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

Baseline metal temperature

Current metal turbine airfoil system

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

2700-3000°F EBCs

Tsurface 200-500°F increase

Thin turbine coating development

2700°F CMCs

2400°F CMCs
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

Cooling – high velocity air or air-water mist
Achieved heat transfer coefficient 0.3 W/cm\textsuperscript{2}-K
High Power CO$_2$ Laser Based High Heat Flux Testing for SiC/SiC and Environmental Barrier Coatings Development

- 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\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
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
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

Steam during cooling cycles

High temperature testing with steam flow
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

High heat flux tensile TMF and rupture testing
Thermal Conductivity Measurement by a Laser High-Heat-Flux Approach

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

where

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

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

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

8 \, \mu\text{m} pyrometer 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_{surface} 1482°C/T_{interface} 1175°C

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

Evans and Hutchinson model, Surface Coating Technology, 2007

\[ G = \frac{1}{6} \frac{1 + \nu_1}{1 - \nu_1} E_1 h (\alpha_1 (T_h - T_b))^2 \]

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 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 $\text{Yb}_2\text{SiO}_5$ (with $\text{HfO}_2$ Composite)/$\text{Yb}_2\text{Si}_2\text{O}_7$/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

After 50hr Cyclic Testing

Thermal conductivity, W/m-K

Temperature, °C; heat flux, W/cm$^2$

Time, hours

0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
200
400
600
800
1000
1200
1400
1600
0 10 20 30 40 50 60 70
kcera
Tsurface
Tinterface
Tback
qthru
Thermal conductivity, W/m-K
Temperature, °C; heat flux, W/cm$^2$
Time, hours

After 50hr Cyclic Testing
Fatigue Testing using a Laser High-Heat-Flux Approach for Environmental Barrier Coated Prepreg SiC/SiC CMCs

- Environmental Barrier Coatings Yb₂SiO₅/Yb₂Si₂O₇/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: $T_{\text{EBC surface}}$ 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 $T_{EBC\text{-}surface} 1537°C$, $T_{bond\,coat} 1480°C$, $T_{back\,CMC\,surface} 1250°C$
- 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

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
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