SHAPE EFFECT ON PERFORMANCE OF MULTILAYER CERAMIC ACTUATOR

S. B. Wee [†] , S. J. Jeong[‡] , J. S. Song[‡]

[†] School of Information Technology, Korea University of Technology and Education, P.O.Box55,Chonan,Chungnam,330-600,Korea, weesb@kut.ac.kr

[‡] Korea Electrotechnology Research Institute, 28-1 Seongju-dong, Changwon, 641-600, Korea

Keywords : Multilayer Ceramic Actuator, piezoelectricity, electric field-induced deformation, geometric factor, X-ray method

Abstract

In the present study, the piezoelectricity and polarization of multilayer ceramic actuator, being designed to stack PMN-PZ-PT ceramic layers and Ag-Pd electrode layers alternatively, were investigated under a consideration of geometric factor, the volume ratio of the ceramic to the electrode layers. The actuators were fabricated by tape casting of $0.2Pb(Mg_{1/3}Nb_{2/3})O_3$-$0.38PbZrO_3$-$0.42PbTiO_3$ followed by lamination and burnout & co-firing processes. The actuators of $10 \times 10 \times 0.6\sim2$ mm^3 in size were formed in a way that 60 ~ 200 μm thick ceramics were stacked alternatively with 5 μm thick electrode layer. Increases in polarization and electric field-induced displacement with thickness of the ceramic layer were attributed to change of $90^o/180^o$ domain ratio, which was affected by interlayer internal stress. The piezoelectricity and actuation behaviors were found to depend upon the volume ratio (or thickness ratio) of ceramic to electrode layers.

Introduction

Recently, multilayer ceramic actuators (hereafter called MCA) have been extensively used in controlling moving electric machines such as micro-mirror, micro-sized machining tool, micro-pippets and so on [1]. The design of MCA has been carried out on a basis of low field piezoelectric constant of the piezoelectric materials. In practice, the high field-actuation behavior of the MCA was observed to be different from the calculated strain based on the piezoelectric constant [2]. According to previous studies [3, 4], bulk-type actuators subjected to relative high electric fields exhibited the larger displacement than the value estimated from the d-coefficient measured using the resonance method.

Besides the piezoceramics' properties, the high field strain behavior and its related domain motion for MCA are also dependent upon the geometry. The actuators are designed to stack the piezoelectric ceramic layer and electrode layer alternatively. In the MCA the electrode

Ag-Pd layer exists as inactive part with strong elastic modulus and acts as a resistance to deformation of the actuator. On the actuation mode where an electric field is applied along one direction, the electrode layers tend to act a resistance to deformation along the direction and compression along perpendicular to the direction. Accordingly, the field-induced deformation is affected by the relative thickness of two ceramic and electrode layers.

The purpose of the present study is to understand electric-induced deformation of multilayer ceramic actuator with regard to the relative ceramic layer thickness. The electric and piezoelectric properties were investigated with a consideration of geometric factor, thickness fraction of ceramic to electrode layers.

Experimental Procedure

Ceramic powder used was $0.42PbTiO_3$-$0.38PbZrO_3$-$0.2Pb(Mg_{1/3}Nb_{2/3})O_3$ (PT-PZ-PMN). Various thick green sheets were made by passing the slurry below a doctor blade and drying. By printing Ag-30Pd paste on the sheet, electrode layers were made in 10 × 10 mm^2. The stacking of 10 layers was carried out. The actuators were poled at 3 kV/mm in an electric field at 120°C for 30min.

The basic piezoelectric coefficients d_{31}, d_{33} and k_p of the ceramic material (PZ-PT-PMN) used in the actuator were measured in a circular plate (diameter 18 mm, thickness 1mm) by the resonance method, using an impedance analyzer (HP 4194, Hewlett-Packard Co.), as listed in Table 1. The electric field-induced strain of the poled actuators was measured in the longitude direction, using a laser-based displacement measurement system (OFV 303 vibrometer scanning head, Polytech Co.) at room temperature.

Table 1. Piezoelectric and electric properties of the piezoelectric ceramics used.

D_{33} (pC/N)	d_{31} (pC/N)	K_p	Q_m	Z_r (at 1kHz)	$\varepsilon_{33}/\varepsilon_o$	E_{11} (GPa)
450	-230	0.58	75	196 Ω	2500	22 GPa

To analyze the deformation mechanism, in-situ XRD patterns were collected for the poled actuator under various electric field applications. The diffraction experiment was performed at an applied electric field of 2 kV/mm with step scanning at ~ 45°, where (200) and (002) diffracted peaks are placed.

Composite Model

The multilayer actuator can be considered to be basically the same geometrical structure as composite. In the actuator, the ceramic layer and electrode layer are connected in series along x_3 axis and in parallel along x_1 axis, as shown in Figure 1. Since the two layers are in series along x_3 axis, they experience the same stress. This assumes that the two layers do not exert forces on one another and hence generate no internal stress. In the x_3 axis of the multilayer actuator, the interlayer stress must be taken into consideration. Thus, there are two contributions of d_{33} of the multilayer: those arising from electric field E_3 along x_3 direction and those arising from internal stress.

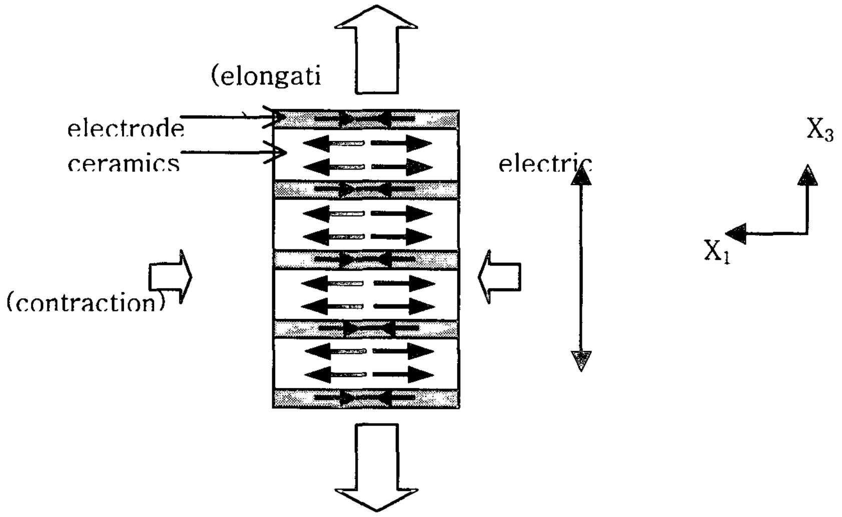


Figure 1. Schematic diagram showing the internal stress configuration in the inner structure of multilayer actuator subjected to an electric field along x_3 axis

Considering only the external electric field E_3, the displacement appearing along the polar direction is given by the following equation

$$P_3 = \varepsilon_o \varepsilon_{33} E_3 = \varepsilon_o \varepsilon_{33(C)} E_3 V_{(C)} \text{ ---------------------------------- } (1)$$

, where P_3 is polarization along x_3 axis, $\varepsilon_{33(C)}$ the relative permittivity of ceramics, E_3 the applied field along x_3 axis, $V_{(C)}$ the volume fraction of ceramic layers.
However, if internal stress $\sigma^{(i)}_1$ is considered as shown in the figure 1, a correction factor should be included. The correction arises from piezoelectric d_{31} coefficient. Thus, the expression can be explained by,

$$P_3' = \varepsilon_o \varepsilon_{33(C)} E_{3(C)} V_{(C)} + d_{31}\sigma^{(i)}_{1(C)} V_{(C)} \text{ ---------------------------- } (2)$$

, when the actuator is stretched along x_3, it contracts along x_1. This contraction is controlled by the elastic compliance. If the two constituents contract equally, an internal stress is generated. The magnitude of the internal stress can be estimated by assuming that the strains are equal along x_1 ($\varepsilon_{1(C)} = \varepsilon_{1(E)}$) and that the sum of internal stress over the actuator structure is zero ($\Sigma\, \sigma^{(i)}V = \sigma^{(i)}_{1(C)}V_{(C)} + \sigma^{(i)}_{1(E)}V_{(E)} = 0$). Under these assumptions, it can be shown that the internal stress on the ceramic layer is given by

$$\sigma^{(i)}_{1(C)} = - d_{31} E_3/(S_{11(C)} + S_{11(E)} \cdot V_{(C)}/ V_{(E)}) \text{ ------------------------- } (3)$$

The internal stress $\sigma^{(i)}_{1(C)}$ produces a piezoelectric effect by coupling through coefficient d_{31}. If both the electric field E_3 and the internal stress $\sigma^{(i)}_{1(C)}$ are acting, the polarization along x_3 is given by

$$P'_3 = \varepsilon_o \varepsilon_{33(C)} E_{3(C)} V_{(C)} - d_{31}^2 \cdot E_3/(S_{11(C)}/V_{(C)} + S_{11(E)}/V_{(E)}) \text{ ---------------- } (4)$$

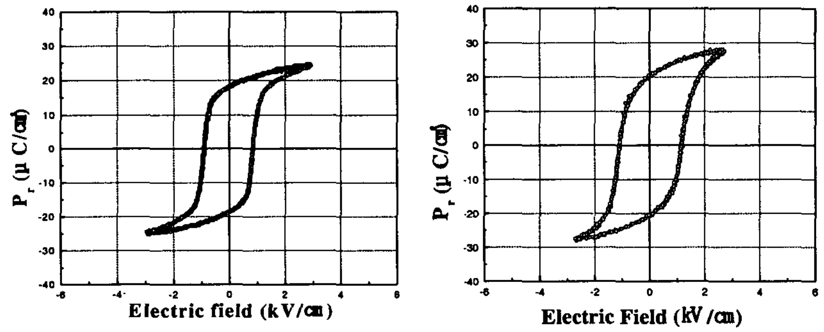
The first term on the right is the electric field induction contribution and the second term is caused by the internal stress contribution occurred between ceramic and electrode layers. Coefficient d_{33} of the actuator is given by

$$\begin{aligned} d_{33}' &= \varepsilon_3/E_3 = Q_{33} \cdot P'^2_3 / E_3 \\ &= Q_{33}(\varepsilon_o \varepsilon_{33(C)} E_3 V_{(C)})^2/E_3 \times [1 - d_{31}^2/\{\varepsilon_o \varepsilon_{33(C)} \cdot (S_{11(C)} + S_{11(E)} V_{(C)}/V_{(E)})\}]^2 \\ &= d_{33(bulk)} \cdot V_{(C)}^2 \times [1 - d_{31}^2/\{\varepsilon_o \varepsilon_{33(C)} \cdot (S_{11(C)} + S_{11(E)} V_{(C)}/V_{(E)})\}]^2 \text{ -------- } (5) \end{aligned}$$

Experimental Results and Discussion

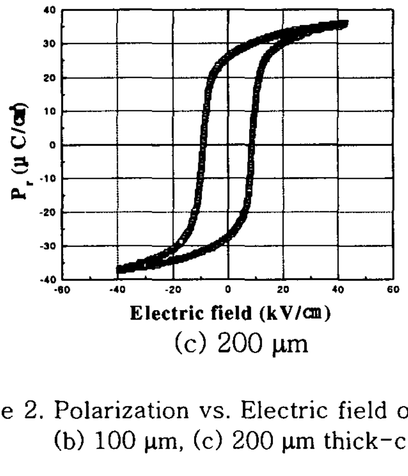
Figure 2 represents polarization vs. electric field curves of multilayer actuators, designed by various thick ceramic layers. As can be seen in the (a) ~ (c), the actuators with the thicker ceramic sheet have the increased spontaneous polarization (P_s) from 23 μC/cm^2 for 60μm-thick layer to 38 μC/cm^2 for 200μm-thick layer.

Figure 3 shows the X-ray patterns of the actuators after the sintering process and the reflected X-ray of (200) relative to (002). As can be seen in (a), only (200) peak was detected in zero-electric field application. In order to observe the relationship [5] between the polarization process and domain switching in the actuator, the X-ray diffraction experiments of the actuators with various thick layers were carried out under an electric field application of 2 kV/mm and the results were shown in the Figure 3 (b) ~ (d). In the case



(a) 60 μm

(b) 100 μm



(c) 200 μm

Figure 2. Polarization vs. Electric field on the multilayer ceramic actuators with (a) 60 μm, (b) 100 μm, (c) 200 μm thick-ceramic layers.

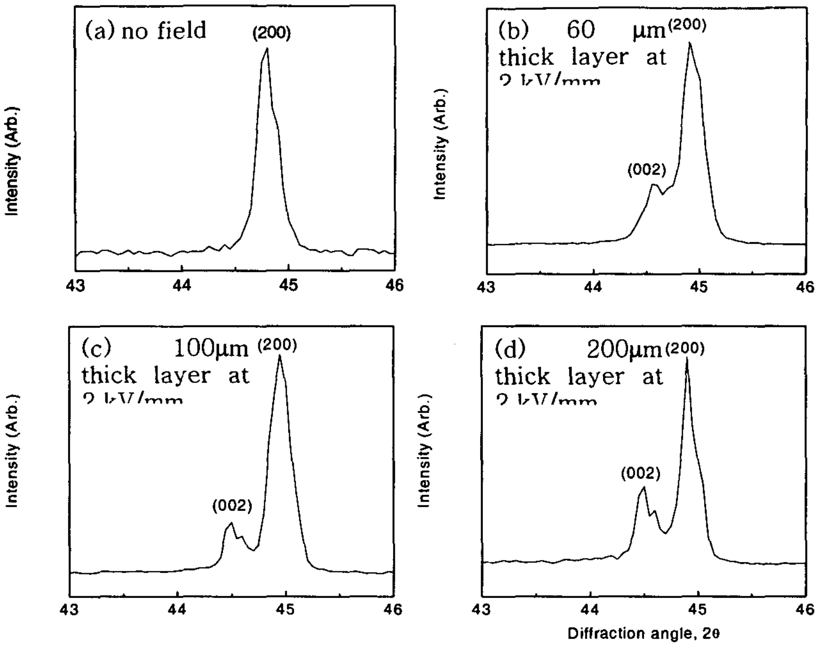


Figure 3. (002) and (200) X-ray diffraction peaks taken on (a) the multilayer actuator without electric field application, and (b) 60μm thick, (c) 100 μm thick and (d) 200 μm thick ceramic layer-actuators under an applied electric field of 2 kV/mm.

of the MCA with 60, 100 and 200 μm-thick ceramic layers, the intensity ratio of X-ray peaks (002) to (200) under the electric field increases with the ceramic thickness, indicating the increased ration of 90° domain relative to 180° domain [6].

Figure 4 is the plots of strain vs. ceramic layer thickness of the MCAs subjected to electric fields of 300 and 600 V/mm. As can be seen in the figure, the MCA containing thick ceramic layer shows the larger strain.

It can be shown from Eg. (5) that d_{33} is considerably decreased due to internal stress and its resultant resistance to contraction along x_1 and elongation along x_3. The calculations were performed on a basis of the data listed in Table 1. The relative amount of 90° domain reorientation observed from the XRD diffraction indicates that the internal stress are generated between the two layers in a manner that the ceramic tends to contract along x_3 axis

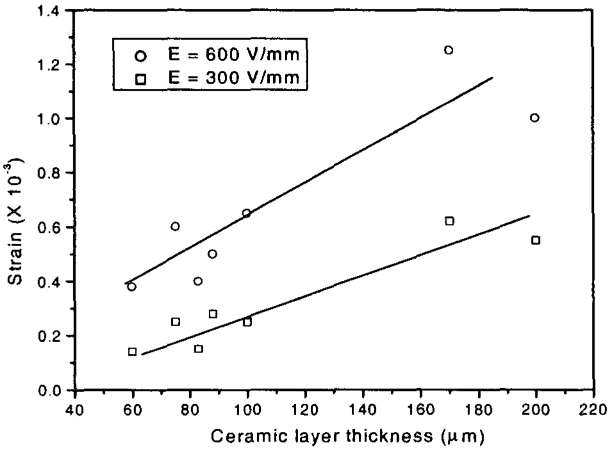


Figure 4. Strain with respect to ceramic layer thickness of MCA subjected to electric fields of 300 and 600 V/mm

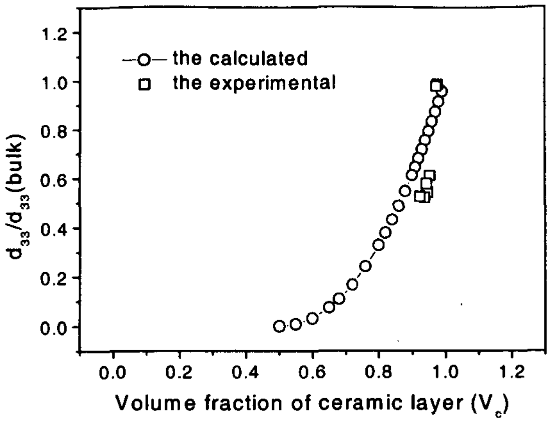


Figure 5. Piezoelectric d_{33}-coefficient ratio of multilayer actuator ceramics relative to bulk type as a function of volume fraction of ceramic layer in the MCA

and to elongate along x_1 axis. Decrease of d_{33} coefficient relative to bulk type specimen coefficient $d_{33(bulk)}$ is shown by the internal stress effect for the case of volume ratio of ceramic layer. Comparing the calculated with the experimental as shown in the Figure 5, the spontaneous polarization and d_{33} as a function of ceramic volume (thickness) fraction is in fairly agreement with the measured values from the Figure 4.

Conclusions

The piezoelectricity and polarization of multilayer actuator were investigated under a consideration of stacking conditions including the thickness of the ceramic layer. The increase in polarization and electric field-displacement with thickness of the ceramic layer was attributed to the interlayer internal stress.

References

1. C. Schuh, K. Lubitz, Th. Steinkopff, and A. Wolff: Advances in Science, Technology and Applications, 2000, Kluwer Academic Publishers, p. 391.
2. M. Marutak: J. Phys. Soc. Japan Vol.11(1956), p. 807.
3. H. Fujii: Jpn. J. Appl. Phys. Vol. 24[3 Suppl.](1985), p. 103.
4. E.I. Bondarenko, V. Yu. Topolov, A.V. Turik: Ferroelectrics Vol. 110(1990), p. 53.
5. G. Li, E. Furman, G.H. Haertling: J. Am. Ceram. Soc. Vol. 80(1997), p. 1382.
6. J. Mendiola and L. Pardo: Ferroelectrics Vol.54(1984), p. 199.