European Microelectronics and Packaging Symposium

Prague 16th to 18th June 2004, Czech Republic

STRENGTH OF CERAMIC SUBSTRATES FOR PIEZORESISTIVE THICK-FILM SENSOR APPLICATIONS

T. MAEDER, C. JACQ, H. BIROL, P. RYSER

École Polytechnique Fédérale de Lausanne, Faculty of Engineering Sciences and Techniques,
Department of Microengineering, EPFL-IPR-LPM, CH-1015 Lausanne, Switzerland
E-mail:Thomas.maeder@epfl.ch

Abstract: Force and pressure sensors based on the piezoresistive properties of thick-film resistors are widely used due to their reliability, simplicity and low cost. Recently, the introduction of low-temperature co-fired ceramic (LTCC) substrates has allowed further increases in miniaturisation and integration, while new high-strength ceramic substrates such as zirconia-toughened alumina (ZTA) has enabled better sensor response.

However, the materials' properties are still insufficiently characterised for sensor applications. Properties such as long-term strength, and especially the effect on the strength and reliability of thick-film processing, have received insufficient attention so far. In this work, the short and long-term strength of these substrates is compared with that of standard 96% alumina, and the effect of various thick-films (resistors, dielectrics, conductors) on the mechanical behaviour is studied. It is shown that thick-film compositions can have a dramatic effect on the strength of the substrates.

Keywords: thick film, substrates, sensors, strength, zirconia, ZTA, LTCC

1. Introduction

Thick-film force and pressure sensors using piezoresistive compositions in the 10…100 kOhm range are widely used in industry, due to their simplicity and reliability [1]. In almost all cases, the standard 96% alumina used as a substrate material for thick-film electronics is also used for the sensor elastic element, in spite of its relatively poor mechanical properties.

Although metals can be the ideal structural material for high-range sensors once the relevant issues have been resolved [2][3], sensors for measurement of minute forces or pressure are more likely to be made out of ceramic materials, as thin metal sheets undergo extensive warpage upon deposition of thick-film materials – especially given the fact that they have to be covered with insulating dielectric.

Better ceramic materials than alumina do exist – a previous study [4] showed that zirconia-toughened alumina (ZTA) is a very suitable replacement for alumina, as it has higher strength while retaining good compatibility with standard piezoresistive compositions such as Du Pont 2041. On the other hand, zirconia (the high-strength yttria-stabilised form) can be problematic due to extensive property changes of resistors. Also, zirconia has low thermal conductivity, which can give rise to thermal drift of piezoresistive bridges placed on thin, elongated measurement cells.

An other interesting structural material is low-temperature cofired ceramic (LTCC). Although its strength to elastic modulus ratio is not purported to be much better than that of alumina, it has the advantage of being easily processed into complex 3D structures, providing superior levels of integration. Moreover, its availability as very thin foil allows fabrication of very sensitive devices.

Although the previous study [4] showed that strength is also quite process sensitive, and is degraded by selection of inappropriate thick-film materials, it was also shown that ZTA beams with a force-sensing thick-film bridge had the same short-term strength as the blank ZTA beams – it was possible to retain the full original strength of the material.

The present study extends this work in a twofold manner:

1. The long-term strength of the beams, blank or with force-sensing bridge, is characterised for alumina, ZTA and zirconia.
2. Short and long-term strength results are presented for a commercial LTCC composition.

2. Experimental

Alumina (Al_2O_3, Kyocera A–476 96% purity standard thick-film grade), Yttrium-stabilized zirconia ("zirconia", ZrO_2, Coors), and ZTA (Ceramtec) substrates ca. 0.25 mm thicknesses were used for testing. Individual cantilevers were prepared by laser scoring the substrate and then breaking off individual pieces. According to previous results [4], the beam are always stressed so that the scored side is in compression, in order to avoid weakening by the flaws created by scoring.

LTCC beams (material : Du Pont 951 green tape, ca 0.25 mm thickness), on the other hand, were laser cut from the green tape, and then fired at 875°C.

Overlying thick films were applied by screen printing onto the substrate, and fired in a belt furnace using a standard 850 C, 10 min profile, except for overglaze (630 C, 10 min). The circuit applied on the beam is the force-measuring bridge shown in Fig. 1. Materials are 1) ESL 9635B (Ag:Pd 3:1 with glass frit), hole metallization and solder pads; 2) ESL 8837 (metalorganic Au), conductor tracks and resistor terminations; 3) Du Pont 2041 (10 kOhm), strain-measuring resistors; and 4) ESL G–481, overglaze.

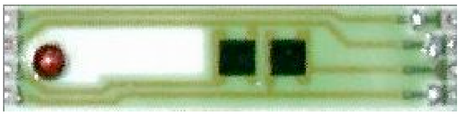

Fig. 1. Top side (side stressed in tension) of force measuring circuit – "MilliNewton" sensor.

The beam-shaped samples were mechanically stressed in bending, as shown in Fig. 2. The load was applied with a Royce Instruments 552 tester, with a TABTM–2KT 2 kgf (ca. 20 N) push cell. Total test duration to breakage was ca. 5 s. The given strength values are averages, with error bars corresponding to the standard variation.

Long-term tests were carried out with a similar configuration, but by applying a constant force at the end of the cantilever beam and measuring the time to failure. The environment for long-term strength tests (static fatigue) was moist air (>90% humidity) at room temperature.

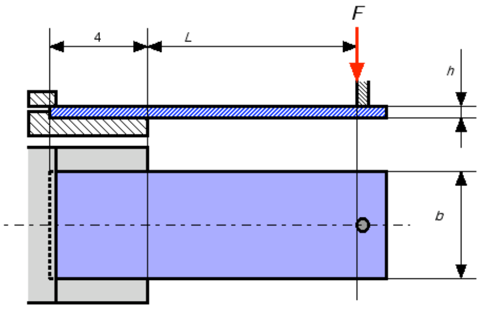

Fig. 2. Mechanical testing jig. L range: 5.0 to 12.0 mm; b range: 3.0 to 3.1 mm; h range: 0.16 to 0.28 mm.

3. Results and discussions

The long-term strengths of blank beams of all materials (alumina, ZTA, zirconia and LTCC) are given in Fig. 3, and those of beams with force-measurement bridges ("mN") on alumina, ZTA and zirconia in Fig. 4. The results are fitted according to the formula:

$$\sigma = \sigma_0 \cdot \left(\frac{t}{t_0}\right)^{-1/n} \text{; for the fit: } \log\sigma = \log\sigma_0 - \frac{1}{n}\log\left(\frac{t}{t_0}\right)$$

σ is the long-term strength, t the time and σ_0 the short-term strength at time t_0. t_0 was taken here to be 1 s. The continuous line denotes the fit, and the dashed one gives the lower confidence boundary (fit – 3 standard deviations).

With reasonable amount of data, one can extrapolate a lower confidence limit for 10 years, a typical required lifetime for sensors, which can be used as a design stress σ_d. This, divided by the elastic modulus E, gives the design strain ε_d available for piezoresistive sensing.

$$\sigma_d = \sigma_0 \cdot \left(\frac{10\,years}{t_0}\right)^{-1/n} \cdot 10^{-3\Delta} \text{ ; } \varepsilon_d = \frac{\sigma_d}{E}$$

The symbol Δ denotes the standard deviation from the fit of the long-term strength data. These results, together with those of the short-term tests, are summarized in Tab. 1. Blank ZTA and zirconia suffer very little strength degradation over time (e.g. they have high n values), which is expected because they do not contain a significant amount of glassy phase subject to stress corrosion in contact with moisture [5][6]. Conversely, LTCC, being the most glassy material, is most subject to stress corrosion in moist air. Although LTCC is the weakest material, this disadvantage compared to alumina is in great part offset by its lower elastic modulus, resulting in comparable values of the design strain.

The long-term behavior of the beams with the thick-film bridge is very different from that of the blank beams: in all cases, the long-term strength is reduced compared to the blank beam. This is not the case for short times (see results of short-term tests and values of σ_0). Also, the dispersion of the results increases. One can attribute this degradation of long term as opposed to short term strength, to the presence of glassy layers (resistors and overglaze) on the surface of the beams. For short test times, their influence is small because, although their lower strength is compensated by their lower elastic modulus. For long times under stress and moist air, however, stress corrosion sets in, and cracks most likely initiate in these layers.

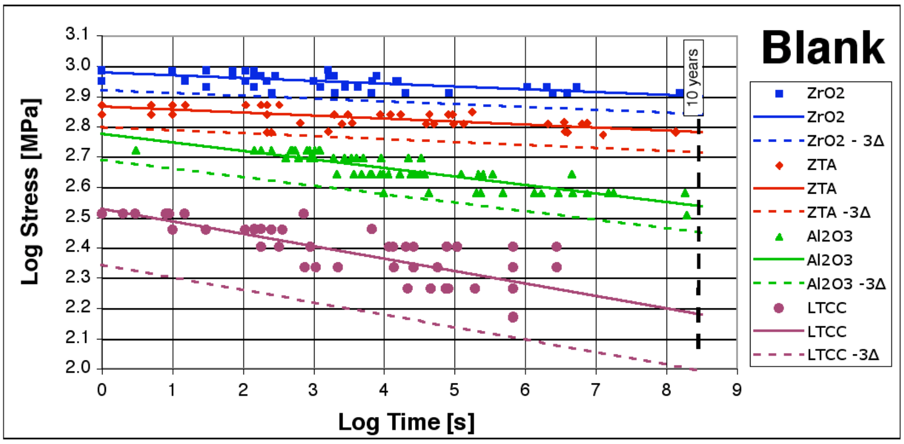

Fig. 3. Long term strength of blank cantilever beams.

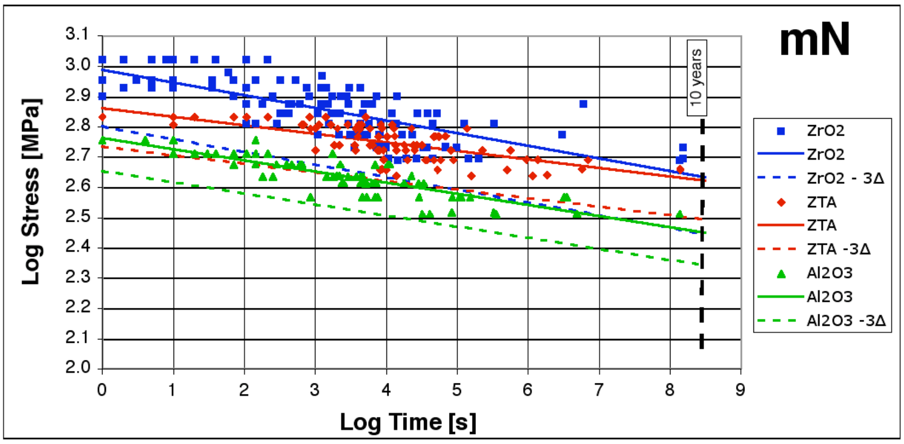

Fig. 4. Long-term strength of beams with thick-film force sensing bridge.

Material	**Alumina**	**ZTA**	**Zirconia**	**LTCC**
Short-term average strength [MPa]	630 **710**	830 **940**	1'150 **1'121**	360 -
Short-term std. dev. of strength [MPa]	50 **60**	100 **120**	80 **200**	40 -
Long-term tests, σ_0 [MPa]	600 **580**	730 **730**	950 **970**	340 -
Long-term tests, σ_d [MPa]	300 **220**	520 **311**	690 **280**	100 -
Long-term tests, n	35 **27**	102 **36**	108 **24**	24 -
Elastic modulus	330	330	200	150
Long-term tests, ε_d [ppm]	850 **664**	1'570 **940**	3'160 **1'270**	650 -

Tab. 1. Summary of the results. Normal = blank ; **bold** = with thick-film force sensing bridge.

4. Conclusions

In this study, the long-term strength of ceramic cantilever beams, blank or with a thick-film force sensing bridge, has been measured in moist air. Materials studied were standard 96% alumina, ZTA, zirconia and (only blank) LTCC.

ZTA and zirconia offer significant strength – and signal – increases over alumina or LTCC, especially under long term stress. However, this advantage is strongly reduced by the presence of thick-films, most likely because lifetime becomes limited by stress corrosion of the glassy films under moisture. Nevertheless, the higher long term strength of ZTA and zirconia can be fully utilized in designs where the sensing resistors are under compression only (single-side, half-bridge configuration).

The first results of an LTCC material, Du Pont 951, are quite promising. The long-term design strain is almost equal to that of alumina. This needs confirmation by also measuring this material with a thick-film sensor bridge. Also, the effects of potential edge damage wrought by processing on the strength must be studied, as was the case [4] with alumina, ZTA and zirconia.

5. Acknowledgements

This work was financed by the Swiss CTI (Committee for Technology and Innovation). The ZTA samples from CeramTec are also gratefully acknowledged.

6. References

[1] B. Morten, M. Prudenziati, *Piezoresistive thick-film sensors*, Handbook of Sensors and Actuators vol. 1: Thick Film Sensors, Prudenziati-M (Ed.), Elsevier, Amsterdam 1, 189-208, 1994.

[2] L. Fraigi, D. Lupi, L. Malatto, *A thick-film pressure transducer for cars propelled by natural gas*, Sensors and Actuators A 41, 429-441, 1994.

[3] C. Jacq, T. Maeder, P. Ryser, *High-strain response of piezoresistive thick-film resistors on titanium alloy substrates*, Journal of the European Ceramic Society 24 (6), 1897-1900, 2004.

[4] T. Maeder C. Jacq H. Birol P. Ryser, *High-strength ceramic substrates for thick-film sensor applications*, Proceedings, 14th European Microelectronics and Packaging Conference, Friedrichshafen (DE), 133-137, 2003.

[5] S. Pearson, *Delayed fracture of sintered alumina*, Proceedings of the Physical Society of London B69 (12), 1293-1296, 1956.

[6] A. Krell, E. Pippel, J. Woltersdorf, W. Burger, *Subcritical crack growth in* Al_2O_3 *with submicron grain size*, Journal of the European Ceramic Society 23, 81-89, 2003.