Magnetomechanical damping in cryogenic TbDy

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Abstract

Vibration damping in polycrystalline TbDy alloys was studied at cryogenic temperatures. The material was prepared by cold-rolling to induce crystallographic texture, and was then heat-treated to relieve internal stress. Mechanical hysteretic losses were measured at various strains, frequencies, and loading configurations at 77 K. Some textured TbDy materials demonstrated 22.6% energy dissipation in mechanical measurements at low frequency (0.01 Hz) and a mean logarithmic decrement of 0.23 at a higher frequency (25 kHz). Ultrasonic velocities of longitudinal and shear elastic waves were measured on single and polycrystalline TbDy; little variation in ultrasonic velocities was found even for samples with large variation in crystallographic texture and magnetomechanical properties.

Introduction

Ferromagnetic TbDy alloys exhibit giant magnetostriction, approaching 1% at saturation. This large coupling between mechanical energy and magnetic energy enables the dissipation of mechanical energy through the dynamics of magnetic domain motion. For low-frequency, low-amplitude vibrations, magnetization proceeds largely by domain wall motion; these processes are subject to hysteretic losses and result in mechanical damping. The damping depends on the magnetomechanical coupling factor describing the efficiency of converting elastic to magnetic energy, the magnetic anisotropy describing the difficulty of moment rotation, the Young's modulus, the magnetization, the magnetostriction and the crystallographic texture.[1] These properties and hence the damping characteristics of the material can be optimized through microstructural control. We expect the damping of optimized polycrystalline TbDy to be substantial based on its large magnetostriction, magnetomechanical coupling factors as high as 0.75,[2] and the relatively large hysteresis measured in curves of magnetostriction versus applied field.[3-5]

In previous work with polycrystalline TbDy, we measured quasi-static magnetomechanical energy dissipation as the ratio of the area of the stress-strain hysteresis loop to the mean area under the loading and unloading curves, $\Delta E/E$, at ~0.01 Hz.[6] The energy lost is the product of the fractional dissipation with the total potential energy stored in the sample. The fraction of mechanical energy dissipated in the material was 19.2% over a range of 0-27 MPa for commercial purity TbDy textured alloys at 77 K.

In contrast to viscoelastic materials, rheological fluids, viscous root dampers and many piezoelectric systems, the damping properties of magnetoelastic TbDy alloys and related materials are retained at low temperatures. In particular, space-based precision optical systems being developed for future NASA missions demand high-performance cryogenic damping for vibrations ranging from tens to hundreds of Hz and with amplitudes on the order of a few ppm. This has led us to investigate the magnetomechanical properties of polycrystalline TbDy alloys as candidate materials for dampers of mechanical vibrations.

Experimental

The Tb-Dy alloys were prepared as drop-cast ingots by T. Lograsso of Ames Laboratory. The cylindrical ingots initially had a radial texture. The ingots were cold-rolled by 35% in thickness and annealed at 950°C for 1.5 hours. The plane-rolling deformation is performed to reorient the grains such that the hard c-axes lie in the direction of applied deformation stress, and the annealing allows for strain relief and grain growth. A second cold-rolling deformation of 55% and heat treatment at 350°C further reoriented the grains in the samples, which measured 9x8x4 mm (commercial-grade) and 17x5x4 mm (high-purity). The well-defined c-axis grain orientation was confirmed by thermal expansion analysis of the textured samples, an as-cast specimen and a single crystal TbDy control, the results of which are summarized in Table 1. Specimens were prepared from commercial-grade TbDy with a typical purity of 99.7%, with the main impurities being Ta, O, and N, and from high-purity 99.94% TbDy. Optical microscopy showed large variations of grain sizes and no clear differences between commercial and high-purity samples. The processed samples were textured polycrystals with measured magnetostrictive strains of up to 56% of single crystal values.[3-5]

Ultrasonic measurements were made by affixing a piezoelectric transducer to the specimen, introducing a series of elastic pulses at 5 MHz, and measuring the round-trip sound wave propagation time with an oscilloscope. Measurements were made with different transducers for both shear and longitudinal waves. A screw-driven Instron load frame was operated in stroke control to apply compressive stresses to a prismatic bar of TbDy instrumented with electrical resistance strain gauges. Measurements were performed at room temperature and with the sample immersed in liquid nitrogen. The stress-strain data showed magnetomechanical hysteresis when the sample was at 77 K. High-frequency dynamic magnetomechanical damping measurements were made for comparison with the quasi-static results. The sample rested on an aluminum plate within the solenoid while immersed in LN_2. A mechanical impulse was imparted to the sample and the induced current in a solenoid around the sample was measured.

Results

Further analysis of the previously-reported quasi-static minor loop stress-strain curves[6] shows a number of interesting relationships summarized in Table 2, with a typical TbDy stress-strain curve at 77 K and 300 K shown in Figure 1. The commercial-grade specimen consistently showed larger strain amplitudes for the same applied stresses as compared to high-purity specimens. For commercial-grade material, $\Delta E/E = 22.6\%$ was measured for quasi-static damping of polycrystalline TbDy at 77 K over a range of 0-900 ppm, compared to $\Delta E/E = 16.7\%$ for high-purity TbDy. For the ranges measured, a 27-35% larger fractional energy dissipation was measured on commercial-grade specimens, with the highest ratio seen for the minor loops at low amplitudes. At low frequencies, $\Delta E/E$ of the minor loops varies inversely with the applied stress; for example, the commercial purity specimen shows a $\Delta E/E = 22.6\%$ over a range of 0-900 ppm, compared to $\Delta E/E = 16.5\%$ over a range of 1250-2100 ppm – a difference of 37%. In general, minor loops at lower appled stresses exhibited lower Young's moduli as measured by the slopes of the stress-strain curves.

Measurements of ultrasonic velocities of shear and longitudinal waves in single crystal and textured TbDy samples at room temperature are summarized in Table 3. While fairly large differences in magnetostrictive and magnetostrictive damping performance were seen between commercial-grade and high-purity samples of polycrystalline TbDy, the ultrasonic measurements revealed only small differences. Nevertheless, we expect a correlation between the measured ultrasonic velocities and the magnetization arising from an elastic wave traveling through the material. In addition, we include in Table 3 values of Young's modulus calculated from the ultrasonic velocities of the polycrystalline samples determined from the formula $Y=\rho V_l^2(1-\nu)/(1+\nu)(1-2\nu)$, with Poisson's ratio $\nu=(V_l^2/\ V_t^2-2)/2(V_l^2/\ V_t^2-1)$ with V_l and V_t being the longitudinal and shear velocities, respectively[7]. These results agree well with our measured room temperature Young's moduli in Table 2.

Several aspects of the magnetoelastic behavior of the samples are apparent from the dynamical damping data. A typical result is shown in Fig. 2, with the induced voltage of the solenoid (proportional to current) plotted versus time. Since the magnetic sample is excited mechanically by an impact force, the decay of the inductive pickup can be attributed to the dissipation of vibrational energy within the sample. The approximately 35-40 ms period corresponds to sound velocities of 1.6-1.8 km/s across a specimen of 32.4 mm. These are similar to measured sound velocities in polycrystalline TbDy of 1.7 km/s and 2.9 km/s for ultrasonic shear and longitudinal waves, respectively.

The corresponding mean logarithmic decrement $\delta = \Delta E/2E = \ln(A_n/A_{n+1})$ is often used to describe the damping capacity of materials, with A_n corresponding to the vibrational amplitude of the n^{th} oscillation of a vibrating element. By fitting the peaks of the oscillations in Fig. 2 to decaying exponential curves, we observe a decay in the amplitude of the signal peaks corresponding to $\delta = 0.23$. This is within a factor of two of our measured low-stress quasi-static damping capacities of TbDy alloys shown in Table 2. This variation is not unexpected owing to the slightly different composition and a number of additional damping sources in the test system, for example the interface of the specimen with the coil and the presence of external noise sources. Nevertheless, from these data the high frequency damping capacity of TbDy is apparent and compares to $\delta = 5 \times 10^{-5}$ for a 77 K suspended prismatic rectangular beam (508 x 50.8 x 1.51mm) of 6061-T6 Al vibrating at 18.2 Hz.[8]

Discussion

At lower stresses, the magnetization proceeds by rearrangement of domain morphology, which is subject to losses associated with microstructural features. Perhaps the impurities in the commercial-grade material could be responsible for additional dissipation. Higher stresses can cause the magnetization to orient out of the basal plane along higher-energy directions, causing an effective stiffening of the material and a higher elastic modulus as shown in Table 2.

A number of potential device configurations could use TbDy to provide vibrational damping. In a passive device, the material could be incorporated into a system as a sputtered thin film, a laminate applied to structural elements or affixed to a flexure mount, or as a bulk element designed to sit directly in line with the load path. Clearly the materials properties, and therefore the processing methods, of Tb-Dy that optimize the damping properties at cryogenic temperature will depend on the implementation. In an active device applied magnetic fields or stresses could alter the damping response of the device.

Conclusions

Polycrystalline TbDy alloys with crystallographic texture were prepared, and their mechancial hysteresis was measured. An approximately 30% larger fractional energy dissipation was found for commercial-grade materials than for high-purity materials. At 25 kHz, a $\delta = 0.23$ was measured for TbDy at 77 K, comparable to the largest measured quasi-static fractional energy dissipation of 22.6%. Ultrasonic velocity measurements showed little variation between specimens with different crystallographic texture and magnetomechanical properties. The high magnetomechanical damping capacities of textured TbDy polycrystalline alloys at low frequencies in quasi-static loadings and at higher frequencies in cyclic loading demonstrate the potential use of this material in cryogenic vibration damping applications.

Acknowledgements

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Figure 1.

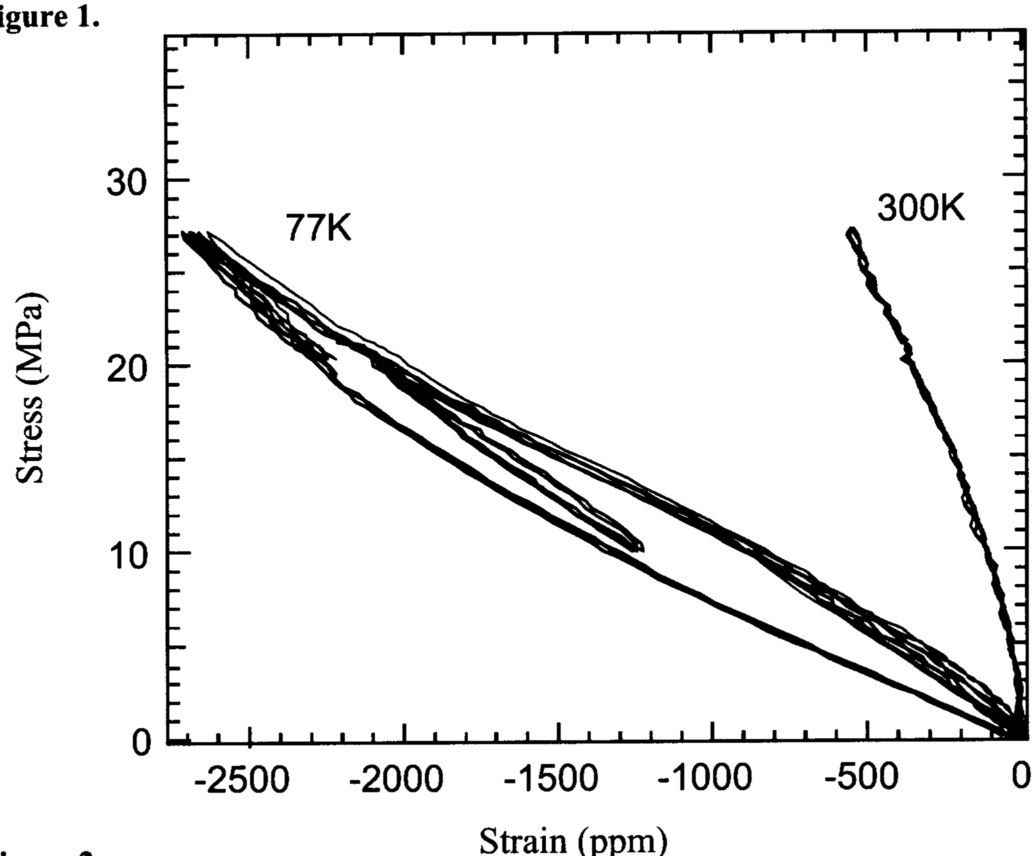

Figure 2.

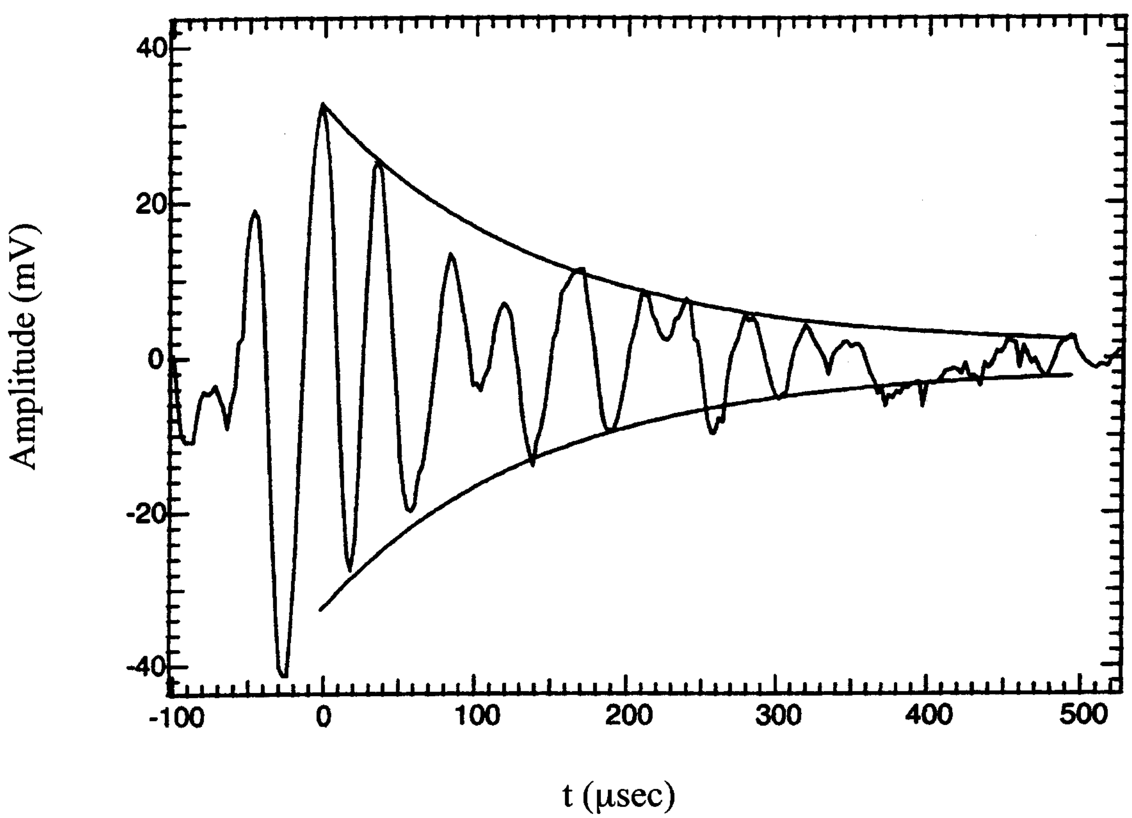

Figure Captions

Figure 1. Quasi-static magnetoelastic damping of $Tb_{76}Dy_{24}$ (99.7% purity) at 77 K and 300 K.

Figure 2. Dynamic magnetoelastic damping signal from polycrystalline $Tb_{60}Dy_{40}$ at 77 K.

Table 1.

Sample	x-axis expansion $10^{-6}/K$	y-axis expansion $10^{-6}/K$	z-axis expansion $10^{-6}/K$	x+y/ 2z
$Tb_{60}Dy_{40}$, single crystal	3.3	3.3	14.7	0.22
$Tb_{76}Dy_{24}$, as-cast, 99.7% purity	5.4	7.1	8.1	0.77
$Tb_{76}Dy_{24}$, textured, 99.94% purity	6.2	5.2	10.7	0.53
$Tb_{76}Dy_{24}$, textured, 99.7% purity	4.2	5.3	12.1	0.39

Table 2.

Sample	Applied Stress Range (MPa)	Strain Range (ppm)	Fractional Dissipation	Young's Modulus (GPa)
$Tb_{76}Dy_{24}$, polycrystalline 99.94% purity	0-36	0-2150	13.8%	17.2*
	0-14	0-900	16.7%	15.6
	14-28	1100-1750	12.9%	21.5
$Tb_{76}Dy_{24}$, polycrystalline 99.7% purity	0-27	0-2700	19.2%*	10.0*
	0-10	0-900	22.6%	10.5
	10-20	1250-2100	16.5%	13.3

* Previously reported values.[6]

Table 3.

Sample	Ultrasonic Velocity (km/s)		Measured Young's Modulus (GPa)	Derived Young's Modulus (GPa)
	Shear	Longitudinal		
Tb, single crystal, c-axis	1.70	3.23		
Dy, single crystal, c-axis	1.71	3.09		
$Tb_{60}Dy_{40}$, single crystal, b-axis	1.64	2.89		
$Tb_{76}Dy_{24}$, polycrystalline 99.7% purity	1.60	3.05	49.6	54.1
$Tb_{76}Dy_{24}$, polycrystalline 99.94% purity	1.60	3.00	57.2	55.2

Table Captions

Table 1. Thermal expansion analysis summary of polycrystalline and single-crystal TbDy.

Table 2. Fractional energy dissipation and Young's modulus of polycrystalline TbDy for various ranges of applied stress at 77 K.

Table 3. Ultrasonic velocities of shear and longitudinal waves in single crystal and polycrystalline TbDy at room temperature. Room temperature Young's moduli as measured by the slope of the stress-strain curve and derived from ultrasonic velocity measurements.