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Metglas/Pb(Zr,Ti)O_3/Metglas laminates

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Enhanced magnetoelectric effect in self-stressed multi-push-pull mode Metglas/Pb(Zr,Ti)O₃/Metglas laminates

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Two methods to effectively induce self-stress on Metglas/Pb(Zr,Ti)O₃/Metglas laminate are presented: (i) applying a dc magnetic field to the Metglas layers or (ii) applying a dc electric field to the core piezoelectric composites. An optimum self-stress enhances the magnetoelectric (ME) effect in the laminates. With a 20 Oe dc magnetic bias, the value of $\varepsilon_{\text{ME}}$ for the self-stressed laminate was enhanced to 31.4 V/cm·Oe, which was by a factor of 1.24× compared to the laminate without self-stress. Furthermore, the equivalent magnetic noise floor was reduced by the self-stress at low frequencies. © 2012 American Institute of Physics.

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The value of $a_{ME}$ increased with increasing magnetic fields until $H_{bias} = 20$ Oe and then decreased with further increase in $H_{bias}$. As shown in Fig. 2(b), without self-stress in the laminate, the maximum value of $a_{ME}$ was 25.3 V/cm · Oe, which agrees well with data previously reported. However, for $H_{bias} = 20$ Oe, the maximum value of $a_{ME}$ was 31.4 V/cm · Oe, which was a factor of $1.24 \times$ higher than that for $H_{bias} = 0$. This value of $a_{ME}$ in the self-stressed state is higher than any data ever reported for ME laminates having a core PZT layer.

The enhanced value of $a_{ME}$ was due to the increases in the magnetostrictive and piezoelectric properties induced by the self-stress in the respective layers of the laminates. In Metglas layers, the easy magnetization direction is perpendicular to the long axis of the Metglas foil. Tensile stress applied along the longitudinal direction causes the magnetization vector of the magnetic domains to change from a random orientation to being parallel to the easy magnetization axis. When $H_{dc}$ is applied along the longitudinal direction, higher magnetostriction and piezomagnetic coefficients may then be achieved. Furthermore, the self-stress increases the possibility of domain switching and the generation of $90^\circ$ domains in the core PZT layer.

Figure 3 shows the maximum value of $a_{ME}$ of the laminates as a function of $E_{bias}$. The highest value was 29.2 V/cm · Oe for $E_{bias} = 2.4$ kV/cm, which was 1.15 times higher than the laminate without self-stress. This highest value under $E_{bias}$ is a little lower than that of laminates epoxied together under $H_{bias}$. This may be due to the stress transferred to Metglas not being uniform in each layer. There are three Metglas layers bonded on both sides of the core piezoelectric composite. The stress from the PZT is transferred to each Metglas layer by the adhesive epoxy. The stress in the outmost two Metglas layers is smaller than that in the innermost two layers. Under such nonuniform stress, it is difficult to maximize the effective linear piezomagnetic coefficient in each Metglas layer. Thus, the highest value of $a_{ME}$ of laminates epoxied under $E_{bias}$ may be lower than that under $H_{bias}$.

The noise charge density of a ME laminate is mainly determined by the dielectric properties: the capacitance ($C$) and the dielectric loss ($\tan \delta$). The values of $C$ and $\tan \delta$ were measured at an ac magnetic field of $H_{ac} = 0.1$ Oe and at a frequency of $f = 1$ kHz.
were measured using an impedance analyzer (Agilent 4292 A). No obvious changes were found between laminates with or without self-stress at low frequencies. If having similar dielectric properties, ME laminates with higher values of $\alpha_{\text{ME}}$ should exhibit lower equivalent magnetic noise floors. Self-stressed Metglas/PZT/Metglas laminates epoxied under $H_{\text{bias}} = 20$ Oe and $H_{\text{bias}} = 0$ (i.e., without self-stress) were then packaged with a simple low-noise charge amplifier having a gain of $5.1 \text{ V/pC}$ over the frequency range of $0.1 < \nu < 100$ Hz (designed by SAIC). The unit was placed inside a high-mu-metal magnetic shielded chamber, and connected to a dynamic signal analyzer (SR-785) to measure the voltage noise. The voltage noise was then converted to the equivalent magnetic noise floor using $\alpha_{\text{ME}}$ and $C$ of the laminate. Figure 4 shows the equivalent magnetic noise floor of the self-stressed Metglas/PZT/Metglas laminate epoxied together under $H_{\text{bias}} = 20$ Oe, which is compared to the laminate prepared without self-stress. The results show a decrease in the equivalent magnetic noise floor for the self-stressed laminate over the frequency range of $0.1 < \nu < 30$ Hz. At $\nu = 1$ Hz, the noise floor was reduced from $13.3 \text{ pT/Hz}^{0.5}$ to $9.8 \text{ pT/Hz}^{1.5}$, which was by a factor of about $1.35 \times$.

In summary, application of a dc magnetic field to the Metglas layers, or a dc electric field to the core piezoelectric composites, can effectively induce self-stress to the laminate when bonding Metglas and PZT layers. The value of $\alpha_{\text{ME}}$ for the laminate epoxied under $H_{\text{bias}} = 20$ Oe was enhanced by a factor of $1.24 \times$, compared to the laminate prepared without self-stress. Subsequently, the equivalent magnetic noise floor was reduced over the frequency range of $0.1 < \nu < 30$ Hz.