CMC Research at NASA Glenn in 2019: Recent Progress and Plans

Joseph E. Grady
Ceramic & Polymer Composites Branch
joseph.e.grady@nasa.gov

for the 43rd Annual Conference
on Composites, Materials and Structures
January 28-31, 2019

CMC Research at NASA Glenn

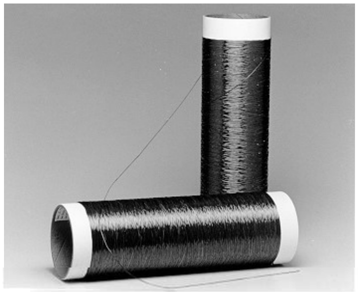
- CMC Development & Characterization
- Modeling & Validation
- Additive Manufacturing

CMC Development and Characterization

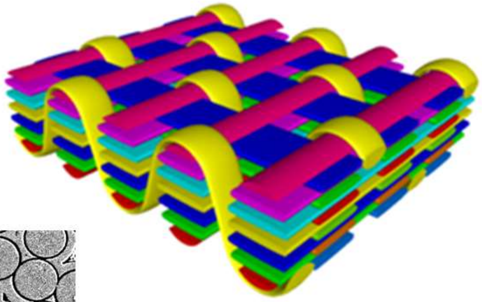
- Demonstrated a durable 2700°F CMC / EBC system in a turbine environment
- Measured effect of through-thickness thermal gradient on CMC deformation in creep and fatigue at 2700°F
- Initiated test program to understand effect of cooling holes on durability of 2700°F CMC
- Used Digital Image Correlation with Acoustic Emission measurements to measure damage progression in CMC/EBC “mini-composites”
- Characterized CMAS infiltration of advanced EBC materials

NASA 2700°F CMC combines three technology advancements

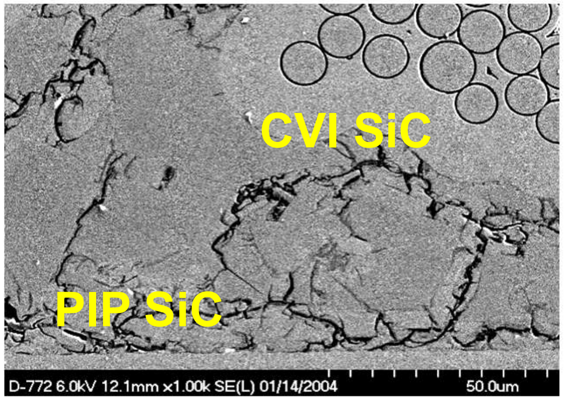
- Creep-resistant Sylramic-iBN fiber



- Advanced 3D fiber architecture



- Hybrid CVI-PIP SiC matrix



Creep and fatigue tests demonstrated durability of 3D hybrid-matrix CMC at 2700ºF

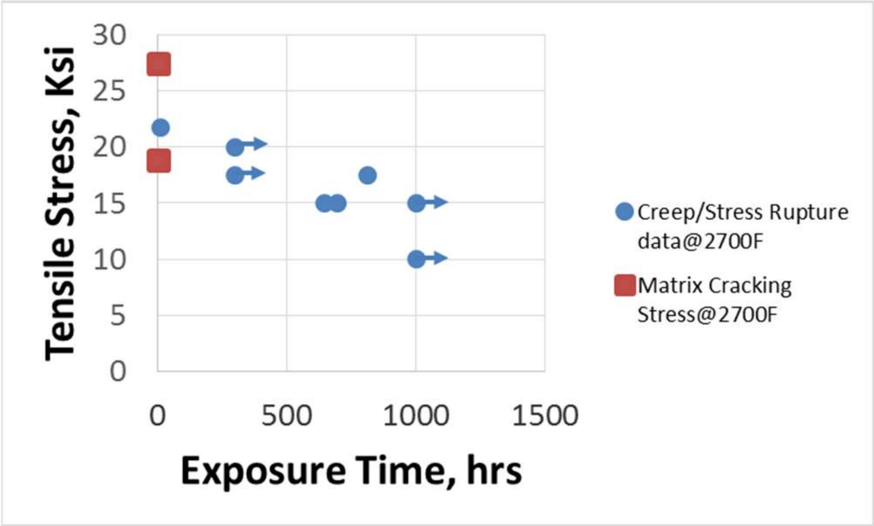
Challenge

Durable 2700°F Ceramic Matrix Composites will reduce cooling air required for turbine engine components, increasing engine efficiency and reducing fuel burn and emissions

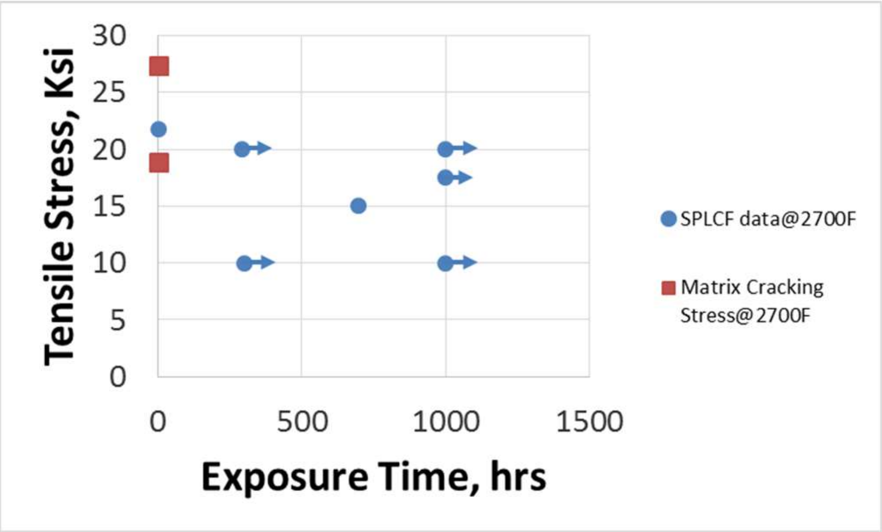
Approach

Characterize mechanical properties and durability of TTT-developed CMC at 2700 °F

Creep Rupture



Fatigue (SPLCF)



CMC shows 1000 hours durability at 2700ºF and 15-20 ksi in creep and fatigue

Contact: Ramakrishna.T.Bhatt@nasa.gov

Durable CMC / EBC system demonstrated in 2700°F turbine environment

Challenge

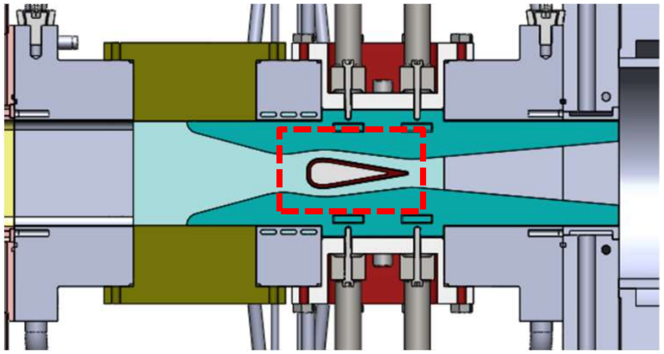
A durable 2700°F Ceramic Matrix Composite with Environmental Barrier Coating would reduce cooling air required for turbine engine components, increasing engine efficiency and reducing fuel burn and emissions

Approach

- Fabricate turbine vane test article from 2700°F CMC recently developed in TTT
- Coat CMC test article with Environmental Barrier Coating, using two different EBC processing methods
- Evaluate durability of CMC / EBC subelements in a TRL 5 rig test simulating a turbine environment, at temperatures to 2700°F

Significance

For the first time, a durable CMC/EBC material system was demonstrated at TRL 5 in a 2700°F turbine environment. Engine implementation could reduce fuel burn 6% in B737-size aircraft



Turbine test rig used by P&W / UTRC

Spall of EB-PVD coating after 7 hours of 2700F cycles

Durable slurry-coated test article after 15 hours at 2500 / 2600 / 2700°F

Key Accomplishment

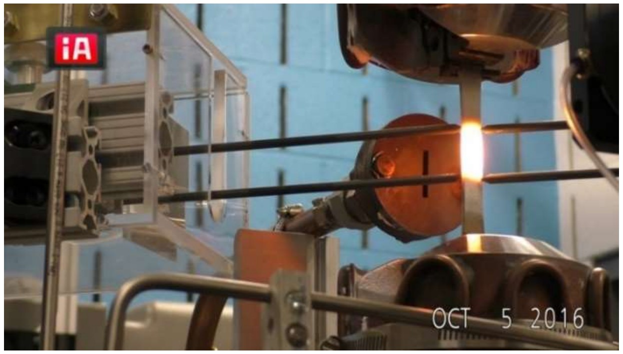
Demonstrated 15-hour durability for a CMC/EBC system with minimal spallation of the coating under simulated engine operating conditions at temperatures to 2700°F

Contact: Ramakrishna.T.Bhatt@nasa.gov

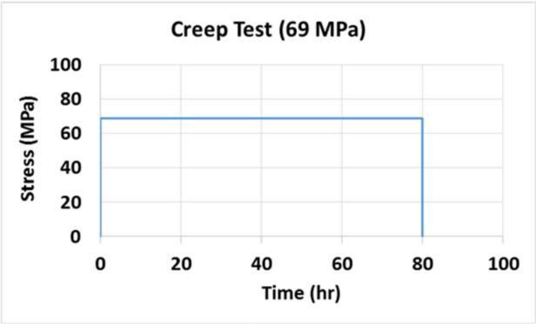
Effect of thermal gradients on sequential tensile creep and SPLCF testing on SiC/SiC CMCs at 2700 °F

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

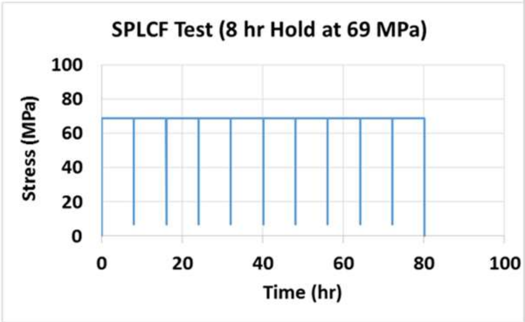


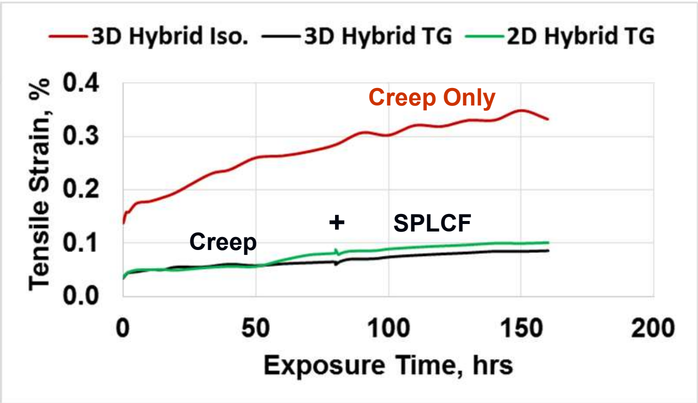
Creep Loading Segment



+

SPLCF Loading Segment



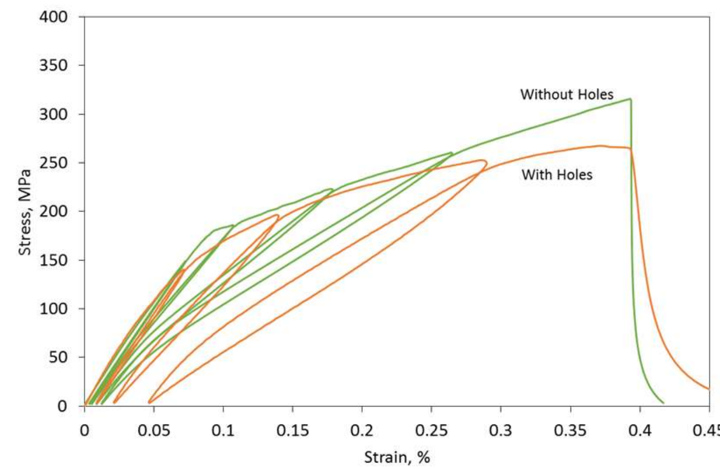


Isothermal tensile creep test on 3D hybrid CMC generated highest tensile strain followed by TG test on 2D hybrid matrix CMC. Uncoated CMCs sustained steady thermal gradients for a total of 160 hr., with creep at 10 ksi for 80 hr. followed by SPLCF at 10 ksi max. stress for 80 hr., without an EBC.

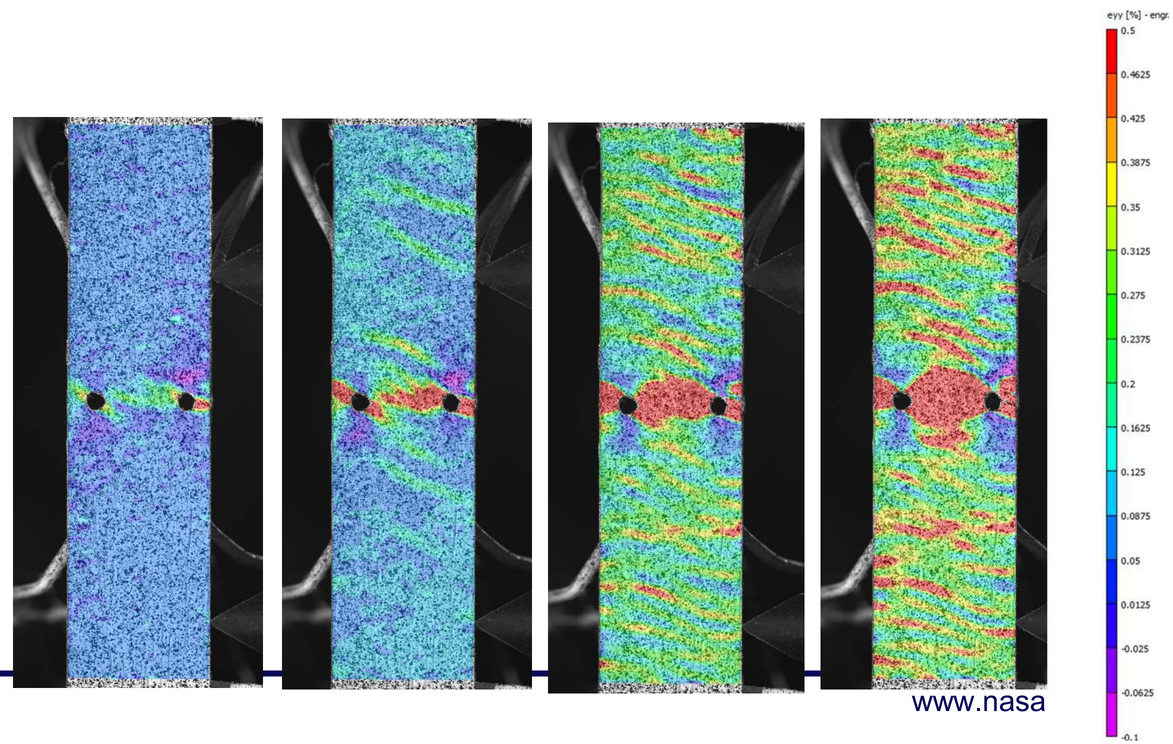
Contact: Sreeramesh.Kalluri-1@nasa.gov

Open Hole Testing to Evaluate Durability of 2700°F CMC with Cooling Holes

Test specimens with various cooling hole configurations are instrumented with Digital Image Correlation, Electrical Resistance and Acoustic Emission sensors to monitor damage progression during load/unload cycles



Results will be used to validate durability models and optimize design of cooled CMC components



Contact: Craig.E.Smith@nasa.gov

Use of Digital Imaging and Acoustic Emission Measurement to Monitor CMC / EBC Damage Progression

Objective:

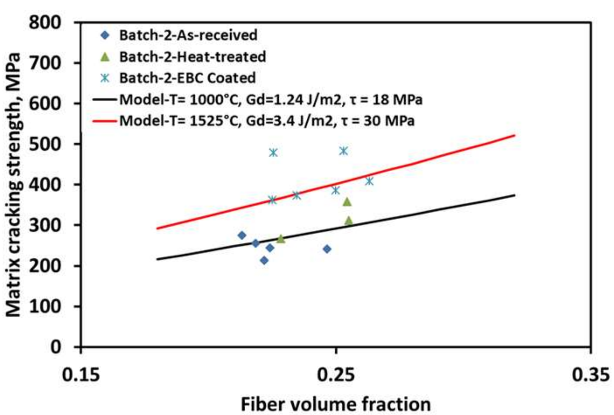
Assess surface and subsurface damage mechanisms, respectively, in the EBC-CMC system

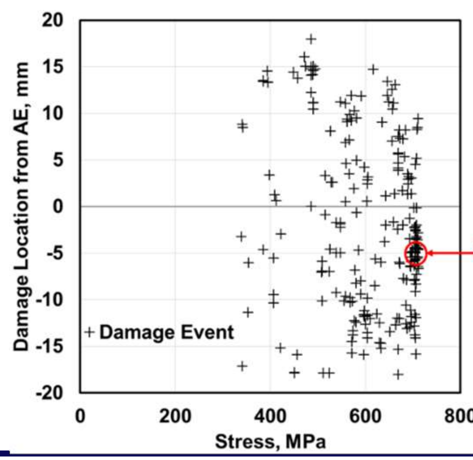
Approach:

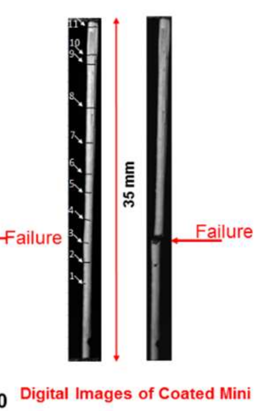
- Test as-received, heat-treated and EBC-coated SiC/SiC minicomposites.
- Micromechanical modeling of matrix cracking strength of the tested minicomposites.
- Digital Imaging and Acoustic Emission health monitoring techniques were used to assess surface and subsurface damage mechanisms, respectively, in the EBC-CMC system.

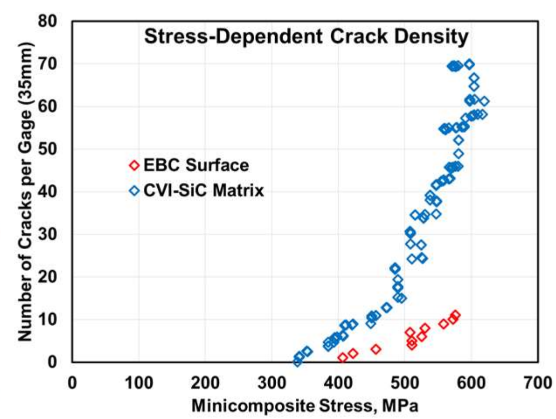
Results:

- Micromechanical modeling of matrix cracking strength showed that the high matrix cracking stress in the EBC coated minicomposites could be due to the increase in thermal residual stresses and the increase in either interfacial shear strength or increase in fiber/BN interphase debond energy due to BN exposure to the high sintering temperatures or both.
- Failure location obtained from AE agrees well with that observed by digital imaging.
- EBC coating appears to have significantly less cracks than CVI-SiC matrix which warrants further investigation.









Contact: Amjad.Almansour@nasa.gov

Consortium Established for CMC/EBC Environmental Durability Testing, Modeling & Validation

NASA Glenn

- Conduct mechanical testing of mini-composites at 2200-2700°F in air and steam environments
- Optimize EBC/CMC interface based on bonding and crack deflection
- Develop and validate models for mini-composite properties, durability and failure modes

Rolls Royce HTC

- Fabricate CMC mini-composites using industry fabrication processes and constituents
- Define relevant material operating conditions; stress, temperature, environment

Univ. California Santa Barbara

- Microstructural characterization of damage progression using Digital Image Correlation, Acoustic Emission measurement and SEM
- NASA Space Technology Research Fellowship

Air Force Research Labs

- Damage characterization using Digital Image Correlation and AE methods
- Microstructural characterization by High Energy x-ray imaging (w/ UC Berkeley) and automated serial sectioning of test specimens with data reconstruction

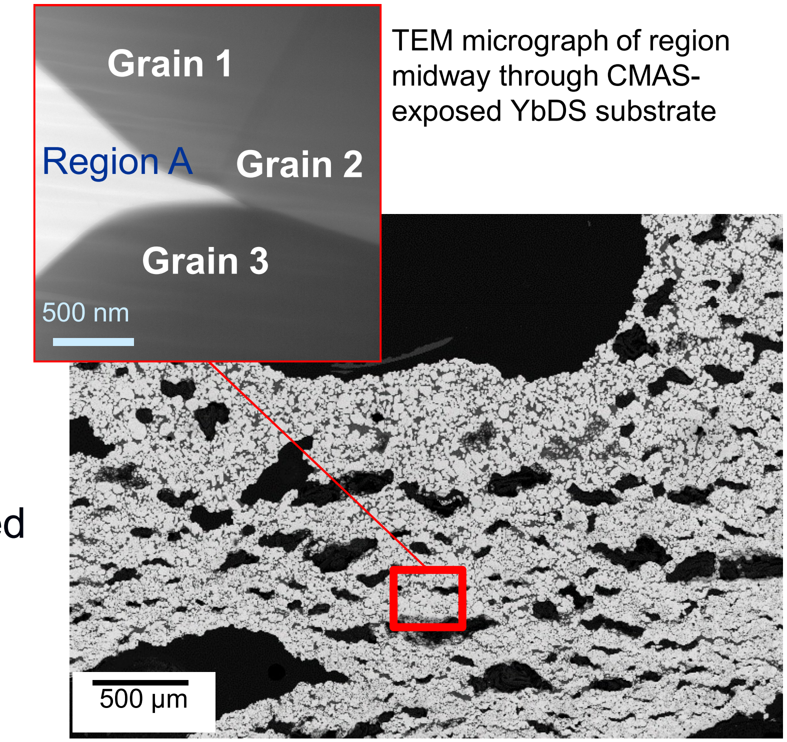
Contact: James.D.Kiser@nasa.gov

Development of CMAS-resistant EBCs

PROBLEM: Above 1100°C, molten calcium-magnesium-aluminosilicate (CMAS) can degrade environmental barrier coatings via thermochemical interactions, resulting in premature EBC failure

APPROACH:

- Understand causes of EBC degradation by characterizing thermochemical interactions of CMAS with ytterbium disilicate (YbDS) EBC
- Expose hot-pressed YbDS substrates to CMAS at 1200-1500ºC for 1- 50 hour durations
- Evaluate CMAS/YbDS interactions using transmission electron microscopy (TEM), selected area diffraction (SAD) and energy dispersive spectroscopy (EDS) for microstructural and compositional analysis



TEM micrograph of region midway through CMAS-exposed YbDS substrate

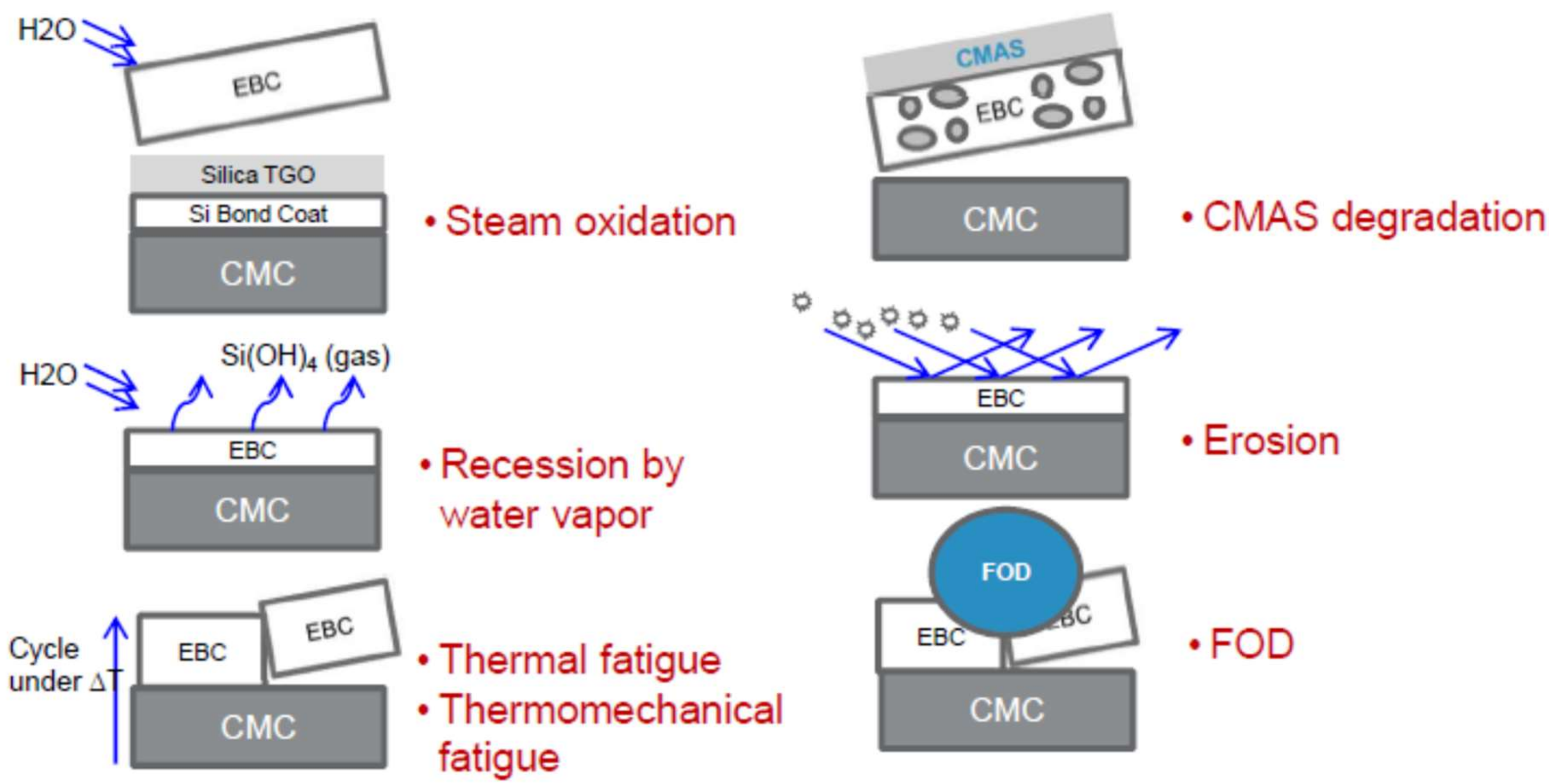
CMAS/YbDS substrate after 1500ºC-50h

OBSERVATIONS:

- CMAS infiltrated YbDS substrate, suggesting ytterbium disilicate is not effective as a standalone CMAS-resistant EBC
- TEM study revealed no apatite ($Ca_2Yb_8(SiO_4)_6O_2$) phase formation, supporting results from previous characterization

Contact: Valerie.L.Wiesner@nasa.gov

EBC Failure Modes Investigated



Contact: Ken.K.Lee@nasa.gov

CMC / EBC Durability

Modeling & Validation

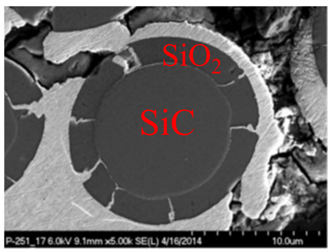
- Demonstrated an analytical model to predict oxidation effects on durability of SiC fibers during creep testing
- Developed a computational approach to simulate CMC damage development in a steam environment

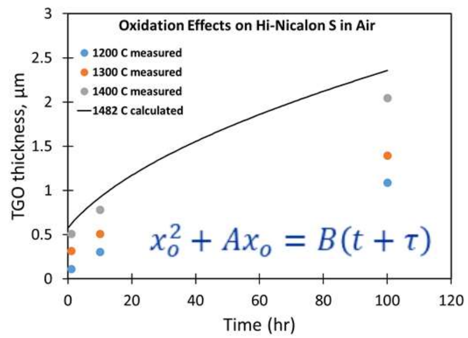
Characterization of SiC Fiber Creep Response During Oxidation

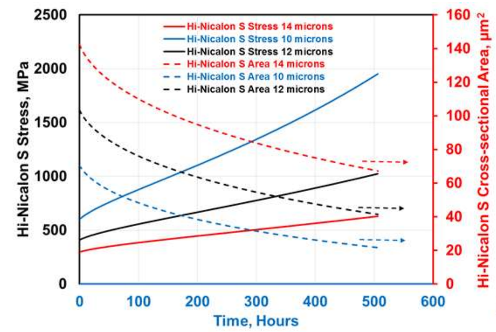
Objective: Isolate SiC fiber creep response from the confounding effects of oxidation at 1482 °C.

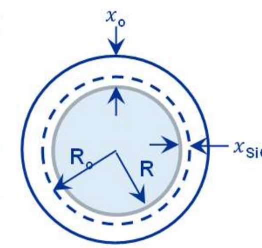
Approach:

- Thermally grown oxide growth was measured @ T≤1400°C. TGO growth model extrapolated to 1482°C.
- Finite element analysis of fiber w/ TGO reveals that TGO provides no structural rigidity to fiber at 1482°C.
- SiC fiber area reduction for Hi-Nicalon S at 1482°C was calculated from TGO growth model.
- Time-varying stress increase due to fiber area reduction was used to extract true Hi-Nicalon S fiber creep parameters from fiber creep test data obtained in air at 1482°C.







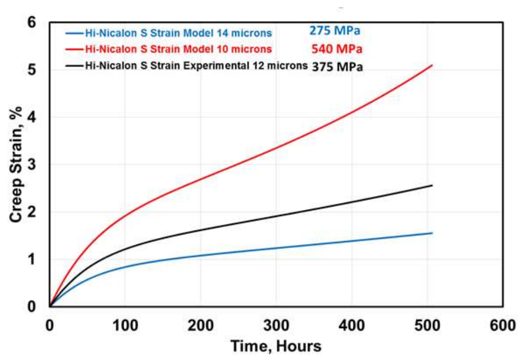


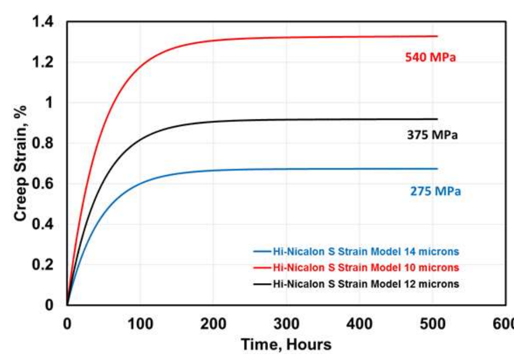
$$R = R_o - \left(\frac{v_{SiC}}{v_{SiO2}}\right)x_o$$

Results:

- Only significant effect of oxidation on creep response is reduction in fiber cross-sectional area.
- Significant increase in fiber stress due to the reduction in Hi-Nicalon S fiber cross-sectional area.
- Creep strain induced by fiber area reduction was much higher than that from initial applied stress.

Creep response w/ time-varying stress



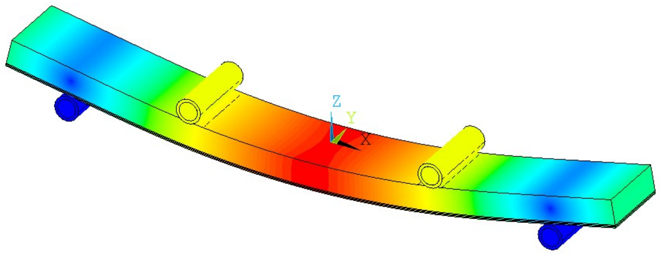


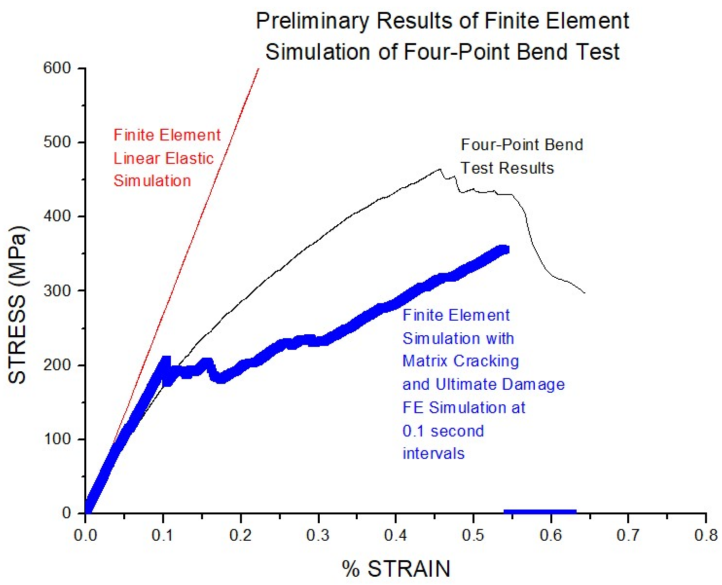
Constant stress creep response

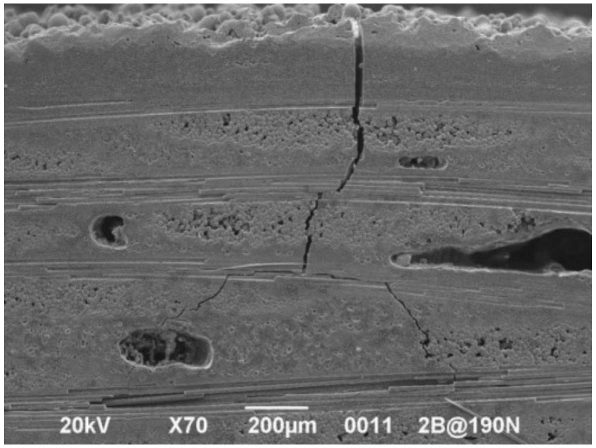
Contact: Roy.M.Sullivan@nasa.gov

Modeling effects of steam environment on CMC durability & failure modes

Finite Element analysis of CMC/EBC deformation under flexural loading







Matrix crack propagation in CMC flexural specimen

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

Additive Manufacturing

- Optimized “Binder Jet” process to maximize density of monolithic SiC matrix for ceramics and CMCs
- Fabricated lightweight and compact electric motor components using Direct Printing & Electron Beam Freeform processes

Additive Manufacturing for Electric Motor Fabrication

Objective: Use additive manufacturing methods to fabricate electric motors with higher efficiency and power density

Approach:

- Use Direct Printing and Electron Beam Freeform processes to build lightweight and compact rotor, stator & motor housings for advanced motors
- Measure improvements in motor efficiency and power density compared to baseline SOA motor

Urban Air Mobility Application

Baseline Motor:
7.5-inch diam and 4 lbs

Advanced Motor Design with AM components

AM motor design enables a 2x increase in power density (10 kW/kg)

LAUNCHPOINT TECHNOLOGIES

UTEP

Contact: Michael.C.Halbig@nasa.gov

NASA GRC Focus in 2019

CMC Development & Model Validation

- Measure effects of engine environment (steam, CMAS) and cooling holes on CMC / EBC durability and failure modes
- Determine effects of CMC / EBC interface surface finish on durability in 2700°F turbine environment
- Validate CMC creep model at 2700ºF with mini-composite tests
- Validate SiC fiber crack growth model for CMC rupture life prediction

Additive Manufacturing

- Develop CMC "Binder Jet" fabrication process using chopped-fiber reinforcement and fully-dense SiC matrix
- Measure improvements in efficiency and power density of lightweight electric motors fabricated using Additive Manufacturing methods

Support for CMC research comes from these NASA programs:

Advanced Air Vehicles Program

- Advanced Air Transport Technology Project

Transformative Aeronautics Concepts Program

- Transformational Tools & Technologies Project
- Convergent Aeronautics Solutions Project