Cryogenic Magnetoelastic Damping of TbDy

Jennifer Dooley

Jet Propulsion Laboratory, California Institute of Technology,
MS 79-24, 4800 Oak Grove Dr., Pasadena, CA 91109

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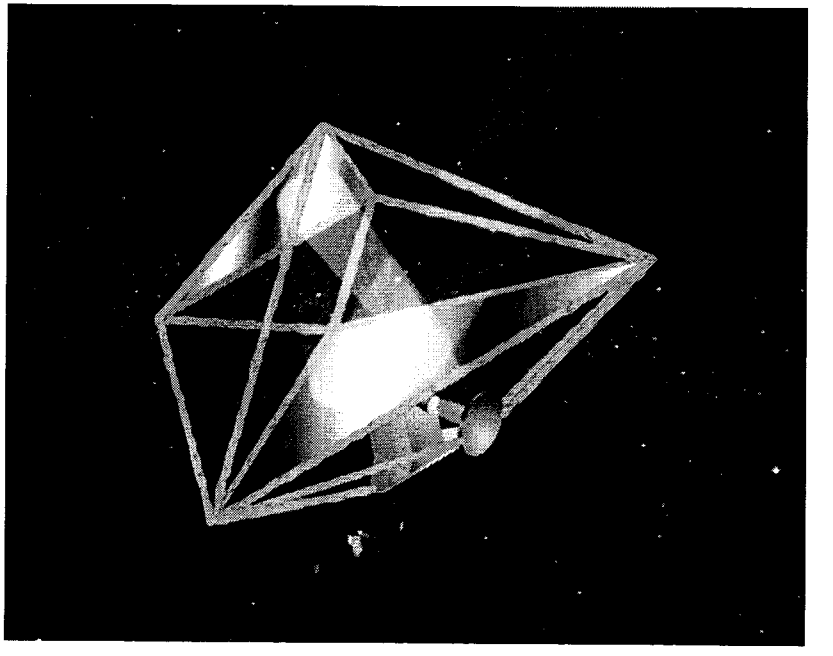
Low Temperature Science & Engineering Group, **JPL**
for further information contact the authors at: jennifer@squid.jpl.nasa.gov

Outline

- Motivation
- Introduction to Magnetoelastic Damping
- Magnetostrictive test results
- Instron crossbeam measurements
    - Change in modulus
    - Quasi-static energy dissipation
- Dynamic Measurements
    - Apparatus
    - Bending
    - Axial Mode
- Conclusions

Motivation

- Degradation due to vibration will be critical for many large, lightweight, missions: TPF, SAFIR, LF, etc.
- Large lightweight structures are lower mode structures and will have larger amplitude vibrations for the same input accelerations
- Cryogenic precision optical structures have both lower intrinsic material and lower structural (at joints, etc.) damping - excited vibrations will persist longer
- Magnetostrictive materials show substantial energy dissipation when subjected to an applied stress
- The magnetoelastic damping is dependent on the material's composition and microstructure, and the amplitude and frequency of vibration



DART

Dual Anamorphic Reflector Telescope

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Magnetoelastic Damping Concept

- Magnetoelastic materials have large coupling between magnetic and mechanical energy - vibrations are subject to magnetic losses
  - **elastic waves (vibrations) cycle the magnetic state of the material**
  - **the magnetization proceeds by domain wall motion, which is subject to hysteretic losses at defects in the crystal, converting energy into heat**

Advantages:

- purely magnetic effect - no atom motion is required for this mechanism so it isn't "frozen out" at low temperatures
- because of the decreasing entropy term with decreasing T, magnetic coupling increases, giving a stronger effect

Damping Dependencies

- magnetization
- magnetostriction
- magnetic anisotropy
- Young's modulus
- magnetomechanical coupling factor
- crystallographic texture

Damping Dependencies

Early studies on Fe and Ni

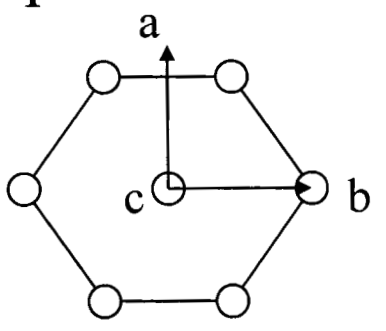
- Literature implies that, below characteristic high frequency, magnetoelastic damping will be independent of frequency

- Literature implies that for low (not a well defined term unfortunately) amplitudes it is independent and increases rapidly at higher amplitudes

- response governed by magnetization processes (different regimes - domain wall motion, moment rotation or eddy current heating)
  - **It is likely where on the major loop the minor loop cycling occurs is critical - bias stresses and fields will be important**

Alloy Selection

- For actuators - large stroke, small applied field
  - minimize the anisotropy
  - maximize the magnetostriction - stroke is 3/2 λ_s
  - maximize coupling coefficient
- Magnetostriction and anisotropy are large and T dependent
- $K_2 \sim 5 \times 10^8$ ergs/cm^3 for Tb and Dy (hexagonal structure)
- Below 20K a 10 Tesla field produces less than a 10% deflection from the basal plane
- For each temperature range of operation, alloy ratio is chosen to minimize the anisotropy in the basal plane
  - Tb has an easy <1010> (b-axis)
  - Dy has an easy <2110> (a-axis)
- $Tb_{0.76}Dy_{0.24}$ for 4K, $Tb_{0.6}Dy_{0.4}$ for 77K



Advantages of Polycrystals

- cost is a major advantage
  - commercial grade material
  - savings of material - will not have to discard unused portions of the ingot
  - rolling processes are fairly cheap
- reliability of processing
- internal stresses in the polycrystal may eliminate the need for the preload spring in actuator design
- additional control over hardness, and response to strain

Disadvantages are smaller magnetostriction, higher hysteresis, and larger required applied fields

High Purity:	Tb $24/gm Dy $9/gm
Commercial:	Tb $4/gm Dy $1/gm

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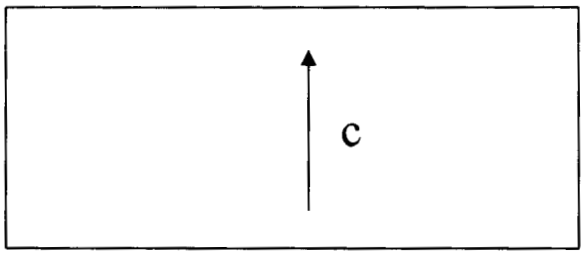
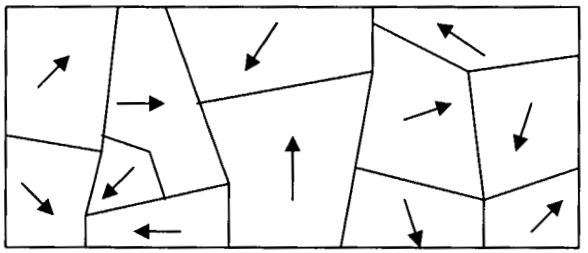
Processing of Polycrystals

- TbDy alloy is also arc melted and dropped into a chilled mold
- as-cast ingot shows strong texture
- material will be form rolled 35% and then heated at 900 °C to recrystallize for 1.5 hrs - possibly more random initial orientation (although bulk thermal expansion measurements indicate significant texture remains)
- material is then plane-rolled in one direction
- final heat treatment at 350–400 °C to relieve strain

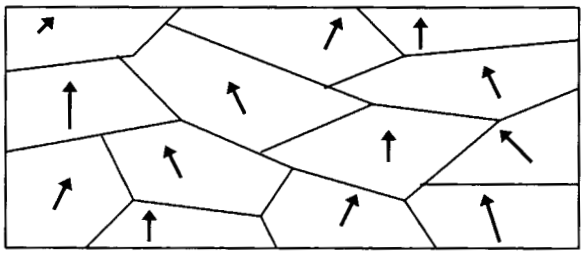
Textured Polycrystalline TbDy



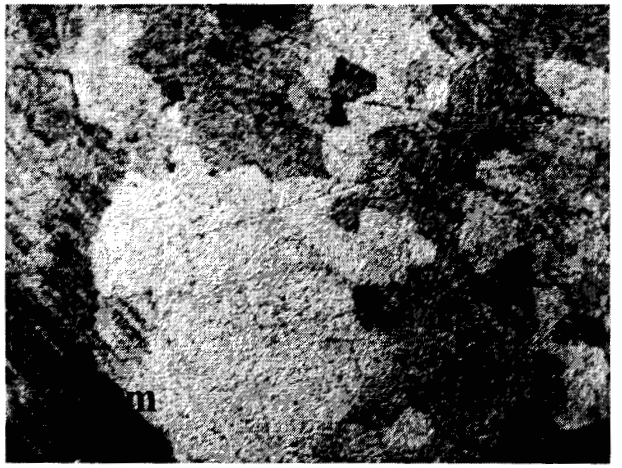
Single Crystal



Randomized Polycrystal



Textured Polycrystal



Spherical grains after recrystallization.

Elongated grains - 50% deformation.

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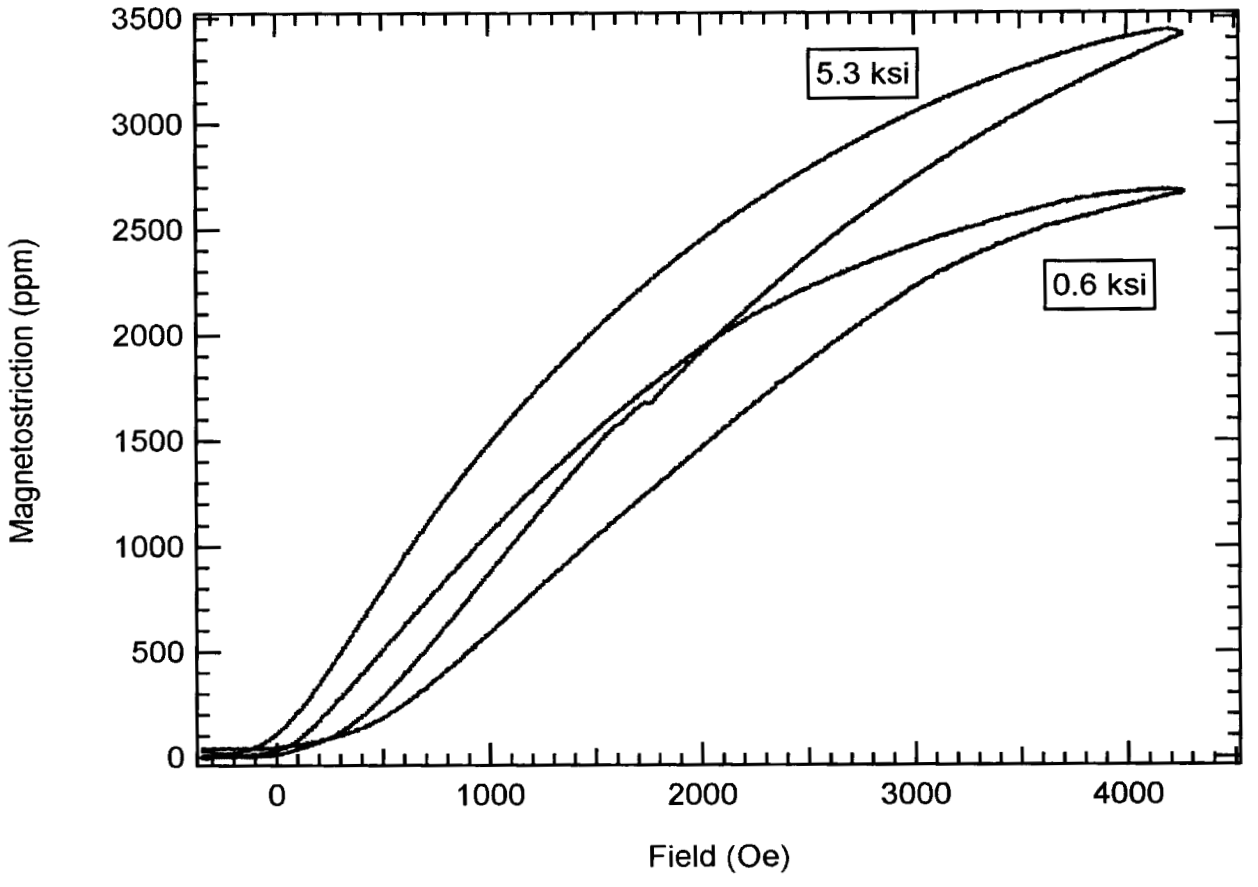
Typical Performance of Plane rolled $Tb_{0.6}Dy_{0.4}$



Plane rolled 55 %, 350 °C 1.5 hrs => 3000 ppm at 6 ksi, 4.5 Oe

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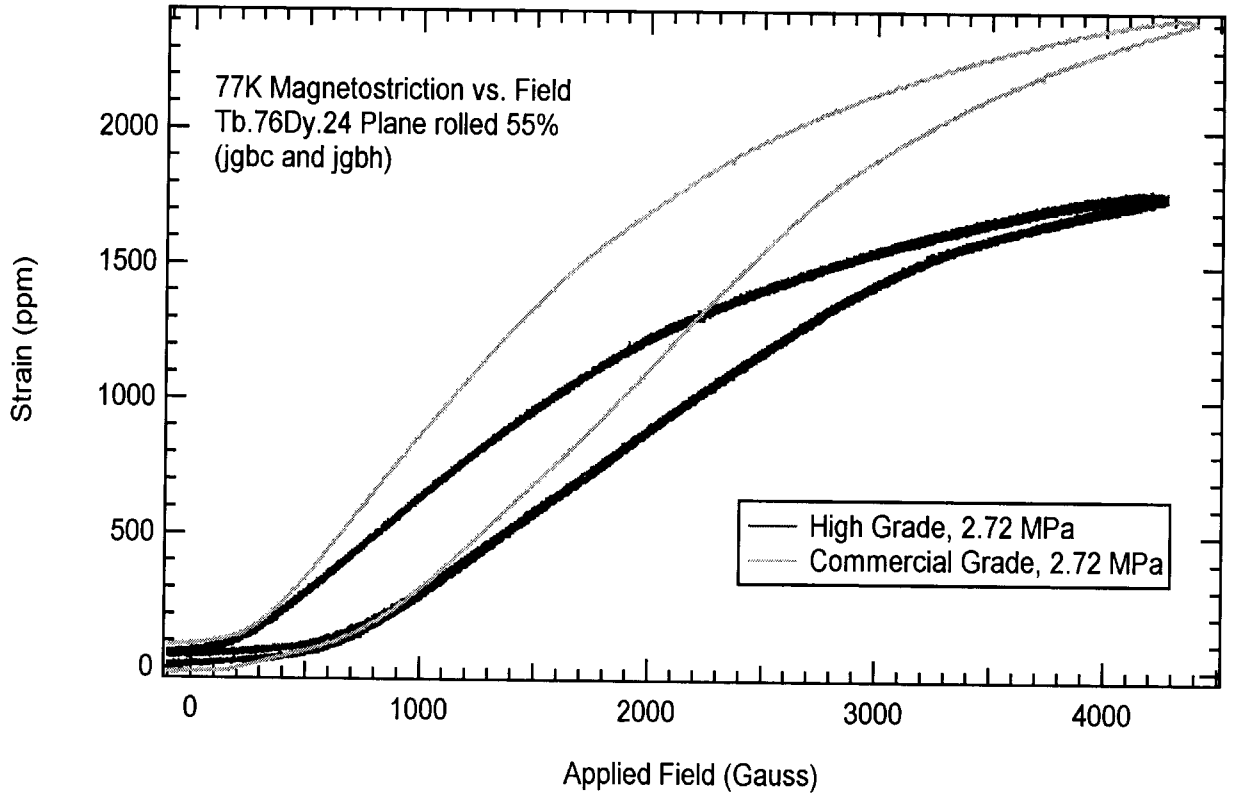
Commercial Grade vs. High Purity Material



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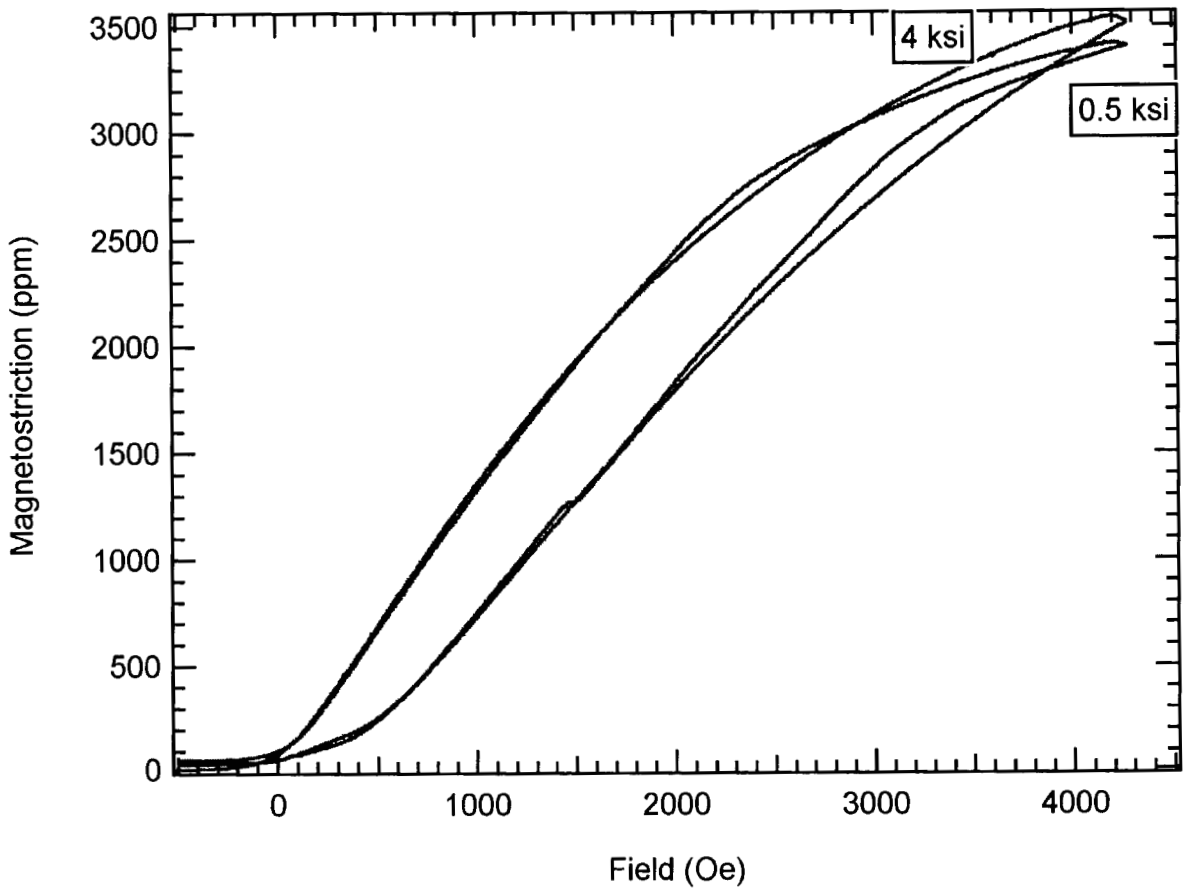
Applied Stress Invariant Response

$Tb_{0.6}Dy_{0.4}$ specimen was (plane rolled 25 %, 350 ^{o}C 3 hrs) x 4



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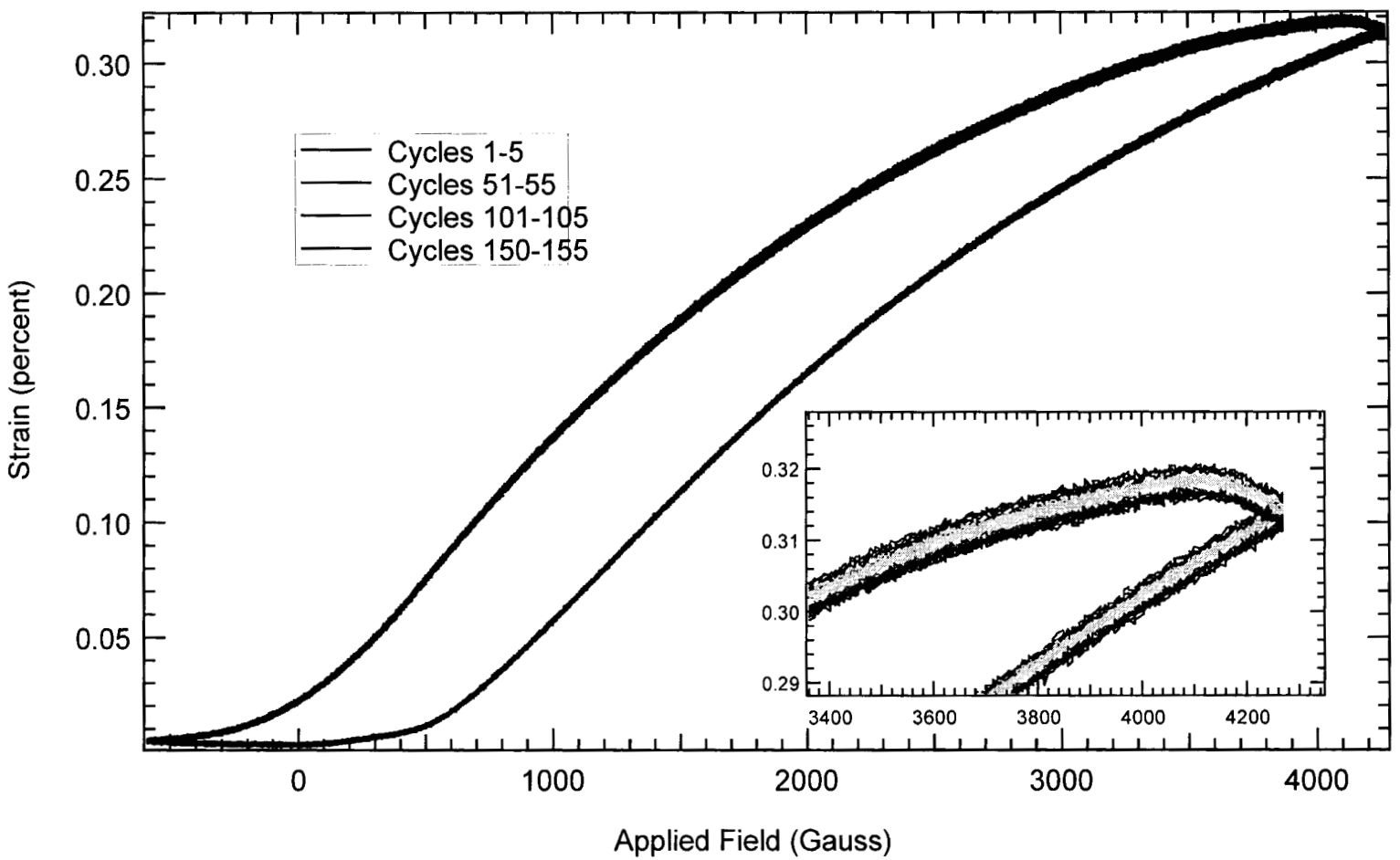
Magnetic Field Cycling of $Tb_{0.6}Dy_{0.4}$ at 77K (0.02 Hz)



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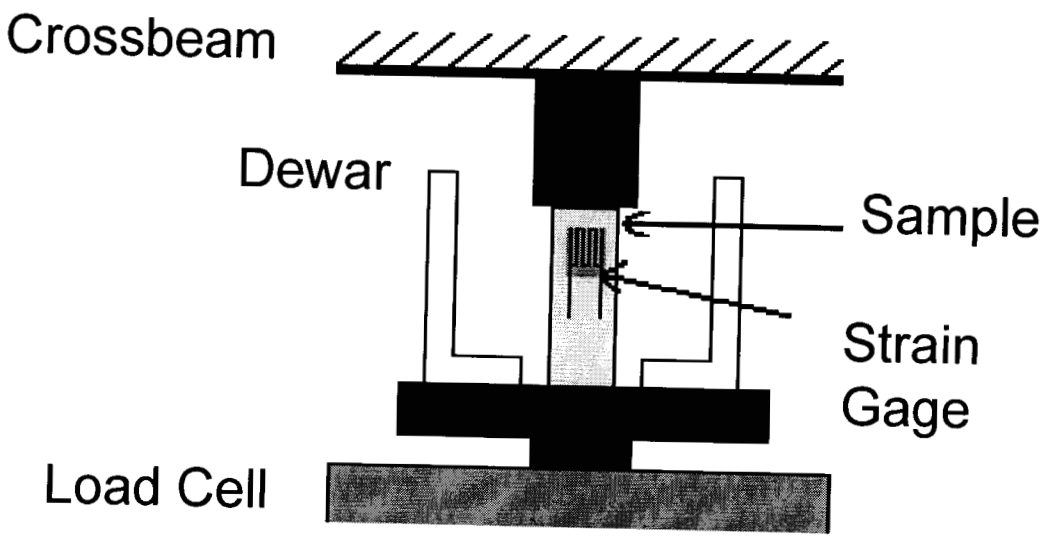
Quasi-static Measurement Apparatus



Crossbeam Control Rate:
0.5 mm/minute

Strain Limits:
0 - 800 Newtons

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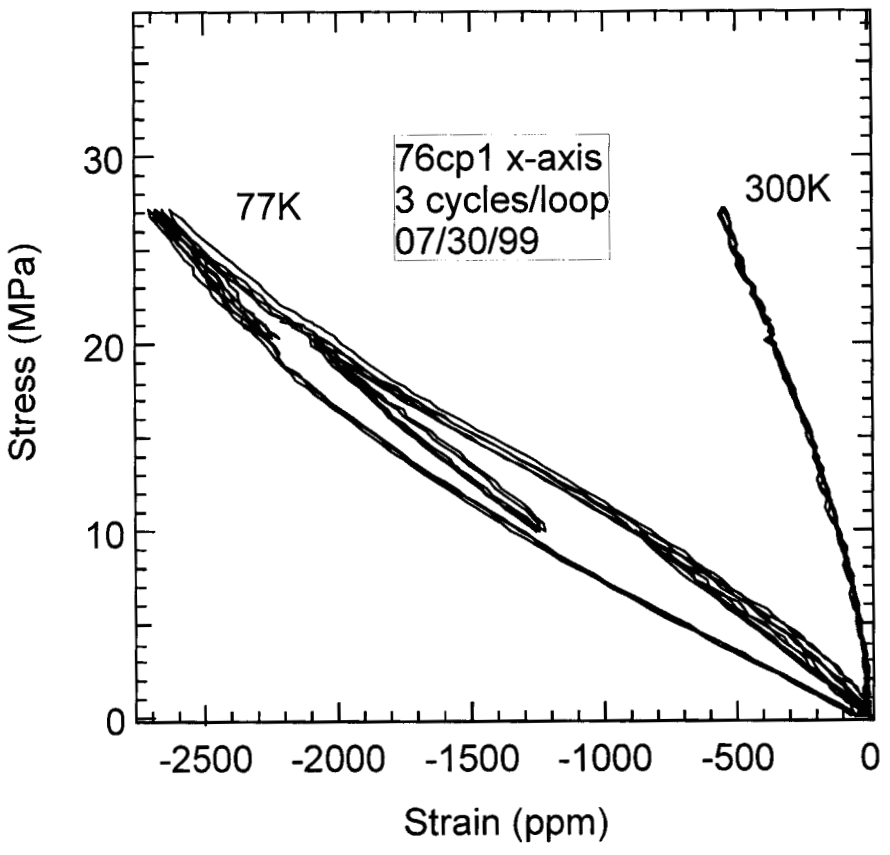
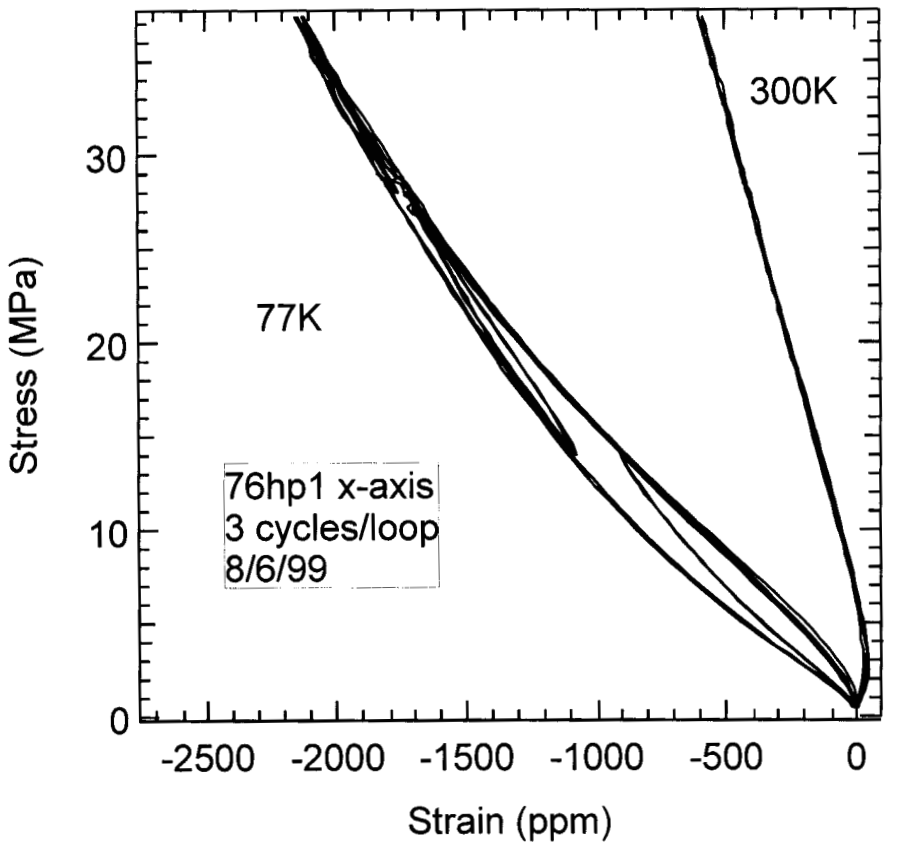
Quasi-Static Stress vs. Strain Curves for $Tb_{.76}Dy_{.24}$

Commercial purity (99.7%)



High Purity (99.94%)



- hysteresis in stress-strain loop represents energy loss in the material
- not practical to study very low amplitudes with this set up

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Elastic Moduli of $Tb_{.76}Dy_{.24}$ (in GPa)

	Young's modulus	
	77K	300K
76hp1 (x axis)	17.2	**57.2**
76cp1 (x axis)	10.0	**49.6**

- Effectively magnetostrictive coupling shows up as a softening of the modulus in the initial strain region
- Young's modulus calculated for 76-24 composition, using a weighted mean of elemental moduli: 59.1GPa
- Deviation from experiment <15%

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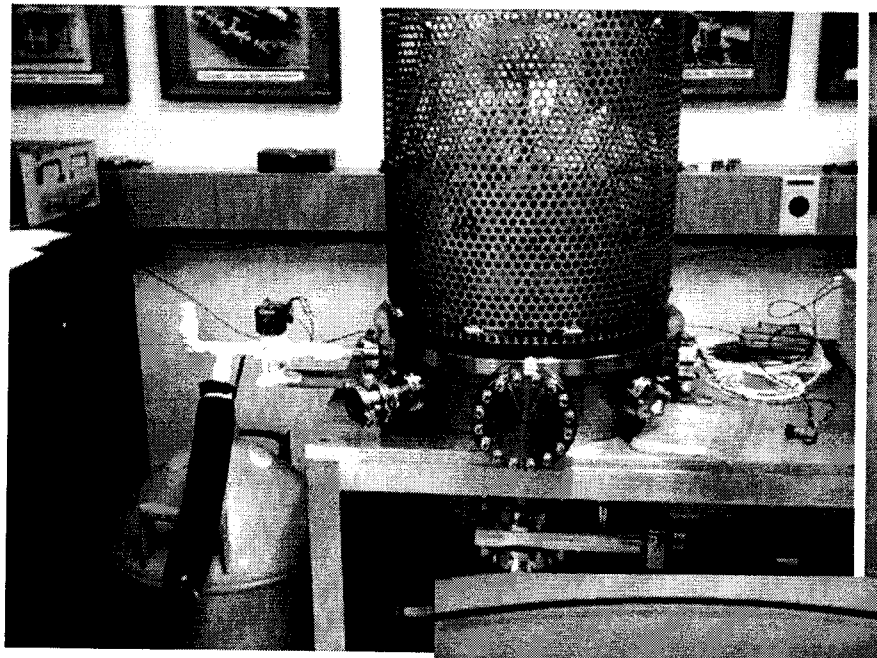
Loss Factor of $Tb_{.76}Dy_{.24}$

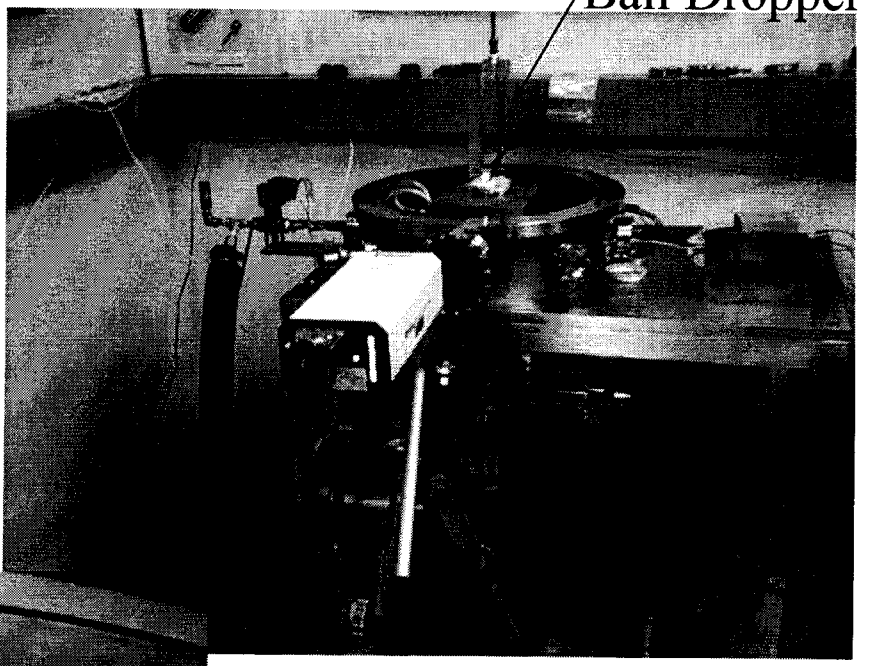
Sample	Strain Range	Loss factor $\eta = \psi/2\pi$
$Tb_{.76}Dy_{.24}$, textured polycrystalline, 99.7% purity	0 to 2700 ppm	0.031
	0 to 900 ppm	0.036
	0 to 600 ppm	0.050
	1250 to 2100 ppm	0.026
	170 to 270 ppm	0.057
$Tb_{.76}Dy_{.24}$, textured polycrystalline 99.94% purity	0 to 2150 ppm	0.022
	0 to 900 ppm	0.027
	1100 to 1750 ppm	0.021

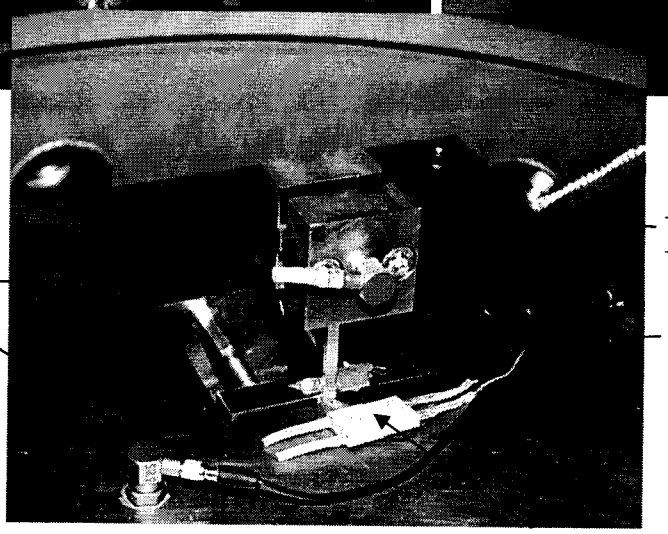
In the range of strains shown here, higher losses are seen for lower strain amplitudes.

Absolute magnitude of damping is very high, indicates potential for engineering applications.

Dynamic Measurement Apparatus







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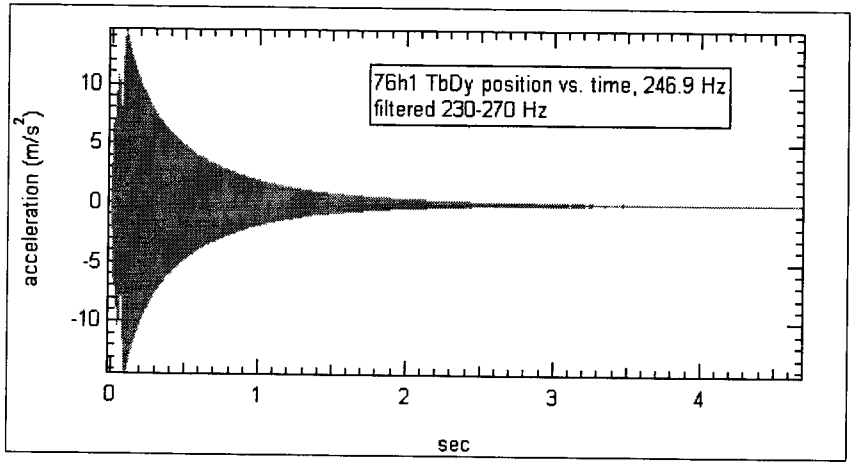
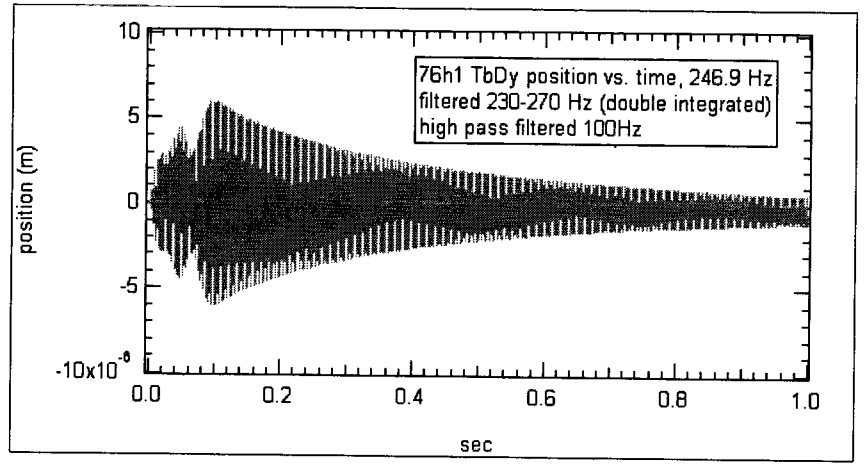
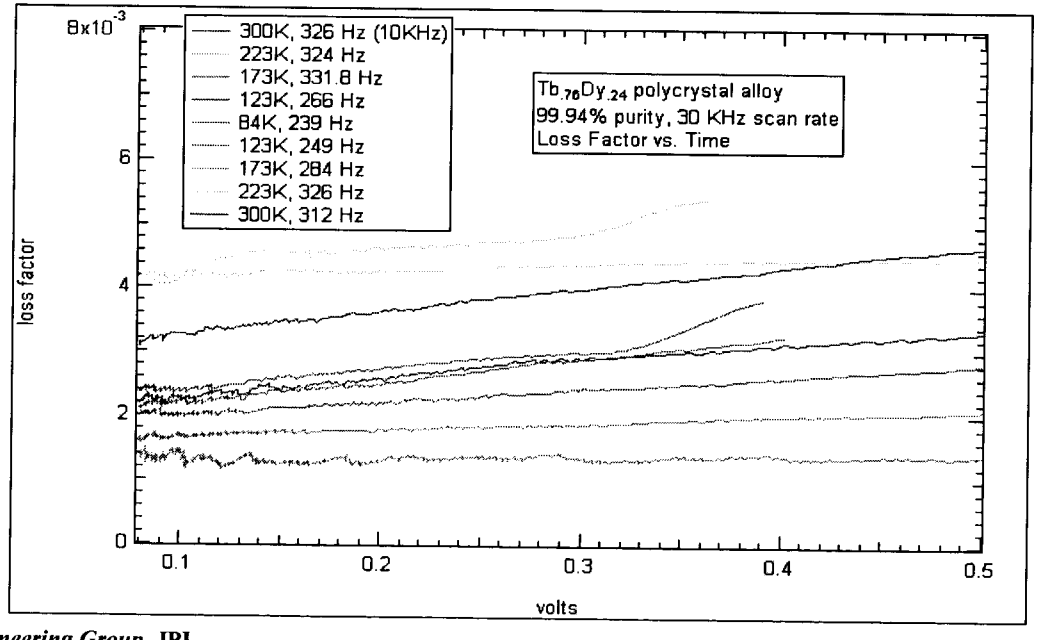
Bending Mode Example







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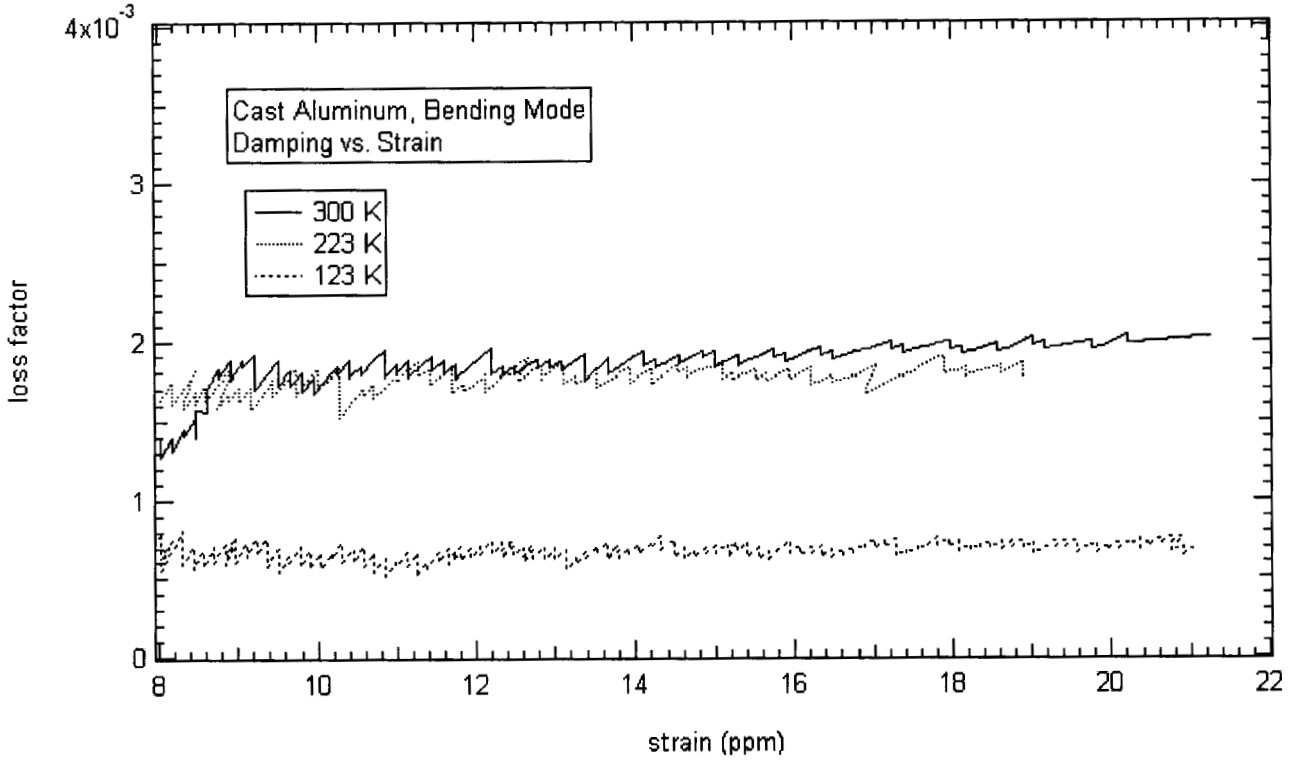
6061 Cast Aluminum in Bending Mode



Strain amplitude independent - expected from previous results and Zener theory

Zener theory predicts $\eta = 1.4 \times 10^{-3}$ - verifying that parasitic losses have been eliminated from the experimental setup

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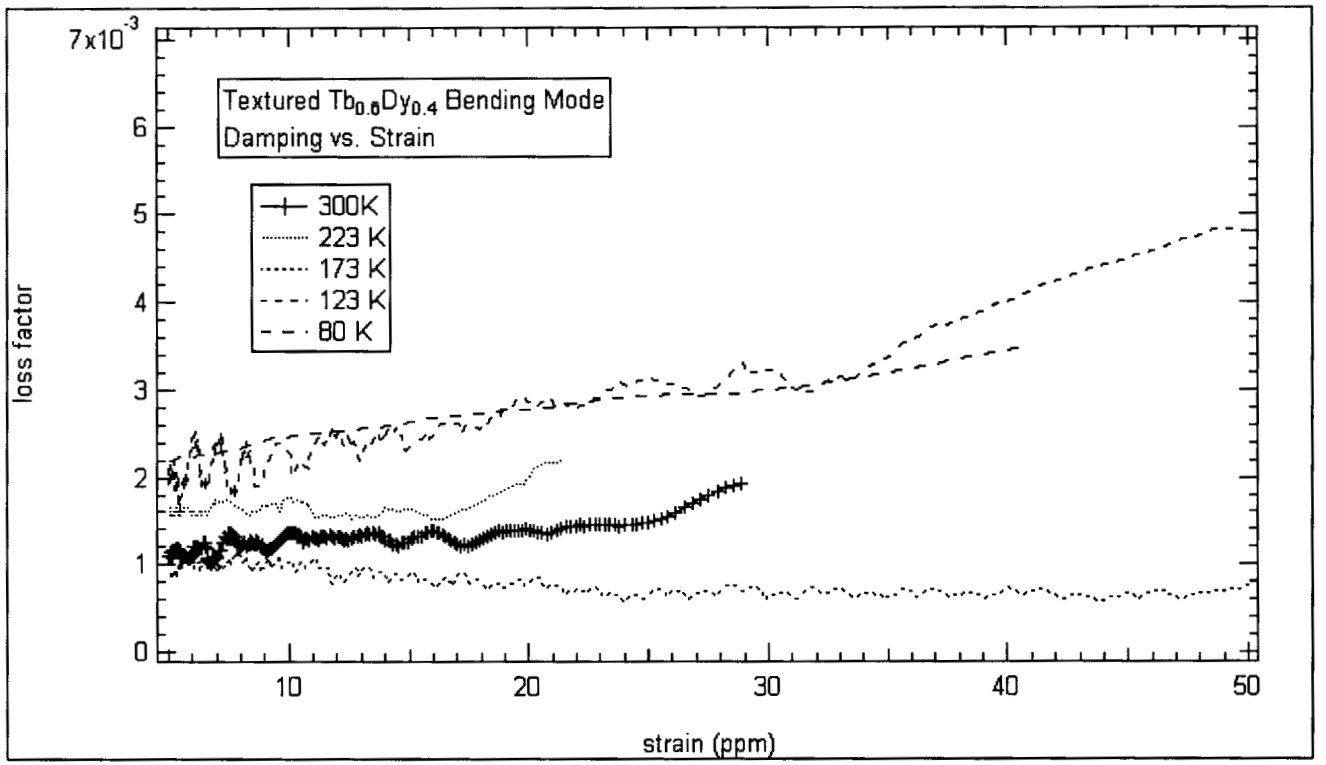
Textured $Tb_{0.6}Dy_{0.4}$ in Bending Mode



- damping smaller above the T_C = 165 K, and lowest at the coldest temperature above T_C, 173 K
- below the T_C, damping is larger, and increases at higher strain amplitudes
- Zener theory not intended to describe magnetoelastic mechanisms of loss
- possible that a small volume of the bulk specimen contributing strain-induced magnetoelastic losses
- suggests the potential for thin coatings to be effective contributors to damping

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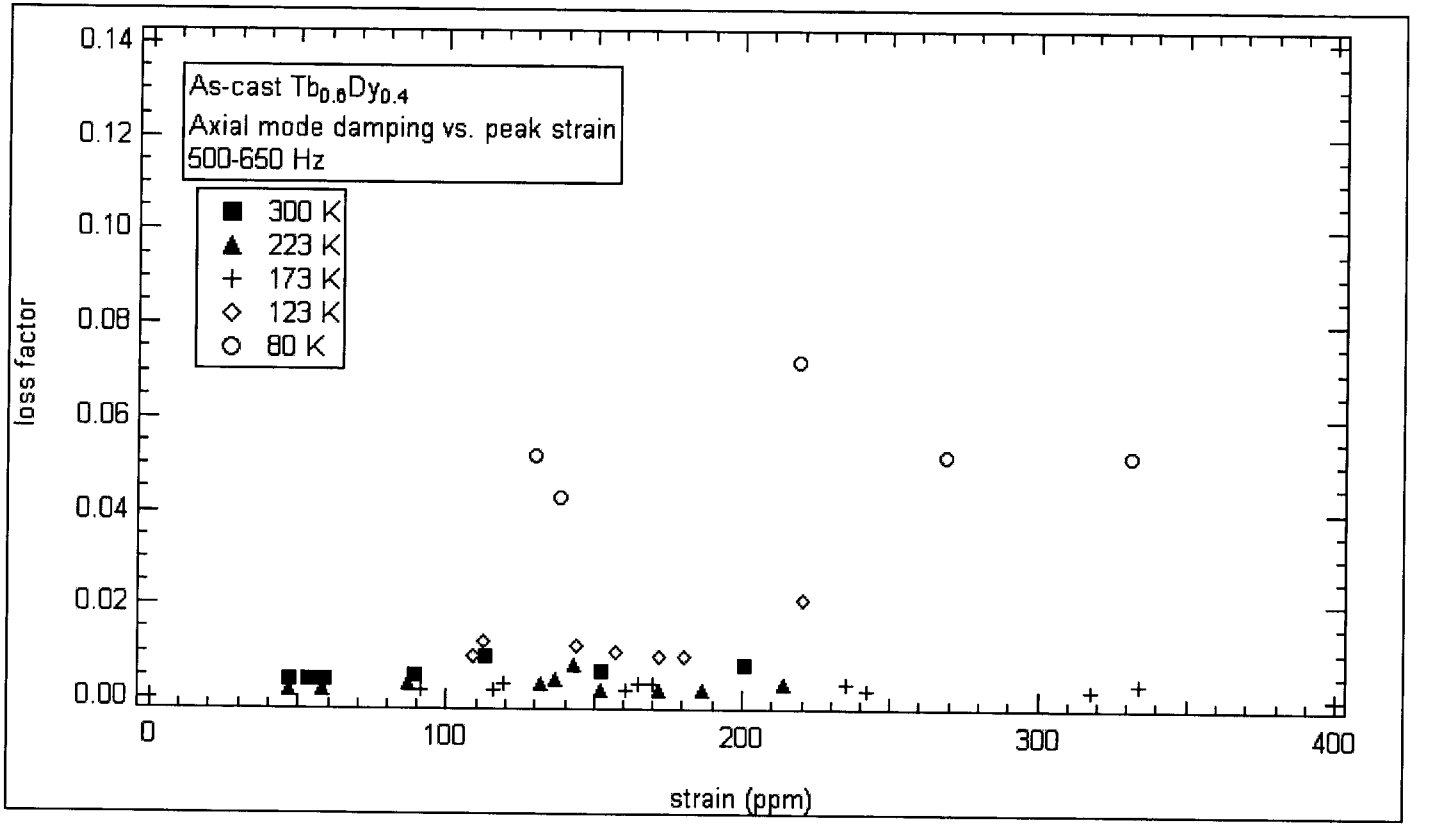
As-Cast $Tb_{0.6}Dy_{0.4}$ in First Axial Mode



- increase in damping at 80K
- amplitude independent behavior above T_C and possibly below

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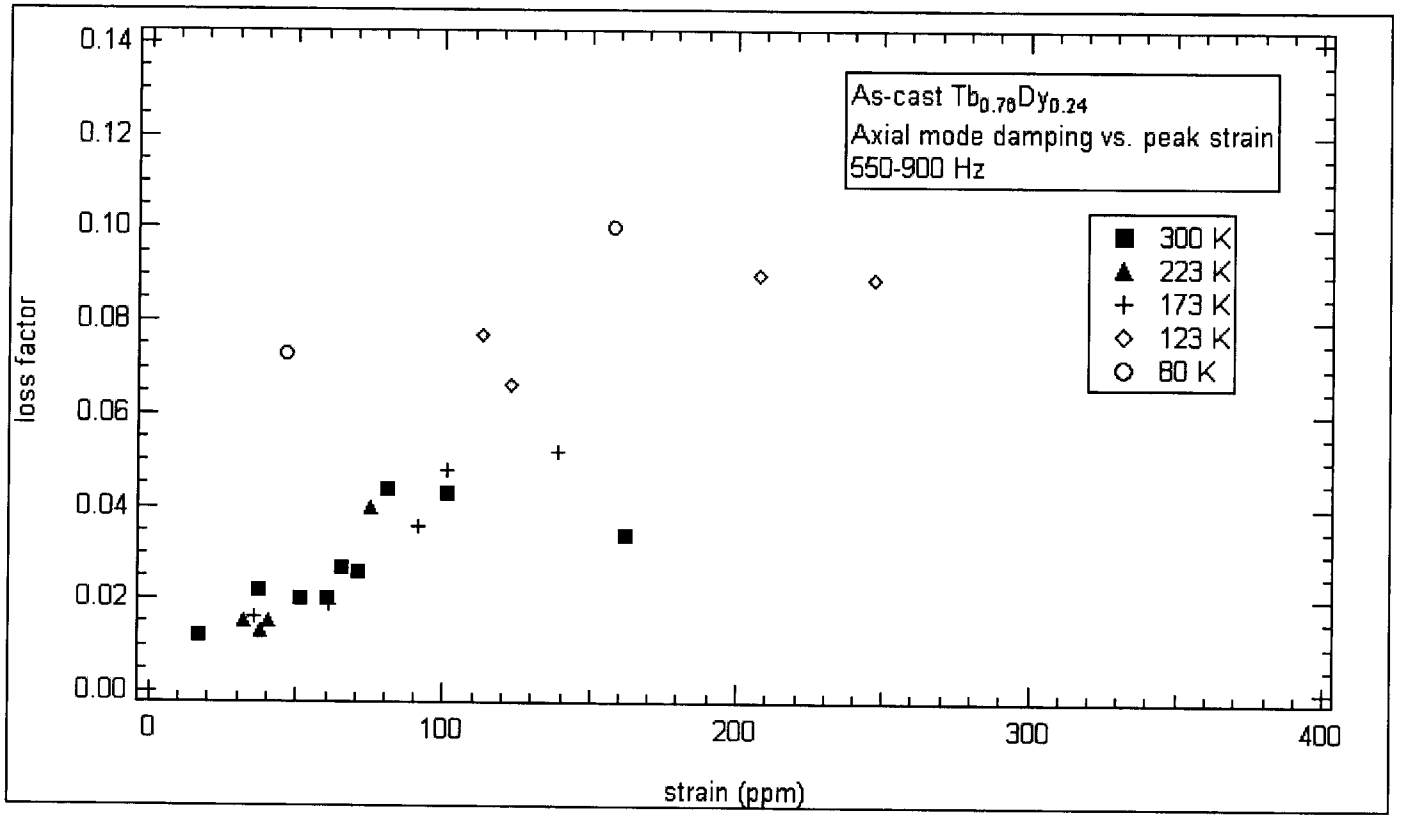
As-Cast $Tb_{0.76}Dy_{0.24}$ in First Axial Mode



- increase in damping at 80K
- amplitude *dependent* behavior above T_C and possibly below

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First & Second Mode Damping Loss Factors

Sample	Average Damping Measured at 300K	Average Damping Measured at 80K
$Tb_{0.6}Dy_{0.4}$ as-cast polycrystalline alloy, 99.7% purity	η=0.023 at 2000 Hz	η=0.110 at 1250-1300 Hz
	η=0.005 at 650 Hz	η=0.054 at 500-550 Hz
$Tb_{0.76}Dy_{0.24}$ as-cast polycrystalline alloy, 99.94% purity	η=0.029 at 2200 Hz	η=0.099 at 1400-1450 Hz
	η=0.028 at 875 Hz	η=0.112 at 580-600 Hz
6061 cast aluminum	η=0.0013 at 1550 Hz	η=0.0009 at 1620 Hz

Expect below T_C :

- amplitude dependent behavior
- frequency independent behavior

Frequency Softening

Sample	Damping at 300K	Damping at 173 K	Damping at 80K
$Tb_{0.6}Dy_{0.4}$ as-cast polycrystalline alloy, Curie point = 165 K, 99.7% purity	η=0.023 at 2000 Hz	η=0.021 at 2050 Hz	η=0.110 at 1275 Hz
$Tb_{0.76}Dy_{0.24}$ as-cast polycrystalline alloy, Curie point = 188 K, 99.94% purity	η=0.029 at 2200 Hz	η=0.044 at 2050 Hz	η=0.099 at 1425 Hz
6061 cast aluminum	η=0.0013 at 1550 Hz	η=0.0009 at 1610 Hz	η=0.0009 at 1620 Hz

- frequency softening below the Curie temperature corresponds to increased damping
- agrees with previous results on Young's modulus softening below Curie temperature

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Comments & Future work

Parameter space:

- ultimately we will seek to control the grain size and orientation, the defect type and distribution (including impurity additions)
- tailor the magnetization properties through alloy composition ratio - slightly off may be preferable - causing increased domain rotation without largely compromising coupling
- apply bias fields or stresses to place system in a favorable range on the magnetization curve

Experimental Efforts:

- incorporate longitudinal shaker (more directly comparable to quasi-static measurements), and shear test fixtures
- single crystal specimen tests
- use laser vibrometer for very small amplitude measurements
- thin film studies - adherence will be an issue
- longer term - in situ TEM magnetization studies will help sort out

Modeling Effort:

- need to develop a model which describes the material dependencies (on T, modulus, λ) and the excitation dependencies (vibration frequency and amplitude)

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Energy Dissipation and Elastic Moduli of $Tb_{.76}Dy_{.24}$

Sample	Applied Stress Range (MPa)	Strain Range (ppm)	Fractional Dissipation	YoungÕs 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

Fractional dissipation is defined as the hysteresis loop area divided by the mean area under loading and unloading stress-strain curves

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