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Multilayer bender-type PZT-PZN actuator by co-extrusion process

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Abstract

A multilayer flextensional bender-type actuator, which was composed of five piezoelectric layers and one passive conducting layer, was fabricated using a co-extrusion process. A low-temperature sinterable PZN-PZT was used for the piezoelectric layer. The conducting inner electrode layers and passive bottom layer were fabricated by dispersing silver particles in the PZN-PZT matrix. For the co-extrusion process, piezoelectric and conducting feedrods were made separately by mixing them with polymers, which was followed by the formation of the initial feedrods. The initial feedrods were co-extruded through a reduction die to produce a continuous multilayer sheet. The binder was burnt out and, the multilayer green bodies were then sintered at 900 °C. The design was suitable not only for applying a high electric field with inner electrodes, but also for inducing a residual tensile stress on the piezoelectric layer. A multilayer actuator with dimensions of 50 mm × 20 mm × 0.84 mm generated a displacement of approximately 400 μm at 400 V, which is more than twice the displacement of a simple two-layer actuator with the same dimensions.

Keywords: Actuators; PZT; Piezoelectric properties; Extrusion; PZN

1. Introduction

Piezoelectric ceramics have been used extensively as actuators and transducers. Among these ceramics, lead zirconate titanate and other lead-based relaxor materials are widely used because they offer excellent electromechanical properties.[1–4] However, the electric field-induced strain is typically less than 0.1% in polycrystalline materials, up to approximately 1% in some single crystals.[5] In order to enhance this small displacement, various types of strain-amplifying architectures have been developed.[6] The recently developed actuators, such as the RAINBOW,[7–8] THUNDER,[9] Moonie[10] have demonstrated large displacements with a reasonable load-bearing capability. However, these actuators have some common problems that are associated with the fabrication procedure, such as cutting-and-bonding or special heat treatment conditions. In particular, the electromechanical performance of these actuators fabricated by using an adhesive strongly depends on the thickness and bonding strength of the adhesive.

Previously, we developed a flextensional actuator composed of a PZN-PZT layer and a PZN-PZT/Ag layer with a high residual stress.[11–14] The actuator, which was co-fired at 900 °C, exhibited a good piezoelectric performance without any long-term reliability or interfacial stability problems, working under a commercially reasonable voltage. The development of a PZN-PZT piezoelectric material that can be sintered to full theoretical density at temperatures as low as 860 °C has made the co-firing process possible. In this study, the displacement was further increased using inner electrodes and rendering a residual stress to the piezoelectric layers. The actuator, which was composed of five active PZN-PZT layers, four conducting inner electrodes (40% PZN-PZT/60% Ag), and a bottom passive layer (60% PZN-PZT/40% Ag), was co-fired after co-extrusion. By utilizing this co-extrusion process, the mass producibility was markedly enhanced and the size limitation of actuator was significantly reduced.

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2. Experimental procedure

For our multilayer actuators, the composition of the PZN-PZT was fixed at $Pb((Zn_{1/3}Nb_{2/3})_{0.2}(Zr_{0.50}Ti_{0.50})_{0.8})O_3$. The bottom PZN-PZT/Ag layer was composed of 60% PZN-PZT and 40% Ag, while the inner electrodes were composed of 40% PZN-PZT and 60% Ag to ensure conductivity at the thin layer. Highly pure PbO, ZnO, TiO_2, ZrO_2, Nb_2O_5 (all purity 99.9%, Aldrich Chemical Co. Inc., Milwaukee, WI, USA) were used as the starting materials. These powders were mixed by ball milling using zirconia balls and ethanol as the media for 24 h, dried on a hot plate, and then subsequently calcined at 850 °C for 4 h. The calcined powder was again ball-milled for 72 h to obtain a fine powder. To make a feedrod for the co-extrusion process, the powders (PZN-PZT or 60 wt% PZN-PZT/40 wt% Ag or 40 wt% PZN-PZT/60 wt% Ag) were mixed with an ethylene ethyl acrylate-based polymer (EEA 6182; Union Carbide, Danbury, CT, USA) at 105 °C using a high shear mixer. The volume fractions of inorganic solid and polymer were 60 and 40 vol%, respectively. Once compounded, the PZN-PZT or 60% PZN-PZT/40% Ag compounds were extruded through a reduction die with the dimensions of 24 mm × 2 mm. The 40% PZN-PZT/60% Ag compound for the inner electrode was also extruded through a 24 mm × 0.6 mm reduction die. The initial feedrod (24 mm × 24 mm) for the multilayer actuator was combined from five PZN-PZT layers, four 40% PZN-PZT/60% Ag layers, and one 60% PZN-PZT/40% Ag layer. The initial feedrod was extruded through a reduction die with dimensions of 24 mm × 1 mm using a piston extruder (Jungmin Ind. Co., Seoul, Korea) at 105 °C at a rate of 3 mm/min, as shown in Fig. 1. The extruded bodies were sintered after binder burn-out in a box furnace at a slow heating rate (7 °C/h) up to 500 °C. The specimens were sintered at 900 °C for 4 h in a sealed alumina crucible in a PbO-rich atmosphere powder in order to minimize PbO loss from the pellets.

The electrodes were prepared by applying a thin silver paste on the face of the PZN-PZT and both lateral sides and then thermally treated at 500 °C for 30 min. The specimens were poled in a silicone oil bath at 150 °C by applying an electric field of 2 kV/mm for 30 min. The piezoelectric coefficient of the specimens was measured using a quasi-static piezoelectric d_{33} meter (model ZJ-3D, Institute of Acoustics, Beijing, China). The transverse electric field-induced displacement (S_{31}) of the poled monolithic PZN-PZT specimen was monitored at the lateral side, and the displacement of the flextensional actuator was observed at the center using a digital displacement probe (DT/2/S, Solarton, Bognor Regis, West Sussex, UK).

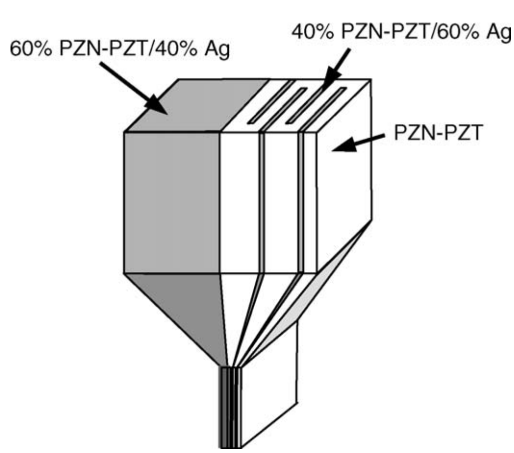

Fig. 1. Schematic illustration for the fabrication process of the multilayer bender-type actuator by co-extrusion.

3. Results and discussion

A multilayer bender-type actuator, 50 mm in length, 20 mm in width, and 0.84 mm in thickness, was fabricated using low-temperature sinterable PZN-PZT and conducting PZN-PZT/Ag by a co-extrusion process. The PZN-PZT showed good electromechanical properties even when sintered at low-temperature (<900 °C).[11,12] The electromechanical properties of the PZN-PZT were as follows; piezoelectric coefficient, $d_{33} = 510$ pC/N, $d_{31} = -230$ pC/N, electromechanical coefficient, $k_p = 0.65$, and relative dielectric constant, $K^T = 1700$. The electrical conductivities of the PZN-PZT and Ag mixtures were higher than 10^6 /Ωm, which indicates good conductivity without any co-firing problems with the PZN-PZT ceramics. The PZN-PZT and Ag did not react, as far as could be evidenced by the SEM micrograph and XRD patterns.[13,14] The Ag concentration was closely related to the thickness of the PZN-PZT/Ag composite. A thick PZN-PZT/Ag composite layer (>100 μm) showed a reasonably good electrical conductivity with 40% Ag. On the other hand, a thin layer (<30 μm) required more than 60% Ag to maintain the conductivity. Therefore, 40% Ag was added to the PZN-PZT passive layer and 60% Ag was added to the inner electrodes.

The initial feedrod, which was composed of five piezoelectric PZN-PZT layers, four inter-digital electrodes, and a passive 60% PZN-PZT/40% Ag layer was fabricated by warm pressing at 105 °C using a nominal pressure of 30 MPa after stacking each layer, as shown in Fig. 2. Inter-digital electrodes were inserted between the PZN and PZT layers in order to increase the electric field at the same voltage. To prevent an electric short circuit, the PZN-PZT was used at one side of the bottom layer.

The co-extruded green bodies were flat and all the layers adhered perfectly without any delamination. However, after sintering at 900 °C, the specimen was slightly bent into a convex shape, which was apparently due to difference in the coefficients of thermal expansion (CTE) of the layers. The CTE of the PZN-PZT, 60% PZN-PZT/40% Ag, and 40% PZN-PZT/60% Ag were estimated by simple rule of mixtures to be 5×10^{-6}, 10.6×10^{-6} and 13.4×10^{-6}/°C, respectively. Therefore, during cooling after sintering, the PZN-PZT/Ag bottom layer contracted more than the PZN-

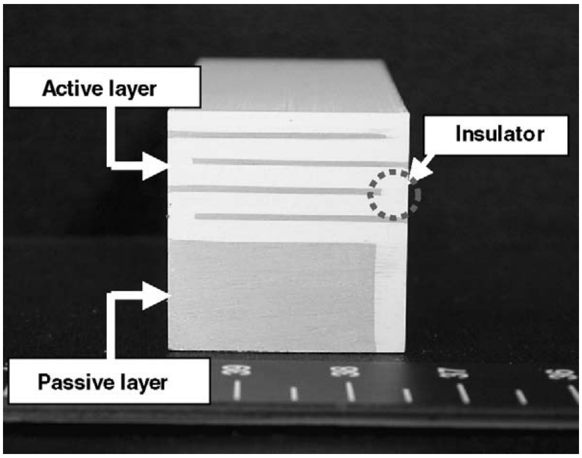

Fig. 2. The initial feedrod for multilayer bender-type actuator, composed of five piezoelectric layers, four inter-digital electrodes, and a passive layer.

PZT layer. The presence of residual stress was evidenced by the X-ray diffraction patterns of the PZN-PZT/Ag system.[14] The residual tensile stress in the active layers plays an important role in enhancing the piezoelectric properties of the specimen.[15–17] A polished cross section of an actuator after sintering at 900 °C is shown in Fig. 3(A). The thicknesses of the active and passive layers were approximately 480 and 360 μm, respectively. The active layer was composed of five 80 μm thick PZN-PZT layers and four 20 μm thick electrodes. The electrode was inserted alternately, so that half of the electrodes reached to one end, while the other half electrodes reached to the other end. Fig. 3(B) shows a SEM micrograph of the inter-digital PZN-PZT/Ag electrodes. The figure shows that PZN-PZT did not react with the silver and adhered almost perfectly to each other.

The transverse strain (S_{31}) as a function of the electric field for the monolithic PZN-PZT ceramic was measured, and the results are shown in Fig. 4. The total bi-polar transverse strain at ±2 kV/mm was observed to be approximately 0.16%, which means that the PZN-PZT ceramic is a good piezoelectric material for a bender-type actuator. The d_{31} (220 pC/N) calculated directly from the slope of the strain versus the electric field curves, matched well with the piezoelectric coefficients previously determined using the resonance method.[18]

Fig. 5(A) shows the electric field application under a flextensional configuration. After sintering, the thicknesses of the active part, which was composed of five PZN-PZT layers and four inner electrode layers in a rectangular-shaped actuator, were 0.48 mm as intended, resulting in a total thickness of 0.84 mm. The length and the width of the specimen were 50 and 20 mm, respectively. When an electric field was applied, the PZN-PZT layer contracted laterally, while the bottom PZN-PZT/Ag layer did not, which yielded a large vertical displacement at the center. The vertical displacements of the flextensional actuator in this configuration were measured as a function of the applied electric field, as shown in Fig. 5(B).

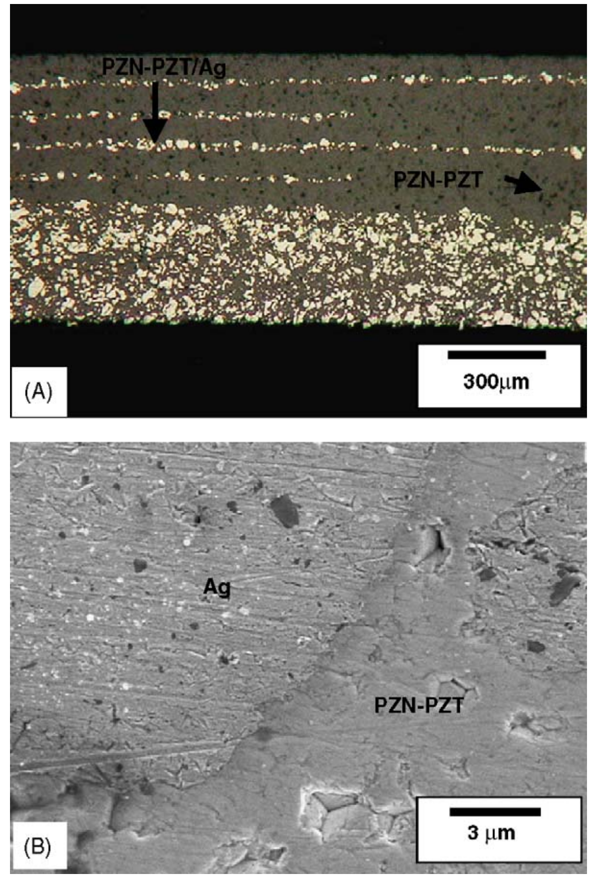

Fig. 3. Micrographs of the polished cross section of the multilayer bender-type actuator: (A) optical micrograph of the specimen and (B) SEM micrograph of the conducting layer.

The multilayer actuator showed a displacement of approximately 400 μm at 400 V. For the purpose of comparison, a conventional two-layer (PZM-PZT and PZN-PZT/Ag layers) actuator with the same dimensions was fabricated by the co-extrusion process and evaluated. The displacement of the two-layer actuator with the same configuration was 190 μm

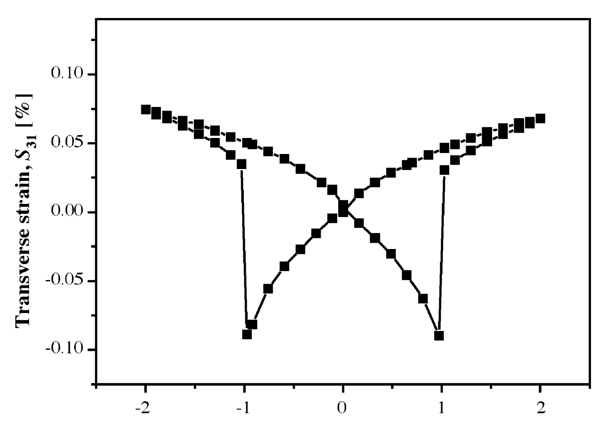

Fig. 4. The field-induced transverse strain (S_{31}) curve of the monolithic 20% PZN-80% PZT ceramic.

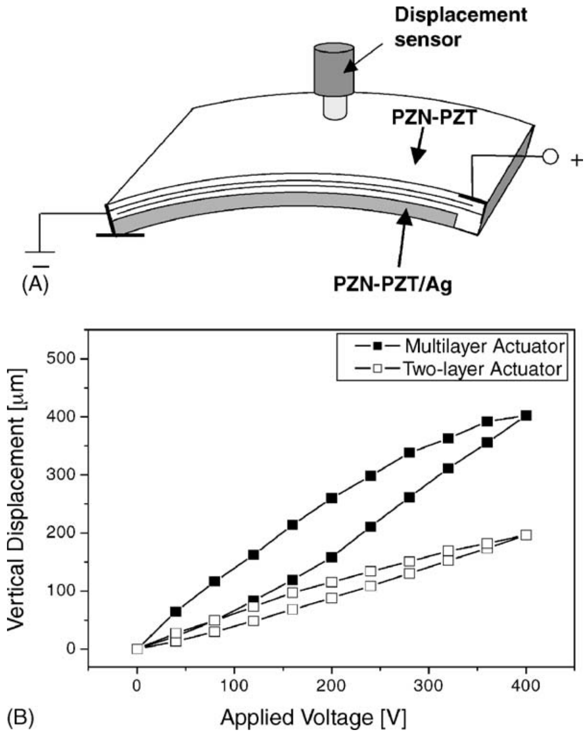

Fig. 5. (A) Schematic illustration for the displacement measurement and electric field application of the flextensional configuration (B) vertical displacements of the multilayer and two-layer bender actuators. The specimens were 50 mm in length, 20 mm in width, and 0.84 mm in thickness.

at 400 V. The effectiveness of the multilayer actuator is well illustrated by these measurements.

4. Conclusions

A multilayer bender actuator was fabricated using a co-extrusion process. The displacement of this bender actuator was remarkably enhanced with inter-digital electrodes. The specimen with dimensions of 50 mm × 20 mm × 0.84 mm showed a displacement of 400 μm, which was more than twice of the simple two-layer bender actuator. This large displacement of the multilayer bender actuator was attributed to the inter-digital electrodes (high electric field) and also to the residual stress (stress-induced domain switching), which is resulted from the CTE difference between active and passive layers. The co-extruded actuators have advantages over the actuators previously used in terms of a possibility for complex design, precise residual stress control, no dimensional restrictions, and mass producibility.

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