Thermal and Environmental Barrier Coatings for Advanced Turbine Engine Applications

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Abstract

Ceramic thermal and environmental barrier coatings (T/EBCs) will play a crucial role in advanced gas turbine engine systems because of their ability to significantly increase engine operating temperatures and reduce cooling requirements, thus help achieve engine low emission and high efficiency goals. Under the NASA Ultra-Efficient Engine Technology (UEET) program, advanced T/EBCs are being developed for the low emission SiC/SiC ceramic matrix composite (CMC) combustor applications by extending the CMC liner and vane temperature capability to 1650 °C (3000 °F) in oxidizing and water vapor containing combustion environments. Advanced low conductivity thermal barrier coatings (TBCs) are also being developed for metallic turbine airfoil and combustor applications, providing the component temperature capability up to 1650 °C (3000 °F). The advanced T/EBC system is required to have increased phase stability, low lattice and radiation thermal conductivity, and improved sintering, erosion and thermal stress resistance, and water vapor stability under the engine high-heat-flux and thermal cycling conditions. Advanced high heat-flux testing approaches have been established for the coating developments. The simulated combustion water-vapor environment is also being incorporated into the heat-flux test capabilities for evaluating T/EBC performance at very high temperatures under thermal cycling conditions.

In this paper, ceramic coating development considerations and requirements for both the ceramic and metallic components will be described for engine high temperature and high-heat-flux applications. The performance and durability of several ZrO₂ or HfO₂/mullite and mullite/BSAS model coating systems were investigated. The underlying coating failure mechanisms and life prediction approaches will be discussed based on the simulated engine tests and fracture mechanics modeling results. Further coating performance and life improvements will be expected by utilizing advanced coating architecture design, composition optimization, in conjunction with more sophisticated modeling and design tools.
Thermal and Environmental Barrier Coatings for Advanced Turbine Engine Applications

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This work was supported by NASA Ultra-Efficient Engine Technology (UEET) Program

2004 MRS Fall Meeting
Boston, MA
November 30, 2004
Motivation

— Advanced thermal and environmental barrier coatings (T/EBCs) can significantly increase gas temperatures, reduce cooling requirements, and improve engine fuel efficiency and reliability.
Revolutionary Ceramic Coatings Greatly Impact Gas Turbine Engine Technology

Ceramic coatings are critical to future engine efficiency, power density and compactness goals.

Temperature Capability

(T/EBC) surface

Gen I

Gen II – Current commercial

Gen III

Gen IV

Increase in $\Delta T$ across T/EBC

Single Crystal Superalloy

Ceramic Matrix Composite

Si$_3$N$_4$ and coating systems

2400 °F

2700 °F

3000 °F+ (1650 °C+)

Coating Development Issues

- Low thermal conductivity
- High temperature stability
- Erosion and radiation resistance

NASA UEET Goals

- 70% NO$_x$ reduction
- 8-15% increase in efficiency
- 8-15% reduction in CO$_2$
OBJECTIVES

• High-heat-flux and simulated engine test capabilities for advanced barrier coating developments
  – In-situ conductivity measurements and coating degradation evaluation
  – Simulated engine testing
  – Sintering, strength and fracture behavior

• Low conductivity thermal barrier coatings

• The 3000 °F (1650 °C) thermal and environmental barrier coatings for SiC/SiC CMC and metallic combustors/vanes

• Advanced Si$_3$N$_4$ coating systems
NASA Steady-State Laser Heat-Flux Approach for Ceramic Coating Thermal Conductivity Measurements

- A uniform laser (wavelength 10.6 µm) power distribution achieved using integrating lens combined with lens/specimen rotation
- The ceramic surface and substrate temperatures measured by 8 micron and two-color pyrometers and/or by an embedded miniature thermocouple
- Thermal conductivity measured at 5 second intervals in real time
Laser Heat Flux Testing in Water Vapor Environments for Si-Based Ceramics/Coatings

- **Laser heat flux steam rig**
  - Precise control of heat flux and temperatures of test specimen
  - Automated control of chamber temperature and steam environments
  - High temperature and high heat flux testing capabilities
  - Innovative “micro-steam environment” concept allows high vapor pressure, velocity and temperature as required
  - Real time specimen health monitoring capability

- Steam injected at up to 5m/sec
- Testing temperature >1700 °C

![Image of the laser heat flux water vapor test rig](image)
High Pressure Burner Rig (HPBR) for Ceramic Coatings Testing

- Realistic combustion environments for specimen and component testing

- Burns jet fuel and air
- \( T_{\text{gas}} \): up to 1650 °C (3000 °F)
- 4-12 atmospheres
- 10-30 m/s (6” ID)
- TC and optical temp. measurement
- Variable geometry

1” button TEBC coating specimen holder for the burner rig testing
Thermal Conductivity of Current Thermal Barrier Coating Systems

Current thermal barrier coatings consist of $\text{ZrO}_2$-8wt$\%$Y$_2$O$_3$

- relatively low intrinsic thermal conductivity $\sim$2.5 W/m-K
- high thermal expansion to better match superalloy substrates
- good high temperature stability and mechanical properties

- Additional conductivity reduction is achieved by incorporating micro-porosity
Coating Thermal Conductivity Reductions by Porosity are limited in Practical Applications

- The conductivity reduction achieved by microcracks and micro-porosity cannot persist under high temperatures due to coating sintering.
- The coating mechanical properties also affected by too high porosity.

![Graph showing thermal conductivity of different coating types](image-url)
ZrO$_2$-8wt%$Y_2$O$_3$/Mullite+BSAS/Si System under High Temperature Steady-State Laser Heat-Flux Testing

- ZrO$_2$-8wt%$Y_2$O$_3$/mullite+BSAS TEBC system on SiC/SiC CMC tested at $T_{\text{surface}}$ 1482 °C (2700 °F) and $T_{\text{interface}}$ 1300 °C (2350 °F)
- Conductivity initially increased due to sintering
- Conductivity later decreased due to delamination resulting from the large sintering shrinkage
- Coating delaminates at temperature due to sintering/creep

Conductivity reduction due to sintering cracking induced delamination cracking

After 20h testing

Sintering cracks
Sintering Behavior of the Plasma-Sprayed ZrO₂-8wt%Y₂O₃ Coatings

- Sintering shrinkage as a function of time and temperature determined using dilatometer
- Sintering can induce surface cracking and delamination

![Graph showing sintering behavior](image-url)
Thermal Conductivity Increase Kinetics of Plasma-Sprayed ZrO$_2$-8wt%Y$_2$O$_3$ Coatings due to Sintering

— The conductivity reduction by microcracks and micro-porosity can not persist under high temperatures due to coating sintering

— The coating durability can be affected by sintering

Thermal conductivity ZrO$_2$-8wt%Y$_2$O$_3$ as a function of time and temperature at up to 1320 °C
Flexure Strength and Toughness Increases Kinetics as a Function of Annealing/Sintering Time

- Initially fast sintering induced strength and fracture toughness increases also observed for plasma-sprayed ZrO₂-8wt%Y₂O₃ coatings
Development of Advanced Defect Cluster Low Conductivity Thermal Barrier Coatings

- Multi-component oxide defect clustering approach used for the advanced coating development – US Patent No. 6,812,176
  
  \[ \text{e.g., } \text{ZrO}_2-\text{Y}_2\text{O}_3-\text{Nd}_2\text{O}_3(\text{Gd}_2\text{O}_3,\text{Sm}_2\text{O}_3)-\text{Yb}_2\text{O}_3(\text{Sc}_2\text{O}_3) \text{ systems} \]

  - Primary stabilizer
  - Oxide cluster dopants with distinctive ionic sizes

- Defect clusters associated with the dopant segregation identified from moiré fringe patterns and electron energy loss spectroscopy (EELS) under high resolution TEM

- The 5 to 100 nm size defect clusters designed for the significantly reduced thermal conductivity and improved stability

Plasma-sprayed ZrO$_2$-13.5mol%(Y, Nd,Yb)$_2$O$_3$

EB-PVD ZrO$_2$-12mol%(Y, Nd,Yb)$_2$O$_3$

EELS elemental maps of EB-PVD ZrO$_2$-14mol%(Y, Gd,Yb)$_2$O$_3$
Low Conductivity Oxide Defect Cluster Coatings Demonstrated Improved High Temperature Stability

- Thermal conductivity rate-of-increase significantly reduced at high temperatures for the low conductivity defect cluster thermal barrier coatings
- Phase stability also improved

![Graph showing thermal conductivity over time](image_url)

**Plasma-sprayed coatings**
Low Conductivity Oxide Defect Cluster Coatings Demonstrated Improved High Temperature Stability

- Thermal conductivity rate-of-increase significantly reduced at high temperatures for the low conductivity defect cluster thermal barrier coatings
- Phase stability also improved

EB-PVD coatings
Both cubic phase low k coatings and t’ tetragonal plasma-sprayed coatings showed significantly lower thermal conductivity as compared to baseline ZrO$_2$-8wt%Y$_2$O$_3$ under higher temperatures.
The cubic-phase ZrO$_2$-based low conductivity TBC durability can be further significantly improved by an 8YSZ or low k tetragonal t’-phase interlayer.

The tetragonal t’-phase low conductivity TBCs achieved at least the baseline 8YSZ life.
Effects of Defect Cluster Dopant Ratio and Bond Coat Optimization on Coating Conductivity and Furnace Cyclic Life

- Optimized dopant ratio lowered coating conductivity and improved furnace cyclic life
- Bond coat and interface processing optimization can also improve durability

Cluster dopants/Total dopants in mol%/mol%

Normalized thermal conductivity, W/m-K

Normalized cyclic life

Howmet processed NASA coating tested at 1371°C (2500°F) & 1204°F (2200°F)
- k0-2500F-low k coatings
- k20-2500F-low k coatings
- k0-2200F-low k coatings
- k20-2200F-low k coatings

Howmet processed NASA coating furnace cyclic tested at 1165 °C (2125 °F)

Normalized cyclic life-low k coatings

Bond coat & interface processing optimization
Low Diffusion and High Toughness Coatings Showed Better Cyclic Life

High toughness t' phase such as in 8YSZ

Fracture surfaces
Larger grains

Fast grain growth and low toughness
ZrO₂–10mol%Y₂O₃

Coating after 430, 1 hr cycles at 1165 °C

Observed grain growth, µm

Cluster oxide coating
YSZ coating

10Y-S-Z 6.0kV 12.0mm x3.50k SE(L) 10/15/2001

10.0µm

Total dopant concentration, mol%
The low conductivity combustor and turbine airfoil thermal barrier coatings successfully tested under laboratory simulated engine thermal gradient cyclic conditions.

**Advanced Low Conductivity TBC Showed Excellent Long-Term High Temperature Cyclic Durability**

- Low conductivity EB-PVD turbine airfoil coating
- 6 min heating, 2 min cooling cycles
- Tsurface=2480 °F (1360 °C)
- Tinterface=2020 °F (1104 °C)
Development of Advanced Erosion Resistant Thermal Barrier Coatings

Advanced high toughness, multi-component erosion resistant low conductivity thermal barrier coatings also under development

(a) Burner rig erosion and impact test results at 2200 °F

(b) Room temperature erosion testing results for 2400 °F thermal gradient tested specimens
Advanced 3000 °F (1649 °C) Coatings

- High temperature stability
- Low thermal conductivity
- Excellent thermal stress resistance
- Enhanced radiative flux resistance and radiation cooling
- Improved environmental protection
- Designed functional capability

High temperature capability thermal and radiation barrier
Energy dissipation and chemical barrier interlayer
Secondary radiation barrier, thermal control with chemical barrier interlayer
Environmental barrier
Ceramic matrix composite (CMC)
Advanced 3000 °F (1649 °C) Coatings Development for SiC/SiC Combustor Liner and Vane Applications

- The multicomponent hafnia(zirconia) coating/modified mullite systems demonstrated excellent cyclic durability and radiation resistance at 1650 °C (3000 °F)
- Advanced high temperature ceramic bond coats also developed

Sintering and cyclic durability evaluations

<table>
<thead>
<tr>
<th>Coating System</th>
<th>Normalized Thermal Conductivity k/k₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>HfO₂-Y₂O₃ coatings</td>
<td></td>
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<tr>
<td>Multi-component HfO₂</td>
<td></td>
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<tr>
<td>coating system</td>
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<tr>
<td>15YSHf</td>
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<tr>
<td>15(YGdYb)Hf</td>
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<tr>
<td>5YSHf</td>
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</tbody>
</table>

T_{\text{surface}}=1650°C, T_{\text{interface}}=1316°C

Modified mullite nano-composite interlayer coating

3100°F coatings
Advanced Environmental Barrier Coatings for Si₃N₄ Applications

- Multi-layered, rare earth and silicon doped HfO₂/mullite 2700 °F environmental barrier coating systems developed:
  - Advanced low expansion doped HfO₂ used for high stability top layer
  - Modified mullite as the interlayer and environmental barrier
  - Doped HfO₂ or mullite 2700 °F+ capable bond coats (eliminating Si bond coat)
- High Temperature plasma-spray technique used for coating processing

Multi-layer coating systems for 2700 °F Si₃N₄ components

Plasma-spray processing of Environmental barrier coating

A 2700 °F capable coating system for Si₃N₄
Coating Radiation Performance Evaluation and Radiation Barrier Coatings Development

— Radiation conductivity evaluated using the laser heat flux approach
— Significant conductivity increase due to increased radiation at high temperatures especially under thermal gradients

\[
\begin{align*}
L_{2}Zr_{2}O_{7} & \\
ZrO_{2} - 8\text{wt}%Y_{2}O_{3} & \text{plasma-sprayed porous coating}
\end{align*}
\]
Evaluation of Radiation Thermal Conductivity of T/EBC Systems at High Temperatures

- Radiation conductivity increases with thermal gradient and thus heat flux
- Advanced HfO$_2$ coatings demonstrated improved radiation resistance compared to the baseline ZrO$_2$-8wt%Y$_2$O$_3$ coating
Summary and Conclusions

• Advanced testing approaches established for ceramic coating development

• Real-time monitoring of coating thermal conductivity demonstrated as an effective technique to assess coating performance under simulated engine heat flux conditions

• The multi-component TBCs demonstrated lower conductivity, improved high temperature stability and cyclic durability required for advanced turbine airfoil and combustor applications

• High toughness erosion resistant turbine airfoil TBC development showed significant progress

• Advanced 1650 °C (3000 °F) T/EBC systems developed for Si-based ceramics
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