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Frequency, magnetic field and size dependence of the magnetic properties of amorphous soft-magnetic fibers

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Abstract

In this paper we show that the magnetic properties in an AC field of fine amorphous magnetic fibers made by the process of melt-extraction is entirely controlled over the frequency range from 5 hz to 20 khz by eddy currents induced in the fiber by the rapidly changing magnetization. Specifically, apparent coercivity of the fibers varies as the square root of both the frequency and the magnitude of the driving field, and linearly with fiber radius, as predicted by a simple model. Eddy currents are also shown to introduce a characteristic asymmetry in the magnetic response.

Keywords: Amorphous fibers; Magnetic properties

1. Introduction

The process of melt-extraction can be used to make fine metal or ceramic fibers of approximate diameter 30 μm or less. The technique typically takes the material in the form of a rod, a few millimeters in diameter, melts the tip by a clean heat source such as RF induction or CW infrared laser, and extracts the fiber from the melt by means of a rapidly rotating sharpened wheel (made from a refractory metal such as molybdenum) moving at tangential speeds between 10 and 50 $\mathrm{m\,s^{-1}}$ [1]. The process produces fibers in long (10 m is typical) but discontinuous lengths. The process can be and has been upscaled to industrial production.[1]

A key advantage to the process is that the method is crucible-free since the melt is supported by the same material in the solid state, and this allows fibers to be extracted from a wide range of metals and oxide ceramics. In addition, the direct quenching is limited to a small line of contact with the sharpened wheel, leading to a fiber surface that is exceptionally clean and free of defects. As a consequence magnetic fibers produced by this method often show spectacular properties. As an example amorphous Co–Fe-based fibers at compositions with near-zero magnetostriction can have DC coercivities of 1 $\mathrm{A\,m^{-1}}$ or less and corresponding permeabilities of 10^6. Such fibers can easily be detected by suitably designed readers in quantities of 1 mg or less, sometimes even at distances of 1 m, and are therefore ideal for use in article tagging applications such as retail anti-theft, or authentication and product-tracking systems [2].

All of these applications involve interrogating the fiber in an AC field and detecting its response, and it is well known that the response in an AC field is often much reduced from that in a DC field.

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[1] MXT Inc. production systems have a capacity of 1 ton yr.

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Generally, magnetic response in an AC field is the result of a combination of physical effects including domain wall motion, skin effects, and, at high frequency, magnetic resonance phenomena. In the case of the high permeability magnetic fibers, however, we have been able to show that the AC magnetic properties, at least in the frequency range of 5 Hz–20 kHz are controlled by a single process: eddy currents induced in the fiber by the rapidly changing magnetization.

2. The model

Consider a fiber subjected to a varying magnetic field H_{app} applied parallel to its long axis. As the applied field passes through zero, the magnetization will attempt to follow it. If the hysteresis loop is square or near square then the rate of change of magnetization will become very large as the magnetization switches sign. This change will induce circulating currents inside the fiber that will oppose the change in magnetization. (This phenomenon is known in transformers as anomalous eddy current loss See for example Ref. [3].) A general solution to the problem is complicated by the fact that the circulating currents at any given radial distance from the center of the fiber will be determined only by the changing magnetization within that radius, which in turn will lead to a non-uniform magnetization across the sample. As a first approximation we ignore this effect. In this case it is simple to show that the magnetic field, H_{ind}, from the induced currents is given by

$$H_{ind} = -(\sigma R^2/4)M'(t),$$

where the negative sign indicates that the field opposes the change in magnetization, $M(t)$. σ is the conductivity, and R is the radius of the fiber.

In addition, a finite length of fiber will experience a demagnetizing field H_d caused by the magnetic poles at the two ends:

$$H_d = -DM/\mu_0,$$

where D is the demagnetizing coefficient. For a fiber whose length L is much greater than its diameter we can use Maxwell's ellipsoid solution for D in the simplified form:

$$D = (\ln 2m - 1)/m^2,$$

where $m = L/2R$. It should be noted here that for extremely soft magnetic material with coercivity less than 10 A m^{-1} and saturation magnetization over 1 T, demagnetization effects could be significant even for an aspect ratio of 10^3.

The field, H, seen by the material is thus given by

$$H = H_{app} + H_{ind} + H_d.$$

We further assume that the magnetization has no intrinsic dependence on frequency, e.g. through motion of domain walls, and is simply given by some function $f(H)$. We can thus write the equation for M as

$$(\sigma R^2/4)M'(t) + (D/\mu_0)M(t) + f^{-1}(M) = H_{app}(t). \quad (1)$$

In order to obtain specific solutions to Eq. (1), we need to take some form for $f(H)$ and $H_{app}(t)$. A simple expression that describes M as measured at very low frequency with sufficient accuracy is

$$M = (2M_s/\pi)\arctan\{(H \pm H_c)/H_w\},$$

where the + sign is taken with H_{app} decreasing and the − sign with H_{app} increasing. We assume a simple sinusoidal form of $H_{app}(t) = H_o \sin(2\pi\nu t)$. Although there is no analytic solution to Eq. (1), it is possible to obtain the following approximate expression for the apparent coercivity, H_c^{app} in the

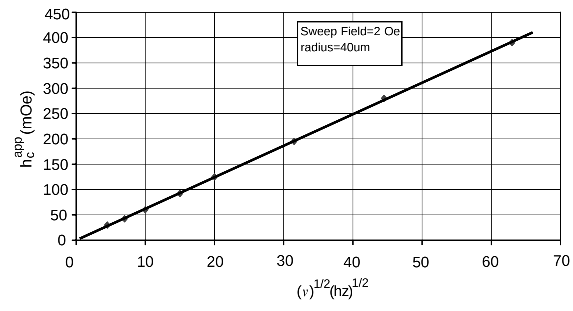

Fig. 1. The measured coercivity against square root of the frequency. 1 Oe is approximately 80 A m^{-1}. The square-root dependence continues at least up to 20 kHz. The line is a least-squares fit through the points.

case where the sample is long enough for the demagnetization term to be neglected:

$$H_c^{app} \approx H_c + \{2\sigma M_s R^2 H_o H_c \nu / H_w\}^{1/2}. \quad (2)$$

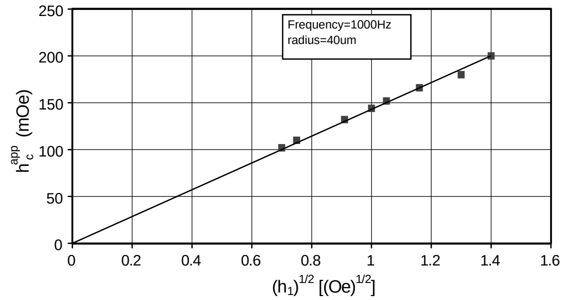

Fig. 2. The apparent coercivity as a function of the amplitude of the sinusoidally varying driving field. The line is a least-squares fit through the points.

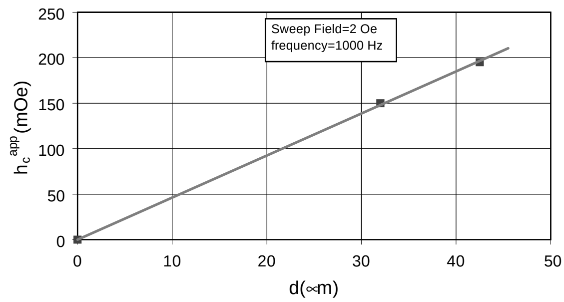

Fig. 3. The apparent coercivity as a function of fiber diameter. The line is a least-squares fit through the points.

3. Results

Eq. (2) shows that H_c^{app} has a characteristic square-root dependence on both frequency and applied field, and a linear dependence on radius. Figs. 1–3 illustrate this dependence in long amorphous fibers of nominal composition $Co_{70}Fe_4Nb_3$-$Si_{10}B_{13}$. These materials have the following properties: $\sigma \approx 7 \times 10^5$ $(\Omega m)^{-1}$; $M_s \approx 0.7$ T (at low field); H_c, $H_w \approx 2$ A m^{-1}. Using these values, and the appropriate values of the other parameters, we find further that the slopes of the various plots are within 10% or better than the values predicted by Eq. (2).

To understand the behavior of shorter fibers, the demagnetization coefficient must be retained in Eq. (1), which must now be solved numerically. Fig. 4 shows a plot of the maximum value of $M'(t)$, normalized per unit mass of the material, as a function of length. The points are experimentally determined values; the continuous line is the theoretical prediction of Eq. (1). The theoretical curve has been scaled to match the behavior of long fibers, but otherwise there are no fvee parameters in the calculation. The fit is excellent.

A final test of the model comes from the detailed shape of the time rate of change of magnetization. As the field sweeps the magnetization through the region of rapid change, $M'(t)$, and hence the indqced field, first increase in magnitude, causing the field in the sample to lag further and further behind the applied field. Once $M'(t)$ passes its

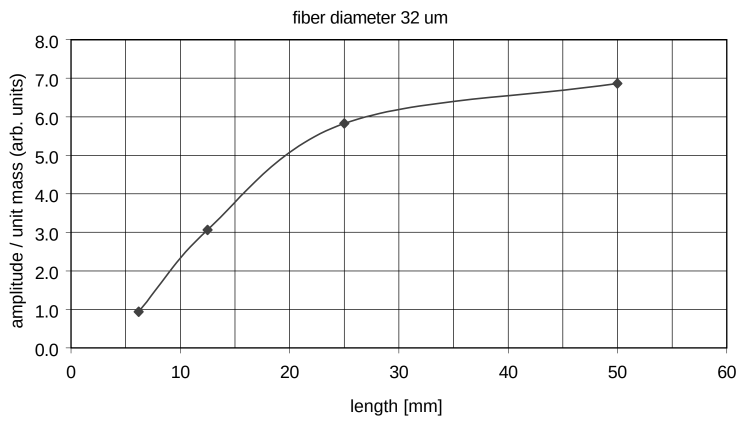

Fig. 4. Effect of length on the amplitude of $M'(t)$. The amplitude of the driving field was 2.5 Oe and its frequency 5 kHz.

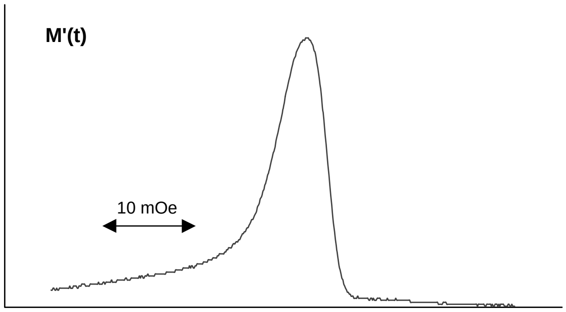

Fig. 5. The measured $M'(t)$, taken directly from an oscilloscope output, through its maximum in a sinusoidal driving field of amplitude 3 Oe and frequency 500 Hz. The scale for $M'(t)$ is arbitrary.

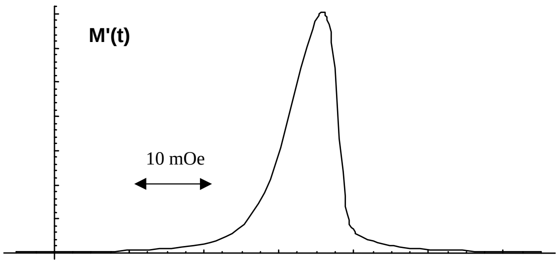

Fig. 6. $M'(t)$ according to Eq. (1) under the same conditions as in Fig. 5 calculated from Eq. (1) with no free parameters. The scale for $M'(t)$ is arbitrary.

maximum, however, the induced field decreases in magnitude, so that the field in the sample rapidly begins to catch up with the applied field. The result is to introduce into the observed $M'(t)$ an asymmetry, with the rise time being slower than the fall. The effect can be quite pronounced as is shown in Fig. 5. Eq. (1) successfully describes this phenomenon, as is shown in Fig. 6. Once again in the calculation there are no free parameters, except for the overall magnitude of $M'(t)$, which is arbitrary.

4. Conclusions

In these high-permeability amorphous magnetic fibers, the AC response over quite a wide range of frequency is controlled solely by eddy currents induced by the changing magnetization. A simple model of this effect describes the behavior with great accuracy, with no free parameters being required, provided that the very low-frequency (i.e. intrinsic) behavior of the magnetization is known. The model may thus be used to predict the behavior of these systems. The same model may be applied to other high-permeability amorphous materials such as melt-spun ribbon, glass-coated melt-spun wire or sputtered film, though the expressions used need to be modified when the material is of non-circular cross section.

Acknowledgements

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