Journal of Electroceramics, 14, 231–238, 2005

Novel Low Voltage Piezoactuators for High Displacements

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Submitted March 30, 2004; Revised December 17, 2004; Accepted December 20, 2004

Abstract. To improve the performance of piezoelectric actuators, new 3-D designs were developed to gain higher displacements or specific bending effects. Such 3-D actuators of e.g. helical structure have next to the standard actuator or sensor applications the potential to be used in Hi-Fi digital sound projectors. To lower the voltage of the power supply for these miniaturized devices, multilayer structures based on thin tapes must be used. Two processing routes to manufacture helical shaped multilayer PZT structures with specific electrode designs are tested. One route starts from tape cast PZT green tapes of 90 μm or 50 μm thickness, the other from extruded and stretched PZT filled thermoplastic films (Solufill^{TM}) of 9 μm thickness. The properties of these two films are compared. The sheets are screen printed and laminated similar to standard planar multilayer processing. To manufacture helical three-dimensional multi-layers from these laminates new processing techniques are required. The most important difference compared to planar multilayer processing is the necessity to bend the laminated structures. The bending behavior depends on the layer thickness, the number of layers, the diameter of the helix and the flexibility of the tape. In addition, specific measures have to be taken to ensure that the bent multilayer keeps its shape and keeps the alignment of the electrode design during binder burnout and sintering. Finally, working products of super-helical structure suitable for miniaturized loudspeaker application are built and tested.

Keywords: piezoelectric, actuator, 3 dimensional, super-helical structure, multilayer ceramics, Solufill

1. Introduction

Piezoceramic devices are used on a large scale in a variety of technical applications. Due to their high innovative potential, the number of applications increases continuously combined with the development of new types of sensors and actuators [1–4]. Modern loudspeakers utilize a technology of over 100 years old based on magnetic coil actuation to a membrane for analog to analog sound production. By Hooley et al. [5] a new concept has been proposed to use piezo-active transducers in a phased array digital sound projector. The inefficiency of the magnetic coil analog transducers are seen as the major potential for further innovation of this digital to analog sound system. In Table 1 an overview is given of the relevant properties for old and target loudspeaker technologies. For the target technology, compact actuators are needed which exhibit a displacement as high as 5 to 10 mm.

A problem with the piezo effect in PZT ceramics is the low expansion under voltage (Fig. 1). The most common method to increase the deflection is by using a bender. However, a bender has the disadvantage that it becomes very long to achieve the desired displacement. To overcome this issue and to achieve the piezo actuator targets, Hooley et al. [7] developed several approaches by rolling up benders with specific electrode designs forming 2-D spirals and 3-D helical structures. The first approach for loudspeaker application was a cylindrical piezoelectric squeezer that contracts asymmetrically and therefore pushes a low density piston on a bearing in a cantilever style forwards and backwards, depending on the polarity of the voltage. An impression gives Fig. 2. In the course of research it was found that a 3-D super-helical structure gain higher

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Table 1. Overview of essential properties for loudspeaker actuators.

	Magnetic coils	Normal PZT actuator	Target novel actuator
Displacement	±5 mm	100 μm	±5–10 mm
Energy efficiency	<1%	>10%	>10%

displacements and specific bending effects [7–9]. Such 3-D super-helical structures were manufactured via tapes of thickness of typically >200 to 300 μm, that had been produced by viscous polymer processing and which were composed of only two layers [8, 9].

For a commercial application of the invention it is necessary to lower the voltage of the power supply. This is achieved by using PZT multilayer structures based on thin tapes <100 μm (Fig. 1). Therefore, methods had to be developed, to manufacture the super-helical structure via multi-layer processing. The method explored is to build up a planar multilayer bender with specific electrode designs based on cast green tapes and rolling it on a cylindrical support. A problem foreseen is the stress on the outer layer when bending a relatively stiff tape. For this reason also Solufill^{TM}, a stretched ultrahigh molecular weight polyethylene based green ceramic tape, is tested because such tapes exhibit an excellent deformation characteristic. Both tapes consist of a polymer matrix, which is filled with the inorganic ceramic powder. For both type of tapes, an appropriate manufacturing route was developed to form a PZT multilayer coils.

2. Experimental

For the piezoelectric based application PZT powders are needed, which result in a sintered PZT ceramic of high modulus or charge constant d_{31}, high flexural modulus y_{11} and a low density. To manufacture the helical shaped multilayer PZT structures with specific electrode designs, two processing routes were tested, which follow the same basic processing flow sheet (Fig. 3).

2.1. Tape Casting of Ceramic Slurries

One route started from ceramic green tapes, which are produced by tape casting [10]. For tape casting the

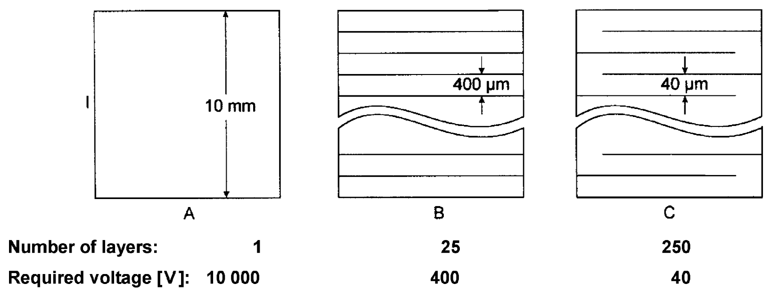


Fig. 1. Voltage for expansion of 100 μm of monolithic vs. multilayer piezo systems based on typical PZT d_{33} values for soft PZT [6].

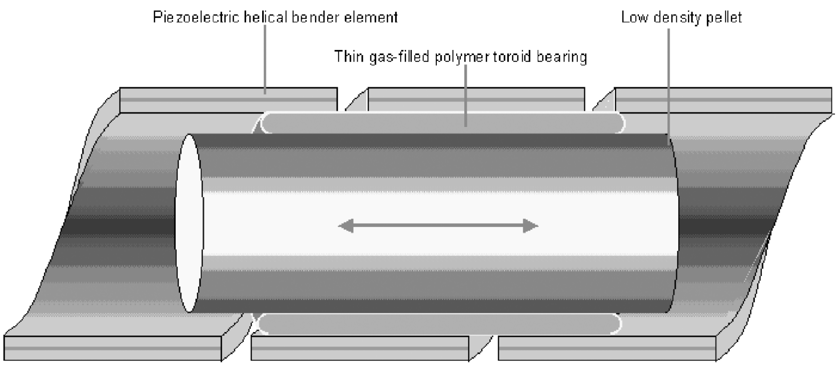


Fig. 2. Concept of cylindrical squeezer pushing a piston on a bearing [1].

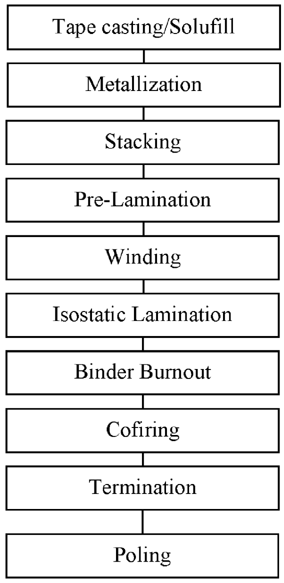


Fig. 3. Processing flow sheet for the fabrication of helical PZT structures.

powder should exhibit a particle size between 0.5 to 3 μm and a specific surface area <10 m^2/g. To cast a film thickness of 50 to 100 μm, the powder should be free of any particles >5 μm. The PZT powder Sonox P53 from CeramTec AG, Germany fulfilled these requirements after milling. The powder was characterized concerning particle size distribution (Mastersizer 2000, Malvern Instr, UK) and specific surface area (ASAP 2000, Micromeritics, Norcross, GA, USA). The data of the powder and sintered ceramic are summarized in Table 2 [11].

The tape casting slurry was based on an ethanol—toluene solvent system, and contained a suitable dispersing agent to disperse and de-agglomerate the particles in the solvent, and a binder poly vinyl butyral (PVB) and plasticizer butyl benzyl phthalate to give the tape strength and flexibility, respectively. The phthalate plasticizer amount was varied to give tapes which are softer and easier to deform. A thermo-compression binder is added to improve the lamination behavior. For the preparation of the tape casting slurry the dispersing agent is added to the solvent followed by the addition of the PZT powder. The mixture is treated in a ball mill with steel balls for 24 h to ensure a complete de-agglomeration. Then the binder, plasticizer and resin are added. The mixture is homogenized for another 24 h. The slurry is passed through a sieve of 40 μm and de-gassed to remove solved air. The composition of the slurry was optimized to achieve a highly loaded slurry of the desired pseudo-plastic rheological behavior.

The evaporated slurry was cast to form the green tapes. The casting was performed on a casting machine of 4 m length with a double chamber casting head equipped with 2 Doctor-blades. A PET polymer film was used as a tape carrier. The casting speed was 5.0 m/h. The two cast tapes had a thickness of 90 and 50 μm, respectively. The green density was 61.3% of the theoretical density. Based on the amount of organic additives a porosity of 9 vol% was calculated. This is an appropriate value for screen printing and lamination. Table 3 summarizes the data of the PZT green tape.

Thermogravimetric investigations (STA 409, Netzsch Gerätebau GmbH, Selb, Germany) showed, that the organic compounds were completely removed at a temperature of 400°C. After binder burnout and sintering in air, the tape exhibited a sintered density of 98% TD at a sintering temperature of 1180°C and a holding time of 3.0 h (alumina kiln furniture). The sintered microstructure with its intergranular fracture behavior is shown in Fig. 4. The average grain size has a diameter of around 1.5 to 2.0 μm. The shrinkage was determined by measuring the dimensions before and after sintering. The shrinkage in z direction is larger than the shrinkage in the plane area, which is typically

Table 2. Data of ceramic powders and sintered ceramics.

	SP 53 [11]	TRS 600 FG [12]
BET surface area (m^2/g)	2.0*	5–6
Particle size d_{50} (μm)	1.6*	0.68*
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
Fired tape thickness (μm)	38 and 70	9

*Data measured after milling.

Table 3. Characterization of PZT green tape.

Thickness	90 μm and 50 μm
Green density	4.8 g/cm^3(61.3% of theoretical density)
Porosity	9 vol%
Shrinkage (1180°C, 3 h)	17.7% in casting direction 17.4% perpendicular to casting direction 20.5% in thickness

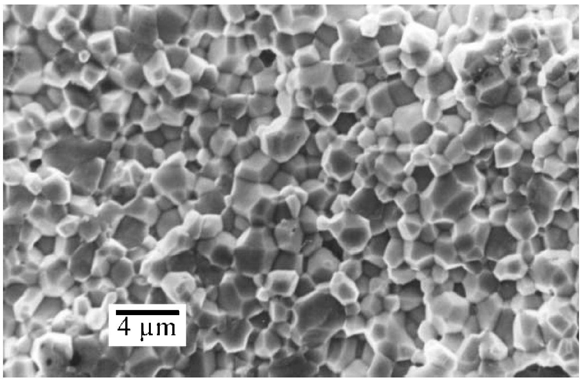


Fig. 4. Sintered PZT microstructure (1180°C, 3 h).

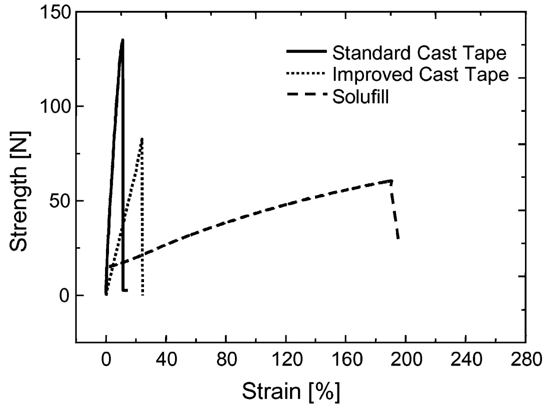


Fig. 5. Strength—strain curve of the different tapes at room temperature.

for tape casting. The shrinkage in x and y direction is around 17.5% and, as expected, a little bit higher in the casting direction (see Table 3).

2.2. *Extrusion and Stretching of Ceramic-Filled Polymers (Solufill^{TM})*

Alternatively, a fine grained soft PZT ceramic was used at DSM Solutech BV, Netherlands, to produce a tape by the Solufill^{TM} process [13, 14]. In this process, a thermoplastic polymer like ultrahigh molecular weight polyethylene (UHMwPE) is filled with the ceramic powder of submicron size. As a filler, the PZT powder 600 FG (TRS Ceramics Inc., State College, PA, USA) with a medium particle size of 0.68 μm was used. The data of the powder and sintered ceramic are listed in Table 2 [12].

The PZT powder/solvent suspension is deagglomerated in a ball mill for 7.5 h and filtered over a 10 and 5 μm sieve in order to separate contamination and large agglomerates. From this suspension and the UHMwPE fine polymer powder, a homogeneous feedstock is prepared. This feedstock is extruded to form a thick base tape, which is consolidated and dried. Afterwards, this base tape is stretched in the appropriate temperature range at first in machine direction and then traverse to it. By this technology, a ceramic filled tape with a final thickness of 50 μm and a porosity of approx. 60 to 70 vol% was achieved. The organic compounds were completely removed at a temperature of 450°C (STA 409, Netzsch Gerätebau GmbH, Selb, Germany).

Before firing, the Solufill tapes must be densified by thermo-compression at a temperature of 155°C and a pressure of 6 to 25 MPa. In this process, a significant and necessary densification of the green tapes occurs, which allows to achieve a sintered tape of 10 μm thickness and fired densities of >96% TD at a temperature of 1160°C for 1 h. In general, by the Solufill^{TM} process thinner sintered tapes down to 1 μm can be manufactured.

Both tapes, the cast tape and the stretched tape, consist of a polymer matrix, which is filled with the inorganic ceramic powder. Due to the different composition, they exhibit a completely different elongation behavior. Using an tensile strength tester (Universal Testing Machine Model 4202, Instron Comp., High Wycom, USA) the elongation behavior of the Solufill tape and the standard cast tape was characterized (Fig. 5). The results show that the standard cast tape exhibit a strain to failure of 11%, whereas the Solufill tape can be stretched for 190% before the tape is destroyed.

2.3. *Metallization*

For screen printing of the electrodes, suitable Pt-pastes for the two tapes had to be developed. This was done in cooperation with Gwent Electronic Materials, UK. The metallization paste must be adapted to the tape concerning printability, lamination behavior and the amount of shrinkage of the two tapes. To determine the amount of adhesion of the paste on the tape and to determine the lamination behavior of the printed tapes lamination tests and peeling tests were performed.

The cast tapes were cut to the desired shape. In the sheets, registration holes were punched. Each sheet was metallized with the desired electrode pattern by screen printing (Model ELA, DEK, UK). To ensure the proper position of the tapes, the optical vision system of ELA was used. The individual tapes had been stacked in the proper sequence on a plate with registration pins.

The Solufill tape was used from the roll. On a Keko PAL 9 fully automated printing stacking machine (Keko Oprema d.o.o., 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 2nd tape layer is cut and transferred onto the 1st layer, and pre-laminated at a low pressure at 120°C. On each layer, the screen printing is done in the accurate position in relation to the previous print, followed by drying at 60°C. This procedure is repeated until the desired number of layers is obtained. The machine can handle 100 devices parallel [15]. On this rotating machine, the entire stack is build up.

2.4. Lamination and Winding

To form coils, the multilayer structure must be twisted. In case of the stack from metallized tape cast sheets, the stack of the multiple printed green tapes is pre-laminated at a low pressure, and cut into stripes by means of a hot knife. The stripes are winded onto a cylindrical ceramic core at elevated temperatures of 50–80°C to get the crack-free helical shaped design. Finally, the wound structure is joined by iso-static lamination to fix the twisted structure and to densify the laminates. For iso-static pressing, it is necessary to seal the helices by a plastic bag. Lamination was done via thermo-compression at a temperature above the glass-transformation temperature of the binder-plasticizer system at 70°C under a pressure of 25 MPa with a holding time of 10 min.

The pre-laminated stack of Solufill tape is directly cut into stripes on a automatic cutting machine (CM12A, Keko Oprema d.o.o., Žužemberk, Slovenia) at a temperature of the cutting knife of 140°C. The laminates are wound onto a core material, vacuum sealed, and finally iso-statically laminated at a pressure of 6–9 MPa at 155°C. This higher temperature is necessary due to the used UHMwPE.

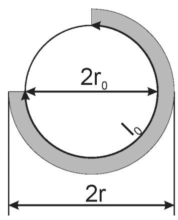
A special mention is made of the pre-pressing and cutting of soft pressed laminates followed by winding, because this step is new to the processing of multi-layers. It is a necessary step in the process to keep sufficient flexibility in the laminates for winding which is lost during the final iso-static lamination step. These steps and the following binder burnout and co-firing procedure had to be developed and optimized.

2.5. Binder Burnout and Co-Firing

The organic additives of this intermediate product will be burnt out. During binder burnout and in the following co-firing process with its shrinkage, the twisted multilayer structure must keep its original shape without crack formation. This is achieved by specific measures concerning core material, shrinking support structures, and oven furniture. E.g., during firing, the PZT laminate would shrink, whereas the core material would not shrink. The hindrance of the shrinkage would result in the destruction of the PZT structure. To enable an undisturbed shrinkage of the PZT laminate, the core is covered with a polymer sheet before the PZT laminate is wound around it. This structure is iso-statically consolidated. The polymeric spacer material burns off during the heat treatment, leaving a gap between core and laminate, which is needed to perform a stress-free shrinkage. In addition, after burnout of the spacer, the contact between laminate and core material is avoided by ceramic spacers, which show the same shrinkage as the laminate.

2.6. Termination and Poling

The sintered PZT multilayers are terminated and poled in an electric field. The schematic for the entire processing was shown in Fig. 3.



$$\varepsilon \approx \frac{\Delta l}{l_0} \approx \frac{r_0 + \Delta r}{r_0} - 1$$

Fig. 6. Estimated strain of bent laminate [16].

3. Results and Discussion

3.1. Tape Flexibility and Winding of Laminate

If a multilayer structure is bent, the inner and outer layers are exposed to different stresses. The bending behavior depends on the layer thickness, the number of layers, the diameter of the helix and the flexibility of the tape. Equation (1) allows to judge the strain which occurs when the laminate is bent onto a core of a specific radius r_0 (Fig. 6) [16].

$$\varepsilon \approx \frac{\Delta I}{I_0} \approx \frac{r_0 + \Delta r}{r_0} - 1 \qquad (1)$$

$2r_0$: inner diameter of the coil, $2r$: outer diameter, Δr: thickness of ceramic multilayer, l_0: circumference of the inner diameter of the coil.

The strain-strength curves for the used tapes were examined in a tensile stress test at room temperature (see Fig. 5). The results show, that the standard cast tape exhibit a strain to failure of 11%, whereas the Solufill tape can be stretched for 190% before the tape is destroyed. This means, that the Solufill tape can be much easier deformed without cracking, which makes it easy to form small inner diameters of <3 mm. For a 10 mm diameter core, a wound 10 layer laminate with 50 μm thickness of the individual cast tapes will show a strain of about 10% of the outer layer. For a diameter of 3 mm, the strain in the outer layer will be 33%. This strain exceeds the maximum strain to failure of the green tapes of standard composition.

To increase the flexibility of the cast tapes, an improved binder/plasticizer system was developed, which fulfills all other processing requirements, but which increases the strain to failure of the green tapes. By decreasing the binder/plasticizer relation of the tapes, the stretching behavior could be improved to 24%. As a side effect, the strength is reduced, and the shrinkage is increased. To achieve a strain of >33%, the winding of the laminate manufactured from the improved tape onto the core was performed at temperatures of 70°C, which approximately doubles the strain to failure compared with the strain at room temperature. In case of Solufill laminates no limitation was found in the green processing up to 32 layers with 9 μm thickness of the single layer and 1 mm diameter of the core. In case of Solufill it was not necessary to work at elevated temperatures during winding.

Only the improved cast tape at 50 to 70°C and the Solufill system meet the elongation criteria for the manufacturing of helices with inner diameters of <3 mm. By the described method the spirals are wound at an elevated temperature (cast tapes) or at room temperature (Solufill tapes). By subsequent iso-static pressing at a temperature above the glass transition point for PVB and above the melting point for Solufill, any residual stresses are completely removed in both tapes. In addition, the Solufill material is recrystallized in the spiral shape under pressure.

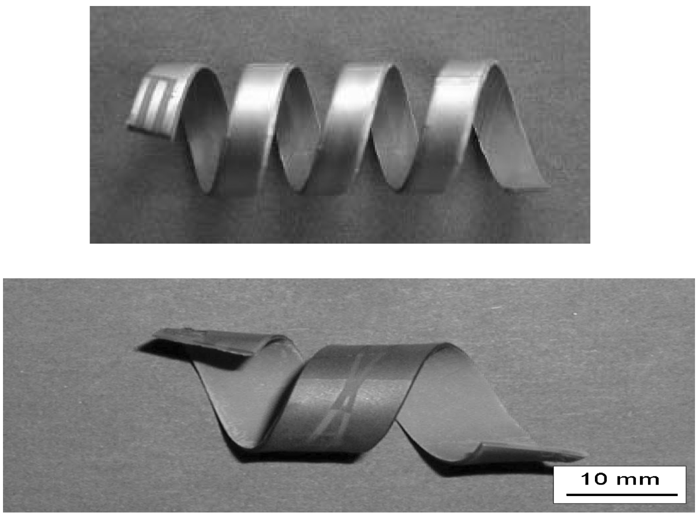


Fig. 7. Sintered 3-D helical shaped PZT structures based on cast tapes (top, 10 active layers of 90 μm thickness, 12 mm inner diameter) and on Solufill tape (bottom, 30 active layers of 9 μm thickness, 10 mm inner diameter) with different design.

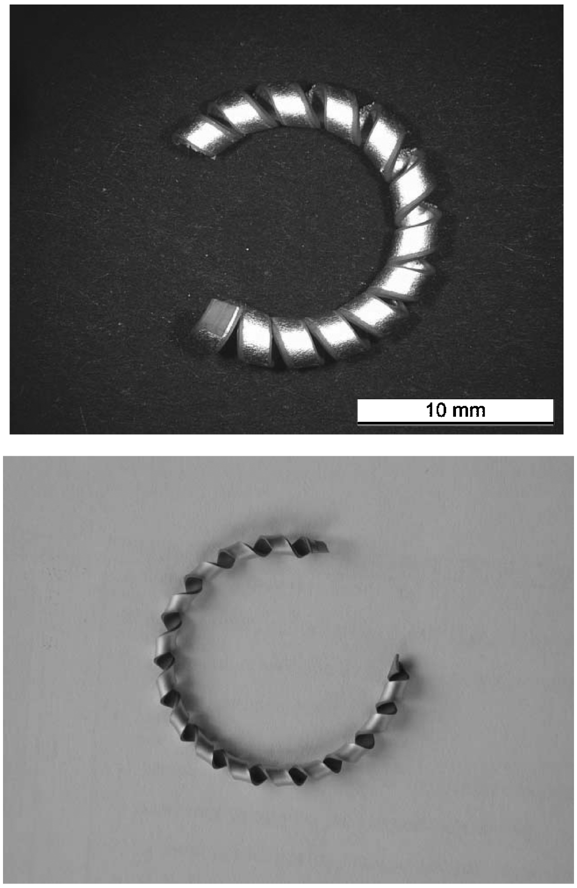


Fig. 8. Sintered 3-D super-helical PZT structures based on cast tapes. Top: 7 layers of 90 μm thickness, 3 mm internal diameter, 15 mm secondary diameter. Bottom: 11 layers of 50 μm thickness, 3 mm internal diameter, 30 mm secondary diameter.

3.2. PZT Helical Shaped Structures and their Performance

By these methods, different 3-D multilayer PZT benders and squeezers were made. 3-D helices with core diameters of about 10 mm, e.g. composed of 10 ceramic layers of metallized cast tapes or of 30 ceramic layers of metallized Solufill tape were manufactured (Fig. 7). Upon actuation the helix structure cones in the desired shape. At 1Limited tests were performed that show a good displacement of the piston with a suitable bearing in a helical bending PZT element.

It turned to be out, that a 3-D helix whose longitudinal axis is itself wound into a helix and which is fixed at one end, shows an improved displacement [8]. These devices are called super-helical structures or Helimorph®. Such structures with inner diameters down to 1 mm can drive a flat membrane for sound generation. The super-helical structures in [8] are composed of only two PZT layers manufactured via viscous polymer processing. In the present paper, Helimorphs® of 3 mm internal diameter were made as multilayer ceramics with 7 to 11 layers of cast tape of 90 or 50 μm thickness via tape technology (Fig. 8). The displacement of the sintered and poled super-helical actuator was measured as a function of applied field at 1 Limited, UK. Figure 9 shows the peak to peak displacements at alternating voltages of 25, 50, 75, and 100 V of the device. A peak displacement of 500 μm at 100 V could be achieved. Blocking forces were found to be in the range of 1 N suitable for loudspeaker application.

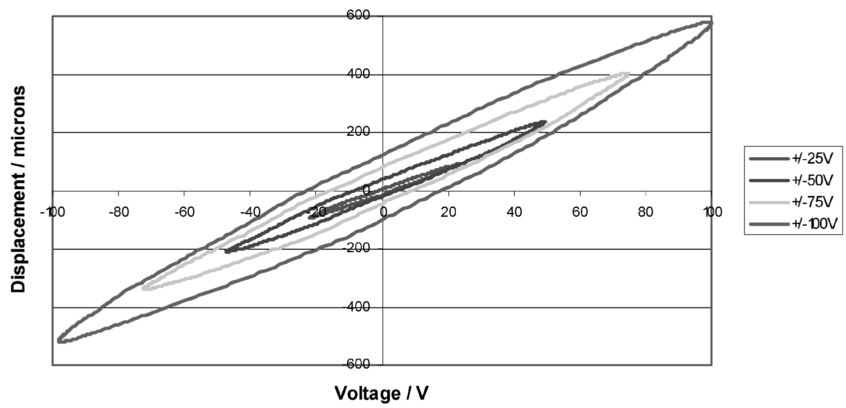


Fig. 9. Peak displacement of sintered super-helical structures in dependence on the applied field (measurements done by D.H. Pearce, 1 Ltd., UK).

4. Summary

A process for the manufacture of helical and super-helical multilayer PZT actuators was developed. The following steps were found to be essential in processing of such 3-D actuators. First, the metallized multi-layers have to be laminated uni-axially at low pressures to leave porosity and flexibility for the winding process. The electrode paste and composition of the tape must allow an elongation above 30%. The Solufill^{TM} UHMwPE tape system matches these requirements fully. In case of cast tapes, the typical composition of standard tapes must be changed to achieve a tape of the desired flexibility. In addition, the operating conditions must be increased to 50 to 70°C. Second, it is necessary to cover the core with a polymer sheet as a sinter shrinkage spacer, before the pre-laminated structure is wound onto the core. Third, it is necessary to fix the wound structure by iso-statically consolidation. Fourth, during binder burnout and co-firing specific supports are needed to avoid geometrical changes of the green body.

With the cast tape system, it is not possible to wind laminated structures with 6 layers crack-free onto a 1 mm core diameter. For core diameters of 3 mm and above, no cracking occurs even for laminates with layers >6. No limitation was found for winding Solufill^{TM} multilayers of 32 layers onto a 1 mm core diameter.

Novel super-helical PZT structures can be made as multilayers for high displacements at low voltages. Using longer length of base benders in multiple turns, the target displacement of ±5 mm in a bass cone can be achieved in the space available. Blocking forces are sufficient for small loudspeaker applications like in mobile phones or in a phased array digital sound projector. Further potential for new miniaturized devices and applications clearly exists.

Acknowledgments

The authors gratefully thank the European Union for financial support under the 5th framework program for the project "High Performance Piezoelectric Devices for Digital Loudspeakers", M. Wong, Haiku Tech Inc, Miami, USA, C. Keintzel, M. Rauscher, and A. Thomsen, University Erlangen-Nuremberg, Germany, Dr. D. Pearce, Dr. U. Lenel, and Dr. T. Hooley, 1 Limited, Cambridge, UK, Dr. T. Button, University of Birmingham, UK, Dr. G. Calis, DSM Solutech B.V., Geleen, The Netherlands, Keko Equipment, Žužemberk, Slovenia, for the use of printing stacking equipment, and CeramTec AG, Lauf, Germany, for the supply of PZT powder.

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