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Enhancement of piezomagnetic response of highly magnetostrictive rare earth-iron alloys at kHz frequencies

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Abstract
The effects of Al and Si additions on the frequency response of highly magnetostrictive Tb–Dy–Fe alloys have been studied. These elements reduced the electrical conductivity of the material, thereby increasing the depth of penetration of acmagnetic fields and extending the operational frequency range. Complex permeability measurements were made on doped and undoped polycrystalline samples with the objective of studying the improvement in energy conversion efficiency at kilohertz frequencies as a result of the alloying additions. The resulting complex permeability was compared with the values for single crystal specimens of $Tb_{0.3}Dy_{0.7}Fe_{1.92}$ at a range of frequencies from 10 Hz to 50 kHz.

Keywords
Alloys, Alternating current power transmission, Aluminum, Doping, Electrical conductivity

Disciplines
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Comments
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INTRODUCTION

The room temperature magnetostriction of rare earth-iron alloys, such as Terfenol-D has a magnitude of typically 1600 ppm.[1] This has stimulated research into their use in sensor and transducer applications. For instance, micropositioning and adaptive vibration control applications require an appropriate high frequency response. Undoped Terfenol-D has a conductivity of 60×10^{-8} Ω m which significantly reduces the magnetic field penetration. For example, the skin depth is typically 1.5 mm in Terfenol-D at 50 kHz. This limits the diameter of a Terfenol-D rod that can usefully be employed and consequently restricts the load bearing capability of an actuator. Doping Terfenol-D with light elements such as aluminum, silicon, or boron could offer a route whereby the electrical resistivity can be increased by providing scattering sites for the conduction electrons, thereby reducing eddy current effects without having a large adverse effect on the magnetoelastic properties.

EXPERIMENTAL TECHNIQUES

Measurements of complex permeability were taken as a function of frequency for both doped and undoped polycrystalline samples and for twinned single crystal samples of Terfenol-D. Each specimen was approximately 50 mm long and 9 mm in diameter. The voltage signal from an encircling flux coil on the specimen was analyzed using a lock-in amplifier. The lock-in amplifier provided the reference signal driving the solenoid which generated the applied magnetic field. An ac magnetic field amplitude of 240 A/m was applied at frequencies in the range 10 Hz–50 kHz. The variation of complex permeability with frequency is shown in Fig. 1 for single crystal Terfenol and three specimens of polycrystalline Terfenol. Resonance–antiresonance data obtained from the rate of change of magnetic induction are shown in Fig. 2.

The performance of the materials was quantified in terms of the two piezomagnetic coefficients, $d=(d\lambda/dH)_B$ and $g=-(d\lambda/dB)_\sigma$ and the magnetomechanical coupling coefficient k. Real and imaginary components of the piezomagnetic strain coefficient g, elastic compliance s, and complex permeability μ were determined for the polycrystalline samples.

The magnetomechanical coupling coefficient k is often calculated from resonance-antiresonance data using

$$k^2=\frac{\pi^2}{8}\left[1-\left(\frac{f_r}{f_a}\right)^2\right], \tag{1}$$

where f_r is resonant frequency and f_a is the antiresonant frequency. Another method for calculating k is using the piezomagnetic coefficient g, permeability at constant stress μ_s and compliance at constant induction s_B. This is the so-called *three parameter* method. The value of k is obtained from

$$k^2=g^2\,\frac{\mu_s}{s_B}. \tag{2}$$

Both of these methods for determining k have limitations, however. The resonance method takes no account of the behavior of the material other than the locations of the

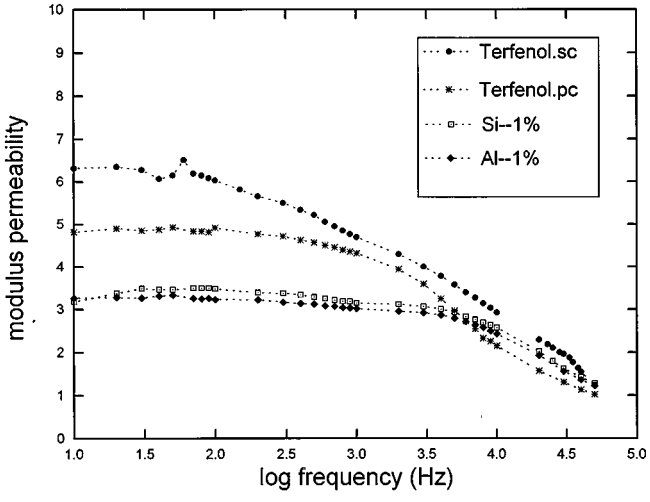

FIG. 1. Complex permeability for (a) single crystal Terfenol, (b) undoped polycrystalline Terfenol, (c) polycrystalline Terfenol +1% Si, (d) polycrystalline Terfenol +1% Al.

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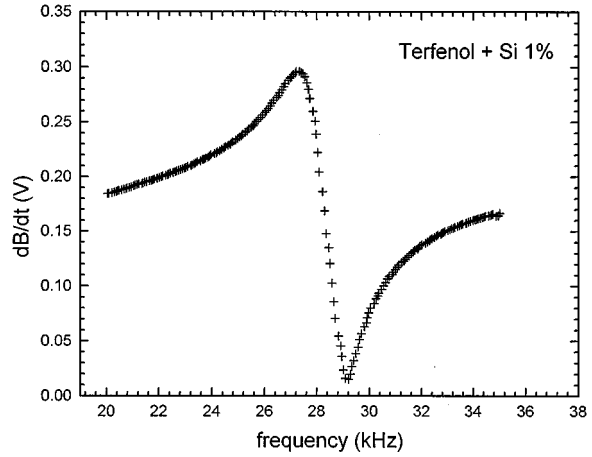

FIG. 2. Resonance–antiresonance peaks for polycrystalline Terfenol +1% Si.

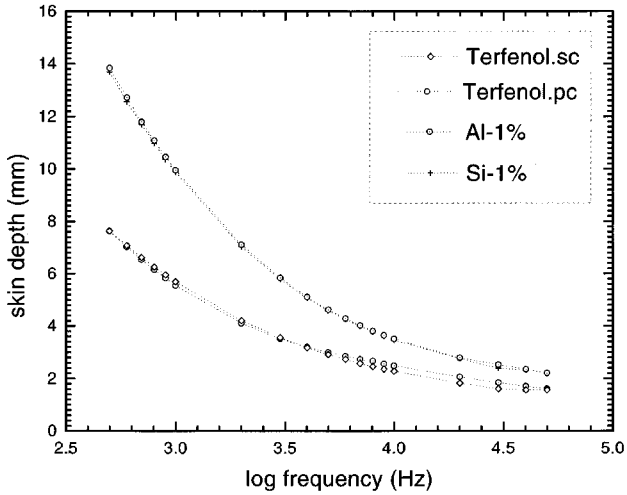

FIG. 3. Calculated skin depth of Terfenol samples as a function of frequency of applied field.

resonance and antiresonance frequencies, and therefore is highly susceptible to slight shifts, or even inaccuracies in the determination of these frequencies.

On the other hand, the analysis leading up to the derivation of Eq. (2) for the three parameter method is flawed because it rests on the assumption of small amplitude, linear and reversible displacements, all three of which are disputable in the case of a ferromagnetic material.

Recently an improved method has been developed for the determination of the coupling coefficient k using plane wave modeling techniques.[2] This allows the shape of the entire frequency response curve of Fig. 2 to be used to determine k. Such a calculation is both more robust and more appropriate than the conventional methods used to date.

The coupling factor, k was obtained from the magnetomechanical resonance in rods of different compositions, each approximately 50 mm long and 9 mm in diameter. With no applied prestress, a longitudinal dc bias field of 52 kA/m was sufficient to obtain maximum coupling. The frequency of an oscillatory excitation field of amplitude 80 A/m was swept through a range of frequencies including the resonance and antiresonance. The amplitude and phase of the emf induced in a flux coil wound around the sample were recorded continuously through the whole resonance region. The calculated values of coefficients, g, μ_s, and s_B were corrected for the effects of specimen shape and resonant frequency using the plane wave model.[2]

A comparison was made of the measured response with that predicted from a model based on plane acoustic wave propagation in a magnetoelastic medium.[3,4] Values for the piezomagnetic strain coefficient g, permeability at constant strain μ, and the elastic compliance at constant induction s_B, enabled the magnetomechanical coupling coefficient k to be calculated. The resistivities of the specimens were measured using a standard four probe method.

RESULTS AND DISCUSSION

Nominal skin depth δ was calculated for all samples using

$$\delta = \sqrt{\rho/\nu\pi\mu}, \tag{3}$$

where ρ is the resistivity, ν is the frequency, and μ is the permeability. Skin depth variation for the different samples as a function of frequency is shown in Fig. 3. The skin depths for the doped specimens were calculated using Eq. (3) together with the measured values of the resistivity ρ. The resistivities of the doped samples are an average of 125% greater than the pure Terfenol samples. The skin depths at 1 kHz were found to be 80% greater in the doped specimens than in both the pure polycrystalline Terfenol and the pure single crystal Terfenol.

The polycrystalline unalloyed Tb–Dy–Fe material had $d = 1.37\times10^{-9}$ m/A, $g = 0.756\times10^{-3}$ A s^2/kg, and $k = 0.23$. An addition of 1% Al increased d to 1.89×10^{-3} m/A and increased k to 0.287. An addition of 1% Si increased d to 1.92×10^{-9} m/A and increased k to 0.290. These results showed that alloying additions of either 1% Al or Si led to an increase of typically 55% in energy conversion efficiency in the material (see Table I). This improvement arises primarily because of the improved depth of penetration of the magnetic field in the material as shown in Fig. 3.

CONCLUSION

There is a need to extend the useful operating range of magnetostrictive materials such as Terfenol-D. Presently, material performance is limited by skin depth, which depends on conductivity of the material, and decreases with frequency. The most obvious means to achieve improved performance at high frequency is to limit or reduce the con-

TABLE I. Magnetomechanical coupling coefficients and energy conversion efficiency for various samples.

Sample	k	$(\Delta k)^2$
Polycrystalline Terfenol	0.232	⋯
Terfenol +1% Al	0.287	53%
Terfenol +1% Si	0.290	56%

ductivity. In this work we have alloyed 1% Al or Si with Terfenol to decrease the conductivity. A concomitant reduction in permeability occurs on the addition of Al or Si to Terfenol. This is due to pinning of domain walls by the impurity atoms. Results show that the addition of 1% Al or Si increased the resistivity thus leading to an improvement of field penetration at kHz frequencies and to a 53% or 56% improvement in energy conversion efficiency. However, the addition of higher concentrations of Al or Si resulted in specimens which were extremely brittle and this was recognized as disadvantageous. An alternate method of improving the performance would be through the fabrication of layered specimens consisting of alternate layers of Terfenol and a material of lower conductivity such as silicon.

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