Advanced Environmental Barrier Coating Development for SiC-SiC Ceramic Matrix Composite Components

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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

Fixed Wing Subsonic Aircraft  Supersonics Aircraft  Hybrid Electric Propulsion Aircraft
NASA Environmental Barrier Coating Development Goals

Emphasize temperature capability, performance and durability

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

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

Temperature Capability

- 2800°F combuster TBC
- 2500°F Turbine TBC
- 3000°F+ (1650°C+)

Increase in \(\Delta T\) across T/EBC

- 2700°F (1482°C) Gen III SiC/SiC CMC airfoil and combustor technologies
- 2700°F SiC/SiC thin turbine EBC systems for CMC airfoils
- 2400°F (1316°C) Gen I and Gen II SiC/SiC CMCs
- 2000°F (1093°C)

Step increase in the material’s temperature capability

Ceramic Matrix Composite

Single Crystal Superalloy

Gen I – Current commercial

Gen II – Current commercial

Gen III

Gen. IV

Year
Outline

— Advanced EBC systems development for CMC airfoils and combustors
  • Prime-reliant EBCs for CMCs: a turbine engine design requirement
  • Fundamental recession of SiC/SiC
  • Thermomechanical, environment and thermochemical stability design considerations
  • Advanced EBC processing, testing and durability
  • NASA 2700-3000°F (1482-1650°C) EBC material systems
  • Current turbine and combustor EBC coating emphases – coating configurations

— Environmental barrier coating system development
  • NASA 2700°F EBC technologies

— Design tool and life prediction perspectives of EBC coated CMC components

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

- Recession of Si-based Ceramics
  (a) Convective; (b) Convective with film-cooling
  - High temperature Capable and Low SiO₂ activity EBC system development

- Advanced rig testing and modeling
  More complex recession behavior of CMC and EBCs in test rigs simulated combustion flow and pressure conditions

Recession rate = \text{const.} \ \sqrt[2]{V} \dfrac{P_{(H₂O)}^{2}}{(P_{\text{total}})}^{\frac{1}{2}}

\text{Combustion gas}

\text{SiO₂} + 2\text{H₂O}(g) = \text{Si(OH)}₄(g)

...
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 environments
- Focused on 2700-3000°F EBCs
- More stable turbine coatings developed under NASA programs for advanced engine applications

Stability and temperature capability improvements through coating composition and architecture innovations

First generation EBC: CMC/Si/Mullite/BSAS
Advanced EBC Developments

• Fundamental studies of environmental barrier coating materials and coating systems, stability, temperature limits and failure mechanisms

• Focus on high performance, high stability HfO$_2$ - and ZrO$_2$-RE$_2$O$_3$-SiO$_2$/RE$_2$Si$_{2-x}$O$_{7-2x}$ environmental barrier systems
  • More advanced, multicomponent composition and composite EBC systems to improve the temperature capability, strength and toughness
  • Develop HfO$_2$-Si based + X (dopants) bond coat systems for 2700°F (1482°C) long-term applications
  • Develop prime-reliant 2700°F+ (1482°C) Rare Earth (RE)-Si + X (dopants) bond coat systems for advanced integrated EBC-CMC systems, improving bond coat temperature capability and durability

• Processing optimizations for improved composition control and process robustness
Advanced EBC Developments – Development Timelines

— Major development milestones:

• 1995-2000: BSAS/Mullite+BSAS/Si
• 2000-2004: RE$_2$Si$_2$O$_7$ or RE$_2$SiO$_5$/BSAS+Mullite/Si
• 2000-2004 - 3000°F EBC systems:

  Low conductivity (HfO$_2$-RE$_2$O$_3$-X Dopants) EBCs / RE$_2$Si$_2$O$_7$ or RE$_2$SiO$_5$ and/or BSAS+Mullite/Si and Oxide + Si bond coats;
  – HfO$_2$-Si based bond coats developed to overcome low melting point Si bond coat issues
  – Along with ceramic component demonstrations in rigs
• 2005-2011 - Turbine coating systems:

  Multi-component, HfO$_2$-Rare Earth Oxide-SiO$_2$/ multi-component Rare Earth Silicate/ HfO$_2$-Si systems
  – RE-HfO$_2$-X/Multicomponent RE-silicate / HfO$_2$-Si +X (doped)
• 2009 - present: Improved EBC compositions and processing; advanced 2700F RE-Si bond coats
  – e.g., (Gd,Yb,Y)Si bond coats and top coats
EBC Processing using Plasma Spray and EB-PVD

Triplex Pro (Oerlikon Metco) Processing and Advanced NASA EBCs – combustor liner demos

Directed Vapor EB-PVD Processed Advanced EBCs – Turbine Vane Airfoil Demos

HfO$_2$-Si bond coat

EBC Coated SiC/SiC CMC Inner and Outer Liner Demo

EBC coated SiC/SiC CMC Vane Airfoils Demo
Plasma Sprayed-Physical Vapor Deposition (PS-PVD) Processing of Environmental Barrier Coatings

— NASA PS-PVD and PS-TF coating processing using Sulzer (Oerlikon) newly developed technology

• High flexibility coating processing – PVD - splat coating processing at lo pressure (at ~1 torr)
• High velocity vapor, non line-of-sight coating processing potentially suitable for complex-shape components
• Significant progress made in processing the advanced EBC and bond coats

100 kW power, 1 torr operation pressure

HfO$_2$-Si bond coat

NASA PS-PVD Coater System

Processed coating systems
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>
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<th>EB-PVD</th>
<th>APS*</th>
<th>FurnaceLaser/CVD/PVD</th>
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Process and composition transitions

- APS*: or plasma spray related processing methods

Used in ERA components as part of bond coat system

Used also in ERA components as part of bond coat system

- FurnaceLaser/CVD/PVD process and composition transitions
Furnace Cycle and Oxidation Test Results of Selected RESi and ZrSi Based Bond Coats

- Testing in Air at 1500°C, 1 hr cycles

- Multi-component RESiO+X series 2700°F+ EBC bond coat compositions and processing developed

- The 2700°F+ EBC bond coat systems showed promise for furnace cyclic durability and oxidation resistance at 1500°C tests

- Completed initial composition down-selects

An oxidation tested bond coat EBC specimen after 1500°C 100 h testing
Laser Rig Thermomechanical Creep - Fatigue Tests of Advanced 2700°F+ RESi Bond Coats and EBC Systems

- APS, PVD and EB-PVD processed 2700°F bond coats and EBCs on SiC/SiC CMC: focus on creep, fatigue high heat flux testing at temperatures of 1316-1482°C+ (2400-2700°F+) – Selected Examples

EB-PVD Rare Earth Silicate EBC/YbGdYSi bond coat on Hyper Therm CVI-MI

- \( T_{EBC\, surface} = 2850-3000°F \) (1600-1650°C)
- \( T_{cmc\, back} \approx 2600°F \) (1426°C)

Creep and Fatigue Tests with CMAS

Air Plasma Sprayed YSi+Hf-RESilicate EBC Bond Coat series on CVI-MI SiC/SiC 1400°C, at 10 ksi, 400 h

EB-PVD (Hf,Yb,Gd,Yb)\(_2\)Si\(_2\)O\(_7\)-x EBC/GdYbSi bond coat on Rolls Royce CVI-MI SiC/SiC (with CMAS) 1537°C, 10ksi, 300 h fatigue (3 Hz, R=0.05)

Fatigue Tested

- PVD GdYSi coated on Hyper Them CVI-MI SiC/SiC 1316°C, 10ksi, 1000 h fatigue (3 Hz, R=0.05)
- PVD GdYbYSi coated on GE Prepreg SiC/SiC 1316°C, 15ksi, 1169 h fatigue (3 Hz, R=0.05)
- NASA 2700°F(1482°C)+ EBC System 188 on SA Tyrannohex SiC Composite, 1482°C 15 ksi, 500hr
High Stability and CMAS Resistance Demonstrated by Advanced High Melting Point Coating, and Multi-Component Compositions

- Demonstrated Calcium-Magnesium-Alumino-Silicate (CMAS) resistance for NASA RESi system at 1500°C, 100 hr
- Silica-rich phase precipitation
- Still some rare earth elements leaching into the melts (low concentration ~9 mol%)
The Advanced EBCs 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

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

Uncoated vane tested 15 hr

EBC Coated Rig Inner and outer liner testing 2500°F, completed 250 h

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

Swirl jet flows
Thermal Gradient Fatigue-Creep Testing of Advanced Turbine Environmental Barrier Coating SiC/SiC CMCs

- Advanced environmental barrier coatings – Prepreg CMC systems demonstrated long-term EBC-CMC system creep rupture capability at stress level up to 20 ksi at $T_{EBC} = 2700^\circ F$, $T_{CMC \text{ interface}} \approx 2500^\circ F$
- The HfO$_2$-Si based bond coat showed excellent durability in the long term creep tests

Hybrid EBCs on Gen II CMC after 1000 h low cycle creep fatigue testing

FEM modeling of EBC-CMC creep and thermal gradient and stress rupture interactions

Advanced EBC coated CMC subelement testing and modeling

EBC-CMC vane laser rig testing

EBC-2.5D CMC Sub-element demo in HPBR

FEM modeling of EBC-CMC vane trailing edge rig test failure
Summary and Future Directions

- **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 with higher stabilities
    - Improved strength and toughness
    - HfO$_2$-Si and RE-Si bond coats for realizing prime-reliant 2700°F EBC-designs
  - EBC processing and testing capabilities significantly improved, more advanced compositions designed and realized for complex turbine components
  - Develop rig EBC-CMC subelement simulated tests, helping develop coating property databases and validated life models, aiming at more robust EBC-CMC designs
  - Emphasized turbine airfoil EBC developments, demonstrated component EBC technologies in simulated engine environments of TRL 5, further maturing advanced coating technologies