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Contributed Paper

Electrophoretic Deposited Monomorph Actuator

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ABSTRACT

Monomorph actuators, fabricated using electrophoretic deposition (EPD), were investigated in this paper. Three systems, 2-, 4- and 6-layer, were fabricated. Using EPD, monomorph with miniaturized dimension can be fabricated. The monomorph was first characterized in structural properties. Perovskite structures were observed in all the three systems from XRD patterns. The gradient change in microstructure can be found over the cross sections from the SEM photographs. The electromechanical properties were also studied. The displacement variation as a function of number of layers and frequency were examined. A model based on Euler beam theory was proposed to describe the vibration behavior of the monomorph. It is found that in the static case, the 2-layer system generates largest displacement under the same conditions, followed by 4- and 6-layer systems. In the resonance state, the similar trend was also observed.

Keywords : Actuator, Displacement, EPD, Monomorph.

1. INTRODUCTION

Piezoelectric bimorphs or unimorphs are well known displacement bending actuators. They have many applications, such as positioners, valves, motors and vibration dampers. This type of actuator is usually constructed by bonding the piezoelectric layers with elastic layers. The advantage of the actuator is the larger displacement compared with the piezo stacks or multilayer actuators [1]. However, the bimorphs have the shortcoming of low reliability. This is due to the poor interfacial bondings, which may result in the cracking and peeling of the bonding agent in severe conditions. This shortcoming discourages the applications of the bimorphs. Therefore, it is desirable to develop actuators with lower or minimized structural discontinuities. A monolithic actuator, called FGM monomorph, has been proposed to solve this problem [2]. The FGM monomorph has a compositional or functional gradient over the cross section. The purpose of this configuration is to smooth the stress distribution and minimize the stress peaks. In this paper, a FGM monomorph actuator fabricated using EPD was illustrated. EPD is an effective method to form the functionally gradient and multilayer ceramic composites [3]. Three monomorph systems have been fabricated using this method. They are characterized both in structural and electromechanical properties.

2. MATERIALS AND METHODS

The initial powders involve two kinds of piezoelectric ceramics: PZT1 ($0.95Pb(Zr_{0.52}Ti_{0.48})O_3 \cdot 0.03BiFeO_3 \cdot 0.02Ba(Cu_{0.5}W_{0.5})O_3 + 0.5wt\%MnO_2$) and PZT0 ($Pb(Zr_{0.52}Ti_{0.48})O3$). Both powders were prepared using conventional oxide mixing method. The raw oxide powders were calcined at 750 °C and 800 °C for 2 hours for PZT1 and PZT0, respectively. Then they were ball-milled at 150 rpm for 8 hours. The two powders were mixed into different ratios and suspensions were prepared accordingly. The suspension composition of the three systems are: in the 2-layer system, there are 0% and 60% PZT1 content in each suspension respectively; Similarly in the 4- and 6- layer systems, the PZT1 content in each layer is 0%, 20%, 40%, 60% and 10%, 20%, 30%, 40%, 50%, 60% respectively. The powder concentration in the suspension was 50 g/l and the suspension pH was controlled to be 4.6. The suspensions were deposited consecutively to the substrates. After deposition, the deposits were dried for 12 hours. The deposits were then sintered at 1100 °C for 1 hour. Finally they were cut into rectangular shape and coated with silver electrode and poled in silicone oil at 100 °C for 30 minutes under 2 kV/mm.

3. RESULTS AND DISCUSSIONS

To exhibit the piezoelectric properties, PZT materials must be perovskite structure. To examine the structural properties, XRD was performed. Figure 1 shows results of the 2-, 4- and 6-layer systems, respectively. The expected perovskite structure can be found from the XRD pattern in all the three systems.

Figure 2 illustrates the cross section of the FGM monomorph of the 2-, 4- and 6-layer systems after sintering, respectively. For all the three systems, the gradient change in grain size can be observed over the cross sections. From left to right side, the grain size increases as the PZT1 content increases. The compositional and microstructural gradient induced variation in piezoelectric properties over the cross section is the driving source to actuate the monomorph. The observed image in microstructure gradient confirms the microstructural effectiveness of the procedure to fabricate FGM monomorph actuator.

Figure 3 shows the static bending displacement hysteresis loop. The displacement is measured using a system containing RT6000HVS ferroelectric tester and MTI2000 fotonic sensor. The applied frequency is 2.5 Hz. The dimensions of the three systems from 2- to 6-layer are 14.5-2.94-0.23, 15.0-2.62-

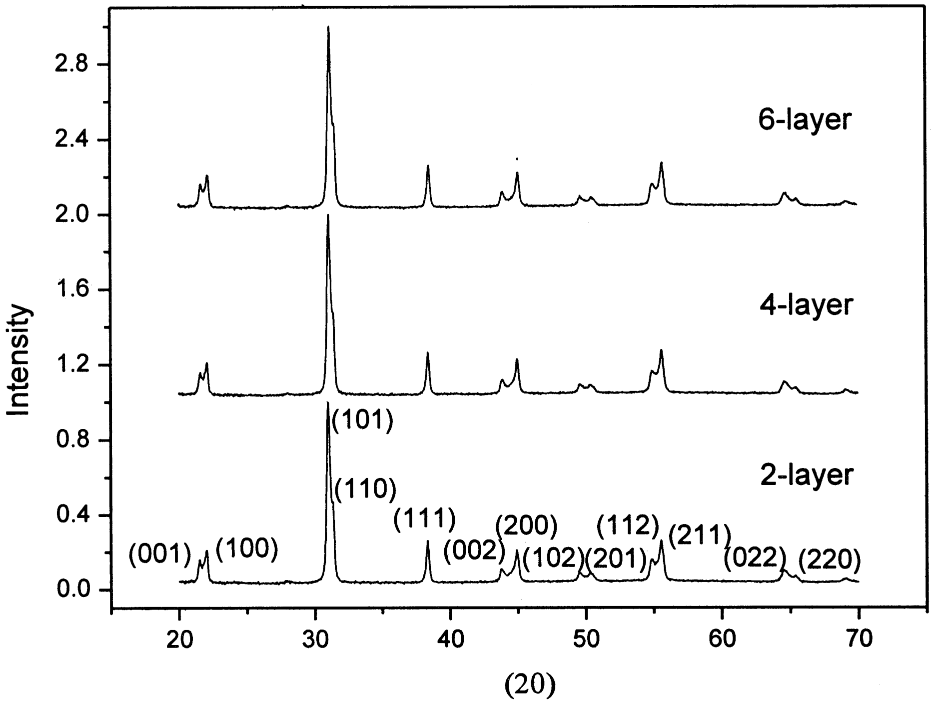
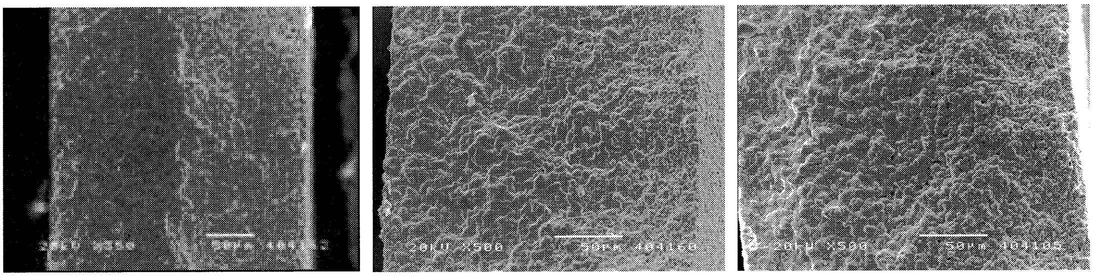


Figure 1. XRD patterns of the 2-, 4- and 6- layer monomorph.



(a) 2-layer (b) 4-layer (c) 6-layer

Figure 2. Gradient variation of microstructure of the 2-, 4- and 6-layer monomorph over the cross section.

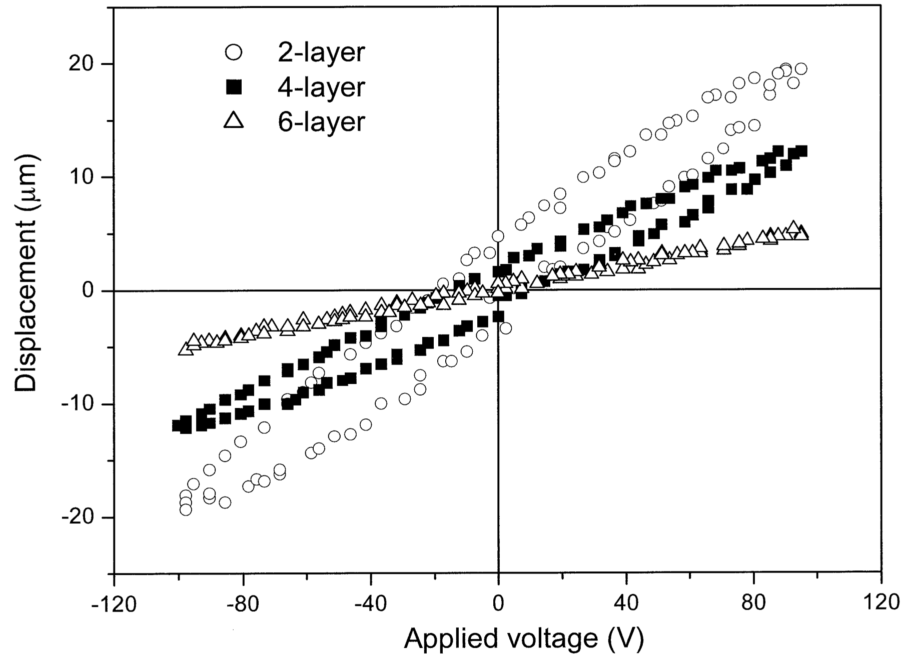


Figure 3. Displacement hysteresis loop of the 2-, 4- and 6-layer monomorph.

0.26, 15.0-2.55-0.34 (mm), respectively. Displacements of approximately 19.39, 12.13 and 5.29 μm were achieved at a voltage of 100 V for the three systems. The bending displacement tends to decrease with the increase of the number of layers. This is because that the increase of the number of layers will smooth the distribution of piezo-electric constant, which will produce more restrictions on the extension or contraction of each layer in the actuator [4]. From Figure 3, it is also found that the monomorphs with more layers show better linearity and smaller hysteresis than those with fewer layers. The hysteresis indicates the losses due to domain wall motions and switching [5]. The low hysteresis and good linearity is an important factor in the control ability of the actuator for precision applications.

Figure 4 shows the behavior of the monomorphs in the dynamic state. A sinusoidal wave was applied through a FG 3000 function generator at 1 Vp-p. The studied frequency range is from 100 to 700 Hz. The

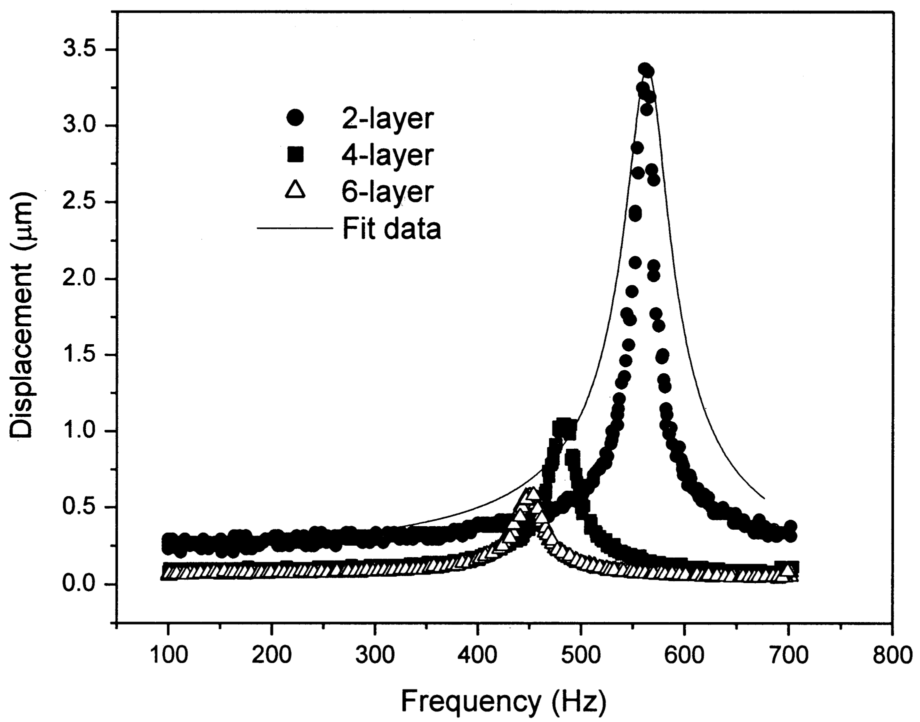


Figure 4. Dynamic displacement of the 2-, 4- and 6-layer monomorph.

bending displacement is frequency dependent and reaches maximum at the resonant frequency. The magnitude of resonant displacement follows the same trend as that in the static measurement, i.e., the 2-layer system has the largest dynamic displacement, followed by 4- and 6-layer systems. The constitutive relation, which is based on conventional Euler beam theory and describes the dynamic behavior of the actuator, has been proposed in the following expressions

$$u(x,t,\omega) = 0.2227Y(x)\frac{M_0}{EI}l^2\frac{\cos(\omega t-\phi)}{\sqrt{\left[1-(\omega/\omega_n)^2\right]^2+4\xi^2(\omega/\omega_n)^2}} \quad (1)$$

$$M_0 = \frac{h^2w}{2n^2}\left[\sum\frac{(2i-1)Y_{(i)}d_{31(i)}nV}{h\varepsilon^T_{33(i)}\sum_1^n 1/\varepsilon^T_{33(i)}} - \frac{\sum\left(Y_{(i)}d_{31(i)}nV\right)\Big/\left(h\varepsilon^T_{33(i)}\sum_1^n 1/\varepsilon^T_{33(i)}\right)\sum(2i-1)Y_{(i)}}{\sum Y_{(i)}}\right] \quad (2)$$

$$EI = \frac{h^3w}{3n^3}\sum\left(3i^2-3i+1\right)Y_{(i)} - \frac{h^3w}{4n^3}\frac{\left[\sum(2i-1)Y_{(i)}\right]^2}{\sum Y_{(i)}} \quad (3)$$

$$Y(x) = \cosh\lambda x - \cos\lambda x + \alpha(\sinh\lambda x - \sin\lambda x) \quad (4)$$

In the above expressions, λ is the wave number, x is the position, h is the thickness, w is the width, n is the number of layers, $Y_{(i)}$ is the Young's modulus in the ith layer, $d_{31(i)}$ is the piezoelectric constant, $\varepsilon^T_{33(i)}$ is the dielectric constant, V is the applied voltage, ω is the applied angular frequency, ω_n is the natural frequency, t is the time, ϕ is the phase difference, ξ is the damping ratio and u is the dynamic displacement. Fig. 4 also shows the fit data calculated using the above expressions for the 2-layer system. It shows the consistent trend with the measured data. The displacement varies with the frequency. However, the fit resonant peak is a little wider than the measured one. This is because that only the first order vibration and viscoelastic damping properties were considered in the modeling.

4. CONCLUSIONS

EPD has been proven to be a good method to fabricate FGM monomorph actuator. The obtained monomorphs have a smooth and fine gradient microstructure. Nearly 20 μm displacement can be achieved for the 2-layer system at 100 V. The displacement tends to decrease with the increase of number of layers both in static and dynamic states. The modeling result shows the consistent trend with the measured data.

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