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

Dongming Zhu

Structures and Materials Division
NASA John H. Glenn Research Center
Cleveland, Ohio 44135

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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
National Aeronautics and Space Administration

**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)

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### Temperature Capability

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

**Increase in ΔT across T/EBC**

- **2700°F (1482°C)** Gen III SiC/SiC CMCs
- **3000°F+ (1650°C+)** 3000°F SiC/SiC CMC airfoil and combustor technologies

**2700°F (1482°C) CMCs**

**2400°F (1316°C) Gen I and Gen II SiC/SiC CMCs**

**2000°F (1093°C)**

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- **Gen I**
- **Gen II** – Current commercial
- **Gen II**
- **Gen III**
- **Gen IV**

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*Step increase in the material’s temperature capability*
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/SiO$_2$ 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

TEBC with BSAS-Si bond coat systems evaluated in laser high heat flux rig
NASA Environmental Barrier Coating Technology Development - Continued

• 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 HfO₂ and ZrO₂ -RE₂O₃-SiO₂/RE₂Si₂-xO₇-2x environmental barrier systems
  • Controlled silica content and transition element and rare earth dopants to improve EBC stability and toughness
  • Develop HfO₂-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 HfO₂ 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

Cracking and Delamination region

Safe region

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
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 = const. $V^{1/2} \frac{P_{(H_2O)}^2}{(P_{total})^{1/2}}$

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

Combustion gas

Cooling gas

(a) (b)
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

Non-film cooling recession at 2400°F (model extrapolated to 300m/s gas velocity)

Film cooled recession at 2400°F

Non-film cooling recession at 2100°F

Film cooled recession at 2100°F

Recession rate, mg/cm²-hr

300 m/s, 16 atm

High temperature recession kinetics for film-cooled and non-film cooled SiC/SiC specimens tested at NASA High Pressure Burner rig

Zygo surface contour
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

(c) High heat flux and high steam rig
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 multi-component and multilayer turbine EBC systems

NASA HfO$_2$-Si bond coat on SiC/SiC

NASA Hybrid EBC on SiC/SiC

Directed Vapor Processing Systems
**Advanced EBC Bond Coats for Turbine Airfoil and Combustor**

- 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

**Processed Subelement**

Steamed heat flux test rig of the bond coat

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

RESi-Hf, 100 hr
RESi+Al, 50 hr
RESi+Al, 50 hr

100% steam

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 $\text{Al}_2\text{O}_3$ content $\sim 1200^\circ \text{C}$ melting point
  - Loss of $\text{SiO}_2$ due to volatility

Fig. 4. The 10% MgO plane of the system CaO-MgO-Al$_2$O$_3$-$\text{SiO}_2$ showing the isotherms and fields of primary crystallization. A.T. Prince, J. Amer. Ceram. Soc., 37(9)1954 p402-408

200 hr, 1500°C

NASA modified CMAS

Grain boundary final phase – low $\text{SiO}_2$ and high Alumina
**Advanced 2700°F Based Bond Coats – System Processing for Various Process and Component Applications**

- 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

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**PVD-CVD**

**EB-PVD**

**APS*:** or plasma spray related processing methods

**FurnaceLaser/CVD/PVD**

- used in ERA components as part of bond coat system
- used also in ERA components as part of bond coat system
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)

Oxidation rate constant vs. Si content

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

Transition region between Si-rich and silicate regions
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

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

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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