Interface-Related Damage Evolution in Air-Plasma-Sprayed Thermal Barrier Coatings

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### GE's 9H Gas Turbine

#### Combined-Cycle Performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Output</td>
<td>480 MW</td>
</tr>
<tr>
<td>Net Efficiency</td>
<td>60%</td>
</tr>
<tr>
<td>Firing Temperature</td>
<td>2600°F / 1430°C</td>
</tr>
<tr>
<td>Compressor Pressure Ratio</td>
<td>23:1</td>
</tr>
<tr>
<td>Air Flow</td>
<td>1510 lbs/sec</td>
</tr>
</tbody>
</table>

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National Institute of Standards and Technology
Thermal Barrier Coatings (TBC's) on Gas Turbine Buckets

• In production since 1997 on 7FA class
  ▪ coated multiple parts on H class in 1998
  ▪ expanded to service market in 1999

• Air Plasma-Spray (APS) process used for ZrO₂ top coat
  • bulk temperature reduction (> 75°C) significantly increases creep life

• Vacuum Plasma-Spray (VPS) or High Velocity Oxy-Fuel (HVOF) process used for MCrAlY bond coat
  protection of substrate alloy from oxidation and hot corrosion

first stage of industrial gas turbine
Types of Thermal Barrier Coatings and Deposition Processes

Two-layer structure:
- ceramic top coat: \((\text{ZrO}_2 + \text{Y}_2\text{O}_3)\) thermal barrier
- metallic bond coat: MCrAlY oxidation protection

Two deposition processes:
- air plasma spray (APS) & physical vapor deposition (PVD)
Industrial Needs for TBC Life Modeling

• Translate laboratory results to engine life models and life prediction
• Develop microstructural failure models to guide development of improved materials and processing techniques

"... microstructurally-based models are needed,"
"...can be qualitative or quantitative"
Micromechanical Damage Model

Freborg et al. proposed a failure scenario based on the stress reversal above asperities with TGO growth.

Spallation Failure Mechanism for Thermal Barrier Coating

Stresses in TBC-Substrate System:

- Result from mechanical loading, thermal expansion mismatch, & TGO growth
- Stress relaxation time in TBC is short compared to engine operation time, but long compared to engine cool-down time
Coating Failure: when pieces of the top coat spall

- Damage accumulates near metal-ceramic interface due to mechanical, thermal expansion, & TGO growth stresses
- When damage produces a critical-size crack, the top coat locally buckles and spalls, due to large in-plane stresses
Air Plasma Spray TBC on HVOF CoNiCrAlY

0 cycles

100 cycles

350 cycles

740 cycles

Courtesy of Jim Ruud, GE CR&D
Residual Stresses
Above Asperities on Cooling

Tensile Normal Residual Stress

(Compressive In-Plane Residual Stress)

René N5 substrate (not shown)

NiCrAlY bond coat

air-plasma-sprayed 8 wt% Y₂O₃ partially stabilized ZrO₂ topcoat

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Residual Stresses from Thermal Misfit Strains

- YSZ (CTE = 10.0 ppm/K) in tension
- Bond Coat (CTE = 15.2 ppm/K) in compression

Cooling from strain-free temperature
Stress Reversal with TGO Growth

Compressive Normal Residual Stress

NiCrAlY bond coat

René N5 substrate (not shown)

air-plasma-sprayed
8 wt% Y₂O₃ partially stabilized ZrO₂ topcoat
α-Al₂O₃ thermally grown oxide scale

Top coat

TGO

bond coat

(Compressive In-Plane Residual Stress)
Residual Stresses from Thermal Misfit Strains

YSZ
< CTE =10.0 ppm/K >

Alumina
< CTE =8.0 ppm/K >

Cooling from strain-free temperature

YSZ

Alumina

tension
compression
This Process Can Be Modeled With Three Concentric Spherical Shells

Effective CTE of the Inner Two Shells

- Effective CTE of Bond Coat
- Effective CTE of Bond Coat and TGO
- CTE of YSZ

Normalized TGO Thickness, \((t_{TGO}/R_{BC})\)
Residual Radial Interfacial Stress

Normalized TGO Thickness, \( t_{\text{TGO}} / R_{\text{BC}} \)

- Bond Coat - TGO interface
- TGO - YSZ interface

3 spheres

\( R_{\text{YSZ}} / R_{\text{BC}} = 5 \)
\( R_{\text{YSZ}} / R_{\text{BC}} = 20 \)
Failure Scenario based on Stress Reversal above Asperities with TGO Growth

Fracture Mechanics Model

Determine crack stability from an appropriate set of fracture mechanics expressions:

\[
K_I = \int_0^a G\left(\frac{x}{a}\right) \sigma(x, y; t_{TGO}, \text{asperity geometry, etc.}) \, dx
\]

asperity tension
\(t_{TGO} < t_{critical}\)

Griffith crack:

\[
K_{Ia} = \sqrt{\pi a} \frac{2}{\pi} \int_0^1 \frac{1}{\sqrt{1-\zeta^2}} \sigma(\zeta a) \, d\zeta
\]

\[\zeta = \frac{x}{a}\]
Crack Stability for Tensile Stresses

\[ \sigma(x/w) \]

\[ K_I(a/w) \]

\[ K_{IC} \]

\[ \sigma \text{ dx/w} \]

\[ \frac{x}{w} \text{ and } \frac{a}{w} \]
Fracture Mechanics Model

Determine crack stability from an appropriate set of fracture mechanics expressions:

\[ K_I = \int_{c}^{a} G \left( \frac{x}{a}, \frac{c}{a} \right) \sigma(x, y; t_{TGO}, \text{asperity geometry, etc.}) dx \]

Asperity compression 
\( t_{TGO} > t_{\text{critical}} \)

Crack closure due to compressive stresses

\[ \zeta = \frac{x}{a} \]

Crack Stability for Compressive Stresses

\[ \sigma(x/w) \]

\[ K_{IC} \]

\[ K_{Ic} \text{ closure (c/w, a/w)} \]

\[ K_{Ic} \text{ closure (c/w, a/w)} \]

\[ \sigma \text{ dx}/w \]

\[ \text{crack closure} \]

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Crack Stability for Compressive Stresses

\[ \sigma(x/w) \]

\[ K_I(a/w) \]

\[ \sigma \, dx/w \]

\[ x/w, c/w, \text{ and } a/w \]

\[ \text{crack closure} \]

\[ \text{neglecting closure} \]
Three-Parameter Roughness Model

Three-Parameter Roughness Model

valley-to-peak curvature ratio: \((R_p/R_v)\)

\[
(R_p + R_v) = \frac{w}{\sin(\Psi)}
\]

\[
h = w \cot(\Psi)
\]

peak-to-valley amplitude

\[
2H = w \tan(\Psi/2)
\]
Factorial Experimental Design

twelve (12) simulated interface microstructures

wavelength, $w$

amplitude, $H$

curvature ratio: $R_p/R_v$

90 \( \mu \text{m} \)
60 \( \mu \text{m} \)
45 \( \mu \text{m} \)
20 \( \mu \text{m} \)

0.5 1.0 2.0
Residual Stress as a Function of Microstructure: $R_p/R_v$

Only the roughness parameters $H/w$ & $R_p/R_v$ have a significant effect on the stress distribution.
Residual Stress versus Oxide Thickness

-0.1
-0.05
0
0.05
0.1
0.15

-100 -50 0 50 100

Position (µm)

-100 -50 0 50 100

No Oxide
2 µm Oxide
8 µm Oxide
12 µm Oxide

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Fracture Mechanics Results

90-45-2 (w-H-Ratio)

Mode I Stress (GPa)

90-45-2

$K_I (\text{MPa} \cdot \text{m}^{1/2})$
Influences of YSZ Microcrack Sintering

90-45-1

0 oxide
6 oxide
12 oxide
18 oxide

Stiffened YSZ

0 oxide
6 oxide
12 oxide
18 oxide
Modeling Real Microstructures

normal stress: $\sigma_{yy}$

-1.5 GPa  0  +1.5 GPa

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Interface-Related Damage Evolution in APS TBC's

**SUMMARY:**

- A damage evolution mechanism proposed by Freborg et al. was quantitatively analyzed with a fracture mechanics weight function approach.
- Reversal in residual stress distribution above interface asperities drives damage evolution.
- Microstructural variables studied with a three parameter roughness model:
  - Wavelength
  - Peak Sharpness
  - Amplitude
  - TGO Thickness
Interface-Related Damage Evolution in APS TBC’s

SUMMARY:

- Crack closure enhances the crack-tip stress intensity factor
- However, calculated $K_I$-fields are still below the expected threshold for crack growth
- Top coat sintering enhances damage evolution
- Several other factors are under investigation, e.g., top coat sintering, TGO growth strain, bond coat creep, crack path
Abstract

INTERFACE-RELATED DAMAGE EVOLUTION IN AIR-PLASMA-SPRAYED THERMAL BARRIER COATINGS

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Spallation of air-plasma-sprayed (APS) thermal barrier coatings (TBC's) typically stems from the damage that accumulates near the metal-ceramic and ceramic-ceramic interfaces in these coatings. Damage evolution is driven by stresses perpendicular to the interface that result from rough interfaces in combination with thermal-expansion-anisotropy and oxide-growth strains. These stresses are incorporated into a fracture-mechanics weight-function formalism to quantify the driving forces for crack growth near the interface. Residual stresses as a function of interfacial structure are derived for both periodic and random structures, and are used to derive crack-driving, stress-intensity-factor fields as a function of the interfacial, thermally grown oxide (TGO) thickness, and other microstructural parameters. Residual stresses and associated stress intensity factors are presented for both model and real interfaces, attempting to identify critical microstructural features for predicting damage evolution, and hence, reliability of TBC’s.