Delamination of thermal barrier coatings under thermal shock

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Thin Film Cracking: Part 2

Christopher Harvey  
c.m.harvey@lboro.ac.uk

Simon Wang  
s.wang@lboro.ac.uk

Department of Aeronautical and Automotive Engineering  
Loughborough University, UK

2nd International Conference on Mechanics of Composites
Agenda

Part 1 (15 min)
1. Introduction
2. Partition of mixed-mode cracks
3. Macroscopic fracture
4. Thin film delamination

Part 2 (15 min)
5. Room temperature α-alumina spallation
Spallation of $\alpha$-alumina

- Tolpygo and Clarke’s (2000) experimental study

- $\alpha$-alumina films formed on the surface of Fe-Cr-Al alloy substrate by oxidation at 1200°C

- Cooling causes compressive in-plane residual stress due to thermal expansion mismatch

- No separation or spallation failure occurs during cooling at any rate

- $5^\circ$–$200^\circ$C min$^{-1}$: Circular interfacial separations between film and substrate nucleate, grow in separation distance and propagate radially

- $\leq 2^\circ$C min$^{-1}$: No separation or spallation occurs at any point

- $\geq 500^\circ$C min$^{-1}$: No separation or spallation occurs at any point

- After a period of slow and stable growth, some separations then grow abruptly and spall off
Specimens with 1.05-mm thick substrate and 4.9-µm oxide after 25 h oxidation at 1200°C cooled to room temperature at the rates indicated.

Nucleation and growth of a separation bubble with time at room temperature. ▶

Images from Tolpygo and Clarke (2000)
Possible explanations

• **Flaw** on oxide-substrate interface:
  – pre-existing defects
  – pre-existing inclusions such as Zirconium oxides
  – Impurity segregation
  – All invalidated with microscopy
  – Zr oxide particles too small to cause buckling

• Stress corrosion due to moisture:
  – specimens placed zero humidity environment
  – Spallation still as prevalent as in ambient atmosphere

• Metal **plastic strain** during cooling:
  – Not sufficient to cause spallation
Pockets of energy concentration

• A new hypothesis: Pockets of energy concentration (PECs) in the film-metal material system
  – Exist due to dynamic and non-uniform plastic relaxation or creep in the film and substrate during cooling
  – Are formed during cooling and are randomly distributed
  – Energy depends on cooling rate, film thickness, metal thickness, etc.
# Pockets of energy concentration

<table>
<thead>
<tr>
<th>Rate of Cooling</th>
<th>Plastic or Creep Relaxation</th>
<th>Stress in Film</th>
<th>Stress at Interface</th>
<th>Pockets of Energy Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fast cooling rates</strong></td>
<td>No plastic or creep relaxation, i.e. closely thermo-elastic</td>
<td>Uniform in-plane compressive stress in film; no interfacial stress</td>
<td>No PECs even though the film has the largest residual stress</td>
<td></td>
</tr>
<tr>
<td><strong>Extremely slow cooling rates</strong></td>
<td>‘Complete’ plastic or creep relaxation</td>
<td>Uniform in-plane compressive stress in film; no interfacial stress</td>
<td>No PECs (with the film having the smallest residual stress)</td>
<td></td>
</tr>
<tr>
<td><strong>Intermediate cooling rates</strong></td>
<td>Unable to produce steady and uniform plastic relaxation</td>
<td>Time dependence of the process is apparent</td>
<td>Pockets of tensile stress and shear stress on the interface and in its adjacent material</td>
<td></td>
</tr>
</tbody>
</table>
Mechanical model

- Assume bubble separation shape:
- Can now calculate:
  - Crack tip loads (bending moment only)
  - Energy release rate $G$ and 2D partitions, $G_I$ and $G_{II}$
  - (1) bending strain energy $U_b$, (2) in-plane strain energy $U_i$, (3) surface energy $U_s$
- Separation causes combined $U_b$, $U_i$, $U_s$ to increase by $U_a$

Separation grows if PEC energy can provide $(U_a)_{GR}$

\[ w(r) = A \left[ 1 + \cos \left( \frac{\pi r}{R_B} \right) \right] / 2 \]
Predicted growth behaviour

\[ (U_a)_{GR} \times 10^{-5} \text{ N/mm} \]

\[ (R_B/h)^2 \]

\[ (R_B/h)_{UG}^2 \]

\[ (R_B/h)_{MU}^2 \]

Kink-off angle, $\beta$

\[ (R_B)_{SP} \]
Comparison with test

Separation bubble radius versus time at room temperature for three different samples, each with the oxide under a similar residual stress (~4.5 GPa) but with a different oxide thickness.
Comparison with test

- 23 specimens
- Different substrate thicknesses
- Oxidized for 25 h at 1200°C
- Oxide thickness of 4.9 µm
- Cooled at different rates (5°–200°C min⁻¹)
- Spallation radius measured on 50–60 circular spalls on each specimen
- Residual compressive stress measured far from the spalls.
Comparison with test
Conclusions

• Model predicts several aspects of the α-alumina spallation behavior very well
  – Initiation of unstable growth
  – Size of spallation

• Hypothesized PEC is a new failure mechanism of thin films under compressive residual stress

• Failure mechanism might occur in other situations:
  – E.g. In TBC material systems.

Suggests that 2D elasticity-based partitions are appropriate for micro. scale
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