ENVIRONMENTAL BARRIER COATINGS FOR TURBINE ENGINES: A DESIGN AND PERFORMANCE PERSPECTIVE

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Ceramic thermal and environmental barrier coatings (TEBC) for SiC-based ceramics will play an increasingly important role in future gas turbine engines because of their ability to effectively protect the engine components and further raise engine temperatures. However, the coating long-term durability remains a major concern with the ever-increasing temperature, strength and stability requirements in engine high heat-flux combustion environments, especially for highly-loaded rotating turbine components. Advanced TEBC systems, including nano-composite based HfO$_2$-alumino-silicate and rare earth silicate coatings are being developed and tested for higher temperature capable SiC/SiC ceramic matrix composite (CMC) turbine blade applications. This paper will emphasize coating composite and multilayer design approach and the resulting performance and durability in simulated engine high heat-flux, high stress and high pressure combustion environments. The advances in the environmental barrier coating development showed promise for future rotating CMC blade applications.
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Revolutionary Ceramic Coatings Greatly Impact Turbine Engine Technology

— Ceramic barrier coatings can significantly increase gas temperatures, reduce cooling requirements, improve engine fuel efficiency and reliability.

(a) Current T/EBCs (b) Advanced T/EBCs

CMC combustor liner and vane

>300°F increase
Revolutionary Ceramic Coatings Greatly Impact Turbine Engine Technology

— Ceramic barrier coating system development goals
  - Meet next generation engine temperature, performance and durability requirements
  - Help fundamental scientific understanding, database and design tool development
  - Increase the coating Technology Readiness Levels (TRL)

![Diagram showing temperature capabilities and material improvements](attachment://diagram.png)

- Increase in $\Delta T$ across T/EBC
- 3000°F+ (1650°C+)
- 2700°F (1482°C)
- 2400°F (1316°C)
- 2000°F (1093°C)

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Gen I

Gen II – Current commercial

Gen III

Gen IV

Si$_3$N$_4$ and coating systems
Outline

— High-heat-flux and simulated engine test approaches for ceramic coating development

— The 2700°F thin turbine TEBC systems for SiC/SiC CMCs and Si₃N₄

— Coating durability and stability evaluations

— Summary and directions
High-Heat-Flux Testing Approach

- High-heat-flux tests crucial for the coating development
  - Temperature gradient requirements: 400-600°F across 5-10 mil coatings

Current capability up to 315 W/cm² for TBCs
High Pressure Burner Rig for Thermal and Environmental Barrier Coating Development

— Realistic engine combustion environments for specimen and component testing

![Test Section](image1)

![Combustor](image2)

High Pressure Burner rig (6 to 12 atm)

![Coated turbine vane test fixtures](image3)
High Pressure Burner Rig for Thermal and Environmental Barrier Coating Development

- High Velocity and High Pressure Burner Rig Testing
  - High velocity testing for ceramic specimens
  - Optimum heat flux regime determined
Multi-Functionally Graded Environmental Barrier Coatings for Si-based Ceramic Components

- Multifunctionally Graded Materials for SiC/SiC CMC and Si₃N₄ applications

  - High stability oxide composite layer with graded interlayer, environmental barrier and advanced bond coats
  - Alternating composition layered coatings (ACLCs) and nano-composite coatings

![Diagram showing the layers and components of the environmental barrier coatings system.](image)

- Low expansion, high strain tolerance HfO₂ & RE aluminosilicates
- Interlayer: Compositional layer graded system - composite
- Advanced EBCs bond coats
- SiC/SiC CMC or Si₃N₄
- Increased Si activity
- HfO₂ and HfO₂ composites
- Doped mullite/HfO₂ with ACLC (Hf rich bands)
- Increased dopant RE/Transition metal concentrations & increased Al/Si ratio
- Oxide and RE aluminiosilicate bond coats (High temperature capable with self-healing)
Environmental Barrier Coatings Processed on Complex-Shaped Specimens

- Thinner coating processing technologies developed for complex shaped components

Plasma-spray processing of Environmental barrier coatings for various components
Thin Turbine Blade CMC Coatings will be Pursued using Hybrid Plasma Vapor Deposition Technique

- **APS**
- **VPS/LPPS**
- **LPPS-Thin Film**

- **Standard APS**
  - Well established process for high quality functional coatings
  - Various gas-turbine, aero, medical and special applications
  - Pressure range typically 50 - 200 mbar

- **Standard LPPS**:
  - High flexibility of operation conditions
  - Pressure range down to 1 - 2 mbar
  - High enthalpy plasma stream (up to 180 kW)
  - Special applications in film thickness range of 5 - 200 μm
  - Use of fine powders and suited injection (modified nozzles)
  - Fast coverage on large surfaces with thin & dense layers
  - Capable for deposition from vapor phase
  - Non line-of-sight coating due to highly forced gas stream

Sulzer plasma vapor deposition
TEBCs Evaluated for Thermomechanical Fatigue (TMF) Resistance

- 10 Hz, R ratio ~0, maximum mechanical load 250 MPa (36ksi) at 2200°F
- Coating achieved excellent durability without failure after 250 hour testing
- The system durability is currently limited by the CMC TMF capability and variability

(a) Specimen testing
(b) Specimen failure
Max 250 CMC MPa@2200°F, cyclic; Failed at $5 \times 10^5$ cycles
Long-Term High Heat Flux Thermal Gradient Cyclic Testing of an Advanced TEBC Coating on SiC/SiC Ceramic Matrix Composite

- Coating successfully tested at Tsurface 2700°F and Tinterface 2400°F 250 hrs (1 hr hot hour cycles in air)

Thin coating turbine CMC demonstrated high-heat-flux cyclic durability at 2700°F
High Pressure Burner Rig Durability Evaluations

- High Pressure Burner Rig Stability being evaluated for TEBCs on SiC/SiC
- High stability coatings being down-selected

![Graph showing specific weight change vs. 1/T, K⁻¹ for different materials.](image)
Summary

- Advanced ceramic turbine component testing capabilities established
- Advanced thermal and environmental barrier coatings developed and processed on complex-shaped components
- Coating stability demonstrated in high velocity-high pressure burner rig simulated engine environments
- Coated CMC system low cycle fatigue durability demonstrated at 2700°F
- Coated CMC system TMF evaluated at 2200°F
- Heat transfer, fracture mechanics and stochastic approaches being established to develop coated CMC life prediction models
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