Creep, Fatigue and Fracture Behavior of Environmental Barrier Coating and SiC-SiC Ceramic Matrix Composite Systems: The Role of Environment Effects

Dongming Zhu and Louis J. Ghosn

Materials and Structures Division
NASA Glenn Research Center
Cleveland, Ohio 44135, USA

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Durable Environmental Barrier Coating Systems for Ceramic Matrix Composites (CMCs):
Enabling Technology for Next Generation Low Emission, High Efficiency and Light-Weight Propulsion

— NASA Environmental barrier coatings (EBCs) development objectives
  • Help achieve future engine temperature and performance goals
  • Ensure system durability – towards prime reliant coatings
  • Establish database, design tools and coating lifing methodologies
  • Improve technology readiness

Fix Wing Subsonic Aircraft

Supersonics Aircraft
NASA Environmental Barrier Coating Development Goals

- Emphasize temperature capability, performance and durability
- Develop innovative coating technologies and life prediction approaches
- 2700°F (1482°C) EBC bond coat technology for supporting next generation
- 2700-3000°F (1482-1650°C) turbine and CMC combustor coatings
  - Meet 1000 hr for subsonic aircraft and 9,000 hr for supersonics/high speed aircraft hot-time life requirements

Step increase in the material’s temperature capability

**Temperature Capability**

- **2800°F** combustor TBC
- **2500°F** Turbine TBC

=T/EBC= surface

- **2700°F** (1482°C) Gen III SiC/SiC CMCs
- **3000°F** SiC/SiC CMC airfoil and combustor technologies
- **2700°F** SiC/SiC thin turbine EBC systems for CMC airfoils

2700°F (1482°C) Gen III SiC/SiC CMCs

Increase in ΔT across T/EBC

- 2400°F (1316°C) Gen I and Gen II SiC/SiC CMCs
- 2000°F (1093°C)

Gen I

- Year

Gen II – Current commercial

Gen III

Gen. IV

* Recession: <5 mg/cm² per 1000 hr (40-50 atm, Mach 1~2)
** Component strength and toughness requirements
Outline

- Environmental barrier coating system development: challenges and limitations

- Advanced environmental barrier coating systems (EBCs) for CMC airfoils and combustors
  - NASA EBC systems and material system evolutions
  - Current turbine and combustor EBC coating emphases
  - Advanced EBC development: processing, testing and durability

- Design tool and life prediction perspectives of coated CMC components

- Advanced CMC-EBC rig demonstrations

- Summary and future directions
Fundamental Recession Issues of CMCs and EBCs

- Recession of Si-based Ceramics
  (a) Convective; (b) Convective with film-cooling
  - Low \( \text{SiO}_2 \) activity EBC system development emphasis

- Advanced rig testing and modeling
  More complex recession behavior of CMC and EBCs in High Pressure Burner Rig

Recession rate = const. \( V^{1/2} \frac{P_{(\text{H}_2\text{O})}^2}{(P_{\text{total}})^{1/2}} \)

\[ \text{SiO}_2 + 2\text{H}_2\text{O}(g) = \text{Si(OH)}_4(g) \]
Fundamental Recession Issues of CMCs and EBCs - Continued

Weight Loss of SiC in High Pressure Burner Rig
6 atm 20 m/s

- Early generation coatings - EBC systems

Robinson and Smialek, J. Am. Ceram Soc. 1999

SiC Wt. Loss (mg/cm²)

Exposure Time (hrs)

0 20 40 60 80 100

-15
-10
-5
0

1385 C
1446 C
1252 C
1343 C

Combustor coating

Turbine coating

HfO₂ based low k – APS

HfO₂ based low k – EB-PVD
SiC/SiC CMC and EBC Recession Kinetics Determined for CMCs-EBCs in High Pressure Bruner Rig and Laser Steam Rig Testing

— Determined recession under complex, and realistic simulated turbine conditions

High temperature recession kinetics for film-cooled and non-film cooled Gen II SiC/SiC CMCs

Examples of environmental barrier coating recession in laboratory simulated turbine engine conditions
Degradation Mechanisms for Si Bond Coat

- Silicon bond coat melts at 1410°C (melting point)
- Fast oxidation rates (forming SiO₂) and high volatility at high temperature
- Low toughness at room temperature (0.8-0.9 MPa m¹/²; Brittle to Ductile Transition Temperature about 750°C)
- Low strength and high creep rates at high temperatures, leading to coating delamination
- Interface reactions leading to low melting phases
  - A more significant issue when sand deposit Calcium- Magnesium – Alumino-Siliacte (CMAS) is present
- Si and SiO₂ volatility at high temperature (with and without moisture)

Brittle to Ductile transition in polycrystalline Si
Degradation Mechanisms for Si Bond Coat – Interface reactions

- Significant interfacial pores and eutectic phases formation due to the water vapor attack and Si diffusion at 1300°C
- Heat flux condition further limit the use temperatures

SEM images Interface reactions at 1300°C; total 200 hot hours

Si bond coat after 1350°C, 50 hr furnace test in air; 1” dia plasma sprayed EBC button specimen

Hot pressed BSAS+Si button specimen after 1350°C, 50 hr furnace test in air

Interface Si bond coat melting of selected coating systems, under laser heat flux tests, 1” dia button specimen

BaO-Al₂O₃-SiO₂ ternary phase diagram
# Evolution of NASA EBC Technology for SiC/SiC Ceramic Matrix Composites: Current State of the Art

## Advanced EBC system developments

<table>
<thead>
<tr>
<th>Engine Components:</th>
<th>Combustor</th>
<th>Combustor/ (Vane)</th>
<th>Combustor/ Vane</th>
<th>Vane/ Blade</th>
<th>- Vane/Blade EBCs - Equivalent APS combustor EBCs</th>
<th>Airfoil components</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Top Coat:</strong></td>
<td>BSAS (APS)</td>
<td>RE$_2$Si$_2$O$_7$ or RE$_2$SiO$_5$ (APS)</td>
<td>- (Hf,Yb,Gd,Y)$_2$O$_3$ - ZrO$_2$/HfO$_2$+RE silicates - ZrO$_2$/HfO$_2$+BSAS (APS and EB-PVD)</td>
<td>RE-HfO$_2$-Alumino silicate (APS and/or 100% EB-PVD)</td>
<td>RE-HfO$_2$-X advanced top coat RE-HfO$_2$-graded Silica (EB-PVD)</td>
<td>Advanced EBC</td>
</tr>
<tr>
<td><strong>Interlayer:</strong></td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>Nanocomposite graded oxide/silicate</td>
<td>Gen IV interlayer not required (optional)</td>
<td></td>
</tr>
<tr>
<td><strong>EBC:</strong></td>
<td>Mullite+ BSAS</td>
<td>BSAS+Mullite</td>
<td>RE silicates or RE-Hf mullite</td>
<td>RE doped mullite-HfO$_2$ or RE silicates</td>
<td>Multi-component RE silicate systems</td>
<td>Multicomponent RE-silicate /self grown</td>
</tr>
<tr>
<td><strong>Bond Coat:</strong></td>
<td>Si</td>
<td>Si</td>
<td>Oxide+Si bond coat</td>
<td>HfO$_2$-Si-X, doped mullite/Si SiC nanotube</td>
<td>Optimized Gen IV HfO$_2$-Si-X bond coat 2700°F bond coats</td>
<td>RE-Si+X systems</td>
</tr>
<tr>
<td><strong>Thickness</strong></td>
<td>10-15 mil</td>
<td>10-15 mil</td>
<td>15-20 mil</td>
<td>10 mil</td>
<td>5 mil</td>
<td>1-3 mils</td>
</tr>
<tr>
<td><strong>Surface T:</strong></td>
<td>Up to 2400°F</td>
<td>2400°F</td>
<td>3000°F/2400CMC</td>
<td>2700°F/2400F CMC</td>
<td>3000°F</td>
<td></td>
</tr>
</tbody>
</table>

### Challenges overcome by advancements:
- Improved phase stability, recession resistance of top coat
- Increased phase stability and toughness

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**Engine Components:**
- Combustor
- Combustor/ (Vane)
- Combustor/ Vane
- Vane/ Blade

**Top Coat:**
- BSAS (APS)
- RE$_2$Si$_2$O$_7$ or RE$_2$SiO$_5$ (APS)
- Hf$_2$O$_3$, Y$_2$O$_3$, and Yb$_2$O$_3$

**Interlayer:**
- Nanocomposite graded oxide/silicate

**EBC:**
- Mullite+ BSAS
- BSAS+Mullite
- RE silicates or RE-Hf mullite

**Bond Coat:**
- Si
- Oxide+Si bond coat
- HfO$_2$-Si-X, doped mullite/Si SiC nanotube

**Thickness:**
- 10-15 mil
- 15-20 mil
- 10 mil
- 5 mil
- 1-3 mils

**Surface T:**
- Up to 2400°F
- 2400°F
- 3000°F/2400CMC
- 2700°F/2400F CMC
- 3000°F

**Bond Coats:**
- Advanced compositions & processing for thinner coatings, higher stability and increased toughness
Major development milestones:

- **1995-2000:** BSAS/Mullite+BSAS/Si
- **2000-2004:** $\text{RE}_2\text{Si}_2\text{O}_7$ or $\text{RE}_2\text{SiO}_5$/BSAS+Mullite/Si
- **2000-2004 - 3000°F EBC systems:** $\text{HfO}_2$ systems (**HfO$_2$ version four-component low k**) / $\text{RE}_2\text{Si}_2\text{O}_7$ or $\text{RE}_2\text{SiO}_5$ / BSAS+Mullite/Si and Oxide+Si bond coats; component demonstrations
  - Modified mullite (with transition metal and RE dopants) to replace BSAS+mullite
  - Many compound oxide top coat materials explored
- **2005-2011 - Turbine coating systems:** Multi-component, graded $\text{HfO}_2$-Rare Earth Oxide-$\text{SiO}_2$/ multi-component Rare earth Silicate/ $\text{HfO}_2$-Si systems
  - $\text{RE-HfO}_2$-$X$/Multicomponent RE-silicate / $\text{HfO}_2$-$\text{Si} +X$ (doped)
- **2009-present:** Improved EBC compositions in progress; RE-Si bond coat
  - (Gd,Yb,Y)Si bond coat and top coat
NASA EBC Technology for SiC/SiC Ceramic Matrix Composites: Current State of the Art - Continued

- Develop processing capabilities, experience and demonstrate feasibilities in various techniques: air plasma spray, Electron Beam - Physical Vapor Deposition (EB-PVD), Plasma Sprayed-Physical Vapor Deposition (PS-PVD):

  • Efforts in developing turbine EBC coatings with Directed Vapor Technologies using Directed Vapor EB-PVD: Turbine Airfoils
  • In-house APS, and Triplex Pro APS (with Sulzer/Oerlikon Metco) - for Combustor applications
  • Cathodic arc and Magnetron PVD processes: bond coat developments
  • In-house PS-PVD
  • Some planned EBCs DVM/DVC coatings (with Praxair): aiming at combustor EBC
Environmental Stability of Selected Environmental Barrier Coatings Demonstrated in NASA High Pressure Burner Rig

- EBC stability evaluated on SiC/SiC CMCs in high velocity, high pressure burner rig environment
- Advanced EBC recession met NASA Fundamental Aeronautics Project goals (2011)

Stability of selected coatings systems

Specific weight change, mg/cm²-h

1/T, K⁻¹

NASA EBC development stability goal

Stability and temperature capability improvements through coating composition and architecture innovations

SiC, 20m/s, 6 atm; Robinson and Smialek, J. Am. Ceram Soc. 1999;
NASA Turbine Environmental Barrier Coating Developments - Continued

- Advanced EBC top coats tested in coupons under laser heat flux cyclic rigs up 1700°C
- Coated subelements coating tested up 1500°C under laser thermal gradient for 200 hr
- EBC systems show high stability in High Pressure Burner Rig Tests
- Low thermal conductivity of 1.2 W/m-K for optimized turbine airfoil coatings

High pressure burner rig, 16 atm, 31 hr – no measureable weight loss
Development and Processing of Directed Vapor Electron Beam - Physical Vapor Deposition (EB-PVD)

– NASA programs in supporting processing developments and improvements with Directed Vapor Technologies International, Inc.
  • Multicomponent thermal and environmental barrier coating vapor processing developments
  • High toughness turbine coatings
  • Affordable manufacture of environmental barrier coatings for turbine components

Advanced multi-component and multilayer turbine EBC systems

Directed Vapor Processing systems

Processed EBC system
Plasma Sprayed-Physical Vapor Deposition (PS-PVD) Processing of Environmental Barrier Coatings

— Focused on advanced composition and processing developments using state-of-the-art techniques
— Improved processing envelopes using high power and higher velocity, graded systems processing for advanced TEBCs and thermal protection systems

NASA EBC processed by Triplax pro

Sulzer Triplex Pro system having high efficiency and high velocity processing

EBC coated SiC/SiC CMC Inner and Outer Liner components

Inner and outer liner articles

HfO₂-Si bond coat
Plasma Sprayed-Physical Vapor Deposition (PS-PVD) Processing of Environmental Barrier Coatings

- NASA PS-PVD and PS-TF coating processing using Sulzer newly developed technology
  - High flexibility coating processing – PVD - splat coating processing at low pressure (at ~1 torr)
  - High velocity vapor, non line-of-sight coating processing for complex-shape components
  - Emphasis on fundamental process and powder composition developments for EBC depositions

100 kW power, 1 torr operation pressure

NASA hybrid PS-PVD coater system

Processed coating systems
Advanced EBC Coating Material Strength Evaluations

- EBC and bond coat constituents are designed with high strength and high toughness to improve coating durability
  - Advanced EBC 150-200 MPa strength achieved at high temperature
  - Multicomponent silicates showed excellent high temperature properties
  - Toughness 3-4 MPa m$^{1/2}$ also achieved (tested at room temperature)
- HfO$_2$-Si based systems showed promising strength and toughness
- More advanced bond coats showed higher temperature capabilities and improved strength
NASA EBC Bond Coats for Airfoil and Combustor EBCs

– Advanced systems developed and to improve Technology Readiness Levels (TRL)

– Composition ranges studied mostly from 50 – 80 atomic% silicon
  • PVD-CVD processing, for composition downselects - also helping potentially develop a low cost CVD or laser CVD approach
  • Compositions initially downselected for selected EB-PVD and APS coating composition processing
  • Viable EB-PVD and APS systems downselected and tested; development new PVD-CVD approaches

<table>
<thead>
<tr>
<th>PVD-CVD</th>
<th>EB-PVD</th>
<th>APS*</th>
<th>FurnaceLaser/CVD/PVD</th>
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<tr>
<td>YSi</td>
<td>YbGdYSi</td>
<td>GdYSi</td>
<td>HfO2-Si; REHfSi YSi+RESilicate</td>
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<tr>
<td>ZrSi+Y</td>
<td>YbGdYSi</td>
<td>GdYSi</td>
<td>YSi+Hf-RESilicate</td>
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<tr>
<td>ZrSi+Y</td>
<td>YbGdYSi</td>
<td>GdYSi</td>
<td>REHfSi</td>
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<tr>
<td>ZrSi+Ta</td>
<td>YbGdYSi</td>
<td>GdYSi-X</td>
<td></td>
</tr>
<tr>
<td>HfSi + Si</td>
<td>YbGdSi</td>
<td>GdYSi-X</td>
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<tr>
<td>HfSi + YSi</td>
<td>YbGdSi</td>
<td></td>
<td>Hf-RESilicate Used in ERA components as part of bond coat system</td>
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<tr>
<td>HfSi+Ysi+Si</td>
<td>YbGdSi</td>
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<td></td>
</tr>
<tr>
<td>YbSi</td>
<td>YbGdSi</td>
<td></td>
<td>Hf-RE-Al Silicate Used also in ERA components as part of bond coat system</td>
</tr>
<tr>
<td>HfSi + YbSi</td>
<td>YbSi</td>
<td></td>
<td></td>
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<tr>
<td>GdYbSi(Hf)</td>
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<tr>
<td>YYbGdSi(Hf)</td>
<td>YbYSi</td>
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<td>APS*: or plasma spray related processing methods</td>
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<td>YbHfSi</td>
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<td>YbHfSi</td>
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<tr>
<td>YbSi</td>
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</table>

- Process and composition transitions

- Used in ERA components as part of bond coat system
- Used also in ERA components as part of bond coat system
- APS*: or plasma spray related processing methods
NASA EBC Bond Coats for Airfoil and Combustor EBCs

Continued

- 1500°C (2700°F) capable RESiO+X(Ta, Al, Hf, Zr …) EBC bond coat compositions and related composite coatings developed for combustor and turbine airfoil applications
- The bond coat systems demonstrated durability in the laser high heat flux rig in air and steam thermal gradient cyclic testing
- The bond coatings also tested in thermal gradient mechanical fatigue and creep rupture conditions

Processed Subelement

Steam heat flux test rig of the bond coat

Selected Composition Design of Experiment Furnace Cyclic Test Series 1500°C, in air, Demonstrated 500hr durability

Laser high heat flux cyclic rig tested Zr/Hf-RE-Si series EBC bond coats on the bond coated woven SiC/SiC CMCs at 1450°C in air and full steam environments
Furnace Cycle Test Results of Selected RESi and ZrSi + Dopant Bond Coats
- Testing in Air at 1500°C, 1 hr cycles

- Multi-component systems showed excellent furnace cyclic durability at 1500°C
Advanced Bond Coats for Turbine Airfoil and Combustor
EBCs Developed - Continued

- 1500°C (2700°F) capable RESiO+X(Ta, Al, Hf, Zr …) EBC bond coat compositions and related composite coatings developed for combustor and turbine airfoil applications
- Oxidation kinetics studied using TGA in flowing O₂
- Parabolic or pseudo-parabolic oxidation behavior observed

An oxidized bond coat after 1500°C 100 h creep testing
Advanced EBC developments – Some Hybrid APS-PVD Systems and Qualification Tests

• EB-PVD HfO$_2$-RE$_2$O$_2$ (Silicate) top coat EBC with plasma-spayed multi-component advanced silicate sublayer EBC/HfO$_2$-Si bond coat systems
• Low thermal conductivity ranging 1.0 - 1.7 W/m-K
• Demonstrated high pressure environmental stability at 2600-2650°F, 12-20 atm in the high pressure burner rig

2” diameter ND3 EBC/SiC/SiC specimen after testing in the high pressure burner rig
At 2600°F

High pressure burner rig tested new ND series Hybrid EBC systems coated on 2” diameter Gen II Prepreg SiC/SiC CMCs
Understanding High Velocity Gas Flow Interactions – Columnar Structure and Toughness Considerations

- High velocity, high pressure gas impingements and shear force induced erosion in turbine engine flow condition can be of concern for low toughness coating systems.
- High toughness, optimum coating density and architectures are required for durability.

If the coating is formed from columnar structures:

\[
\tau = \frac{F}{A} = C_D \left( \frac{1}{2} \rho V^2 \right)
\]

\[
F \quad \text{Shear Force}
\]

\[
A \quad \text{area}
\]

\[
C_D \quad \text{drag coefficient}
\]

\[
\rho \quad \text{density}
\]

\[
V \quad \text{velocity}
\]

For Ideal Gas:

\[
\rho = \frac{P}{R T}
\]

\[
\tau = C_D \left( \frac{1}{2} \frac{P V^2}{R T} \right)
\]

Modeled parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
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<td>Drag Coefficient</td>
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<tr>
<td>Pressure</td>
<td>750, psi</td>
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<td></td>
<td>5171068 Pa</td>
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<tr>
<td>Velocity</td>
<td>1200 m/sec</td>
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<tr>
<td>Temperature</td>
<td>3000, F</td>
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<tr>
<td></td>
<td>1921.039 K</td>
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<tr>
<td>Gas Constant</td>
<td>461.5 J/Kg/K</td>
</tr>
<tr>
<td>Column Height</td>
<td>0.0002 m</td>
</tr>
<tr>
<td>Column Radius</td>
<td>0.00001 m</td>
</tr>
<tr>
<td>Stress</td>
<td>1.34E+08 Pa</td>
</tr>
</tbody>
</table>
Thermal Gradient Tensile Creep Rupture Testing of Advanced Turbine Environmental Barrier Coating SiC/SiC CMCs

- Advanced high stability multi-component hafnia-rare earth silicate based turbine environmental barrier coatings being successfully tested for 1000 hr creep rupture
- EBC-CMC creep, fatigue and environmental interaction is being emphasized

![EBC coated tensile specimen](image1)

![Laser beam delivery optic system](image2)

![Cooling shower head jets](image3)

![High temperature extensometer](image4)

![Test specimen](image5)

![Graph](image6)
Advanced environmental barrier coatings – Prepreg CMC systems demonstrated long-term EBC-CMC system creep rupture capability at stress level up to 20 ksi at $T_{\text{EBC}}$ 2700°F, $T_{\text{CMC}}$ interface ~2500°F

- The HfO$_2$-Si bond coat showed excellent durability

EBCs on Gen II CMC after 1000 hr fatigue testing  

Hybrid EBCs on Gen II CMC after 100 hr low cycle creep fatigue testing
Fatigue Tests of Advanced RESi Bond Coats and EBC Systems

- Uncoated CMCs, Bond coat/CMC and EBC/Bond Coat/CMC systems tested flexural fatigue tests with 15 Ksi loading
- Heating provided by steady-state laser
- Strength and Fatigue cycles tested
- Fatigue tests at 3 Hz, 2600-2700°F, stress ratio 0.05, surface tension-tension cycles

Achieved long-term fatigue lives (near 500 hr) with EBC at 2700°F
Thermal Gradient Fatigue-Creep Testing of Advanced Turbine Environmental Barrier Coating SiC/SiC CMCs - Continued

- Effects of temperature, load, heat flux and environments (steam and combustion air) for coated SiC/SiC CMC are being investigated

- EBC coated CMCs showed improved durability

- Effects of temperature, load, heat flux and environments (steam and combustion air) for coated SiC/SiC CMC are being investigated.

- EBC coated CMCs showed improved durability.

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![Graph showing creep rates and stress levels for different CMC samples.](image-url)
Advanced HfO$_2$-Si Bond Coats: Effects of Compositions on Strength and Creep Rates

- The HfO$_2$-Si composite coatings showed high strength, and improved creep resistance at high temperatures.
- Increased HfO$_2$-HfSiO$_4$ contents improve high temperature strength and creep resistance.
EBC-CMC Thermal Gradient Creep Rupture and Delamination Modeling

- An equivalent stress model is established for EBC multicrack stress intensity modeling: emphasize creep, thermal gradient and stress rupture interactions
- Benchmark failure modes established in EBC systems

Stress gradients in Prepreg SiC/SiC CMC substrates under thermal gradient + mechanical creep loading
EBC-CMC Thermal Gradient Creep Rupture and Delamination Modeling - Continued

- An equivalent stress model is established for EBC multicrack stress intensity modeling: emphasize creep, thermal gradient and stress rupture interactions
- Benchmark failure modes established in EBC systems

Finite Element Analysis (FEA) Modeling
EBC-CMC Thermal Gradient Creep Rupture and Delamination Modeling – Bond Coat Stiffness Effect

- Delamination driving forces: uniform remote applied stress case, 0.300 mm thickness coating with ~ 0.06% total strain
- Effect of bond coat elastic modulus: $E = 150$ GPa vs. $E = 50$ GPa
- Strong bond coats expected to have less creep damage (lower strain energy release rate $G$ for strong bond coats)

Solid Lines-strong bond coat
$E = 150$ GPa EBC
$E = 150$ GPa bond coat

Dashed Lines: Soft bond coat
$E = 150$ GPa
$E = 50$ GPa
EBC-CMC Thermal Gradient Creep Rupture and Delamination Modeling – Bond Coat Stiffness Effect

- Advanced EBCs designed with higher strength and stiffness to improve creep, fatigue, and cyclic durability.
The Advanced EBC on SiC/SiC CMC Turbine Airfoils Successfully Tested for Rig Durability in NASA High Pressure Burner Rig

- NASA advanced EBC coated turbine vane subcomponents tested in rig simulated engine environments (up to 240 m/s gas velocity, 10 atm), reaching TRL of 5
- Turbine EBCs generally intact (some minor partial coating top coat spalling for the Prepreg MI SiC/SiC vane)
- Some minor CMC vane degradations after the testing

EBC Coated CVI SiC/SiC vane after 31 hour testing at 2500°F+ coating temperature
EBC Coated Prepreg SiC/SiC vane after 21 hour testing at 2500°F
EBC Coated Prepreg SiC/SiC vane tested 75 hour testing at 2650°F
The EBC Coated SiC/SiC CMC Combustor Liner Successfully Demonstrated for Rig Durability in NASA High Pressure Burner Rig (First Inner Liner Processed at Sulzer with Triplex Pro)

- Tested pressures at 500 psi external for outliner, and up to 220 psi inner liners in the combustion chamber (16 atm), accumulated 250 hours in the high pressure burner rig
- Average gas temperatures at 3000°F (1650°C) based on CEA calculations, the liner EBCs tested at 2500°F (1371°C) with heat fluxes 20-35 W/cm², and the CMC liner component at 1800-2100°F (~1000-1100°C)

![Graph showing ideal flame temperature calculation]

- Hot streaks with possible gas temperature over 2000°C, with minimum back cooling

![Image of swirl jet flows]

![Image of some minor coating spalling at hot streak impingement]
Summary

• **Durable EBCs are critical to emerging SiC/SiC CMC component technologies**
  — The EBC development built on a solid foundation from past experience, evolved with the current state of the art compositions of higher temperature capabilities and stabilities
    — Multicomponent EBC oxide/silicates
    — RE-Si bond coat
  
  — Advanced EBC processing and testing capabilities significantly improved, helping more advanced coatings to be realized for complex turbine components
  
  — Better understood the coating failure mechanisms, and helping developing coating property databases and life models, aiming at developing higher stability, higher strength EBC and bond coats
  
  — Emphasized thin coating turbine and combustor EBC coating configurations, demonstrated component EBC technologies in simulated engine environments – TRL 5
Future Directions and Opportunities

• High stability turbine airfoil and combustor coating system development continues to be a high priority
  – Advanced composition development, optimization, down-select a EBC coating System(s)
  – Reduce recession rates, improve the temperature stability and complex environment resistance, such as in CMAS environments
  – Low thermal conductivity

• Advanced environmental barrier coatings with significantly improved thermal and mechanical load capability
  – Emphasize coating strength and toughness
  – Better understand and improve creep, fatigue, and environment interactions
  – Design and demonstrate long-term high heat flux cyclic stability

• Materials and component system integration
  – Develop robust and economical processing capabilities
  – Optimize and validate coatings with more complex sub-elements and components

• Laboratory simulated high heat flux stress, environment testing and life prediction methodology development, validating model developments
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