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Characteristics of piezoelectric cantilevers embedded in LTCC

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Abstract

Accurate modelling is required for the effective utilization and optimization of embedded functional materials and structures. In this study, piezoelectric cantilevers with passive low temperature co-fired ceramic (LTCC) and steel layers were modelled and manufactured. The displacement performance of the actuators was studied utilizing FEM models created with ATILA software. Commercial piezoceramic PZ29 was used for the actuators with an active size of 17 mm × 5 mm × 0.25 mm. The displacement characteristics of the actuators with different electric fields and passive layer thicknesses were measured. Both manufactured actuator types exhibited high effective d_{31} piezoelectric coefficients and large displacements e.g., ∼120 μm under ±0.35 V/μm electric field. The influence of the LTCC process and modelling parameters for the piezoelectric material were characterised for the further utilization of embedded actuators in the ceramic circuit board.

Keywords: Piezoelectric properties; PZT; Actuators; Electromechanical modelling

1. Introduction

Piezoelectric benders, such as unimorphs or bimorphs, generate high displacements but low forces and have been utilized in many fields of application e.g. in fine mechanics, telecommunication, vibration control and fluidics.[1,2] Conventionally the benders have been manufactured by gluing a passive layer on the piezoelectric material. This method, however, might cause reduced performance due to de-laminations and weak physical bonding in the developed interlayer between the active and passive layers.[3,4] Consequently, bending actuators utilizing a monomorph structure, i.e., without a bonding layer, have been developed.[5,6] In some cases, such actuators also exploit mechanical pre-stress to enhance the piezoelectric d_{31} coefficient which is mainly responsible for the axial displacement in the benders.[7–10]

In practical applications, however, the functionality, size and overall cost play an important role. The integration of actuators into a circuit board is one answer for these requirements. It also opens up new possibilities for novel and smart applications as multifunctional modules with a combination of sensors and actuators can be fabricated. Such an approach requires detailed analysis about the effect of the integration on the actuator and sensor behaviour. Modelling is an effective way to customize, optimize and develop new systems and structures. However, the model requires accurate knowledge of specific material parameters under the operating conditions.

In this work, unimorph type pre-stressed cantilever actuators were embedded in low temperature co-fired ceramic (LTCC) circuit board material. The passive material for the bender is implemented in two ways; using LTCC with the sintering phenomenon[10] or steel sheets with gluing. For further development of the embedded actuators, the discrepancies between the modelled and measured components were defined and methods to improve the accuracy of the finite element modelling (FEM) conducted with ATILA software were utilised.[11]

2. Experimental

Piezoelectric bulk material PZ29 (Ferroperm piezoceramics A/S, Denmark) was used in the experiments. The length, width and thickness of the manufactured cantilever actuators were 19 mm × 5 mm × 0.25 mm, respectively, with 2 mm of the length being used for clamping (Fig. 1). The cantilever actuators were laser cut (Nd:YVO-laser, Siemens Microbeam 3200, Siemens Dematic AG, Germany) from electroded and poled bulk discs with a thickness of 250 μm and a diameter of 29 mm.

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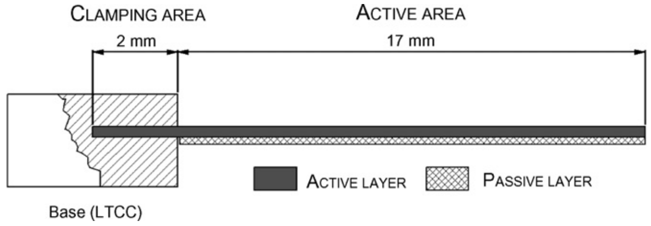

Fig. 1. Actuator structure for piezoelectric actuators embedded in LTCC.

Two different piezoelectric cantilever batches were manufactured. In the first batch, the cantilever actuator was embedded into a LTCC substrate and LTCC layers with thicknesses of 70, 105 and 170 μm (measured after sintering) were added under the piezoceramic and co-fired at 875 °C. The actuator structure and manufacturing process are described elsewhere in more detail.[10] In order to investigate the possible harmful effects of the elevated temperatures, bulk actuators without the LTCC layers were subjected to the same firing process. The remanent polarisation, relative permittivity and coercive electric fields were investigated with a Radiant RTV6000HVS system (Radiant technologies, USA) to find the optimal poling conditions. The bulk and unimorph type actuators were poled under electric fields of 1.5 V/μm at 125 °C temperature for 30 min.

The second batch of the actuators was manufactured from cantilever bulk actuators bonded to steel layers with thicknesses of 50, 100 and 150 μm (5 mm × 17 mm) using cyanoacrylate glue. Additionally, some of the bulk actuators were left without the passive layer so that the properties of the identically processed bulk actuators could be measured.

The displacement of the actuators was measured using a system based on a Michelson interferometer.[12] Instead of the Round Robin jig, a similar mechanical set-up was used enabling high axial displacement measurements. Electric fields from ±0.2 to ±0.35 V/μm at a frequency of 10 Hz (sinusoidal signal) were used in the measurements. The actuators were clamped tightly with screws and a plastic holder at the fixed end. For the unimorphs and bulk actuators, the deflection of the tip and the piezoelectric d_{31} coefficients were measured, respectively.

3. Modelling procedure

The displacement performance characteristics of the cantilever actuators were studied with FEM modelling using ATILA software (Cedrat Recherche, ATILA, Version 5.2.4., France). The modelling of the actuators commenced with the making of a 2D wire model, which was further processed into a 3D model. The required data for the FEM calculations, i.e., clamping, polarization and excitation signals, were introduced as described by Heinonen et al.[11] The excitation signals (sinusoidal) used in the simulations were 0.4–0.7 V/μm with a frequency of 10 Hz. The glue layer, of thickness 20 μm, between the steel and the piezoceramic was also included in the models.

Three sets of actuator models were created. In the first set, the original material parameters (Table 1) were used. In the second set, the piezoelectric coefficient d_{31} value was modified as presented by Heinonen et al.[11] In the third set, the d_{31} values measured from the corresponding bulk PZ29 actuators were used. Also, reference values for the effective d_{31} coefficient of the actuators were calculated using the formulas presented by Wang et al.[13] The d_{31} values used in modelling sets 1 and 2 and the calculated d_{31} reference values are presented in Table 2.

Table 1
Properties of the piezoelectric material PZ29, steel, LTCC and glue

Material	Elastic compliance coefficients ($\times 10^{-12}$ m^2/N)					
	s_{11}	s_{12}	s_{13}	s_{33}	s_{44}	s_{66}
pz29	17.0	−5.78	−8.79	22.9	54.1	45.6

Material	Density (kg/m^3)	Piezoelectric coefficients (pm/V)			Relative permittivity	
		d_{31}	d_{33}	d_{15}	$\varepsilon_{11}/\varepsilon_0$	$\varepsilon_{33}/\varepsilon_0$ (K_{33})
pz29	7460	−243	574	724	1340	1220

Material	Density (kg/m^3)	Young's modulus (GPa)	Poisson's ratio
LTCC	3100	120	0.17
Steel	7800	210	0.30
Glue	1200	6	0.30

4. Results and discussion

Because the ATILA program uses a linear approach in the calculations,[11] the original material parameters used in the modelling (Table 1) were adjusted to improve the correspondence

Table 2
Different piezoelectric coefficient d_{31} (pm/V) values of the actuators, I: estimated, II: calculated, III: measured

Sample	Electric field (V/μm)			
	0.4	0.5	0.6	0.7
70 μm LTCC				
I	−282	−297	−315	−331
II	−223	−235	−249	−262
105 μm LTCC				
I	−276	−292	−316	−334
II	−231	−245	−264	−280
170 μm LTCC				
I	−263	−279	−294	−309
II	−246	−260	−275	−289
All LTCC samples				
III	−322	−339	−355	−370
50 μm steel				
I	−250	−265	−281	−295
II	−201	−213	−226	−237
100 μm steel				
I	−265	−279	−296	−310
II	−224	−251	−263	−275
150 μm steel				
I	−241	−255	−267	−280
II	−212	−225	−235	−247
All steel samples				
III	−292	−310	−328	−344

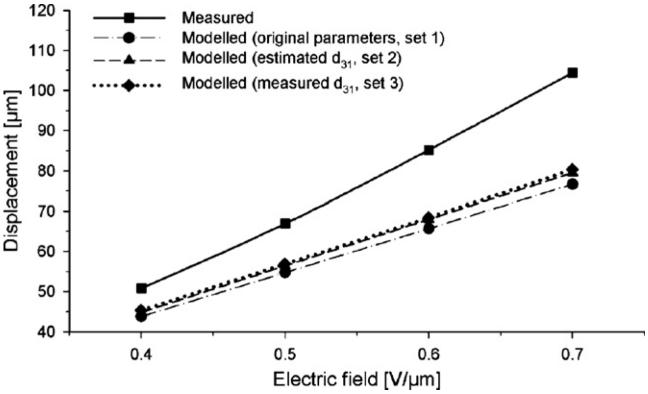

Fig. 2. Modelled and measured results of the *z*-axis displacement as a function of electric field (70 µm thick LTCC layer).

between the modelled and the measured results. The calculated d_{31} values (Table 2) using the formulas presented by Wang et al.[13] were ∼ ±10% of the original d_{31} values (Table 1). However, the calculated d_{31} values were reasonably smaller compared to those acquired from the estimation method or measured values (Table 2). The best correspondence between the modelled and measured results was achieved by using the measured d_{31} values.

The modelling results of the manufactured actuators with 70, 105 and 170 µm thick LTCC and 100 µm thick steel passive layers, compared to the measured results are presented in Figs. 2–5, respectively. Good correspondence was obtained with the steel and 170 µm thick LTCC layers.

It is notable that the modelled displacement results of the actuators with 70 and 105 µm thick LTCC layers (Figs. 2 and 3, respectively) improved only ∼ 5–10%, even if the measured d_{31} values used in the modelling (Table 2) were ∼ 32–52% larger than the original values. Also, the real d_{31} values of the LTCC actuators are probably higher than those measured from the bulk samples because of the pre-stress.[7–10] Therefore, the effective d_{31} values should also be larger, which would result in increased displacements of the modelled results. Adjusting other parameters, for example, increasing the Young's modulus of the passive layer or decreasing the Young's modulus of the PZT layer, would also result in higher displacements.

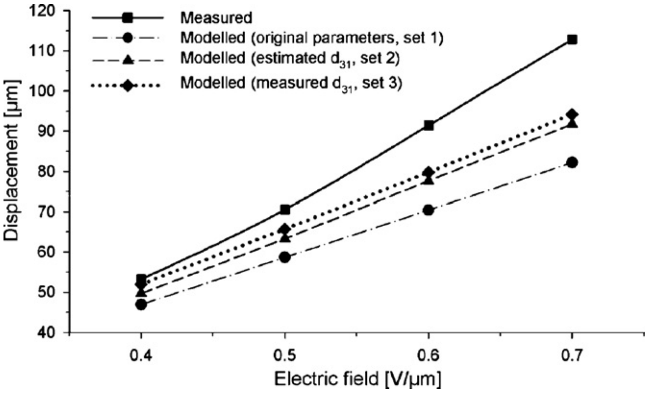

Fig. 3. Modelled and measured results of the *z*-axis displacement as a function of electric field (105 µm thick LTCC layer).

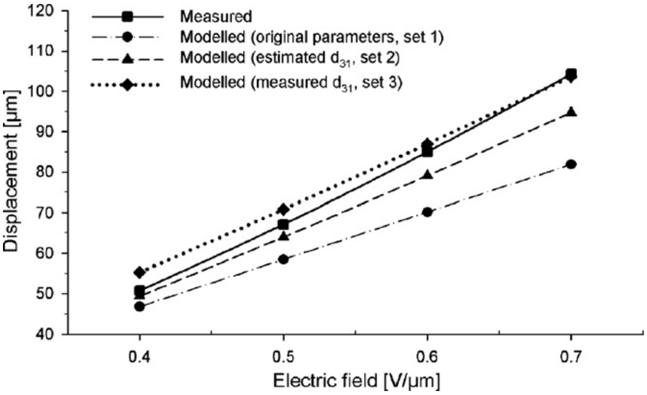

Fig. 4. Modelled and measured results of the *z*-axis displacement as a function of electric field (170 µm thick LTCC layer).

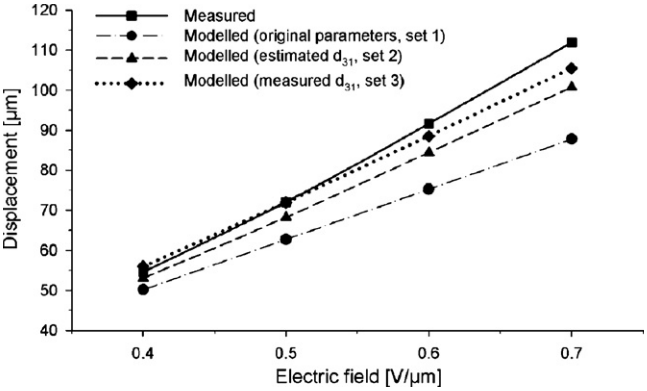

Fig. 5. Modelled and measured results of the *z*-axis displacement as a function of electric field (100 µm thick steel layer).

The differences in the *z*-axis displacement between the modelled (using the original material parameters) and measured results obtained with unimorph type actuators having 70, 105 and 170 µm thick LTCC and 100 µm thick steel passive layers were 16–36, 13–37, 8–27 and 9–34%, respectively. Using the modified d_{31} parameters, the accuracy of the models was improved to 12–30, 2–20, 1–8 and 1–9%, respectively.

The ratio of the steel and PZT layer thickness of the manufactured actuators can be seen in Fig. 6. According to both modelled and measured results, the actuator has an optimum

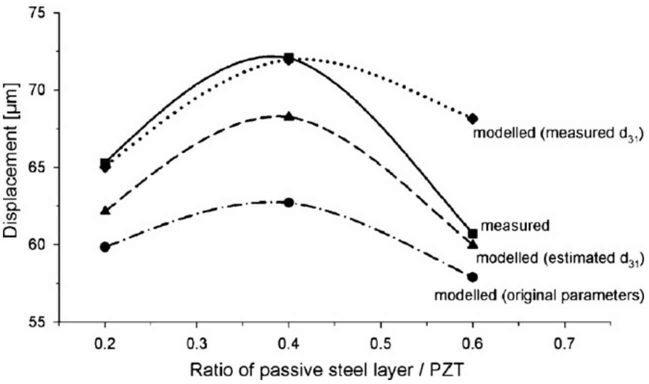

Fig. 6. Displacement as a function of thickness ratio of steel and PZT layers under 0.5 V/µm electric field and 10 Hz.

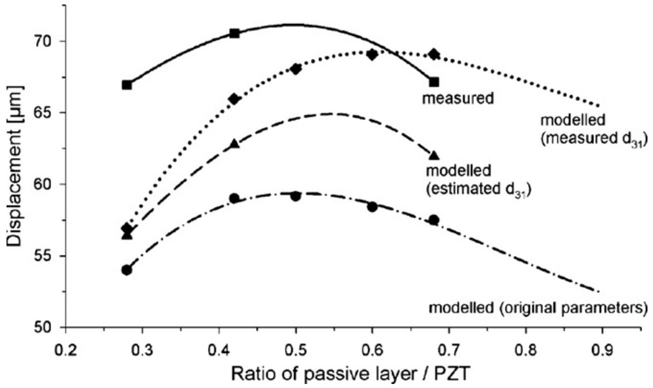

Fig. 7. Displacement as a function of thickness ratio of LTCC and PZT layers under 0.5 V/µm electric field and 10 Hz.

thickness ratio ∼ 0.4, which corresponds to a steel thickness of 100 µm.

The ratio of the LTCC and PZT layer thickness of the manufactured actuators can be seen in Fig. 7. According to the measured results, the actuator has an optimum thickness ratio ∼ 0.5, which corresponds to an LTCC thickness of 125 µm. The modelling results using the measured d_{31} coefficients show that the thickness ratio should be ∼ 0.6. The results indicate that the d_{31} values affect the optimum thickness ratio of the actuator. This behaviour, however, requires further investigation and more test samples.

5. Conclusions

The bonding of the passive layer occurs in the co-firing process of the LTCC, which improves the reliability of the actuator compared to that of traditional unimorphs. The pre-stress of the actuators can also enhance the load bearing capability, which will be researched in the future.

Accurate modelling of the unimorph type actuators can be achieved with the ATILA software with certain conditions. However, further parameter verification and performance characterisation, especially in the case of pre-stressed actuators, is still required.

The manufactured cantilever actuators embedded in the LTCC showed good displacement characteristics compared to the actuators with steel as the passive layer. This implies that the LTCC process does not have a significant effect on the piezoceramic properties.

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