Magnetic Anisotropy: Measurements with a Vector Vibrating Sample Magnetometer

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An automated vector vibrating sample magnetometer (VVSM) is described which, in addition to standard hysteresis loop measurements, provides for measurement of the angular dependence of the vector components of the total magnetization. This is of particular utility in investigations of rotational hysteresis and anisotropy in magnetic materials.

The VVSM affords the opportunity to determine anisotropy constants from torque curves. Two sets of sensing coils are employed to measure the components of **M**, from which $M_{\parallel}$ the component parallel to the applied field H, and $M_{\perp}$ the component perpendicular to H are deduced. The torque density exerted on the sample by the applied field is $\tau = \mu_o \mathbf{M} \times \mathbf{H} = -\mu_o M_{\perp} H \hat{\mathbf{k}}$. Data are presented for metal particle and CrO_2 tape media with in-plane anisotropy, and compared with results obtained from a torque magnetometer.

Introduction

Anisotropy is a basic property of magnetic materials[1,2,3]. The magnetization tends to lie in certain preferred directions, and the energy of the ferromagnet includes an anisotropy term $E_a(\theta,\phi)$ where the angular coordinates θ,ϕ define the direction of magnetization. The anisotropy can be intrinsic, related to atomic scale interactions which define easy directions in the crystal (magnetocrystalline anisotropy), or it can be related to the energy of the sample in its own demagnetizing field (shape anisotropy). Magnetic anisotropy is a very important parameter in connection with the characterization of materials utilized in technical applications, particularly magnetic recording media.

The usual method for anisotropy determinations is torque magnetometry, which directly measures the macroscopic torque exerted by an applied field on the magnetization of a sample that is not precisely aligned with the field. Although torque magnetometers enjoy the advantage of high sensitivity and accuracy, they are unsuited to measure other magnetic parameters of interest, e.g., hysteresis loops, remanence curves, etc. Measuring magnetization curves for different orientations of a sample with a normal Vibrating Sample Magnetometer (which measures only $M_{\parallel}$, the parallel component of the magnetization) is an indirect method of studying the anisotropy field. Here we present a vector magnetometer which is capable of measuring the magnetization component perpendicular to the applied field. This component is directly related to the macroscopic torque[4,5,6,7,8], and hence the VVSM provides information that is essentially identical to that provided by a torque magnetometer. In addition, the VVSM offers all the advantages of a normal VSM for measuring magnetization, susceptibility, hysteresis, and remanence[9].

Theory: Anisotropy Constants from Vector Magnetization Data

The anisotropy is obtained in a manner very similar to torque magnetometry, the difference being that instead of measuring torque directly, which is the product $HM_{\perp}$, one obtains the transverse magnetization $M_{\perp}$, and the longitudinal magnetization $M_{\parallel}$ from the components M_x and M_y measured by the vector magnetometer coils. These experimental quantities are related to the torque and anisotropy constants. The formalism is as follows.

The energy of the system is given by the sum of anisotropy and magnetic potential energies,

$$E_T = E_a + E_M$$

In the case of uniaxial symmetry we have,

$$E_a = K_o + K_1\sin^2\theta + K_2\sin^4\theta + \ldots..$$

Where θ is the angle between **M** and the easy direction of magnetization of the sample, and K_o is constant and independent of angle. The potential energy is given by - μ_o $\mathbf{M}\bullet\mathbf{H}$, hence

$$E_p = -\mu_o MH\cos(\psi - \theta)$$

where ψ is the angle between **H** and the easy direction of magnetization (see figure 1). If $K_2 << K_1$

$$E_T = K_o + K_1\sin^2\theta - \mu_o MH\cos(\psi - \theta) \qquad (1)$$

At equilibrium the total energy is minimized, which requires that $dE_T/d\theta = 0$, hence

$$K_1\sin(2\theta) = \mu_o MH\sin(\psi - \theta). \qquad (2)$$

The expression on the left is the torque $\tau = -dE_a/d\theta$ exerted on the magnetization M by the crystal, and the expression on the right is the torque exerted on M by the applied magnetic field. Since $M\sin(\psi - \theta) = M_{\perp}$, the transverse magnetization,

$$K_1\sin(2\theta) = \mu_o M_{\perp}H.$$

When $M_{\perp}$ is a maximum, $\sin(2\theta) = 1$. Hence,

$$K_1 = \mu_o M_{\perp}^{max}H. \qquad (3)$$

Measurement of $M_{\perp}$ as a function of angle ψ therefore allows determination of the anisotropy constant K_1 and torque τ. In the VSM where a resistive electromagnet is employed for field generation, the angle ψ is varied by rotating the sample relative to the magnetic field that is fixed in direction.

An alternative method of extracting a value for K_1 and also a value for K_2 is by fitting the torque curve to a Fourier series. All data in the torque curve is then used to calculate the anisotropy, not just the peak value.

Keeping terms in the energy to order $\sin^4\theta$, the torque is:

$$\tau(\theta) = (K_1+K_2)\sin(2\theta) - 2K_2\sin(4\theta).$$

K_1 and K_2 can both be extracted by least-squares fitting the torque curve to this function. If the magnitude of the Fourier components for 2θ and 4θ are $\tau_{2\theta}$ and $\tau_{4\theta}$ respectively, then $K_2 = -\tau_{4\theta}/2$, $K_1 = \tau_{2\theta} - K_2$. If we only keep terms to order $\sin^2\theta$ in the energy, then $K_1 = \tau_{2\theta}$.

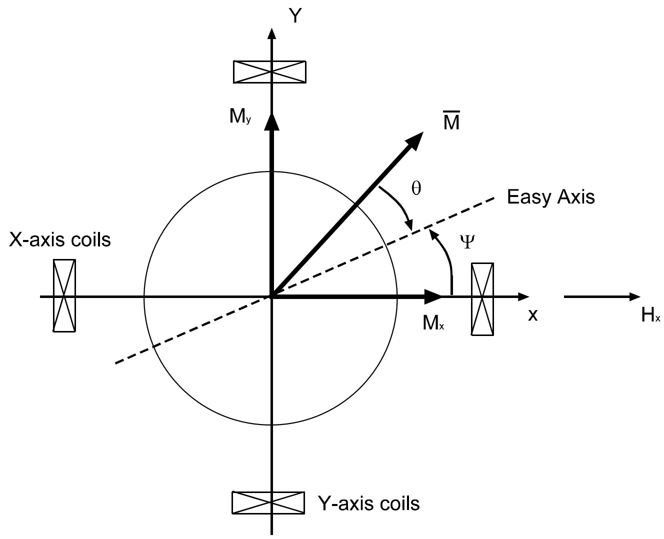

Figure 1: *Schematic top view of the EM vector VSM*

Experimental

A schematic illustration of an electromagnet vector VSM (EM-VVSM) is shown in figure 1 with the different angles defining the directions of magnetization and applied field. One pair of sensing coils are parallel to the applied field and sense the magnetization component longitudinal to the field $M_{II} = M_x$. A second set of coils is mounted at right angles to the applied field and senses the magnetization component transverse to the field $M_{\perp} = M_y$. Hence the VVSM is a *bi*axial VSM and may be used to measure anisotropy in the xy plane. Although not considered in the present discussion, note that a third set of coils to measure M_z may also be utilized. In the case where the magnetization is a true 3-dimensional vector, e.g., perpendicular recording media, obliquely deposited tapes with anisotropy tilted out of the film plane, etc, the *tri*-axial VSM provides for similar anisotropy determinations. Sample rotation, ψ, in the xy-plane is achieved via a computer-controlled motor attached to the VSM head. M_x and M_y are recorded simultaneously as a function of (H_x, ψ) under full computer control in the EM-VVSM.

Results

Data were recorded for a iron metal-particle (MP) tape sample, and a CrO_2 tape sample. Tape areas were 0.317 cm^2, and tape thickness were 0.69 μm and 0.55 μm, respectively. Both M_x and M_y were recorded as a function of magnetic field H_x, and as a function of angle ψ in the EM-VVSM. The CrO_2 tape was also measured using a conventional torque magnetometer.

Figures 2 and 3 illustrate results of the EM-VVSM measurements and show the response of both the x and y axis coils as a function of magnetic field for various angles ψ of the applied field relative to an initial arbitrary orientation ψ_o with respect to the sample's easy axis for the iron-particle and CrO_2 tapes, respectively. The $M_x(H_x)$ response is the classical hysteresis loop normally measured in a single-axis VSM.

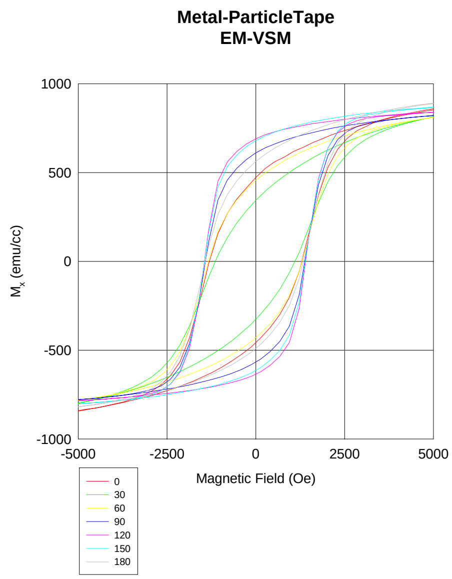

Figure 2a: *$M_x(H_x)$ for a MP tape sample*

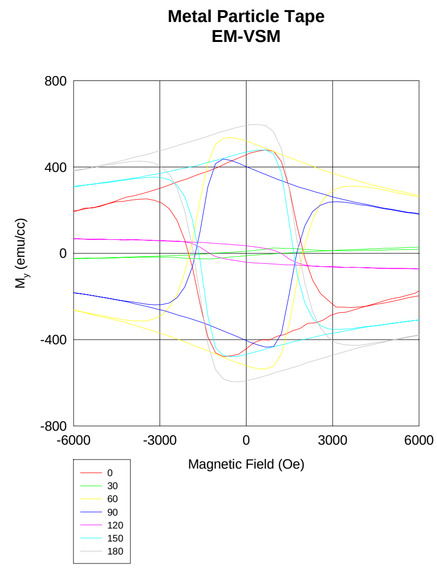

Figure 2b: *$M_y(H_x)$ for a MP tape sample*

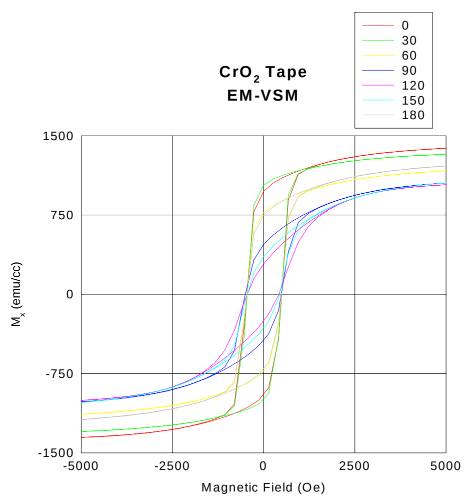

Figure 3a: *$M_x(H_x)$ for a CrO_2 tape sample*

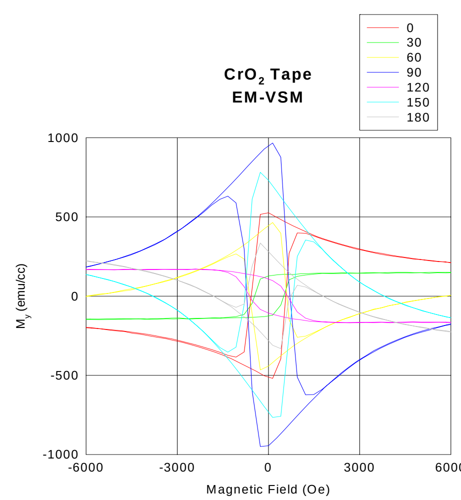

Figure 3b: *$M_y(H_x)$ for a CrO_2 tape sample*

Shown in figure 4 are the x and y moments recorded at a field strength of 5 kOe as a function of angle from 0° to 360° as recorded on the EM-VVSM for an MP tape sample. The m_y value goes to zero when the easy axis of magnetization is aligned with the field direction. At remanence, $m_y = 0$ and m_x = maximum when the easy axis is aligned with the x-axis coils, or alternatively m_y = maximum and $m_x = 0$ when the easy axis is aligned with the y-coils. Thus, automated easy axis determinations are possible employing the vector VSM technique.

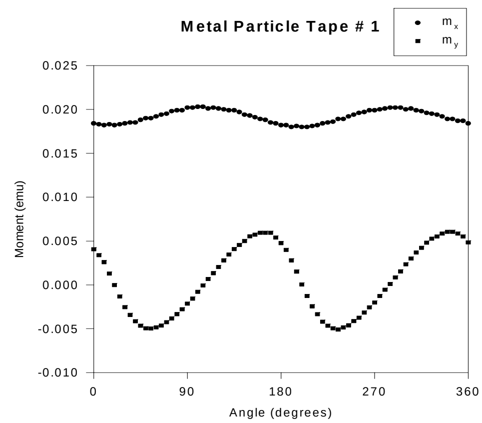

Figure 4: *$m_x(\psi_o+\psi)$ and $m_y(\psi_o+\psi)$ at 5 kOe for a MP tape sample*

Applying equation 3, $K_1 = M_yH = m_yH/V$ at the maximum in m_y. Alternatively, the torque (in dyne-cm) τ = $\mathbf{m} \times \mathbf{H} = m_yH_x\mathbf{k}$, and hence $\tau(\theta)$ may be similarly derived. From the data shown in figure 4, the anisotropy constant for the ME tape is: $K_1 = 1.27 \times 10^6$ ergs cm^{-3}. From similar data recorded for the CrO_2 sample, $K_1 = 0.91 \times 10^6$ ergs cm^{-3}. Figure 5 shows the angular dependence of the torque for both the MP and CrO_2 tapes.

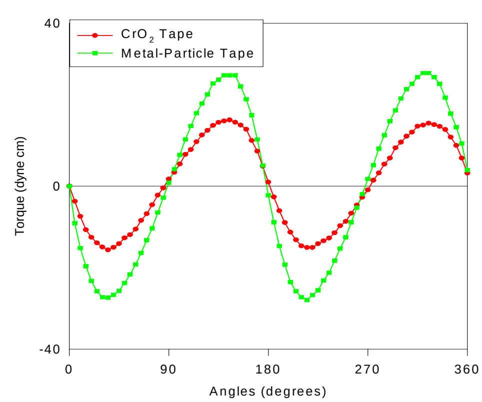

Figure 5: *$\tau(\theta)$ (dyne-cm) for both MP and CrO_2 tapes as determined from the EM-VVSM data*

To check the validity of the anisotropy derived from the EM-VVSM data, the CrO_2 tape sample was also measured in a normal torque magnetometer. Figure 6 shows the resultant torque density (dyne cm^{-2}) curves for the EM and torque magnetometer. The anisotropy constants determined from these data are:

	Torque Magnetometer	**EM-VVSM**
K_1 (ergs cm^{-3})	0.96×10^6	0.91×10^6

These data agree to the few percent level, thus verifying the vector VSM anisotropy determination. In order to obtain reliable values of the anisotropy constants, especially K_2, it is important to use an applied field that is sufficient to saturate the sample. A good K_2 value would require at least double the 5.5 kOe fields used in these measurements.

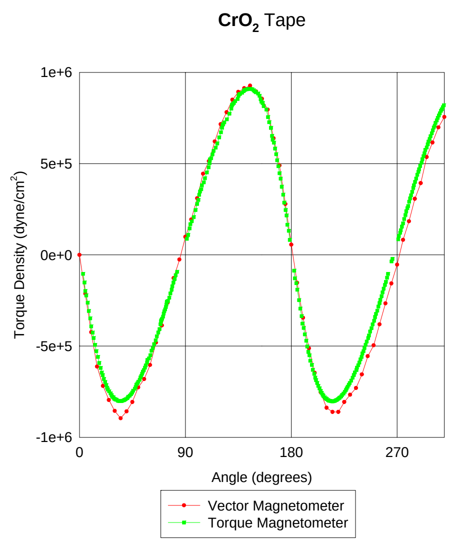

Figure 6: *Torque density vs. angle for CrO_2 tape as determined from the EM vector VSM and a torque magnetometer*

Summary

This paper has discussed the use of a vectorial measurement employing a bi-axial VSM for evaluating the anisotropic magnetic behavior of metal particle and chromium oxide tape samples exhibiting uniaxial in-plane anisotropy due to alignment of the acicular particles. In addition to measuring hysteresis loops, the VVSM may also be used to measure anisotropy and torque curves. It has been shown that the VVSM yields results in good agreement with curves measured using a classical torque magnetometer. Although the discussion here was limited to a 2-dimensional treatment, extension to 3-dimensional anisotropy, for example in obliquely deposited films with anisotropy tilted out of the film plane and perpendicular magnetic media, is possible employing a tri-axial VSM.

References

1. R. F. Pearson, in Experimental Magnetism, Vol. 1 (G. M. Kalvius and R. S. Tebble, editors) Wiley, Chichester 1979, Ch. 3.
2. Ferromagnetism, Richard M. Bozorth, IEEE Press, NY 1951
3. Introduction To Magnetic Materials, B.D. Cullity, Addison-Wesley, MA, 1972
4. Magnetometer For Anisotropy Measurement Using Perpendicular Magnetization, E. Joven, A. Del Moral, and J. I. Arnaudas, Journal Of Mag. And Mag. Mat, 83, pg. 548, 1990
5. Analysis of Perpendicular Recording Media Using Biaxial VSM, K. Ouchi and S. Iwasaki, IEEE Trans. On Mag., 24 (6) pg 3009, 1988
6. Measurement of Magnetization on an Obliquely Deposited Film by Using 3-dimensional Vector VSM, N. Matasubara and F. Sai, IEEE Trans. On Mag., 27 (6), pg. 4748, 1991
7. Fourfold Anisotropy of An Electrodeposited Co/Cu Compositionally Modulated Alloy, R. D. McMichael, U. Atzmony, C. Beauchamp, L. H. Bennett, L. J. Swartzendruber, D. S. Lashmore, and L. T. Romankiu, Journal Of Mag. And Mag. Mat., 113, pg. 149, 1992
8. R. Josephs, D. S. Crompton, and C. S. Kraft, Invited Talk, Intermag Conference, 1987
9. Versatile and Sensitive Vibrating Sample Magnetometer, S. Foner, Rev. Sci. Instr, 30, pg. 548, 1959