Condition for Precise M–H Loop Measurement of Magnetic Films Using an Alternating-Gradient-Force Magnetometer

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The effect of an alternating field on an M–H loop shape was investigated by using an alternating-gradient-force magnetometer on several film samples with different coercivities. It was found that the coercivity became larger with a decrease in the alternating field at the sample edge and reached a constant value at the lower alternating field. The magnitude of the alternating field at the sample edge for obtaining precise M–H loops was discussed quantitatively.

Key words: magnetometer, alternating-gradient-force magnetometer, magnetic thin film, magnetic measurement

1. Introduction

An alternating-gradient-force magnetometer (AGFM) is said to have higher sensitivity than a conventional vibrating sample magnetometer.¹⁾ The high sensitivity seems to be favorable to measure M–H loops of very small magnetic particles²⁾ or ultra-thin magnetic films.³⁾ Since the alternating field from the gradient coils is not zero except the center of symmetry, the greater part of the sample experiences an ac field together with a dc field. Especially for magnetic films, which have a finite plane size, the net ac field reveals pronounced effect on the shape of a M–H loop. The obvious effect is a decrease in the coercivity H_c with an increase in the alternating field gradient.³⁾ Although this variation is assumed as due to the same origin as that of the anhysteretic magnetization curve, the effect of the alternating field gradient on H_c has not been studied yet quantitatively. The purpose of the present report is to make clear quantitatively the condition or the magnitude of the ac field at the sample edge for the precise M–H loop measurement by using the AGFM.

2. Experimental Method

The apparatus used here was manufactured by us previously.⁴⁾ Figure 1 shows the schematic diagram of the apparatus. The sample 6 is attached to the end of the extension rod 4 with an adhesive and is placed in the x – y plane. The bimorph 3 and the extension rod 4 make a cantilever and the signal voltage produced by a deformation of the bimorph is measured by a lock-in amplifier (not shown). The gradient coil 1 is made of a

pair of split coils connected so as to produce oppositely directed field along x . With a current iA , the ac field and the field gradient along x are $h=9.60ix$ Oe and $\partial h/\partial x=9.60i$ Oe/mm, respectively, through $x=\pm 2$ mm around the center. It results that, for the sample of which size is $2a$ along x , the ac field of $9.60ia$ Oe is applied at the sample edge. The sensitivity of the present apparatus is about 1×10^{-6} emu at $\partial h/\partial x=4.80$ Oe/mm and is about 100 times less sensitive than that reported.¹⁾

Table 1 shows the magnetic films and their magnetic properties used in the experiment, where samples a to e are Permalloy thin films, f is an iron film, and other two are magnetic tapes. The coercivity H_c and the squareness ratio M_r/M_m of the soft magnetic films were measured using a 50 Hz M–H loop tracer, where M_r and M_m are the remanent magnetization and the maximum magnetization, respectively. From these original sam-

Fig. 1 Schematic diagram of the apparatus.

Table 1 Magnetic films used in the experiment

Sample	H_c (Oe)	M_r/M_m	$m_s \times 10^3$ (emu)	Ref.
a	0.25	0.775	1.5	○
b	10.8	0.748	1.3	□
c	19.9	0.688	1.0	△
d	7.50	0.870	1.0	●
e	2.60	0.950	2.8	■
f	35.5	0.870	1.7	▲
CrO ₂	680		2.6	×
Co-γ Fe ₂ O ₃	765		2.5	×

Fig. 2 Variations in the coercivity and loop squareness with the field gradient for sample f.

ples, about $2 \times 2 \text{ mm}^2$ pieces were cut and employed for the investigation. The saturation magnetic moments of these small samples are shown in Table 1 by m_s .

3. Experimental Results and Discussion

Figure 2 shows the variations of H_c and M_r/M_m with the RMS field gradient for sample f shown in Table 1. The variation of M_r/M_m with field gradient is very small over the range measured. On the other hand, though H_c is independent of the field gradient at small field gradient ($< 0.4 \text{ Oe/mm}$), it starts to decrease for larger field gradient. The value of the coercivity which is independent of the field gradient (hereafter denoted as H_{c0}) is assumed as the precise coercivity for the sample. Similar measurements were made for all other samples shown in Table 1. The normalized values of the coercivity H_c/H_{c0} are plotted as a function of normalized ac field h_e/H_{c0} in Fig. 3, where h_e is an ac field at the sample edge. Symbols in the figure correspond to those shown in Table 1. For two kinds of magnetic tapes, the same symbol ($\times$) is used. From Fig. 3, it may be reasonable to say that the value of h_e/H_{c0} should be set at smaller value than $0.03 \sim 0.05$ for obtaining the coercivity with an accuracy over 95%.

Since the alternating field acts as an additional fluctuation field to assist magnetic moment reversal, its effect is assumed to be related with the switching field distribution and to be larger in the hard direction than in the easy direction. We measured the M-H loops at the easy ($M_r/M_m = 0.87$) and the hard ($M_r/M_m = 0.49$)

Fig. 3 Variation in the normalized coercivity with a normalized ac field at the sample edge.

directions for sample d. It was found that the decrease in H_c/H_{c0} was slightly larger in the latter than in the former at $h_e/H_{c0} > 0.1$, though the difference in h_e/H_{c0} giving $H_c/H_{c0} = 0.95$ was not clear.

It was also found that the variation in M_r/M_m with h_e/H_{c0} was far smaller than that of H_c .

From our results it is clear that the field gradient around the symmetry center should be set at $\partial h / \partial x \approx h_e / a < (0.03 \sim 0.05) H_{c0} / a$ for obtaining a precise M-H loop. As reported in ref. 1, the sensitivity of the AGFM is proportional to $\partial h / \partial x$. The present result means that, even if the sensitivity is $1 \times 10^{-8} \text{ emu}$ at $\partial h / \partial x = 4 \text{ Oe/mm}$,¹⁾ the minimum magnetic moment m_1 which can be detected grows worse as

$$m_1 > \frac{4 \times 10^{-8}}{(0.03 \sim 0.05) H_{c0} / a} \quad (\text{emu})$$

It may be concluded that the AGFM has not always a higher sensitivity than the VSM, especially for soft magnetic films. It is our view that the AGFM will be rather suitable for hard magnetic materials.

References

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