Abstract
The combined mode I-mode II fracture behavior of anisotropic ZrO$_2$-8wt%Y$_2$O$_3$ thermal barrier coatings was determined in asymmetric flexure loading at both ambient and elevated temperatures. A fracture envelope of $K_I$ versus $K_{II}$ was determined for the coating material at ambient and elevated temperatures. Propagation angles of fracture as a function of $K_I/K_{II}$ were also determined. The mixed-mode fracture behavior of the microsplat coating material was modeled using Finite Element approach to account for anisotropy and micro cracked structures, and predicted in terms of fracture envelope and propagation angle using mixed-mode fracture theories.
Mixed Mode Fracture of Plasma Sprayed Thermal Barrier Coatings: Effects of Anisotropy and Heterogeneity

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Typical Thermal Barrier Coatings Consist of ZrO$_2$-(7-8)wt%Y$_2$O$_3$ Top Coat and Metallic Bond Coat

ZrO$_2$-8wt%Y$_2$O$_3$ is suitable because of its unique properties

- Low intrinsic thermal conductivity
- Good thermal expansion match with metal substrates
- High temperature phase stability and excellent mechanical properties
- This work focuses on plasmas-sprayed coating systems

(a) Plasma-Sprayed TBC coating  
(b) EB-PVD TBC coating
Generalized Thermal Barrier Coating Failure Modes

— Crack propagation is a critical issue especially under surface heat flux, thermal gradient cyclic loading
— Coating delamination is often resulting from mode I and Mode II mixed loading

(a) High Heat Flux and Low Interface Temperature
(b) Low Heat Flux and High Interface Temperature
(c) Medium Heat Flux and Interface Temperature
Crack Propagation of ZrO$_2$-8wt%Y$_2$O$_3$ System under Thermal Gradient Cyclic Loading

— Single crack growth: 0.2 mm thick TBC specimen with a 2 mm substrate center hole pre-cracked coating specimen)

— Typical coating delamination: non pre-cracked coating specimen under thermal gradient cyclic loading)
Objective

• Determine mixed-mode (modes I and II) fracture behavior of free-standing thermal barrier coatings at both ambient and elevated temperatures

• Explore appropriate mixed-mode fracture criteria in conjunction with experimental data

• Finite Element Method Modeling taking into account of anisotropy and heterogeneity effect
Asymmetric Four-Point Flexure Testing

Shear, Moment & Stresses at ‘B-B’ region:

Shear: \( V = \frac{A - B}{A + B} P \)

Moment: \( M = V_s = \frac{A - B}{A + B} P_s \)

Shear Stress: \( \tau = \frac{A - B}{A + B} \frac{P}{bW} \)

Tensile stress: \( \sigma = \frac{A - B}{A + B} \frac{6sP}{bW^2} \)

The mixity of stresses can be changed by changing the distance ‘s’:
* e.g. When s=0 → only shear exists (mode II); otherwise, mixed modes I & II.
Experimental Procedure

**Material:**
- Plasma sprayed ZrO₂-8wt %Y₂O₃ thermal barrier coating
- Free standing TBC billets fabricated
- Flexure specimens [3mm(=B)x4(=W)mmx25mm] machined from billets
Experimental Procedure

- **Sharp precracks generated**
  Single edge V-notched beam (SEVNB) method:
  Saw-notched $\rightarrow$ a sharp V-notch generated with a razor blade with 5µm diamond paste
  Precrack sizes used: $a/W\approx0.5$

- **Test fixture configurations**
  Spans A/B = 12/6, 10/5 (typical), and 5/2.5 mm; s=0-3.6 mm

- **Test temperatures & test rate**
  25 and $1316^\circ$C in air; 0.5 mm/min in Instron 8562

A SEVNB precrack generated (root radius $\approx 10-20\mu$m)

Test fixture configurations ($W=4$ mm, $b=3$ mm)
Experimental Results

• **Mode I, Mode II, and Mixed Mode (at 25 and 1316°C)**

- $\mathbf{K_{IC} > K_{IIC}} \rightarrow \frac{K_{IIC}}{K_{IC}} = 0.64 \ & 0.66$ (at 25 & 1316°C)
- $K_{IC}$ and $K_{IIC}$ at 25°C > $K_{IC}$ and $K_{IIC}$ at 1316°C
- **Elliptical relation** between $K_I$ and $K_{II}$
- Test spans **independent**

<table>
<thead>
<tr>
<th>Test Temp(°C)</th>
<th>No. of specimens used</th>
<th>$K_{IC}$ (MPa√m)</th>
<th>$K_{IIC}$ (MPa√m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>4 in $K_{IC}$</td>
<td>1.15(0.07)</td>
<td>0.73(0.10)</td>
</tr>
<tr>
<td>1316</td>
<td>4 each</td>
<td>0.98(0.13)</td>
<td>0.65(0.04)</td>
</tr>
</tbody>
</table>

RESULTS →
Comparison between TBC & Dense Ceramics

Discrepancy observed for TBCs using energy release and strain energy based criteria

Best fit → ‘empirical’ criterion
$K_{IIc} \approx 0.65K_{IC}$

Best-fit → ‘minimum strain energy density’ criterion; $K_{IIc} \approx K_{IC}$
Comparison Between TBC & Dense Ceramics

- FEM modeling showed good agreement using anisotropic elastic modulus property data
Prediction of Crack Propagation Angle with FEM Anisotropy Models

(a) pure mode II, $\frac{K_I}{K_{II}} = 0$; (b) $\frac{K_I}{K_{II}} = 2.7$, (c) $\frac{K_I}{K_{II}} = 5.5$, and (d) pure mode I, $\frac{K_I}{K_{II}} = \infty$
# Effect of Material Directionality on Fracture Toughness ($K_{IC}$)

<table>
<thead>
<tr>
<th>Direction of crack</th>
<th>Fracture Toughness $K_{IC}$ (MPa√m)</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel to plasma spray direction</td>
<td>1.15±0.07 (4 specimens)</td>
<td>SEVNB (regular method)</td>
</tr>
<tr>
<td>Normal to plasma spray direction</td>
<td>1.04±0.05 (3 specimens)</td>
<td>Double Cantilever Beam (DCB)</td>
</tr>
</tbody>
</table>

**Result** → *No significant difference in $K_{IC}$ -- No directionality effect on $K_{IC}$*
Conclusions

• Mixed mode fracture behavior of TBCs at both 25 and 1316°C follows the ‘empirical’ fracture criterion due to the spat microstructure and anisotropic effect as demonstrated by FEM modeling:

\[
\left(\frac{K_I}{K_{IC}}\right)^1 + \left(\frac{K_{II}}{0.65K_{IC}}\right)^2 = 1 \quad \text{and} \quad \frac{K_{II}}{K_{IC}} = 0.65: \text{ For } 25^\circ C
\]

\[
\left(\frac{K_I}{K_{IC}}\right)^1 + \left(\frac{K_{II}}{0.65K_{IC}}\right)^{1.3} = 1 \quad \text{and} \quad \frac{K_{II}}{K_{IC}} = 0.65: \text{ For } 1316^\circ C
\]

• Prediction of crack propagation angle is also in better agreement when using FEM anisotropic models.
• Anisotropy and heterogeneity contributed to the deviation of mixed mode behavior of TBCs
• Effect of material directionality on fracture toughness \(K_{IC}\) was negligible (through SEVNB and DCB methods).