The effect of thickness on properties of three-phase piezocomposites

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Abstract: In this study, three-phase piezocomposite is fabricated on the basis of the 1–3 composite structure and the cutting–filling method. The 1–3 piezocomposite is used with PZT-5A as the piezoelectrics and epoxy/silicone rubber as the matrix. The relationships between the performance parameters of the 1–3 composites and different thicknesses are analyzed via finite element simulation and experimental measurement. Composite samples with thickness of 3mm-10mm are prepared through an experiment and tested using an impedance analyzer. Simulation results agree well with experiment results, thereby indicating that the composites have a high electromechanical coupling coefficient.

1. Introduction
Piezocomposite is widely used in transducers for acoustics, medical and other fields [1-3]. Many researchers have studied the performances of piezocomposites by changing the thickness of piezoelectric phase materials. This is the result of the thickness of piezoelectric phase materials is an important factor that affects the performance of piezoelectric elements. E et al. [4] investigated the effects of piezoceramic thickness on the hysteresis characteristics of output displacement and creep property of the piezoelectric element. Zhao et al. [5] investigated the effects of piezoceramic thickness on the Vibration characteristics and acoustic radiation of the piezoelectric element. Because the thickness electromechanical coupling coefficient \( k_t \) of piezocomposite reflects the conversion efficiency of mechanical energy and electrical energy in composite materials. In order to improve \( k_t \), a 1–3 piezocomposite structure composed of three-phase materials was proposed by the research group to improve \( k_t \). Rigid polymer epoxy resin and flexible polymer silicone rubber were successively poured into the ceramic skeleton of the 1–3 piezoelectric phase material. In this manner, epoxy resin and silicone rubber were compounded in series. In the previous stage, the influences of polymer volume percentage on the properties of 1–3 piezocomposites were studied by the research group [6]. On the basis of the preceding research, the present work intends to study the effects of the thickness of piezoelectric phase materials on the properties of three-phase composites via finite element simulation and experimental test.

2. Structure of the three-phase 1–3 piezocomposite
The structure of 1–3 piezocomposite is shown in Fig. 1. The composites consist of piezoceramic, epoxy resin, and silicone rubber. In Fig. 1, a and b denote the widths of the piezoceramic pillar and polymer, respectively; \( t \) denotes the thickness of the entire composite; and \( t1 \) and \( t2 \) indicate the thickness of the epoxy resin and silicone rubber, respectively. The volume fraction of the piezoceramic in the composite is \( v_c = a^2 / (a + b)^2 \). The 3D-connected rigid polymer epoxy resin and flexible polymer silicone rubber
are combined in series. Given its large Young’s modulus, low acoustic impedance and a large attenuation coefficient. Therefore, lateral vibration is suppressed to a certain extent, thereby increasing thickness vibration strength [7]. As a soft polymer, silicone rubber has a small Young’s modulus. Hence, it can reduce the binding effect of a rigid polymer on piezoelectric phase materials, thereby improving the electromechanical conversion efficiency of composite materials [8].

3. Finite element analysis

3.1. Finite element analysis of three-phase 1–3 piezocomposite

In this study, were simulated using the finite element software Ansys 15.0. Piezoelectric and dielectric properties were analyzed via harmonic response.

The number of piezoceramic pillars in the model was 16 in the length and width directions. The structure of the simulation model is shown in Fig. 1. The automatic sweeping function was used in mesh generation. The voltage on the upper surface of the material was set to 1 V, whereas that at the bottom of the material surface was set to 0 V for solving. The frequency range was changed with an change in the composites thickness. The substep was 2 kHz apart. To obtain the effect of thickness on properties, piezoelectric pillar width and polymer width was set to fixed value 1mm and 0.56mm in the simulation, respectively. So, volume fraction of the piezoceramic $v_c$ was 0.41 in the simulation. Simultaneously, the thicknesses $t1$ ($t1=0.6t$) and $t2$ ($t2=0.4t$) of the two polymers were changed with an change in the composites thickness.

3.2. Simulation results and calculation

The admittance curve of the 1–3 piezocomposites can be obtained through finite element harmonic response analysis and related postprocessing operations. The variations of resonant ($f_s$) and anti-resonant ($f_p$) frequencies with thicknesses ($t = 3mm~10mm$) can be obtained by analyzing the admittance modulus curves of composites with different thicknesses.

The thickness electromechanical coupling coefficient ($k_t$), relative dielectric constant ($\varepsilon_r$), sound velocity ($v_t$), and characteristic impedance ($Z$) of the piezocomposites can be calculated using Eqs. (1–4) [9]. In these equations, $C_0$ denotes the capacitance of the model at a frequency of 1 kHz, $A$ is the model area, $t$ is the model thickness, $\rho$ is the material density, and $\varepsilon_0(\varepsilon_0 = 8.85 \times 10^{-12}F/m)$ is the vacuum dielectric constant.

$$K_t = \frac{\pi f_s^2 \tan \left( \frac{\pi f_p - f_s}{2 f_p} \right)}{\sqrt{2 f_p}}$$  (1)

$$\varepsilon_r = \frac{C_0 t}{\varepsilon_0 A}$$  (2)

$$v_t = \frac{f_p}{2} \times 2t$$  (3)

$$Z = \rho \times v_t$$  (4)

As shown in Fig. 1, the polymers in the 1–3 piezocomposite is composed of upper rigid polymer epoxy resin and lower flexible polymer silicone rubber in series. Therefore, the equivalent density ($\rho$)
of the piezocomposites is

\[ \rho = v_c \rho^a + (1 - v_c) \rho^b \]  \hspace{1cm} (5)

where \( v_c \) is the ceramic volume fraction; \( \rho^a \) is the density of PZT-5A; and \( \rho^b \) is the equivalent density of the polymer, which is calculated from Eq. (6).

\[ \rho^b = \frac{t_1}{t} \rho^e + \frac{t_2}{t} \rho^s, \]  \hspace{1cm} (6)

where \( \rho^e \) is the density of epoxy resin, and \( \rho^s \) is the density of silicone rubber.

Table 1. Experimental data of the 1–3 piezoelectric composites.

| \( t \) (mm) | \( f_s \) (kHz) | \( f_p \) (kHz) | \( \rho \) (kg/m\(^3\)) | \( K_i \) (pF) | \( C_0 \) (pF) | \( \varepsilon_r \) | \( v_t \) (m/s) | \( Z \) (Mrayl) |
|---|---|---|---|---|---|---|---|---|
| 3 | 458 | 598 | 3712 | 0.680 | 1262 | 719 | 3588 | 13.32 |
| 4 | 348 | 452 | 3712 | 0.676 | 945 | 717 | 3616 | 13.42 |
| 5 | 280 | 364 | 3712 | 0.677 | 755 | 717 | 3640 | 13.51 |
| 6 | 232 | 304 | 3712 | 0.684 | 629 | 717 | 3640 | 13.54 |
| 7 | 202 | 260 | 3712 | 0.668 | 539 | 716 | 3640 | 13.51 |
| 8 | 174 | 228 | 3712 | 0.684 | 471 | 716 | 3648 | 13.54 |
| 9 | 156 | 204 | 3712 | 0.682 | 419 | 716 | 3672 | 13.63 |
| 10 | 142 | 184 | 3712 | 0.674 | 377 | 715 | 3680 | 13.66 |

4. Experiments and data analysis

4.1. Preparation and testing of three-phase 1–3 piezocomposite

Eight types of 1–3 piezocomposites with thicknesses (3mm-10mm) were fabricated in this experiment. The properties of the composites were tested and analyzed experimentally. PZT-5A was used as piezoelectric phase and 618-epoxy resin, silicon rubber were used as polymer. The process flow is illustrated in Fig. 10.

The specific process is as follows: The ceramic substrate was retained, the ceramic arrays were formed by cutting the ceramic along the X and Y directions. Epoxy resin was poured into the ceramic skeleton after the initial cutting, and bubbles were evacuated and cured at room temperature. The ceramic substrate was cut, and the silicone rubber was poured into the ceramic skeleton of the secondary cutting, and bubbles were evacuated and cured at room temperature to produce a composite blank. The composite blank was shaped (ground or cut) and uniformly coated with conductive silver paste on both sides of the ceramic.

![Preparation of 1–3 piezocomposites.](image)

4.2. Relationship between the properties and ceramic thickness of composites

The variation of different composite performance parameters with thicknesses can be obtained by testing and analyzing the eight piezocomposites with different thicknesses.
Fig. 3 shows the curves of $f_s$ and $f_p$ varying with the thickness. As shown in the figure, the experimental results agree well with the simulation results.

Following Eq. (1), the $k_t$ of samples was calculated and compared with the simulation value, as shown in Fig. 4. When the thickness increases from 7mm to 10mm, the experimental results exhibit a slight decline in $k_t$, which differs from the simulation results. The primary reason for this discrepancy is that the material parameters in the simulation calculation are inconsistent with those in the experiment or the composite material has experienced a certain loss during the experiment. Therefore, the simulated values of $k_t$ slightly deviate from the measured values.

As shown in Fig. 5, the relationship between $\varepsilon_r$ and the thickness can be obtained using Eq. (2). A certain deviation exists between the experimental and simulation results. The fluctuation range of simulation data is lower than that of experimental results. The reason for this result is the same as the above. In accordance with Newnham’s parallel theory of composites [10], the dielectric constant of 1–3 parallel composites is

$$\varepsilon_{33} = v_c \varepsilon_{33}^a + (1 - v_c) \varepsilon_{33}^b,$$

where $v_c$ is the 1–3 piezoceramic volume fraction, $\varepsilon_{33}^a$ is the dielectric constant of piezoceramics, and $\varepsilon_{33}^b$ is the dielectric constant of polymer phase materials. The dielectric constant of PZT-5A piezoceramics is considerably higher than those of the polymers (epoxy resin and silicone rubber). Thus, the dielectric constant of composites primarily depends on the piezoceramic volume fraction. Therefore, the dielectric constant of the simulation keep steady when the piezoceramic volume fraction was set to a fixed value (0.41) in the simulation. Although several deviations exist between the experimental and simulation results, the $\varepsilon_r$ values of the prepared composites and the simulations are all lower than that of PZT-5A piezoelectric ceramic (1700).
Figure 6. Comparison of $v_t$ between the experiment and the simulation.

Fig. 6 shows the curves of $v_t$ varying with the thickness. As shown in the figure, the experimental results agree well with the simulation results. As shown in Fig. 7, Z of the simulation slightly increases with an increase in the thickness, and the growth trend of Z is approximately linear. The fluctuation range of experiment data is lower, so the experimental results agree well with the simulation results.

5. Conclusion

The comparison showed that the experimental results are in good agreement with the simulation results. The improved 1–3 piezoelectric composites have a high electromechanical conversion efficiency, wherein the maximum value of electromechanical coupling coefficient is 0.68. Therefore, the improved 1–3 piezoelectric composite structure exhibits considerable advantages in the performance of the thickness electromechanical coupling coefficient.

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