Combined Thermomechanical and Environmental Durability of Environmental Barrier Coating Systems on SiC/SiC Ceramic Matrix Composites

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9th International Conference on High Temperature Ceramic Matrix Composites (HTCMC-9)
Toronto, Canada
June 26-July 1, 2016
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>
<th>Gas</th>
<th>TBC Bond coat</th>
<th>Metal blade</th>
</tr>
</thead>
<tbody>
<tr>
<td>2900°F (T41)</td>
<td>2500°F TBCs</td>
<td>Tsurface 300°F increase</td>
<td>2700-3000°F EBCs</td>
<td>Tsurface 200-500°F increase</td>
<td>Thin turbine coating development</td>
</tr>
<tr>
<td>2200°F TBCs</td>
<td>Current metal turbine airfoil system</td>
<td>State of the art metal turbine airfoil system 2500°F TBCs</td>
<td>2700-3000°F CMC turbine airfoil systems</td>
<td>2400°F CMCs</td>
<td></td>
</tr>
</tbody>
</table>

Baseline metal temperature
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

Heat flux

Distance from surface

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 CO$_2$ 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\textsubscript{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, relatively high velocity under very high temperature condition
- Used for 3000°F EBC-CMC developments

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

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

\( q_{\text{delivered}} \)

\( q_{\text{reflected}} \)

\( q_{\text{radiated}} \)

\( q_{\text{thru}} \)

\( \Delta T_{\text{tc}} \)

\( \Delta T_{\text{measured}} = \Delta T_{\text{ceramic}} - \Delta T_{\text{bond}} - \Delta T_{\text{substrate}} \)
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:
\[ T_{\text{surface}} = 1482^\circ\text{C} \quad T_{\text{interface}} = 1175^\circ\text{C} \]

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

\[ G = \frac{1}{6(1-\nu)} E h \left( \frac{T_s - T_0}{\Delta M} \right)^2 \]

Evans and Hutchinson model, Surface Coating Technology, 2007

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 driving force (E=\(~50GPa\))*

*Crack extension driving force (E=\(~200GPa\))*

Temperature, °C

1467 °C

1315 °C

1066 °C

4mm delamination length
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

- $T_{\text{surface}} \sim 1482-1500^\circ\text{C}$, $T_{\text{interface}} 1350^\circ\text{C}$, $T_{\text{back surface}} 1225^\circ\text{C}$, heat flux 110 W/cm$^2$
- Localized pore formation

![Graph showing thermal conductivity, temperature, and heat flux over time with localized pore formation after 50hr Cyclic Testing.](after_50hr_cyclic_testing.png)
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
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: $T_{\text{EBC surface}}$ 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: 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 $f=3\text{Hz}$, 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) on 14C579-011001_#8 CVI-MI SiC/SiC (with CMAS)
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
Acknowledgements

• The work was supported by NASA Fundamental Aeronautics Program (FAP) and Transformational Tools and Technologies Projects

NASA colleagues include:
Sue Puleo and Rick Rogers – X-ray
Terry McCue, Serene Farmer, Francisco Solá, SEM and TEM
Valerie Wiesner and Narottam Bansal, Gustavo Costa: Fundamental CMAS behavior