Towards Efficient Integrated Piezoelectric Transducers for Sensing, Actuation and SHM

Peter Neumeister, Markus Flössel, Sophia Eßlinger, Sylvia Gebhardt, Andreas Schönecker

7th European Workshop on Structural Health Monitoring
July 8-11, 2014. La Cité, Nantes, France

TOWARDS EFFICIENT INTEGRATED PIEZOELECTRIC TRANSDUCERS FOR SENSING, ACTUATION AND SHM

Peter Neumeister[1], Markus Flössel[1,2], Sophia Eßlinger[1], Sylvia Gebhardt[1], Andreas Schönecker[1]

[1] *Fraunhofer Institute for Ceramic Technologies and Systems IKTS, Winterbergstraße 28, 01277 Dresden, Germany*
[2] *currently at: Von Ardenne GmbH, Plattleite 19/29, 01324 Dresden, Germany*

peter.neumeister@ikts.fraunhofer.de

ABSTRACT

The present contribution investigates the piezoelectric performance of novel ceramic modules for SHM applications. The multilayer technique is used to embed piezoceramic plates into an encasement made of low temperature cofired ceramics, including electric wiring and electronics. With the help of finite element analyses, the piezoelectric properties are derived from static bending experiments using large signal electrical loads. A significantly increased piezoelectric coupling is found for the embedded piezoelectric elements compared to single elements. This finding is explained by the particular stress state in the embedded piezoelectric element due to the fabrication process.

KEYWORDS : *LTCC/PZT multilayer, poling simulation, effective piezoelectric parameters, bending experiments*

INTRODUCTION

Piezoelectric transducers are well suited for characterising the mechanical behaviour of structures in terms of monitoring of vibrations as well as sending and receiving of acoustic and structural waves. The success of SHM systems demands cheap and robust transducers with integrated electronics and state-of-the-art data processing, potentially self-sustaining and wireless. In addition, such SHM modules have to be designed to allow for simple integration into structural parts, preferably directly during fabrication. A variety of these approaches has been summarized in [1]. They include the fabrication of piezoelectric composites with spherical particles and fibres made of ferroelectric ceramics [2], the serial production of polymer packages [3] and thermoplastic composite structures [4], the direct injection of piezoelectric fibres and particles during the forming process [5], metal die casting [6, 7] as well as ceramic packages [8, 9, 10].
A key role plays the fabrication of the piezoceramic components and their efficient processing, demanding new approaches in design and technology. For this reason, current technological approaches are introduced, which may give rise to future SHM applications, in the next section. Then, the approach of encasing piezoceramic components into LTCC packages (LTCC – low temperature cofired ceramics) is detailed in Section 2, focussing on the evaluation of the effective piezoelectric performance of one particular LTCC/PZT multilayer as well as the embedded piezoelectric element. A summary of the contribution and issues of interest for future research are given in the conclusions.

1 TRANSDUCER APPROACHES AND TECHNOLOGIES AS BASIS FOR NEW SHM SYSTEMS

By means of screen printing, aerosol-, electrophoretic-, hydrothermal-, modified-sol-gel-deposition, and inkjet printing, thick films can be applied directly onto various ceramic substrates such as Al_2O_3, ZrO_2, Si and LTCC as well as glass and selected metals. In the general notation they cover a thickness range of 10-200 µm. Combining individual layers of piezoelectric, conductive, and insulating thick films, active sheet structures can be build up, being suitable for sensing and actuation purposes [11]. Deposition is possible on planar or curved surfaces. The pure inorganic assembly promises a wide temperature range of operation as well as chemical robustness. Figure 1(a) shows a PZT thick film sensor printed onto an alumina tube, yielding a highly stiff load cell. Equally applied to frame structures or trusses, it could be used to measure dynamic or cyclic deformation/loading.

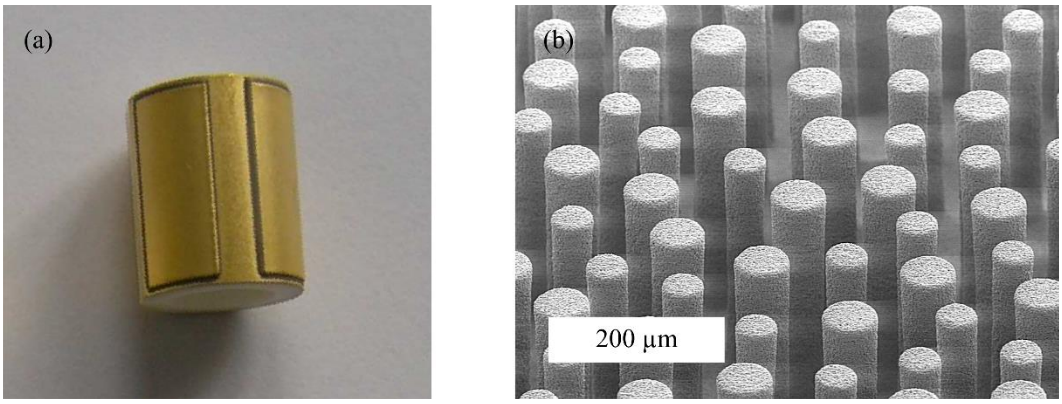

Figure 1: (a) PZT thick film with electrode layers on Al_2O_3 cylinder [11]; (b) fine scaled PZT rod structure for piezoelectric 1-3 composite manufactured with the soft mold process [12].

The soft mould technique [13] allows for a direct forming of fine scaled PZT rod structures for 1-3 composites designed for ultrasonic transducers. The time and cost consuming manufacturing steps dicing or etching of the rod structure out of bulk ceramics or single crystals are omitted. Besides the possibility of a highly open design concerning rod arrangement as well as cross section shape and size (see Figure 1(b)), the usage of permanent moulds assures economic efficiency for medium or large production series.

Manufacture of piezoelectric fibre composites by the arrange-&-fill technique has been introduced in [14] and commercialised by Smart Materials GmbH, Germany. Figure 2(a) shows 1-3 composite block ready for dicing. A new approach considers direct interweaving of such fibres into carbon fibre or glass fibre composites [15]. The fibres possess ring electrodes for poling and driving or sensing. Conductive fibres or yawns within the textile are used for wiring. At first view, the success of this approach seems very limited due to the brittleness of the ceramic fibres. However, bending tests have shown that, due to the ferroelastic behaviour of the piezoceramic, sufficient bending flexibility is present. Figure 2(c) shows a PZT fibre of 0.29 mm diameter made of Sonox® P505 (CeramTec, Lauf, Germany) [2] remanently bent in a 4-point bending set-up. Such composites could measure vibrations or detect impact over a large area.

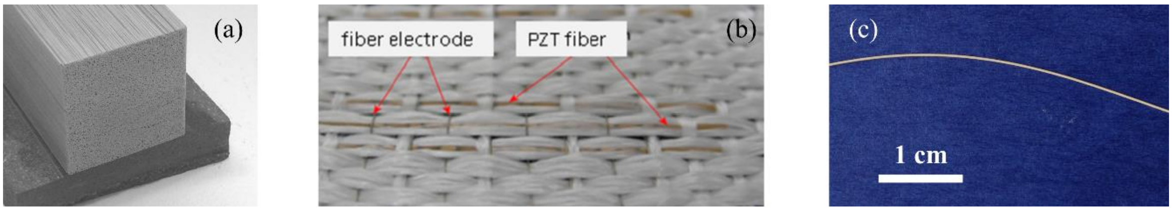

Figure 2: (a) PZT fibres/epoxy 1-3 composite block [14]; (b) PZT fibres weaved into a glass fibre textile and contacted electrically by transversal electrode fibres [1]; (c) remanently bent PZT fibre.

The integration of piezoceramic components into a package of LTCC (low temperature co-fired ceramics) enables the fabrication of compact piezoelectric transducers for SHM applications with integrated electronics. Equipped with self-sustaining energy devices like a piezoelectric energy harvester and wireless communication adapters, these transducers can be applied easily to remote positions in the structure that is to be monitored. Figure 3(a) shows a LTCC/PZT multilayer SHM module with a data processing unit for the generation and evaluation of radial lamb waves [16].

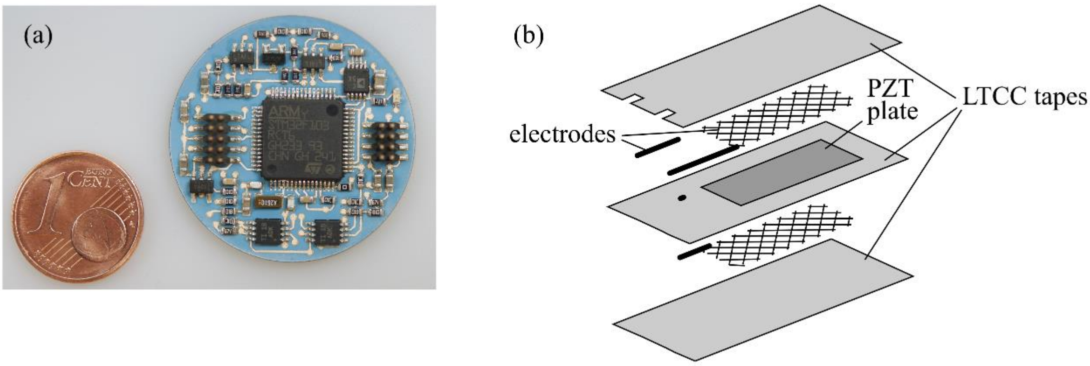

Figure 3: (a) LTCC/PZT ultrasonic transducer with integrated electronics [14]; (b) Schematic explosion image of the LTCC/PZT multilayer [8].

2 POLARISATION AND PIEZOELECTRIC PERFORMANCE OF LTCC/PZT MULTILAYERS

Flössel et al. [8] developed a LTCC/PZT multilayer similar to the SHM module described above but rectangularly shaped. The layout is sketched in Figure 3(b). The piezoelectric element is made of SONOX® P53 (CeramTec AG, Multifunctional Ceramics Devision, Lauf, Germany; referred to as SP53 in the following), which, being a PZT-5H type PZT, possesses very soft ferroelectric characteristics. It measures 25 x 10 mm^2 with a thickness of h = 0.2 mm. It is positioned in the centre of the height of the multilayer. The encasement is made of LTCC tapes from Heraeus HeraLock® Tape-HL2000. The sintered multilayer has a total thickness of 1 mm and planar dimensions of 45 x 20 mm^2.

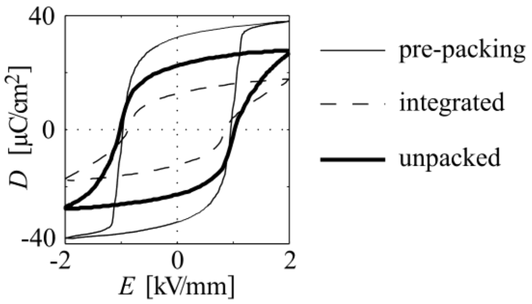

Figure 4: Polarisation hystereses of SP53 before integration (thin solid line), integrated (dashed line) and after removal of the LTCC encasement (thick solid line) [17].

After sintering, the piezoelectric element has to be poled. In order to characterise the ferroelectric potential, the polarisation behaviour due to bipolar electric loading was studied. The results drawn in Figure 4 reveal a drastic deterioration of the polarisation hysteresis (dashed line: integrated) compared to the behaviour of the PZT element before integration (thin solid line: pre-packing). As possible causes, chemical changes due to lead diffusion during sintering as well as mechanical clamping due to the LTCC package have been named [8]. Based on the assumption that the reduction caused by mechanical clamping is revoked when unpacking the PZT elements, the characterisation of the polarisation behaviour of unpacked PZT elements allows for the quantification of both phenomena [17]. Following the found bipolar hysteresis (thick solid line: unpacked), both phenomena affect the absolute attainable remanent polarisation in equal amounts.

The bipolar loading experiments prove that the intrinsic dipoles are aligned only partially when poling the integrated PZT element, suggesting low piezoelectric coupling and thus lower piezoelectric performance of the LTCC/PZT multilayer compared to single PZT plates. A definite statement on the piezoelectric properties of the LTCC/PZT multilayer necessitates direct measurements of the electromechanical coupling. In [8], deflection measurements with a LTCC/PZT multilayer in comparison to a single PZT element, both glued on the steel cantilever, are described. The single PZT element is identical to the embedded element in material and size. The set-up is outlined in Figure 5. The cantilever beam made of stainless steel (X5CrNi18-10) is clamped on one side. With a gap of 10 or 25 mm the LTCC/PZT multilayer or the single PZT element, respectively, is glued on top of the sheet, so that the PZT elements have the same position along the beam axis in both cases. In a distance of 210 mm from the support, deflection was measured by means of laser triangulation. Applying a constant electric potential, which corresponds to an electric field of 2 kV/mm in the PZT element, causes a deflection of 126 μm and 253 μm for the LTCC/PZT multilayer and the single PZT element, respectively.

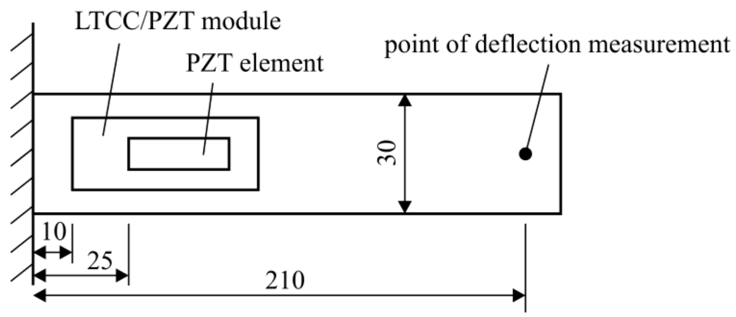

Figure 5: Sketch of beam set-up; the LTCC/PZT module and the PZT element are positioned on top of the metal sheet centred to its symmetry axis.

Compared to the single PZT element arrangement, the LTCC/PZT multilayer arrangement shows two principal differences: (i) reduced actuation due to stiffening caused by the LTCC frame and (ii) a larger distance of the PZT element from neutral axis of beam. Since both differences affect the actuation performance contrarily, it is not possible to draw a precise conclusion from the measured deflection alone. For this reason, finite element analyses of the bending set-up were performed, in order to directly evaluate the piezoelectric properties of the piezoelectric element in both configurations. Based on an initial parameter set, the piezoelectric coefficients are equally scaled so that the simulated bending magnitudes match the measured values. Obtaining parameters for SP53 proved to be difficult. In order to derive the full set of required parameters, a least square optimisation was performed to find the missing mechanical compliances at constant electric field S_{12}^E, S_{13}^E, and S_{44}^E based on the given values for C_{33}^D, C_{55}^D, ε_{11}^T, and ε_{33}^T provided by the supplier [18] together with ε_{11}^S, ε_{33}^S, S_{11}^E, S_{33}^E, d_{31}, d_{33}, and d_{15}. An additional constraint for the lateral compliances reading $S_{13}^E / S_{12}^E \approx 1.3$ is defined, ensuring admissible values for S_{12}^E. The ratio is taken according to the soft piezoceramic PIC151 (PI Ceramic, Lederhose, Germany). The resulting parameters are summarised in Table 1. The isotropic elastic parameters of LTCC and steel, Young's modulus Y and Poisson's ratio ν, are set to $Y_{\mathrm{LTCC}} = 105\ \mathrm{GPa}$ and $\nu_{\mathrm{LTCC}} = 0.31$ [17] as well as $Y_{\mathrm{steel}} = 200\ \mathrm{GPa}$ and $\nu_{\mathrm{steel}} = 0.30$ [19], respectively. Thickness and mechanical compliance of the glue are neglected, assuming a rigid connection between ceramic and steel. The so computed effective piezoelectric strain constants d_{31}^{eff} are given in Table 2. The analyses show that the actual piezoelectric performance of the integrated PZT element is significantly higher than that of the single element by a factor of 1.55, despite the low remanent polarisability of the integrated PZT element. In the following, this result is discussed.

Table 1: Estimated initial parameter set used for SP53.

quantity	value	quantity	value
$\varepsilon_{11}^S / \varepsilon_0$	1670	C_{11}^E /(GPa)	160.0
$\varepsilon_{33}^S / \varepsilon_0$	1625	C_{33}^E /(GPa)	114.0
e_{13} /(C / m ^{2})	-8.68	C_{12}^E /(GPa)	114.6
e_{33} /(C / m ^{2})	23.48	C_{13}^E /(GPa)	98.3
e_{15} /(C / m ^{2})	21.93	C_{44}^E /(GPa)	28.5

Table 2: Measured deflection and computed effective piezoelectric strain constants.

configuration	v^{meas} / µm at 2 kV/mm	d_{31}^{eff} /(10^{-12} C/N)
Single PZT element	253	-201
LTCC/PZT module	126	-313

In a previous work [17], the mechanical stress state and its effect on the remanent state of the embedded piezoceramic in terms of remanent strain and polarisation is investigated during cooling from the sintering temperature and subsequent poling. A simplified axisymmetric layered disc model is derived, utilizing a micromechanical material description of the piezoelectric (or better: ferroelectric) ceramic element. The experimental findings of the strongly reduced polarisation behaviour were well reproduced. They were attributed to the large thermal shrinkage of the used

PZT material compared to the LTCC, causing significant tensile stresses between 60 and 80 MPa in the multilayer plane inside the PZT element. The effect of these stresses on the piezoelectric performance was discussed by stating that this tensile stress state acts equivalently to a state of uniaxial compression parallel to the remanent polarisation for which numerous experimental data is at hand. This analogy is possible under the assumptions that (i) the effect of the mechanical stress state on the piezoelectric performance of a piezoelectric ceramic arises from domain contributions and that (ii) the deviatoric stress is decisive. The latter can be reasoned from experience that the switching strain is volume conservative. The large signal piezoelectric response of PZT-5H type ferroelectrics was investigated in [20] for electric field amplitudes of 2 kV/mm and varying compressive load. By dividing the measured strain changes with the electric field amplitude, the large signal d_{33} -coefficient is computed, depending on the applied compressive load, see Figure 6.

The change of d_{33} related to the mechanically unloaded case lies in the range of a factor of 1.89 to 1.38 for the predicted tensile loads within the LTCC/PZT multilayer. If a similar behaviour is assumed for the lateral deformation (i.e. d_{31}), this behaviour explains the ratio of the effective d_{31}^{eff} -values derived above from the bending experiments, despite the presumed chemical changes within the embedded PZT material.

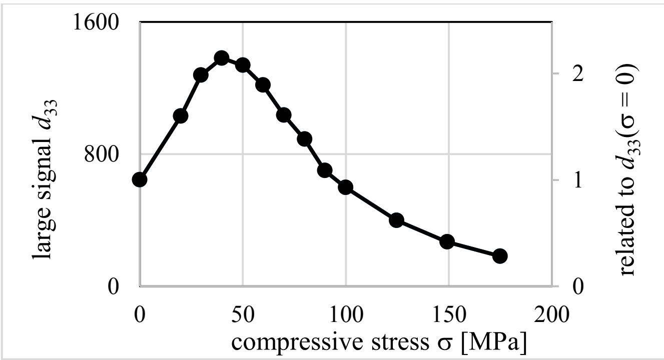

Figure 6: Large signal piezoelectric stain constant for an electric field load of 2 kV/mm against applied mechanical bias load derived from the strain data measured in [20] for 5H-type PZT.

CONCLUSIONS

With the help of the multilayer technique it is possible to fabricate highly robust LTCC/PZT modules with high potential as electromechanical transducers for SHM applications. However, chemical changes during sintering as well as the thermal strain misfit due to cooling after sintering may affect the polarisation behaviour and the piezoelectric performance of the embedded piezoelectric elements significantly. Although the attainable remanent polarisation is observed to be strongly reduced for the module investigated here, an increased piezoelectric coupling was found. This finding is explained with high tensile stresses in the piezoelectric element, which questions the mechanical robustness of the module. Therefore, further investigations have to focus on material selection, taking into account polarisability, piezoelectric performance, and reliability.

ACKNOWLEDGEMENT

This research is supported by the Deutsche Forschungsgemeinschaft (DFG) in context of the Collaborative Research Centre/Transregio 39 PT-PIESA, subprojects C3 and A1, as well as by the FhG Internal Programs under Grant No. Attract 064-692 018.

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