



Understanding the durability of SiC based ceramic matrix composites (CMCs) for gas turbine engine hot section components

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Outline

- **Motivation & CMC Applications**
- **CMCs processing, fiber architectures**
- **Use of minicomposites to understand the influence of constituent types and contents on mechanical behavior and creep**
- **Use of minicomposites to screen CMC/EBC systems**
- **Concluding remarks**

SiC/SiC CMC Turbine Engine Hot Section Components

SiC_f/SiC Ceramic Matrix Composites (CMCs) are being implemented in high-temperature applications such as the new generations of aircraft engines to obtain several advantages:

- 1) Engine efficiency can be improved by using high-temperature capable CMC components
- 2) Component weight, cooling requirements, and fuel consumption & emissions (NO_x and CO₂) can be reduced by integrating CMC components.



2400°F (1316°C) **Today**



2700°F (1482°C)+ **Future**

Development of a 2700°F Capable SiC/SiC CMC offers the potential for additional significant fuel burn reduction

Current Approaches for Manufacturing of SiC/SiC CMCs

Preforming and Interphase

- *2D, 3D Woven: require tooling, fiber tows bend within the weave.*
- *Lay-up laminate: requires hand lay-up, fiber tows remain straight.*

Chemical Vapor Infiltration (CVI) Process

A gas mixture is infiltrated and SiC is deposited into a fiber preform.

- *Slow; large objects can take weeks to months.*
- *Produces large pores*

Polymer Infiltration/Pyrolysis (PIP) Process

Preceramic polymer infiltration and pyrolysis to create a SiC based matrix.

- *Multiple steps to achieve matrix density*

Melt Infiltration (MI) Process

Slurry coated preregs or infiltration of slurry/ resins into a fiber preform.

- *Infiltration of liquid silicon to react with carbon to form SiC.*

Hybrid Process

Combination of CVI/PIP, CVI/MI, or PIP/MI to create a SiC based matrix.

- *Several steps to make a matrix*

Post Processing and Nondestructive Evaluation

Machining
(grinding, milling, drilling)

Joining
(brazing and attachments)

Coating and Finishing
NDE

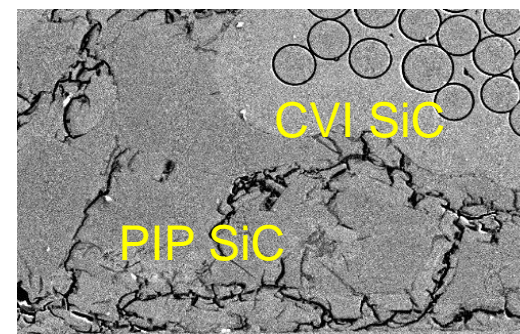
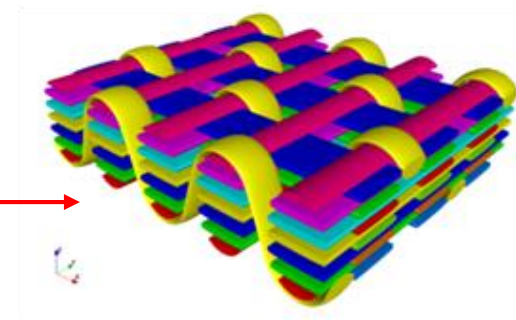
NASA GRC Development of 2700°F (1482°C) - Capable CMCs

Incorporates Several Technology Advancements

Addressed by:

Exploring the combination of:

- **Creep-resistant SiC fiber**
 - Evaluated Hi-Nic S™, Sylramic™-iBN, and Super Sylramic™-iBN
- **Advanced 3D fiber architecture**
 - Evaluated weaves including orthogonal and angle interlock with high fiber content in the “loading” direction
- **“Hybrid” CVI-PIP SiC matrix**
 - CVI SiC matrix around BN-coated SiC fibers, with 30 - 35% porosity remaining, followed by PIP





Considerations for Design of CMCs

Issue: Need for a SiC/SiC CMC with high strength, excellent creep resistance, and good transverse strength and thermal conductivity, for use at 2700°F.

Addressed by optimizing the following:

➤ ***Constituent selection***

- **SiC fiber:** slow crack growth, creep resistance, strength, oxidation, CTE and surface roughness.
- **Single or multi-layered interphase:** crack deflection, debonding, sliding and oxidation.
- **Matrix:** creep resistance, oxidation, density, surface roughness, and CTE compatibility with fibers.

➤ ***Fiber architecture and the resulting constituent content in the various directions***

- **Fiber volume fraction and orientation** with respect to the “loading” direction.
- **Can be tailored** to satisfy specific component geometry and thermostructural requirements.

➤ ***Environmental barrier coating (EBC)***

- **EBC environmental protection** is influenced by EBC bonding to CMC, EBC resistance to cracking, thickness, chemistry, EBC compatibility with CMC (CTE), thermomechanical durability, steam oxidation resistance, hydroxide formation/recession, CMAS attack & infiltration, erosion and FOD.

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

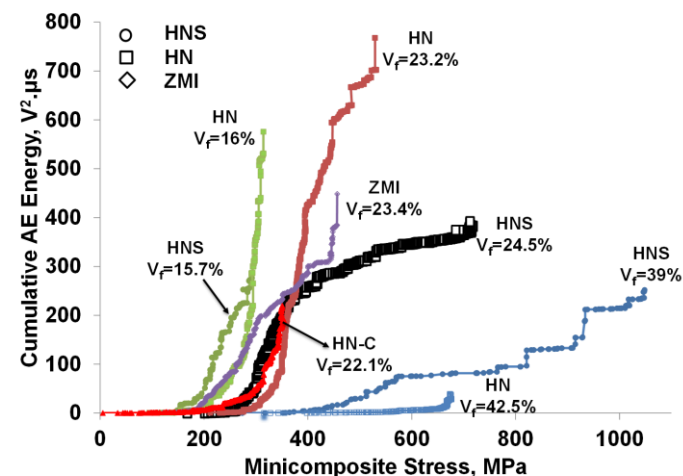
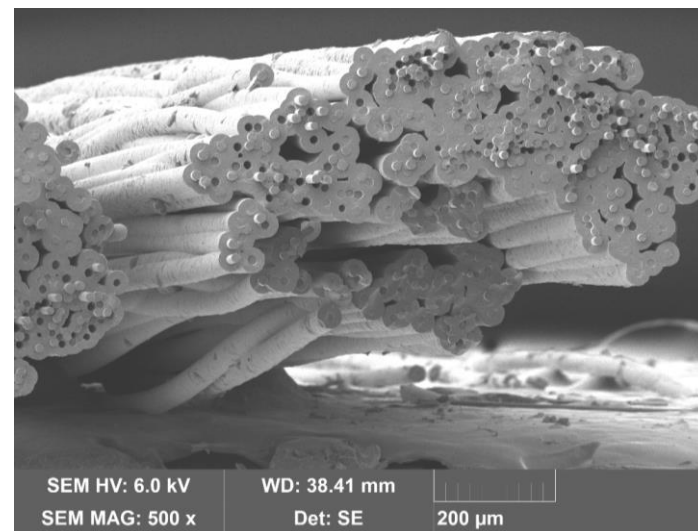
Use of Minicomposites to Study the Role of Different Constituents and Processing Variables

Advantages:

- The minicomposites contain SiC fibers with a boron nitride (BN) interphase and a chemical vapor infiltrated silicon carbide (CVI-SiC) matrix.
- A single fiber tow CVI-SiC/SiC minicomposite can be considered the basic architectural feature of woven and laminate SiC/SiC CMCs.
- The minicomposite mechanical and tensile creep damage behavior represents the creep behavior of 0° fiber tows in the axial loading direction of a macrocomposite or component.
- The minicomposite represents the microstructure in the perimeter of a macrocomposite or component where most of the damage would typically initiate.
- A large number of minicomposite samples can be fabricated at a relatively low cost within a short time.

Limitations:

- Minicomposites can't be used to obtain mechanical properties of the composite in the transverse direction.
- It requires additional careful handling to prevent inducing damage.





Control of CVI-SiC Morphology

Morphological Control of CVI-SiC Matrix

Objective:

- Collaborate with UCONN to optimize processing parameters for chemical vapor deposition of CVI-SiC matrix.

Approach:

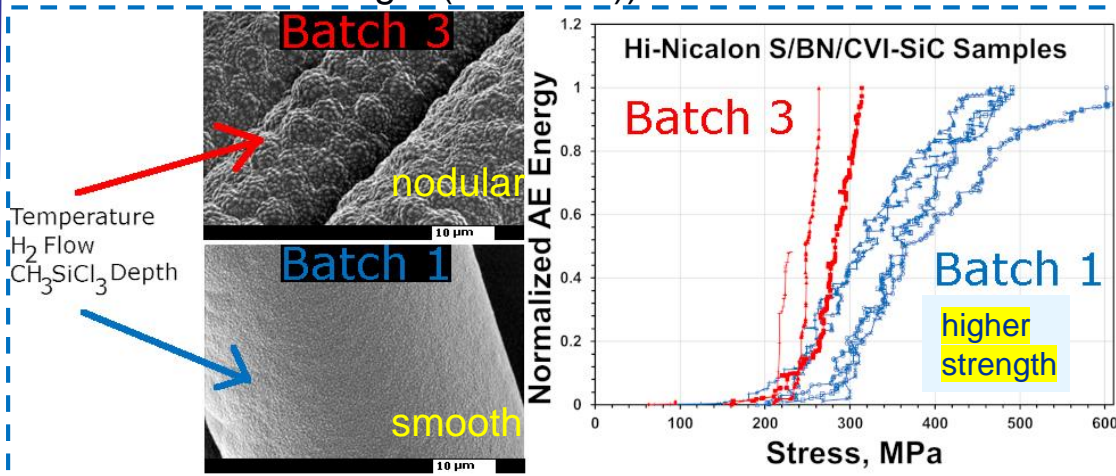
- Tuned the reaction parameters of atmospheric pressure SiC CVI using CH_3SiCl_3 to control the morphology of the coatings produced by varying the depth of CH_3SiCl_3 from 1 to 14 cm, temperature from 1000 to 1100 °C, and flow rate of H_2 carrier gas from 5 to 30 SCCM.
- Coating morphologies ranged from smooth to very nodular, where spherical growths were present along the entire deposition zone. The parameters that yielded a smooth deposition throughout the 20 cm deposition zone were 4–6 cm of $\text{CH}_3\text{SiCl}_3(\text{l})$ depth, 1100 °C, and 10 SCCM of H_2 as a carrier gas.
- Tensile testing with acoustic emission monitoring was performed on fabricated $\text{SiC}_f/\text{BN}/\text{CVI-SiC}$ minicomposites with different coating morphologies.

Approach (continued):

- Correlated the process parameters with the resulting microstructure and its tensile behavior.

Significance:

- Nodular SiC matrix coatings promoted premature cracking and significantly reduced composite toughness. Samples with smooth coatings had higher average matrix cracking strength (248 MPa) and ultimate tensile strength (541 MPa) than the samples with nodular coatings (average matrix cracking strength (147MPa) and ultimate strength (226 MPa)).



Accomplishments:

- Determined the process parameters that can produce a range of different CVI-SiC morphologies and resulting range of mechanical properties.



Testing and Modeling the Tensile Creep of SiC_f/SiC Minicomposites

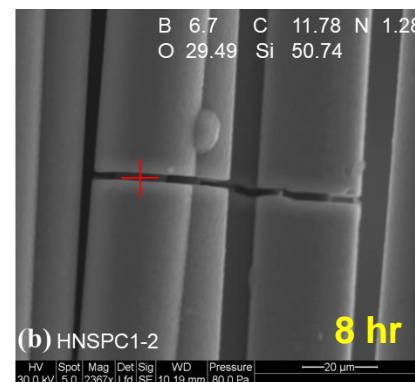
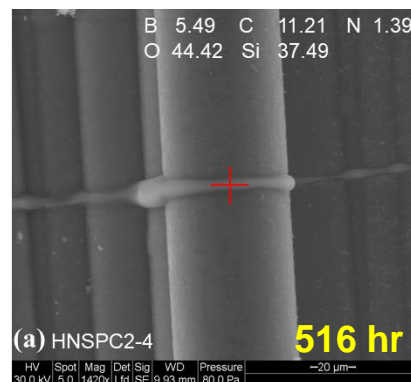
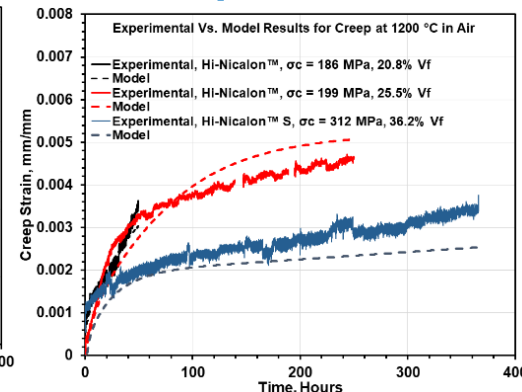
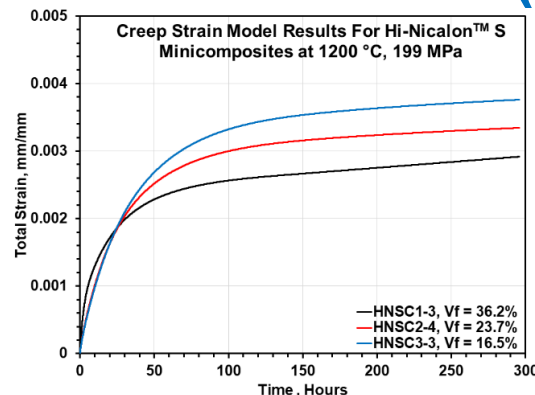
Testing and Modeling the Creep Behavior of Various CMCs and Their Constituents at 1200°C (2200 °F)

Objective:

To understand the effects of fiber type, fiber content, and matrix cracking on tensile creep in SiCf/SiC CMCs, single-tow SiCf/SiC minicomposites with different fiber types and contents were investigated.

Approach:

- Performed tensile creep tests of uncracked and precracked minicomposites, CVI-SiC matrix and single SiC fibers at 2200 °F.
- A bottom-up creep modeling approach was applied where creep parameters of the fibers and matrix were obtained separately at 2200 °F.
- Theoretical model based on the rule of mixtures was derived to model the fiber and matrix creep-time-dependent stress redistribution.
- Fiber and matrix creep parameters, load transfer model results, and numerical modeling were used to construct a creep strain model to predict creep damage evolution of minicomposites with different fiber types and contents.
- The model was validated on SiC/SiC minicomposites containing two different SiC fibers (which had considerable differences in creep behavior) and a range of fiber volume fractions.



Significance:

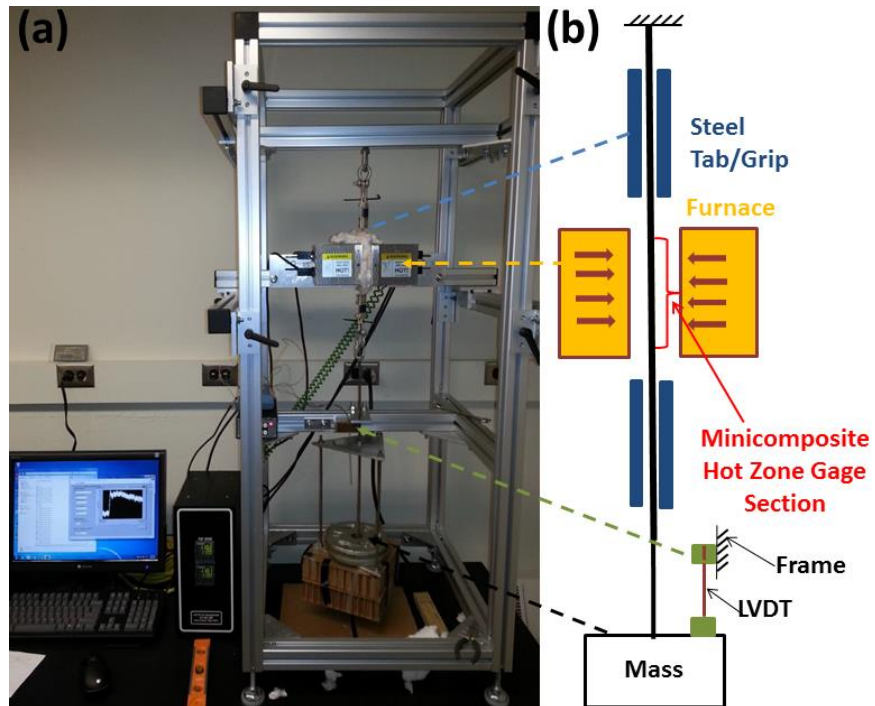
- Testing and modeling the creep behavior of various CMCs and their constituents at 2200 °F.
- Understanding the effect of cracking and oxidation on the tensile creep behavior and life of CMCs.

Accomplishments:

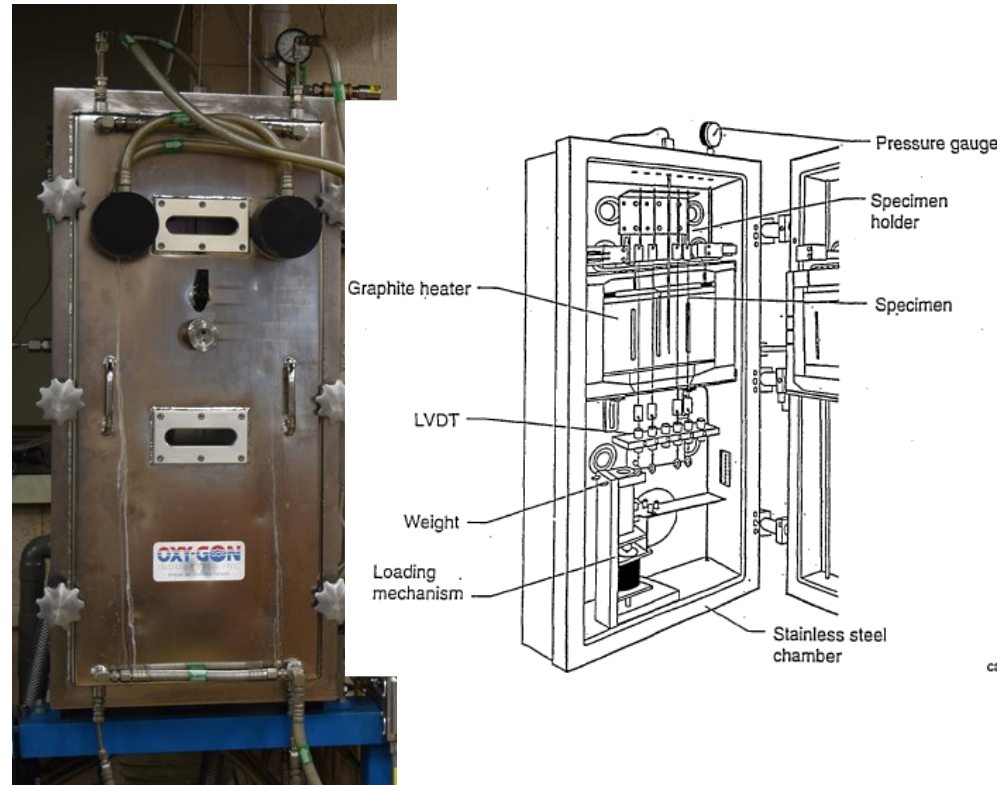
Advanced the understanding of thermomechanical behavior and high temperature durability of CMCs with a wide range of constituents & fiber volume fractions.

Creep Experiments

Minicomposites & Matrix in Air



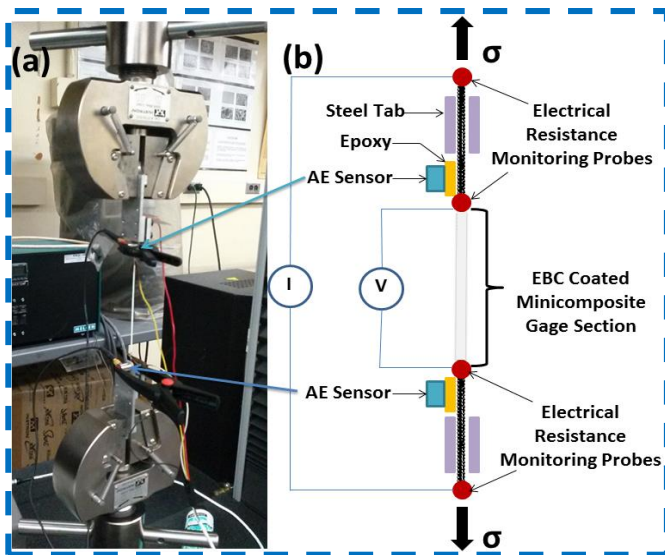
Fiber Creep in Vacuum



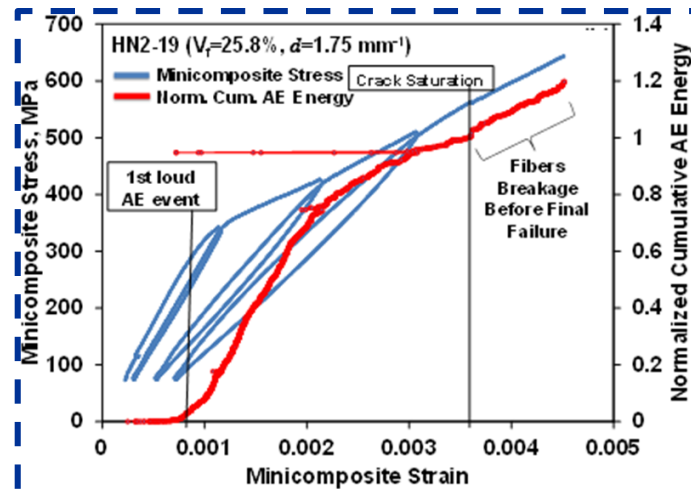
Constituent Type	Elastic Modulus (GPa)	Density (g/cc)	Number of Fibers per Tow	Average Fiber Diameter (μm)	Fiber Volume Fractions (%)
Hi-Nicalon™ S	400	3.1	500	12	3/16/23/43
Hi-Nicalon™	270	2.74	500	14	16/23/42
CVI-SiC Matrix	425	3.2	-	-	-

Fast Fracture and Precracking Methodology

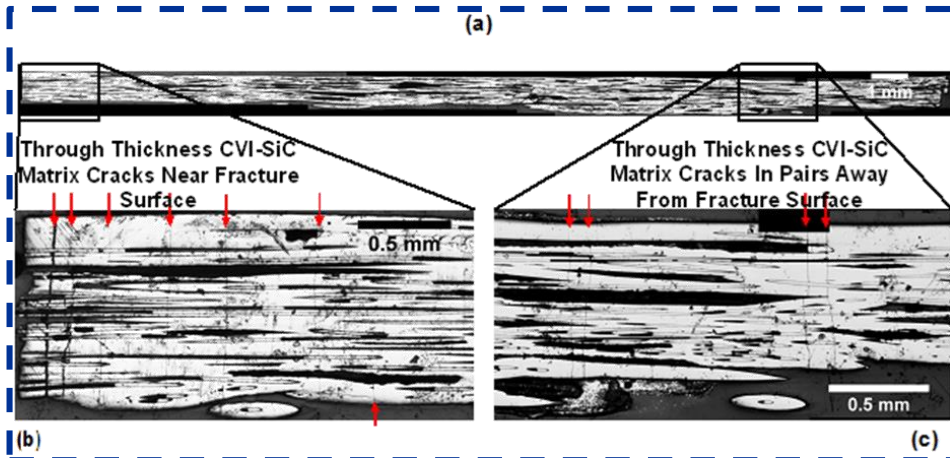
1) Tensile test minicomposite.



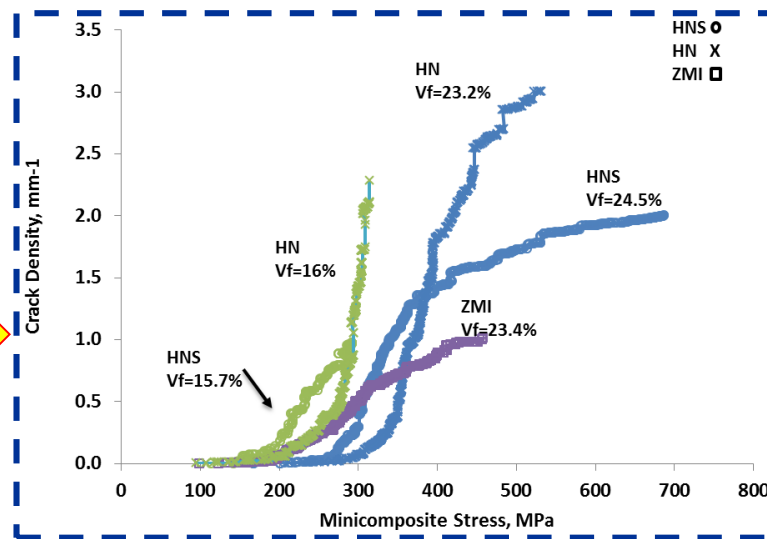
2) Plot Stress-Strain & AE energy.



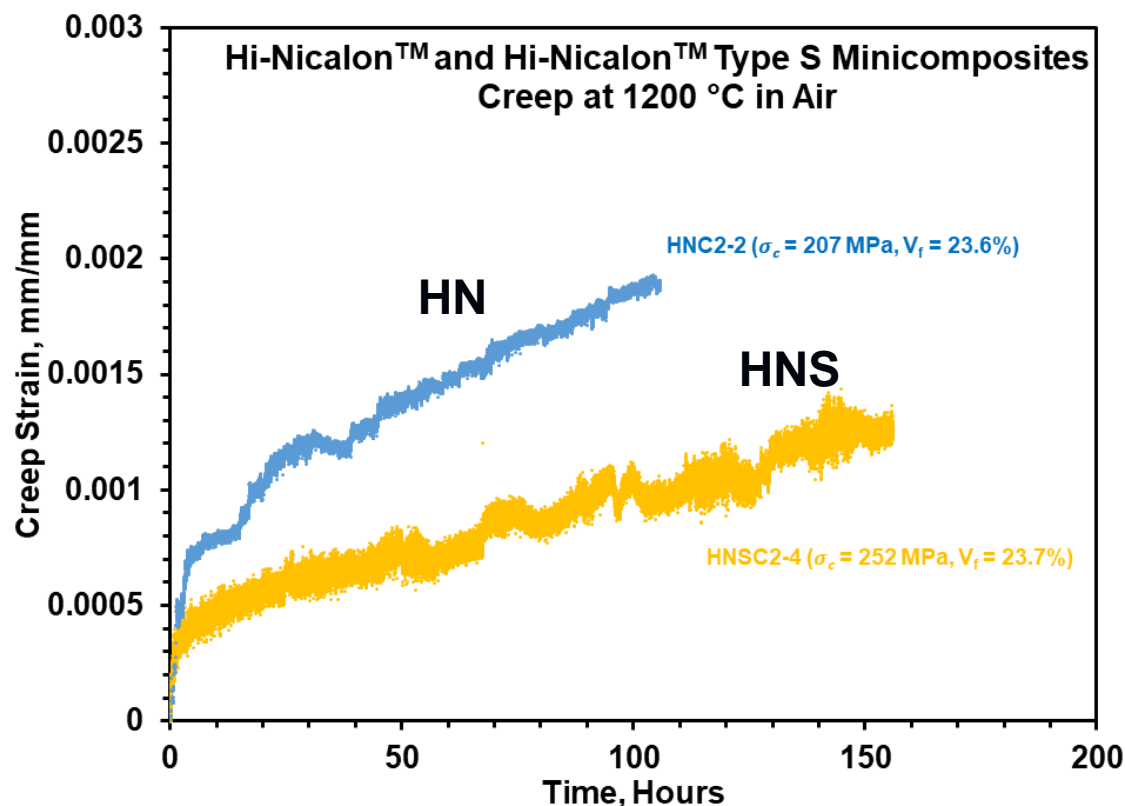
3) Examine cracking along the length.



4) Determine evolution of crack density.

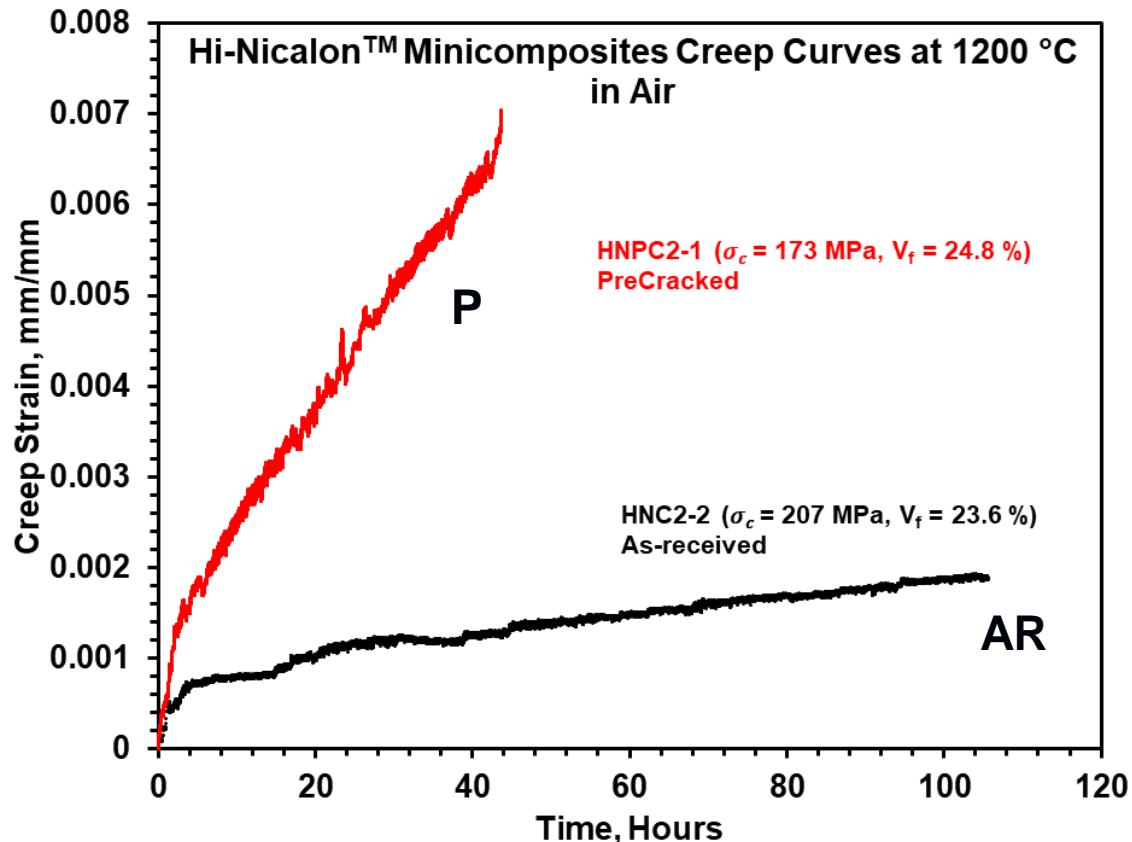


Effect of Fiber Type on Creep



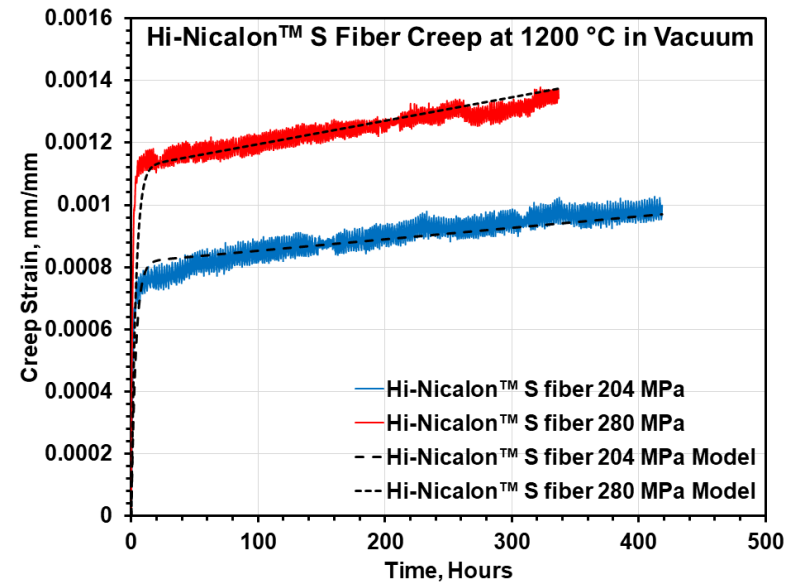
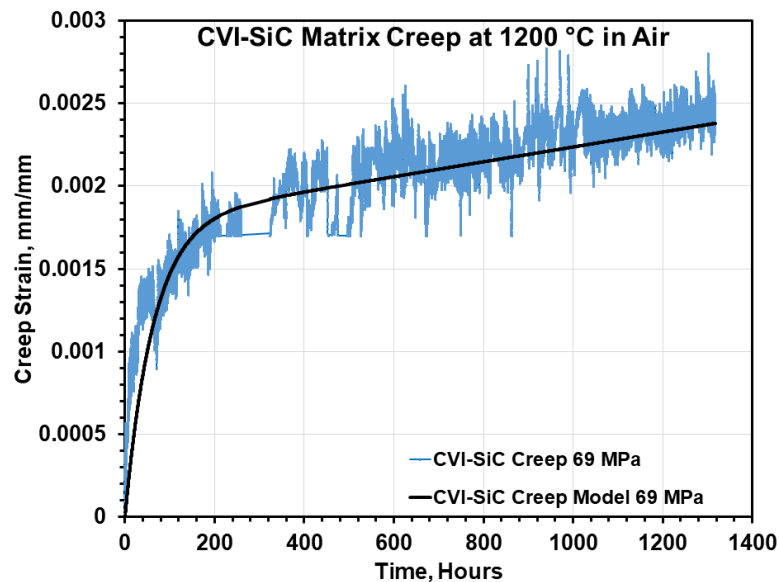
- HN minicomposite: exhibits higher creep strain, strain rate, and total strain as well as a slightly shorter time to rupture than HNS.
- The HN fiber microstructure consists of small SiC grains with an excess of free carbon, whereas HNS fibers have a polycrystalline microstructure with larger grain size and contain less excess carbon and oxygen, and are thus more creep resistant.

Effect of Matrix Damage State on Creep



- Fibers are not fully loaded in the uncracked (AR) specimen. The matrix carries some load, and the stress on the fibers is a fraction of that on fibers in the precracked case.
- Oxidation in the vicinity of matrix cracks in the precracked (P) specimen leads to environmental degradation, causing fiber embrittlement and the loss of fiber load-bearing capacity, increasing creep strain and strain rate, and shortening the life.

Fiber & Matrix Creep Model & Parameters



Matrix Creep Model

$$\varepsilon_m = \frac{\sigma_m}{E_m} + \sigma_m A_m [1 - e^{(-P_m t)}] + B_m \sigma_m^{n_m} t$$

Fiber Creep Model

$$\varepsilon_f = \frac{\sigma_f}{E_f} + \sigma_f A_f [1 - e^{(-P_f t)}] + B_f \sigma_f^{n_f} t$$

Constituent	A (1/MPa)	P (s ⁻¹)	B (s ⁻¹ /MPa)	n (Stress exponent)
Hi-Nicalon™	2.127x10 ⁻⁵	1.485x10 ⁻⁵	1.77x10 ⁻¹⁵	2.3
Hi-Nicalon™ S	4x10 ⁻⁶	8x10 ⁻⁵	6x10 ⁻¹⁶	2.265
CVI-SiC Matrix	2.59x10 ⁻⁵	4.432x10 ⁻⁶	1.81x10 ⁻¹²	1

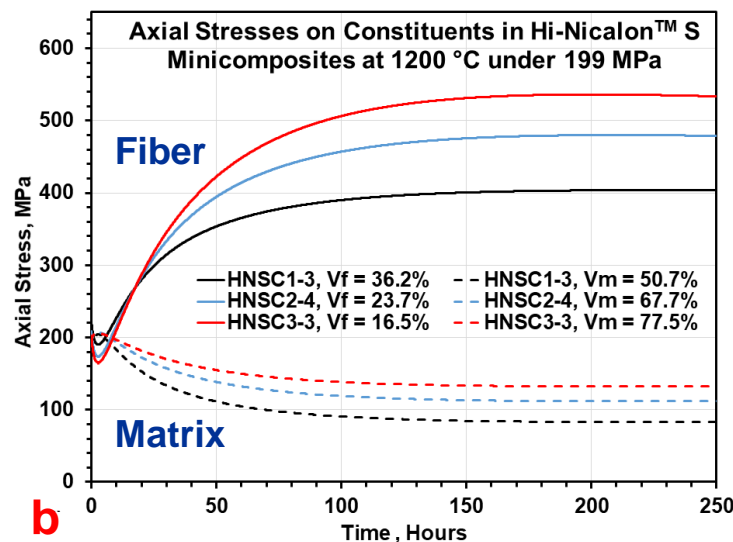
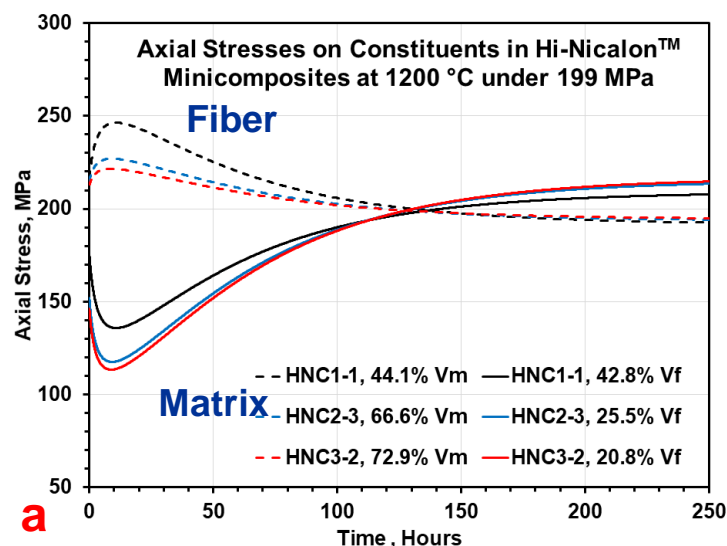
Creep Load Sharing Model Results

Fiber Stress Rate:

$$\dot{\sigma}_f = \frac{\sigma_m A_m P_m [e^{(-P_m t)}] - \sigma_f A_f P_f [e^{(-P_f t)}] + B_m \sigma_m^{n_m} - B_f \sigma_f^{n_f}}{\left[\frac{1}{E_f} + A_f - A_f e^{(-P_f t)} + \frac{V_f}{V_m E_m} + \frac{A_m V_f}{V_m} - \frac{A_m V_f e^{(-P_m t)}}{V_m} + B_f n_f \sigma_f^{n_f-1} t + \frac{B_m n_m V_f \sigma_m^{(n_m-1)} t}{V_m} \right]}$$

Fiber Stress

$$\sigma_{f(i)} = \sigma_{f(i-1)} + \Delta t \dot{\sigma}_{f(i-1)}$$



- Axial stress redistributions on the fibers and matrix were predicted during creep at 1200 °C for different minicomposite stresses and fiber volume fractions.
- The initial increase in stress on the matrices in Figs. a and b during the first few hours of creep is due to the elastic modulus and creep resistance mismatch between the fiber and the matrix.
- Load shedding slows down after 100 hours in creep as the minicomposite secondary creep mechanism becomes more dominant, where the stress on each constituent becomes constant. The fibers start carrying more stress than the matrix at a crossover time of 130 hours for HN fibers and 25 hours for HNS fibers.

Creep Experiment Vs. Model

$$\varepsilon_f(t_i) - \frac{\sigma_f}{E_f} - \sigma_f A_f [1 - e^{-P_f t_i}] - B_f \sigma_f^{n_f} t_i = 0$$

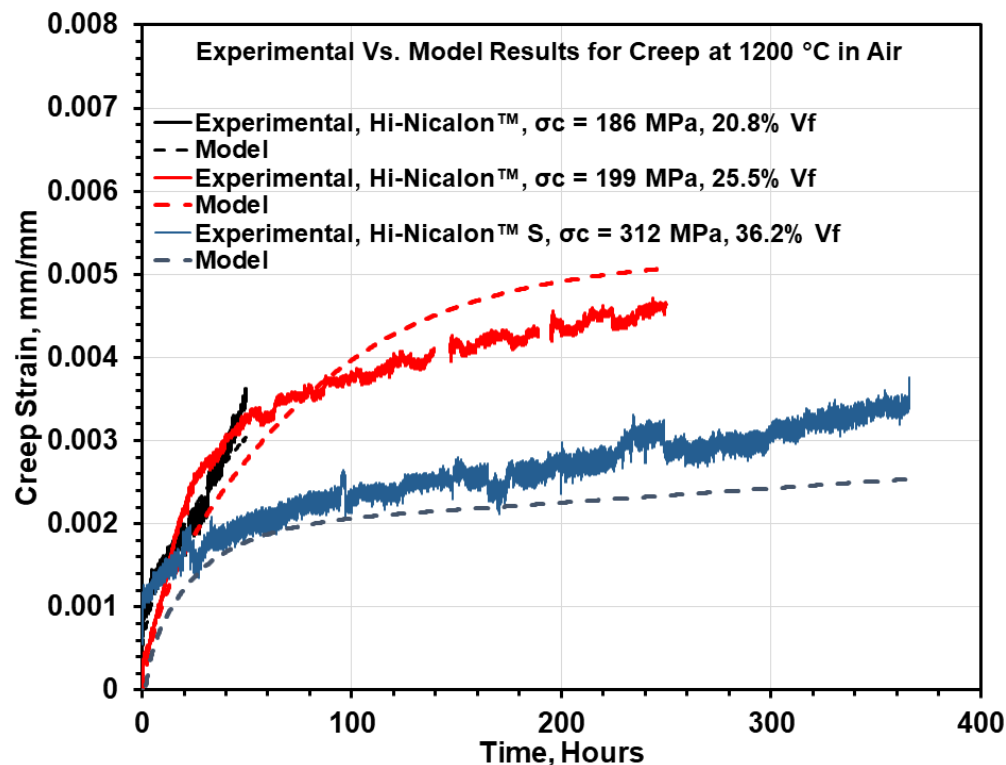
$$t_{i+1}^* = t_i - \frac{\varepsilon_f(t_i)}{\varepsilon_f'(t_i)}$$

$$\varepsilon_f'(t_i) = \frac{\varepsilon_f(t_i) - \varepsilon_f(t_{i-1}^*)}{t_i - t_{i-1}^*}$$

$$t_{i+1}^* = t_i - \frac{\Delta * \varepsilon_f(t_i)}{\varepsilon_f(t_i) - \varepsilon_f(t_{i-1}^*)}$$

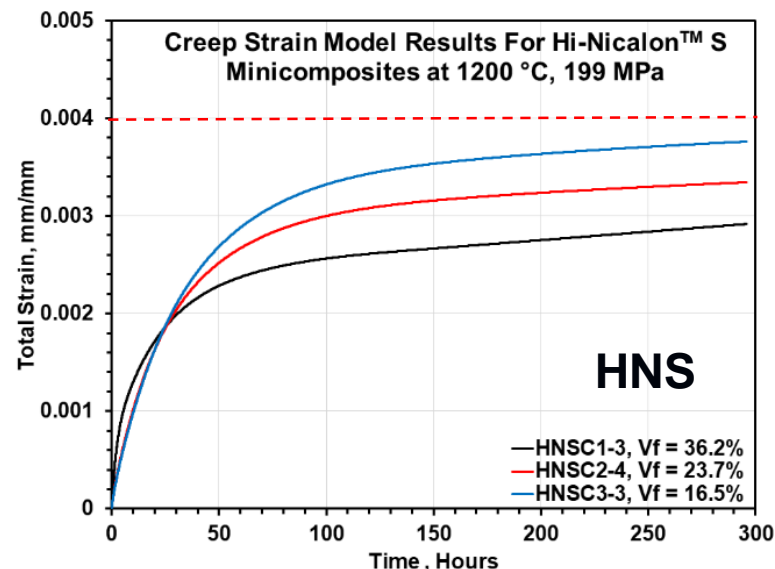
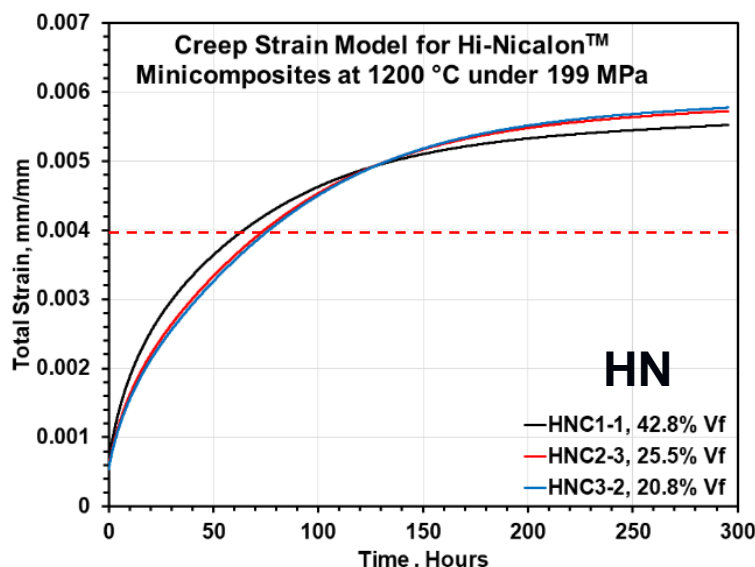
$$\text{with } \Delta = t_i - t_{i-1}^* = 10^{-8} \text{ s}$$

$$\varepsilon_{fi}(10 + t_{i+1}^*) = \frac{\sigma_{fi}}{E_f} + \sigma_{fi} A_f [1 - e^{-P_f (10 + t_{i+1}^*)}] + B_f \sigma_{fi}^{n_f} (10 + t_{i+1}^*)$$



- Good overall agreement is observed between experimental results and model prediction of creep strain evolution for minicomposites of different fiber type and content under stresses below the onset of CVI-SiC matrix cracking stresses.
- Some variation between model and experimental data may be due to the model assumptions of perfectly parallel fibers within the tow with homogenous loading and ideal load transfer across the BN interface. However, in reality there is a random distribution of porosity and flaw sizes and shapes in minicomposites that will change the local effective fiber content, fiber alignment, and cross-sectional area and thus will affect load sharing and creep evolution behavior.

Creep Strain Model Results



Currently, this creep model does not predict failure times. However, the results from stress transfer and creep strain models can be used to help construct an envelope with lower and upper bounds for creep rupture life of uncracked composites that are loaded below the matrix cracking stress.

- A lower bound (minimum time to rupture) can be established by incorporating the modeled evolutions of stresses on the fibers and matrix in creep rupture life models to accurately estimate the probability of failure and time to rupture. Several creep rupture models are reviewed in literature.
- An upper bound (maximum time to rupture) can be constructed by using a known high-temperature average strain to failure to identify the time at which the composite reaches that strain in the creep strain model results.



Steam Oxidation of EB-Coated SiC_f/SiC Minicomposites

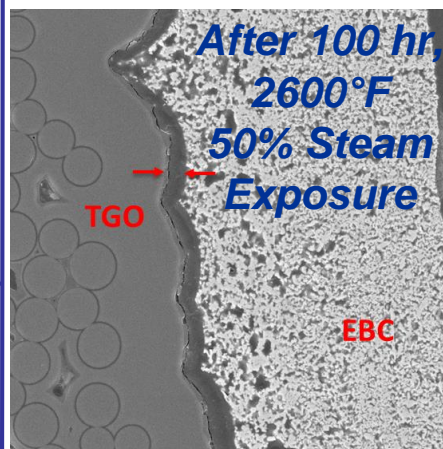
Effects of High Temperature Steam Exposure on 2700°F CMC/EBC Mechanical Properties

Objective:

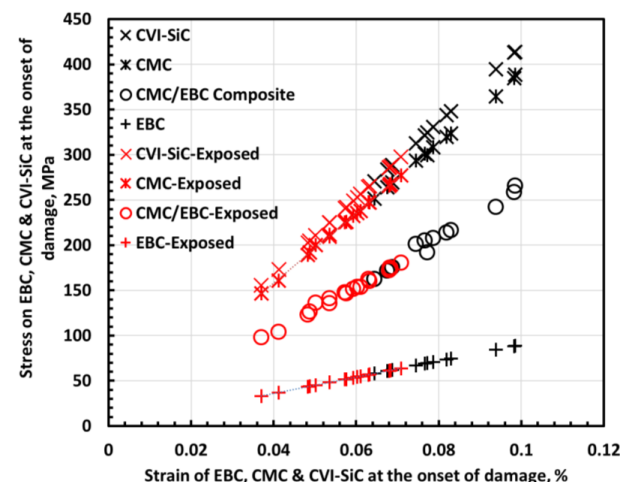
- Establish temperature and time dependence of TGO (thermally grown oxide) formation in steam. Identify effects of TGO growth on 2700°F EBC (environmental barrier coating) and CVI-SiC matrix cracking and strength.

Approach:

- Coat minicomposites with ytterbium disilicate-based EBC bond and top coats.
- Expose 2700°F EB-Coated CVI (Chemical Vapor Infiltration) SiC/SiC minicomposites to 2200, 2400, and 2600°F for 50 and 100 hours in minicomposite steam rig (without load).
- Conduct RT tensile tests of coated minicomposites with in situ AE and digital imaging, and use micromechanics to estimate EBC and CVI-SiC matrix cracking stress as a function of steam exposure time and temperature.
- Identify effects of steam on EBC and CVI-SiC cracking.
- Establish TGO growth temperature and time dependence using microscopy.



CMC/TGO/EBC System



Significance:

Understanding the effect of high temperature steam on the mechanical behavior and durability of CMC/EBC system

Accomplishments:

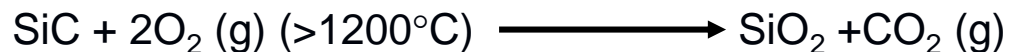
- Coated CVI SiC/SiC minicomposites with 2700°F ytterbium disilicate-based bond coat and top coat prior to steam exposure.
- Compared matrix cracking strength of unexposed vs. steam-exposed coated samples.
- Next step: to measure the EBC/CMC crack densities and TGO thicknesses via microscopy of steam exposed and as-processed samples.



SiC Oxidation and EBC Microstructure

At high temperatures, SiC degrades in air and water vapor as follows:

SiC Degradation in Air:



SiC Degradation in 1 atm Moisture:



Environmental Barrier Coatings (EBCs) are needed for ceramic matrix composite (CMC) components that are being used in water vapor-rich jet engine environments in order to provide protection against oxidation and surface recession. Therefore, slurry based Ytterbium Disilicate EBC system consists of a 35 μm bond coat and a 50 μm top coat that were applied on SiC/SiC minicomposites.

Assumption for calculation of the EBC volume fractions are:

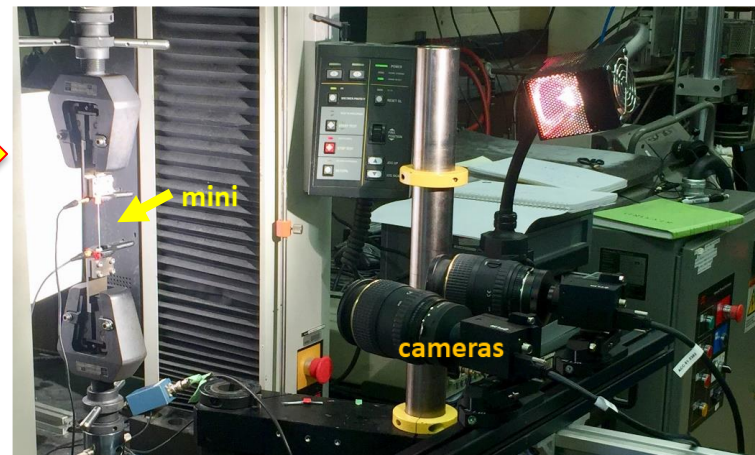
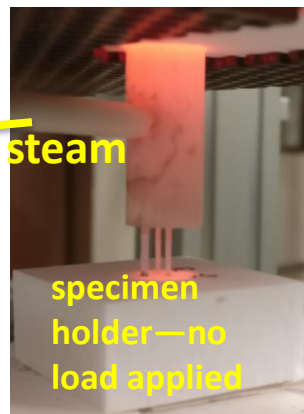
- Macro-composite has a rectangular cross-sectional area with a 0.25-0.5 mm EBC layer.
Typically, 0.25 mm for a vane, shroud or a blade, and 0.5 mm for a combustion liner.
- Mini-composite has a circular cross-sectional area with a 0.085-0.1 mm EBC layer.

Macro SiC/SiC Thickness, mm	2.5
Macro SiC/SiC Width, mm	10
Macro SiC/SiC Area, mm ²	25
Macro EBC Thickness, mm	0.25-0.5
Macro EBC Area, mm ²	6.5-13.5
Macro EBC Volume Fraction	0.21-0.35
Mini SiC/SiC Diameter, mm	0.55
Mini SiC/SiC Area, mm ²	0.2408
Mini EBC Thickness, mm	0.085-0.1
Mini EBC Area, mm ²	0.16-0.2
Mini EBC Volume Fraction	0.42-0.45

- Given the differences in macro- and mini-composites' EBC vol % and thickness, the EBC is expected to have a more noticeable effect on the mechanical behavior of the exposed and as-fabricated EB-coated mini-composites.

Experimental Setup

(Steam Exposure at High Temperatures)



Approach:

- Expose 2700°F EB-Coated CVI (Chemical Vapor Infiltration) SiC/SiC minicomposites to 2200, 2400, and 2600°F for 50 and 100 hours in minicomposite steam rig (without load).
- Room temperature monotonic loading with modal acoustic emission monitoring and digital imaging.

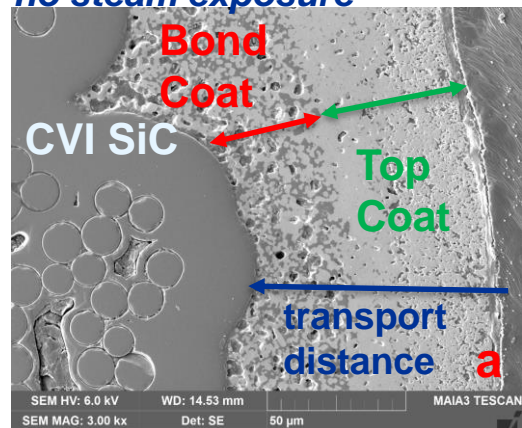
<i>Specimen's Description</i>	<i>Heat Treatment Cycles</i>	<i>Steam Exposure Time, Hours</i>	<i>Steam Exposure Temperature, °F</i>	<i>Number of Specimens</i>	<i>Fast Fracture Test Temperature, °F</i>
<i>Un-Coated</i>	N/A	0	N/A	6	75
<i>Heat-treated Group 1</i>	1	0	N/A	4	75
<i>Heat-treated Group 2</i>	2	0	N/A	4	75
<i>Coated Not Exposed</i>	2	0	N/A	9	75
<i>Coated Exposed Group 1</i>	2	50	2200 °F	3	75
<i>Coated Exposed Group 2</i>	2	100	2200 °F	3	75
<i>Coated Exposed Group 3</i>	2	50	2400 °F	3	75
<i>Coated Exposed Group 4</i>	2	100	2400 °F	3	75
<i>Coated Exposed Group 5</i>	2	50	2600 °F	3	75
<i>Coated Exposed Group 6</i>	2	100	2600 °F	3	75

Significance:

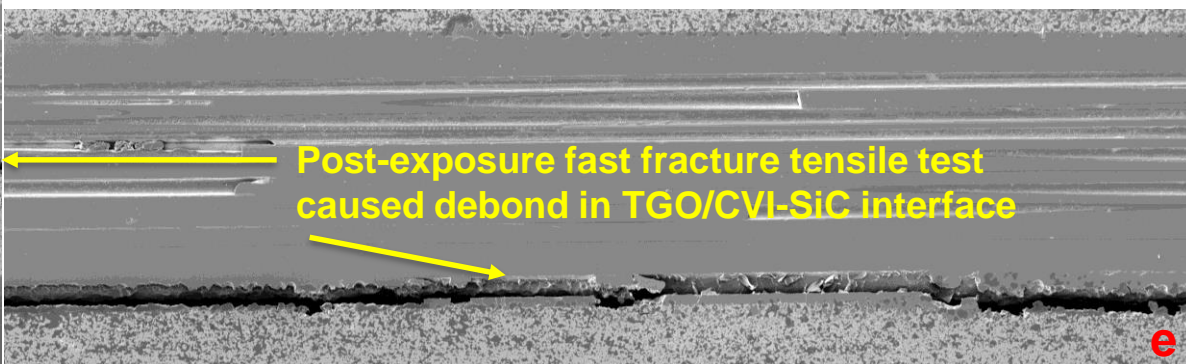
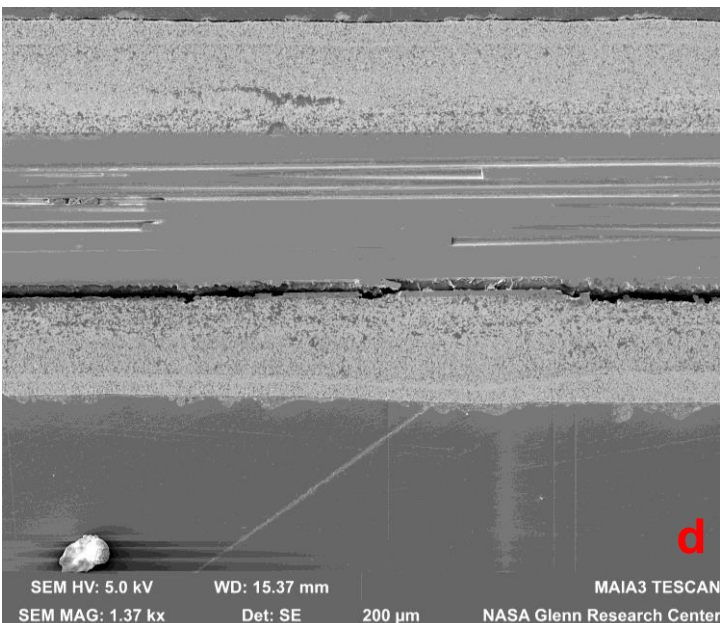
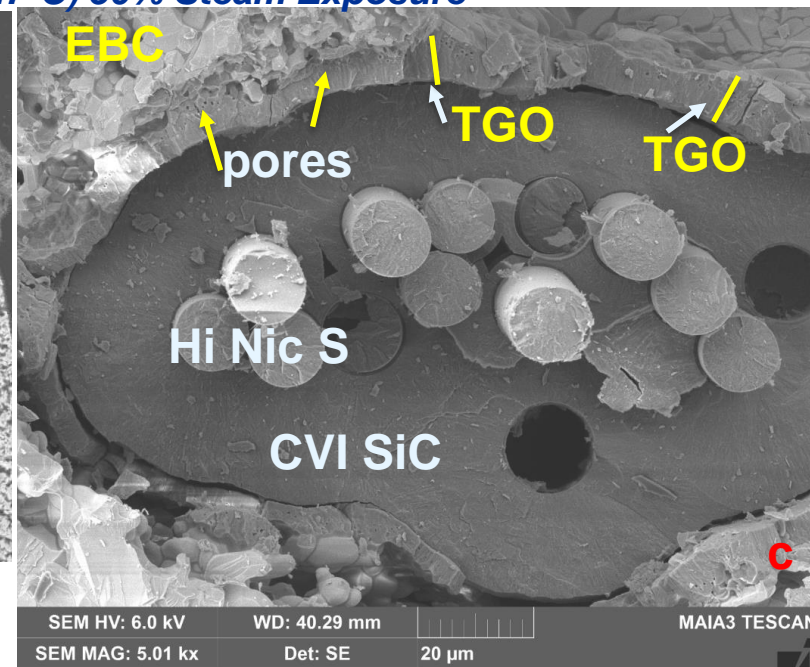
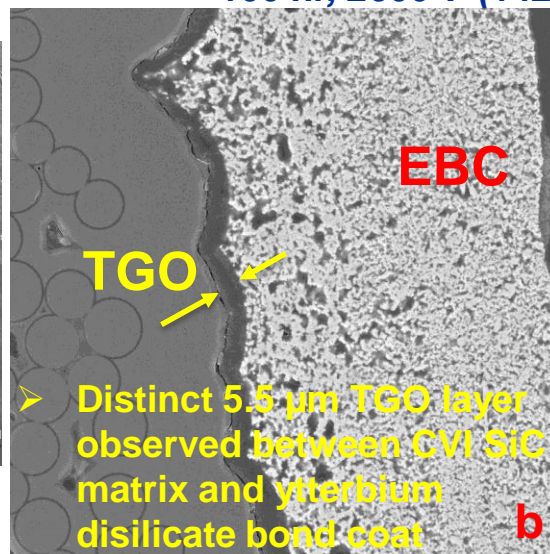
- Understanding TGO formation conditions and effect on the mechanical behavior and durability of coated SiC/SiC composites.

2700°F EB-coated SiC/SiC Minicomposites Microscopy

*Example of baseline sample—
no steam exposure*



100 hr, 2600°F (1427°C) 50% Steam Exposure



100 hr, 2600°F (1427°C) 50% Steam Exposure

Micromechanical Modeling of Matrix Cracking Stress

Modified ACK and Budiansky et. al. equation to model the stress on the matrix only at the onset of matrix cracking for initially bonded, frictionally constrained fibers with residual stresses.

$$\sigma_{cr} = \lambda \left[\frac{6\tau G_m f^2 E_f E_c^2}{(1-f) R E_m^2} \right]^{\frac{1}{3}} - \frac{\sigma'_m E_c}{E_m}$$

$$\sigma_{cr}^m = \left[\lambda \left[\frac{6\tau G_m f^2 E_f E_c^2}{(1-f) R E_m^2} \right]^{\frac{1}{3}} - \frac{\sigma'_m E_c}{E_m} \right] \frac{E_m}{E_c}$$

σ_{cr} is the composite stress at the onset of composite cracking.

σ_{cr}^m is the matrix stress at the onset of matrix cracking.

σ'_m is the thermal residual stress on the matrix.

E_f is the fiber modulus, E_m is the matrix modulus

E_c is the minicomposite modulus

$G_m = 16.7 \text{ J/m}^2$ (CVI-SiC matrix property)

$\alpha_f = 4.6 \times 10^{-6} \text{ C}^{-1}$ $\alpha_m = 4.5 \times 10^{-6} \text{ C}^{-1}$

f is the fiber volume fraction, R is the fiber radius

λ is friction and debond parameter obtained from BHE 1995.

* $G_d = 1.24 \pm 0.49 \text{ J/m}^2$ (fiber/interface debond energy)

* $\tau = 18 \pm 4.78 \text{ MPa}$ (interfacial shear strength)

* Obtained from B. Swaminathan et al., Microscale Characterization of Damage Accumulation in CMCs, JECS, May 2020

$$\sigma_c = \text{Applied Load / Area of EBC and CMC}$$

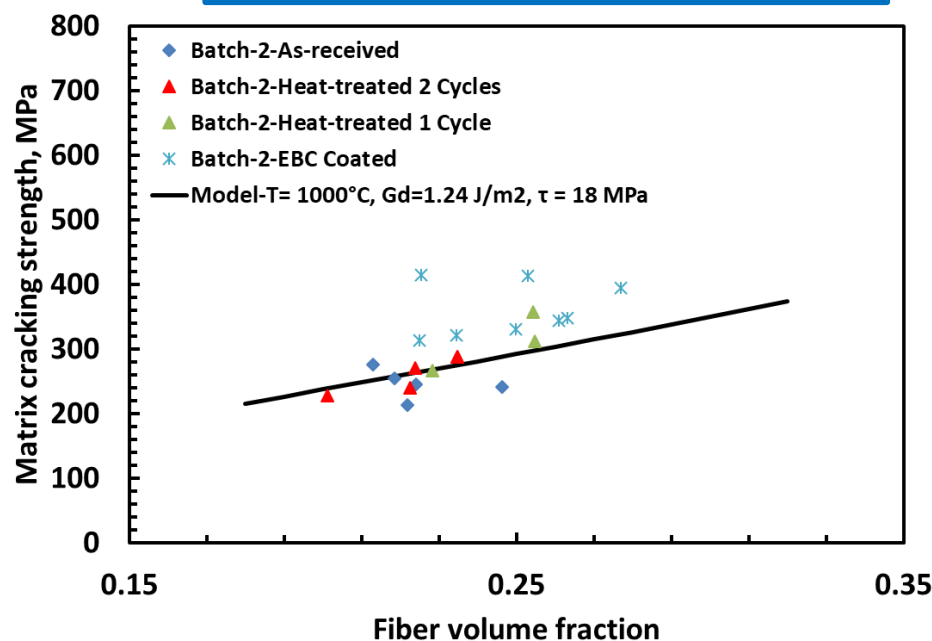
$$\varepsilon_i = \frac{\sigma_{i, \text{experimental}}}{E_{i, \text{theoretical}}}, \quad \varepsilon_c = \varepsilon_{CMC} \Rightarrow \sigma_{CMC} = \frac{E_{CMC}}{E_c} \sigma_c$$

$$\varepsilon_{CVI-SiC} = \varepsilon_{CMC} \Rightarrow \sigma_{CVI-SiC} = \frac{E_{CVI-SiC}}{E_{CMC}} \sigma_{CMC}$$

$$\varepsilon_{EBC} = \varepsilon_{CMC} \Rightarrow \sigma_{EBC} = \frac{E_{EBC}}{E_{CMC}} \sigma_{CMC}$$

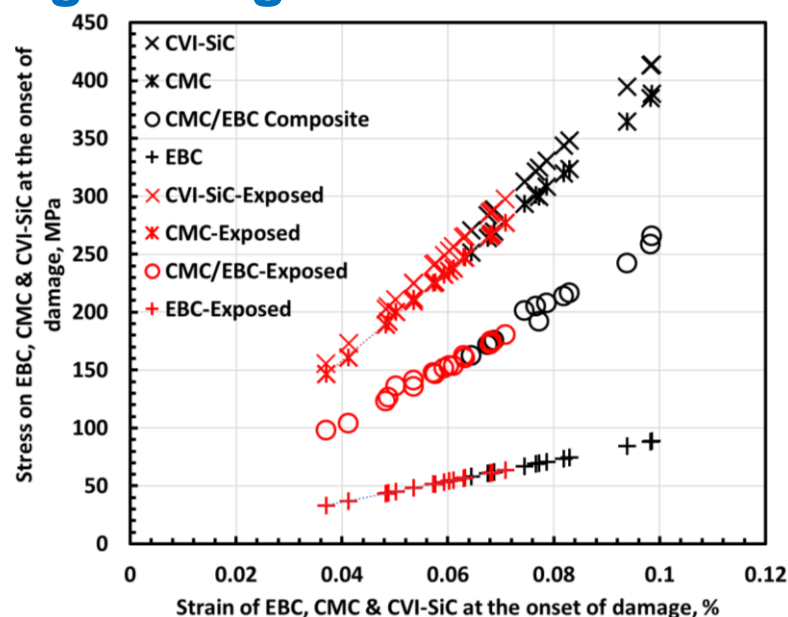
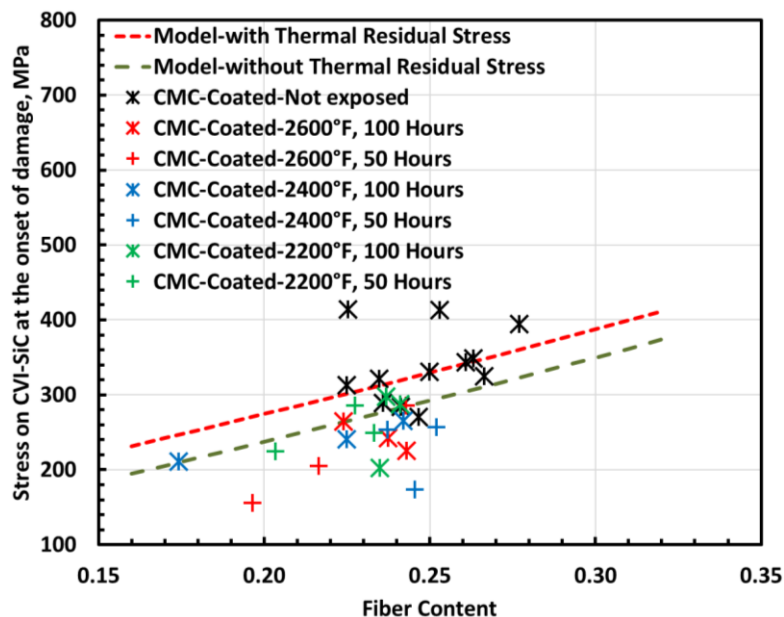
$$E_f = 360 \text{ GPa}, E_{BN} = 25 \text{ GPa}$$

$$E_m = 420 \text{ GPa}, E_{EBC} = 90 \text{ GPa}$$



- Coated samples display a consistently slightly higher CVI-SiC matrix stresses at the onset of cracking than their uncoated equivalents.

Influence of EBC and 50% Steam Exposure on SiC/SiC Cracking Strength



- The majority of the SiC/SiC CMC and CVI-SiC matrix within the coated samples display greater stress at the onset of cracking compared to their uncoated equivalents.
- For unexposed coated samples, the CTE mismatch between the SiC/SiC CMC and the EBC can induce compressive thermal residual stress on the CVI-SiC matrix. (¹ α cristobalite Silica in bond coat CTE = $10.3 \times 10^{-6}/^{\circ}\text{C}$), (² Slurry based Ytterbium Disilicate EBC CTE $4 \sim 5 \times 10^{-6}/^{\circ}\text{C}$) (³ SiC/SiC CTE $4.2 \sim 4.6 \times 10^{-6}/^{\circ}\text{C}$).
- Modeling showed that the high matrix cracking stress in coated minicomposites which were not exposed to steam could be due to the increase in SiC/SiC thermal residual compressive stress induced by the high EBC CTE. ($\sigma_{th} \sim 36 \text{ MPa}$, based on EBC CTE = $4.8 \times 10^{-6}/^{\circ}\text{C}$)
- For steam-exposed coated samples, the degradation of the CVI-SiC and TGO formation due to the reaction with steam reduced the matrix cracking strength. (Need to investigate the relationship between time/temperature with stresses)

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Creep Rupture of EB-Coated SiC_f/SiC Minicomposites

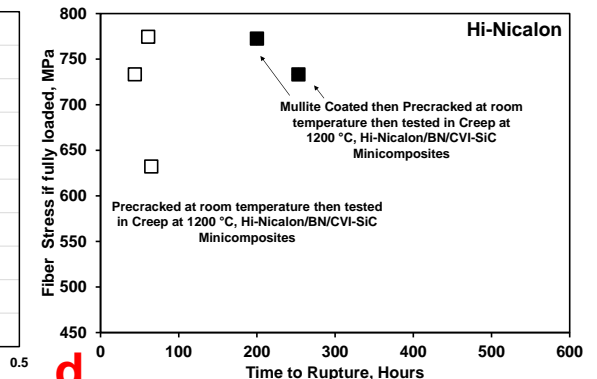
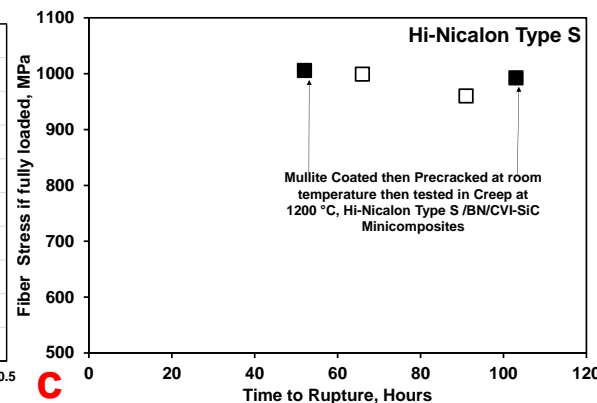
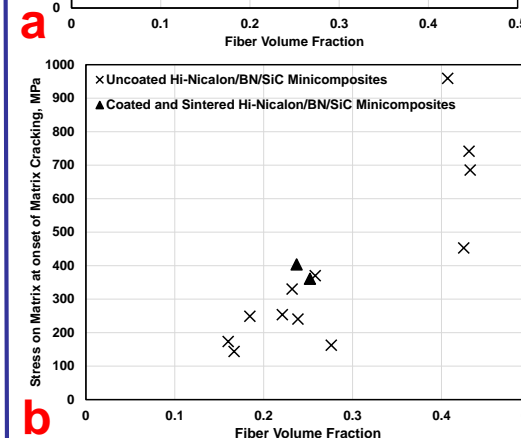
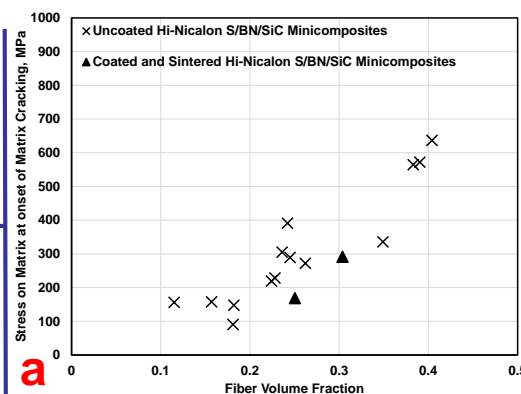
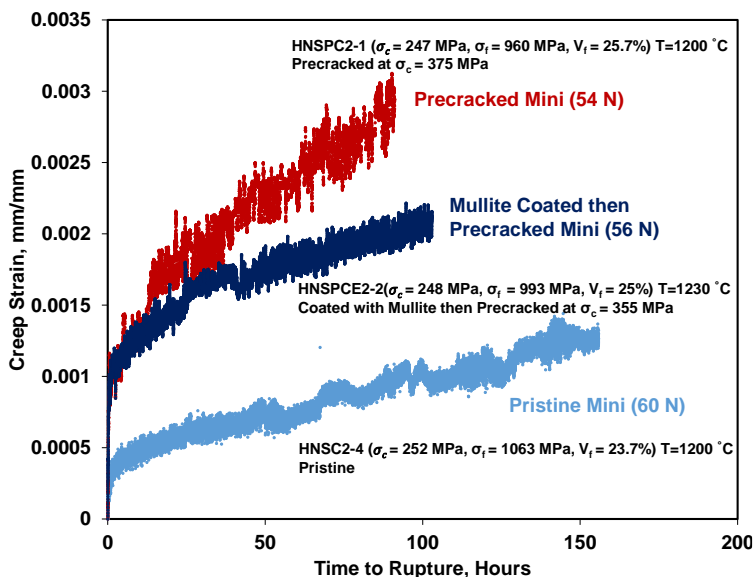
Creep Rupture of EB-Coated Minicomposites

Objective:

To develop slurry based environment barrier coatings for CMCs and characterize their protection against oxidation to improve the creep rupture durability of CMCs.

Approach:

- Processed 23 compositions and combinations of slurries.
- Performed fast fracture testing of coated and uncoated minicomposites to understand the effects of EBC sintering on the strength.
- Performed tensile creep rupture tests of uncracked and precracked coated and uncoated minicomposites at 2200 °F in air.



Significance:

- EBC processing didn't affect the matrix cracking strength.
- EBC layers provided some enhanced stress oxidation protection and longer creep lives to Hi-Nicalon minicomposites at 2200 °F in air.

Accomplishments:

Understanding the effect of EBC processing on the composite cracking strength.
Understanding the effect of cracking and oxidation on the tensile creep rupture behavior and life of coated CMCs.



Concluding Remarks & Acknowledgement

Concluding Remarks:

- Discussed the benefits of using minicomposite testing and modeling to support CMC design for thermostructural applications in extreme environments.
- In order to maximize CMC durability in creep loading, the creep resistance of the fibers and the matrix need to be either equal or at least within the same order of magnitude. This will reduce the time dependent stress redistribution and avoid overloading the constituent that is more creep resistant, thus extending the composite life in creep.
- Operating CMCs at stresses that prevent matrix cracking, in order to prevent oxidation within a cracked region and avoid overloading the fibers, will ensure their durability.
- 2700°F CMC/EBC systems should not contain free silicon (it melts at that temperature). CVI-SiC should be free of impurities including silica for high strength and best creep performance.
- EBC coating should be compatible with the substrate. The bond coat needs to be dense to reduce oxidants' transport path and it should be compliant to allow CMC crack deflection at the interface of CMC/EBC. Top coat needs to be resistant to recession, erosion, impact and it needs to be dense.
- It is important to identify the damage mechanism most critical to the life of the CMC/EBC system to accurately estimate the long term durability, enhance durability and inform CMC design.

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