Journal of the European Ceramic Society **19** (1999) 1153–1156
PII: S0955-2219(98)00396-3
0955-2219/99/$ - see front matter

Comparison Between Bimorphic and Polymorphic Bending Devices

A. Kouvatov,[a] R. Steinhausen,[a] W. Seifert,[a] T. Hauke,[a]* H. T. Langhammer,[a] H. Beige[a] and H. Abicht[b]

[a]Martin-Luther-Universität Halle-Wittenberg, FB Physik, EPII, Friedemann-Bach-Platz 6, D-06108 Halle, Germany
[b]Martin-Luther-Universität Halle-Wittenberg, FB Chemie, EPII, Friedemann-Bach-Platz 6, D-06108 Halle, Germany

Abstract

In the last years a lot of work was done in the field of functionally gradient materials (FGM) especially for their application as monolithic bending devices. For modeling their bending and poling behavior they are mostly treated as a bimorphic structure, although it was shown, that the FGM can have a true gradient or a polymorphic structure. Here we discuss the behavior of a polymorphic structure (PM) consisting of N layers with different piezoelectric properties compared with a bimorphic structure (BM). A finite element method (FEM) modeling shows, that for the same geometrical dimensions and applied voltage the deflection at the end of a cantilever is the smaller the higher the number of layers in the PM. But also for N = *11 the deflection is about 70% of the deflection of the BM. On the other hand, the mechanical stresses are clearly smaller the higher the number of layers. This holds valid even when the voltage applied to a PM with* N > *2 is raised to such an extent, that the deflection of the PM and the BM are equal. In order to compare the modeling with experimental results a BM and a PM with* N = *3 based on $BaTiO_3$-ceramics were prepared. The bending behavior of both structures was observed and the results seems to support the finite element method modeling.*

Keywords: functionally gradient materials, piezoelectric properties, $BaTiO_3$ and titanates, actuators.

1 Introduction

In recent years a lot of work has been done in the development of functionally gradient materials (FGM). It is expected, that these monolithic ceramics will find a wide range of applications due to their simple production and unique properties.[1,2] Especially FGM with a gradient of piezoelectric properties may be used for ultrasonic transducers or, as a natural application, for bending actuators.[3] For that purpose a number of preparation routes have been developed in order to produce ceramics with a one - dimensional gradient of the chemical composition. For the transformation of the gradient of the composition into a gradient of the piezoelectric coefficients after poling different mechanisms are used. For example, a gradient of the electrical conductivity is suited, which can be realized by a gradient of dopants or a chemical reduction of one side of oxide ceramics.[4,5] Another idea is to use the dependence of the Curie temperature on the chemical composition as in the $Pb(Ni_{1/3}Nb_{2/3})O_3$-$PbZrO_3$-$PbTiO_3$-system.[6,7]

For modeling the behavior of such FGM they are mostly treated as a bimorphic structure.[8] They are thought to be composed of only two layers with homogeneous properties. On the other hand it was shown for at least some of these FGM, that the chemical composition is changing rather continuously or is structured with more than two layers within the ceramic.[7] The modeling of the poling process of FGM having such structures remains a still unsolved problem, which should be addressed in the future. However one can expect, that the macroscopic properties, namely the piezoelectric, dielectric and elastic coefficients are changing rather continuously. Consequently also the performance of these FGM bending actuators should differ from that of a bimorph. Sometimes a bending actuator based on a gradient of piezoelectric coefficients is called a 'monomorph'.[9] However, we will use the term '*N*- or polymorph' in this paper, where *N* is the number of layers with different properties in the FGM. The aim of this work is to investigate the behavior of polymorphs with $N \geq 2$

*To whom correspondence should be addressed. Fax: +49-345-5527158; e-mail: hauke@physik.uni.halle.de

layers by means of a finite element method modeling. Special attention is laid on the deflection and the internal mechanical stresses arising within the actuator. Finally experimental results obtained on a bimorph ($N=2$) and a trimorph ($N=3$) based on $BaTiO_3$-ceramics will be compared to the modeling.

2 Modeling

2.1 Basic considerations

The deflection Δz at the end of a cantilever depends on the geometrical dimensions, especially the length l and the thickness t_{ba} of the bending actuator.[10] Therefore the dimensions were chosen to be constant 14·8 × 4 × 1·32 mm for all polymorphs. The coordinates were chosen in a way that z corresponds to the direction of the gradient, e.g. the thickness of the actuator, and x corresponds to the largest dimension of the actuator, e.g. the length of the actuator (see Fig. 1). The polymorphs are composed of N layers each having a thickness of $t_l = t_{ba}/N$, which will be numbered from l at the lower side to N at the upper side. For poled $BaTiO_3$-ceramics there are three independent piezoelectric coefficients d_{ij}, which are reported to be $d_{33} = 160\,\text{pm}\,\text{V}^{-1}$, $d_{31} = -60\,\text{pm}\,\text{V}^{-1}$ and $d_{15} = 250\,\text{pm}\,\text{V}^{-1}$.[12] It was assumed that the upper and the lower layer of all polymorphs are completely poled and have therefore the same values $+d_{ij}$ and $-d_{ij}$, respectively. The inner layers were regarded as partially poled, and the piezoelectric coefficients d_{ijk} of the layer k were chosen to be

$$d_{ijk} = d_{ij}\left(\frac{2k}{N} - 1\right) \qquad (1)$$

In Fig. 2 this is schematically shown for the 2-, 3- and 5-morph. In practice also the dielectric and elastic coefficients depend on the degree of poling. However, this dependence is less pronounced than that of the piezoelectric coefficients, which can take on values between $+d_{max}$ to $-d_{max}$. Therefore, for simplicity, the dielectric and elastic coefficients were kept constant for all layers. For example the values $\varepsilon_{33}{}^{T} = 1950$ and $c_{11}{}^{E} = 166\,\text{GPa}$ were used.

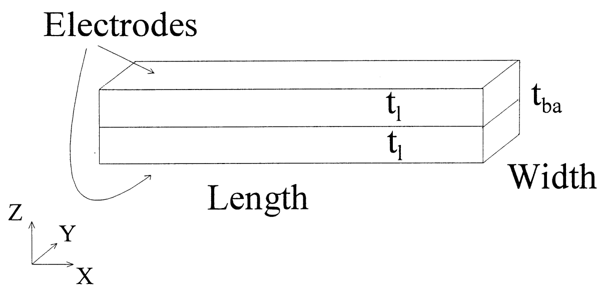

Fig. 1. Schematic illustration of a bending actuator.

For the calculations the commercial FEM package ANSYS 5·3 was used. The model structure consist of up to 17600 elements of the type SOLID5. If not mentioned otherwise, a voltage of 100 V was applied to the polymorphs.

3 Results

Figure 3 shows the dependence of the deflection Δz at the end of the cantilever on the number of layers. The deflection is the highest for the bimorph, and with increasing number of layers Δz is monotonously decreasing. For the trimorph the deflection Δz_3 is still 84·6% of that of the bimorph Δz_2. The corresponding values for the 9- and the 11-morph are 71% and 70%, respectively. For high numbers of layers the deflection seems to approach a constant value asymptotically. From there one can suppose, that the deflection of a FGM bending actuator with a continuous gradient ($N \rightarrow \infty$) of d_{31} is at least 50% of that of bimorph.

Another important feature is the mechanical stress arising within the bending actuator. Due to the bending each layer is contracted at one side and stretched at the other side in the direction of x resulting in the occurrence of high mechanical stresses σ_{xx}. The distribution of σ_{xx} inside the bi- and the

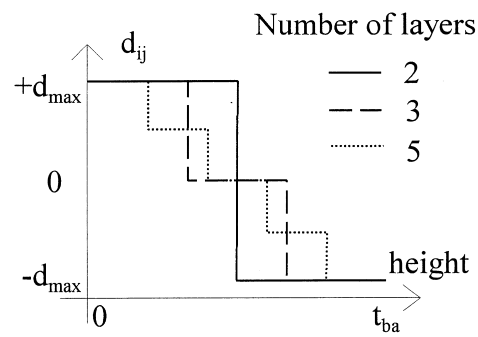

Fig. 2. Schematic illustration of the course of the piezoelectric moduli in polymorphs with different number of layers.

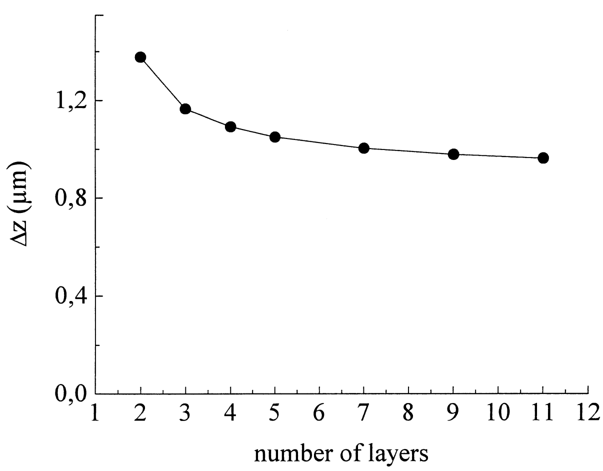

Fig. 3. Dependence of the deflection at the end of the cantilever on the number of layers in the polymorph.

4- morph is shown in Fig. 4. As it was argued by Wu *et al.*,[3] the stress distribution within the 4-morph is smoother than that of the bimorph. Both the mechanical stresses near the interfaces between the layers and the stresses at the surfaces of the sample are clearly reduced. The maximum observed stress $\sigma_{xx,\max}$ is 0·945 MPa for the bimorph and 0·298 MPa for the 4-morph. This stress reduction is an advantage of FGM polymorphic bending actuators compared to a bimorph, because the mechanical stress may reduce life and reliability of the bending actuator.[3]

The dependence of the maximum stress $\sigma_{xx,\max}$ on the number of layers is shown in Fig. 5. A similar dependence as for Δz is observed. With increasing number of layers $\sigma_{xx,\max}$ is decreasing from 0·945 MPa for the bimorph down to 0·162 MPa for the 11-morph. Thus the decrease of $\sigma_{xx,\max}$ seems to be more pronounced than that of Δz. For example, comparing the 11-morph to the bimorph one gets for the deflection a ratio of 0·7 and for the maximum stress a ratio of 0·17. However, it is more sensible to compare the maximum

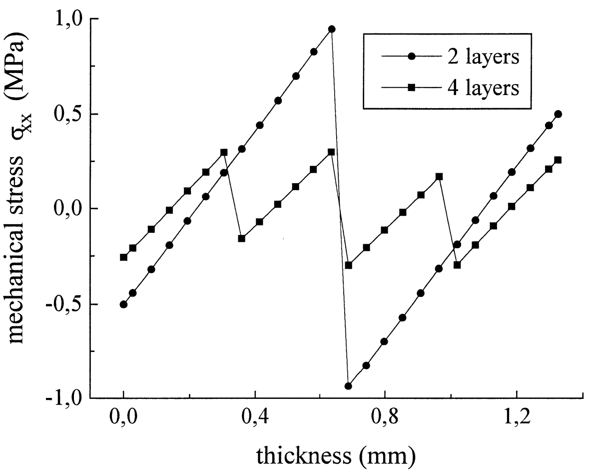

Fig. 4. Dependence of the mechanical stress σ_{xx} on z for the 2-morph and the 4-morph.

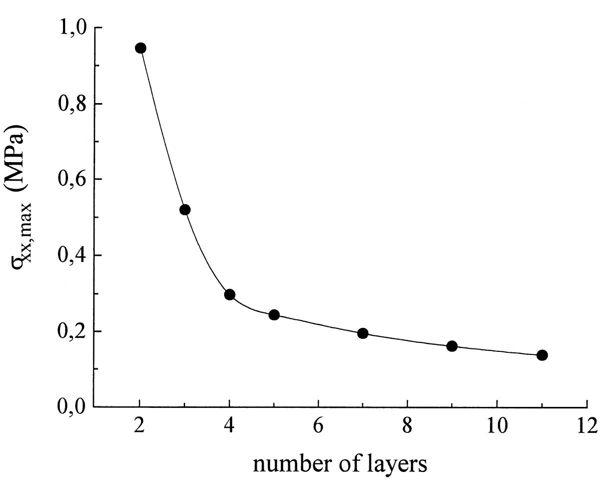

Fig. 5. Dependence of the maximum stress $\sigma_{xx,\max}$ in the polymorph on the number of layers.

stress for the same deflection Δz of the polymorphs and not for the same excitation voltage. For that purpose the voltage applied to an 11-morph was raised to such an extent ($V_{\text{appl.}} = 143$ V), that the deflection of the 11-morph and the bimorph are equal. In this case a maximum stress of 0·198 MPa was observed by the FEM calculations, which is about one-fifth of the maximum stress occurring in the bimorph.

4 Experimental

4.1 Sample preparation

The ceramic powders with a nominal composition of $BaTiO_3$ + 1 mol% TiO_2 were produced by the classical mixed-oxide technique. After mixing and calcining (1100°C, 2 h) of appropriate amounts of $BaCO_3$ (Leuchtstoffwerk Breitungen GmbH, no. 3018) and TiO_2 (Merck, no. 808), the powders were press-granulated using PVA and uniaxially pressed into the same press mould (25×16 mm^2). Then the samples were sintered at 1400°C for 1 h. The samples exhibit a coarse-grained microstructure (average grain size 80 μm). The sintering was performed with a heating and cooling rate of 10 K min^{-1}.

In order to prepare a bimorph and a trimorph pieces of appropriate thickness and an area of 16×4 mm^2 were cut. After evaporating gold electrodes a poling field of 2 kV mm^{-1} at room temperature was applied to the samples. Two days after poling the piezoelectric moduli d_{33} and d_{31} as well as the dielectric constant $\varepsilon_{33}{}^T$ were determined at a frequency $f = 130$ Hz and an electric field strength $E_{\text{appl}} = 20$ V mm^{-1}. The measurement equipment based on a Sawyer-Tower-circuit and a capacitive displacement sensor is described elsewhere.[11] The obtained values $d_{33} = 158$ pm V^{-1}, $d_{31} = 61$ pm V^{-1} and $\varepsilon_{33}{}^T = 1900$ were in a good agreement with data known from literature.[12] One sample, which was used as the middle layer in the trimorph, was electrically depolarized by slowly decreasing the amplitude of an applied ac-voltage. This procedure yields to a dielectric constant $\varepsilon_{33}{}^T$ of 1800 and nearly zero piezoelectric coefficients. After removing the electrodes the samples were glued together using a conductive epoxy (E-Solder 3021, EPOXY Produkte GmbH + Co. Fürth) and gold electrodes were evaporated again. Both, the bimorph and the trimorph had an total thickness of 1·32 mm. For the investigation of the bending behavior of the samples a capacitive sensor was used, too.

4.2 Results

The dependence of the maximum deflection $\Delta z_{\max}$ on the maximum applied voltage $V_{\max}$ is shown in Fig. 6. For both bending actuators having a working

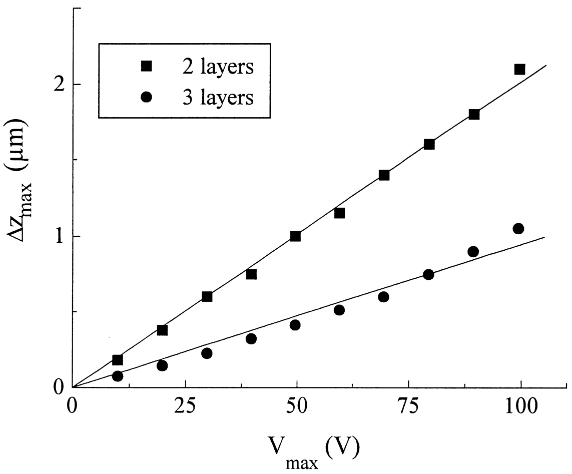

Fig. 6. Experimental dependence of the maximum deflection on the maximum applied voltage for a bimorph and a trimorph.

length 14·8 mm a linear dependence is observed. A linear regression gives a slope $\partial \Delta l_{max}/\partial V_{max}$ of $sl_2 = 0{\cdot}020\,\mu m\ V^{-1}$ for the bimorph and $sl_3 = 0{\cdot}0095\,\mu m\ V^{-1}$ for the trimorph. The slope of the bimorph is somewhat higher than calculated by the FEM. This may be caused by the experimental errors and differences especially in the elastic coefficients between the experiment and the modeling. The slope for the trimorph is lower than that of the bimorph, which supports the results of the modeling. However sl_3 is about 50% of sl_2, whereas from the modeling about 85% is expected. Two reasons may be responsible for this difference. First the trimorph contains two layers of glue, whereas the bimorph contains only one layer of glue. These layers were not taken into consideration for the FEM modeling. Second, the dielectric and elastic coefficients of the middle layer in the trimorph may differ somewhat from those of the upper and the lower layer, which was also not taken into consideration for the modeling.

5 Conclusion

The behavior of FGM bending actuators consisting of N layers with different piezoelectric coefficients was investigated. It was shown, that for the same geometrical dimensions and applied voltage the deflection at the end of a cantilever is the smaller the higher the number of layers in the polymorph. But even for $N = 11$ the deflection is still about 70% of that of the bimorph. On the other hand, the mechanical stresses at the interfaces between the layers decrease with increasing N. This holds valid even when the voltage applied to the polymorph is raised to such an extent, that the deflection of the polymorph and the bimorph are equal. Therefore, FGM seems to be promising candidates for the development of bending actuators with improved life and reliability due to their reduced internal mechanical stresses.[8]

Acknowledgements

This work was supported by the Ministry of Science and Research of Sachsen-Anhalt.

References

1. Niino, M., Development of functionally gradient material. *Journal of the Japan Society of Powder and Powder Metallurgy*, 1990, **37**(2), 241.
2. Kawai, T., Miyazaki, S. and Araragi, M., A piezoelectric actuator using functionally gradient material. *Yokogawa Technical Report*, 1992, **14**, 6.
3. Wu, C. C. M., Kahn, M. and Moy, W., Piezoelectric ceramics with functional gradients: A new application in material design. *Journal of the American Ceramic Society*, 1996, **79**(3), 809.
4. Haertling, G. H., Chemically reduced PLZT ceramics for ultra-high displacement actuators. *Ferroelectrics*, 1994, **154**(1-4), 101.
5. Li, G., Furman, E. and Haertling, G. H., Fabrication and properties of PSZT antiferroelectric rainbow actuators. *Ferroelectrics*, 1996, **188**, 223.
6. Kawai, T., Miyazaki, S. and Araragi, M., A new method for forming a piezo-electric FGM using a dual dispenser system. *In Proceedings of The First International Symposium of Functionally Gradient Materials, Sendai, Japan*, (1990) p. 191.
7. Zhu, X., Wang, Q. and Meng, Z., A functionally gradient piezoelectric actuator prepared by powder metallurgical process in PNN-PZ-PT system. *Journal of Materials Science Letters*, 1995, **14**, 516.
8. Furman, E., Li, G. and Haertling, G. H., An investigation of the resonance properties of rainbow devices. *Ferroelectrics*, 1994, **160**, 357.
9. Marcus, M. A., Performance characteristics of piezoelectric polymer flexure mode devices. *Ferroelectrics*, 1984, **57**, 203.
10. Uchino, K., *Piezoelectric Actuators and Ultrasonic Motors*. Kluwer Academic Publishers, Boston/Dordrecht/London, 1997, p. 136.
11. Sorge, G., Hauke, T. and Klee, M., Electromechanical properties of thin ferroelectric $Pb(Zr_{0{\cdot}53}Ti_{0{\cdot}47})O_3$-layers. *Ferroelectrics*, 1995, **163**, 77.
12. Landolt-Börnstein, *Numerical Data and Functional Relationship in Science and Technology*. Springer Verlag, Berlin Heidelberg New York, 1981, Vol. 16.