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Influence of magnetic fields on the mechanical loss of Terfenol-D/PbZr_{0.52}Ti_{0.48}O₃/Terfenol-D laminated composites

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1. Introduction

The magnetoelectric (ME) effect induced by polarization/magnetization in magnetic/electric fields [1-3] is of fundamental and technological importance. Because the composite consisting of magnetostrictive and piezoelectric phases is expected to show a much stronger ME effect than that of singlephase ME materials, a number of possible applications based on this strain-mediated ME coupling have attracted a surge of interest, such as multifunctional sensors [4], filters [5] and power harvesting [6]. Extensive efforts for obtaining a strong ME effect were carried out in ME composites with ferrite, shape memory alloys or Terfenol-D (Tb_{0.3}Dy_{0.7}Fe_{1.92}) as magnetostrictive components and leadmagnesio-niobate single crystal or lead zirconate titanate PbZr_{1-x}Ti_xO₃ (PZT) ceramics as piezoelectric components [7-11]. A ME laminate composite composed of Terfenol-D and PZT is of particular interest due to the relative large piezoelectric/piezomagnetic coefficient as well as low cost. Many different configurations, including disk, rectangular and ring shapes, for this kind of composites were investigated [11-13], and the ME voltage coefficient can reach as high as several $VOe^{-1} \text{ cm}^{-1}$ at a quasi-static frequency [13-15].

For the resonance situation, the ME coefficient is not only determined by the structures or operation modes but also related to the electromechanical coupling which closely depends on the energy

ABSTRACT

The influence of magnetic fields on the mechanical loss (Q^{-1}) of Terfenol-D/PbZr_{0.52}Ti_{0.48}O₃/Terfenol-D three-layer laminated composites is investigated systemically using the technique for measuring the resonance magnetoelectric (ME) effect. The results indicate that Q^{-1} varies non-monotonically with dc magnetic fields and shows a maximum near 500 Oe for all the samples with different layer thickness ratios (n) of Terfenol-D (Tb_{0.3}Dy_{0.7}Fe_{1.92}). Considering various kinds of mechanical energy dissipation, it is found that Q^{-1} is mainly dominated by the mechanical damping due to the domain wall motion in Terfenol-D under the actions of dc and ac magnetic fields as well as the stress at the interface. In addition, the effect of eddy current losses on the energy dissipation of the system is also discussed.

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dissipation, especially mechanical losses [16,17]. The mechanical losses in Terfenol-D and PZT have been widely investigated. It was reported that the magnetomechanical damping of Terfenol-D measured from the strain-stress hysteresis loop at low frequencies indicates that the energy dissipation is closely related to the non-180° ferromagnetic domain-wall movement induced by magnetic fields and prestress [18–22], and the mechanical loss in PZT is mainly attributed to the irreversible ferroelectric domain-wall movement [17]. However, little effort has been devoted to studying the variation of the mechanical energy dissipation Q^{-1} for Terfenol-D/PZT ME composite. Furthermore, several other crucial questions such as the influences of magnetic fields and frequencies on Q^{-1} in this ME composite are also unclear so far.

In this paper, we systemically investigate the mechanical energy dissipation in the laminate composite composed of Terfenol-D (Tb_{0.3}Dy_{0.7}Fe_{1.92}) and PbZr_{0.52}Ti_{0.48}O₃ (PZT). As the magnetic domain wall motion in Terfenol-D strongly depends on magnetic fields, the investigations of the ratio between Terfenol-D and PZT as well as magnetic field effects on Q^{-1} can effectively clarify mechanical losses of the system in nature. Our experimental results show that the mechanical energy dissipation of the composite is mainly dominated by the mechanical damping of Terfenol-D and can influence the resonance ME coefficient $\alpha_{ME,R}$.

2. Experimental

Three-layer laminates of Terfenol-D/PZT/Terfenol-D with different thickness ratios (*n*) for Terfenol-D were fabricated, here *n* is defined as $2t_{TED}/(2t_{TED} + t_{PZT})$, t_{TED} and t_{PZT} represent the thicknesses of Terfenol-D and PZT plates, respectively. The PZT component with a size of $12 \times 4 \times 1$ mm³ ($t_{PZT} = 1$ mm for all samples) was polarized under an electric field of 3 kV/mm at 120 °C in silicon oil in the thickness direction. The grain-oriented (1 13) polycrystalline Terfenol-D plates were magnetized along the longitudinal direction to form a longitudinal-transverse configuration and their

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Fig. 1. Frequency dependence of the ME voltage coefficient at $H_{ac} = 1$ Oe, n = 0.67, and different H_{dc} from 0 to 6 kOe. The inset shows the schematic configuration of the samples.

dimensions were $12 \times 4 \times t_{\text{TFD}}$ mm³. Here, the values of t_{TFD} are 1, 0.5 and 0.25 mm, and thus the values of *n* are equal to 0.67, 0.5 and 0.33, respectively. The PZT plate was laminated between two Terfenol-D plates using conductive silver epoxy bonder under pressure and the schematic diagram of the samples was shown in the inset of Fig. 1.

The ME voltage coefficient was determined by measuring the electric field generated across the sample with ac magnetic fields (H_{ac} , up to 2 Oe) and dc bias fields (H_{dc} , up to 6 kOe). A signal generator amplified by a power amplifier was used to drive a Helmholtz coil to generate the small H_{ac} superimposed on H_{dc} . The voltage generated across the piezoelectric layer was measured with an oscilloscope or a lock-in amplifier. The ME resonance behaviors were carried out by measuring the ME output around the resonance frequency range with a step of 0.5 kHz.

3. Results and discussion

Fig. 1 shows the frequency dependence of resonance ME properties of the Terfenol-D/PZT/Terfenol-D laminates for n = 0.67 under different H_{dc} with superimposed H_{ac} of 1 Oe. The resonance ME coefficient ($\alpha_{ME,R}$) increases with increasing magnetic bias and reaches up to $\sim 23 \text{ V cm}^{-1} \text{ Oe}^{-1}$ at a resonance frequency f_r of 110 kHz under $H_{dc} = 2 \text{ kOe}$. One of the most interesting results is that as H_{dc} increases, the resonance frequency f_r decreases at first, reaches its minimum near 400 Oe and then shifts up as shown in Fig. 2. This non-monotonic shift in f_r is due to the variation of Young's modulus caused by the domain wall motions of Terfenol-D under magnetic fields [16]. Furthermore, a decrease of f_r with



Fig. 2. Variation of the resonance frequency f_r of the Terfenol-D/PZT laminate as a function of H_{dc} for n = 0.67. The inset shows a close view of f_r at low H_{dc} with $H_{ac} = 0.5$ Oe, 1 Oe, and 2 Oe.

increasing ac magnetic field H_{ac} is observed at a low H_{dc} range, see the inset of Fig. 2. Larger amplitude of H_{ac} forces the domain walls moving back and forth frequently more easily and thus leads to a decrease in f_r . The slow increase of f_r in the field range from 0.5 kOe to 6 kOe corresponds to the gradual saturation of the magnetization in Terfenol-D [23].

From the frequency dependencies of the ME coefficient, one can estimate the total mechanical energy dissipation (Q^{-1}) defined as $Q^{-1} = \Delta f_r/f_r$ [24], here Δf_r represents the 3 dB frequency bandwidth. Fig. 3(a) and (b) show the dc magnetic field dependencies of Q^{-1} under different H_{ac} and n, respectively. It is found that Q^{-1} has a peak near a dc magnetic field of 500 Oe for all n and H_{ac} , and increases with increasing n and H_{ac} . For a Terfenol-D/PZT ME laminate composite, one can regard that the total mechanical energy dissipation Q^{-1} is mainly composed of the mechanical damping of Terfenol-D ($Q_{mech,TFD}^{-1}$), mechanical damping of PZT ($Q_{mech,PZT}^{-1}$), the loss at the interface (Q_{face}^{-1}) between Terfenol-D and PZT. Suppose Q^{-1} can be expressed as:

$$Q^{-1} = nQ_{\text{mech,TFD}}^{-1} + (1-n)Q_{\text{mech,PZT}}^{-1} + Q_{\text{face}}^{-1} = n(Q_{\text{mech,TFD}}^{-1} + Q_{\text{face}}^{-1}) + (1-n)(Q_{\text{mech,PZT}}^{-1} + Q_{\text{face}}^{-1})$$
(1)



Fig. 3. (a) Total mechanical energy dissipation Q^{-1} of the Terfenol-D/PZT laminate as a function of H_{dc} with $H_{ac} = 0.5$ Oe, 1 Oe, and 2 Oe for n = 0.67. (b) Q^{-1} as a function of H_{dc} for n = 0.67, 0.5 and 0.33, and $H_{ac} = 1$ Oe. (c) $Q_{mech, FDT}^{-1}$ and $Q_{mech, FDT}^{-1}$ as a function of H_{dc} , the blue and red lines represent the calculated results with {n = 0.33 and 0.5} and {n = 0.57 and 0.67}, respectively(For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article).

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