EFFECT OF THICK-FILM MATERIALS ON THE MECHANICAL INTEGRITY OF HIGH-STRENGTH CERAMIC SUBSTRATES

Thomas Maeder, Caroline Jacq, Giancarlo Corradini and Peter Ryser

EPFL-LPM, Lausanne, Switzerland

thomas.maeder@epfl.ch

lpmwww.epfl.ch
Need for high-strength substrates

Piezoresistive sensors
- Higher signal / overload capacity
- Simpler fabrication (half bridge)

Power electronics / DCB
- High thermal cycling loads
- Thin substrates for high thermal conductivity

Rugged electronics
- Aerospace
Piezoresistive thick-film sensors

Thick-film resistors possess a **piezoresistive effect**.

**Gauge factor** = rel. variation / strain = \((\Delta R/R) / \varepsilon\)

The **gauge factor** is typ. 12.
(Si : 50 ; metal *DMS - Dehnmeßstreifen* : 2)
Product: force sensor

Stressed films

1. Measuring resistors
2. Terminations / conductor lines
3. Protective glass

Soldered alumina cantilever beam
Candidate ceramic materials

1. High-purity alumina
   + Most similar chemistry
   – Lowest improvement in mechanical properties

2. Zirconia

3. ZTA (ZrO$_2$-Toughened Al$_2$O$_3$)

4. LTCC (Low-Temperature Cofired Ceramic)
Candidate ceramic materials

1. High-purity alumina

2. Zirconia
   + Potentially the highest strain
   – Most expensive
   – Thermal & chemical compatibility problematic

3. ZTA (ZrO$_2$-Toughened Al$_2$O$_3$)

4. LTCC (Low-Temperature Cofired Ceramic)
Candidate ceramic materials

1. High-purity alumina
2. Zirconia
3. ZTA (ZrO$_2$-Toughened Al$_2$O$_3$)
   + Good strength
   ± Medium cost
   + Good thermal & chemical compatibility
4. LTCC (Low-Temperature Cofired Ceramic)
Candidate ceramic materials

1. High-purity alumina
2. Zirconia
3. ZTA (ZrO$_2$-Toughened Al$_2$O$_3$)
4. LTCC (Low-Temperature Cofired Ceramic)
   - Low strength
   + Low Elastic modulus
   + Very sensitive structures attainable
   + 3D structuration can improve properties
Test setup: long & short-term

\[ \sigma_{\text{nominal}} = \frac{6F \cdot L}{h^2} \]

\[ L \approx 8 ; b \approx 3 ; h \approx 0.25 \text{ mm} \]
Effect of metals on strength
(Short-term, absolute)
Effect of metals on strength
(Short-term, relative)

Diagram showing the effect of metals on strength for different materials:
- ESL 8837 (Au)
- ESL 9912A (Ag)
- ESL 9695 (Ag:Pd 25:1)
- ESL 9635B (Ag:Pd 3:1)
- DP 5715 / 5744 (Au)
- DP 9473 (Ag:Pd 3:1)
- DP 5104 (Ag:Pd 3:1)

Materials tested:
- AI2O3
- ZTA
- ZrO2

Strength retention [%]
Effect of conductors: short term

- Conductors with little or no glass frit: retention of original strength
  
  Ag, Ag:(Pd+Pt) 25:1, Au, thin Au

- Conductors with high glass frit: significant loss in strength (25…45%)
  
  Ag:Pd 2:1…4:1
Effect of conductors: glass frit

Local tensile stresses

Substrate grain boundaries
Blank & load cells: short-term stress

- Blank
- Load cells v2

<table>
<thead>
<tr>
<th>Material</th>
<th>Strength [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTCC</td>
<td>~200</td>
</tr>
<tr>
<td>Al2O3</td>
<td>~500</td>
</tr>
<tr>
<td>ZTA</td>
<td>~800</td>
</tr>
<tr>
<td>ZrO2</td>
<td>~1200</td>
</tr>
</tbody>
</table>
Blank & load cells: short-term strain

- LTCC
- Al2O3
- ZTA
- ZrO2

Rupture strain [ppm]

- Blank
- Load cells
Summary: short-term results

ZrO$_2$
- Potentially the highest signal
- Problems: TCR shift, low thermal conductivity, cost

ZTA
- « Drop-in » improvement over Al$_2$O$_3$

LTCC (Du Pont 951)
- Stress: the weakest substrate
- Strain: compares favourably with Al$_2$O$_3$ & ZTA
Long-term strength

- Subcritical crack growth occurs until rupture (static fatigue).
- Stress - time to rupture : Paris’ law.

$$\sigma = \sigma_0 \cdot \left( \frac{t}{t_0} \right)^{-1/n} \quad \log \sigma = \log \sigma_0 - \frac{1}{n} \log \left( \frac{t}{t_0} \right)$$

- The value of $n$ is a quality indicator.
Long-term strength - blank

![Graph showing the long-term strength of various materials over time. The graph compares Alumina, Zirconia, ZTA, and LTCC materials. The x-axis represents log time (s), and the y-axis represents log stress (MPa). The data points show a decreasing trend with time, indicating reduced strength over longer periods.]
Long-term: $n$ values - blank

(several Al$_2$O$_3$ & ZTA series)
Blank substrates - long-term

Two categories:

1. ZTA & zirconia
   - Little or no glassy phase
   - Resistant to static fatigue; high $n$ values, ca. 100

2. Alumina (96%) & LTCC (DP 951)
   - Glassy phase (alumina: at grain boundaries)
   - Pronounced static fatigue; low $n$ values, ca. 30
   - LTCC has lower $n$ than alumina, yet still higher design strain for 10 years.
Long-term strength: load cells

⇒ Much of the advantage of ZrO$_2$ & ZTA is lost!
Long-term $n$ values: load cells

Values of $n$ no longer very different!
Long-term strain (load cells, -3D)

High strength substrates more degraded by films!
Static fatigue - blank

![Graph showing static fatigue data]

- ZTA n=170
- Al2O3 n=36

(blank)
Static fatigue - fritted Ag, low firing

Frit seems less deleterious with low firing.

Ag fritted 500°C firing
Static fatigue - Ag

Ag 850°C little glass (mixed bond)

Moderate degradation of ZTA long-term strength.
Static fatigue - Ag:Pd 3:1

Strong degradation of strength & $n$.

Ag:Pd 3:1
850°C
fritted

[Graph showing Log Stress vs Log Time with data points and lines for Ag:Pd 3:1, ZTA n=41, and Al2O3 n=34]
Static fatigue - Ag:((Pd+Pt) 25:1

Ag:((Pd+Pt) 25:1
850°C fritless

Moderate degradation of long-term strength?
Static fatigue - Au (thin)

Au
850°C
little frit
thin 2µm

No degradation (even increase on alumina)!
Static fatigue - Au (standard)

Au
850°C
little frit
std. thickness

Moderate degradation of long-term strength?
Static fatigue - DP 2041 resistor

DP 2041
850°C
10 kOhm

Moderate degradation of long-term strength?
Static fatigue - ESL G-481 @ 580°C

ESL G-481 overglaze 580°C (matt)

Good long-term strength.
Static fatigue - ESL G-481 @ 630°C

ESL G-481 overglaze 630°C (glossy)

Different behaviour when overglaze is well melted!
Conclusions (1/2)

- Effect of individual layers on strength of ZTA & alumina
- Many conductors & matt fired 600°C overglaze: « no » degradation of long-term strength
- Resistor, some conductors & glossy fired 600°C overglaze: medium degradation
Conclusions (2/2)

• Very deleterious effect of fritted 3:1 Ag:Pd conductors (used for solder & bond pads), even on alumina!
  ⇒ avoid in stressed zones!

• Low-firing fritted Ag conductor: « no » degradation!

• Synergistic effects - multilayers?
THANK YOU!