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Miniature accordion-shaped low voltage piezo actuators for high displacements

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Abstract

New 3D piezoelectric actuators have been developed to gain higher displacements or specific bending effects. Accordion-shaped structures, so called S-morphs, have the potential to be used as miniaturized optical shutters for optical telecommunications. To exhibit the desired displacement of >300 μm, specific multilayer structures and electrode designs must be developed. To lower the voltage of the power supply, multlayer structures based on thin tapes must be used. By the deliberate preparation of alternating laminated and non-laminated areas of the stacked tapes in combination with a specific electrode design for benders, new types of actuator displacement can be achieved. The paper will describe two processing routes to manufacture accordion-shaped multilayer structures. The performance will be demonstrated.

Keywords: Tape casting; Multilayer processing; Piezoelectric properties; PZT; Actuators

1. Introduction

Due to the high innovative potential of piezoceramic devices, new sensors and actuators for new applications are being developed continuously.[1–6] Bookham Technologies, UK and 1 Ltd., UK[7] have proposed a new concept to use piezoelectric devices as miniaturized shutters for high integrated optical telecommunications. For this application, the basic requirement of the actuator was that a linear displacement of over 300 μm was required from a very compact actuator with dimensions of no more than 7.5 mm × 2.5 mm × 1 mm in size.

To magnify the very small strain expansion of PZT ceramics under low voltage, bending-type actuators can be used. However, a bender has the disadvantage that it can become very long to achieve the desired displacement. Therefore, Hooley et al.[5] developed several 2D spirals and 3D helix structures by rolling up benders with specific electrode designs, which exhibited displacements of several millimeters.[8] To lower the required actuation voltage supply, these helix structures also were developed as multilayer structures based on thin tapes <100 μm.[9] A, further, new concept for the development of a miniaturized actuator with high displacement is the use of a concertina principle in a PZT device. This allows a high displacement to be achieved from a much more compact actuator.

These new 3D piezoelectric actuators of accordion-shaped structure, so called S-morphs, require the development of specific multilayer structures and electrode designs. To achieve a linear displacement in the direction perpendicular to the plane of a bimorph beam, the relative rotation produced through bending of the bimorph must be removed. This is achieved by splitting the central electrode and applying opposite actuation field directions over each half of the beam. This makes each bimorph bend in an ‘S’ shape rather than a constant curvature. Further, bimorphs can then be added to increase the displacement further. This concept is illustrated in Fig. 1,

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which shows a single element of an S-morph actuator. The multilayer concept based on thin tapes also permits the operation of the actuator at low voltages. By the deliberate preparation of alternating laminated and non-laminated areas of the stacked tapes in combination with a specific electrode design, actuators can be made fulfilling the target application for an optical shutter proposed by Bookham, fitting into a space of 8 mm × 3 mm × 3 mm.

2. Experimental procedure and results

The basic design of the S-morph is shown in Fig. 1. The lower part consists of the joined layers 1 and 2 and the upper part of the joined layers 3 and 4. These two parts are joined together only at one end. Technologically, this is realized by the application of a fugitive paste in areas where no joining is desired. The structure shown in Fig. 1 is repeated several times to form the S-morph actuator. Then, the PZT layers are on opposite sides alternately joined and not joined. If a voltage is applied, the S-morph actuator shows a strong extension in the indicated direction, expanding and contracting like a concertina. To realize this concept it was necessary to generate a design for the electrodes as well as for the fugitive layers. Between two fugitive layers, three electrode layers are located.

For manufacturing the accordion-shaped actuator two processing routes were used: one route started from cast PZT green tapes; the other from extruded and stretched PZT filled thermoplastic tapes (Solufill®). For the piezoelectric based application PZT powders are needed, which result in a sintered ceramic of high charge constant d_{31}, high flexural modulus y_{11} and a high sintered density.

2.1. Casting of PZT green tapes

For tape casting,[10] powders with a medium particle size between 0.5 and 3 μm and a specific surface area <10 m^2/g are preferred. To cast a film thickness of 90 μm, the powder should be free of any particles >5 μm. The PZT powder

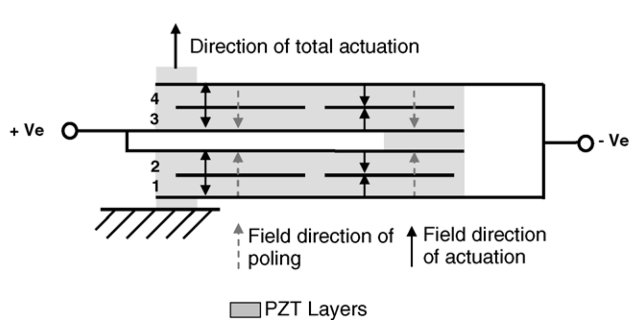

Fig. 1. Simplified schematic diagram of a single ‘S’ unit for an S-morph stack, showing external and internal electrodes and the directions of the electric field for poling and actuation to produce the required actuation displacement.

Table 1
Data of ceramic powders and sintered ceramics (data from powder manufacturer)

	SP 53	TRS 600 FG
BET surface area (m^2/g)[a]	2.0[b]	5–6
Particle size, d_{50} (μm)[c]	1.6[b]	0.68[b]
Theoretical density (g/cm^3)	7.83	7.8
Charge constant, d_{33} (pC/N)	680	660
Charge constant, d_{31} (pC/N)	−275	−300
Elastic stiffness, c_{11}^{E} (GPa)	152	68

[a] ASAP 2000, Micromeritics, Norcross, GA, USA.
[b] Measured after milling.
[c] Mastersizer 2000, Malvern Instr., UK.

Sonox P53 from CeramTec AG, Lauf, Germany fulfilled these requirements after milling (Table 1).

The casting slurry was composed of the PZT powder, an ethanol–toluene solvent mixture and a suitable dispersing agent. The powder was completely de-agglomerated during ball milling with steel balls for 24 h. Then, the binder polyvinyl butyral and the plasticiser butyl benzyl phthalate were added, and the mixture was homogenized for another 24 h. The slurry was then passed through a sieve and degassed to remove dissolved air. The composition of the slurry was optimised to achieve a highly loaded slurry of the desired pseudo-plastic rheological behaviour.

The resulting evaporated slurry was cast on a casting machine with a double chamber casting head (Doctor-blade) onto a PET polymer film to form the green tapes of 90 μm thickness. The green tape density was 61.3% of theoretical density (TD). Based on the amount of organic additives a porosity of 9 vol.% was calculated. This is an appropriate value for screen printing and lamination. After binder burnout and sintering in air (1180 °C for 3 h), the tape exhibited a density of 98% TD and an average grain size of 1.8 μm. The shrinkage was larger in *z* direction (20.5%) than in the planar direction (17.5%).

2.2. Extrusion and stretching of Solufill™ tapes

Alternatively, a fine grained PZT powder (600 FG, TRS Ceramics Inc., State College, PA, USA) (Table 1) was used at DSM Solutech BV, Netherlands, to produce a tape by the Solufill™ process.[11] In this process, a thermoplastic polymer like ultrahigh molecular weight polyethylene (UHMwPE) is filled with the ceramic powder.

The solvent based PZT suspension was de-agglomerated in a ball mill for 7.5 h and filtered over a sieve in order to separate large agglomerates. From this suspension and the UHMwPE fine polymer powder, a homogeneous feedstock was prepared. This feedstock was extruded to form a base tape, which was then consolidated and dried. Afterwards, this base tape was stretched in the appropriate temperature range at first in the direction, in which the tape was extruded and then traverse to it. By this technology, a ceramic filled tape with a final thickness of 50 μm and a porosity of 65 vol.% was achieved.

Before firing, the Solufill™ tapes must be densified by thermo-compression at a temperature of 155 °C and a pressure up to 25 MPa. In this process, a significant densification of the green tapes occurs, which results in a sintered tape of 10 μm thickness and densities of >96% TD (1160 °C for 1 h). In principal, by the Solufill™ process thinner sintered tapes down to 1 μm can be manufactured.

2.3. Manufacturing of S-morph actuators

The actuator units were made via screen printing and lamination in a similar way to standard planar multilayer processing. The main difference however was that for the manufacture of S-morphs, a multilayer structure with non-laminated areas beneath laminated ones was required, and this structure had to be kept during binder burnout and sintering. Finally, the alignment of the electrode design with its alternating termination needed to be controlled throughout the process to guarantee that the electrode configuration could fulfil its function during the polarization step and during the bending actuation.

For screen printing of the electrodes, a suitable Pt-paste for the tapes was developed in cooperation with Gwent Electronic Materials, UK. The metallisation paste needed to be adapted to the tapes in relation to its printability, lamination behaviour and their amount of shrinkage.

To keep the layers partially non-joined, a fugitive paste based on carbon black, was used. Tests with different inks had been performed. The best results were obtained by modifying the ink with the addition of spherical alumina particles of approximately 40 μm size. They guaranteed that the gap was maintained during the entire firing process, and after the carbon was burned away. After co-firing, the particles were removed by ultrasonic treatment.

The dried cast tapes were cut into 84 mm × 84 mm pieces. Four markers of 3 mm in diameter were punched at each corner. The markers were necessary needed for accurate registration of the vision system of the screen printer, and for stacking of the sheets before lamination. The screen designs were adapted to the shrinkage of the tapes to fulfil the geometric requirements of the sintered actuators. On each sheet the desired electrode pattern was screen printed (Model ELA, DEK, UK) (Fig. 2). To ensure the proper position of the print relative to the tape, an optical vision system was employed.

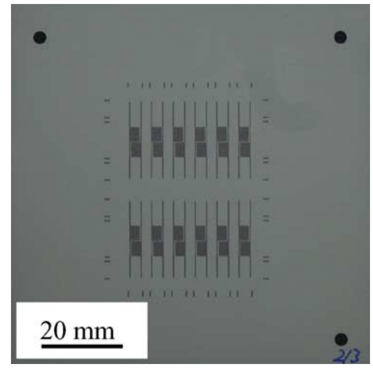

Fig. 2. Centre electrode #3 printed on a green tape sheet (multiple printed panel for 12 actuators), including position holes and cutting markers (cast tape).

After drying of the Pt-paste two ceramic layers (1 and 2, 3 and 4, 5 and 6, etc.) were stacked in the proper sequence on a plate with registration pins and separately joint to form two-layered laminates. Lamination was done via thermo-compression at a temperature of 70 °C under a pressure of 25 MPa for 10 min.

In between each two-layered laminates the fugitive paste was printed to realize the gap between each layer 2 and 3 (Fig. 1). Finally, a stack from, e.g., eight of the two-layered printed laminates was formed on the plate and laminated. The lamination pressure was only applied at the ends of the laminate area by using a specially shaped die. Finally, the 16-layered laminate was cut along the markers by means of a hot knife to form the individual actuators.

In case of the Solufill™ tape, the tape was used from a roll of material. On a fully automated printing stacking machine (PAL 9, Keko, Žužemberk, Slovenia) the tape was cut, laid on a base plate, screen printed and dried on a circulating carrier system. In the second rotation, the second tape layer was cut and transferred onto the first layer, and pre-laminated at a low pressure at 120 °C. On each layer, the screen printed pattern was positioned accurately in relation to the previous print, followed by drying at 60 °C. This procedure was repeated until the desired number of layers were obtained. On this rotating machine, the entire stack was build up. For the S-morph, the top and bottom layer were made with 10 blank Solufill sheets, the active layers with 4 blank sheets in each layer, to achieve a sufficient thickness of these layers.

The pre-laminated stacks of Solufill™ tape were, finally, isostatically laminated at a pressure of 9 MPa at 155 °C, the higher temperature being necessary due to the use of UHMwPE. The laminates were directly cut at 140 °C into strips using an automatic cutting machine (CM12A, Keko, Žužemberk, Slovenia).

On the basis of thermo-gravimetric measurements, an adequate binder burnout program was developed to decompose the organic additives carefully without de-lamination. Co-firing in air resulted in both cases in dense ceramic PZT multilayer devices. Finally, the actuators were terminated and poled in an electric field.

3. Discussion

Under these conditions, crack-free and free-standing S-morphs were realized (Fig. 3). The gaps formed between the layers due to the fugitive material can be clearly seen. Fig. 4

Fig. 3. Side view of a 16-layered, sintered tape cast S-morph structure, showing clear gaps between the layers due to the fugitive material. Scale bar = 1 mm.

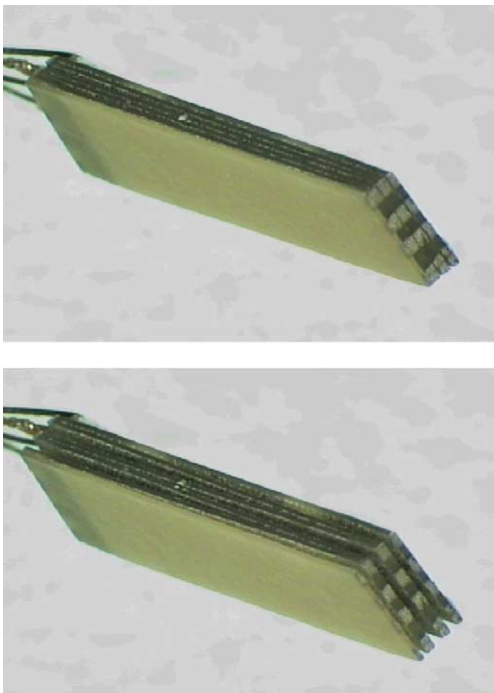

Fig. 4. A sintered Solufill™ tape S-morph. Top: closed configuration with negative voltage applied; bottom: open configuration with positive voltage applied.

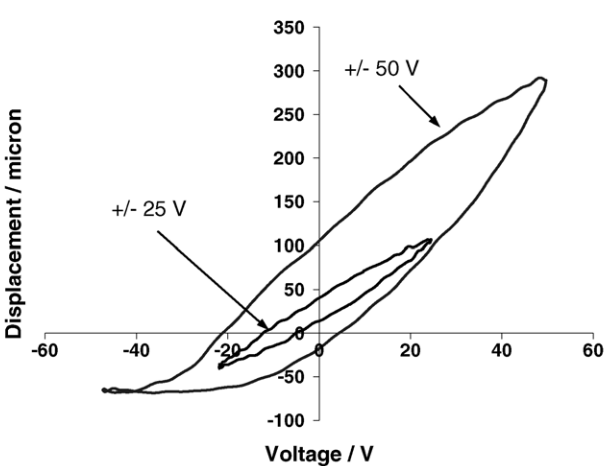

Fig. 5. S-morph displacement as a function of applied electric field (Solufill™ tape, four S-units).

shows the activated S-morph in closed and open configuration. The devices showed the expected concertina movement with a maximum displacement of 350 μm (Fig. 5), by cycling from +50 to −50 V. By increasing the number of stacked layers, this displacement could be increased proportionately.

4. Conclusions

Manufacturing of multilayer S-morph actuators via tape casting and Solufill routes has been achieved, using commercially available equipment. Co-fired samples showed the desired concertina actuation, producing a displacement of up to 350 μm when cycling from +50 to −50 V. Multilayer technology is already used on a large scale to manufacture capacitors, high integrated multilayer circuits, gas sensors and PZT actuators. It is now possible to extend this technology to manufacture high-displacement compact 3D piezoelectric multilayer devices like the S-morph actuator.

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References

1. Newnham, R. E. and Ruschau, G. R., Smart electronics. *J. Am. Ceram. Soc.*, 1979, **74**, 463–480.
2. Uchino, K., *Piezoelectric Actuators and Ultrasonic Motors*. Kluwer Academic Publishers, Norwell, MA, USA, 1997.
3. Mohammadi, F., Kholkin, A. L., Jadidian, B. and Safari, A., High-displacement spiral piezoelectric actuators. *Appl. Phys. Lett.*, 1999, **75**, 2488–2490.
4. Hooley, A., Linear motor and bearings therefore. Patent, GB 2322232 A, 1998.
5. Hooley, A., Pearce, D. H., Lenel, U. R., McKevitt, G. and Shepherd, M. R., Electro-active devices. World Patent, WO 01/47041 A3, 2000.
6. Su, B., Pearce, D. H. and Button, T. W., Routes to net shape electroceramics devices and thick films. *J. Eur. Ceram. Soc.*, 2001, **21**, 2005–2009.
7. EU Project, High performance piezoelectric devices for digital loudspeakers and steered array antennas, 2003.
8. Pearce, D. H., Hooley, A. and Button, T. W., On piezoelectric super-helix actuators. *Sens. Actuators*, 2002, **A 100**, 281–286.
9. Wagner, M., Roosen, A., Oostra, H., Hoeppener, R. and De Moya, M., Novel low voltage piezoactuators for high displacements, *J. Electroceram.*, 2005 (in press).
10. Roosen, A., Tape casting of ceramic green tapes for multilayer device processing. In *Ceramic Transactions,, Vol. 97*, ed. H. J. Jean, T. K. Gupta, K. M. Nair and K. Niwa. The American Ceramics Society, Columbus, Ohio, USA, 1999, pp. 103–121.
11. Hoeppener, R. and Daemen, A., A new tape technology to produce multilayer ceramic capacitors. In *Proceedings of the 4th Capacitor and Resistor Technology Symposium*, March 1994, pp. 122–129.