Magnetic viscosity in perpendicular media

A. Lyberatos
Electrical Engineering Laboratories, The University, Dover St., Manchester M13 9PL, United Kingdom

R. W. Chantrell
Physics Department, University of Keele, Keele, Staffordshire, ST5 5BG, United Kingdom

E. R. Sterringa and J. C. Lodder
Faculty of Electrical Engineering, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

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The remanent magnetization of fine particle media of perpendicular anisotropy is known to exhibit a time decay of pseudologarithmic form. The viscous properties are to a large extent determined by the magnetostatic particle interaction and the particle size. A mean-field model of a perfectly aligned ensemble of Stoner–Wohlfarth particles is presented that gives a qualitative description of the hysteretic and time-dependent properties of particulate perpendicular media. The time decay of the remanent magnetization of Alumite media after initial magnetic saturation was measured. The decay was found to be logarithmic within the measuring period, and a coefficient of magnetic viscosity was obtained. Although the reversal mechanism for the particles in Alumite media is known to be incoherent, a good qualitative agreement between the theoretical model and the measurements was found by introducing a reduced effective volume acting as a scaling factor that accounts for the discrepancy in reversal mechanisms.

I. INTRODUCTION

In modern recording media, whether particulate or continuous films, the thermal stability of the magnetization is a subject of increasing interest. The viscous effects become more pronounced by the continuous reduction in magnetic switching "unit" size, in the effort to achieve higher recording densities. The magnetic properties of a recording medium on a short-time scale are different from the long term properties. An example of practical importance is the frequency dependence of the coercivity.[1] The short-time properties will not be discussed here further, but are of interest in the recording process. This paper concentrates on the long-term behavior associated with the storage properties.

The time dependence is physically the result of thermal fluctuations over local energy barriers, which can arise from different sources, including, for example, the shape and magnetocrystalline anisotropy in fine particle systems or the pinning of the magnetization in materials dominated by domain-wall motion. The magnetization decay over a limited number of decades of time is observed[2,3] to be logarithmic,

$$M(t)=M(t_0)-S\ln(t/t_0), \tag{1}$$

where S, the coefficient of viscosity, varies slowly over very long-time intervals. The logarithmic time dependence has been interpreted[4] on the basis of the superposition of a large number of exponential decays with a spread in relaxation times. A distribution in relaxation times arises physically from the dispersion in individual particle properties[4] or the fluctuations in the local interaction field.[5]

The time-dependent properties of perpendicular media are qualitatively different. The characteristic feature is the presence of a strong, internal, time-dependent demagnetizing field of magnitude $N_s M(t)$, where N_s is the sheet demagnetization factor. The demagnetizing field provides a driving force for the thermally activated demagnetization but diminishes in magnitude during the process. The time dependence of the demagnetizing field effectively induces a spread in relaxation times and its presence is a sufficient condition for logarithmic decay.[6]

The viscosity of perpendicular media has not been investigated in detail. The viscous properties are to a large extent determined by the volume of material involved in the thermal activation process. This volume is not very well known, since the presence of the strong demagnetizing field and the incoherent magnetization reversal mechanisms make any correlation to the size of the particles difficult. For Co-Cr continuous thin-film media having perpendicular anisotropy and for certain in-plane particulate media, there is experimental and theoretical evidence[5–7] that the effective volume involved in the activation process is only a fraction of the physical particle volume. In the present study we concentrate on the behavior of Alumite media, in which the curling reversal mode is well established.[8,9] Experimental data are compared with a mean-field model of perpendicular media, based on the assumption of single-domain particles undergoing a coherent magnetization rotation. From this comparison we are able to determine an estimate of the effective activation volume of reversal in Alumite columns. Alumite media were chosen instead of Co-Cr thin films, since Co-Cr media do not have a clear particulate behavior and their morphology is rather complicated.

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II. DESCRIPTION OF THE MEAN-FIELD MODEL

The perpendicular medium is represented by an ensemble of perfectly aligned particles of uniaxial anisotropy and uniform magnetization. The particle size distribution is given by a normalized function $f(V)$.

The magnetostatic coupling between the particles is represented by a mean-field formalism. The total field H is therefore given by the sum of the applied and the mean demagnetizing field,

$$H=H_a-N_sM. \tag{2}$$

The medium is assumed to be thin so that $N_s = 1$. The spatial and temporal fluctuations in the interaction field are here ignored although they might be expected to affect the detailed behavior. The model is similar to that in Ref. 6 although the development here is different and includes the effect of a particle size distribution.

Initially, at time $t = 0$, the medium is assumed to have been saturated by a strong field, and the vectors of magnetization in all particles point in the same direction. Irreversible magnetic transitions will occur between the two fixed directions defined by the axis of anisotropy. The thermal fluctuations of the magnetization vectors about the easy axis are ignored. The thermal relaxation of the magnetization of particles of a given volume V is exponential,

$$I(V,t)=I(V,t_0)+[I_e(V)-I(V,t_0)]\times(1-e^{-(t-t_0)/\tau(V)}), \tag{3}$$

where the magnetization is expressed in reduced form $I = M/M_s$ (M_s is the saturation magnetization of the film). $I(t_0)$, I_e refer to the initial and equilibrium value of the magnetization respectively and τ is the relaxation time. It can be shown from the kinetics of systems with two energy levels that

$$I_e=(\tau_1-\tau_2)/(\tau_1+\tau_2), \tag{4}$$

$$\frac{1}{\tau}=\frac{1}{\tau_1}+\frac{1}{\tau_2}, \tag{5}$$

where τ_1, τ_2 are the relaxation times for the switching along and against the direction of the field H, respectively. The relaxation times for moments rotating coherently are related to the energy barriers E_B by the Arrhenius–Néel law[10]

$$1/\tau_{1,2}=f_0e^{-E_{B_{1,2}}/kT}, \tag{6}$$

$$E_{B_1}=K_pV[1-(H/H_K)]^2, \tag{7}$$

$$E_{B_2}=K_pV[1+(H/H_K)]^2, \tag{8}$$

where f_0 is a frequency factor taken usually as 10^9 Hz, K_p is the anisotropy constant of the particles, $H_{K_p} = 2K_p/\mu_0M_{sb}$ is the anisotropy field of the particles, and M_{sb} is their bulk saturation magnetization. Using Eqs. (6)–(8), it is possible to express Eqs. (4) and (5) in the following form:

$$I_e(V)=\tanh(\mu_0M_{sb}HV/kT) \quad \text{if } |H|<H_K, \tag{9}$$

$$\frac{1}{\tau(V)}=\begin{cases}2f_0e^{-(K_pV/kT)[1+(H/H_K)^2]}\cosh\left(\dfrac{\mu_0M_{sb}HV}{kT}\right), \\ \text{if } |H|<H_K \\ f_0, \quad \text{if } |H|>H_K\end{cases} \tag{10}$$

The total magnetization is calculated as an integral over the volume distribution,

$$I=\int I(V)f(V)dV. \tag{11}$$

In order to calculate the time evolution of the magnetization we approximate the decay by a series of discrete time intervals that can be made arbitrarily small thereby resembling a continuous process. Using Eq. (3), the time dependence can be expressed as an integral over the particle size distribution,

$$I(t_{n+1})=I(t_n)+\int[I_e(V,I)-I(V)]\times(1-e^{-(t_{n+1}-t_n)/\tau(V,I)})f(V)dV. \tag{12}$$

We used Eq. (12) to evaluate numerically the decay of the remanent magnetization using the following procedure. The integral is replaced by a sum over a large number of volume elements δV. The time t is initialized to a value smaller than the relaxation time of any particle. It is then incremented by setting $t_{n+1} = \gamma t_n$. A value $\gamma = 1.01$ is sufficiently small to minimize the discretization error in the algorithm. The magnetization I required to evaluate the mean field is taken as the average value $[I(t_n) + I(t_{n+1})]/2$ to ensure a second-order accuracy. $I(t_{n+1})$ is then evaluated self-consistently from Eqs. (2) and (9)–(12) using the bisection method.[11] A lognormal size distribution was used in the calculations,

$$f(V)=\frac{1}{\sqrt{2\pi}V\sigma}e^{-(1/2)(\ln(V/V_m)/\sigma)^2}, \tag{13}$$

where V_m is the median size and σ is the standard deviation of the distribution. The calculations do not depend strongly on the exact form of the distribution $f(V)$ when it is narrow, for example, in simulations of Alumite particles characterized by a near-identical morphology.

Particles with lower volumes tend to relax magnetically more rapidly. In polydispersed ensembles ($\sigma \neq 0$), the magnetization relaxes to a local equilibrium state $I_e(V)$ which is time dependent. In the absence of an external field ($H_a = 0$), this local equilibrium is determined by the demagnetizing field, which is sufficiently strong in recording media so that $I_e(V) = -1$. The relaxation then proceeds with the smaller moments switching to the direction of the demagnetizing field, whereas the larger moments remain "frozen." When the demagnetization becomes complete ($I = 0$), the demagnetizing field vanishes and transitions to the original direction become more probable.

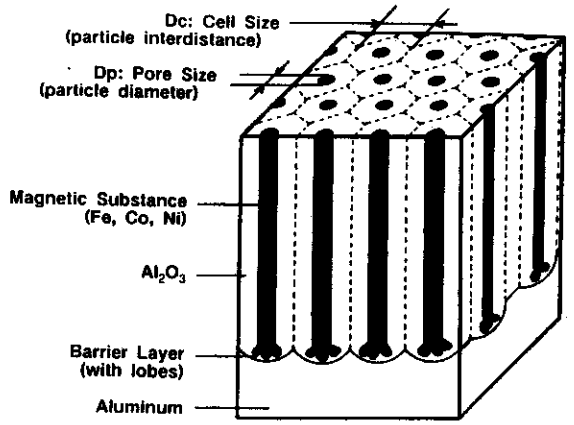

FIG. 1. Schematic representation of Alumite morphology showing a regular structure of perpendicularly aligned magnetic particles in a nonmagnetic matrix.

This eventually leads to thermodynamic (global) equilibrium, where the condition $I_e(V) = 0$ is satisfied. The global equilibrium state of the magnetization, however, is only obtained in the limit $t \to \infty$, so that it is never observed in practice. It can be evaluated self-consistently for any applied field using Eqs. (2), (9), and (11) and letting $I(V) = I_e(V)$.

III. EXPERIMENT

Alumite media are prepared by electrodeposition of a magnetic substance into the micropores in aluminum oxide formed by the anodic oxidation of aluminum.[12] The morphology of Alumite is schematically shown in Fig. 1. It consists of a regular structure of nearly perfect cylindrical magnetic particles with axes aligned perpendicular to the plane of the medium, in a nonmagnetic substrate matrix. Although in principle all ferromagnetic materials can be deposited in the pores, here only the case of iron particles is considered ($M_{Sbulk,Fe} = 1700$ kA/m). The particle dimensions can be varied over a large range, are quite well known by the reproducible fabrication process, and have a narrow distribution. Scanning electron microscopy (SEM) observations have shown that the actual morphology fits this model well. While the particles by their dimensions are single-domain particles, the ensemble of particles in this arrangement acts as a continuous thin film having perpendicular anisotropy. In the case of Fe-filled Alumite the particle anisotropy is uniaxial, with easy axis along the long axis of the particles and arises mainly from the shape anisotropy of the particles.

The hysteresis loops of typical samples measured with a vibrating sample magnetometer (VSM) show the shearing by the demagnetizing field expected for a thin film. The loops of two samples with rather different coercivity and packing fraction are shown in Fig. 2. The slope of the hysteresis loops of perpendicular media is assumed to be very close to one, as is, for example, shown for Co-Cr continuous films.[13] For practical packing fractions this is also assumed for Alumite. It has been shown before[8,9] that the coercivity of Fe-filled Alumite, measured with the applied field perpendicular to the surface, exhibits a particle diameter dependence that matches the (incoherent) curling reversal mode well for a large range of diameters. As shown in Fig. 3, the A- and B-type samples match the curling model well. For samples with a diameter under 30 nm the reversal mode changes, as the coercivity no longer increases in the extent expected by curling.

The near-perfect morphology of the single-domain particles with known reversal mode in combination with the thin-film behavior make Alumite ideal as a model material to investigate the behavior of certain physical processes.

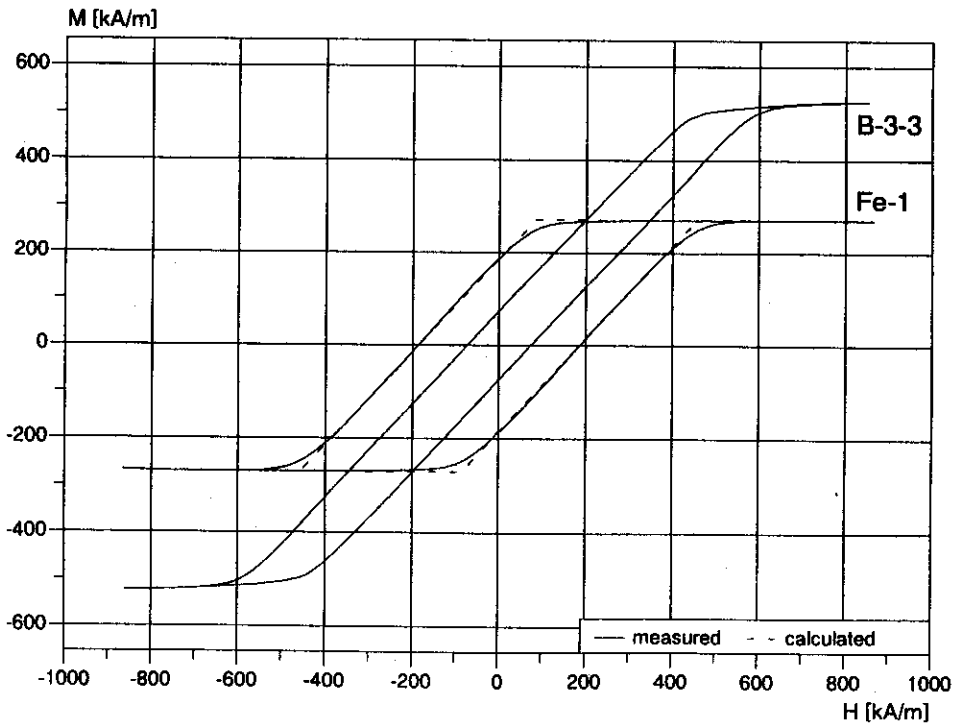

FIG. 2. The perpendicular hysteresis loops of samples Fe-1 and B-3-3. Fe-1 has a high coercivity and a low packing fraction, so also a low M_r. B-3-3 has a moderate coercivity and a high packing fraction and M_r. The slope is nearly 1 for both loops. The dotted curve is the loop evaluated using the theoretical model for sample Fe-1.

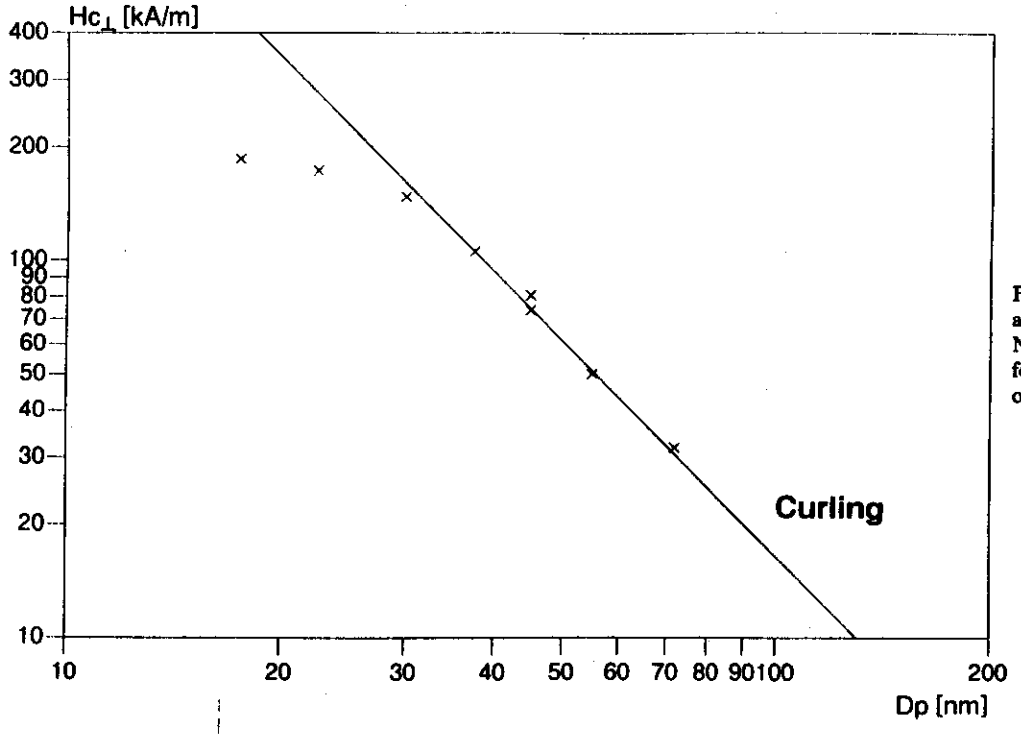

FIG. 3. The perpendicular anisotropy as a function of the particle diameter. Note the match with the curling model for samples with particle diameters over 30 nm.

Materials such as Co-Cr thin films have a rather complex structure. Consequently we believe that Alumite is better suited to investigate the time-dependent behavior of thin particulate media with perpendicular anisotropy than the materials used so far to investigate the effect.

The VSM measurements of the magnetic viscosity of the remanent state at room temperature under zero external field conditions were carried out as follows. In all measurements, a large perpendicular field (>900 kA m^{-1}) was initially applied to the samples to saturate them magnetically. By switching off the field, the magnetization decreases rapidly to a remanent value $M_r(\approx H_{Cl})$. The magnetization was then measured as a function of time, starting from the time at which the field was switched off, over a period between 10 s and 1 day ($\approx 10^5$ s) using increasingly larger time intervals between the measurement points. This period was chosen as our equipment did not allow us to measure the magnetization decay under 10 s with the accuracy needed, and measurement times well over 1 day (on a logarithmic scale) that could reveal a different viscosity for very long times are impractical because of the small but inevitable drift of the equipment. For easy comparison, all our data are normalized to 60 s. By plotting the measured points on a logarithmic time scale, a near-logarithmic time dependence is found as shown in Fig. 4 for a typical sample. The slope of a straight line fitted through the points is equal to the magnetic viscosity S_r (scaled by the remanence M_r).

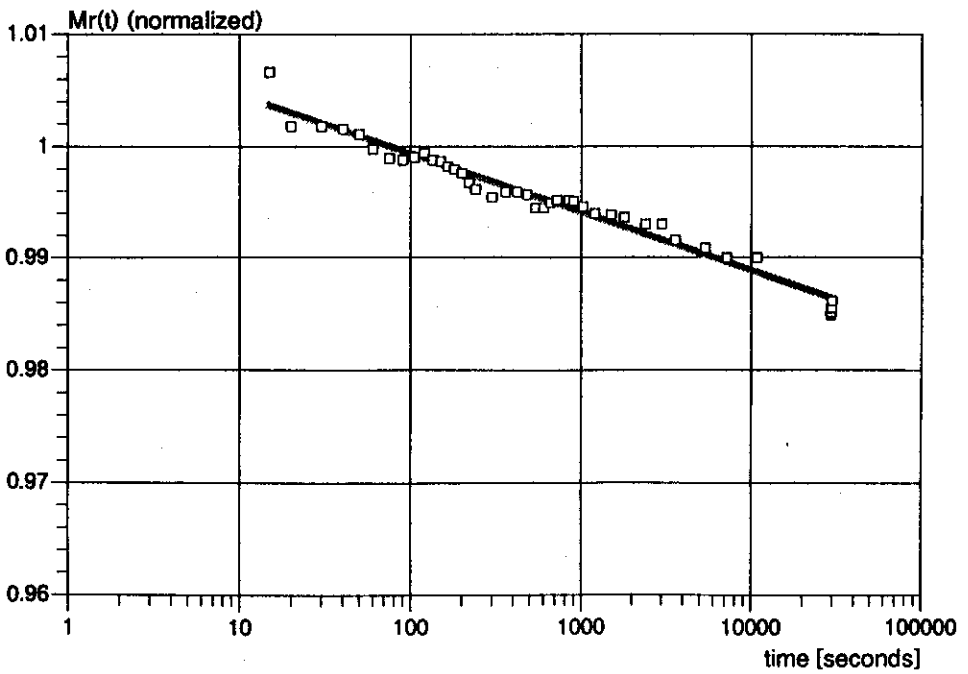

FIG. 4. The normalized decay of the remanence after the initial saturation of the sample A-1-1. The decay is near logarithmic for the time range used in the experiment. The slope of the line is the viscosity S.

TABLE I. Fe-Alumite sample data. $k = 1.38 \times 10^{-23}$ J/K, $T = 295$ K

Sample	D_c (nm)	D_p (nm)	Length (μm)	p	$H_{Cl}(\approx M_r)$ (kA/m)	M_s (kA/m)	$K_{particle}$ (10^5 J/m^3)	kT/KV (10^{-6})	Normalized S_r
Fe-1	40.5	17.5	1	0.17	186	271	8.6	19	0.0041
Fe-2	40.5	22.5	0.9	0.28	173	353	7.9	14	0.0040
B-1-1	74.5	30	1	0.15	147	240	7.4	7.8	0.0030
B-2-1	74.5	37.5	0.75	0.23	105	362	7.5	6.6	0.0028
B-3-3	74.5	45	0.77	0.33	73.4	525	7.5	4.4	0.0025
A-1-1	117	45	1.03	0.13	80.4	258	7.1	3.5	0.0023
A-2-1	117	55	0.88	0.20	49.9	369	7.0	2.8	0.0017
A-3 2	117	72	1.15	0.34	31.8	616	7.3	1.2	0.0011

In Table I the most relevant data on all investigated samples are given. The packing fraction p can be calculated from the particle diameter D_p and separation D_c. For the values given in Table I, a perfect hexagonal particle array was assumed. Although the saturation magnetization M_s of a film should be equal to pM_{sb}, the errors in dimension specifications and the fact that not all micropores are actually filled imply that the usual methods to determine M_s will only give results with large errors. So here we chose to calculate M_s from H_{Cl} and the ratio M_s/M_r (which both can be measured accurately by VSM), assuming the magnetization curve to have a slope equal to one. The ratio kT/K_pV as given in Table I was calculated for each sample using the following data. V was calculated from the particle dimensions as given in the sample specifications; K_p was calculated from torque magnetometry results; and $T = 295$ K, since all measurements were at room temperature.

The coefficient of viscosity S_r appears to be strongly dependent on the particle size, but the relation is not simple as a result of the influence of the perpendicular demagnetizing field. The mean-field model presented will next be used to interpret the experimental data.

IV. RESULTS AND DISCUSSION

The initial objective is to determine the effect of the mean demagnetizing field on the viscosity of the perpendicular media. We therefore restricted our attention to the time dependence at zero external field conditions ($H_a = 0$).

The concept of a critical volume is very useful in interpreting the results of our calculations. The critical volume $V_c(t)$ is defined as the volume of particles with relaxation times $\tau = t$. The relaxation time dependence on particle size is exponential [Eq. (6)], so it is often assumed that particles with $V < V_c$ have already undergone an irreversible transition whereas particles with $V > V_c$ are still magnetically blocked. The transitions against the demagnetizing field can be ignored except near equilibrium, when $I = 0$ and the demagnetizing field vanishes. It is straightforward to show from Eq. (6) that

$$V_c(t) = kT \ln(f_0 t)/K_p(1 - \lambda I)^2, \tag{14}$$

where λ is defined as

$$\lambda = N_s M_s / H_{Kp} \tag{15}$$

and represents the ratio between the demagnetizing field at saturation (N_sM_s) and the field at which a single isolated particle switches irreversibly (H_{Kp} for coherent rotation). The parameter λ is a convevient parameter in fitting the experimental data. The coefficient of viscosity has been shown to be dependent on the critical volume[4]

$$S(t) = \frac{2M_s f[V_c(I,t)]V_c(I,t)}{\ln(f_0 t)}. \tag{16}$$

It should be noted, however, that our numerical model is more rigorous in that it allows for a gradual transition from a magnetically "frozen" to an equilibrium state. The critical volume approach is unsatisfactory when the spread in particle sizes is small ($\sigma \to 0$) and also during the initial stage of the demagnetization process, since the distribution in relaxation times is then narrow. Comparison of the two approaches has shown that the relaxation in our model is more rapid.

The results of our computations of the time dependence of the magnetization are shown in Fig. 5 as a function of interaction strength. The standard deviation of the particle lognormal size distribution is $\sigma = 0.2$. The slope of the curves gives the coefficient of viscosity in reduced form $\bar{S} = d(M/M_s)/d[\ln(t)]$. In the case of a noninteracting ensemble ($\lambda = 0$), a point of inflexion is observed where $\bar{S}$

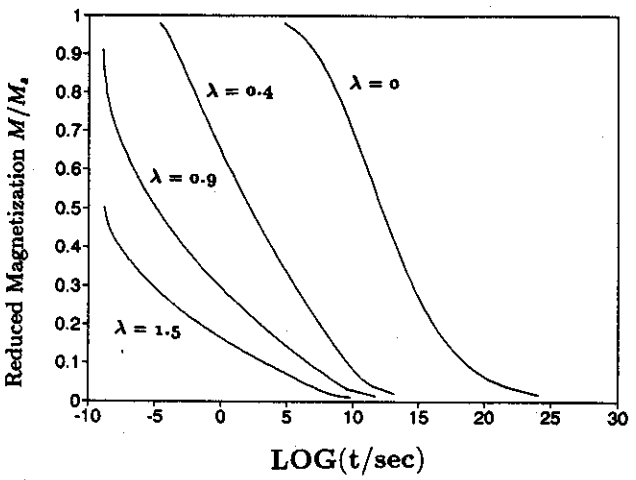

FIG. 5. The magnetization decay in theoretical particulate perpendicular media. The decay curves were evaluated for a noninteracting ($\lambda = 0$) and interacting ($\lambda = 0.4, 0.9$) ensembles of particles.

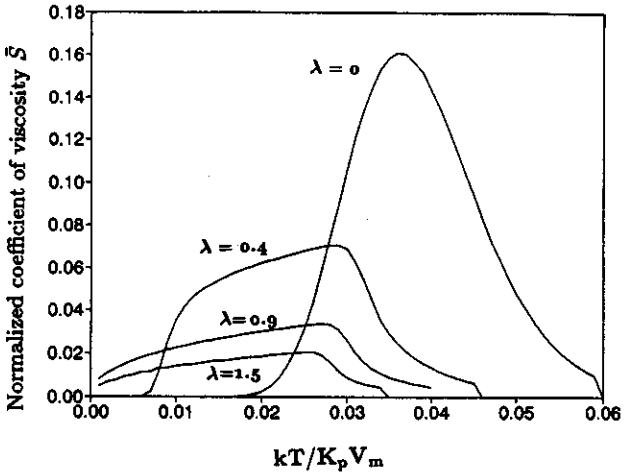

FIG. 6. The coefficient of viscosity $\bar{S}$ dependence on the ratio kT/K_pV_m. Interaction effects are shown by the increase in the demagnetization coefficient λ.

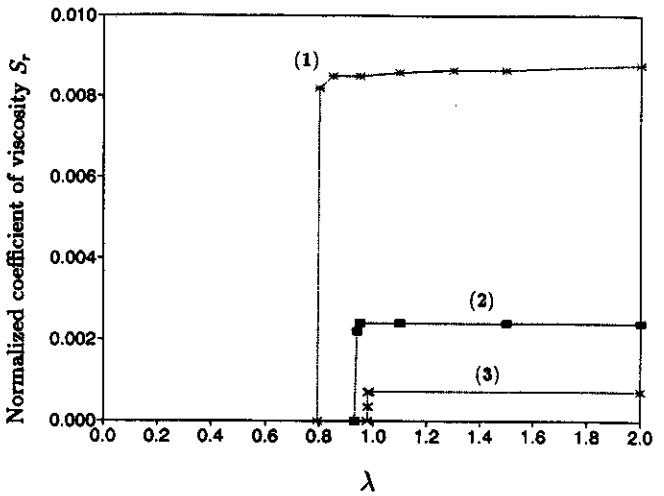

FIG. 7. The coefficient of viscosity S_r as a function of the effective interaction strength λ. Curves (1), (2), and (3) are associated with values for the ratio kT/K_pV_m (10^{-3}, 10^{-4}, and 10^{-5}, respectively).

is a maximum. In the critical volume formalism this maximum is associated with a well-defined volume V_0 which is entirely determined by the volume distribution function $f(V)$ according to Eq. (16). With increasing interaction field strength ($\lambda = 0.4$, 0.9, 1.5), the point of inflexion vanishes and $\bar{S}$ decreases monotonically with time. The decay observed experimentally in samples of Co-Cr (Ref. 2) exhibits the form of the curve with $\lambda = 0.9$, 1.5. The gradual reduction of the rate of demagnetization results from the time dependence of the mean field. Initially, the decay is rapid since the demagnetizing field is at full strength. In the case $\lambda > 1$, the energy barriers for reversal vanish and the decay is initially spontaneous. Subsequently, the demagnetizing field diminishes in strength and the viscosity is gradually reduced.

The coefficient of viscosity $\bar{S}(t = 100\ \text{s})$ was also calculated as a function of the ratio kT/K_pV_m. The results are shown in Fig. 6. With increasing temperature (or decreasing particle size), a larger fraction of moments becomes susceptible to irreversible switching. The peak $\bar{S}_{\max}$ occurs when $V_c(T) = V_0$ as defined above. The presence of the demagnetizing field has a twofold effect. First, the maximum viscosity $\bar{S}_{\max}$ is shifted to lower values for kT/K_pV_m. The shift results from the increase of the critical volumes by the mean field according to Eq. (14). Clearly, the critical volume V_0 will be reached at a lower temperature. The second effect is the broadening of the peaks. The broadening is a direct consequence of the spread in the critical volume distribution $V_c(T)$ induced by the time dependence of the mean field. In the case of strong interactions ($\lambda = 0.9$, 1.5), a finite viscosity is observed even at very low temperatures and the shape of the curve is in good qualitative agreement with measurements on Co-Cr thin films.[2] A broad peak $S_{\max}$ has already been observed experimentally in Co-Cr films.[2] In a previous Monte Carlo study,[5] a maximum viscosity was not observed before complete demagnetization. Clearly, in that case the fluctuations in the local field resulted in a peak that was too broad to be observed. In this respect, our mean-field model may represent a better description of the time dependence in perpendicular media, although the physical reason is not clear.

These initial calculations summarized in Figs. 5 and 6 suggest that the demagnetizing field must be calculated correctly, before a meaningful comparison to experimental data can be attempted. It is shown, later, that under certain conditions, including an appropriate normalization of S and realistic (small) values for the ratio kT/K_pV_m in Alumite, the coefficient of viscosity at the remanent state becomes independent of the magnitude of the demagnetizing field.

It is possible to evaluate the effective strength of demagnetization λ by comparison of theoretical hysteresis loops with those measured on the Alumite media. The hysteresis loops were calculated as follows. An external field H_a was applied, sufficiently strong to saturate the medium, and was allowed to decrease at a constant rate $R = dH_a/dt$. After each time interval δt, the magnetization of the ensemble is evaluated from Eq. (12). If the magnetic reversal of particles takes place by an incoherent reversal mode, the external field that has to be applied for irreversible switching of the particle is much lower than the value H_{Kp} expected by the coherent rotation mode. As the coercivity of the Alumite film corresponds to the coercivity (and nucleation field) of the mean particle in this film, H_{Kp} in Eq. (15) must be replaced by H_{Cl} to determine λ. This substitution is necessary to relate the model based on coherent rotation with the incoherent rotations found in practical particulate media. While for coherent rotation it can be shown that $\lambda = 2p$, the correct value to be used in the numerical calculations of time dependence of particulate perpendicular media is in general,

$$\lambda = \frac{N_s M_s}{H_{Kp}} \approx \frac{N_s M_s}{H_{Cl}} \approx \frac{M_s}{M_r}, \tag{17}$$

λ is simply the inverse of the remanence ratio. For an Alumite sample the value of λ can be calculated from the measured data (Table I). The hysteresis loop calculated

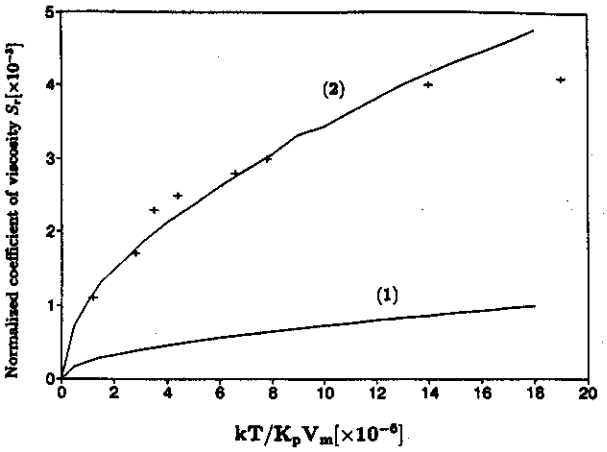

FIG. 8. The coefficient of viscosity S_r in Alumite as a function of the ratio kT/K_pV_m. The experimental data on Alumite are denoted by crosses. The theory predicts curve (1) with an effective volume $V_{\text{eff}} = V_m$ and curve (2) with $V_{\text{eff}} = V_m/20$.

for sample Fe-1 (for which $\lambda = 1.457$) is shown by the dotted curve in Fig. 2, in which the measured loop was already given. The theoretical loop displays the correct shearing with a slope determined by the demagnetization coefficient $N_s = 1$. The hysteresis loops were insensitive to small variations in the spread σ of the particle size distribution.

Any effect that the mean demagnetizing field has on the viscosity of the Alumite media depends on its value relative to the coercivity of the particles [Eqs. (7) and (8)]. The effective reduced value of the demagnetizing field close to the nearly stable remanent state is $N_sM_r/H_{C1} \approx 1$, independent of the packing density, as a result of the assumptions made in the model. Consider the coefficient of viscosity scaled by the remanence $S_r = d(M/M_r)/d[\ln(t)]$. For a fixed value of the ratio kT/K_pV_m, it is expected that S_r is independent of the packing fraction as a consequence of the invariance of the interaction field. The results of our calculations are shown in Fig. 7 where S_r is plotted as a function of λ for different values of the ratio kT/K_pV_m. If λ is too small, no irreversible magnetization changes occur at the remanent state so that $S_r = 0$. The slope in the hysteresis loop then becomes finite only on the application of a reverse field. The hysteresis loops of Alumite media are characterized by $M_r/M_s < 1, \lambda > 1$. For these media, the calculated viscosity S_r appears to be independent of the packing density (Fig. 7), in agreement with our measurements (Table I) and with the above prediction.

The experimental data on the viscosity S_r of the Alumite media are illustrated in Fig. 8 as a function of kT/K_pV_m. Two curves evaluated using the model are also shown. A small value $\sigma = 0.1$ was chosen in our calculations, since the Fe particles in Alumite are of a relatively uniform size. Small variations in σ did not have a pronounced effect on the dependence of S_r on the ratio kT/K_pV_m. We assumed a particle length 1 μm, $K_p = 7.5 \times 10^5$ J m^{-3}, $T = 295$ K, and $M_{sb} = 1.7 \times 10^6$ A m^{-1}. These values represent averages over the measured data in Table I. In the range where the curling model applies, for iron-filled Alumite there is a notable contribution by the shape anisotropy to the nucleation field that is assumed to correspond in value to the coercivity

$$H_{C1} = -(27.2A/\mu_0 M_{sb})(1/D_p^2). \tag{18}$$

The exchange constant was calculated from the slope of the fitted curve through the measured points in which H_{C1} is plotted as a function of $1/D_p^2$. For the available (A and B type) Alumite samples it was found that $A = 1.17 \times 10^{-11}$ J m^{-1} in the case of curling. The numerical results are independent of the value for λ chosen, provided that $\lambda > 1$. The viscosity S_r evaluated using the model (shown in curve 1) is clearly too low. Good agreement with the experimental data is obtained, only on the assumption (curve 2) that the effective volume involved in the switching process is 5% of the physical volume of the particles. A similar effect has been observed by de Witte *et al.*,[7] who also showed that the "activation volume" (equivalent to the fraction of the particle volume involved in magnetization reversal) is in many cases dependent on the applied magnetic field. However, their experimental technique involved the measurement of the irreversible susceptibility, which is currently very difficult in perpendicular media due to the effects of the demagnetizing field. The variation of the activation volume with applied field is an interesting study of the reversal mechanism. The small effective volume found for matching the experimental data with the calculated S_r is attributed to the incoherent reversal mechanism. A more detailed theoretical and experimental investigation of this aspect is planned. The 5% curve fits the experimental data well but there is a significant deviation for sample Fe-1. The curling reversal model does not apply for samples with D_p under 30 nm, hence we might expect the effective volume to be different.

It is interesting to consider an alternative possibility. The incoherent reversal mechanism can be represented by an effective value of K derived from the value of H_{C1}. However, it should perhaps be noted that an effective anisotropy constant is already introduced into the energy barrier expression by replacing H_K with H_{C1} in order to achieve the correct limiting value for the coercivity. Use of a value $K_{\text{eff}} = I_sH_{C1}/2$ leads to effective volumes that become larger (as a fraction of the particle volume) as the coercivity decreases (corresponding to a larger particle volume and a greater degree of incoherent rotation). Consequently the use of the effective volume defined previously would seem to be reasonable.

V. CONCLUSION

A mean-field model of the self-demagnetization in thin particulate media of perpendicular anisotropy has been developed. The magnetization reversal is assumed to occur by coherent reversal over an energy barrier determined by uniaxial anisotropy and the demagnetizing field. The demagnetizing field leads to a monotonic reduction of the coefficient of viscosity S with time and also to a broadening

of the maximum in the temperature dependence $S(T)$, in agreement with experimental observations on Co-Cr thin films. Realistic hysteresis loops were generated that exhibit the pronounced shearing in perpendicular media.

The mean-field model was tested by comparison with experimental data on Alumite media. Good agreement was obtained for the hysteretic behavior and also for the time-dependent behavior on the assumption that the effective volume involved in the thermal activation process is 5% of the physical particle volume. The reduced effective volume is attributed to the incoherent magnetization reversal that generally applies for practical particulate media, e.g., also for Alumite, whereas the model presented in this paper is based on coherent rotation. The model can in principle be employed to investigate the relationship between the static and dynamic properties of perpendicular media, for example the fluctuation field and the activation volume.[7] Clearly, however, a more realistic micromagnetic model of the nonuniform magnetization reversal is required for a better description of the time-dependent properties of Alumite media.

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