MAGNETOSTRICTION OF TbDy SINGLE CRYSTALS UNDER COMPRESSIVE STRESS

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Abstract - Linear magnetostriction, magnetization, and Young's modulus were measured in a b-axis single crystal rod of $\text{Tb}_{0.5}\text{Dy}_{0.5}$. Huge magnetostrictions reaching 0.5% - 0.6% in fields of 2000 Oe were observed at 77 K. Three magnetization regions can be distinguished: (1) a low field region where the magnetization process is dominated by moment rotation; (2) a region where the magnetization jumps from one easy direction (a-axis) to another closer to the applied field direction; (3) a slow approach to saturation as the applied field pulls the magnetization into the hard b-axis direction. The crossover from one region to another is determined by the applied stress and the demagnetization factor. A simple theory explaining each process is presented.

INTRODUCTION

The basal plane magnetostriction of $\text{Tb}_x\text{Dy}_{1-x}$ alloys approaches 1% at low temperatures^[1] and is 0.6 - 0.7% at temperatures between that of liquid nitrogen and those of the new superconducting materials (77 - 120 K). Alloys of Tb and Dy, in conjunction with superconducting circuitry, are expected to provide superior performance in low temperature, high power actuators and transducers. In this paper we report the first known values of linear basal plane magnetostriction for rare earth crystals under compressive stress. The measurements were made at 77 K on single crystals of $\text{Tb}_{0.5}\text{Dy}_{0.5}$ with applied stresses along the orthohexagonal b-axis ranging from 7 to 25 MPa. This composition is particularly interesting since the ratio of the magnetostriction to the basal plane magnetic anisotropy is minimal at 100 K.^[1]

In addition we have simultaneously measured the magnetic hysteresis loop at several applied stresses. The experimental apparatus also allows us to determine Young's modulus at constant field (Y^H) for applied stresses in the basal plane.

EXPERIMENTAL

The single crystal TbDy rods were grown by a strain anneal technique from 99.9% pure rare earth elements at Ames Laboratory.^[2] The 3.5 cm x 0.6 cm x 0.6 cm rods are oriented so that the hexagonal b-axis is along the length of the rod, while the a- and c-axes are each perpendicular to a side face of the rod. After cleaning, sanding and chemically etching the rod surface, strain gages were affixed to the center of each of the four long faces of the rod. After wrapping the rod and gage assembly in paper, a pickup coil of 85 turns was wound around the center portion of the rod to sense changes in magnetic flux in the rod. The rod was then inserted into a copper field coil (capable of producing almost 2000 Oe) and placed on a iron pedestal with a 2:1 steel moment arm placed on top of the rod. This arm allows the application of large compressive stresses to the rod. In addition the arm is inset with a soft iron plate which, along with a similar plate under the iron pedestal, partially closes the magnetic path. Thus the demagnetizing effect is greatly reduced. The rod and coil assembly was enclosed by a styrofoam box, open on the top, that could be filled with liquid nitrogen, allowing the sample to be cooled to 77 K.

The output of the pickup coil is integrated by a Magnetic Multimeter (integrating op amp), the output of which is digitized by an HP 3457 high speed voltmeter. The strain gage resistances are measured by another HP 3457 voltmeter with a high speed relay multiplexer built in. The voltmeters are controlled by a Compaq 386/20e computer which also analyzes and displays the data. The time to measure one magnetic loop is between 30 - 40 seconds.

MAGNETIZATION DATA

The magnetization data at 77 K are shown in Fig. 1 for applied stresses of (a) 7.4 MPa, (b) 13.2 MPa, (c) 19.0 MPa, and (d) 24.8 MPa. All have very large saturation magnetizations of about 3 T. Note that all the curves may be considered to be composed of three different regions: a straight segment near the origin (region 1), a steeper straight segment at intermediate applied field (region 2), and a slow approach to saturation (region 3). In particular note that, as the applied stress is increased, the region 1 slope decreases, while the region 2 slope remains essentially unchanged.

Fig. 1 Magnetization vs. applied field for TbDy single crystal rods for applied stresses of (a) 7.4 MPa, (b) 13.2 MPa, (c) 19.0 MPa, and (d) 24.8 MPa.

MAGNETOSTRICTION DATA

The magnetostriction curves are presented in Fig. 2 with applied stress as noted in Fig. 1. Note that the strain is of the order of 0.5%. With a lower applied stress (excluding the very lowest, since this amount of stress is apparently not sufficient to completely turn the moment perpendicular to the rod axis, as discussed below) the strain is 5.7×10^{-3} , while at the highest stress it is only slightly less at 5.3×10^{-3} . The general shapes of curves b, c, and d are similar; the applied stress serves mainly to decrease the overall magnitude of the strain by a few percent. The fact that curve d does not close is due to the fact that, at that large stress, the rod started to deform.

Fig. 2 Magnetostriction vs. applied field for TbDy single crystal rods for applied stresses of (a) 7.4 MPa, (b) 13.2 MPa, (c) 19.0 MPa, and (d) 24.8 MPa.

MODULUS DATA

It was possible to measure the elastic modulus for TbDy at 77 K. Because of the magnetoelastic coupling the modulus is strongly affected by the applied field and the applied stress. Due to details of our experimental apparatus it was only possible to measure the modulus in zero applied field. The applied stress was varied from 7 to 13 MPa. The modulus was determined to be approximately 15×10^9 Pa.

THEORY

It is important to realize that at 77 K the a-axis is the easy direction. Since these are b-axis rods, it means that the moments tend to lie perpendicular to the rod. This tendency is reinforced by the compressive stress. Thus it is reasonable to begin any model of these rods with the magnetization along the a-axis direction perpendicular to the rod axis. A low field applied along the rod axis would be expected to perturb this arrangement slightly by causing the magnetization to rotate toward the axis. The energy of the magnetoelastic system would be:

$$E = -M_s H_i \cos \theta + \frac{1}{2} M_s H_d + K_6^6 \cos 6\theta + \lambda_s \sigma \cos^2 \theta \quad (1)$$

where M_s is the saturation magnetization, H_i is the internal field, θ is the angle between the magnetization and the rod axis, H_d is the demagnetizing field, K_6^6 is the hexagonal basal plane anisotropy, λ_s is the saturation magnetostriction, and σ is the applied stress. Using the facts that $H_d = N M_s \cos \theta$ and that $H_i = H - H_d = H - N M_s \cos \theta$ (where H is the external field and N is the demagnetizing factor) and then minimizing this energy with respect to θ , we find:

$$H = \frac{36K_6^6}{M_s} \cos \theta \left[1 - \frac{16}{3} (\cos^2 \theta - \cos^4 \theta) \right] + \frac{2\lambda_s \sigma}{M_s} \cos \theta + N M_s \cos \theta \quad (2)$$

For both high fields ($\cos \theta \sim 0$) and low fields ($\cos \theta \sim 1$) we can neglect the higher order terms in $\cos \theta$ and thus find for the magnetization along the rod axis, M_z :

$$M_z = M_s \cos \theta = \frac{H}{\left[\frac{36K_6^6}{M_s^2} + \frac{2\lambda_s \sigma}{M_s^2} + N \right]} \quad (3)$$

That is, M_z varies linearly with field at the high and the low field extremes (regions 1 and 3), as was observed.

When K_6^6 is large, as it is for TbDy at 77 K, individual moments will "jump" from the perpendicular easy a-axis direction to the easy a-axis direction 30 degrees from the rod axis as the field is increased. Magnetization likely proceeds by domain wall motion. The magnetoelastic energy in the limiting case of large K_6^6 is:

$$E = -\frac{\sqrt{3}}{2} x M_s H_i + \frac{1}{2} \frac{\sqrt{3}}{2} x M_s H_d + \left(\frac{\sqrt{3}}{2} \right)^2 x \lambda_s \sigma \quad (4)$$

where x is the fraction of the moments which have jumped to the other easy axis. Again using the appropriate definitions for H_i and H_d ($H_d = x N M_s \cos \pi/6$ and that $H_i = H - H_d = H - x N M_s \cos \pi/6$) and minimizing with respect to x , we discover that:

$$x = \frac{1}{N M_s} \left(\frac{H}{\sqrt{3}/2} - \frac{\lambda_s \sigma}{M_s} \right) \quad (5)$$

Thus we find for the case of magnetization jumping:

$$M_z = \frac{1}{N} \left(H - \frac{\sqrt{3}}{2} \frac{\lambda_s \sigma}{M_s} \right) \quad (6)$$

for $H > H_c = \sqrt{3} \lambda_s \sigma / 2 M_s$. Thus we expect a break in the $M_z(H)$ curves at some H_c , beyond which the magnetization is also linear in H but with a steeper slope than in region 1. Knowing that the magnetostriction along the rod $\lambda_z = x \lambda_s \cos^2 \pi/6$ and using Eq. 5, we conclude that in region 2 the strain is linearly proportional to H also. Fig. 2 confirms this prediction.

Fig. 3 Magnetostriction vs. magnetization for TbDy rods. Note that for applied stresses greater than 13 MPa the curves are virtually identical.

COMMENTS

Binary alloys of the rare earth elements Tb and Dy have several properties that make them ideal for high power transducer applications: (1) they have the largest magnetostrictions of any material: 0.5% under an applied stress at liquid nitrogen temperatures. (2) These materials also have very large magnetizations. (3) By varying the ratio of Tb to Dy, one can construct an alloy with a large magnetostriction to basal plane anisotropy ratio for any temperature in a wide range. (4) Such alloys also have a low hysteresis, as may be seen in Fig. 1. (5) The magnetization is linear over large regions of applied field. (6) In region 2 the *magnetostriction* is linear with respect to the applied field. (7) As shown in Fig. 3, the strain as a function of magnetization is nearly completely non-hysteretic and is linear over an extremely wide range; more importantly $\lambda(M)$ is essentially independent of the load (stress). All of these features contribute to making Tb-Dy alloys the preferred materials for low temperature, high power transduction.

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