The Development of 2700-3000°F Environmental Barrier Coatings for SiC/SiC Ceramic Matrix Composites: Challenges and Opportunities

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Outline

— Environmental barrier coating system development: needs and challenges

— Advanced environmental barrier coating systems for CMC airfoils and combustors
  • NASA coating development goals
  • Current turbine and combustor EBC coating development emphases

— Development of next generation environmental barrier coatings
  • Advanced processing
  • Subelement and subcomponent demonstrations

— Summary and Emerging Opportunities
**NASA EBC and CMC System Development**

- Emphasize temperature capability, performance and *long-term* 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) **thin** turbine and CMC combustor coatings  
  - Recession: <5 mg/cm² per 1000 h
- Highly loaded EBC-CMCs capable of thermal and mechanical (static/low cycle and dynamic) loading  
  - (Strength requirements: 15-30 ksi, or 100-207 MPa)

**Temperature Capability**

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

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- **Increase in ΔT across T/EBC**
- **2700°F (1482°C)** Gen III SiC/SiC CMCs
- **2400°F (1316°C)** Gen I and Gen II SiC/SiC CMCs
- **2000°F (1093°C)**

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- 3000°F SiC/SiC CMC airfoil and combustor technologies
- 2700°F SiC/SiC thin turbine EBC systems for CMC airfoils
Environmental Barrier Coating Development: Challenges and Limitations

— Current EBCs limited in their temperature capability, water vapor stability and long-term durability, especially for advanced high pressure, high bypass turbine engines

— Advanced EBCs also require higher strength and toughness
  • In particular, resistance to combined high-heat-flux, engine high pressure, combustion environment, creep-fatigue, loading interactions

— EBCs need improved erosion, impact and calcium-magnesium-alumino-silicate (CMAS) resistance and interface stability
  • Critical to reduce the EBC Si/SiO₂ reactivity and their concentration tolerance

— EBC-CMC systems need advanced processing for realizing complex coating compositions, architectures and thin turbine configurations for next generation high performance engines
  • Advanced high temperature processing of high stability nano-composites using advanced Plasma Spray, Plasma Spray - Physical Vapor Deposition, EB-PVD and Directed Vapor EB-PVD, and Polymer Derived Coating processing
Environmental Barrier Coating Development: Challenges and Limitations

Interface reactions at 1300°C

TEBC with BSAS-Si bond coat systems evaluated in laser high heat flux rig
• Fundamental studies of environmental barrier coating materials and coating systems, stability, temperature limits and failure mechanisms
• Focus on high performance and high technology readiness level (TRL), high stability HfO$_2$ and ZrO$_2$ -RE$_2$O$_3$-SiO$_2$/RE$_2$Si$_{2-x}$O$_{7-2x}$ environmental barrier systems
  • Controlled silica content and transition element and rare earth dopants to improve EBC stability and toughness
  • Develop HfO$_2$-Si based + X (dopants) and more advanced bond coat systems for 2700°F+ long term applications
  • Develop prime-reliant Rare Earth-Si alloys and composites for integrated EBC-bond coat systems
• Processing optimization for improved coating density and composition control robustness
• Develop advanced NASA high toughness, Alternating Composition Layered Coating (ACLC) compositions and processing for low RE t’ low rare earth dopant low k HfO$_2$ and higher rare earth dopant silicates
  - Achieving high toughness has been one of key emphases for NASA coating technologies
  - Achieving high stability and recession resistance
  - Improve the resistance to CMAS and Volcano ash deposits
Coating Safe Design Approach

Thermal expansion mismatch or thermal gradient

CMC/Bond coat → EBC → TBC (optional)
Advanced EBC System Strength Evaluations

- Evaluate and develop high strength and high toughness EBC materials
- Provide property database for design and modeling

- Graph showing temperature vs. flexural strength for various materials:
  - HfO2-Si
  - t' HfO2
  - HfO2+10wt%Yb2SiOx
  - HfO2+80wt%Yb2SiOx
  - Zr-RE-Si-O
  - HfO2
  - Y2Si2O7
  - Yb2Si2O5
  - RE Silicate
  - Hf-RE-Si-O
Advanced EBC System Recession and Stability Evaluations

— Determining optimum compositions of in a high stability system consisting of (e.g., Yb,Gd,Y+Hf/Zr) silicates and oxide systems

Turbine EBCs: High pressure burner rig, at 10 atm, 2650°F
SiC/SiC and Environmental Barrier Coating Recession in Turbine Environments

- **Recession of Si-based Ceramics**
  (a) convective; (b) convective with film-cooling
- **Advanced rig testing and modeling** (coupled with 3-D CFD analysis) to understand the recession behavior in High Pressure Burner Rig
  - Work primarily supported under the ERA Combustor and FAP Supersonics projects

Recession rate = \( \text{const.} \cdot V^{1/2} \frac{P_{(H_2O)}^2}{(P_{\text{total}})^{1/2}} \)

\[ \text{Combustion gas} \]

\[ \text{Combustion gas} \]

\[ \text{Cooling gas} \]

\[ \text{Cooling gas} \]

\[ \text{SiO}_2 + 2\text{H}_2\text{O}(g) = \text{Si(OH)}_4(g) \]
Recession of Film-Cooled SiC/SiC Specimens

— Potentially improve EBC-CMC stability in combustion environments

The CFD modeling of a film cooled CMC 10 hole subelement, and water vapor fractions in a cross-section view

Zygo surface contour

High temperature recession kinetics for film-cooled and non-film cooled SiC/SiC specimens tested at NASA High Pressure Burner rig.
Recession of EBCs in Laboratory Rig Tests

EBC recession kinetics testing for CMCs-EBCs in NASA High Pressure Bruner Rig and Laser Steam High Heat Flux Rig Testing

Examples of environmental barrier coating recession in laboratory simulated turbine engine conditions
Plasma Spray - Physical Vapor Deposition (PS-PVD) for SiC-SiC CMC Airfoil Coating Processing

Emerging processing methods developed by Sulzer Metco showing promise for next-generation SiC/SiC CMC turbine airfoil coating processing

NASA Hybrid PS-PVD coater system

Vapor NASA low k ZrO$_2$-Y$_2$O$_3$ coating

Splat/partial vapor Yb$_2$Si$_2$O$_7$/Yb$_2$SiO$_5$
Development of Directed Vapor Electron Beam - Physical Vapor Deposition (EB-PVD) Airfoil Environmental Barrier Coating Processing under NASA Programs

— Advanced coatings processed for higher TRL ERA combustor and turbine component EBCs (TRL 4-5) In collaboration with Directed Vapor Technologies
Advanced EBC Bond Coats for Turbine Airfoil and Combustor

EBCs Developed

- 1500°C (2700°F) capable NASA RESi+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

High heat flux cyclic rig tested Zr/Hf-RE-Si series EBC bond coats on the bond coated woven SiC/SiC CMCs at up to 1500°C in air and full steam environments
Effect of CMAS Reactions on Grain Boundary Phases

- CMAS Related EBC Degradations
- Grain boundary low melting phases
  - Eutectic region with a high Al₂O₃ content ~1200°C melting point
  - Loss of SiO₂ due to volatility

NASA modified CMAS

Grain boundary final phase – low SiO₂ and high Alumina

200 hr, 1500°C
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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| YSi     | YbGdYSi| GdYSi| HfO2-Si; REHfSi
| ZrSi+Y  | YbGdYSi| GdYSi| YSi+RESilicate
| ZrSi+Y  | YbGdYSi| GdYSi| YSi+Hf-RESilicate
| ZrSi+Ta | YbGdYSi| GdYSi| REHfSi
| ZrSi+Ta | YbGdSi  | GdYSi-X| Used in ERA components as part of bond coat system
| HfSi + Si | YbGdSi | GdYSi-X| Process and composition transitions
| HfSi + YSi | YbGdSi | Hf-RESilicate | Used also in ERA components as part of bond coat system
| HfSi+YSi+Si | YbGdSi | Hf-RE-Al-Silicate | APS*: or plasma spray related processing methods
| YbSi    | YbGdSi | Hf-RE-Al-Silicate | Used in ERA components as part of bond coat system
| YbYSi   | YbHfSi | YSi+RESilicate |
| GdYbSi(Hf)| YbHfSi | YSi+Hf-RESilicate |
| YYbGdSi(Hf)| YbHfSi | YSi+RESilicate |
|         | YbHfSi | YSi+Hf-RESilicate |
|         | YbHfSi | YSi+Hf-RESilicate |
|         | YbHfSi | YSi+Hf-RESilicate |
|         | YbSi   | YSi+RESilicate |
Oxidation Resistance of Doped Rare Earth Silicide - Effect of Stoichiometry (oxidation vs. atomic percent Si)

- Thermogravimetric analysis (TGA) in dry O₂ at 1500°C, using SiC/SiC CVI CMC substrate
- Excellent oxidation resistance with composition optimizations
- “Protective” scale of rare earth di-silicate formed (10-15 micrometers)

Multicomponent doped RE Silicide system after 100 hr exposure at 1500°C in O₂

Transition region between Si-rich and silicate regions

Oxidation rate constant vs. Si content

Silicon composition, at%  Kp, mg/cm²/sec

0.0000  0.0002  0.0004  0.0006  0.0008  0.0010  0.0012

0.0000  0.0002  0.0004  0.0006  0.0008  0.0010  0.0012

1500°C
High Stability Rare Earth Silicon Bond Coat with High Melting Point Coating Compositions: Designed with Improved Temperature Capability and CMAS Resistance

- Furnace cyclic or high heat flux test life evaluated at 1500°C up to 1000 hours

An Yb-Gd 2700°F EBC bond coat showed 500hr cyclic durability

FCT life of NASA RE-Si (O) series coatings
Thermal Gradient Tensile Creep Rupture Testing of Advanced 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 fatigue and environmental interaction currently being emphasized
Thermal Gradient Tensile Creep Rupture Testing of Advanced Environmental Barrier Coating SiC/SiC CMCs

- Controlling CMAS wetting, viscosity, stability and melting points
- Providing better EBC protections for CMCs in CMAS environments
- EBC durability initially validated under long-term CMAS-mechanical loading

400 hr, 69 Mpa creep rupture at EBC surface temperature 1400°C

202 hr, 69 MPa creep rupture at EBC surface temperature 1540°C EBC, 1650°C+; CMC failure
Creep-Fatigue of EBCs-CMCs in Complex Heat Flux and Simulated Engine Environments

- Long-term creep and fatigue used to validate EBCs at various loading levels
- Demonstrated 2700°F EBC and bond coat capability in complex environments

Fracture surface; 200+ hr at 2700°F+ (1482°C) creep rupture testing with CMAS; Advanced EBC protected CMCs

Advanced Bond Coat on CMC – intact after fatigue test with 15 ksi load and 2600-2700°F surface temperature for 460 hot hours

Stress-oxidation and stress-CMAS environmental testing
Advanced Rig Tests for SiC/SiC CMC EBC Demonstrations

- Advanced EBC coated turbine airfoils and subelements demonstrated in high pressure burner rig and high heat flux laser rig simulated engine environments

Vane leading edge seen from viewport in High Pressure Burner Rig Testing

50 hr EBC-CMC vane laser rig testing

50 hr EBC-2.5D CMC Sub-element demo in HPBR

NASA EBC coated turbine airfoils and testing
The Advanced EBC on SiC/SiC CMC Turbine Components Successfully Tested for Rig Durability in NASA High Pressure Burner Rig

- NASA advanced EBC coated turbine vane subcomponents tested in the NASA High Pressure Burner Rig simulated engine environments (up to 240 m/s gas velocity, 10 atm), reaching TRL of 5
- Combustor EBC-CMC also demonstrated

Uncoated vane tested 15 hr

EBC coated SiC/SiC CMC inner and outer liner components

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
Summary

- **Advanced high temperature SiC/SiC CMC environmental barrier coatings development**
  - Developed new compositions for meeting current coating and component performance requirements
  - Emphasized advanced thinner coating configurations with long-term stability and durability
  - Demonstrated higher temperature capability, improved environmental stability and coating thermal - mechanical stress and creep-rupture resistance
  - Focused on coating composition developments and architecture designs to improve stability and durability at 2700-3000°F

- **Advanced high temperature SiC/SiC CMC environmental barrier coatings Testing Developments**
  - Developed advanced coating and subelement testing methods relevant to turbine CMC combustors and vanes, establishing initial property database, degradation and lifing prediction models
  - Developed advanced combustor and turbine vane EBC component technologies, and demonstrating the full feature EBC - CMC sub-components in relevant rig simulated engine environments
Advanced Environment Barrier Coating Material System Development - Emerging Opportunities

— High stability, low expansion top coat development
  • Advanced high stability nano-phase composite designs
  • Rare earth dopants and silica clusters for improved thermal stability
  • Transition metal dopants for phase stability and temperature capability of EBCs
  • Reducing interface reactions – self-forming diffusion and reaction barriers
  • Minimizing grain boundary Si segregation, SiO\(_2\) phase formation, and low melting phase formation
  • Implementing new architecture PVD composite columnar structures to achieve high stability, high strength, low expansion, low conductivity and high erosion resistance
  • Thin coating configurations emphasized for both turbine CMC airfoil and advanced combustor applications
  • Advanced non-line-of-sight hybrid, high efficiency PVD and CVD processing for economical airfoils inner and outer surfaces, cooling holes with high coat EBC compositions
  • High adhesion and intergraded EBC/CMC interfaces

— Low stress, strain tolerant interlayer and high strength bond coats
  • Thin, nano-layered layered high toughness coatings with minimum thickness
  • Novel compositional and architectural designs to achieve maximum energy dissipation and durability
  • High strength and high toughness, combined with optimized strain tolerance for superior erosion and impact resistance

— Environmental barrier and high strength bond coats
  • Low expansion, high stability, low diffusivity, high strength and strain tolerance to allow a few micron thick coating designs
  • Self repairing and/or self-growing of slow growth adherent protective coatings, i.e., Design of alloys, intermetallic and composites capable of self growing EBCs needed

— Multifunctional compositions for high temperature sensing, health monitoring, and reduced heat transfer
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