Magnetomechanical Properties and Anisotropy Compensation in Quaternary Rare Earth-Iron Materials of the Type $Tb_xDy_yHo_zFe_2$

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Abstract — The static and dynamic magnetomechanical properties, in the temperature range -60 °C to +100 °C, of quaternary compositions of the type $Tb_xDy_yHo_zFe_2$ (x+y+z=1) which have K_1 close to zero at +20 °C are presented The maximum room temperature values of d_{33} (7.9 nm A^{-1}) and k_{33} (0.62) are achieved for $Tb_{0.20}Dy_{0.22}Ho_{0.58}Fe_2$, the composition for which K_2 is also close to zero at +20 °C. Calculations performed with an anisotropy model including an eighth-order term show a 20 fold decrease in the anisotropy of $Tb_{0.20}Dy_{0.22}Ho_{0.58}Fe_2$ in comparison with Terfenol-D. This decrease is not as effective in improving material performance as the opposing influence of the reduction in saturation magnetostriction.

INTRODUCTION

The change in magnetomechanical properties of $Tb_{0.27}Dy_{0.73}Fe_2$ and $Tb_wHo_{1-w}Fe_2$ with variations in temperature and composition have been well characterised around the K_1 anisotropy compensation point [1, 2]. Interest in the $Tb_xDy_yHo_zFe_2$ (x+y+z=1) quaternary materials arises from the opposite sign of K_2 in $Tb_{0.27}Dy_{0.73}Fe_2$ and $Tb_wHo_{1-w}Fe_2$, thereby allowing suitable values of x, y and z to be found for which K_1 *and* K_2 are close to zero [3]. In this work we assess the effect of K_2 anisotropy compensation on the magnetomechanical properties of compositions for which K_1 is close to zero, and relate our findings to the easy axis of magnetisation [4].

EXPERIMENTAL

Magnetomechanical measurements were made on arc melted and vertical zone refined rods with nominal <112> orientation. Static measurements of the magnetostrain, λ, the magnetisation, M, and the bias field, H, were made by strain gauge, two coil induction and Hall effect techniques respectively. Measurements of the dynamic strain coefficient, d_{33}, and the dynamic susceptibility, χ_{33}, were made using lock-in techniques by applying a small alternating magnetic field of 400 A m^{-1} rms superimposed on H. The magnetomechanical coupling coefficient, k_{33}, was determined by the three-parameter method. All parameters were measured as a function of H, over the temperature range -60 °C to +100 °C, on quaternary compositions for which K_1 was expected to be small at +20 °C.

MAGNETOMECHANCIAL PROPERTIES

Static Characteristics

Fig. 1 shows a plot of λ vs. bias field, H, for $Tb_{0.20}Dy_{0.22}Ho_{0.58}Fe_2$ at different constant temperatures. The general shape of the curves is common to all the compositions investigated and shows a tendency for the composition to become more difficult to saturate as the temperature is reduced. This arises because, with decreasing temperature, the easy direction of magnetisation changes from <111> at high temperatures to <100> at lower temperatures [4]. When <100> is easy, larger fields are required to rotate the magnetisation into the <112> applied field direction.

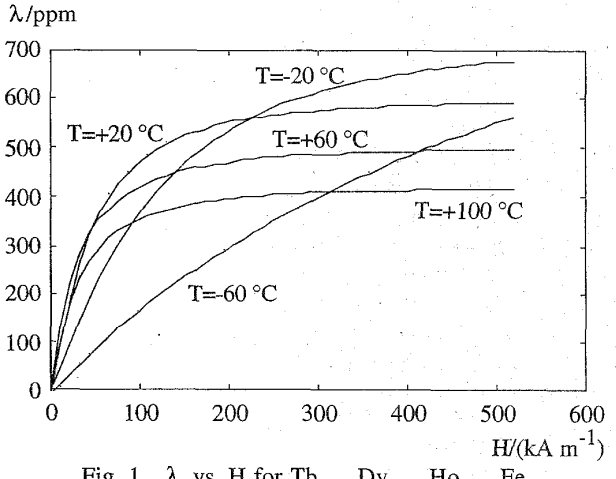

Fig. 1. λ vs. H for $Tb_{0.20}Dy_{0.22}Ho_{0.58}Fe_2$

The re-orientation of the magnetic moment also alters the shape of the curves of other static properties. As the temperature is reduced, the M vs. H curves indicate a higher static permeability at low values of bias field, followed by a sharper 'knee' and a slower approach to saturation at higher bias fields [1]. The normalised λ vs. M curves indicate that increasing H at low temperatures results in a higher fraction of saturation magnetisation, M_{sat}, being reached before significant strain is produced, followed by a more rapid approach to saturation via a much larger slope. These curves are shown in fig. 2 for $Tb_{0.20}Dy_{0.37}Ho_{0.43}Fe_{1.9}$ at different, constant, temperatures. We have previously related the details of these changes to the magnetisation process [5].

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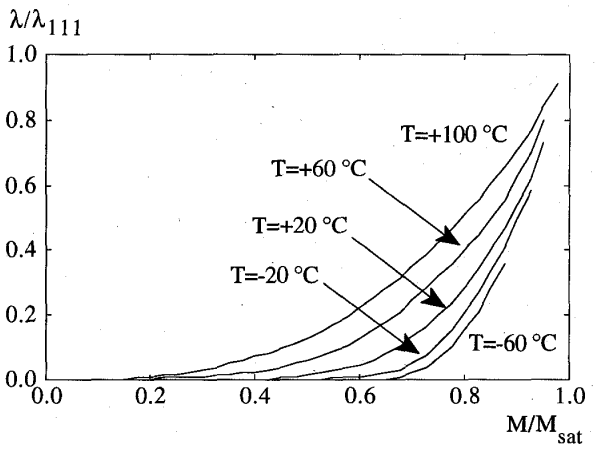

Fig. 2. Normalised λ vs. M for $Tb_{0.20}Dy_{0.37}Ho_{0.43}Fe_2$

Dynamic Characteristics

Fig. 3 shows a plot of d_{33} for $Tb_{0.20}Dy_{0.22}Ho_{0.58}Fe_2$ vs. H at different, constant, temperatures. d_{33} takes its maximum value of approximately 8 nm A^{-1} at a temperature of +40 °C with an applied bias field of approximately 10 kA m^{-1}. For temperatures higher than +40 °C, the magnitude of d_{33} at any value of H decreases slightly due to the reduction in the saturation magnetostrain, λ_{sat}. For temperatures below +40 °C, the easy direction of magnetisation changes to <100> resulting in a dramatic reduction of d_{33} and a tendency for it to become almost independent of H. Similar curves have been recorded for k_{33}, with the largest value (0.62) being obtained for this composition at a temperature of +40 °C.

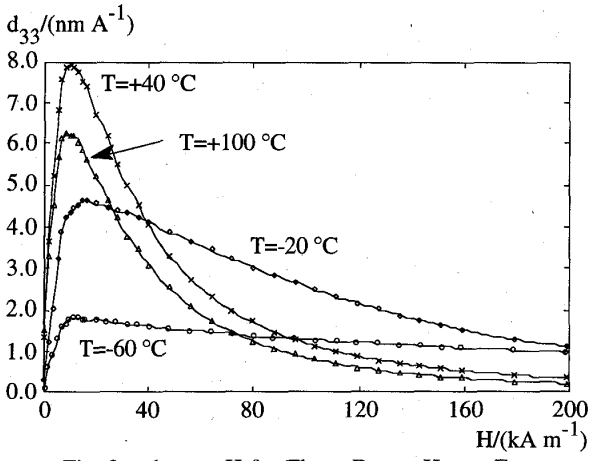

Fig. 3. d_{33} vs. H for $Tb_{0.20}Dy_{0.22}Ho_{0.58}Fe_2$

All of the compositions investigated displayed similar static and dynamic characteristics to those presented, and have much in common with the composition known as Terfenol-D ($Tb_{0.27}Dy_{0.73}Fe_2$). This similarity is attributable to the close proximity of the K_1 anisotropy point to room temperature.

The maximum value for d_{33} found for each composition is given in Table 1 together with the λ_{sat}, and k_{33} values, all measured at +20 °C. The compositions are arranged in order of increasing Dy content, and all have K_1 close to zero at room temperature. The values of d_{33} and k_{33} for the quaternaries are greatest for those compositions for which K_2 is smallest [3], but are all disappointingly lower than the corresponding values for $Tb_{0.27}Dy_{0.73}Fe_2$. Also shown in Table 1 is the ratio d_{33max}/λ_{sat}, which gives the maximum value of d_{33} per unit of saturation magnetostrain (at +20 °C). This ratio does show a peak for the composition $Tb_{0.20}Dy_{0.22}Ho_{0.58}Fe_2$, which is nearest to the K_2 anisotropy compensation point.

Composition			λ_{sat}	max d_{33}	max k_{33}	$(d_{33max}/\lambda_{sat})$
x	y	z	/10^{-6}	/nm A^{-1}		/(nm A^{-1} x 10^3)
0.13	0.00	0.87	320	2.8	0.30	8.8
0.20	0.22	0.58	640	7.9	0.62	12.3
0.23	0.26	0.51	900	6.2	0.46	6.9
0.20	0.37	0.43	680	4.4	0.36	6.5
0.27	0.73	0.00	1100	8.5	0.68	7.7

Table 1. Some Magnetomechanical Properties of $Tb_xDy_yHo_zFe_2$ at +20 °C

We have additionally observed that the rate of change in the magnetomechanical properties with temperature (i.e. the rate at which the easy direction of magnetisation changes from <111> to <100> with decreasing temperature) reduces with increasing Dy content.

Anisotropy Behaviour

According to Atzmony and Dariel [6], the change in the easy direction of magnetisation with temperature can be understood by including an eighth-order anisotropy constant, K_3, in the normal phenomenological equation for anisotropy energy, E_A:

$$E_A = K_0 + K_1(l^2m^2 + m^2n^2 + n^2l^2) + K_2(lmn)^2 + K_3(l^4m^4 + m^4n^4 + n^4l^4) \quad (1)$$

where l, m, and n are the usual direction cosines.

The results of their analysis, summarised in fig. 4, show the existence of stable <1uu>, <1u0> and <11u> easy direction regions, as well as the more familiar <111>, <100> and <110> regions. Our previous observations of the changes in the domain patterns of $Tb_{0.10}Ho_{0.90}Fe_{1.9}$ with temperature support the existence of a <1uu> easy region [7]. This is consistent with the expected signs of K_2 and $K_3(>0)$; values of $\alpha_2>0$ (as in the case for $Tb_wHo_{1-w}Fe_2$) requires the easy direction of magnetisation to change between <111> and <100>

via <1uu>, or <110> and <1u0>, or <11u>, <110> and <1u0>. Values of $\alpha_2<0$ (as is the case for $Tb_{0.27}Dy_{0.73}Fe_2$) allow a much more direct transition between <111> and <100>.

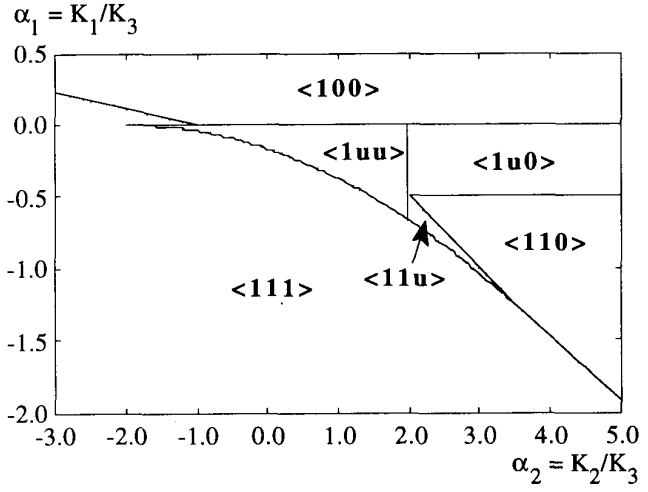

Fig. 4. Easy directions of magnetisation as given by equ. (1)

Now, if a composition is to be useful as a dynamic transducer, a large d_{33} and k_{33} are required. This implies that the easy direction of magnetisation should be <111>, since $\lambda_{111}>>\lambda_{100}$. Assuming our interpretation of the domain patterns to be correct, it follows that <111> will be easy provided that [6]:

$$\alpha_1 < \frac{-(\alpha_2 + 2)^2}{24} \qquad (2)$$

In that case the energy required to overcome the anisotropy to change the direction of magnetisation from <111> to <112> (the axial direction of the rod-shaped samples), ΔE_A:

$$\frac{\Delta E_A}{K_3} = \frac{\alpha_2^2}{288} - \frac{\alpha_2}{216} + \frac{1}{432} \qquad (3)$$

ΔE_A is plotted as a function of α_2 in fig. 5. We have taken $K_3 = +10^5$ J m^{-3} [6] and $-2 < \alpha_2 < +3$ (this is consistent with K_2 changing from ~ $+10^5$ J m^{-3} to -10^5 J m^{-3} as the composition changes with increasing Dy content from $Tb_{0.13}Ho_{0.87}Fe_2$ to $Tb_{0.27}Dy_{0.73}Fe_2$). ΔE_A exhibits a minimum when $\alpha_2 = 0.66$. It is interesting to note that the position of this minimum and the composition exhibiting the largest value of d_{33}/λ_{sat} both occur on the Ho rich side of the composition lying mid-way between $Tb_{0.13}Ho_{0.87}Fe_2$ to $Tb_{0.27}Dy_{0.73}Fe_2$.

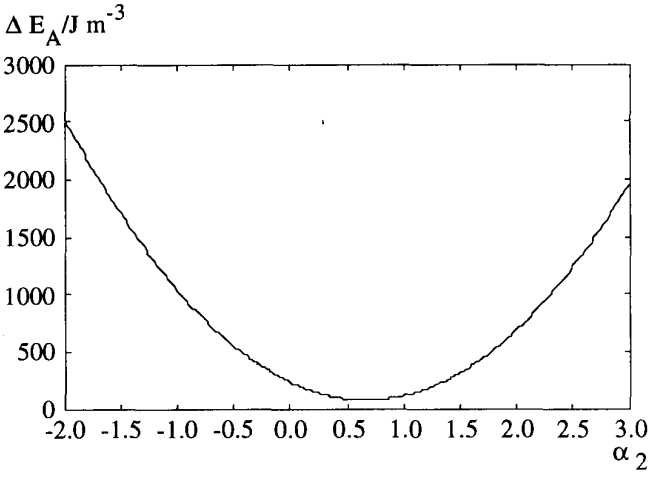

Fig. 5. ΔE_A plotted as a function of α_2 (equ. 3)

With ΔE_A dropping by a factor of about 20 over this composition range, it is surprising that there is not a corresponding increase in k_{33}. However, since the magnetomechanical energy required to saturate such materials is about 10^4 J m^{-3}, it appears that the effect of the reduction in anisotropy energy is less effective in increasing d_{33} and k_{33} than the opposing influence of the reduction in λ_{sat}.

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