Performance and Durability of Environmental Barrier Coatings on SiC/SiC Ceramic Matrix Composites

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**NASA Turbine Environmental Barrier Coatings for CMC-EBC Systems**

- Emphasize temperature capability, performance and durability for next generation turbine engine systems
- Increase Technology Readiness Levels for component system demonstrations
Environmental Barrier Coating and SiC/SiC System Development: Testing Challenges

- High Temperatures: 2700 to 3000°F (1500-1650°C) along with higher interface temperatures
- Exposure to water vapor and combustion products
- High Cyclic Stresses: thermal and mechanical, creep-fatigue effect
- Combined Interactions, in-plane and through-thickness gradients
- High Velocity Gases: Mach 1 and 2
- High Pressures: ~ up to 40 to 50 atmospheres
- Long term durability: 20,000 hr design life
Outline

– Advanced testing approaches for SiC/SiC and ceramic coating development: laser high heat flux based testing approaches
  – NASA CO$_2$ laser rig development
  – Thermal conductivity
  – Cyclic durability and monitoring degradations of EBCs and CMCs

- Laser high heat flux and mechanical tests
  - Combined high heat flux - mechanical tests
  - High heat flux biaxial creep/fatigue test rigs
  - Sub-element testing

– Summary and future directions
High Power CO\textsubscript{2} Laser Based High Heat Flux Testing for SiC/SiC and Environmental Barrier Coatings Development

– Developed in 1990’s, the rig achieved turbine level high-heat-fluxes (315 W/cm\textsuperscript{2}) for turbine thermal barrier coating testing
– Crucial for advanced EBC-CMC developments

Turbine: 450°F across 100 microns
Combustor: 1250°F across 400 microns

Heat flux

Distance from surface

Cooling – high velocity air or air-water mist
Achieved heat transfer coefficient 0.3 W/cm\textsuperscript{2}-K

Test rig
High Power CO$_2$ Laser Based High Heat Flux Testing for SiC/SiC and Environmental Barrier Coatings Development - Continued

- NASA high power CO$_2$ laser rig systems
- Various test rigs developed
- 7.9 micron single wavelength and 1 micron two color wavelength pyrometers for temperature measurements
- Thermography system for temperature distribution measurements
- Capable of programmable test mission cycles
- Capable of mechanical load cycles under high heat flux
- Environment test conditions (e.g., steam and vacuum)
High Power CO\textsubscript{2} Laser Based High Heat Flux Testing for SiC/SiC and Environmental Barrier Coatings Development – Continued

– Controlled beam profiles, beam size and power density were major emphases, by using rotating ZnSe integrating lens with various focus lengths
– Uniform distribution up to 2-3” diameter beam size for various testing

Example of 1” diameter disc specimen tests and beam profile

2” beam size subelement tests
High Power CO$_2$ Laser Based High Heat Flux Fatigue Test Rig

- Laser creep and fatigue testing capable of full tension and compression loading
- Uniform distribution up to 2-3” diameter beam size for various testing, depending on the heat flux requirements

Laser heat flux Thermal HCF/LCF Rig – Overall View

Specimen under testing in tensile-compression fatigue rig
High Heat Flux Rig Testing with Water vapor Steam Chamber – Established in Early 2000

- High temperature and high-heat-flux testing capabilities
- “Micro-steam environment” allowing high water vapor pressure (100% steam), relatively high velocity under very high temperature condition
- Used for 3000°F EBC-CMC developments

- Steam injected at up to 5 m/sec
- Testing temperature >1700°C

CFD modeled steam velocity from the steam jets
High Heat Flux Thermomechanical Testing for EBC Development

- High heat flux and combined thermal-mechanical loading capabilities established to allow SiC/SiC system performance data to be obtained under simulated operating thermo-mechanical and environmental conditions.

High heat flux tensile TMF and rupture testing

High heat flux flexural TMF testing: HCF, LCF, interlaminar and biaxial strengths
Thermal Conductivity Measurement by a Laser High-Heat-Flux Approach

\[
k_{\text{ceramic}}(t) = \frac{q_{\text{thru}} \cdot l_{\text{ceramic}}}{\Delta T_{\text{ceramic}}(t)}
\]

and

\[
q_{\text{thru}} = q_{\text{delivered}} - q_{\text{reflected}} - q_{\text{radiated}} \quad \text{and} \quad \Delta T_{\text{ceramic}}(t) = T_{\text{ceramic-surface}} - T_{\text{metal-back}} - \int_{0}^{l_{\text{bond}}} q_{\text{thru}} \cdot dl \cdot k_{\text{bond}}(T) - \int_{0}^{l_{\text{substrate}}} q_{\text{thru}} \cdot dl \cdot k_{\text{substrate}}(T)
\]

Where

8 \(\mu\)m pyrometer for \(T_{\text{ceramic-surface}}\)

Two-color and 8 \(\mu\)m pyrometers for \(T_{\text{substrate-back}}\)

Optional miniature thermocouple for additional heat-flux calibration
Thermal Gradient Cyclic Behavior of a Thermal Environmental Barrier Coating System

- Sintering and delamination of coatings reflected by the apparent thermal conductivity changes

Cyclic Testing of 8YSZ/mullite/mullite+20wt%BSAS/Si on SiC/SiC:
- $T_{\text{surface}}$ 1482°C/$T_{\text{interface}}$ 1175°C

Steady-State Testing of 8YSZ on Rene N5 Superalloy:
- $T_{\text{surface}}$ 1371°C/$T_{\text{interface}}$ 1163°C
Environmental Barrier Coating and High Heat Flux Induced Delaminations

Evans and Hutchinson model, Surface Coating Technology, 2007

\[ G = \frac{1}{6} \left( \frac{1 + \nu_2}{1 - \nu_1} \right) E_{\perp} h \left( \alpha_{\parallel} (T_s - T) \right)^2 \]

The FEM model

Crack Extension Force $G$ as a function of time for 2.0mm half delamination length and crack depth of 0.08mm

Crack Extension Force $G$ as a function of time for 4mm delamination length and crack depth of 0.08mm

Crack extension driving force ($E \approx 50$GPa)

Crack extension driving force ($E \approx 200$GPa)

The FEM model

Mullite Mullite+BSAS Si

1467 °C

1315 °C

1066 °C

Temperature, °C

Evans and Hutchinson model, Surface Coating Technology, 2007
Thermal Gradient Cyclic Behavior of Air Plasma Sprayed Yb$_2$SiO$_5$ (with HfO$_2$ Composite)/Yb$_2$Si$_2$O$_7$/HfO$_2$-Si Coatings on SiC/SiC CMCs

- $T_{\text{surface}} \sim 1482$-$1500^\circ$C, $T_{\text{interface}} 1350^\circ$C, $T_{\text{back surface}} 1225^\circ$C, heat flux 110 W/cm$^2$
- Localized pore formation
Fatigue Testing using a Laser High-Heat-Flux Approach for Environmental Barrier Coated Prepreg SiC/SiC CMCs

- Environmental Barrier Coatings $\text{Yb}_2\text{SiO}_5/\text{Yb}_2\text{Si}_2\text{O}_7/\text{Si}$ on MI Prepreg SiC/SiC CMC substrates
- One specimen tested in air, air testing at 1316°C
- One specimen tested in steam, steam testing at $T_{\text{EBC}}$ 1316°C, $T_{\text{CMC}}$ at ~1200°C
- Lower CMC failure strain observed in steam test environments

Fatigue strains (amplitudes) – Time Plot

Thermal conductivity – Time Plot
Fatigue Testing using a Laser High-Heat-Flux Approach for EBC Coated Prepreg SiC/SiC CMCs - Continued

- Crack and recession failure in air and steam tests

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In Air: EBC cracking

In steam: EBC cracking and volatility

EDS 25D
EBC Coated CMC 2650°F (1454°C) Creep Rupture Durability Test

- SiC/SiC CMC SiC/SiC CVI-MI CMC specimen
- Coated with RESi and Rare Earth EBC
- Test temperatures: $T_{\text{EBC surface}}$ at 2850-3000°F (1600-1650°C), and $T_{\text{cmc back}}$ at ~2600°F (1426°C)

Creep rate $7.1 \times 10^{-6}$ 1/s
Advanced EBC-CMC Fatigue Test with CMAS: Tested 300 h Durability in High Heat Flux Fatigue Test Conditions

- A turbine EB-PVD turbine airfoil EBC system with advanced HfO$_2$-rare earth silicate and GdYbSi (controlled oxygen activity) bond coat tested at $T_{\text{EBC-surface}}$ 1537°C+, $T_{\text{bond coat}}$ 1480-1500°C, $T_{\text{back CMC surface}}$ 1250-1300°C
- Fatigue Stress amplitude 69 MPa, at mechanical fatigue frequency $f=3\text{Hz}$, stress ratio $R=0.05$
- Low cycle thermal gradient fatigue 60min hot, 3min cooling

1537°C, 69MPa (10ksi), 300 h fatigue (3 Hz, R=0.05) CVI-MI SiC/SiC (with pre-applied CMAS, 35mg/cm$^2$)

Fatigue strain-time plot

Strain amplitude

Fatigue temperature-time plot
Generally Observed EBC Test Failure with CMAS

- An alternating HfO$_2$-and RE-silicate coatings (EB-PVD processing) – HfO$_2$- layer infiltration and rare earth silicate layer melting

**EB-PVD Processed EBCs:** alternating HfO$_2$-rich and ytterbium silicate layer systems for CMAS and impact resistance
Advanced EBC-CMC Fatigue Test with CMAS and in Steam Jet: Tested 300 h Durability in High Heat Flux Fatigue Test Conditions

- Advanced Hf-NdYb silicate-NdYbSi bond coat EBC coatings on 3D architecture CVI-PIP SiC-SiC CMC (EB-PVD processing)
**SiC/SiC Turbine Airfoil Trailing Edge Tests**

- Subelement wedge testing, by applying trailing-edge element opening stresses for simulating high pressure turbine airfoil stress conditions, aiming at understanding the CMC and EBC degradation.
Summary and Future Plans

- **Advanced high heat flux creep rupture, fatigue rigs established for simulated turbine engine EBC-CMC testing**
  - High temperature comprehensive environment testing capability including heat flux, steam and CMAS, at very high temperature
  - Real time coating degradation monitoring and fatigue-creep stain monitoring
  - Testing capabilities incorporated into the advanced EBC-CMC developments
- **Long term creep rupture and fatigue behavior evaluated for Hafnium Rare Earth silicate and Rare Earth-Silicon based EBCs-CMCs at 1482°C+ (2700°F+)**
  - Crucial for advanced EBC-CMC development and validations
  - Advanced EBC coated 3D architecture SiC/SiC CMCs tested at 1500°C in steam and CMAS environments
  - Compared to baseline materials
- **The heat flux thermomechanical testing of subelements for the EBC-CMC subelement**
  - Important for durability and life modeling

Future plans

- **HCF high heat flux rig with additional environmental testing capabilities (steam-air mixture environments and controlled steam or vacuum capabilities)**
- **EBC erosion-impact capabilities also planned in combination of laser high heat flux, creep-fatigue, high velocity steam, and CMAS integrated tests**
- **Additional full field strain measurement experiments, in particular at high temperatures**
- **Planned a multi-axial testing rig for CMC and EBC testing**
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