Slurry-Based Environmental Barrier Coatings

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Implementation of ceramic matrix composite (CMC) in Gas Turbines

- **CFM International LEAPx**: HPT* Shroud in A320neo (2016) & B737max (2017)
- **GE 9X**: Combustor Liner, HPT* Shroud, HPT* Vanes in B777x (~2019)

* High Pressure Turbine
Evolution of Environmental Barrier Coatings (EBCs) at NASA

- An external coating to protect CMCs from recession by \( \text{H}_2\text{O} \)
- Enabling technology for CMCs

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\text{CMC Recession}
\]
\[
\text{SiO}_2 (s) + 2\text{H}_2\text{O} (g) = \text{Si(OH)}_4 (g)
\]

\[
\text{Volutility} \propto v^{1/2} \times \frac{P(\text{H}_2\text{O})^2}{(P_{\text{TOTAL}})^{1/2}}
\]

- \( v \): gas velocity
- \( P(\text{H}_2\text{O}) \): water vapor pressure
- \( P_{\text{TOTAL}} \): total pressure


\[
\text{EBC}
\]
\[
\begin{align*}
\text{H}_2\text{O}(g) & \quad \text{Si(OH)}_4(g) \\
\text{H}_2\text{O}(g) & \quad \text{H}_2\text{O}(g)
\end{align*}
\]


Mullite Coating (NASA-1993)

Gen 1 EBC (EPM: NASA-GE-PW-1997)
Silicon Bond Coat, mp = 1416°C(2580°F)


Next Gen EBC (NASA Developmental)
2700°F (1482°C) Bond Coat
Objective

• Develop next Gen EBCs with $2700^\circ$F ($1482^\circ$C) bond coat capability using slurry process
  • Bond coat: $\text{Yb}_2\text{Si}_2\text{O}_7$-Based, Mullite-Based
  • Sintering aids: Oxide-based
  • Validation: Steam cycling rig, Combustion rigs

Feasibility Demonstrate of Slurry EBC (mid 2000’s)

Steam Cycle, $1350^\circ$C, 90% $\text{H}_2\text{O}$, 100h
TGO $\sim$10$\mu$m

Key EBC Failure Mode: Oxidation-Induced Spallation

15,144-h Solar Combustor Liner Engine Test

5,366-h GE Shroud Rig Test

- Water vapor ($H_2O$) is the primary oxidant
- $SiO_2$ TGO (thermally grown oxide) forms due to Si bond coat oxidation
  - Growth stress (~2.2x volume expansion)
  - Phase transformation stress (~5% volume expansion due to $\beta$ to $\alpha$ cristobalite at $\sim$200°C)
  - CTE* mismatch stress ($\alpha$ cristobalite =10.3 x $10^{-6}$/C vs. $Yb_2Si_2O_7$ = 4.7, Si = 4.4, SiC = $\sim$5)
- Causes large residual stresses that provide the strain energy release rates required to drive EBC delamination cracks

*Coefficient of thermal expansion


Slurry EBC with $\text{Yb}_2\text{Si}_2\text{O}_7$-Based Bond Coat

[Steam Oxidation: 1 hr at 2600°F (1427°C) / 20 min at T<100°C, 90% H$_2$O]

- Yb$_2$Si$_2$O$_7$-based top coat for recession resistance
- Sintered at T>2700°F (1482°C)
- Excellent microstructural & chemical stability
- EBC remained adherent after 500h
Slurry EBC w/ Mullite-Based Bond Coat
[Steam Oxidation: 1 hr at 2600°F (1427°C) / 20 min at T<100°C, 90% H₂O]

- Yb₂Si₂O₇-based top coat for recession resistance
- HfSiO₄-based chemical barrier
  - Yb₂Si₂O₇-Mullite Eutectic = ~1500°C
- Sintered at T> 2700°F (1482°C)
- Excellent microstructural & chemical stability
- EBC remained adherent after 500h
Steam Oxidation Rates of Slurry EBCs in Steam Cycling [2700°F (1482°C) in 90% H₂O+10% O₂, 1h cycles]

- Both slurry coatings provide substantial mitigation of steam oxidation
  - Mullite-based bond coat shows slightly lower TGO growth rates
- TGO is thicker on the internal surface (~25%) than under the EBC
  - Oxidation mechanism studies in progress

Parabolic Oxidation Plot of Slurry EBCs
[1 hr at 2600°F (1427°C) / 20 min at T<100°C, 90% H₂O]

*Chemical vapor infiltration

<table>
<thead>
<tr>
<th>Substrate</th>
<th>CVI* CMC</th>
<th>CVI* CMC</th>
<th>CVI* CMC</th>
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<tbody>
<tr>
<td>Coating</td>
<td>Yb₂Si₂O₇-Based</td>
<td>Mullite-Based</td>
<td>Uncoated</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Internal Surface)</td>
</tr>
<tr>
<td>k (µm²/h)</td>
<td>0.70</td>
<td>0.47</td>
<td>2.11</td>
</tr>
</tbody>
</table>

- Parabolic rate constant is ~50% higher with Yb₂Si₂O₇-Based bond coat
- Uncoated CMC (Internal surface) shows ~2x – 3.5x higher parabolic rate constant than coated CMC
Spin-Dip Coater

- Durability testing in a combustion rig at 2500°F-2700°F (1371-1482°C) is in progress
- Steam cycling test of witness coupons at 2600°F (1427°C) in progress
EBC on Monolithic SiC (3”x 3”) – 1st Airfoil Spin-Dip Trial

As-Coated

100h-100 cycles at 2700°F in Air

- Demonstrated 2700°F (1482°C) temperature capability in air cycling
- SiC substrate broke due to thermal shock
Slurry EBC Fabrication on Mini-composite (via Air Brush)

As-Deposited and Dried (Fractured Surface)

As-Sintered (Polished Surface)

• Steam oxidation and mechanical testing in progress
Cyclic Oxidation of Slurry EBC on SiC Heating Element
(1 hr at 2600°F (1427°C) / 20 min at T<100°C, 90% H₂O)

- High oxidation rate of uncoated SiC due to additives and high porosity
- EBC is effective in reducing oxidation rate in air and steam
Conclusion

• Two slurry-based EBCs capable of 2700°F have been developed
  • Low-cost, non-line-of-sight EBC technology
  • Coating can be readily applied on components of various complexities and shapes

• Coated coupons demonstrated 500h-500 cycle steam oxidation durability at 2600°F (1427°C)
  • Parabolic oxidation rate is ~1/3 of the rate on uncoated internal CMC surface

• Coated SiC airfoil demonstrated 100h-100 cycle cyclic durability in air at 2700°F (1482°C)
  • A spin-dip coating process developed for airfoils

• Coated CMC airfoil combustion rig test at 2500°F-2700°F (1371-1482°C) in progress
Acknowledgement

- Deborah Waters for the initial development work of slurry EBCs (NASA GRC)

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