, we found that the effective switching volumes obtained by fitting are much smaller than the column volumes, indicating that the reversal mechanism is incoherent.

Keywords

Perpendicular media, Alumite, Time-dependence effects, Viscosity, Activation volume, Reversal mechanism.

1. Introduction

Alumite media for perpendicular recording were first introduced by IBM in 1969 [2]. Later on, more intensive studies on alumites were carried out by Kawai et al. [3, 4]. Although there is still much doubt about possible applications of this type of media, alumites are often considered as a good model to study switching mechanisms in recording media having perpendicular anisotropy. This is because their morphology is more regular and less complicated than sputtered continuous media.

Alumite media consist of long separate Co (or Ni, Fe, etc.) columns perpendicular to the substrate (see Fig. 1). These columns are realized by depositing a desired magnetic material into micro-pores in an aluminum oxide layer. The aluminum oxide layer is made by anodic oxidation of aluminum substrate surface. This technique allows realizing an aluminum oxide layer with hollow pores perpendicular to the substrate, arranged in a nearly perfect hexagonal pattern. Details about fabrication method, morphology and other properties of the media can be found in [5-7].

In a previous paper [8], we have investigated magnetic viscosity as a function of applied field (viscosity curve) in CoCrTa/Cr in-plane media. The experimental curves were fitted to the analytical model of Chantrell [1], from which we were able to interpret the correlation between the viscosity and other magnetic and structural properties of the media. Based on the fitting results, the nature of the viscosity curve has been proposed. Besides, the reversal mechanisms of the samples were suggested. In this paper, we will present our study on time-dependence effects in alumite perpendicular media of different thicknesses. Similarly to the previous paper, the experimental curves were fitted to the model, taking into account the demagnetization effect.

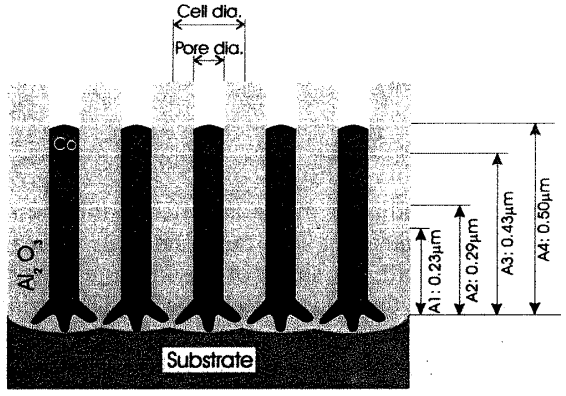

Fig. 1. Diagram of an original alumite hard disk sample. The black parts are the Co-filled columns surrounded by the aluminum oxide (gray parts). The sample was sawn into several 1×1cm pieces and then they were thinned down to four different thicknesses by polishing, indicated by 4 horizontal white lines. The polished samples are named as A1, A2, A3 and A4.

In the first part of this paper, we will give a short introduction to the time-dependence effects in magnetic thin films and the analytical model used in the paper to fit experimental curves. The next parts of the paper will deal with experimental results and fitting results with discussions.

2. Some basics about magnetic viscosity

After a change in the energy barrier, caused by a change in the applied field for instance, the magnetization of a sample performs a relaxation process which can be formulated as a logarithmic behavior [9, 10] : $M = M_0 + S \ln t$; where M_0 is the magnetization of the sample at the beginning of the relaxation curve. The quantity S is the magnetic viscosity and t is the elapsed time since the measurement starts.

Recently, Chantrell et al. [1] proposed an analytical model, allowing to formulate the viscosity S of a magnetic sample. The essential point of the model is the assumption of a critical energy barrier $\Delta E_c = kT \times \ln(tf_0)$, where kT is the thermal energy and f_0 is the frequency of gyromagnetic precession, considered constant ($\approx 10^9$ Hz). It is assumed that: magnetization of all switching units of the sample having the energy barrier $\Delta E < \Delta E_c$ is switched to the opposite direction while magnetization of the switching units having $\Delta E > \Delta E_c$ still remains in the original direction. By this assumption, the calculation of the model can be simplified, resulting in the final formula of viscosity:

$$S = \frac{dM(t)}{d\ln(t)} = -\frac{AkT}{\Delta E_m} f(y_c) \qquad (1)$$

where $A = M(t=0) - M(t=\infty)$; $y_c = \Delta E_c / \Delta E_m$, the reduced critical energy barrier of the switching units. ΔE_m is the median energy barrier; f is the distribution function of the energy barrier. In the calculations, the log-normal distribution is used:

$$f(y) = \frac{1}{\sqrt{2\pi} \times y \times \sigma} \exp\left[-\frac{1}{2} \left(\frac{\ln(y/y_m)}{\sigma} \right)^2 \right] \qquad (2)$$

in which $y = \Delta E / \Delta E_m$, σ is the standard deviation.

The energy barrier is calculated for a Stoner-Wohlfarth particle, which is field-dependent:

$$\Delta E = K V_{switching} (1 - H/H_K)^2 \qquad (3)$$

in which K and H_K are the anisotropy constant and anisotropy field, respectively; $V_{switching}$ is the volume of the switching unit which is in principle the volume of a Stoner-Wohlfarth particle.

In our study, viscosity of alumite samples was measure in perpendicular direction, therefore, correction for the demagnetizing field is needed. Lyberatos and Chantrell [11] have developed theoretically the relationships between the intrinsic and the observed values of χ_{irr}, S and H_f:

$$\chi_{irr}^{i} = \frac{\chi_{irr}}{1 - D\chi} \quad (4)$$

$$S_0 = S\left[\frac{1 - D\partial M_{rev}/\partial H|_{M_{irr}}}{1 - D\chi}\right] \quad (5)$$

$$H_f^i = H_f\left(1 - D\frac{\partial M_{rev}}{\partial H}\Big|_{M_{irr}}\right) \quad (6)$$

where χ^{i}_{irr} and χ are the intrinsic irreversible susceptibility and the intrinsic total susceptibility (which is equal to irreversible + reversible susceptibilities), respectively; D is the demagnetization factor of the sample. S_0 and S are intrinsic and observed viscosities, respectively; $\partial M_{rev}/\partial H|_{Mirr}$ is the reversible susceptibility measured at constant irreversible magnetization and H^i_f is the intrinsic fluctuation field. It should be noted here that the intrinsic parameters (such as intrinsic viscosity, intrinsic fluctuation field, etc.) are parameters that one would observe if the demagnetization effect were eliminated.

Another volume which is often studied is the activation volume, V_{act}. This volume presents the volume of material covered by a single jump of the domain wall between pinning centers in case of materials switching by domain wall motion or the volume that nucleates the magnetization reversal in other cases [12]. The activation volume is defined as [9]:

$$V_{act} = \frac{kT}{\mu_0 H_f M_S}; \quad (7)$$

in which H_f is the fluctuation field [13]:

$$H_f = S/\chi_{irr} \quad (8)$$

where χ_{irr} is the irreversible susceptibility.

In our study, we tried to fit experimental data to the above model. The inputs of the fit are the main magnetic parameters of the sample such as H_c, K, M_s, and the applied field. In the calculation of ΔE [Eq. (3)], $V_{switching}$ is treated as a fitting parameter. This means that by fitting, we try to make the experimental viscosity equivalent to that of an ideal sample having Stoner-Wohlfarth particles of volume $V_{switching}$. The standard deviation σ is treated as the fitting parameter. In the fit, the factor A in Eq. (1) is replaced by F×A. F is a fitting parameter. Factor A, the difference between the initial and the equilibrium magnetization, can be approximated as the difference between M_s and the value M on the hysteresis loop at the applied field of interest. Factor F is introduced because the analytical theory is applicable only to perfectly aligned systems, where all reversal events contribute the same change of magnetization. However, the real materials generally have a distribution of orientation, which affects not only the energy barrier distribution, but also implies that not all reversal events contribute the same change of magnetization [14]. Besides, F is used to absorb all errors coming from the simplifications and assumptions of the model.

3. Experiments

In this study, we used an experimental alumite hard disk made of Co-filled alumite with a thickness of 1μm. To have a systematic series of samples, the disk was sawn into several 1×1cm^2 samples and they were thinned down to different thicknesses by mechanical polishing. There are four samples of thickness ranging from 0.23 to 0.50μm. Names of the samples are given in Fig. 1. The most important parameters of the samples are given in Table 1.

Magnetic properties of the samples were measured using a VSM and a torque magnetometer. To measure magnetic viscosity, the sample is first saturated at -1000 kA/m before a positive measuring field is applied. The magnetization M of the sample is then recorded for 2000 seconds. The viscosity is calculated by fitting a line to the relaxation curve (the curve of M vs. lnt). The non-linear part of the relaxation curve, which appears during the first few minutes of the measurement at some field values, is omitted in the fit. To obtain the fluctuation field and the activation volume, the irreversible susceptibility (χ_{irr}) should be measured and therefore DC demagnetization (DCD) measurements are required. To get correct values of H_f and V_{act}, both S and χ_{irr} (which is the result of DCD curve) should be measured in the same magnetic state. Therefore, in the DCD measurement, before being removed for measuring the remanence, the applied field must remain for an appropriate waiting duration.

Table 1. Important parameters of the alumite samples.

Parameters	Sample A1	Sample A2	Sample A3	Sample A4
Cell diameter (nm)	95.7			
Pore diameter (nm)	40.0			
Packing density	0.16			
Thickness (col. length) (μm)	0.23	0.29	0.43	0.50
Total magnetic volume (m^3)	3.65E-11	4.72E-11	6.85E-11	8.04E-11
Column volume V_{col} (m^3)	2.85E-22	3.69E-22	5.36E-22	6.29E-22
Saturated moment I_S (μAm^2)	8.9	11.5	16.7	19.6
M_S (kA/m)	243.8			
In-plane H_c (kA/m)	27.02	28.2	30.1	34
Perpendicular H_c (KA/m)	98.54	98.80	88.44	81.6
K_1 (J/m)	4.75E+4	4.98E+4	5.16E+4	5.08E+4

4. Experimental results

From torque measurement data, it could be concluded that the samples have perpendicular anisotropy. According to [15], the contribution of the shape anisotropy of the columns is dominant over the crystalline anisotropy of Co. Table 1 shows more measured parameters of the samples.

4.1. Viscosity and remanence measurements

Relaxation curves were measured on the alumite samples in perpendicular direction at different applied fields. Viscosity S normalized on M_s of all samples as a function of applied field is illustrated in Fig. 2.

Generally, viscosity of the investigated samples has a short plateau at low field and when the applied field increases further, it decreases monotonously with the field. Finally all of S values vanish at above 500 to 600kA/m. This general behavior is different from that of in-plane media investigated in the previous paper [8] where we found that viscosity always performs a peak near the remanence coercivity H_{cr} and it vanishes at zero and high

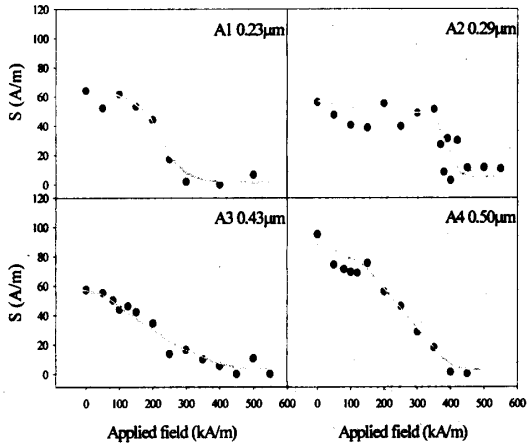

Fig.2. Measured viscosity as a function of applied field. The black dots are experimental points and the gray lines are guides for the eyes.

field. The difference between viscosity curves of perpendicular and in-plane media is certainly attributed to the demagnetizing field perpendicular to the sample surface.

In order to correct for the demagnetizing field of the viscosity measurements and furthermore, to calculate fluctuation field and activation volume, perpendicular DCD measurements were carried out. The intrinsic viscosity versus internal field was obtained by correcting for the demagnetization effect (Fig. 3). We used the measured viscosity versus applied field, the total susceptibility ($\chi_{tot}=dM_{hys}/dH$) and the reversible susceptibility ($\chi_{irr}=dM_{DCD}/dH$) for the correction, according to Eq. (5).

After correction, the shapes of the viscosity curves change totally: the viscosity values increase about 10 times while the field range of the curves is compressed to a smaller range (for instance, from 500 to about 60 kA/m for Sample A1). It can also be seen that after the correction,

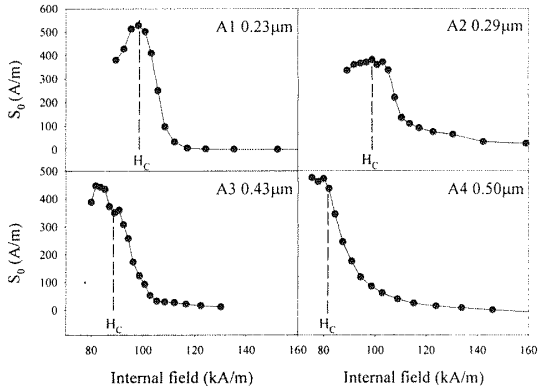

Fig. 3. Intrinsic viscosity versus internal field, obtained by correction for the demagnetization effect of the measured viscosity curves

intrinsic viscosity curves exhibit a peak near H_c, somewhat similar to the in-plane case. We cannot compare the position of the peak to H_{cr} as in the in-plane case, because a correction to get a real H_{cr} is needed. Nevertheless, in general, H_{cr} should be very close to H_c. For Samples A4 whose peak appears at a lower internal field, if more points were measured further at negative applied field, one would observe the downhill part on the left side of the viscosity peak.

Among two components of susceptibility, irreversible component, χ_{irr}, is more significant because the time-dependence effects are only attributed to the change in irreversible component of magnetization. Figure 4.a shows χ_{irr} versus applied field. The maximum value of χ_{irr} seems to decrease with increasing layer thickness. Using Eq.(4), intrinsic irreversible susceptibility ($\chi_{irr\text{-}i}$) is calculated (Fig. 4.b). The quantity $\chi_{irr\text{-}i}$ is the susceptibility that one would observe if there is no

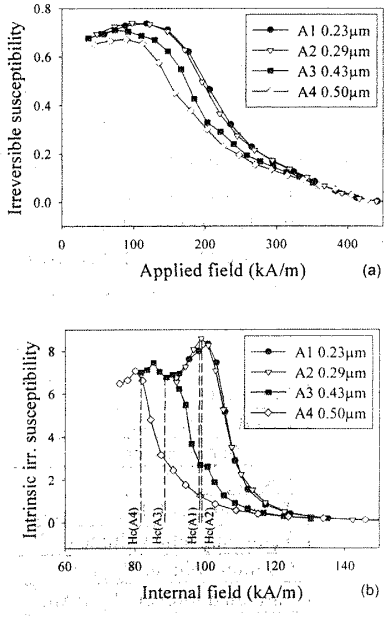

Fig. 4. (a) Irreversible susceptibility (χ_{irr}) calculated directly from the derivative of DCD curves. (b) Intrinsic irreversible susceptibility ($\chi_{irr\text{-}i}$) calculated by Eq.(4). Values of corresponding H_c are also indicated by dashed lines.

demagnetization effect involved. There is a close correlation between intrinsic irreversible susceptibility and intrinsic viscosity curves: they both have a peak near H_c.

4.2. Activation volumes

Activation volumes have been calculated (Fig. 5) using Eq. (7) and (8). In the graphs of Fig. 5, volumes of one column are indicated by the dashed lines. Table 2 shows the relations between the column volumes and the activation volumes at coercivities.

It could be seen at a glance that activation volumes, V_{act}, are generally smaller than the column volumes, V_{col}. This phenomenon agrees with results of other researchers working on alumite media or in general, on particulate media. Studying α-Fe filled alumite films, Li and Metzger [16, 17] found that the activation volumes are an order of magnitude smaller than the experimentally measured average particle (or column) volumes. In another case, calculations of V_{act} of Co-epitaxial γ-Fe_2O_3 particles revealed that the ratio $V_{act}/V_{particle}$ is as small as 0.21 [18].

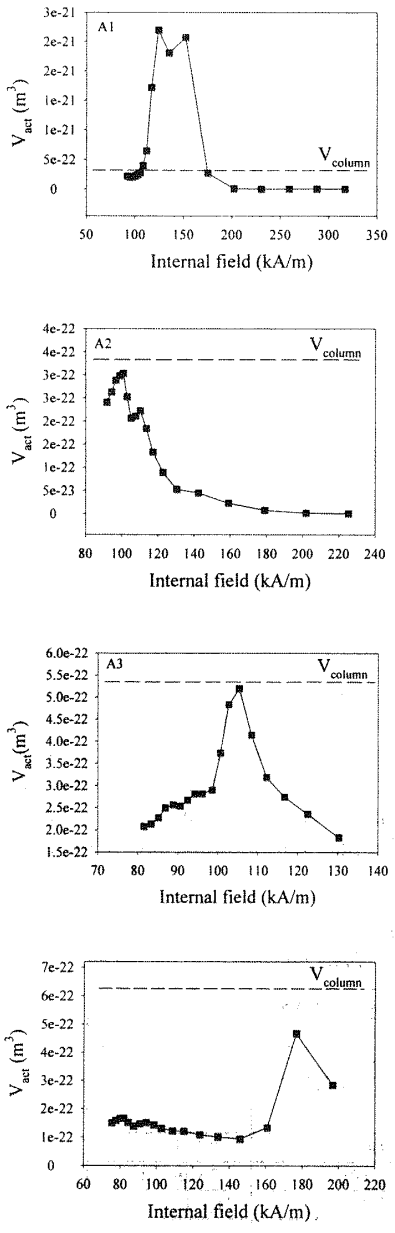

Fig.5. Calculated activation volume versus internal field.

Table 2. Relations between column volumes (V_{col}) and activation volumes at H_c ($V_{act@Hc}$). t is the thickness of the samples (i.e. column length).

Para.	Sample A1	Sample A2	Sample A3	Sample A4
t (μm)	0.23	0.29	0.43	0.50
$V_{act@Hc}$ (m^3)	2.00E-22	2.90E-22	2.56E-22	1.65E-22
V_{col} (m^3)	2.85E-22	3.69E-22	5.36E-22	6.29E-22
$V_{act@Hc}/V_{col}$	0.702	0.786	0.478	0.262

Another remark from Fig. 5 is that the curves of V_{act} versus H_i of all samples exhibit a peak. There seems to be no correlation between the position of this peak and coercivities as observed earlier in the in-plane media [8]. The variation of V_{act} with field cannot be easily interpreted [18], especially in the case of perpendicular media where the demagnetizing field has a strong influence.

In a Stoner-Wolhfarth particle where the reversal mechanism is coherent rotation, the activation volume is identical to the particle volume. The small ratios $V_{act}/V_{particle}$ or V_{act}/V_{col} observed above reflect the existence of incoherent rotation in the sample. In this case, thermal activation takes place in tiny volumes (V_{act}) and then propagating throughout the entire particle. By angle dependence of coercivity and hysteresis loss, Huysmans and Lodder [7, 19] have proven that the reversal mechanism of alumite media is curling rotation which belongs to incoherent mode. This conclusion agrees with the small ratio V_{act}/V_{col} found in our study.

Looking into detail in our case, one can see that V_{act} becomes closer to V_{col} with decreasing layer thickness, or in other words, with decreasing V_{col}. This fact is illustrated in Fig. 6, in which it is shown that the ratio $V_{act@Hc}/V_{col}$ is approaching one with decreasing V_{col} (or thickness). It is straightforward that when the ratio V_{act}/V_{col} approaches one, it means the switching

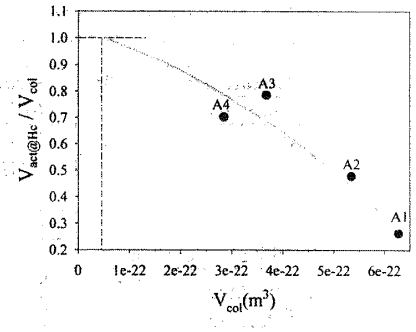

Fig. 6. Ratio between activation volume at H_c and column volume versus column volume.

mechanism is closer the coherent rotation. By another approach, Chantrell [20] also supposed that the reversal mechanism tends toward coherent rotation in smaller particles. We can conclude here that the thinner the alumite film, the closer the switching mechanism to the coherent rotation is. If the trend in Fig. 6 is roughly extrapolated to smaller values of V_{col}, $V_{act@Hc}/V_{col}$ becomes one when the column volume is about 5×10^{-23} m^3 (or thickness is about 0.04μm). At this point, the switching mechanism is supposed to be coherent. Unfortunately, we were not able to make such a thin sample because it is so thin that the polishing technique fails to keep the homogeneity of the thickness. Calculation of critical diameter d_{crit} between coherent and incoherent mode [21] for Co revealed that the volume at which a Co particle changes its reversal mode from incoherent to coherent rotation is about $2.6\times10^{-23}m^3$ (equivalent to $d_{crit} \approx 36.6$nm). This is very close to our value.

4.3. Fitting results and discussion

The intrinsic viscosity, S_0, as a function of internal field of the alumite samples has been fitted to the analytical model of Chantrell [1] (see Section 2). The fit (see Fig. 7) was carried out in the same manner as in the case of in-plane media [8], except that in all calculations, external field is replaced by internal field.

The fit is pretty good, except for some points at the end of the slopes. This misfit is similar to that observed in the fit applied for the in-plane case [8]. The fitted curves reflect quite well the existence of the viscosity peak near coercivity as in the in-plane case.

Some important parameters of the fit are listed in Table 3.

The standard deviation σ [see Eq. (2)] of alumite samples is found to increase almost linearly with increasing film thickness (Fig. 8). This phenomenon could be caused by the change of the column length distribution with thickness. From SEM observations of various samples, we concluded that in many samples, a substantial part of the pores was not fully filled. Consequently, in the unpolished sample (A4), which is an "as-made" alumite sample, there is a certain distribution of the column length, resulting in a relatively high standard deviation. When the "as-made" sample was polished to make thinner samples (A3-A1), the columns were gradually trimmed off. Therefore, in the thinned samples, column length is more uniform, which causes the standard deviation to decrease.

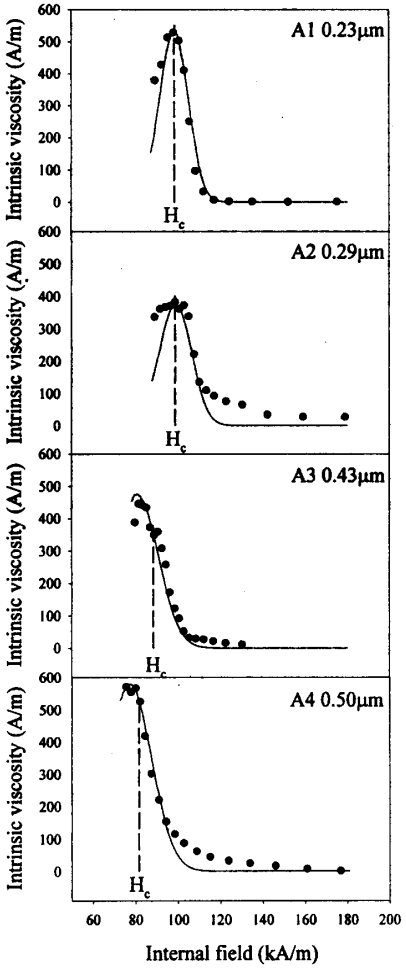

Fig. 7. Fitting results of the alumite samples. Back dots are S_0 calculated from experiments and solid curves are the fitted curves. Positions of H_c are also indicated.

The switching volumes, $V_{switching}$, found from the fit are much smaller than V_{col} and $V_{act@Hc}$. This fact has been found by some other researchers who tried to fit experimental data to a theory using the Stoner-Wolhfarth model to calculate the energy barrier. Lyberatos et al. [22] proposed a mean-field model to solve the demagnetizing field problem in alumite media. They tried to simulate temperature dependence of the viscosity

Table 3. Some important input and out put parameters of the fit. Parameters in italic are inputs, the others are outputs. The switching volume is actually an effective volume found to fit to the model.

Parameters of the fit	Sample A1	Sample A2	Sample A3	Sample A4
Fitting parameter F	*0.010*	*0.0076*	*0.017*	*0.02*
Standard deviation σ	*0.066*	*0.07*	*0.085*	*0.093*
Switching volume, $V_{switching}$ (m^3)	*5.073E-24*	*4.649E-24*	*3.698E-24*	*3.648E-24*
$V_{switching}/V_{col}$	0.0180	0.0130	0.0069	0.0058
Critical volume (m^3)	2.406E-24	2.297E-24	2.219E-24	2.250E-24
Calculated H_c (kA/m)	96.64	96.63	75.9	71.09
$KV_{switching}/kT$	58.3	55.9	46.1	44.8

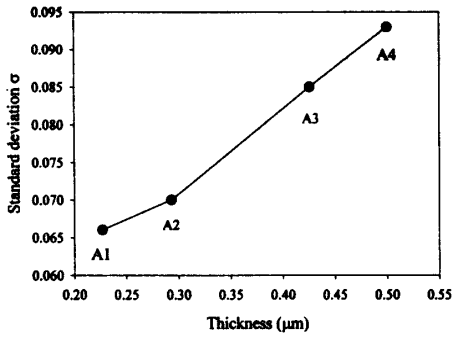

Fig. 8. Standard deviation σ found in the fit.

and found that the effective volume (similar to the switching volume in our case) involved in the switching process is only 5% of the physical volume of the particles, which is probably attributed to the incoherent reversal mechanism. In our case, the switching volume is as small as about 1% of the column volume (see the ratio $V_{switching}/V_{col}$ in Table 3).

Commonly, the switching volume should be close to the activation volume. In our case, they are not equal, because the model is based on coherent rotation whereas the activation volume which is derived from experiments probably switches by incoherent rotation. However, by fitting the theoretical viscosity curves to the experimental ones, we tried to make two phenomena equivalent: the incoherent rotation which happens in reality with the coherent rotation of the effective switching volume as found from the fit. This equivalence is just an assumption, still, it reflects, to a certain extent, the real reversal process.

The switching volume is considered as a small portion of a column which reverse coherently. These tiny volumes are

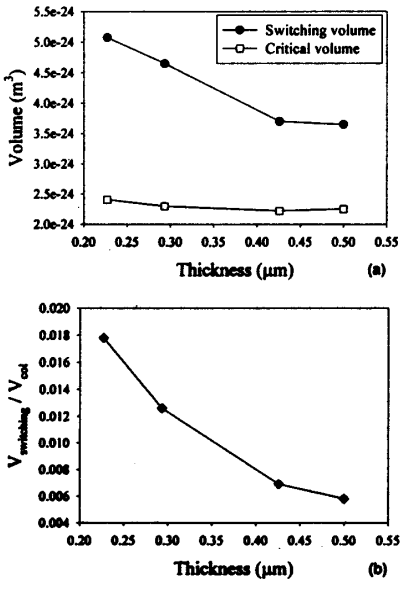

Fig. 9. (a) Switching volumes versus sample thickness, compared to critical volumes, below which the material is superparamagnetic. (b) Ratio between the switching volume $V_{switching}$ and column volume V_{col}.

slightly bigger than the critical volume* (Fig. 9.a). Figure 9.b shows that the ratio between the switching volume and the column volume $V_{switching}/V_{col}$ decreases with increasing film thickness. This behavior is similar to that of $V_{act@Hc}/V_{col}$ (Fig. 6).

It is more reasonable to calculate the ratio KV/kT from the switching volume rather than from the column volume. This ratio is around 50 (Table 3), increasing when the thickness of alumite film is reduced. Relaxation time τ is calculated from this ratio (Fig. 10). By reducing film thickness from 0.5μm down to about half of that, the relaxation time is enormously increased, from about 10^3 to 10^8 years.

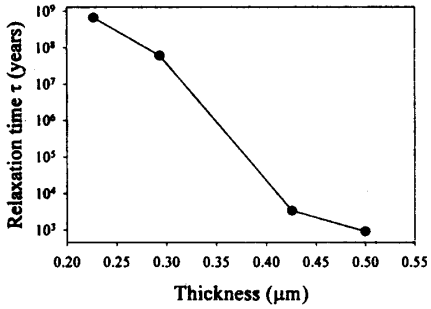

Fig. 10. Relaxation time τ is calculated from $KV_{switching}/kT$. Note that τ is plotted in log scale.

5. Conclusion

We have presented a study on time-dependence effects in alumite perpendicular media at different thicknesses (from 0.23 to 0.50 μm).

Generally, measured at different applied field, magnetic viscosity of the samples exhibits a short plateau at low field and then decreases monotonously with increasing applied field. After correcting for this effect, the shape of the intrinsic viscosity curves changes to the well-known shape of viscosity curve of in-plane media, i.e. they have a peak near perpendicular coercivity H_c. Measurements of activation volume revealed that the ratio of activation volume to column volume tends to increase (from 0.26 to 0.70) with decreasing sample thickness. The intrinsic viscosity curves obtained from experiments were fitted to an analytical model proposed by Chantrell et al. [1]. From the fitting results, we found that the standard deviation σ of the distribution function of energy barrier increases with increasing sample thickness. The effective switching volumes obtained from fitting are much smaller than the column volumes. This indicates that the reversal mechanism is incoherent rather than coherent. The fitting results also indicated that by reducing media thickness from 0.5 down to 0.23 μm, the relaxation time is largely increased.

* Critical volume is the volume below which the material is superparamagnetic.

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