Magnetostriction and Magnetomechanical Coupling of Grain Oriented Tb$_{0.6}$Dy$_{0.4}$ Sheet

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Abstract—The magnetostriction, magnetization, and Young's moduli were measured on laminated rods of thin hot rolled sheets of Tb$_{0.6}$Dy$_{0.4}$ at 77 K. The results were compared to those obtained on single crystals. Approximately 65% of the single crystal saturation magnetostriction was achieved in the rolled samples. While the hot rolling produces the desired planar texture, the magnetostriction and magnetomechanical coupling strongly depend upon the final heat treatment.

I. INTRODUCTION

Very large basal plane magnetostrictions ($\lambda T^{2}$-$\delta$) are found in the rare earth elements Tb and Dy at cryogenic temperatures. [1] At these temperatures Tb and Dy also possess huge uniaxial magnetocrystalline anisotropies, which keep the magnetizations essentially in the basal plane, plus very large basal plane anisotropies, which localize the magnetizations along the basal plane “b” axis in Tb ($K_b > 0$) and along the basal plane “a” axis in Dy ($K_a < 0$). Recently it was shown that the basal plane anisotropy in Tb$_x$Dy$_{1-x}$ alloys could be minimized with the proper choice of x. [2]

Since $\lambda T^{2}$ is large and positive for all Tb$_x$Dy$_{1-x}$ (0 $\leq x < 1$), these alloys are excellent candidates for high power magnetostrictive devices at temperatures below 100 K. The magnetostrictive properties of single crystal Tb$_x$Dy$_{1-x}$ alloys have already been reported for samples with 0.5 $\leq x < 0.67$. [3]-[4] At 77 K, x $\equiv 0.6$ for anisotropy minimization. High magnetostrictions ($\lambda T^{2}$ > 0.6%) were found and magnetomechanical coupling factors larger than 0.92 were measured in single crystal samples. However, because of a solid state phase transition near the melting point large high quality single crystals are difficult to prepare by standard means. Methods such as annealing of highly strained polycrystalline alloys yield samples of limited size.

In this paper we report the magnetostrictions, elastic moduli, and magnetomechanical coupling factors of Tb$_{0.6}$Dy$_{0.4}$ alloys prepared by a conventional hot rolling process. X-ray studies have shown that hot rolling produces a high degree of planar texturing [5]-[6]. Since the $\gamma$ axis prefers to lie perpendicular to the rolling direction, hot rolling produces the type of texturing needed for highly magnetostrictive performance in laminated sheet samples. With this method, large laminated samples (> 15 cm long x 5 cm x 5 cm) with excellent eddy current properties can be mass produced with minimal fabrication expense.

II. EXPERIMENTAL

Large strips of oriented Tb$_{0.6}$Dy$_{0.4}$ alloys were prepared by a method consisting of three parts: (1) hot rolling of thick Tb$_{0.6}$Dy$_{0.4}$ billets at 550 C for a 25-fold reduction in thickness, (2) cold rolling at room temperature for a further reduction of 40%, and (3) a final strain relief/grain growth heat treatment. [6] Magnetization, magnetostriction, and elastic moduli were measured on laminated bars (-0.6 cm x -0.6 cm x -3.6 cm) consolidated using Hysol XEA 9361 structural adhesive. While the rolling greatly improves the crystalline orientation, the final heat treatment governs crystallite size and degree of internal stresses. Even though desired texturing was obtained ($\gamma$ axis lies within $5^\circ$ of the normal to the rolled surfaces), the final heat treatment was found to be crucial. For this study samples of Tb$_{0.6}$Dy$_{0.4}$ having heat treatments ranging from 6 hours to 48 hours and 700 C to 1200 C were examined. (Following the 1200 C anneal, crystallites were 1 - 2 mm in size.) All measurements were made at 77 K utilizing a weighted platform which allowed compressive stresses from 4 MPa to 50 MPa to be applied under magnetic fields ranging from -2 kOe to +2 kOe. Frictional changes in sample length ($\lambda$) were calculated from resistance changes of strain gages attached to opposite sides of the samples plus voltage changes averaged from three axially mounted LVDT’s. The magnetization (in Teslas), $M$, was obtained by subtracting the magnetic field induction, $B$, from the integrated output of a pick-up coil wound near the center of the sample. Moduli measurements were calculated from sample length changes resulting from stress changes due to fixed weights added and subtracted from the platform. Young's moduli measurements were made under magnetically free conditions (constant magnetic field), $Y^H$, and under magnetically blocked conditions (constant total magnetic induction), $Y^B$. Since the square of the coupling factor equals 1 - $Y^H/Y^B$, an experimental determination of the $Y^H/Y^B$ ratio is important.
III. MAGNETIZATION AND MAGNETOSTRICTION

Since the magnetostrictions (λ) are large in the Tb$_{0.6}$Dy$_{0.4}$ alloy and work must be done against external forces, the slope of the magnetization and magnetostriction curves are dependent upon external stress. In Fig. 1 the field dependence of the magnetization and magnetostriction of two hot rolled polycrystal laminates are compared to the magnetization and magnetostriction of a basal plane oriented single crystal at compressive stresses of -7.5 and -15 MPa. First, note the difference between the hot rolled textured samples and the single crystal sample. While the overall shapes of the curves are the same, for all fields the magnetizations are slightly smaller for the rolled samples and, importantly, the magnetostrictions are only 50% to 70% of the full single crystal magnetostriction (λ$^2$). Secondly, although alloys of Fig. 1a and Fig. 1b were rolled under identical conditions, the alloy heat treated at 1200 C is far superior to that heat treated at 700 C. The magnetostrictions are ~30% higher. The high initial magnetization observed in the hot rolled samples at low fields may be due to 180° domain wall motion thereby resulting in the lower value of overall magnetostriction.

In Fig. 2 are plotted the magnetization and magnetostriction vs H for three heat treated samples of Tb$_{0.6}$Dy$_{0.4}$ at a compressive stress of -15 MPa, a typical stress for magnetostrictive devices. Both the magnitude and field dependence of the magnetostriction are strongly dependent upon the heat treatment. The required large secondary grain growth was inhibited in the 1200 C heat treated sample containing 370 ppm Ta (curve d), yielding a low magnetostriction. From the slopes of these curves the permeability μ and the piezomagnetic constant d can be obtained (μ - μ$_0$ = dM/dH, d = dλ/dH). An instructive way to compare the performance of these hot rolled laminated samples with each other, with single crystals and with theoretical predictions is to plot the normalized magnetostriction λ/λ$^2$ vs the...
part of the magnetization curve. In fact for the sample heat treated at 700°C, (YH/YH), -1.5 compared with values of -1.0 for 3513, probably because of 180° domain wall motion at the initial part of the magnetization curve. In fact for the sample heat treated at 700°C, 25% of the magnetization occurs without any magnetostriction.

IV. ELASTIC MODULI

The fraction of magnetic energy which can be converted to mechanical energy per cycle in a magnetostrictive material is defined as the square of the magnetomechanical coupling factor, k. For large magnetomechanical couplings (k > 0.7) it is difficult to obtain the coupling by the conventional resonant/antiresonant method in rod shaped samples since the magnetic field and magnetization are not uniform throughout the sample. In this paper we employ a method which measures the deviation of the coupling factor from unity. From the standard linearized piezomagnetic relationships, it is easily shown that 1 - k^2 = YH/YB. [7] In highly magnetomechanical materials YH/YB becomes small and accurate values of k can be obtained. In Fig. 4 we plot YH and YB vs H for -15 MPa and fields from 0 to 1700 Oe. The maximum change in YH and corresponding ΔE Effect, (YB - YH)/YH, occurs near 200 Oe. Values of (YB - YH)/YH are ∼1.5 compared with values of ∼5 for the single crystal [4]. The easy magnetization rotation process under stress which is characteristic of the single crystals is absent in the rolled samples. The modulus under constant induction (YB) has no dip and only a small field dependence as expected. In Fig. 4 are also plotted the coupling factor determined from \(1 - \frac{\text{YH}_{\text{avg}}}{\text{YB}_{\text{avg}}^{1/2}}\). While these values are not as high as the single crystal values reported earlier [3], they are comparable to those for Terfenol-D and typical high power piezoceramics, such as PZT-4.

V. CONCLUSIONS

Hot rolling of the highly magnetostrictive Tb0.6Dy0.4 alloy produces the required crystallographic orientation for the best magnetostrictive properties (c axis perpendicular to the rolling direction). However, the final heat treatment of the rolled samples is crucial in achieving large magnetostriiction and magnetomechanical coupling factors currently available in the basal plane oriented single crystals. In the best heat treated samples reported here, -65% of the single crystal saturation magnetostriiction and coupling factors greater than 0.75 have been attained. Further refinement of the heat treatment process will very likely achieve the extraordinarily high saturation magnetostrictrions and coupling factors of the single crystal alloys by an inexpensive processing method.

REFERENCES