Combined Thermomechanical and Environmental Durability of Environmental Barrier Coating Systems 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

<table>
<thead>
<tr>
<th>Gas</th>
<th>TBC Bond coat</th>
<th>Metal blade</th>
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<th>Metal blade</th>
<th>Gas</th>
<th>EBC Bond coat</th>
<th>CMC airfoil</th>
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<tr>
<td>2900°F (T41)</td>
<td>2500°F TBCs</td>
<td>3200°F TBCs</td>
<td>2700-3000°F EBCs</td>
<td>2700°F CMCs</td>
<td>2400°F CMCs</td>
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Baseline metal temperature

Current metal turbine airfoil system

State of the art metal turbine airfoil system 2500°F TBCs

2700-3000°F CMC turbine airfoil systems
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 CO₂ 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$_2$ 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$^2$) for turbine thermal barrier coating testing
- Crucial for advanced EBC-CMC developments

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

Cooling – high velocity air or air-water mist
Achieved heat transfer coefficient 0.3 W/cm$^2$-K
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)

Some temperature thermal gradient cycles

High heat flux combustor rig
High Power CO₂ 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 CO₂ 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, relatively high velocity under very high temperature condition
- Used for 3000°F EBC-CMC developments
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 conditions
- A 1000 Hz high heat flux HCF testing rig is being established this year
**Thermal Conductivity Measurement by a Laser High-Heat-Flux Approach**

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

\[
q_{\text{thru}} = q_{\text{delivered}} - q_{\text{reflected}} - q_{\text{radiated}}
\]

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

Where

- \( q_{\text{delivered}} \)
- \( q_{\text{reflected}} \)
- \( q_{\text{radiated}} \)

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

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

Optional miniature thermocouple for additional heat-flux calibration

\[\Delta T_{\text{ceramic}} = \Delta T_{\text{measured}} - \Delta T_{\text{substrate}} - \Delta T_{\text{bond}}\]
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

\[ G = \frac{1}{6} \left( \frac{1 + \nu_2}{1 - \nu_1} \right) E \alpha (T_s - T_b)^2 \]

Evans and Hutchinson model, Surface Coating Technology, 2007

The FEM model
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

- $T_{\text{surface}} \approx 1482$-1500°C, $T_{\text{interface}} 1350$°C, $T_{\text{back surface}} 1225$°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 Yb$_2$SiO$_5$/Yb$_2$Si$_2$O$_7$/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 $T_{EBC}$ 1316°C, $T_{CMC}$ 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

In Air; EBC cracking

In steam; EBC cracking and volatility
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

In Air; EBC cracking

In steam; EBC cracking and volatility
EBC Coated CMC 2650°F (1454°C) Creep Rupture Durability Test

- SiC/SiC CMC 12C-470-022 SiC/SiC CVI-MI CMC specimen
- Coated with 2700°F (1482°C) RESi and Rare Earth EBC
- Test temperatures: $T_{EBC\ surface}$ at 2850-3000°F (1600-1650°C), and $T_{cmc\ back}$ at ~2600°F (1426°C)

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

- A thin 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°C, $T_{\text{back CMC surface}}$ 1250°C
- Fatigue Stress amplitude 69 MPa, at mechanical fatigue frequency f=3Hz, stress ratio R=0.05
- Low cycle thermal gradient fatigue 60min hot, 3min cooling
EBC Fatigue Test Failure with CMAS

- Advanced alternating HfO$_2$-RE-silicate coatings (EB-PVD processing) – HfO$_2$-layer infiltration and rare earth silicate layer melting
- Advanced composition clustering EBCs being developed

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: Successfully Tested 150 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 and high temperature tests, aiming at understanding the CMC and EBC degradation

Subelement Load-Displacement curve – CVI CMC trailing edge

Subelement Load-Displacement curve – Prepreg MI CMC trailing edge
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

• 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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