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Abstract
$Tb_{1-x}Dy_xZn$(0 axes can be changed to very hard <100> axes by increasing x from 0 to 1. (In fact, the existence of a near zero magnetic anisotropy by the proper choice of x is the origin of the well-known Terfenol-D alloys, Tb1-xDyxFe2). The Tb$1-x)DyxZn system discussed here is particularly attractive because of the simplicity of its crystal structure (CsCl), its relatively high Curie temperatures (for rare earth alloys), and the existence of a large (uv0) phase for T < 50K. A summary of some of the important properties of these three alloy systems is given in Table I. In all these systems, at least one of the magnetostriction constraints is very large.

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Magnetostrictive and piezomagnetic properties of $Tb_{1-x}Dy_xZn$ at low temperatures

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EXTENDED ABSTRACT

$Tb_{1-x}Dy_xZn$ (0 < x < 1.0) is one of a class of highly magnetostrictive alloys based upon the anisotropic 4f electron shell of rare elements, such as Tb, Dy, and Sm. The interaction of the oblate 4f electron distribution of Tb and Dy with nearest neighbor ions in these alloys is the source of a huge magnetic anisotropy and high (~1%) positive magnetostriction. (Alternatively, the prolate shape of the Sm 4f shell gives rise to very large negative magnetostrictions.) Surprisingly, in all measurements to date, the high magnetic anisotropies are independent of crystal structure. Notably, $Tb_{1-x}Dy_x$ alloys exist in the hexagonal phase, with the c-axis extremely hard, whereas for $Tb_{1-x}Dy_xFe_2$, a cubic Laves phase alloy, very hard <111> axes can be changed to very hard <100> axes by increasing x from 0 to 1. (In fact, the existence of a near zero magnetic anisotropy by the proper choice of x is the origin of the well-known Terfenol-D alloys, $Tb_{1-x}Dy_xFe_2$.) The $Tb_{1-x}Dy_xZn$ system discussed here is particularly attractive because of the simplicity of its crystal structure (CsCl), its relatively high Curie temperatures (for rare earth alloys), and the existence of a large [u,v,0] phase for T < 50 K. A summary of some of the important properties of these three alloy systems is given in Table I. In all these systems, at least one of the magnetostriction constants is very large.

Table I. Magnetic and Magnetostrictive Properties of High Power Magnetostrictive Materials.

	Tb_xDy_{1-x}	$(Tb_xDy_{1-x})Zn$	$(Tb_xDy_{1-x})Fe_2$
T_C	~200 K	~200 K	~700 K
Magnetization ($\mu_o M_s$)	3.4 T @ 77 K	2.2 T @ 77 K	1.0 T @ 300 K
Elastic Modulus (Y^B)	~60 GPa @ 77 K	~50 GPa @ 77 K	~100 GPa @300 K
Dominant Magnetostriction Coefficient (λ)	$\lambda^{\gamma,2}$	λ_{100}	λ_{111}
Saturation Magnetostriction (λ_s)	6.5 x 10-3 @ 77 K	5.5 x 10-3 @ 77 K	2.0 x 10-3 @ 300 K
Coupling factor (k_{max})	~0.9	~0.9	0.75 – 0.80
Mechanical Properties	Ductile	Tough	Brittle
Useful Temperature Range	0 – 150 K	0 – 150 K	250 K – 525 K

The huge magnetostriction of equiatomic TbZn and its dependence on magnetic field and compressive stress are illustrated in Fig. 1.[1] For each stress, the rapid change in magnetization and magnetostriction with magnetic field is a reflection of the very large magnetic anisotropy as the easy axis jumps from one particular [100] direction perpendicular to the applied field to a second easy [100] direction parallel to the applied field. Young's modulus similarly is strongly affected by the large anisotropy and large magnetically induced strains. Its field dependences for typical compressive stresses of 14.9 MPa and 31.1 MPa are shown in Fig. 2. The huge softening of the modulus in the region of the magnetization jump reveals a ΔE Effect [$(E_{H=0}-E_H)/E_H$] greater than a factor of 10. Similar values are found for equiatomic DyZn[2], but not reported here.

The unusual [u,v,0] phase diagram of the $Tb_{1-x}Dy_xZn$ alloys, which appears at low temperatures, is outlined in Fig. 3 for 0 < x < 0.55.[3] It is not possible to generate this phase with only conventional single ion lowest order magnetic anisotropy constants. Representing these lowest order constants by K_4 and modeling the higher anisotropy constant by K_8, we have:

$$E_{anis}(\varphi) = K_4 \cos 4\varphi + K_8 \cos 8\varphi,$$

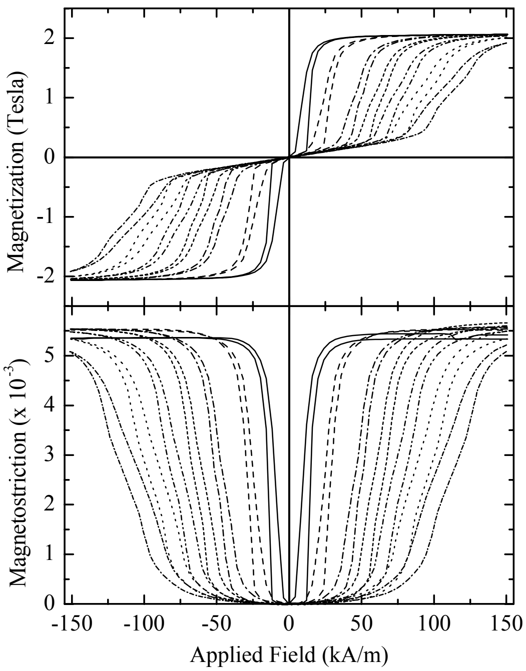

Fig. 1. Magnetization and magnetostriction of single crystal TbZn along the easy [100] axis at 77 K for compressive stresses of 5.3 MPa (——), 13.3 MPa (— — —), 24.6 MPa (— · — · —), 31.1(- - -), 37.5 MPa (-·-·-·-·), 44.0 MPa (·····), 50.5 MPa (-·-·-·).

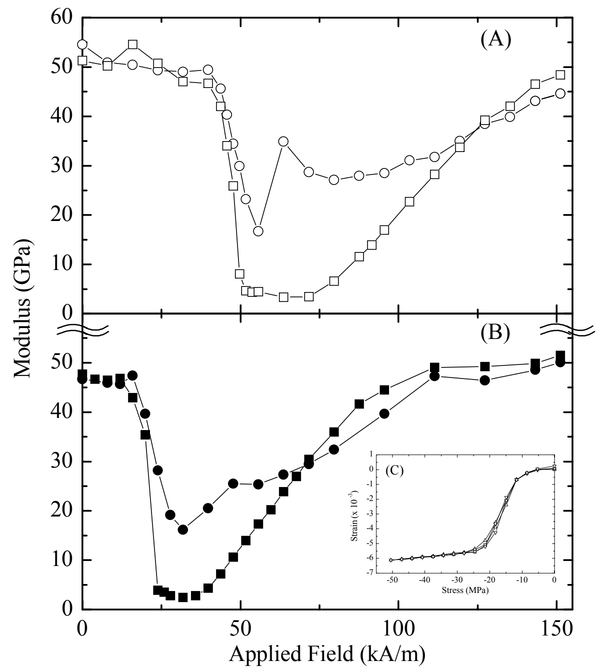

Fig. 2. Young's moduli (Y^H [■, □]; Y^B [●, ○]) of single crystal TbZn along the easy [100] axis at 77 K for compressive stresses of (A) 31.1 MPa and (B) 14.9 MPa. Inset C is an example of a strain vs. stress curve for a constant magnetic field. Here H = 32 kA/m.

where φ is the angle between the magnetization and the crystalline [100] direction. Fig. 3 illustrates the lines of constant K_4/K_8 in the [u,v,0] phase. Note: $-4 < K_4/K_8 < +4$.

The dependence of the magnetostriction on temperature is of theoretical interest. Fig. 4 illustrates the temperature dependence of the saturation magnetostriction, $(3/2)\lambda_{100}$, of $Tb_{.88}Dy_{.22}Zn$ taken between the Curie temperature and the [100]/[110] phase boundary. The magnetostriction in this region is well behaved, as expected, with the magnetostriction increasing substantially with decreasing temperature. Unfortunately, the magnetostriction at lower temperatures (See Fig. 4) could not be saturated under our highest magnetic fields of 26 kOe.

Piezomagnetic properties of the binary limiting compounds, TbZn and DyZn, are listed in Table II for compressive stresses ranging from ~10 MPa to 44 MPa. For many values of compressive stress and magnetic field, the magnetomechanical coupling is almost perfect (k > 0.9).

Table II. Relative permeability, μ_R, piezomagnetic *d*-constant, *d*, and Young's moduli, Y^H and Y^B, of TbZn and DyZn at 77 K. The magnetomechanical coupling constant $k = (1 - Y^H/Y^B)^{1/2}$.

	σ [MPa]	*H* [kA/m]	μ_R	*d* [nm/A]	Y^H [GPa]	Y^B [GPa]	*k*
TbZn	13.3	30	110	320	2.9	23	0.93
	31.1	65	54	180	3.4	28	0.94
	44.0	100	30	100	4.0	29	0.93
DyZn	11.8	30	110	360	---	---	---
	24.8	31	54	295	5.0	30	0.91
	44.0	54	30	140	6.6	28	0.87

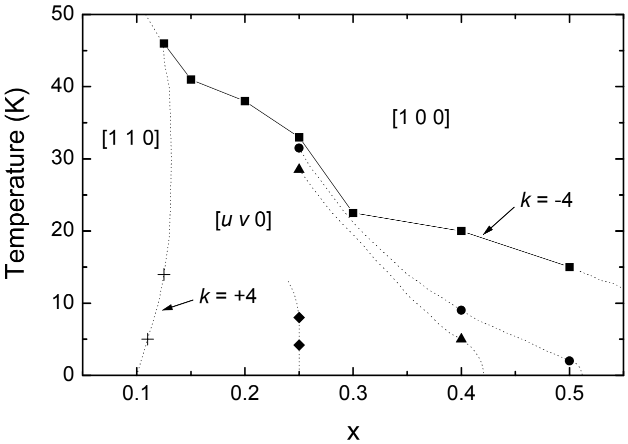

Fig. 3. A diagram showing curves of constant 4th to 8th order ratio of anisotropy coefficients, *k*, in *T*, *x* space: (■) *k* = -4.0, (●) *k* = -3.0, (▲) *k* = -2.0, (◆) *k* = +0.96, (+) *k* = +4.0.

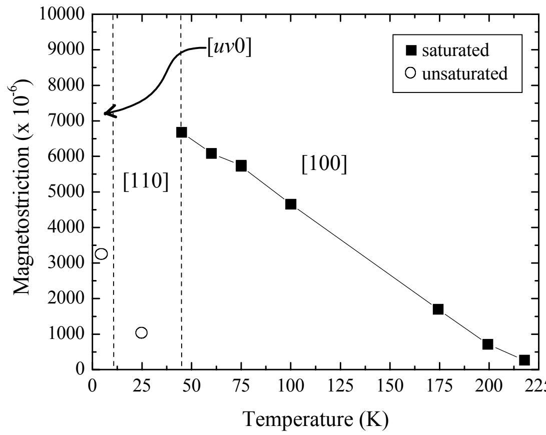

Fig. 4. Magnetostriction vs. temperature for $Tb_{0.88}Dy_{0.12}Zn$.

Keywords: magnetostriction, piezomagnetic properties, rare-earth zinc alloys

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