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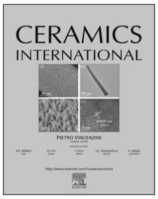

Short communication

Electromechanical coupling coefficient and acoustic impedance of 1-1-3 piezoelectric composites

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ABSTRACT

1-1-3 piezoelectric composites consisting of a PZT-5H ceramic, an epoxy resin matrix and a silicone rubber filler were prepared using a modified 'slice and fill' method. The effect of the ceramic volume percentage on the properties of the composite was analyzed both through experiments and simulations. By adopting the 1-1-3 structure, the electromechanical coupling coefficient of the piezoelectric composites could be increased to 0.69, and the acoustic impedance reduced to 6.81. The experimental results further showed that the variation of the ceramic volume percentage had no effect on the electromechanical coupling coefficient of the composites, but only affected the acoustic impedance. The presented piezoelectric composites can be used to design high-performance transducer.

1. Introduction

Piezoelectric composites are key materials for the fabrication of nondestructive testing, underwater transducer and medical ultrasound devices. However, the limitations of conventional piezoelectric composites, such as type 0–3 [1], 2–2 [2], 1–3 [3,4] PZT/polymer composites, have become more and more obvious over the past years. For instance, it has proven difficult to further enhance the piezoelectric properties, e.g., the electromechanical coupling coefficient (K_t) and the acoustic impedance (Z). 1–3 piezoelectric composite is widely studied because it has the higher piezoelectric performance than other type composites. 1–3 composite consist of parallel aligned piezoceramic rods imbedded within a three-dimensional polymer host matrix [5]. This composite design is intended to operate in longitudinal expansion mode (k_{33}) of piezoceramic rod instead of thickness mode (k_t) of piezoceramic plate. Take PZT-5H piezoceramic as an example, the k_t is about 0.505, but the k_{33} can reach a value of 0.75 [6]. Li et al. [7] fabricated high-temperature 1–3 composites using $BiScO_3$–$PbTiO_3$ ceramics and cyanate ester as the filler. The K_t value of the composite material increased from 0.58 to 0.69 when the temperature was increased from 25 to 300 °C, and the Z value approached 19 MRayl, demonstrating that the composite material has a high electromechanical coupling coefficient at high temperatures. Li [8] also found that, when the temperature reached 250 °C, K_t reached a value of 0.6. Li et al. [9] used the dice-fill method to fabricate $0.96Bi_{0.5}(Na_{0.84}K_{0.16})_{0.5}TiO_3$–$0.04SrTiO_3$ ceramic/epoxy 1–3 composites. Their composite showed the best electrical properties at a ceramic volume fraction of 27.6%. They were able to achieve a K_t value of 0.547, a moderate relative dielectric constant of 128.4 and an acoustic impedance of 9 MRayl. Wang et al. [10] found that K_t not only depends on the aspect ratio of the piezoelectric column, but also on the elastic stiffness of the kerf filler. In their study, the electromechanical coupling factor increased when the elastic stiffness of the kerf filler decreased. Furthermore, they reported that the K_t value of rubber-filled composites is higher than that of epoxy-filled composites and that the rubber-filled composites exhibit a better thermal stability [11].

In order to improve the piezoelectric properties of such composites and reduce the influence of the temperature on the piezoelectric properties, 1-1-3 piezoelectric composite materials have been developed in previous work [12]. The combination of a flexible polymer with a rigid polymer can reduce the transverse coupling in the composites and may improve their piezoelectric properties. In this study, the effect of the ceramic volume percentage on the properties of the composite was analyzed both through experiments and simulations.

2. Structure of the prepared 1-1-3 composite

A schematic illustration of the structure of the prepared 1-1-3 composite element is shown in Fig. 1. The three numbers 1-1-3 represent the three kinds of materials. The first type of material is a piezoelectric ceramic with polarization along the Z direction, which acts as the active vibration element of the whole composite. The second type of material is silicone rubber, which is also self-connected in the Z direction with respect to the surrounding columns. The third type of

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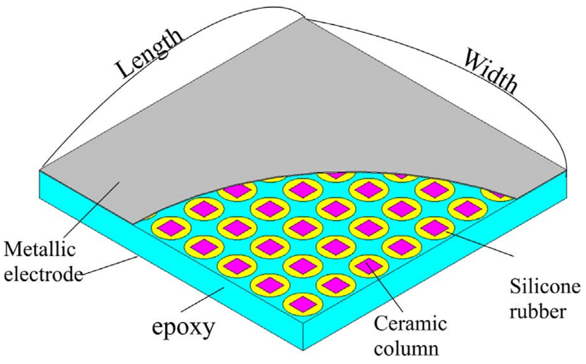

Fig. 1. Schematic illustration of the structure of the prepared 1-1-3 piezoelectric composite.

material is the epoxy resin, which is connected in all three directions and acts as a bracket to support the entire component. Consequentially, this type of piezoelectric composites is called a 1-1-3 composite. In order to reduce the clamping force acting on the ceramic column and induced by the polymer, silicone rubber is introduced between the ceramic column and the epoxy resin frame. Thus, the ceramic column is more likely to vibrate freely. The electrical contacts were fabricated by sputtering silver on the top and bottom surfaces of the piezoelectric composite along the Z direction. Through the combination of silicone rubber and epoxy resin, the lateral coupling between the composite elements is reduced and a higher electromechanical coupling coefficient can be achieved.

3. Finite element analysis

In order to analyze the piezoelectric composite material, a preliminary finite element analysis (FEA) was conducted using the ANSYS software. Only one unit cell had to be modeled because of the periodicity of the composite. The FEA model is shown in Fig. 2. The middle part (pink) corresponds to the ceramic, the outer layer (blue) is the epoxy resin, and the gap between the ceramic and the epoxy resin (yellow) is filled with silicone rubber. Voltages of 1 and 0 V were applied to the top and bottom surfaces in the Z direction of the model. In the simulation, displacement symmetry constraints were applied to the lateral surface of the model to more accurately simulate the vibration of the whole element. Firstly, a modal analysis was carried out, and the thickness vibration mode was observed. Fig. 2 also illustrates the thickness vibration mode. The ceramic vibrates as an active element, and it drives the silicone rubber to vibrate passively. At the same time, the epoxy resin basically does not move because the silicone rubber's Young's modulus is quite small compared with the Young's modulus of the epoxy resin, which makes the vibration mode of the ceramic similar to a free vibration. And because the impedance of the epoxy resin does not match the impedance of the silicone rubber, the transverse coupling of the element is significantly reduced.

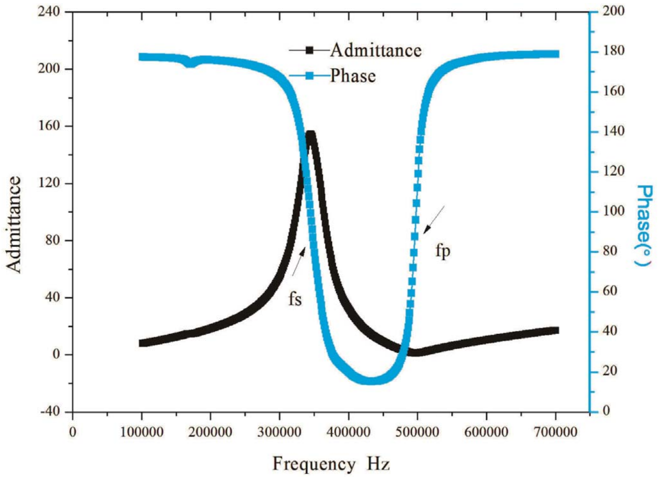

Fig. 3. Electrical admittance of the 1-1-3 composite with a ceramic volume percentage of 21 vol%.

A harmonic response analysis was performed next. Fig. 3 shows the admittance curve obtained through the harmonic response analysis, which was again performed using the ANSYS software. At a ceramic volume percentage of 21%, the series resonant frequency was simulated to be 347.2 kHz and the parallel resonant frequency was 496.0 kHz, resulting in an electromechanical coupling coefficient of 0.71, as calculated through Eq. (1). In the simulation, the volume percentage of the ceramic columns was varied between 10 and 40 vol%, and the variation of the electromechanical coupling coefficient was observed. As shown in Fig. 4, the electromechanical coupling coefficient remained almost constant when the volume percentage of the ceramic was changed in the simulation. This indicates that the ceramic column works in k_{33} mode, i.e., the width-to-thickness ratio remains lower than 0.2. This also means that the silicon rubber hardly affects the vibration of the ceramic.

$$k_t = \sqrt{(f_p{}^2 - f_s{}^2)/f_p{}^2} \tag{1}$$

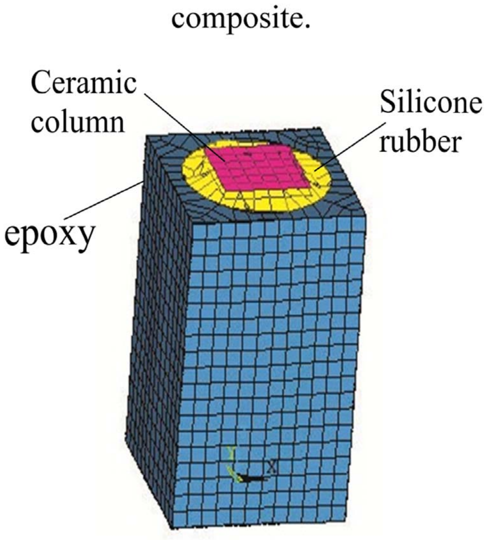

Fig. 2. Schematic illustration of FEA model of the 1-1-3 composite.

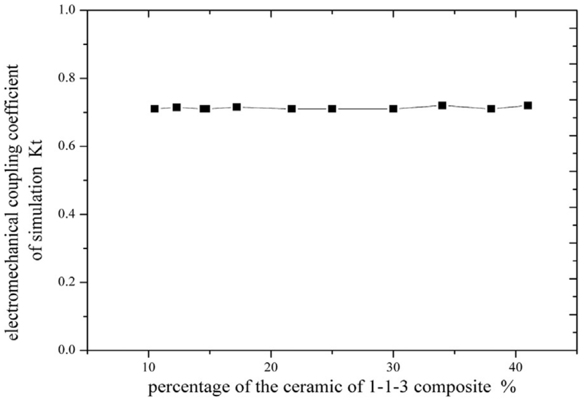

Fig. 4. Simulation of the variation of the electromechanical coupling coefficient with the ceramic volume percentage.