Magnetostriction of single crystal and polycrystalline $Tb_{0.60}Dy_{0.40}$ at cryogenic temperatures

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At cryogenic temperatures, single crystals of TbDy alloys exhibit giant magnetostrictions of nearly 9000 ppm, making these materials promising for engineering service in cryogenic actuators, valves, and positioners. The preparation of single crystals is difficult and costly. Preliminary results on the magnetostriction of textured polycrystalline materials are presented here. For instance, polycrystalline $Tb_{0.60}Dy_{0.40}$, plane-rolled (one direction of applied stress) to induce crystallographic texture, has shown magnetostrictions at 77 K of 3000 ppm for an applied field of 4.5 kOe and an applied load of 23 MPa, or 48% that of a single crystal under similar conditions. Comparisons are presented between the magnetostrictive response of plane- and form-rolled (two orthogonal directions of applied stress) polycrystalline $Tb_{0.60}Dy_{0.40}$ at 10 and 77 K. It is reported that at 10 K plane-rolled $Tb_{0.60}Dy_{0.40}$ exhibits 1600 ppm magnetostriction at an applied field of 4.4 kOe with a minimal applied load of 0.28 MPa. An observed restoration of the initial unstrained state may be a useful feature of polycrystalline materials for engineering service. Finally it is reported that thermal expansion measurements provide a measure of crystallographic texture for comparison with the magnetostriction. [S0021-8979(99)44008-3]

I. INTRODUCTION

In recent years there has been considerable interest in using the large magnetostrictive strains of rare earth alloys for low temperature actuator applications such as liquid helium valves,[1] which operate at or below 4.2 K, and micropositioning devices for infrared (IR) satellite optics,[2] which operate at 50 K and below. Traditional actuator materials such as piezoelectrics perform poorly at and below liquid nitrogen temperatures. The advantages of having a cold prime mover are driving the push for new actuators. The combination of rare earth magnetostrictive materials and high-T_c superconductors is a promising solution for problems of low temperature actuation. TbDy alloys exhibit saturation magnetostrictions approaching 1.0% at low temperatures,[3] but the preparation of hexagonal single crystals of TbDy is currently possible only by a strain anneal method, which is expensive and difficult to control. Because impurities inhibit grain growth, expensive high purity material is required for single crystal growth.[4] (Our commercial grade material has a total purity 99.7%, whereas the high purity material has a total purity of 99.94%.) The Next Generation Space Telescope may require 2000–3000 cryogenic actuators. Since it is not possible to produce single crystals in such numbers, textured polycrystals are being developed for use in actuator applications. Polycrystalline $Tb_{0.60}Dy_{0.40}$, cold-rolled to induce crystallographic texture, has shown magnetostrictions at 10 K of 0.2%, and 0.3% at 77 K.[5] Even with this fraction of the single crystal performance, the polycrystalline samples have two major advantages. First, large samples can be prepared easily and at low cost. Second, for single crystals it is necessary to include preload stresses in the design of devices in order to force the magnetization to return to its original state, whereas for polycrystalline TbDy alloys an applied stress may not be required. The microstructural origin of this ''internal spring'' of polycrystals is likely related to elastic interactions between neighboring crystallites. It is possible that the need for a preload can be eliminated entirely by controlling the texture of the specimen. The texture of the material is critical due to the elastic interactions of misaligned grains and the large anisotropy of the material.

II. MATERIALS PREPARATION

For preparation of our polycrystalline samples, the $Tb_{0.60}Dy_{0.40}$ alloy was arc melted and dropped into a chilled copper mold. Since the as-cast ingots had strong crystallographic texture, the material was first deformed by 35% and heat treated for 1.5 h at 950 °C to induce recrystallization. We expected this treatment to produce a more random orientation distribution of equiaxed grains. Bulk thermal expansion measurements, as described below, indicated that significant texture remained, however. The specimen was then form- or plane-rolled, as shown in Fig. 1, by 55% to a cross-section of approximately 0.025 in.^{2} and heated to 350 °C in order to relieve strain.

III. EXPERIMENTAL METHODS

At 10 K the materials were characterized with a cryogenic test facility,[3] which measures displacement with a Polytec laser vibrometer. A mechanical load is applied, and the applied force is measured with a strain gauge load cell. The magnetic field is applied with a superconducting coil. For measurements at 77 K, the linear displacement is mea-

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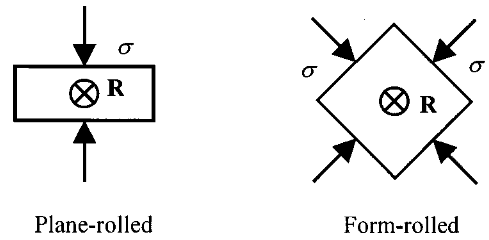

FIG. 1. The directions of applied stress for both plane- and form-rolled deformation processing methods. **R** is the rolling direction.

sured by a Capacitec capacitance gauge and a room temperature electromagnet was used to produce fields up to 4.5 kOe. The single crystal magnetostriction was measured along the *b* axis and the polycrystalline magnetostrictions were measured along the rolling direction, **R**.

To obtain information on the crystallographic texture, thermal expansion measurements were performed on either a Perkin Elmer Thermomechanical Analyzer 7 or on a Theta Industries, Inc. Dilatronic dilatometer. Thermal expansion measurements were made from 30 to 300 °C under inert atmosphere to prevent oxidation.

IV. MATERIAL PERFORMANCE

At 10 K a *b*-axis single crystal of $Tb_{0.60}Dy_{0.40}$ exhibits 8800 ppm magnetostriction at a field of 3 kOe with an applied stress of 27.5 MPa, as reported previously.[5] At 77 K magnetostrictions of 6300 ppm were reported.[4] The magnetic fields required to saturate the textured polycrystalline specimens are higher than our test apparatus can provide. Crystallographic texture should differ for the plane- and form-rolled specimens, since plane-rolled material will have better alignment of the basal planes. It is hence not surprising that the plane-rolled specimen has a higher magnetostriction than the form-rolled specimen. As shown in Fig. 2, with applied fields of 4.4 kOe, magnetostrictions of 2300 ppm are possible with an applied load of 13 MPa, as compared to 1600 ppm with a minimal applied load of 0.28 MPa at 10 K. Textured polycrystalline $Tb_{0.60}Dy_{0.40}$ does not require a large applied stress in order to return to an unstrained state, unlike single crystal materials.

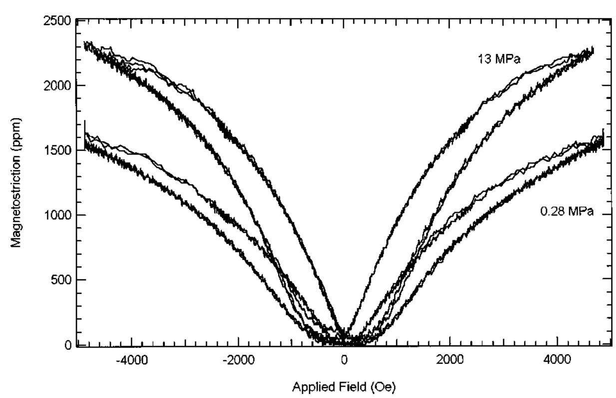

FIG. 2. Magnetostriction of $Tb_{0.60}Dy_{0.40}$ plane-rolled polycrystalline specimen for applied load of 0.28 and 13 MPa at 10 K.

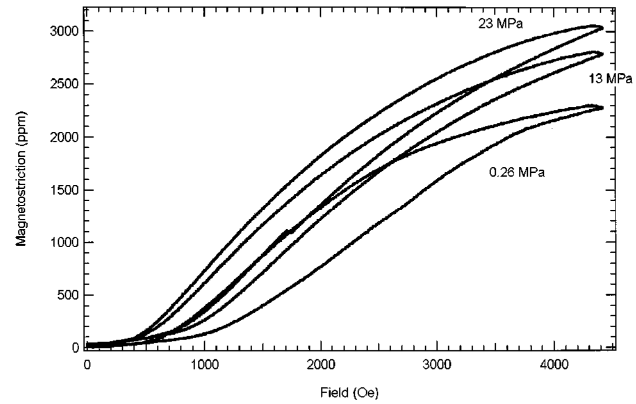

FIG. 3. Magnetostriction of $Tb_{0.60}Dy_{0.40}$ plane-rolled polycrystalline specimen for applied load of 0.26, 13, and 23 MPa at 77 K.

Magnetostriction measurements were made at 77 K on both the form- and plane-rolled samples for fields of 4.4 kOe and applied loads up to 23 MPa (Fig. 3). The magnetostriction of the plane-rolled specimen was measured to be 3000 ppm, 48% of the single crystal value. The polycrystalline samples show larger magnetostrictions at 77 K than at 10 K, even though the magnetostriction of the single crystals is monotonically increasing with decreasing temperature. This is likely related to both the internal stresses and to the fact that as the temperature increased from 10 to 77 K, the $Tb_{0.60}Dy_{0.40}$ alloy approaches its anisotropy minimum. It is interesting to note that the plane-rolled specimen shows smaller magnetostrictions than the form-rolled specimen when there is a very small applied load, at higher loads the plane-rolled sample shows larger magnetostrictions.

V. TEXTURE DETERMINATION BY THERMAL EXPANSION MEASUREMENTS

Crystallographic texture is critical to the magnetostrictive performance of the polycrystalline material. It is therefore important to relate the bulk magnetostriction of the polycrystals to the crystallographic texture. X-ray determination of the full orientation distribution function is impractical, however, due to shallow x-ray penetration into the rare earth metals. We have found it useful to study crystallographic texture by measuring bulk thermal expansion.

Above room temperature the thermal expansion of the rare earths is extremely anisotropic, with the expansion along the *c* axis several times that along the *a* axis. Previously reported values of the thermal expansion coefficients for single crystal Tb (Dy), as determined by x-ray diffractometry, are, for the *c*-axis direction, 17.9×10^{-6} K (20.3×10^{-6} K) and 9.1×10^{-6} K (4.7×10^{-6} K) for the *a* axis at 400 °C.[6] Elemental Tb and Dy single crystals were measured along the *a* and *c* axes. At 200 °C the linear coefficients of thermal expansion for Tb (Dy), were found to be, for the *c*-axis direction, 14.5×10^{-6} K (15.2×10^{-6} K) and 3.8×10^{-6} K (3.4×10^{-6} K) for the *a*-axis single crystal.

The linear thermal expansion was measured for each of the $Tb_{0.60}Dy_{0.40}$ test specimens along the direction parallel to the magnetostriction measurement direction. At 200 °C the

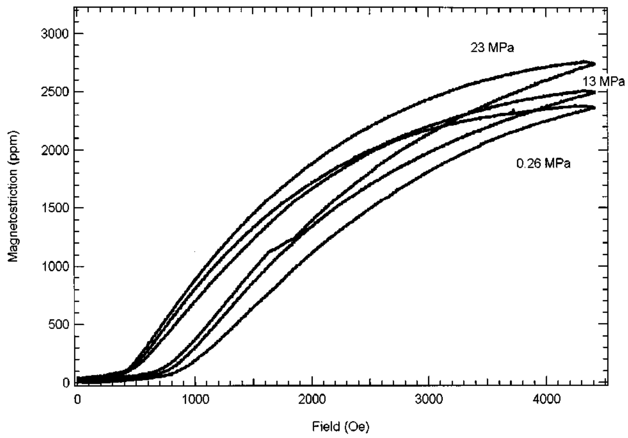

FIG. 4. Magnetostriction of $Tb_{0.60}Dy_{0.40}$ form-rolled polycrystalline specimen for applied load of 0.26, 13, and 23 MPa at 77 K.

single crystal value was found to be 3.1×10^{-6} K. The plane-rolled specimen exhibited 4.0×10^{-6} K, while 4.5×10^{-6} K was found for the form-rolled specimen. It can be seen that for applied stresses over 13 MPa, the greater the deviation of the rod axis thermal expansion from the single crystal *a*-axis value, the smaller the magnetostriction. At 77 K the plane-rolled specimen exhibits 3000 ppm at 4.4 kOe with an applied load of 23 MPa, while the form-rolled specimen exhibits 2750 ppm magnetostriction under the same conditions (Fig. 4).

VI. CONCLUSION

A textured polycrystalline material has been prepared with a bulk magnetostriction of 3000 ppm, which is 48% that of the magnetostriction of a single crystal. Preliminary results indicate thermal expansion measurements are useful for monitoring crystallographic texture in these materials.

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