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

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CMC Research at NASA Glenn

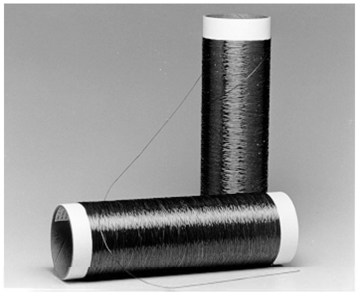
- CMC Development & Characterization
- Modeling & Validation
- Additive Manufacturing

Material Development and Characterization

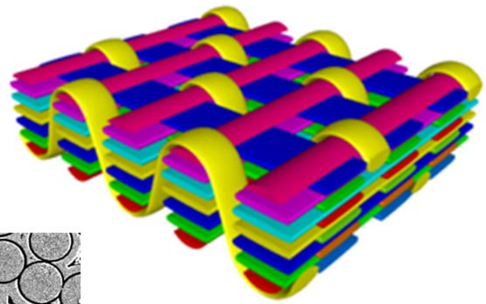
- Demonstrated a durable 2700°F CMC / EBC system in a turbine environment
- Established a facility for long-term fatigue testing of CMC's in a steam environment at turbine temperatures
- Implemented Digital Image Correlation capability for full-field strain characterization showing failure progression 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

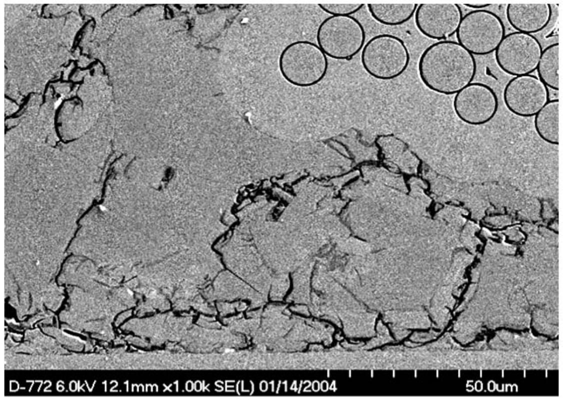
- **Creep-resistant Sylramic-iBN fiber**



- **Advanced 3D fiber architecture**



- **Hybrid CVI-PIP SiC matrix**

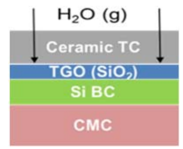


Contact: Ramakrishna.T.Bhatt@nasa.gov

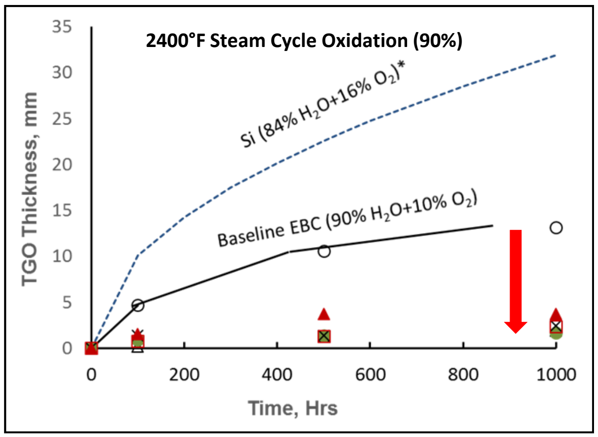
Recent progress toward a durable 2700°F CMC / EBC

APS $Yb_2Si_2O_7$ 2400°F EBC Modified for Long Life

- TGO is life-limiting failure mechanism for SOA 2400°F EBC

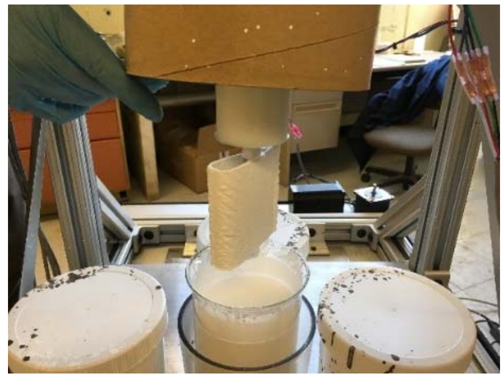


- Certain oxides known to reduce diffusivity in SiO_2



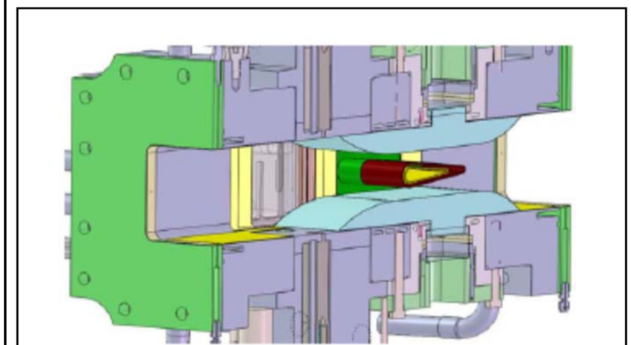
- Modified EBCs reduced TGO by 80% (~20x life improvement)
- Hypothesis: modifiers dissolve in SiO_2, modify structure, slow TGO

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



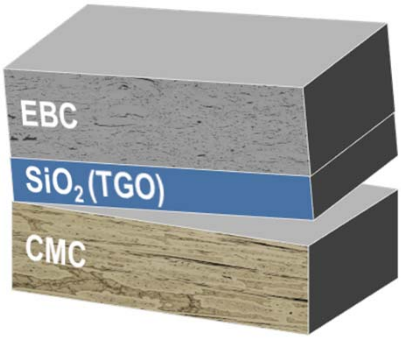
Cooled CMC / EBC Airfoils Evaluated in Turbine Rig Tests

- Synergy of failure mechanisms
- (3) Test Articles, 45 hrs total
- Compared in-house against commercial EBCs
- 2500-2700°F

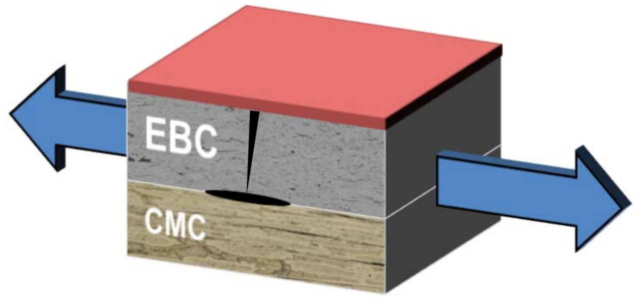
Contact: Raymond.Robinson-1@nasa.gov

Fundamental tests characterize CMC/EBC failure modes

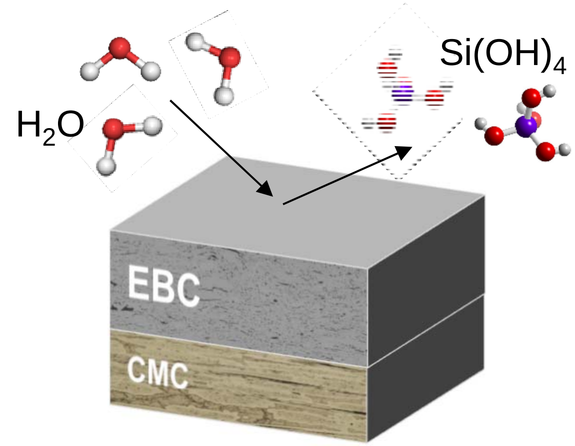
damage models are incorporated into life prediction codes



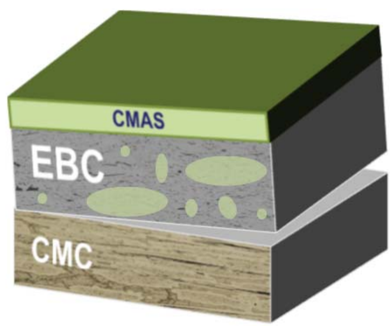
Steam Oxidation



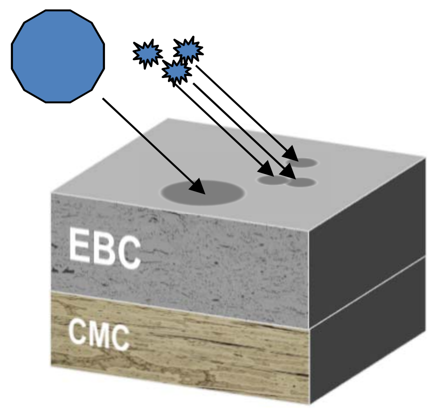
Thermomechanical Durability



Hydroxide Formation/Recession



CMAS Attack & Infiltration

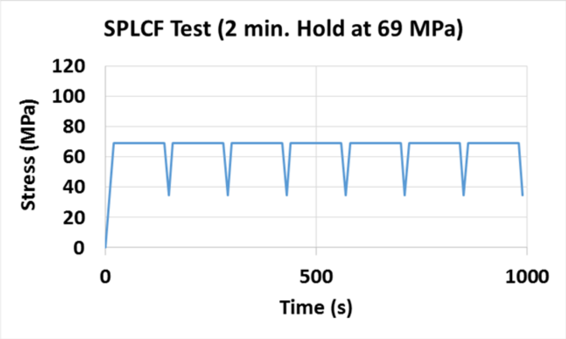


Erosion and FOD

Contact: Ken.K.Lee@nasa.gov

K. N. Lee, "Environmental Barrier Coatings for CMC's"; in *Ceramic Matrix Composites*, Wiley, New York (2015)

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



Tensile SPLCF at 2200 °F in Steam
Two minute hold at, 69 MPa max. stress; R = 0.5
Time to failure = 48 hours; ~ 1,200 cycles

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.

Failed in gage section after 48 hours (1,200 cycles)

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 2200ºF

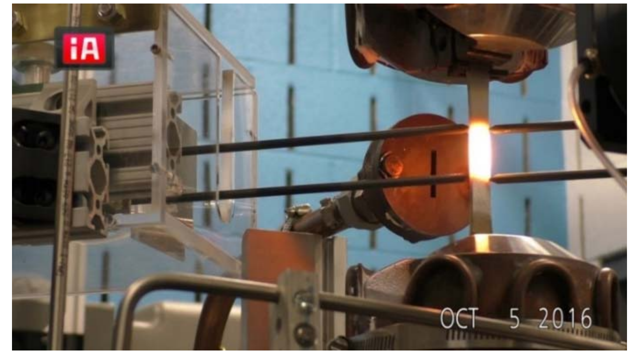
- 3D hybrid CMC/EBC in steam at lasted 160 hours
- Hexoloy with EBC did not fail after 200 hours
- 3D CMC / EBC failed at 48 hours
- Test of MI SiC/SiC with Gen 2 EBC is underway

Contact: Sreeramesh.Kalluri-1@nasa.gov

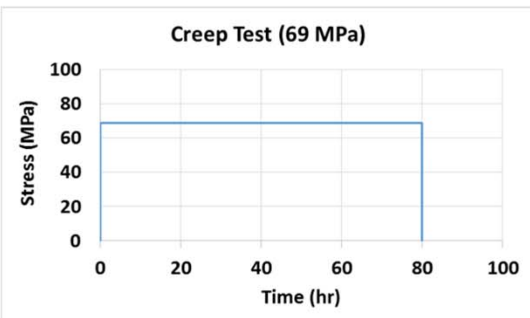
Effect of thermal gradients on sequential tensile creep and SPLCF testing on SiC/SiC CMCs at 2700 °F

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



Creep Loading Segment



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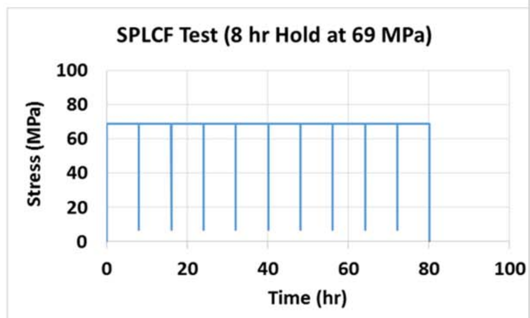
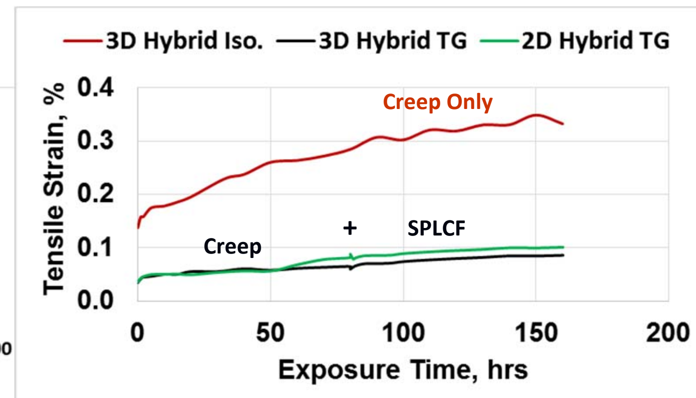
SPLCF Loading Segment





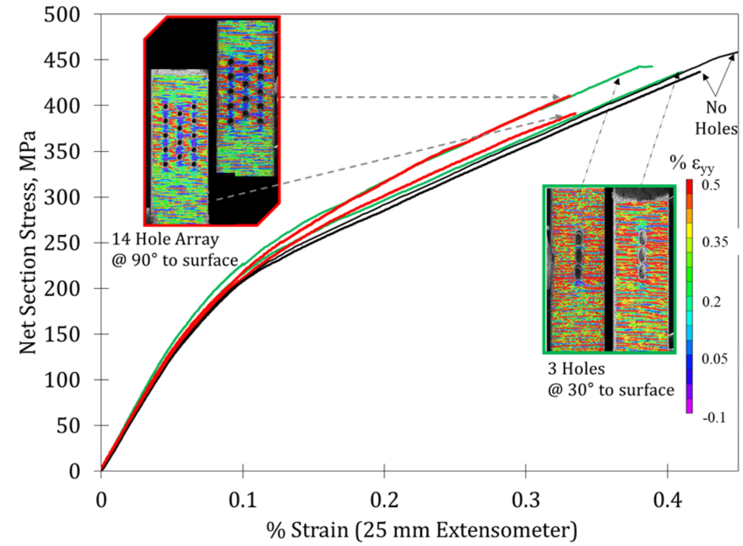
Isothermal tensile creep test on 3D hybrid CMC generated highest tensile strain followed by TG test on 2D hybrid matrix CMC. Uncoated CMCs sustained steady thermal gradients for a total of 160 hr., with creep at 10 ksi for 80 hr. followed by SPLCF at 10 ksi max. stress for 80 hr., without an EBC.

Contact: Sreeramesh.Kalluri-1@nasa.gov

Digital Image Correlation shows how cooling holes affect damage progression

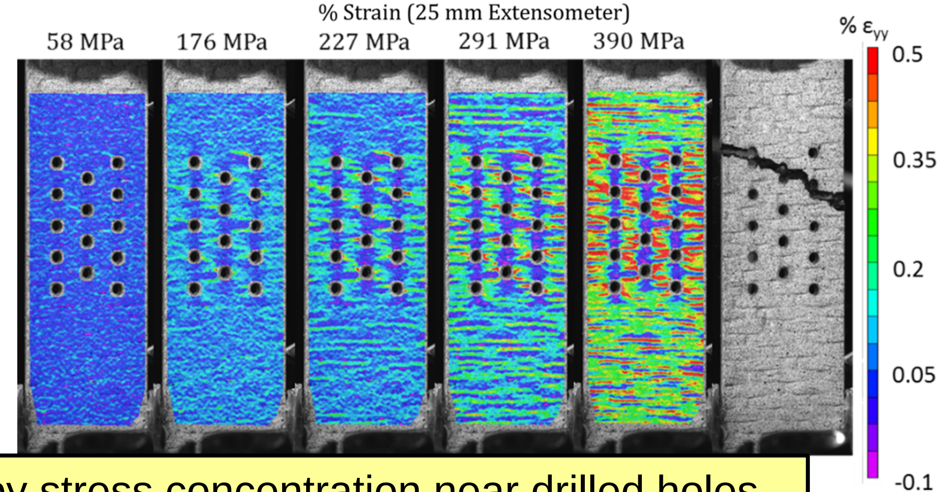
Objective

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.



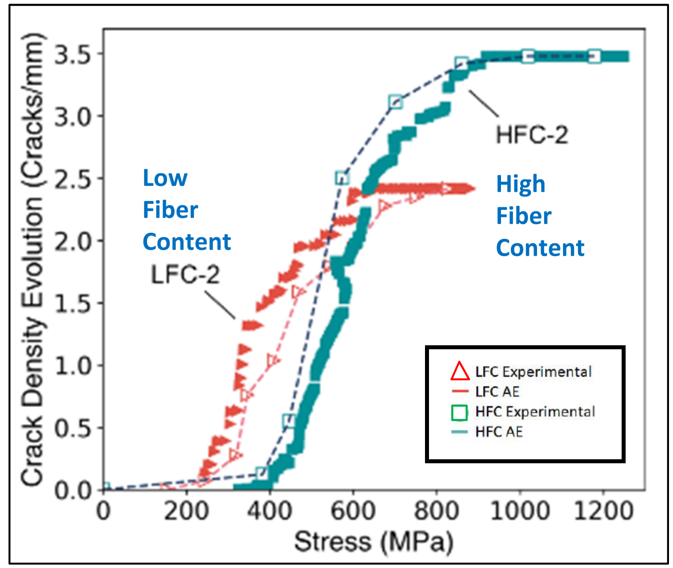
Proportional limit stress was not affected by stress concentration near drilled holes.

Contact: Craig.E.Smith@nasa.gov

Multi-Modal Characterization of CMC Damage Accumulation

Objective:

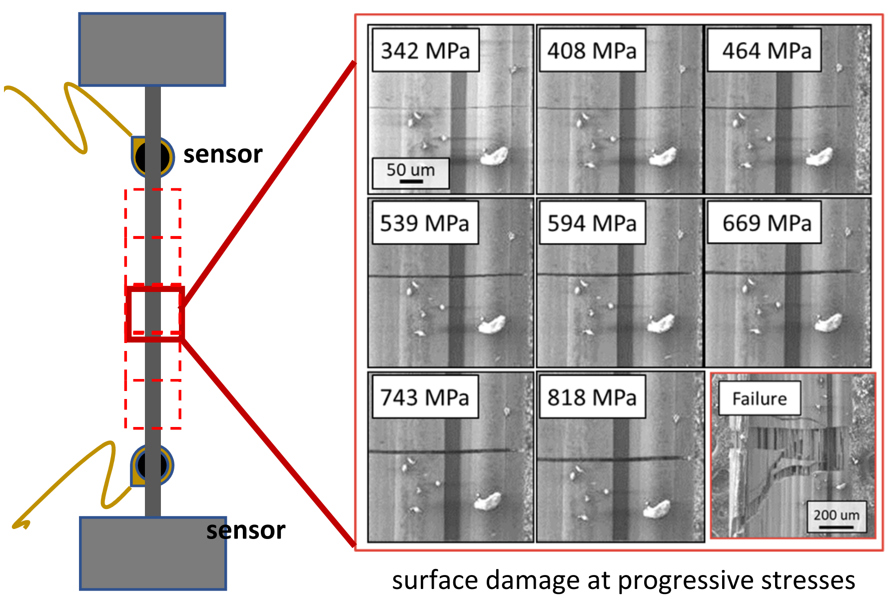
- Quantify damage initiation and evolution at room temperature in SiC/SiC CMCs towards understanding microstructure effect on damage mechanisms



Observed crack density vs AE signal

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



surface damage at progressive stresses

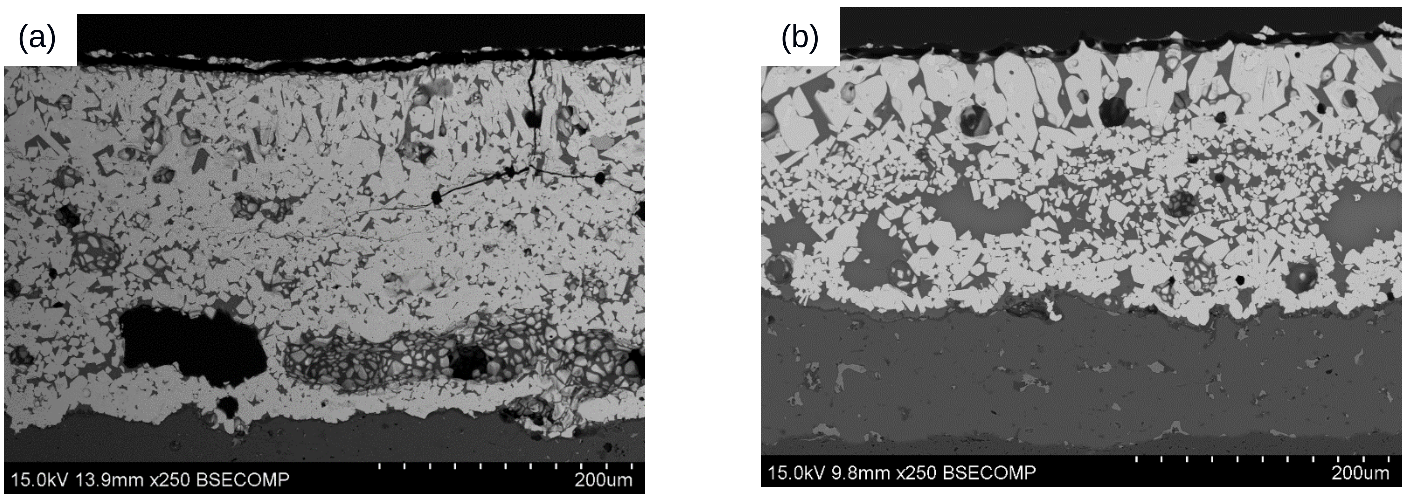
Results

- 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

Contact: James.D.Kiser@nasa.gov, Amjad.S.Almansour@nasa.gov, or Bhavana Swaminathan (UCSB)

CMAS Studies for Advanced EBCs

- Investigation of EBC degradation by molten CMAS at low concentrations
  - Microstructural characterization of first set of specimens exposed to 10 mg/cm^2 of CMAS at 1310°C for 10h completed
  - Heat treatment of second set of specimens with ~1-2 mg/cm^2 of CMAS underway
  - Preliminary results were summarized at MS&T'19 in Portland, OR (Oct 2019)



BSE-SEM micrographs of (a) ytterbium disilicate (YbDS) and (b) YbDS-alumina EBC topcoats exposed to CMAS at 1310°C for 10h revealing degradation via dissolution-precipitation mechanism

- Investigation of thermochemical interactions between CMAS and Apatite EBCs
  - Thermochemical interactions between $Ca_2Y_8(SiO_4)_6O_2$ apatite and CMAS have been investigated at 1200 – 1500 C using XRD, SEM, TEM and EDS
  - A paper "Thermochemical interactions between CMAS and $Ca_2Y_8(SiO_4)_6O_2$ apatite co-authored by J. Sleeper, A. Garg, V. Wiesner and N.P. Bansal has been published in J. European Ceramic Society, **39** (2019)5380-5390

Contact: Narottam.P.Bansal@nasa.gov or Valerie.L.Wiesner@nasa.gov

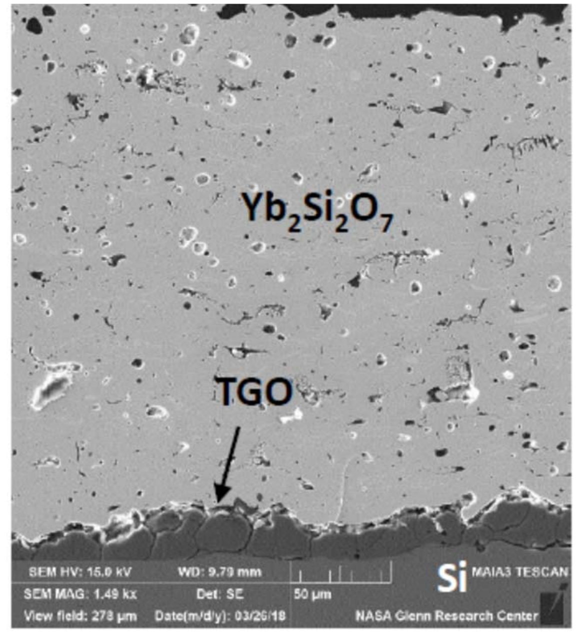
CMC / EBC Durability

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 $Yb_2Si_2O_7$ top coat.

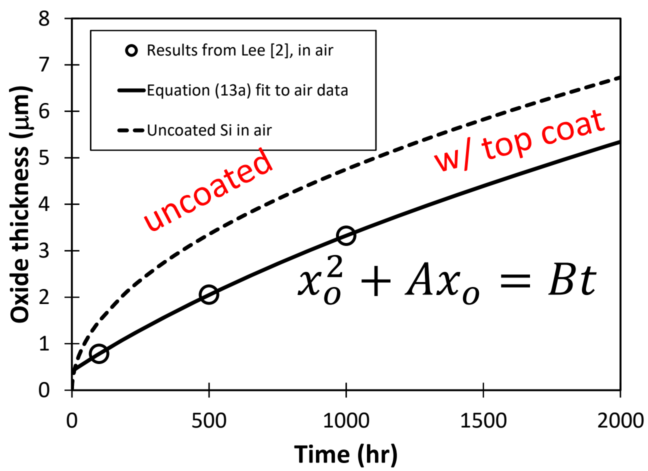


Approach:

- 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: $\mathrm{A}' = \mathrm{A} + 2(\gamma_{ox}/\gamma_c)\delta$, where δ is the top coating thickness and γ_{ox} and γ_c are the oxidant permeability in the oxide and coating layers, respectively.



Oxide thickness x_o vs. time for coated and uncoated silicon surfaces in air at 1316 °C

Contact: Roy.M.Sullivan@nasa.gov, "Reformulation of oxide growth equations for oxidation of silicon bond coat in environmental barrier coating systems," *Journal of the European Ceramic Society* Vol. 39 pp. 5403-5409 (2019).

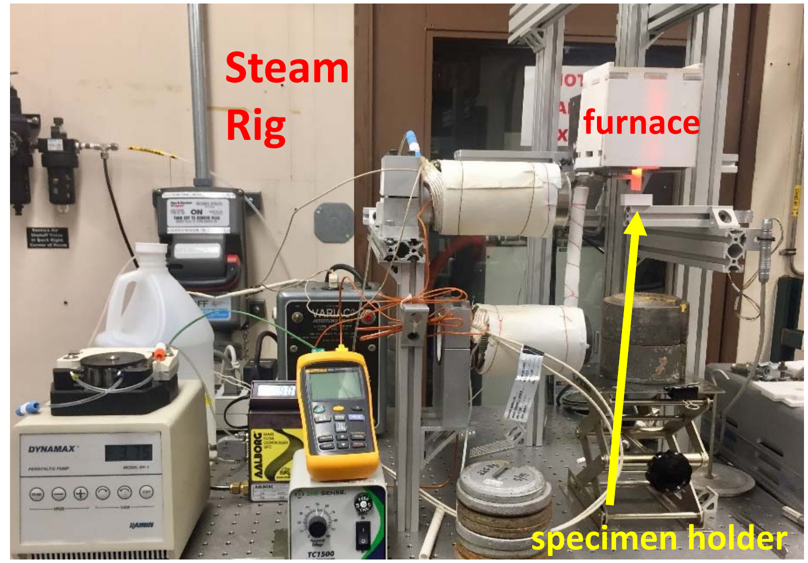
Accomplishments:

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

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.

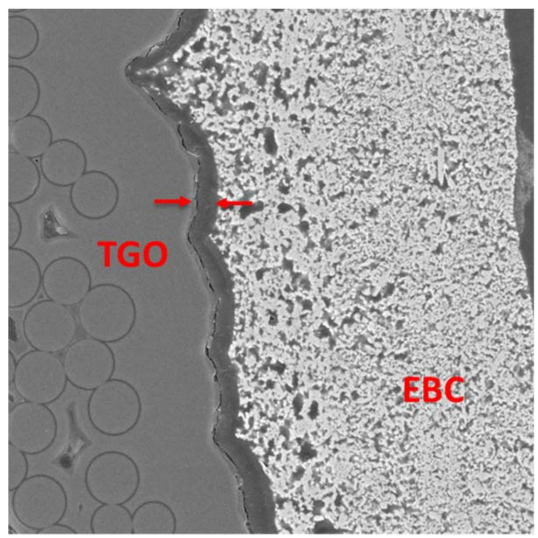


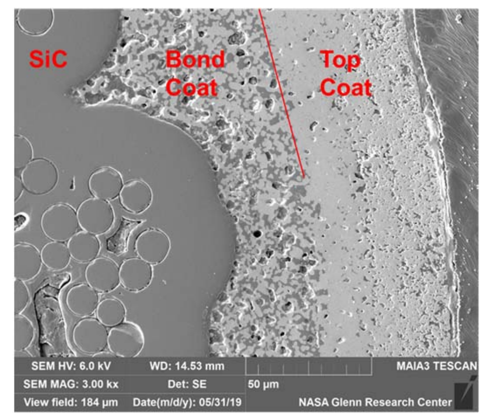
Approach:

- 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



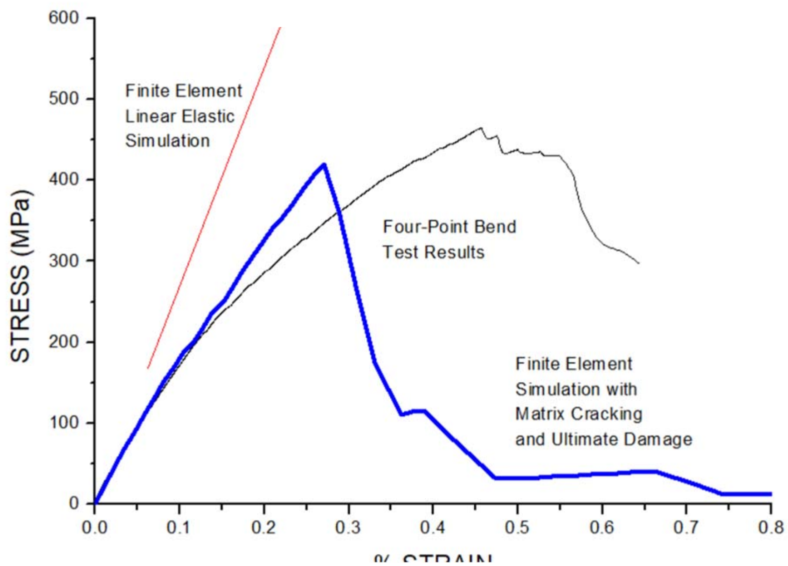


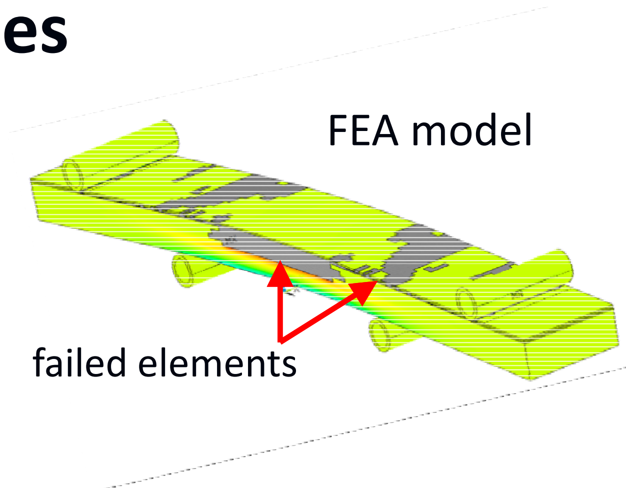
EBC/CMC System

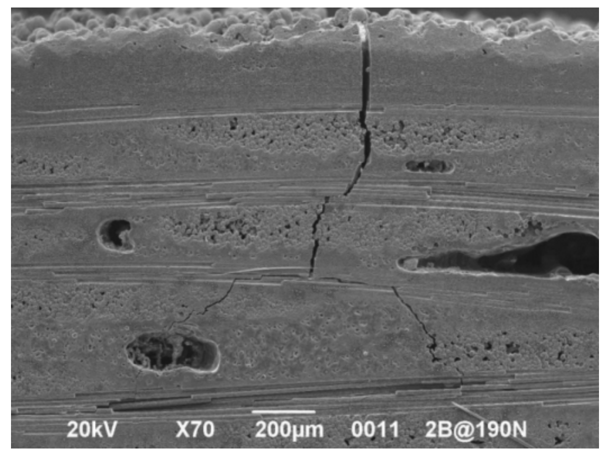
Contact: Amjad.S.Almansour@nasa.gov

Modeling effects of steam environment on CMC durability & failure modes

Finite Element analysis
of CMC 4-point bend specimen







Matrix crack
propagation
in CMC
bend
specimen

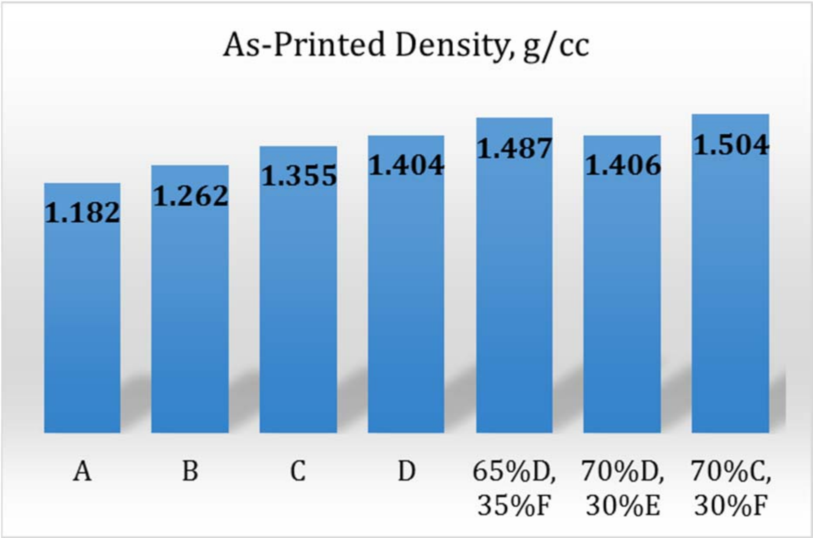
Results will provide the baseline to assess effects of steam on CMC/EBC fatigue life

Contact: Jerry.Lang-1@nasa.gov

Additive Manufacturing

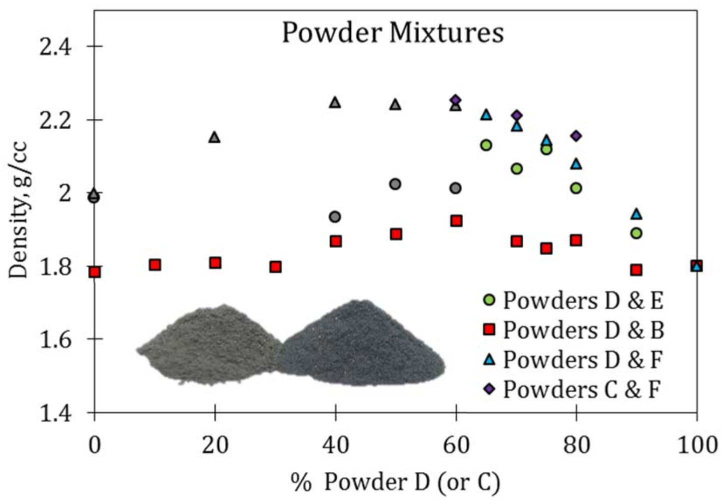
- Used Additive Manufacturing Binder Jet process to evaluate SiC processing parameters
- Fabricated lightweight and compact electric motor components using Direct Printing & Selective Laser Sintering processes

Densification of Binder Jet Fabricated SiC

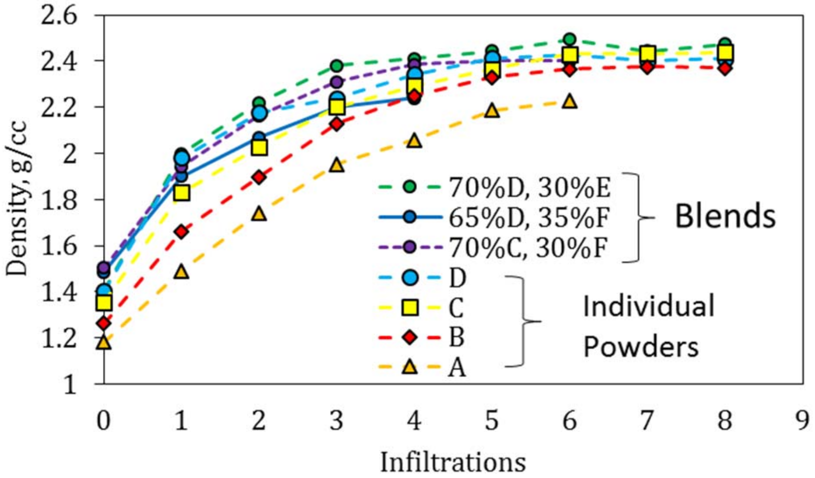


Binder Jet Machine

Density of Green Printed SiC



PIP Densification

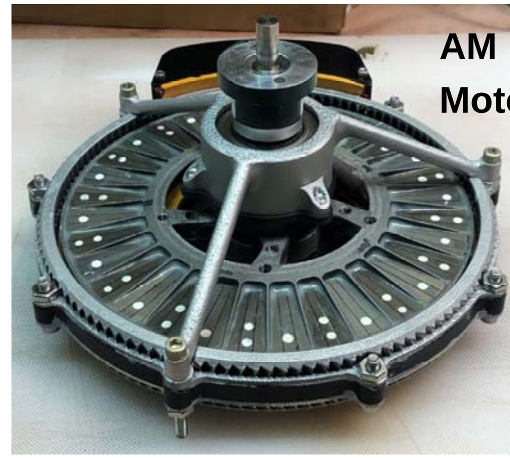


Contact: Craig.E.Smith@nasa.gov

Additive Manufacturing for Electric Motor Fabrication

Objective: Use additive manufacturing methods to fabricate new motor designs that have significantly higher power density and efficiency

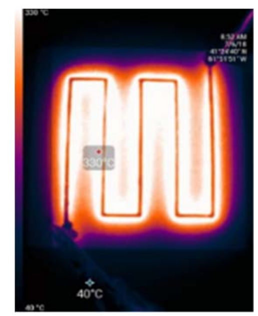
- Stator designs with direct printing and iron cores, increase max temp, torque and motor constant
- Selective Laser Sintering of structural components reduce mass & improve cooling



Improvements include:

Light Weight Motor Housing

Integrated Cooling



Higher Temp Stator

A 2x improvement in power density (10 kW/kg) is estimated using AM methods

Contact: Michael.C.Halbig@nasa.gov

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

This work is sponsored by the Aeronautics Research Mission Directorate

and the following projects:

- Advanced Air Transport Technology
- Convergent Aeronautics Solutions
- Transformational Tools and Technologies
- Revolutionary Vertical Lift Technology