Property Evaluation and Damage Evolution of Environmental Barrier Coatings and Environmental Barrier Coated SiC/SiC Ceramic Matrix Composite Sub-Elements

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Objectives

– Develop advanced, high performance environmental barrier coatings (EBC) and SiC/SiC ceramic matrix composite (CMC) systems relevant to next generation turbine engines

– Develop advanced testing methodologies for long-term durability improvements, emphasizing creep, fatigue and complex environment interactions in simulated operating conditions

  • Focus on advanced NASA high heat flux – thermomechanical test rigs for element evaluations
  
  • Evaluate properties or behavior of complex turbine component elements
    - Current CVI, Prepreg, and CVI-MI SiC/SiC systems, commercially purchased

  • Help develop testing parameters, establish understand damage evolution and performance database, and advancing environmental barrier coating technologies
Outline

- Creep and fatigue of coated CMCs under thermal gradients
- Thermal conductivity of advanced EBCs based on turbine vane leading edge (LE) elements
- SiC/SiC turbine vane leading edge (LE) and trailing edge (TE) sub-element testing: heat flux durability and mechanical loading
- Summary and Conclusions
EBC – CMC Degradations under Fatigue Loading

- EBC coated 1847-01-007 #5, fatigue cycles tested at 3 Hz frequency, maximum stress 20 Ksi, stress ratio R=0.05 at 2400°F (1316°C)

A 20 micrometer thick EBC bond coated Prepreg SiC/SiC CMC after 40 hr, maximum stress 20 Ksi, stress ratio R=0.05 fatigue testing in air
The EBC coated Prepreg SiC/SiC achieved approximately total 1.0% creep strains at 20 Ksi stress at 2400°F (1316°C)
High Temperature Creep of SiC/SiC and Environmental Barrier Coating Recession in Turbine Environments

- Accelerated degradation observed for an uncoated CVI-MI CMC under a single notched specimen at high temperature (stress concentration factor considered and also verified with strain gauged tests)
- Heat flux and environmental degradation being studied
Laser Heat Flux Rigs for Advanced EBC-CMC Developments

- Turbine level heat flux, environment and load testing capabilities
- Quantitative one dimensional (one-D) steady-state thermal conductivity measurements and durability testing
- Two dimensional (2D) coating and component material degradation real time monitoring under development

\[
k_{\text{ceramic}}(t) = \frac{q_{\text{thru}} \cdot l_{\text{ceramic}}}{\Delta T_{\text{ceramic}}(t)} \quad \text{and} \quad \Delta T_{\text{ceramic}}(t) = T_{\text{ceramic-surface}} - T_{\text{metal-back}} - \int_0^{\Delta T_{\text{bond}}} \frac{q_{\text{thru}} \cdot dl}{k_{\text{bond}}(T)} - \int_0^{\Delta T_{\text{substrate}}} \frac{q_{\text{thru}} \cdot dl}{k_{\text{substrate}}(T)}
\]

Where

- \( k_{\text{ceramic}}(t) \): Thermal conductivity of ceramic coating at time \( t \)
- \( q_{\text{thru}} \): Heat flux through the coating
- \( l_{\text{ceramic}} \): Thickness of ceramic coating
- \( \Delta T_{\text{ceramic}}(t) \): Temperature change in ceramic coating
- \( T_{\text{ceramic-surface}} \): Surface temperature of ceramic
- \( T_{\text{metal-back}} \): Backing metal temperature
- \( k_{\text{bond}}(T) \): Bond layer thermal conductivity
- \( k_{\text{substrate}}(T) \): Substrate thermal conductivity

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

Optional miniature thermocouple for additional heat-flux calibration

A 3500Kw high power CO\textsubscript{2} laser
Thermal Conductivity of Environmental Barrier Coating Systems Determined for SiC/SiC CMC Leading Edge (LE) Elements

- Thermal conductivity test cycles of CVI SiC/SiC sub-elements

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![Temperature profiles](image)

- Thermal conductivity, W/m-K
- Coating temperature, °C
- Time, hours

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![Graphs showing thermal conductivity and temperature profiles](image)

- Turbine coating EBC 148/on CVI element LE4A with 31 cycles
- Turbine coating EBC 148/on CVI element LE4B with 35 cycles

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Continued

- In-situ, real time 2D or 3D thermal conductivity monitoring being implemented

- 1” and 2” specimens in testing
- Heated area 1.25” diameter
Thermal Conductivity of Environmental Barrier Coating Systems
Determined for SiC/SiC CMC Leading Edge (LE) Elements - Continued

- Thermal conductivity of turbine EBCs on Prepreg LE subelements determined
- The data used to evaluate processing consistency, composition effect and reliability

![Temperature profiles](image)

![Thermal image of EBC 148-LE3 at 20 cycles](image)
Turbine Environmental Barrier Coating System Long-Term Durability Testing on a Prepreg SiC/SiC Subelement

- The LE element tested at $T_{EBC \text{ surface}} \approx 2700^\circ\text{F} (1482^\circ\text{C})$, $T_{EBC-CMC \text{ interface}} = 2400-2460^\circ\text{C} (1300-1348^\circ\text{C})$
- Completed 550, 1 hr cycles
- Coating damage evolution was monitored during the entire testing
- The coating had only very minor degradation after the long term testing

At 550 cycles
EBC-CMC Turbine Trailing Edge (TE) Fatigue Testing

- Testing approaches developed for EBC-CMC trailing edge thermomechanical testing
- High heat flux capability to simulate required high thermal gradients and more complex temperature distributions in a turbine engine
- Mechanical loading to simulate the high pressure turbine airfoil pressure (ballooning) effects
- EBC-CMC durability being evaluated, planned incorporation of stream jet environments
EBC-CMC Turbine Trailing Edge (TE) Fatigue Testing - Continued

• Testing approaches developed for EBC-CMC trailing edge thermomechanical testing
• High heat flux capability to simulate required high thermal gradients and more complex temperature distributions in a turbine engine
• Mechanical loading to simulate the high pressure turbine airfoil pressure (ballooning) effects
• EBC-CMC durability being evaluated, with and without stream jet environments
Strain Measurements for Uncoated and Coated Airfoil Trailing Edge (TE) Sub-elements

- Strain gauges installed in the high strain thin wall and thick wall areas
- Uncoated elements used for measuring strains near “coating interface areas”
- Coated elements used for measuring the strains near “coating surface areas”
- Data help understand coating design and testing requirements
- Fatigue cycles performed at 200, 300 and 500 lbf loading, 0.1 Hz, stress ratio R=0.05
- Both CVI and Prepreg SiC/SiC CMC elements with EB-PVD EBCs studied

Example of initial testing, showing non recoverable deformation of the element, suggesting some damage accumulation in the element

Strain gauges:
- Thin wall (6 mils) inner
- Thin wall (6 mils) outer
- Thick wall (8 mils) inner
- Thick wall (8 mils) outer

Modeled Woven CVI
Strain Measurements for Uncoated and Coated Airfoil Trailing Edge (TE) Sub-elements - Continued

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• Coated for measuring the strains neat “coating surface areas”
• Data help understand coating design and testing requirements
• Fatigue cycles performed at 200, 300 and 500 lbf loading, 0.1 hz, stress ratio initially 0.05
• Both CVI and Prepreg SiC/SiC CMC elements with EB-PVD EBCs studied

The experiments helped the validation of early modeling
Strain Measurements for a Uncoated Trailing Edge (TE) Sub-elements

- Strain gauge (thick wall outer) showed the increased strains with fatigue cycles
- Also reduced component stiffness
Strength Tests of Trailing Edge (TE) Sub-elements

- Maximum failure strain observed from the gauge at Thin Wall inner location, at ~0.5%
- Failure load at 538 lbf (approximately corresponding to 20 ksi stress at the thin wall inner location)
- The coated element failure load 700 lbf after the progressive fatigue cycles
- Lower than the previous failure load of 800 lbf for an as-received element specimen
Strain Measurements for Coated Airfoil Trailing Edge (TE) Sub-elements

- Higher surface strains measured for the coated specimen
- Out of phase Load (stress) – Strain behavior in fatigue cycles
Strain Measurements for Coated Airfoil Trailing Edge Sub-elements at High Loads

- Higher strains measured at 500 lbf load amplitude for the coated specimens
- Possibly changed neutral axes of the deflections of the CMC thin and thick walls
- Observed damped EBC surface strains ("Strain thin out" and "Strain thick out") as compared CMC side strain gauges
- Observed gradually changed out of phase strain cycles on the EBC coated sides
- The results showed complex coating cycling behavior
The results showed complex coating cycling behavior.

- Fully reversed, out of phase coating surface strain cycles
Summary and Conclusions

• Creep and fatigue data are continued to be obtained for robust turbine coating systems, in particular under thermal gradients
  
  — 2700°F turbine environmental barrier coatings being developed and tested in various conditions
  — Thermal conductivity data determined for selected coating systems on the SiC/SiC CMC sub-elements
  — Thermal gradient durability of element coatings demonstrated, coating damage in-situ monitoring viable during testing
  — Advanced turbine trailing edge testing approaches developed, validating modeling
  — Combined environmental, heat flux and fatigue loading durability testing in progress