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Design and properties 1–3 multi-element piezoelectric composite with low crosstalk effects

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ABSTRACT

Piezoelectric composites are gaining increasingly importance in ultrasonic fields due to their superior properties. Here novel 1–3 multi-element piezoelectric composites were developed by using piezoelectric ceramic as functional phase, epoxy resin as matrix phase, and silica gel and polyurethane as decoupling materials. The effects of decoupling materials and composite thickness on dielectric, piezoelectric and electromechanical coupling properties of the composites were investigated. The coupling response among various elements of the composites was discussed by setting up an ultrasonic testing platform. The results show that the multi-element piezoelectric composites have larger piezoelectric voltage factor than piezoelectric ceramic, however, less relative permittivity and piezoelectric strain factor. With decreasing the composite thickness, the thickness resonant peaks of the piezoelectric composite shift toward high frequency direction, and no obvious high-order and coupling resonant peaks appear. The multi-element piezoelectric composites have larger thickness electromechanical coupling coefficient k_t and less mechanical quality factor Q_m than piezoelectric ceramic. When composite thickness is 5 mm, the epoxy/silica piezoelectric composite has a maximum k_t value of 70.41%, and a minimum Q_m value of 11.29. The coupling response testing results show that epoxy/silica piezoelectric composite shows less crosstalk effect than epoxy/epoxy and epoxy/polyurethane piezoelectric composites.

1. Introduction

Piezoelectric transducers can realize conversion of electrical energy and sound energy, which are widely used in ultrasonic fields due to high electro-acoustic efficiency, large power capacity and structural designability. Piezoelectric composites were usually used as core element of piezoelectric transducers because of the flexible acoustic matching ability, large electromechanical coupling coefficient and piezoelectric voltage factor [1–3]. According to connectivity of two-phase composite, piezoelectric composites can usually be divided into ten basic connectivity patterns [4,5]. The 1–3 piezoelectric composite is composed of piezoelectric phase in one dimension and matrix phase in three-dimensions, which is paid comprehensive attention for its high sensitivity, low acoustic impedance and density [4,6,7]. The 1–3 piezoelectric composites were originally developed by Safari et al. [8], and Wang, Auld et al. [9,10] established a theoretical model of 1–3 piezoelectric composites with piezoelectric ceramic ($Pb(ZrTi)O_3$, PZT) column cycle. In the following years, the theoretical and experimental findings further push forward the development of various novel piezoelectric composites [11–17].

Recently, with the increasingly requirement on online monitoring technology, the common 1–3 piezoelectric composite consisting of piezoelectric ceramic and epoxy resin cannot meet the requirements of piezoelectric transducer on low coupling and high response because of the crosstalk effect between piezoelectric elements. The novel 1–3 piezoelectric composites with low crosstalk effect attract researchers' interest. Xu et al. [18] developed 1–3 piezoelectric composites with varied piezoelectric phase distribution to reduce the crosstalk effect. Qin et al. [19] developed triphase multli-element piezoelectric composite through adding decoupling material in the matrix to decrease the coupling vibration between each element. Zhou et al. [20] investigated the properties of 1–3 multli-element piezoelectric composites with silicone as the decoupling material.

The decoupling material has a high acoustic attenuation coefficient, which can ensure the emission independence of each acoustic beam by effectively blocking the acoustic energy propagation in the composite. Therefore, the crosstalk effect can be effectively reduced by adding decoupling material in the piezoelectric composite. In this research, 1–3 multi-element piezoelectric composites were fabricated by using secondary cutting-casting method, where PZT ceramic and epoxy were used as

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Table 1
Properties of PZT piezoelectric ceramic.

Properties	k_t (%)	d_{33} (pC N^{-1})	tanδ (%)	ε_r	g_{33} ((mV) m N^{-1})	Q_m
PZT	60	400	2	1500	30	70

(Note: k_t-thickness electromechanical coupling coefficient; d_{33}-piezoelectric strain factor; tanδ-dielectric loss; ε_r-relative permittivity; g_{33}-piezoelectric voltage factor; Q_m-mechanical quality factor).

Table 2
Parameters of the decoupling materials.

Polymer	Acoustic impedance (kg s^{-1} m^{-2})	Density (10^3 kg m^{-3})	Elastic modulus (MPa)	Sound speed (m s^{-1})
Epoxy resin	0.32	1.20	1000.0	2400–2900
Polyurethane	1.72	1.04	39.4	1600–1650
Silica gel	1.01	1.12	7.8	1320

piezoelectric and matrix phase, and silica gel and polyurethane were used as decoupling materials, respectively. The effects of decoupling materials and composite thickness on dielectric, piezoelectric and electromechanical coupling properties of the composites were investigated.

2. Experiments

2.1. Experimental procedure

The basic properties of PZT ceramic, epoxy resin, silica gel and polyurethane were shown in Tables 1 and 2.

The fabrication procedure of the piezoelectric composites was shown in Fig. 1. Firstly, the pre-polarized PZT piezoelectric ceramic block with a dimension of 14.5 mm × 14.5 mm × 13.3 mm was accurately cut along the polarization axis direction, and a foundation of 2 mm was left. The mixture of epoxy resin and curing agent with a mass ratio of 4:1 was poured into the grooves of 0.5 mm in width, and the samples were cured for 24 h around 25 °C. Then the pre-polarized PZT piezoelectric ceramic block was again cut vertical to the first cut, and epoxy resin, polyurethane and silica gel were poured into the grooves. Finally, the ceramic foundation was cut off and the silver paint were coated on surfaces of the composites after polishing. The dimension of PZT piezoelectric ceramic rod in the composites was 2.0 mm × 2.0 mm × 11.3 mm, and the piezoelectric ceramic volume fraction was 51.7 vol%. The fabricated piezoelectric composites were shown in Fig. 2, which are termed as epoxy/epoxy piezoelectric composite (EPC), epoxy/polyurethane piezoelectric composite (PPC) and epoxy/silica piezoelectric composite (SPC).

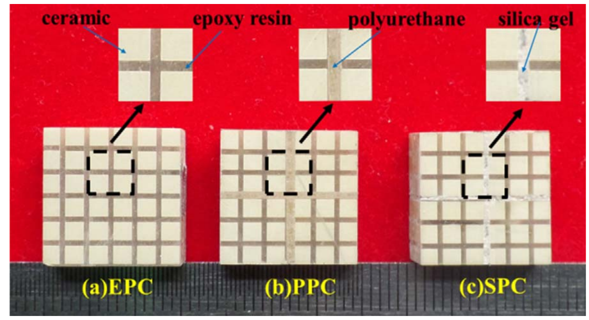

Fig. 2. Photos of the 1–3 multi-element piezoelectric composites.

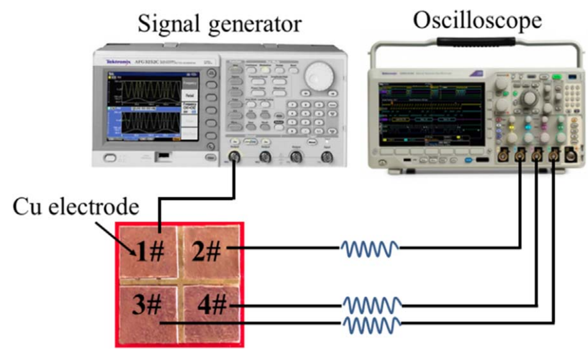

Fig. 3. Ultrasonic testing platform for coupling response test.

2.2. Performance testing

Model ZJ-3A d_{33} quasi-static meter was used to test piezoelectric strain factor d_{33} of the composites. Agilent 4294A impedance analyzer was used to measure the resonant frequency f_s, anti-resonance frequency f_p, capacitance C and dielectric loss tanδ of the composites. The ultrasonic testing platform consisting of Tektronix MDO3024 oscilloscope and AFG3022B function signal generator was built up to test the coupling response among various piezoelectric element, as shown in Fig. 3. The conductive copper tape was used as electrode of each element in the composite, and the pulse signal was applied to 1# element with a frequency of 120 kHz and an amplitude 10 V, and the response signals from 2#, 3# and 4# elements were recorded by the oscilloscope.

3. Results and discussion

3.1. Piezoelectric and dielectric properties

The relative permittivity ε_r, piezoelectric voltage factor g_{33} of the piezoelectric composites were calculated by Eqs. (1) and (2).

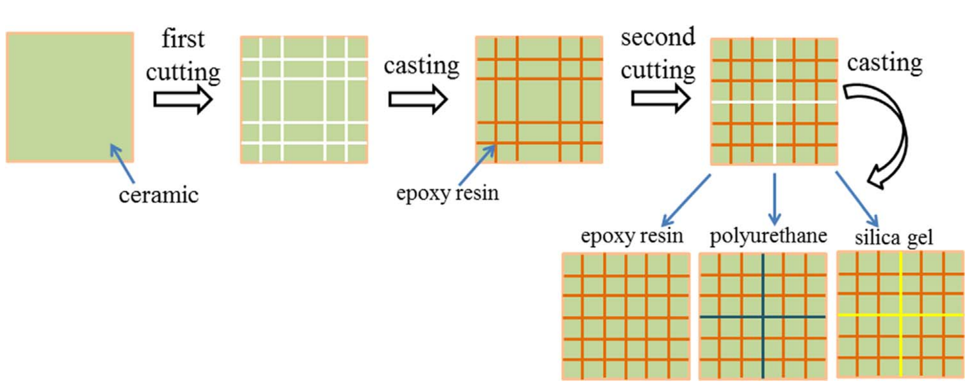

Fig. 1. Fabrication schematic of the 1–3 multi-element piezoelectric composites.