Low-cost LTCC-based sensors for low force ranges

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Original version: Procedia Chemistry 1 - Proceedings of Eurosensors XXIII, 2009, 899-902
http://dx.doi.org/10.1016/j.proche.2009.07.224

Abstract

We have designed and fabricated a low-range (ca. 100 mN) thick-film piezoresistive force sensor with a cantilever beam fabricated in LTCC (Low Temperature Co-fired Ceramic). The beam was soldered onto a standard thick-film 25.4 x 12.7 mm signal conditioning base [1]. Switching from a classical Al2O3-based thick-film beam to LTCC allows design of a 3D structured beam with increased sensitivity of the piezoresistive bridge, yet largely conserved strength and stiffness. Another advantage of LTCC compared to alumina is a lower Young's modulus (approx. 3 times lower), more suitable for the measurement of small loads.

Keywords: *LTCC; low force sensor; piezoresistive bridge; 3D structured beam*

1. Introduction

Our laboratory has developed a series of low-cost force sensors based on thick-film technology [1, 2]. The low force range is covered by sensors based on an alumina cantilever beam, where the signal is measured through a piezoresistive bridge (Fig. 1a).

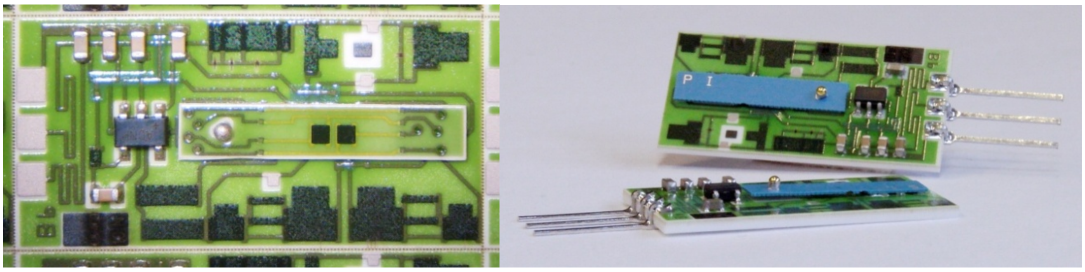


Fig. 1. (a) Standard alumina-beam "MilliNewton" force sensor (400, 1'000 and 2'000 mN force ranges). The base dimensions are 25.4 x 12.7 mm and the force is applied onto the ball at the end of the cantilever; (b) Completed new low-range sensors using an LTCC beam (in blue). The sensing, structured face is not apparent, as it faces the base.

Practically speaking, the minimum reasonable thickness (to avoid excessive breakage during processing) for the alumina beam is ca. 250 µm, corresponding to a sensor with 400 mN nominal range. Extension to a lower force range requires new materials and/or concepts, which led to the selection of LTCC. This technology allows easy creation of 3-D structures and is inexpensive, provided the sensors are relatively small (Fig. 1b).

Structuration of the beam allows a high compressive strain at the measuring resistors while keeping dangerous tensile stresses low, a concept that was validated by finite element modelling (FEM). The goal was to further extend the range of our force sensors while keeping the same base (containing electronics for the signal conditioning) and piezoresistive measuring principle. This choice imposes to keep approximately the same dimensions for the beam (15.6 x 3 mm). Nevertheless, we can choose the thickness in function of the standard thickness of LTCC sheet.

Different design variants were explored; one of the principal differences is the placement of the two measuring beams, in series or in parallel. Other varied parameters were the number and the thickness of the LTCC tapes. Finally, the last varied parameters were technological in nature: laser-shaping of the measurement resistors or not, piezoresistor and termination materials.

1.1. Design choices and dimensioning

We have created a discrete model of the beam to calculate stresses in the structure, aiming to maximise the signal of the piezoresistors while keeping dangerous tensile stresses at a minimum, taking into account the constraints of the screen-printing process (resolution) and the parameters imposed by the base (outer dimensions + solder pads). Thus, the principal available dimensional parameters are the following:

- Thickness of the beam
- Width of the structure carrying the 2 sensing resistors
- Distance between sensing resistors and solder pads

All this parameters were optimised to find a compromise with a good signal, possible structures, screen-printing resolution limits and a deflection sufficient to allow protection against overload by contact with the base. We have to optimise independently series and parallel variants, as the design is substantially different (Fig. 2).

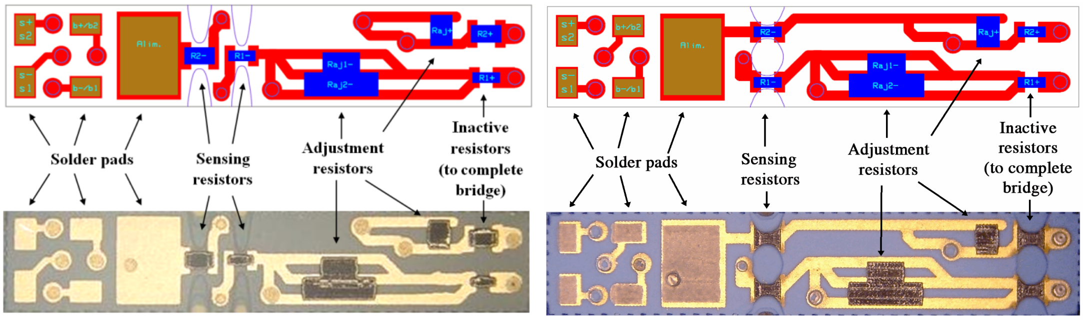
Three thickness of the *DuPont (DP) 951 GreenTape™* system were selected: 114, 165 and 254 µm (unfired). 51 µm tape was abandoned, as it tended to warp excessively during co-firing with conductors. Three different combinations of tapes were selected (Table 1).

1.2. Finite element method

Our discrete model permits to rapidly estimate compressive stresses on the sensing resistors and tensile stresses on the top of the beam, but these values are just local averages. In contrast, FEM analysis using a complete 3D model (Fig. 3) reveals some border effects, not evidenced in our discrete model. Nevertheless, these analyses ensure compressive stresses are under the security limit (110 MPa for a deflection of 100 µm corresponding to the gap between the beam and the base).

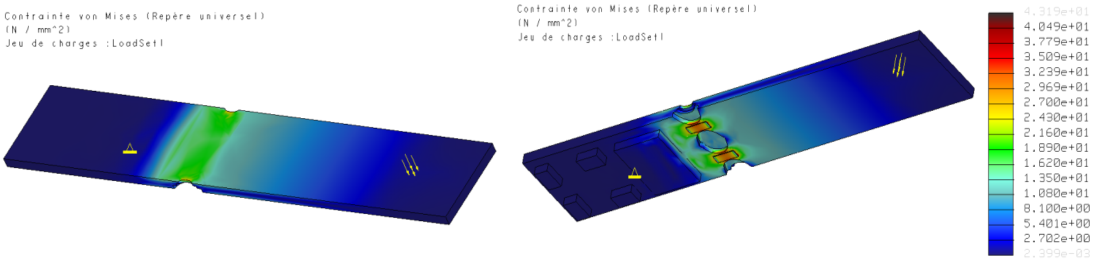
Table 1. Combinations of thickness (for 2-layer versions, we consider that tape 2 is omitted).

References	3 tapes (P2b)	2 tapes (PX)	2 tapes (P2)
Tape 1 (top)	114 µm	114 µm	165 µm
Tape 2 (spacer)	114 µm	-	-
Tape 3 (bottom)	165 µm	254 µm	165 µm



(a) (b)

Fig. 2. Layout and photograph of the bottom, (a) active face of the series variant, where sensing resistors are align to the length; (b) active face of the parallel variant, where both sensing resistors lie side by side.



(Top of the beam) **(Bottom of the beam)**

Fig. 3. Result of a finite element modelling run: stress distribution on the beam when the nominal force is applied (100mN).

2. Fabrication and trimming

- The LTCC green tapes were first cut with an LS9000 laser (Laser Systems GmbH, Germany), leaving out some excess area in the case of laser-shaped resistors (Fig. 2b).
- The paste for the termination / conducting tracks (DP CDF-34, Au or DP 6145, Ag), followed by that of the piezoresistive composition (DP 2041, 10 kΩ/□ or DP 2051, 100 kΩ/□) were then screen-printed and dried.
- In the case of laser-shaped resistors (Fig. 2b), the laser was again used to obtain the final shape for the narrowed structures.
- After stacking, the tapes were laminated using a rubber disk to achieve "pseudo-isostatic" lamination [3] and the resulting stacks fired in an ATV PEO-601 furnace using a standard LTCC profile, with a 25 min peak at 895°C.
- After firing, DP 6135D (AgPd conductor) was printed and post-fired at 850°C for the solder pads.
- After the last firing, a coarse digital laser trimming (using the LS9000) of the offset was carried out by cutting conductor tracks to activate selected adjustment resistors (Fig. 2).

- This was followed by singulation of the beams and soldering onto bases (with out without signal-conditioning electronics) using Sn62 (62% Sn + 36% Pb + 2% Ag) solder. The bases with signal conditioning were further actively trimmed to obtain fully calibrated force sensors.

3. Results

All variants, tested with signal-conditioning electronics, gave good results in sensitivity and linearity, as exemplified in Fig. 4. To directly compare the raw signal of the different versions, we also tested samples without signal conditioning (Fig. 5). From these results, we observe that laser-shaped resistors tend to give a somewhat lower response than traditional ones, i.e. entirely defined by screen-printing, which suggests that laser-shaping may affect final resistor properties. Moreover, it appears that sensing resistors with the smallest values (silver terminations and 10 kΩ/□ paste) seem less stable. Finally, response is quasi-equivalent between parallel and series versions. Overall, the tape thickness is the predominant parameter defining the sensitivity. Besides optimising the response for a given nominal load, we also have to consider the following aspects:

- Simplicity of the fabrication process (influencing cost production)
- Appropriate stiffness, to allow protection against overloads by contact with the base
- Reliability
- Signal stability

Thus, for the future 100 mN version, we chose the LTCC 114/254 parallel version with traditional resistors type (outer structures cut and gold terminations).

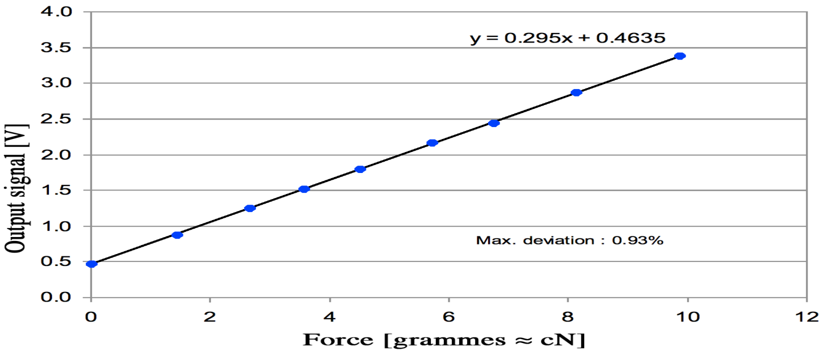


Fig. 4. Force response of a complete sensor (sensor + signal conditioning base).

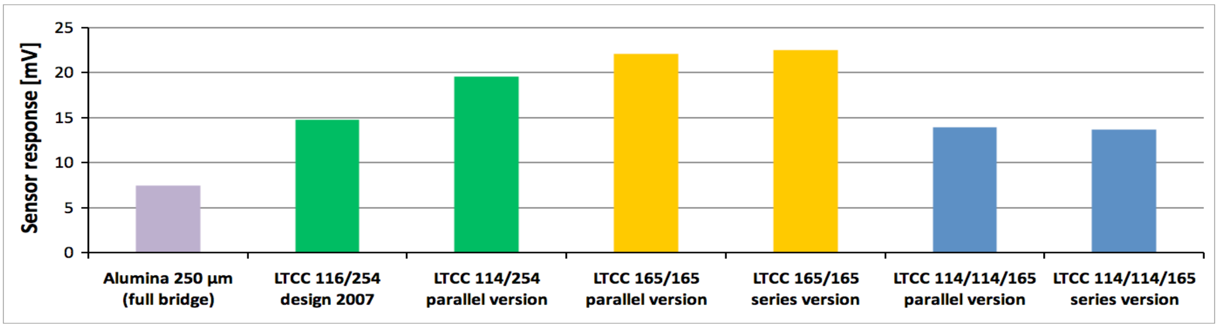


Fig. 5. Output signal response for a 200 mN load, measured on different beam types, at 5 VDC excitation. Values for Alumina and LTCC design 2007 (series version) are taken from a previous study [2]. Sensing resistors for the results shown here are from the same type (outer structures cut, gold terminations and 100 kΩ/□ paste).

4. Conclusion

In this work, LTCC optimised low-range piezoresistive force sensors were successfully produced using standard thick-film / LTCC processing, and assembled onto an existing standard thick-film base, yielding functional fully calibrated devices. For the next step, the most promising variants will be validated with a pilot production run. Batch fabrication, optimisation of the LTCC fabrication process and compatibility with an existing standard sensor base allow low-cost fabrication of these sensor structures, and open the way to even more sensitive versions.

Acknowledgements

The writers are thankful to Mr. Matthias Garcin and Mr. Stanislas Wuilloud of Laboratory for Production of Microtechnology (LPM) at EPFL for their useful helps with screen-printing and assembling operations.

References

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