MAGNETIC AFTEREFFECTS OF PARTICLES FOR HIGH-DENSITY MAGNETIC RECORDING MEDIA

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Thermal fluctuation aftereffect constant S_v of particles for high-density magnetic recording media, whose mean volume V and coercive force H_c differed, were measured at the practical temperature range from 196 to 413 K. As for longitudinal magnetic recording particles, this experiment showed that the relationship of $H_c \sim v^{-0.67}$ can be obtained among the activation volume v calculated from S_v , H_c , and mean volume V of magnetic particles. V/v is large, 4 to 50, and there is possibility that magnetization reversal caused by domain wall displacement will occur inside particles. On the other hand, unlike longitudinal magnetic recording particles, the relationship with perpendicular magnetic recording particles is $H_c \sim v^{-1.9}$ and V/v is small, 1.4 to 2.3, surmised to have a mechanism of magnetization similar to that of single domain particles.

INTRODUCTION

Recently, parallel with the demand for high-density magnetic recording, the mean volume V of magnetic particles used for magnetic recording media has further been reduced. In the future, in order to increase the density of magnetic recording further, it is important to determine the limit of V of magnetic particles. Comparative studies of the decay of magnetization to the logarithmic time $\Delta M / \ln t$, magnetic aftereffect constant S_v and activation volume v [1] were made from the standpoint of magnetic aftereffect regarding longitudinal magnetic recording acicular particles, which have already been industrialized, and perpendicular magnetic recording Ba-Ferrite particles, which have recently been developed. The magnetic aftereffect studied for this purpose is the magnetic aftereffect by the so-called thermal fluctuations. In the last stage, superparamagnetism is caused by reduction of V of particles. It affects the decay of recording signals (magnetization) [2] and print through.

This paper reports the results of magnetic aftereffects of longitudinal and perpendicular magnetic recording particles.

EXPERIMENTAL PROCEDURE

Table 1 shows the properties of typical magnetic particles used in the experiments. The shapes of the particles are acicular with the exception of Ba-Ferrite (hexagonal platelet shape) and the mean particle size were obtained by a TEM.

The thermal fluctuation aftereffect is known to depend on the magnetic aftereffect constant S_v , the irreversible susceptibility χ_{irr} , and the logarithmic time $\ln t$ [3, 4]. S_v can be expressed by the following equation when the time change in magnetization M by thermal fluctuation aftereffect at time t_1 to t_2 is regarded as ΔM :

$$S_v = \frac{\Delta M}{\chi_{irr} \cdot (\ln t_1 - \ln t_2)} \quad (1)$$

A fully-automatic vibrating sample magnetometer (VSM), which was designed with special consideration to stability, was developed and used in measuring the change of magnetization ΔM , the total differential susceptibility χ_{tot} and reversible susceptibility χ_{rev} , when magnetic field H was kept constant. Table 2

Table 1
Comparison of mean size, V, Ms and Hc at 293 K for magnetic recording particles.

Sample	Mean size (nm)		V ($\times 10^{-16}\text{cm}^3$)	Ms (emu/g)	Hc (Oe)
	(D)	(t)			
Ba-Ferrite (A)	53.6	14.5	0.33	55.0	520
Ba-Ferrite (B)	53.0	14.5	0.32	54.9	840
Ba-Ferrite (C)	54.8	13.7	0.32	56.0	1300
	(a)	(b)			
Metal (D)	392	41	5.17	120.0	1200
Metal (G)	169	14.7	0.29	123.8	1470
Co- γ -Fe ₂ O ₃ (J)	442	63	13.8	77.3	615
γ -Fe ₂ O ₃ (K)	497	66	17.0	72.7	350

Table 2.
Typical performance of VSM used in the experiments

Item	Performance
VSM System	Frequency (80Hz) and amplitude (0.9 mm) are always constant.
M and H stability	$\pm 0.02\%$ /40 min
Sweep rate of H	31 Oe/s constant
Data and analyzing method	Fully automatic by a 16 bit personal computer

shows the typical performance of the VSM used in the experiments.

As shown in Fig. 1 (a), while holding H constant at a certain magnetic field H_A on the major curve, after applying a magnetic field of 19KOe to the sample, and change in magnetization ($M_A - M_B$) are measured for 1000 s from Point A to Point B. Let the amount of magnetization change be denoted ΔM . Immediately thereafter, H is changed by ΔH from H_A to H_D and held for the same time at Point D on the major curve. By reducing H from H_D to H_A by ΔH , and by measuring the difference of magnetization between E and F ($M_F - M_E$), X_{rev} can be obtained.

Fig. 1 (a) Schematic illustration of the relationship between the amount of magnetic aftereffect and magnetic fields. (b) Typical measuring results of magnetic aftereffect of Ba-Ferrite (c) of 413 K.

X_{tot} is obtained by differentiating the major curve by H. The irreversible susceptibility X_{irr} becomes $(X_{tot} - X_{rev})$. The aftereffect constant S_V can be calculated using Eq. (1). Fig. 1 (b) shows an example of measurement of the magnetic aftereffect of Ba-Ferrite (c) at 413 K.

The effective unit of volume for magnetization reversal, namely, the activation volume v , in the magnetization process by domain wall displacement is calculated using S_V , saturation magnetization M_S , and activation energy kT based on the following equation [1, 7].

Fig. 2 Magnetic field dependence of the magnetic aftereffect of longitudinal and perpendicular magnetic recording particles for the logarithmic time at 293 K.

$$kT = v \cdot M_s \cdot S_v \quad (2)$$

EXPERIMENTAL RESULTS AND DISCUSSION

Decay of magnetization

Figs. 2 and 3 show the decay of magnetization $\Delta M/(\ln t_1 - \ln t_2)$ and magnetic field dependence of χ_{irr} to the logarithmic time for longitudinal and perpendicular magnetic recording particles, when the specimen temperature was set constant at 293 K. With all the magnetic particles, the magnetic field that shows the maximum $\Delta M/(\ln t_1 - \ln t_2)$ and χ_{irr} coincide, and the shapes of them are similar. The values of $\Delta M/(\ln t_1 - \ln t_2)$ are larger in the order of $\gamma\text{-Fe}_2\text{O}_3$, $\text{Co-}\gamma\text{-Fe}_2\text{O}_3$, Metal, and Ba-Ferrite. The proportion of the maximum value ΔM_p of the decay of magnetization to M_s from 1 s to 10^5 s (approximately 1.16 days) is small: $\Delta M_p/M_s = 1.4\%$, at $\gamma\text{-Fe}_2\text{O}_3$ (K). However, the value is $\Delta M_p/M_s = 10.3\%$ with Ba-Ferrite (C), which cannot be ignored to be small. Metal (G), whose V is nearly the same as that of Ba-Ferrite, is known to be relatively small in $\Delta M_p/M_s = 3.0\%$. With

Fig. 3 Magnetic field dependence of the irreversible susceptibility χ_{irr} of longitudinal and perpendicular magnetic recording particles at 293 K.

$\text{Co-}\gamma\text{-Fe}_2\text{O}_3$ (J), $\Delta M_p/M_s$ is 3.1%, which is nearly identical to that of Metal (G).

Relationship among coercive force H_c , activation volume v and mean volume V of particles

Fig. 4 shows the magnetic field dependence of the magnetic aftereffect constant S_v obtained based on Figs. 2 and 3 using Eq. (1). With all the magnetic particles, S_v does not depend on the magnetic field near a magnetic field whose χ_{irr} value is more than one half of the maximum value. This shows that S_v tends to increase on the high magnetic field side. However, S_v 's tendency to increase in a low magnetic field differs from that of a Nd-Fe-B sintered magnet [6] and this necessitates further research. It shows that magnetic recording particles that have a large value of $\Delta M/(\ln t_1 - \ln t_2)$, also have a large

Fig. 4 Magnetic field dependence of the magnetic aftereffect constant S_V for longitudinal and perpendicular magnetic recording particles at 293 K.

S_V value.

It is generally known that Barbier's relation [8], which establishes that $\ln S_V$ and $\ln H_C$ vary in proportion in a wide range of H_C , from soft to hard magnetic materials, and $H_C \sim v^{-0.73}$ [1] is established. Fig. 5 shows the relationships between S_V and H_C in a range in which S_V does not depend on the magnetic field, and the relationship between v which is calculated using Eq. (2) and H_C . Barbier's relation establishes that with longitudinal magnetic recording particles, $H_C \sim v^{-0.67}$ can be obtained. However, in contrast to longitudinal magnetic recording particles, $H_C \sim v^{-1.9}$ results with perpendicular magnetic recording particles.

Fig. 6 shows the relationship between V and v . Local magnetization fluctuations by domain wall displacement inside particles are anticipated the larger the difference between V and v is. Not every particle can be considered a complete single domain particle. However, each particle is considered to behave like a single domain particle the smaller the difference is between V and v . The proportion with longitudinal magnetic

Fig. 5 Plots of the magnetic aftereffect constant S_V and activation volume v against the coercive force H_C for magnetic recording particles.

recording particles of $V > 3 \times 10^{-16} \text{ cm}^3$ is large, $V/v = 17 \sim 50$. However, V is anticipated to approach v at $V < 0.3 \times 10^{-16} \text{ cm}^3$. The proportion with perpendicular magnetic recording particles is small, $V/v \approx 1.4$ to 2.3.

The present development trend of longitudinal magnetic recording particles is to make the particle size distribution uniform, to reduce the volume of particles, and to increase the coercive force H_C . The limit volume, whose magnetic particles show superparamagnetism is expected to be approximately 1/500 compared with V of Ba-Ferrite and of Metal (G) used in the experiment. Even though there will still be a margin, V will approach v and S_V will increase if H_C is increased as anticipated in Figs. 5 and 6. Further, $\Delta M / \ln$ will increase. These phenomena are not desirable from the standpoint of magnetic aftereffects.

Temperature dependence of thermal fluctuation aftereffect constant S_V

Fig. 7 shows the temperature dependences of S_V in the range in which S_V is independent of the magnetic field.

Fig. 6 Plot of the activation volume v against the mean volume V of magnetic recording particles.

These temperature dependences can be classified into two trends. One trend is that $\gamma\text{-Fe}_2\text{O}_3$ and Metal, with which the shape magnetic anisotropy is considered to be the main cause for generation of the coercive force, are similar. The other trend is that $\text{Co-}\gamma\text{-Fe}_2\text{O}_3$ and Ba-Ferrite, with which both the shape magnetic anisotropy and magnetocrystalline anisotropy are considered to be the cause for generation of the coercive force, are similar. S_v of $\gamma\text{-Fe}_2\text{O}_3$ and of Metal increase linearly if the temperature increases. The value of S_v of $\gamma\text{-Fe}_2\text{O}_3$ and the temperature dependence of it are particularly small. S_v of $\text{Co-}\gamma\text{-Fe}_2\text{O}_3$ and of Ba-Ferrite becomes minimum near room temperature and tends to increase at temperatures lower than room temperature. S_v of Ba-Ferrite in particular increases rapidly at higher temperatures. This may be attributed to the temperature dependence of the anisotropy constant. The peak value of $\Delta M / (\ln t_1 - \ln t_2)$ of Ba-Ferrite (C) at 413 K is the largest among the magnetic recording particles used in the experiment. $\Delta M_p / M_s$ from 1 to 10^5 s becomes 21.6%, increasing approximately twice compared with that of 293 K. This requires special attention. Under the same conditions, $\Delta M_p / M_s$ of Metal (G) is 4.0% and is relatively small.

Fig. 7 Temperature dependence of the magnetic aftereffect constant S_v for longitudinal and perpendicular magnetic recording particles in the temperature range from 196 to 413 K.

SUMMARY

The major results are summarized as follows:

- 1) The decay of magnetization increases in the order of $\gamma\text{-Fe}_2\text{O}_3$, $\text{Co-}\gamma\text{-Fe}_2\text{O}_3$, Metal and Ba-Ferrite. The decay of magnetization of Ba-Ferrite increases particularly rapidly at a high temperature.
- 2) S_v of all magnetic recording particles, is constant in a wide range regardless of the magnetic field. Magnetic recording particles with large S_v correspondingly have a large decay of magnetization.
- 3) The relation of Barbier and $H_c \sim v^{-0.67}$ are obtained with acicular magnetic particles. V/v is large when $V > 3 \times 10^{-16} \text{ cm}^3$, and magnetization reversal caused by domain wall displacement may occur inside the particles. If $V < 0.3 \times 10^{-16} \text{ cm}^3$, behaviors similar to those of single domain particles are anticipated.
- 4) The relation of $H_c \sim v^{-1.9}$ is ob-

tained with Ba-Ferrite. V/v is close to 1 and behaviors similar to those of single domain particles are conceived.

5) The temperature dependence of S_v is similar between γ - Fe_2O_3 and Metal, and between Co- γ - Fe_2O_3 and Ba-Ferrite. It seems to differ in accordance with the principal cause of generation of H_c .

It is necessary to study magnetic aftereffects of magnetic recording tapes which are coated then orientated before using the findings in applications.

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