Rotational Hysteresis in Thin Films

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Rotational losses in films of nickel-iron have been studied over a wide range of frequencies and applied fields by measuring the torque exerted on the films by a rotating magnetic field. Rotational frequencies from 10 cps to 1 me and field intensities from zero to 100 oe were used with films ranging in nickel content from 70% to 90%, and in thickness from 300 A to 12000 A.

For applied fields less than $2K/M$, the observed losses agree well with the theory of rotational hysteresis in materials with uniaxial anisotropy. When combined with standard torque or hysteresis loop data, these losses yield information regarding the uniformity of the true anisotropy within the sample. In fields considerably greater than $2K/M$, the loss per cycle for any given sample is found to be independent of the rotational frequency. According to the analysis of Gilbert and Kelly, in which the high-field losses are proportional to the intrinsic magnetic parameter, these experimental results imply a inverse frequency dependence of the damping parameter. However, correlations between the high-field and the low-field losses, as well as the results of certain auxiliary experiments indicate that the high-field losses are of essentially the same origin as the low-field losses and are not a measure of the intrinsic rotational damping.

INTRODUCTION

ROTATIONAL ferromagnetic damping in thin films of nickel-iron has been studied by means of the rotating-field experiment. In this technique, a thin sheet of ferromagnetic material is subjected to a magnetic field of intensity $H$, which rotates in the plane of the sheet with constant angular velocity $\omega$. Provided that $H$ is considerably larger than both the wall-motion coercive field $H_c$ and the maximum anisotropy field $2K/M$, the motion of the magnetization $M$ is essentially a uniform rotation, with $M$ lagging $H$ by an angle proportional to the sum of the eddy-current and the intrinsic losses. Because of this lag, $H$ exerts a torque upon $M$, which may be measured with a torsion balance.

For metal films about 2000 A thick and rotational frequencies below $10^6$ cps, the eddy-current torque is a negligible part of the observed torque, and the Gilbert-Kelly expression for the time average of the total damping torque per unit volume reduces to

$$T_D = (M_0/\alpha/\gamma)[1+(7/4)(K/\mu H)^2],$$

where $\alpha$ is the damping parameter defined by the equation of motion

$$dM/dt = \gamma M \times [H_n - (\alpha/\gamma)M]dM/dt.]$$

$H_n$ is the total effective field, and $K$ is the uniaxial anisotropy constant.

I. EXPERIMENTAL TECHNIQUES

The rotating field was produced by two solenoids, one within the other, with axes mutually perpendicular, carrying sinusoidally oscillating currents 90° out of phase. The sample, a disk-shaped film 10 to 18 mm in diameter evaporated onto a glass substrate, was contained in a Lucite holder suspended in the field space by a quartz fiber which served as part of a null-deflection torsion balance. The sample holder was shielded from static electrical charges and from the oscillating electrostatic fields within the solenoids, and was protected from air convection currents set up by ohmic losses in the windings.

Certain nonlinear effects caused by the earth's field were compensated for by taking $T_D$ equal to half the net change in torque observed upon reversal of $H$. Spurious torques associated with periodic variations of $H$ were eliminated by insuring, in effect, that the locus of $H$ was not elliptical to the extent of an eccentricity greater than 0.002. The residual possible error from these effects does not exceed ±10% of $T_D$ for any sample.

II. EXPERIMENTAL RESULTS AND INTERPRETATION

The films studied fall rather naturally into two groups. The samples in group A were deposited in vacuo of $10^{-4}$ mm of mercury and had been considerably aged and handled; those in group B were deposited in vacuo of $10^{-2}$ mm and were aged for about two weeks prior to measurement. Chemical, interferometric, and other analyses indicate that the films in group B are more homogeneous in thickness and composition than those in group A. Total magnetizations ($M_T$) and total anisotropy energies ($K$) were measured with a torque magnetometer. Longitudinal and transverse coercivities, $H_c$, and $H_{c|\mu}$, were determined from 60-cycle hysteresis loops.

Several samples were studied at rotational frequencies of 0.010, 0.200, 0.650, 2.15, 6.65, 23.0, 62.0, 200, and 800 kc, with fields from zero to 100 oe. In each case, the loss torque was independent of the frequency, disregarding a random scatter of about 5%. The dependence of the torque upon $H$ was qualitatively the same for all samples.
samples, and is illustrated in Fig. 1; as the field is increased the torque rises steeply to a sharp maximum at some point \((H_P, T_P)\), declines more gradually until \(H = 4H_P\), and then very slowly approaches some limiting value.

As was first pointed out by J. C. Slonczewski,\(^4\) the observed torque peak can be interpreted in terms of rotational switching effects (abrupt reorientations of \(M\)) which must occur when \(K/M \leq H < 2K/M\). Formally, the theory of these effects\(^5\) is equivalent to the theory of rotational hysteresis in fine particle magnets.\(^6\) If \(\alpha\) is the small switching process occurring during a negligible change in \(H\), so that the energy loss per cycle is independent of \(\alpha\) despite the fact that this loss equals the work done against the damping field. The simple theory of the low-field hysteresis which is applicable to homogeneously anisotropic films predicts that \(T_P = 2.60K/\pi\) and that \(H_P = K/M\), and in several respects is in excellent quantitative agreement with the experimental results. However, in general the observed values of \(H_P\), \((T_PV)\), \((KV)\), and \(H\), are most consistently reconciled by assuming that each film has a distribution of the easy-axis orientation which is characterized by considerable spherical randomness plus some degree of uniaxial tendency.

According to Eq. (1), the frequency independence of the torque at high fields implies that \(\alpha\) is inversely proportional to \(\omega\). However, there is evidence that the frequency-independent mechanism responsible for the low-field hysteresis does not vanish for \(H > 2H_P\), as would be predicted by the simple theory, and that the residue of this effect accounts for the high-field losses. As may be seen from Table I, the magnitude of \(T_P/M = (T_PV)/(MV)\), measured at the arbitrarily chosen field \(H = 27\) oe, covers relative ranges of 47.1 and 6.1 in sample groups \(A\) and \(B\), while the corresponding ranges of \(T_P/T_P\) are only 6.1 and 3.1. Another correlation of the high- and low-field effects consists in the fact that \(T_P\) itself is approximately proportional to the cube of \(H_P\).

Direct evidence of the persistence of the "low-field" hysteresis at higher fields was obtained by determining the rotational motion of the magnetization in detail. The sample was enclosed in a small pick-up loop, the fundamental-frequency components in the output voltage corresponding to both \(dM/dt\) and \(dM/dt\) were "backed-out," and the remaining signal was integrated and displayed on an oscilloscope, taking care to introduce no spurious phase shifts. It was found that small irreversible reorientations of the net magnetization occurred abruptly each time the magnetization passed near the hard axis, even though \(H > 2H_P\), and that the losses associated with these reorientations were about equal to the total losses deduced from torque measurements. The origin of this effect has not as yet been established, although several plausible mechanisms have been suggested.

**III. CONCLUSIONS**

It must be concluded that the high-field losses observed in thin films at frequencies below 1 mc are of essentially the same origin as the low-field hysteresis and are not a measure of the intrinsic damping. It is suggested that no experiment performed at such low frequencies can measure \(\alpha\) itself, as distinct from other quantities which may be related to \(\alpha\) only via detailed microscopic mechanisms.

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\(4\) J. C. Slonczewski (private communication).
