CMC / EBC Research at NASA Glenn in 2020: Recent Progress and Plans

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CMC Research at NASA Glenn

• CMC Development & Characterization
• Modeling & Validation
• Additive Manufacturing
Material Development and Characterization

• Demonstrated a durable 2700°F CMC / EBC system in a turbine environment

• Established a facility for long-term fatigue testing of CMC’s in a steam environment at turbine temperatures

• Implemented Digital Image Correlation capability for full-field strain characterization showing failure progression in cooled CMC

• Measured effect of through-thickness thermal gradient on CMC deformation in creep and fatigue at 2700°F

• Characterized CMAS infiltration of advanced EBC materials
NASA 2700°F CMC combines three technology advancements

- Creep-resistant Sylramic-iBN fiber
- Advanced 3D fiber architecture
- Hybrid CVI-PIP SiC matrix

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Recent progress toward a durable 2700°F CMC / EBC

**APS Yb$_2$Si$_2$O$_7$ 2400°F EBC**
- Modified for Long Life

- TGO is life-limiting failure mechanism for SOA 2400°F EBC
- Certain oxides known to reduce diffusivity in SiO$_2$
- Modified EBCs reduced TGO by 80% (~20x life improvement)
- Hypothesis: modifiers dissolve in SiO$_2$, modify structure, slow TGO

**PS-PVD & Slurry Coat Process**
- Development & Optimization

- Slurry provides economical, non-line of sight, and chemistry friendliness.
- PS-PVD is a hybrid process (plasma and/or vapor) that provides variable microstructure along with non-LOS.
- Both methods demonstrating 2700°F capable coatings.

**Durable 2700°F CMC / EBC**
- Material demonstrated

**Cooled CMC / EBC Airfoils**
- Evaluated in Turbine Rig Tests
- Synergy of failure mechanisms
- (3) Test Articles, 45 hrs total
- Compared in-house against commercial EBCs
- 2500-2700°F

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Fundamental tests characterize CMC/EBC failure modes

Damage models are incorporated into life prediction codes

Steam Oxidation

Thermomechanical Durability

Hydroxide Formation/Recession

CMAS Attack & Infiltration

Erosion and FOD

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Capability for 2700°F fatigue testing in steam environment is being developed

**OBJECTIVE**
Characterize fatigue durability of Ceramic Matrix Composites (CMCs) coated with Environmental Barrier Coatings (EBCs) in steam environment up to 2700 °F for future turbine engine components.

**APPROACH**
- Initially demonstrate fatigue testing capability at 2200 and 2400 °F in steam environment; eventually develop fatigue testing capability up to 2700 °F in steam.
- Perform sustained peak, low-cycle fatigue (SPLCF) tests on EBC coated MI SiC/SiC composite at 2200 and 2400 °F in steam environment up to 300 hours.
- Develop fatigue testing capability in steam up to 2700°F and perform SPLCF testing on EBC coated CMCs with 3D fiber architectures and hybrid (CVI+PIP) matrices.

**SIGNIFICANCE**
Assessment of long-term fatigue durability of EBC coated CMCs in steam environment up to 2700°F will enable development of future aero-propulsion engines with greatly improved performance metrics.

**STATUS & ACCOMPLISHMENTS**

**SPLCF loading at 2200°F**
- 3D hybrid CMC/EBC in steam at lasted 160 hours
- Hexoloy with EBC did not fail after 200 hours
- 3D CMC / EBC failed at 48 hours
- Test of MI SiC/SiC with Gen 2 EBC is underway

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Effect of thermal gradients on sequential tensile creep and SPLCF testing on SiC/SiC CMCs at 2700 °F

CMCs with 2D & 3D fiber architectures and CVI (2D only), PIP (2D only), and hybrid (CVI+PIP) matrices tested for 80 hr. in creep at 10 ksi [69 MPa] followed by 80 hr. in SPLCF at 10 ksi (8 hr. hold at max stress/cycle) under isothermal (Iso.) & thermal gradient (TG) conditions (2700 °F hot side and 2400 °F cold side)

Through-thickness TGs generated in uncoated SiC/SiC CMCs with laser heating and backside air cooling. Front and back side temp. measured with pyrometers and IR camera

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Isothermal tensile creep test on 3D hybrid CMC generated highest tensile strain followed by TG test on 2D hybrid matrix CMC. Uncoated CMCs sustained steady thermal gradients for a total of 160 hr., with creep at 10 ksi for 80 hr. followed by SPLCF at 10 ksi max. stress for 80 hr., without an EBC.
Digital Image Correlation shows how cooling holes affect damage progression

**Objective**
Quantify the effect of holes and hole orientation on the material properties of SiC / SiC composites with EBC. Monitor crack evolution and compare to baseline

**Results**
- Tensile samples were tested with cooling holes ultrasonically drilled at 30° and 90° to the loading direction.
- The net-section Proportional Limit (PL) was the same as it was for samples without holes.
- The ultimate strength of samples with 90° holes was reduced by 10%, while samples with 30° holes showed no reduction.
- Local DIC strain accumulated near the 90° holes at stress well below the PL.
- Local DIC strain did not accumulate near 30° holes until the PL.
- For EBC coated samples, local DIC strain indicated that near 90 holes the EBC cracked before the CMC. Near 30° holes, the EBC and CMC cracked at the same time.

Proportional limit stress was not affected by stress concentration near drilled holes.

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Multi-Modal Characterization of CMC Damage Accumulation

Objective:
- Quantify damage initiation and evolution at room temperature in SiC/SiC CMCs towards understanding microstructure effect on damage mechanisms

Approach:
- Conducted tensile tests of CVI SiC/SiC mini-composites in SEM
- Documented damage evolution while making Acoustic Emission measurements to determine damage location and magnitude

Results
- Characterized CMC damage in two systems (LFC, HFC)
- Detected damage initiation & progression below the proportional limit
- Correlated AE measurements to microscale damage development
- Obtained Crack Opening Displacements vs. stress

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CMC / EBC Durability
Modeling & Validation

• Developed & validated an enhanced oxidation (TGO) model for silicon bond coat

• Studying TGO formation conditions in steam and effect on the mechanical behavior of coated SiC/SiC minicomposites.

• Validated a computational approach to simulate CMC damage development under flexural fatigue in steam environment
**Reformulation of Oxide Growth Equations for Silicon Bond Coat Oxidation in Environmental Barrier Coatings**

**Objective:** Revisit Deal and Grove’s original formulation for silicon oxidation and include the effect of a Yb$_2$Si$_2$O$_7$ top coat.

**Approach:**
- Assume oxidant diffusion mechanisms through the oxide and coating layers. Derive oxidant mass flux equations.
- Derive equation for oxide thickness as a function of time.

**Results:**
- The original linear-parabolic growth equation ($x_o^2 + Ax_o = Bt$) developed for uncoated silicon surfaces is still applicable, except $A$ is modified to include the effect of the top coat: $A' = A + 2(\gamma_{ox}/\gamma_c)\delta$, where $\delta$ is the top coating thickness and $\gamma_{ox}$ and $\gamma_c$ are the oxidant permeability in the oxide and coating layers, respectively.


**Accomplishments:**
- Understand how top coat affects oxide growth on bond coat
- Simple approach for sizing top coat thickness of EBC

**Oxide thickness $x_o$ vs. time for coated and uncoated silicon surfaces in air at 1316 °C**
Effects of High Temperature Steam Exposure on 2700°F EB-Coated SiC/SiC Minicomposites

Objective:
- Establish temperature and time dependence of TGO (thermally grown oxide) growth in steam. Identify effects of TGO growth on EBC and CVI-SiC matrix cracking.

Approach:
- Coat minicomposites with ytterbium disilicate-based EBC bond coat and top coat
- Expose EB-coated SiC/SIC minicomposites to 2200, 2400, and 2600°F steam environment to establish temperature and time dependence of TGO growth
- Conduct RT tensile tests of coated minicomposites with insitu AE and digital imaging to estimate EBC cracking stress
- Use polished sections to establish TGO growth temperature and time dependence, and quantify EBC and CVI-SiC cracking

Results:
- Measuring TGO thickness for a given exposure condition and comparing that with EBC thickness

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Modeling effects of steam environment on CMC durability & failure modes

Finite Element analysis of CMC 4-point bend specimen

Results will provide the baseline to assess effects of steam on CMC/EBC fatigue life

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NASA GRC Focus in 2020

CMC Development & Model Validation

• Determine durability limits and model failure process of 3D Hybrid and Melt-infiltrated CMC under fatigue load in steam environment
• Extend capability for fatigue testing in steam environment to 2700ºF
• Extend temperature capability of Digital Image Correlation measurements
• Validate model of cooling hole effect on failure initiation & progression
• Evaluate durability of alternate turbine blade / disk attachment designs

Additive Manufacturing

• Fabricate stator conductive coils and insulation for a large-scale electric generator using additive manufacturing technologies
• Optimize Binder Jet fabrication & densification processes for SiC with chopped-fiber reinforcement
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- Advanced Air Transport Technology
- Convergent Aeronautics Solutions
- Transformational Tools and Technologies
- Revolutionary Vertical Lift Technology