Development Status and Performance Comparisons of Environmental Barrier Coating Systems for SiC/SiC Ceramic Matrix Composites

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Light-Weight SiC/SiC Ceramic Matrix Composite (CMC) – Environmental Barrier Coating (EBC) Development

— Enabling next generation turbine engine hot-section technology: increased materials temperature capability and improved future engine performance

— EBCs are critical to long-term environmental durability and life of Si-based ceramic engine components

Metal components with TBCs
- Combustor
- Vane
- Blade

Monolithic/Hybrid Ceramic Nozzles/Blades

Light-weight SiC/SiC CMC components
NASA Environmental Barrier Coating System Development – For Turbine Engines

- Emphasize temperature capability, performance and durability for next generation for next generation vehicle airframe or engine systems
- Increase Technology Readiness Levels for component system demonstrations

<table>
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<th>Gas</th>
<th>TBC</th>
<th>Bond coat</th>
<th>Metal blade</th>
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<th>TBC</th>
<th>Bond coat</th>
<th>Metal blade</th>
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<tr>
<td>Baseline metal temperature</td>
<td>2200°F TBCs</td>
<td>Tsurface</td>
<td>300°F increase</td>
<td>2500°F TBCs</td>
<td>3200°F (T41)</td>
<td>2700-3000°F EBCs</td>
<td>Tsurface</td>
<td>200-500°F increase</td>
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<td>Current metal turbine airfoil system</td>
<td>Current metal turbine airfoil system 2500°F TBCs</td>
<td>State of the art metal turbine airfoil system</td>
<td>2700-3000°F CMC turbine airfoil systems</td>
<td>2400°F CMCs</td>
<td>2700°F CMCs</td>
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</table>
Fundamental Recession Issues of CMCs and EBCs

Recession rate = constant $\times V^{1/2} \frac{P(H_2O)^2}{(P_{total})^{1/2}}$

$\text{SiO}_2 + 2H_2O(g) = \text{Si(OH)}_4(g)$

Combustion gas

Cooling air

Temperature, °C

SiC/SiC under high velocity

BSAS Baseline

Specific weight change, mg/cm²-h

1/T, K⁻¹

Supersonics EBC stability development goal - 2005
Outline

— Environmental barrier coating systems: design approach for stability

— Next generation environmental barrier coating systems for CMC airfoils and combustors
  • NASA coating technologies – advanced composition and system development
    — Fundamental research emphasis in understanding degradation, property evaluation, and performance modeling
    — Multi-component, multi-layer and composite systems
  • EBC processing: plasma spray, electron beam-physical vapor deposition and plasma spray-physical vapor deposition approaches
  • Advanced testing methodologies and simulated engine heat flux and stress testing
    — Laser high heat flux test rig and coating thermal conductivity
    — High temperature durability tests

— Summary and Conclusions
Advanced Environmental Barrier Coating and Architecture Development

— High temperature and environmental stability
— Lower thermal conductivity
— Balance designs of low thermal expansion, high strength and high strain tolerance
— High toughness
— Excellent resistance to thermal-mechanical loading, impact and erosion
— Interface, grain boundary stability and compatibility
— Dynamic characteristics to resist harsh environments and with self-healing capability

Multilayer Architecture due to Performance Requirements

- High temperature capable, high strength coatings
- Energy dissipation and chemical barrier interlayer
- Environmental barrier
- Nano-composite bond coat
- Ceramic matrix composite (CMC)
Advanced Environmental Barrier Coating Systems: Coating Material System Developments and Architecture

• High-stability multi-component ZrO$_2$/HfO$_2$, Hafnium-Rare Earth (RE) silicates, or Hafnium-Rare Earth (RE) aluminosilicate composites
• Alternating Composition Layered Composite (ACLC) and Sublayer EBCs systems
  – Advanced multi-component and RE silicate EBCs
  – Oxide-Si composite bond coats, in particular, HfO$_2$-Si bond coats
  – Self-healing and protective coating growth capability

![Diagram showing the structure of advanced environmental barrier coating systems](image)
### Advanced Environmental Barrier Coating Systems

<table>
<thead>
<tr>
<th>Material Systems</th>
<th>Temperature capability</th>
<th>Thermal expansion</th>
<th>Resistance to oxidation and combustion environment</th>
<th>Mechanical stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>HfO$_2$-RE$_2$O$_3$</td>
<td>~3000°C</td>
<td>8-10x10$^{-6}$ m/m-K</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>HfO$_2$-Rare Earth silicates</td>
<td>~1900-2900°C</td>
<td>8-10x10$^{-6}$ m/m-K</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Rare Earth Silicates</td>
<td>~1800-1900°C</td>
<td>5-8.5x10$^{-6}$ m/m-K</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Rare earth – aluminates and Alumino silicates</td>
<td>~1600-1900°C</td>
<td>5-8.5x10$^{-6}$ m/m-K</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>HfO$_2$-Si and RE-Si bond coat</td>
<td>Up to 2100°C</td>
<td>5-7x10$^{-6}$ m/m-K</td>
<td>Good</td>
<td>Excellent</td>
</tr>
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</table>
EBC Processing using Atmospheric Plasma-Spray (APS) and Hybrid Plasma Spray / Electron Beam - Physical Vapor Deposition (EB-PVD) Coatings

Plasma-spray processing of environmental barrier coatings

EB-PVD Advanced HfO$_2$

Plasma spray ytterbium silicate

Plasma spray HfO$_2$-Si

Early generation hybrid environmental barrier coatings systems processed with combined Plasma Spray and EB-PVD processing
EBC Processing using Plasma Spray and EB-PVD

Oerlikon Metco Triplex Processed Advanced EBCs

Directed Vapor EB-PVD Processed Advanced EBCs
EBC Processing using Plasma Spray - Physical Vapor Deposition (PS-PVD)

- NASA advanced PS-PVD coating processing using Sulzer technology
- EBC is being developed for next-generation SiC/SiC CMC turbine airfoil coating processing
  - High flexibility coating processing – PVD, CVD and/or splat coating processing
  - High velocity vapor, non line-of-sight coating processing for complex-shape components

NASA Hybrid PS-PVD coater system

Vapor ZrO$_2$-Y$_2$O$_3$ coating

Splat/partial vapor Yb$_2$Si$_2$O

HfO$_2$-Si bond coat

PS-PVD processed coatings
Laser High Heat Flux Approach

- Turbine level high-heat-flux tests crucial for CMC coating system developments
- Real-time thermal conductivity measurements
- Advanced complex combined mechanical loading conditions and environments incorporated

**Thermal gradients:**

Turbine: 450°F across 100 microns
Combustor: 1250°F across 400 microns
Real-Time Thermal Conductivity Measurements and Damage Monitoring

7.9 µm pyrometer for $T_{\text{ceramic-surface}}$

$T_{\text{reflected}}$

$T_{\text{radiated}}$

Surface flow

$\Delta T_{\text{ceramic}} = \Delta T_{\text{measured}} - \Delta T_{\text{substrate}} - \Delta T_{\text{bond}}$

$\Delta T_{\text{tc}}$

Two-color and 7.9 µm pyrometers for $T_{\text{substrate-back}}$

$q_{\text{thru}}$

Optional miniature thermocouple for additional heat flux calibration
Plasma Spray EBC Processing and Heat Flux Testing for CMC Component EBC Validations

- Advanced plasma sprayed multicomponent HfO$_2$-rare earth silicate with HfO$_2$-Si based environmental barrier coating optimized and down-selected
- Thermal conductivity ranged from 0.4 – 1.7 W/m-K

Laser heat flux test under thermal gradients
Thermal Conductivity of PS-PVD Yb$_2$Si$_2$O$_7$ Coatings For Process Optimization

— Processing and microstructural optimizations, aiming at achieving coating stability and maintaining lower thermal conductivity

![Image of Yb$_2$Si$_2$O$_7$ Coatings](image.png)

Thermal conductivity modeled using FEM

<table>
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<tr>
<th>Coating System</th>
<th>Porosity Modeled</th>
<th>Porosity Measured</th>
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<tbody>
<tr>
<td>System 2</td>
<td>16%</td>
<td>13%</td>
</tr>
<tr>
<td>System 3</td>
<td>28%</td>
<td></td>
</tr>
<tr>
<td>System 4</td>
<td>18%</td>
<td></td>
</tr>
<tr>
<td>System 6</td>
<td>20%</td>
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</tr>
</tbody>
</table>

Porosity, %

0 10 20 30 40 50 60

Thermal conductivity, W/m-K

0.0 0.5 1.0 1.5 2.0 2.5 3.0

Thermal conductivity modeled using FEM

Processing and microstructural optimizations, aiming at achieving coating stability and maintaining lower thermal conductivity.
PS-PVD Ytterbium Silicate EBC Tested in Heat Flux Conditions

- Demonstrated initial durability of HfO$_2$-ytterbium silicate-silicon at 1400-1500°C test temperatures in air and laser heat flux steam tests
- Thermal conductivity ranged from 0.6 to 2.5 W/m-K
- Achievable low thermal conductivity and unique structures with coatings

Three layer HfO$_2$-ytterbium silicate-Si completed 50hr laser heat flux thermal conductivity-durability tests in air and steam
PS-PVD Ytterbium Silicate EBC Tested in Heat Flux Conditions - Continued

- Demonstrated initial durability of ytterbium silicate with advanced HfO$_2$-Si bond coats at 1400-1500°C test temperatures in air and laser steam tests
- Thermal conductivity ranged from 0.6 to 2.5 W/m-K
- Some sintering led more significant thermal conductivity increases
Composite EBCs Considered for Improved Stability –
Process also developed for EBC systems

- Layered and nano-composite designs incorporated in various processing approaches
- Advanced composite systems shown to improve the temperature capability and recession resistance
- Improved mechanical properties for erosion and impact resistance
- Improved CMAS resistance
EB-PVD Composite Environmental Barrier Coatings – CMAS Reaction Tested

EB-PVD Processed EBCs: alternating HfO$_2$-rich and ytterbium silicate layer systems for CMAS and impact resistance
Advanced NASA 2700°F HfO2-Si and Rare Earth-Si Based Bond Coats

- Continued improvements in processing robustness and composition optimization
Advanced EBC Successfully Tested under 1000 hr Stress-Rupture Conditions at 2700°F

- EBC systems tested included various processed APS and EB-PVD EBCs

![Diagram of test setup]

- Laser beam delivery optic system
- Cooling shower head jets
- High temperature extensometer
- Test specimen

![Graph showing strain vs. time]

- Total strain vs. time graph with data points:
  - Gen II CMC, 1.98x10^{-7} /s; 15 ksi
  - Tsurface = 2700°F
  - Tinterface = 2500°F
  - TCMC back = 2320°F

- Gen I CMC, 7.19x10^{-8} /s; 15 ksi
  - Tsurface = 2400°F
  - Tinterface = 2300°F
  - Tback = 2050°C

- Gen I CMC, 4.10x10^{-8} /s; 10 ksi
  - Tsurface = ~2500°F
  - Tinterface = ~2350°F
  - Tback = ~2200°F

![Microstructures after testing]

- Microstructures after 1000 hr, 1482°C (2700°F), 1371°C (2500°F), 103 MPa (15 ksi) testing
Advanced EBC-CMC Fatigue Test with CMAS: Successfully Tested 300 h Durability in High Heat Flux Fatigue Test Conditions

- A thin EB-PVD turbine airfoil EBC system with advanced HfO$_2$-rare earth silicate and GdYbSi (controlled oxygen activity) bond coat tested at $T_{EBC\text{-surface}}$ 1537°C, $T_{\text{bond coat}}$ 1480°C, $T_{\text{back CMC surface}}$ 1250°C
- Fatigue Stress amplitude 69 MPa, at mechanical fatigue frequency $f$=3Hz, stress ratio $R=0.05$
- Low cycle thermal gradient fatigue 60min hot, 3min cooling

1537°C, 69MPa (10ksi), 300 h fatigue (3 Hz, R=0.05) on 14C579-011001_#8 CVI-MI SiC/SiC (with CMAS)
Advanced EBC Fatigue Creep-Fatigue of EBCs-CMCs in Complex Heat Flux and Simulated Engine Environments

- Long-term creep and fatigue validated EBCs and CMCs at various loading levels
- Demonstrated advanced 1482°C (2700°F) EBC and bond coat capabilities in complex environments
- Advanced coatings have minimized environment degradations of CMCs, demonstrating durability in fatigue and CMAS environments

Stress-oxidation and stress-CMAS environmental testing summary
Summary and Conclusions

• Advanced EBCs being developed and evaluated using APS, hybrid APS/EB-PVD, EB-PVD and PS-PVD
  – Achieved advanced composition designed EBCs
  – Significantly expanding envisioned high performance coating architecture development
  – Demonstrated initial durability

• Advanced, high temperature testing approaches showed significant advantages in the development of advanced environmental barrier coating systems
  – Simulated engine thermomechanical conditions
  – Simulated environment conditions
  – Real time thermal conductivity, stability and durability
  – Capable quantifying the EBC degradation and performance
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