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Mechanical stability limits of bi-layer thermal barrier coatings

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Mechanical Stability Limits of Bi-Layer Thermal Barrier Coatings

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Ongoing effort to increase operating temperature / efficiency

However, the temperature limit of 7YSZ is around 1250°C due to phase transformations above this temperature [1] → Search for new materials / new TBC solutions

Approach – Bi-Layer TBC

Bi-Layer Concept:
- surface temperatures > 1250 °C
- crack resistance to TGO growth induced stresses
- avoiding unwanted reactions between GZO and TGO

GZO: Gd$_2$Zr$_2$O$_7$ (APS)

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>APS YSZ</td>
<td>100µm</td>
</tr>
<tr>
<td>TGO bond coat</td>
<td>250µm</td>
</tr>
<tr>
<td>Ni-base substrate</td>
<td></td>
</tr>
</tbody>
</table>

- Optimization of spray process
- Sample manufacturing
- Oxidation testing
- Mechanical testing (Charalambides test, $G_{ic}$)
- TGFM testing

- Oxidation testing
- Mechanical testing (4-point bending test, $\varepsilon_c$)
- Lifetime modeling
4-Point Bending

50kN Universal Testing Machine

Testing was performed at RT
4-Point Bend Testing – TBC in Tension

1. Segmentation

Mode I failure
TBC outer fiber strain

2. Delamination

Mode II failure
TBC/BC interface strain
4-Point Bend Testing – TBC in Compression

1. Delamination

not always observed, → strong interface

1. Delamination

Mode I failure
TBC/BC interface strain

2. Shear cracking

Mode II failure
TBC outer fiber strain
Experimental Results

Compressive Loading of TBC, Bi-Layer System
Two distinct peaks can be identified in the acoustic emission signal under compressive loading!

1. 

2. 

What are the individual peaks?
4-PB Results - Compression

1. 4-PB in compression

2. 500h 1050°C

Outer fiber strain [%]

AE Energy

1. GZO shear failure

2. YSZ shear failure

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Tensile Loading of TBC, Bi-Layer System
4-PB Results - Tension

500h 1050°C
What are the individual peaks?

- Tensile geometry does not lead to well separated peaks
- Some samples show gradually increasing AE signal at the beginning

However, maybe 3 signals can be identified:

1. 2. 3.
Macroscopic images do not provide sufficient insight. Only final failure can be observed.

1. Segmentation failure of GZO-layer
2. Delamination of GZO along GZO/YSZ interface
3. Segmentation failure of YSZ layer
Critical Strain Values

Bi-Layer TBC
Isothermal Oxidation 1050°C

→ max. tolerable strain at TBC/BC interface
May be used in similar manner as SN-curves for lifetime assessment
Fracture Mechanics Approach

Griffith-Criterion:
\[ \sigma_c = \frac{K_c}{\sqrt{\pi c}} \]
\[ \varepsilon = \frac{\sigma}{E} \]

Critical Strain:
\[ \varepsilon_c = \frac{K_{lc}}{f \cdot E_{TBC} \sqrt{\pi c}} \]

Geometry Factor
(Defect geometry)
Possible Values:
1.12 surface defect of infinite length
1.0 burried defect
0.64 semi-circular surface defect

Material Constant
(But: Measurements may be influenced by sample history)

Damage Parameters
\( c \) – defect size
\( E \) – Young’s modulus
Possible Failure Modes in 4-Point Bending

\[ \varepsilon_c^{d-} = \frac{K_{Ic}}{f \cdot \sqrt{\pi c}} \cdot \left(1 + \frac{\gamma_d}{\gamma_c}\right) \cdot (1 + \nu) \]

\[ \varepsilon_c^{s+} = \frac{2K_{IIc}}{f \cdot E_{TBC} \sqrt{\pi c}} \]

\[ \varepsilon_c^{sh} = \frac{2K_{IIc}}{f \cdot E_{TBC} \sqrt{\pi c}} \]

\[ \varepsilon_c^{s} = \frac{K_{Ic}}{f \cdot E_{TBC} \sqrt{\pi c}} \]

\( \varepsilon_c \) is strain in the coating!

M. Schütze, Protective Oxide Scales and their Breakdown, John Wiley, (1997)
Strain gradient across the TBC-thickness under pure bending

~30% difference in strain between TBC/BC interface and outer fiber for 500µm TBC

→ Failure position has to be considered!
Microstructure has an influence on $K_c$-values

- Crack path mostly through spray flats $K_{lc}(\text{path1})$
  - E.g. tensile segmentation

- Crack path along spray flat boundaries $K_{lc}(\text{path2})$
  - E.g. compressive delamination

$K_{lc}(\text{path1}) > K_{lc}(\text{path2})$
Choosing failure mode and critical strain position

Mode I failure
TBC/BC interface strain

Mode II failure
TBC outer fiber strain

not observed → strong interface

1. Segmentation
Mode I failure
TBC outer fiber strain
2. Delamination

Mode II failure
TBC/BC interface strain

1. Delamination
Mode II failure
TBC outer fiber strain
2. Shear cracking
Modeling input values

\[ E_c = \frac{K_c}{f \cdot E_{TBC} \sqrt{\pi c}} \]

**YSZ**

- Defect Size (µm) vs. Time (h)
- Defect Size (µm) vs. Time (h)
- YSZ Stiffness (GPa) vs. Time (h)

**GZO**

- Defect Size (µm) vs. Time (h)
- Defect Size (µm) vs. Time (h)
- GZO Stiffness [GPa] vs. Time (h)

- \( K_c \) currently used as fitting parameter!

- \( K_{lc} = 5.3 \text{ MPa m}^{1/2} \)
- \( K_{llc} = 10.6 \text{ MPa m}^{1/2} \)
- \( K_{lc} = 2.3 \text{ MPa m}^{1/2} \)
- \( K_{llc} = 2.8 \text{ MPa m}^{1/2} \)

- \(~49\text{GPa}\)
- \(~25\text{GPa}\)

- no exp. data yet, assumption: same trend as YSZ
Bi-Layer System – GZO Failure

GZO Failure (Bi-Layer TBC)
Isothermal Oxidation 1050°C

Critical Strain (%)
Oxidation Time (h)

-2.5 -2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0 2.5

0 100 200 300 400 500 600

delamination failure
segmentation failure
shear failure
Bi-Layer System – YSZ Failure

YSZ Failure (Bi-Layer TBC) Isothermal Oxidation 1050°C

Critical Strain (%) vs Oxidation Time (h)

- YSZ segmentation failure
- YSZ shear failure

Offset
YSZ Failure (Bi-Layer TBC)
Isothermal Oxidation 1050°C

Identical values for values for $E$, $K_c$ or $c!$

单层YSZ TBC (500µm)
Bi-Layer System – YSZ Failure

Possible explanation for offset:
Residual stresses in the TBC are relieved by GZO failure prior to measurement of YSZ failure.
...currently under investigation!
Summary

• Mechanical 4-point bending with in-situ acoustic emission measurement is a valuable tool to assess damage processes in bi-layer TBCs

• A modeling approach for bi-layer TBCs has been developed to delineate areas of safe operation from areas where failure is imminent -> mechanical stability diagram
Thank you for your attention!