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Interpretation of the magnetization mechanism in Terfenol-D using Barkhausen pulse-height analysis and irreversible magnetostriction

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Abstract
The ternary alloy $Dy_{0.7}Tb_{0.3}Fe_{1.9}$, known as Terfenol-D, is a highly magnetostrictive alloy with magnetostriction coefficients along the principal crystallographic directions of $\lambda_{1\,1\,1}=1640\times10^{-6}$ and $\lambda_{1\,0\,0}\leq100(\pm30)\times10^{-6}$. The bulk magnetostriction λ is dependent on the state of magnetization M, on the original domain configuration, and on the texture of the material. This paper reports on Barkhausen measurements and magnetostriction. The pulse-height distribution of Barkhausen emissions revealed events occurring at a specific amplitude which were stress dependent. The magnetostriction results gave a saturationmagnetostriction in excess of 2000 μ strain.

Keywords
Ames Laboratory, Magnetostriction, Barkhausen effects, Crystalline alloys, Bulk materials, Magnetic materials

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Interpretation of the magnetization mechanism in Terfenol-D using Barkhausen pulse-height analysis and irreversible magnetostriction

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The ternary alloy $Dy_{0.7}Tb_{0.3}Fe_{1.9}$, known as Terfenol-D, is a highly magnetostrictive alloy with magnetostriction coefficients along the principal crystallographic directions of $\lambda_{111} = 1640 \times 10^{-6}$ and $\lambda_{100} \leqslant 100(\pm 30) \times 10^{-6}$. The bulk magnetostriction λ is dependent on the state of magnetization M, on the original domain configuration, and on the texture of the material. This paper reports on Barkhausen measurements and magnetostriction. The pulse-height distribution of Barkhausen emissions revealed events occurring at a specific amplitude which were stress dependent. The magnetostriction results gave a saturation magnetostriction in excess of 2000 μ strain.

I. INTRODUCTION

In order to obtain the largest bulk magnetostriction possible, $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ specimens should be fabricated as rods with the crystallographic [111] direction aligned along the unique axis. A number of studies have shown that this is extremely difficult to achieve.[1] Therefore, specimens are produced with the [112] direction along the unique axis. The nearest [111] axis is displaced by an angle of 19.5° from the unique axis of the rod as indicated in Table I. Preferential growth along the [112] direction allows easy development of twins, and twinning of the crystal is known to occur in Terfenol. This leads to inhibition of the low-field magnetostriction; however, the saturation magnetostriction along the [112] axis is not affected by the twinning.

To improve the bulk magnetostriction, specimens were subjected to compressive stresses of up to 14 MPa along the unique axis. This had the effect of increasing the amount of 90° domain processes occurring during magnetization by aligning domains preferentially along the $[\bar{1}\bar{1}1]$ of $[11\bar{1}]$ axes in the demagnetized state. These axes were perpendicular to the unique axis of the specimen. When all domains were aligned perpendicular to the unique axis in the demagnetized state, a 50% increase in saturation magnetostriction was observed.[2]

Measurements on some recent specimens have shown that in the materials with $\lambda_s \geqslant 2000 \times 10^{-6}$ there is a very rapid increase in magnetostriction with field H at field strengths of typically 16–40 kA/m (200–500 Oe) when the material is under a compressive load. Although in some cases λ was found to be discontinuous with respect to H,[3] it did not exhibit any unusual behavior as a function of B.[4] However, the hysteresis loop of these high-performance specimens did show a distortion under load as shown in Fig. 1. The rapid change in magnetostriction with field H was found to occur at the location of the maximum in dB/dH.

TABLE I. Orientations of the family of (111) directions with respect to the [112] axis which is parallel with the unique axis of the rod in Terfenol-D.

Axis	Angle
[111]	19.5°
$[\bar{1}\bar{1}1]$, $[\bar{1}11]$	61.9°
$[\bar{1}\bar{1}1]$, $[11\bar{1}]$	90°
$[1\bar{1}\bar{1}]$, $[1\bar{1}1]$	118.1°
$[\bar{1}\bar{1}\bar{1}]$	160.5°

II. RESULTS

The measurement system used in this investigation was similar to that described previously.[5] In all cases we took the magnetostriction in the demagnetized state as the zero reference point. In the unloaded condition it was found that upon

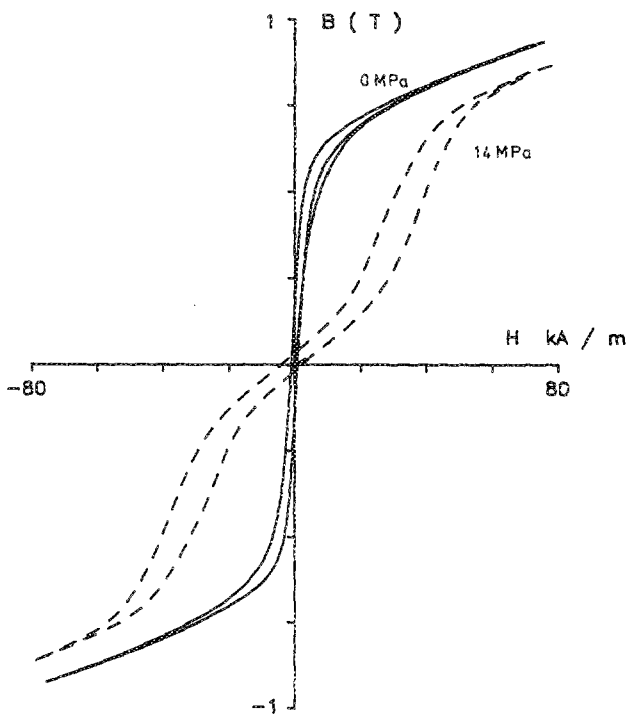

FIG. 1. Changes in the magnetization curve (hysteresis loop) of Terfenol-D under applied stress.

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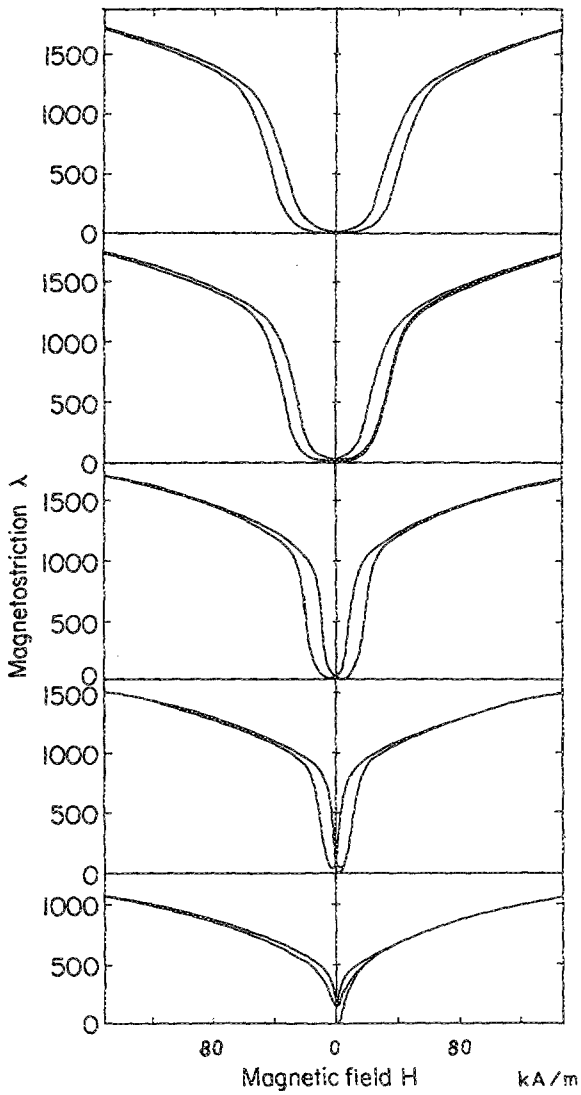

FIG. 2. Magnetostriction as a function of magnetic field H for several different levels of stress, as given in Table II. Top figure is at 18 MPa compression, bottom figure is at 0 MPa.

state we observed a magnetostriction amplitude $\Delta\lambda = 1025\times10^{-6}$ between the saturated and demagnetized states, but only an amplitude $\Delta\lambda = 913\times10^{-6}$ between the magnetizing the specimen the magnetostriction appeared to have two components, a reversible component and an irreversible component. The latter was manifested as a net offset in magnetostriction when the magnetization was reduced to zero after saturation as shown in Fig. 2.

It is known that the bulk magnetostriction λ_S is determined by the initial (demagnetized) domain configuration. Since the magnetostriction λ does not return to its original demagnetization value when the magnetization is reduced to zero after being subjected to an applied field, it is clear that irreversible changes in the domain configuration have occurred between the demagnetized $M = 0$ state and subsequent $M = 0$ states in the cyclic condition. In the unstressed saturated and subsequent $M = 0$ states. This was due to an irreversible offset magnetostriction of 112×10^{-6}.

Under compressive load the magnetostriction amplitude increased, but the irreversible offset magnetostriction decreased rapidly, as shown in Fig. 2. This implies that the domain configuration under an applied stress greater than 3 MPa is recoverable when the magnetization is reduced to zero, and hence that the magnetostriction is reversible under these conditions. When the material was under a compressive load of 14 MPa, the magnetostriction amplitude $\Delta\lambda$ at a field amplitude of 240 kA/M (3000 Oe) was found to lie in the range $(2202–2261)\times10^{-6}$.

The application of a compressive stress favored orientation of the domains along the two axes $[\bar{1}\bar{1}1]$ and $[11\bar{1}]$, which are perpendicular to the field axis. At higher compressive stresses these directions became increasingly favored, so that upon reduction of the magnetization to zero, the domains reverted to these directions perpendicular to the field axis. This led to complete reversibility in magnetostriction. Upon reduction of the magnetization to zero in the unstressed condition when in the cyclic state, some of the domains which were originally in the perpendicular directions in the demagnetized condition failed to revert to the perpendicular directions but rather underwent a nonmagnetostrictive 180° domain rotation. This reduced the magnetostriction amplitude when the material was in its cyclic state under zero stress. There appeared to be very good correlation between the maxima in dB/dH and $d\lambda/dH$, as shown in Table II.

Pulse-height analysis of the Barkhausen events is shown here for the first time in Fig. 3. These were obtained from the pulse-height spectra at various stress levels by subtracting an exponential background spectrum. The difference spectrum

TABLE II. Values of the field strengths at which maxima occur in $d\lambda/dH$ and differential permeability dB/dH for various applied compressive stresses as the magnetic field was swept from saturation in the negative direction to saturation in the positive direction. Two principal peaks in activity occurred: one at a negative field strength and the other at a positive field strength as reported previously (Ref. 4).

	H_μ		H_λ	
Stress (MPa)	− kA/m (Oe)	+ kA/m (Oe)	− kA/m (Oe)	+ kA/m (Oe)
0	−0.75 (−9.42)	0.98 (12.3)	−1.21 (−15.1)	2.86 (35.7)
3.5	−1.78 (−22.3)	1.24 (155)	−2.66 (−33.2)	10.12 (126.5)
7	−8.22 (−102.7)	19.92 (249)	−9.30 (−116.2)	19.95 (249.4)
14	−20.80 (−260)	31.04 (388)	−22.11 (−276.4)	33.76 (422.0)
18	−28.48 (−356)	37.92 (474)	−30.40 (−380)	41.36 (517.0)

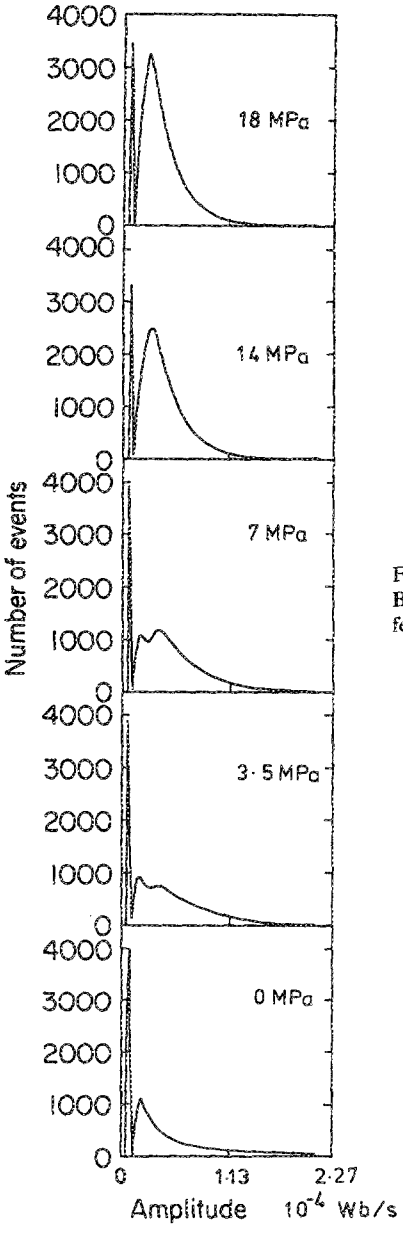

FIG. 3. Pulse-height spectra of Barkhausen emission in Terfenol-D.

obtained thereby revealed details of the Barkhausen activity at higher amplitudes; in particular, it was found that there was Barkhausen activity with a very well-defined amplitude of 1.27 V (3.6×10^{-5} Wb/s) which was strongly dependent on the stress. The occurrence of a number of Barkhausen events of the same amplitude is indicative of a number of identical processes occurring in the material, and the high stress sensitivity indicates that these events are due to the $[\bar{1}\bar{1}1]\rightarrow[111]$ and $[11\bar{1}]\rightarrow[111]$ mechanisms.

III. ANALYSIS

In this material the $\langle 111\rangle$ axes are the magnetic easy axes and so the anisotropy, by convention, is negative. According to Clark and co-workers[3] it has a value of $K_1 = -0.6\times10^5$ J/m^3. The anisotropy as a function of angle is then given by

$$E_a = K_1 \sum_{\substack{i,j=1,2,3 \\ i\neq j}} \cos^2\theta_i \cos^2\theta_j,$$

and therefore the anisotropy energies along the [111], [110], and [100] axes are, respectively, $-K_1/3$, $-K_1/4$, and 0. If we consider the energy needed to rotate the direction of magnetization between any two $\langle 111\rangle$ directions, the energy barrier will be $K_1/6$ with rotation through the [110] direction and $K_1/3$ with rotation through the [100] direction. The critical field H_{cr} required to cause rotation between [111] directions, in the absence of stress, is the field needed to overcome the energy maximum of $K_1/6$ along the [110] direction.[6] This is given by

$$\mu_0 M_s H_{cr} \cos\theta = K_1/6,$$

where $\theta = 54.7°$ is the angle between the field direction [112] and the [110] direction. The critical field strength is then $H_{cr} = 17$ kA/m $= 216$ Oe.

This field strength is comparable with the field strength of 22.4 kA/m (280 Oe) at which Verhoeven *et al.*[7] have observed critical behavior of the magnetostriction in these alloys. It therefore appears that the field strength at which the rapid, and sometimes discontinuous, change in magnetostriction occurs in the vicinity where we should expect rotational processes to occur.

IV. CONCLUSIONS

Results have been presented on the magnetostriction and Barkhausen effect in a recent specimen of high-performance Terfenol-D with composition $Tb_{0.3}Dy_{0.7}Fe_{1.9}$. This specimen had a bulk saturation magnetostriction in excess of 2000×10^{-6} under a compressive stress of 14 MPa. The results showed the emergence of Barkhausen pulses with peak heights of 3.6×10^{-5} Wb/s. The number of pulses of this amplitude was found to be strongly dependent on applied stress, being within the background of typically 700 events per cycle at zero stress, but rising to 3300 events per cycle at 18 MPa. These Barkhausen events, which occurred over a limited range of amplitude, have been attributed to the rotation of magnetization from the $[\bar{1}\bar{1}1]$ and $[11\bar{1}]$ to the [111] directions within the crystal. The field strength H at which these events occurred was consistent with the field strength necessary to cause domain rotation by overcoming the anisotropy energy.

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