National Aeronautics and Space Administration

Modeling of Different Fiber Type and Content SiC_f/SiC Minicomposites Creep Behavior

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Outline

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- **Approach**
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- **Experimental Methodology and Set Up**
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- **Creep Model**
- **Conclusions**

Motivation

- **Ceramic Matrix Composites (CMCs) are candidates for high-temperature applications such as the new generations of aircraft engines and hypersonic vehicles.**

- **Case A: CMCs are loaded below the matrix cracking stress. (Static or Dynamic Loading)**

- **Fibers carry a fraction of the applied load.**
- **Fibers are not exposed to oxidation damage and the most dominant damage mechanism is creep of fibers.**

- **Case B: CMCs are loaded above the matrix cracking stress.**

- **Fibers carry all of the applied load in the vicinity of through-thickness matrix crack.**
- **Fibers are exposed to oxidation and creep damage mechanisms.**
- **Load transfer from oxide layer to the core of the fibers.**
- **Long lengths of fibers at high stress due to multiple matrix cracks and the reduction of fibers' cross-sectional area due to oxidation.**

Approach

1) **Case A:**

Obtain Fibers true creep parameters at 1200-1482 ° C which are needed for modeling fiber/matrix load transfer and creep resistance of the fibers.

A) **Test single fibers and fiber tows in vacuum.**

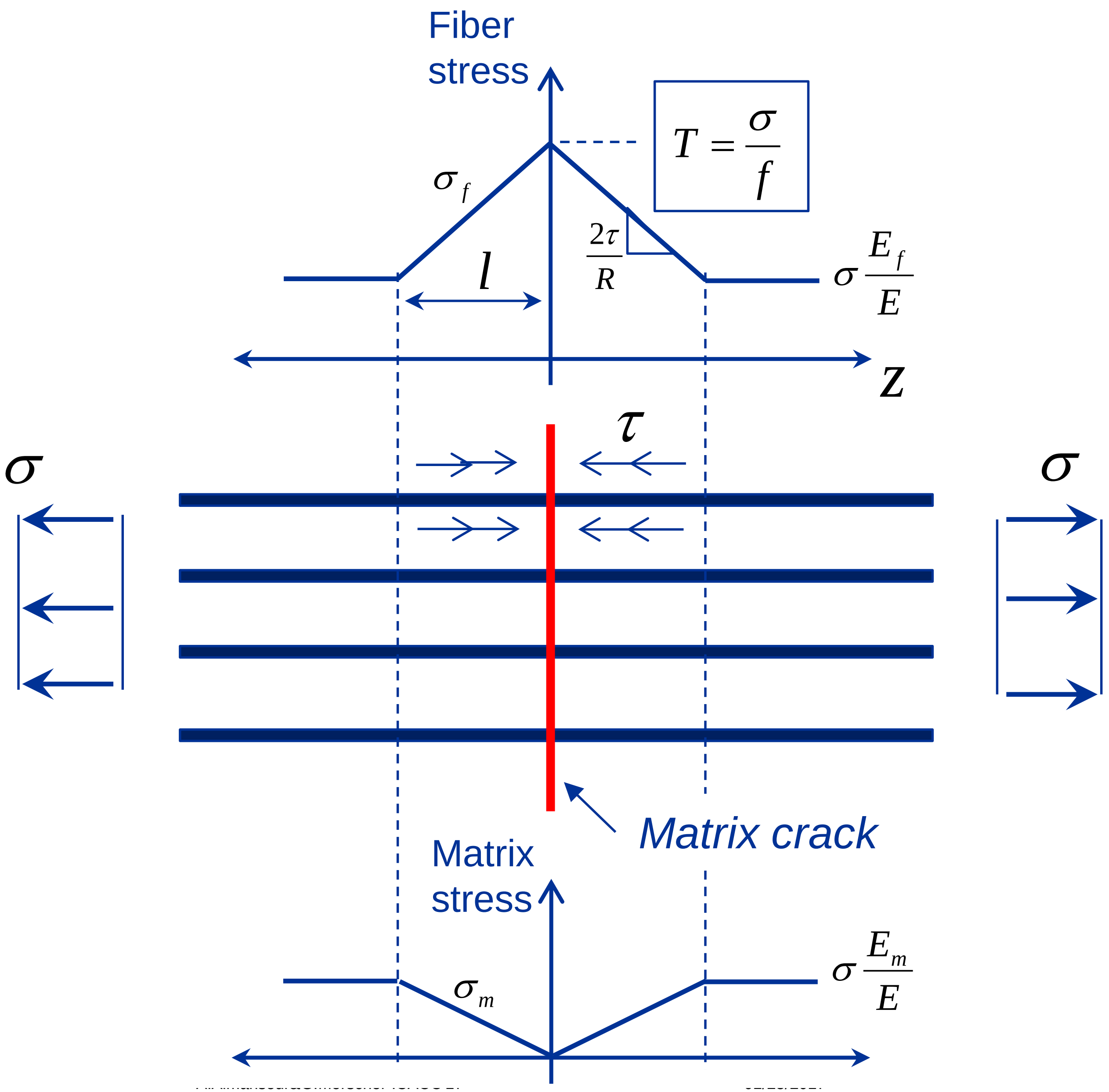
B) **Test single fibers and fiber tows in air *(need to model the evolution of stress increase on fibers during creep due to oxidation).***

Case B:

Obtain Fibers creep parameters at 1200-1482 ° C tows in air, inert and steam.

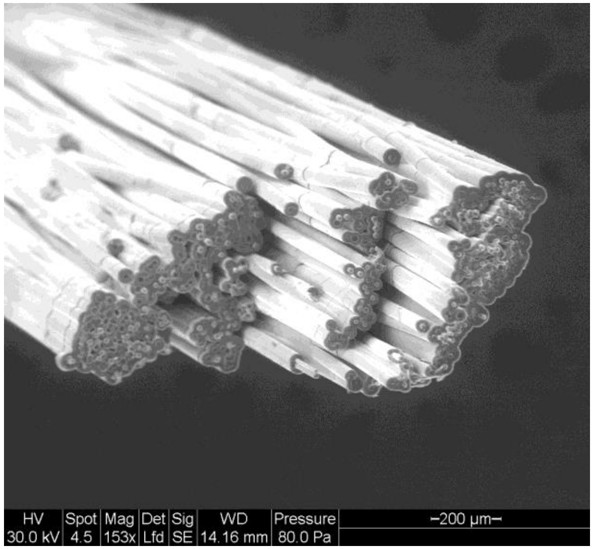
2) Correlate fibers data with minicomposites and macrocomposites data.

3) Provide recommendation for durability improvements & Support CMCs & fibers developments.

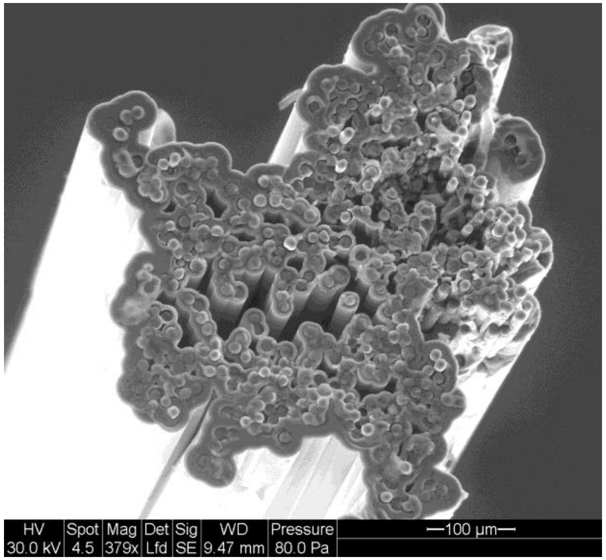


Materials and Properties

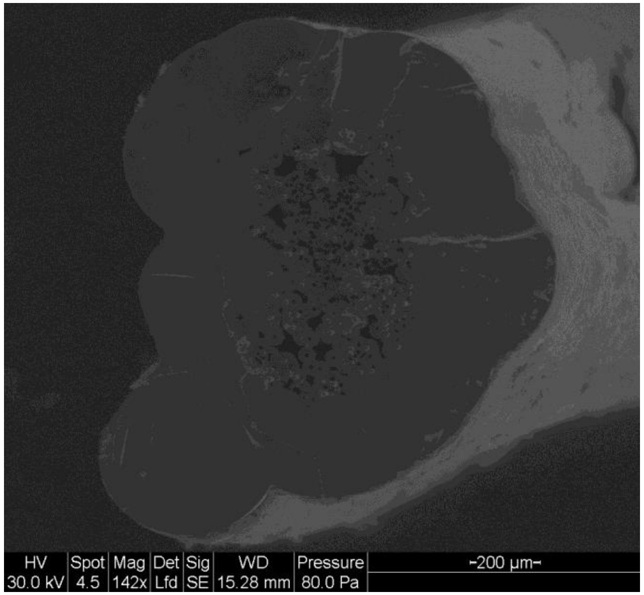
Single Fiber Tow Minicomposite Cross-sections



Hi-Nicalon Minicomposite



Hi-Nicalon S Minicomposite

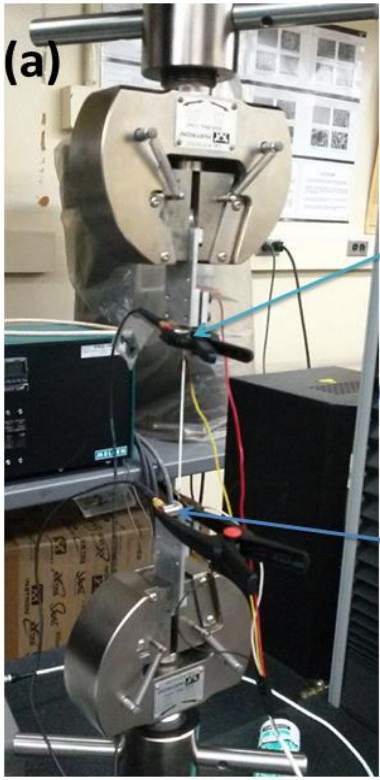


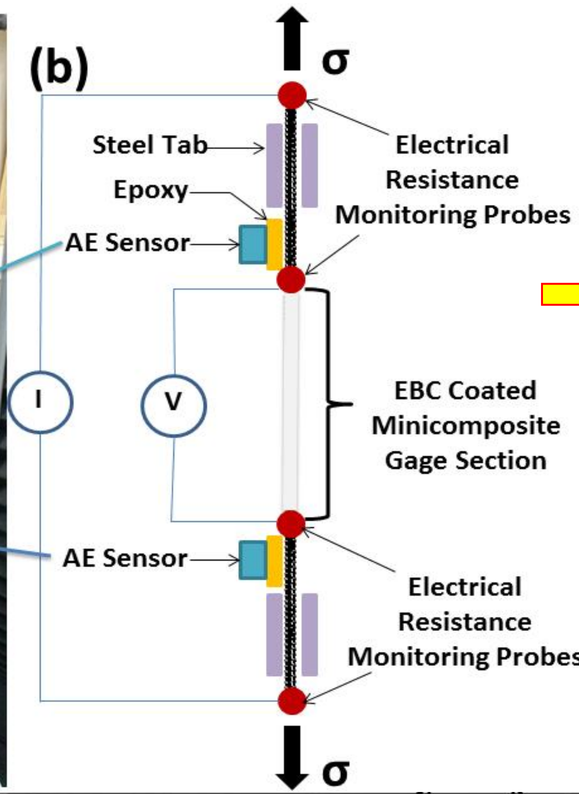
97%CVI-SiC Minicomposite

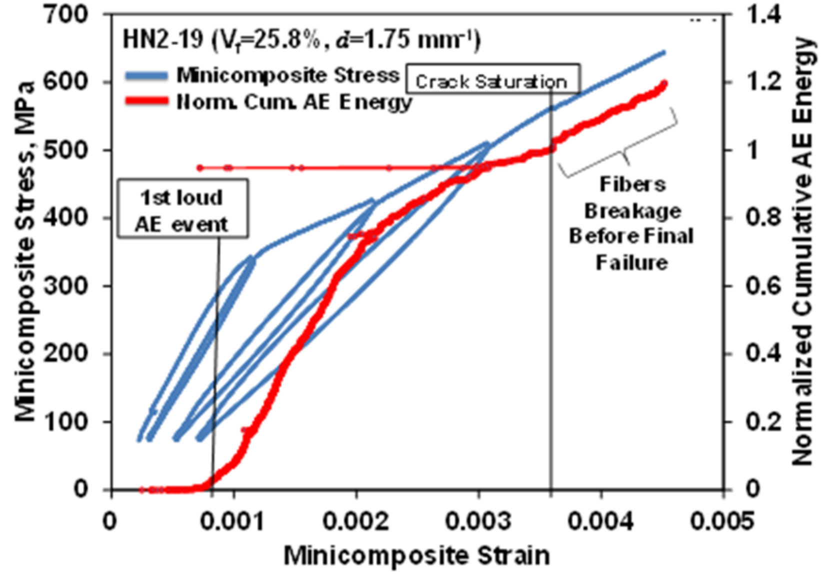
Fiber Type	Number of Fibers per Tow	Fiber Diameter (μm)	Fiber Volume Fractions (%)	Fiber Elastic Modulus (GPa)	Fiber Density (g/cc)	Fiber Coefficient of Thermal Expansion (CTE)($℃^{-1}$)
Hi-Nicalon-S	500	12	16/23/43	400	3.1	4.5 x 10^{-6}
Hi-Nicalon	500	14	16/23/42	270	2.74	3.5 x 10^{-6}
Tyranno-ZMI	400	11	23/28	170	2.35	4.0 x 10^{-6}

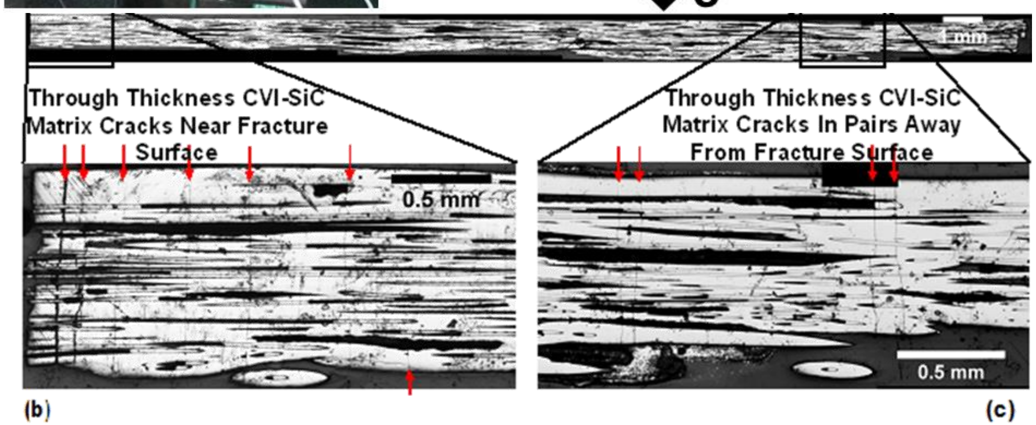
- **The volume and mass of the fiber tow were estimated based on the average fiber diameter, number of fibers per tow, specimen length and density.**
- **The volume and mass of the interphase were estimated considering a constant thickness of 1 µm on each fiber using SEM.**
- **Then backed out the volume and mass of the matrix from ROM.**

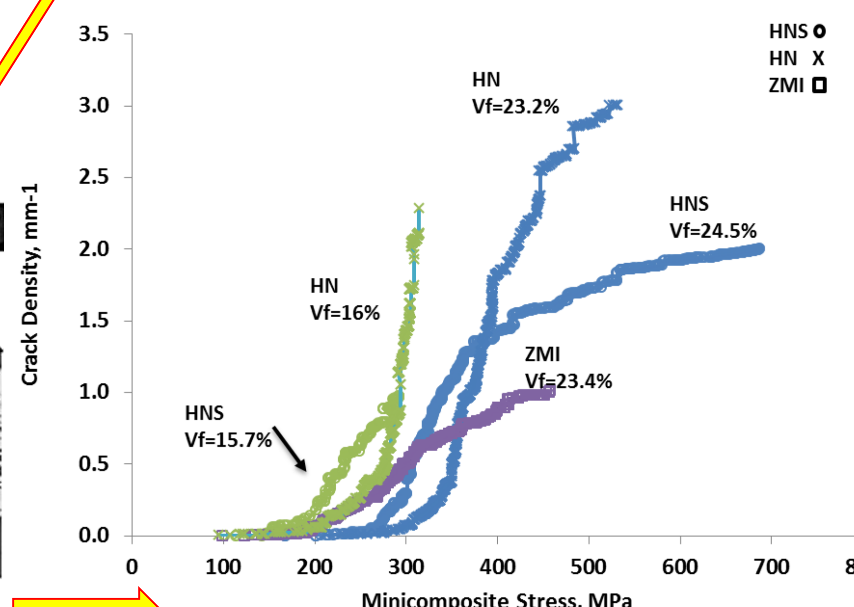
Precracking Minis Methodology at Room Temperature





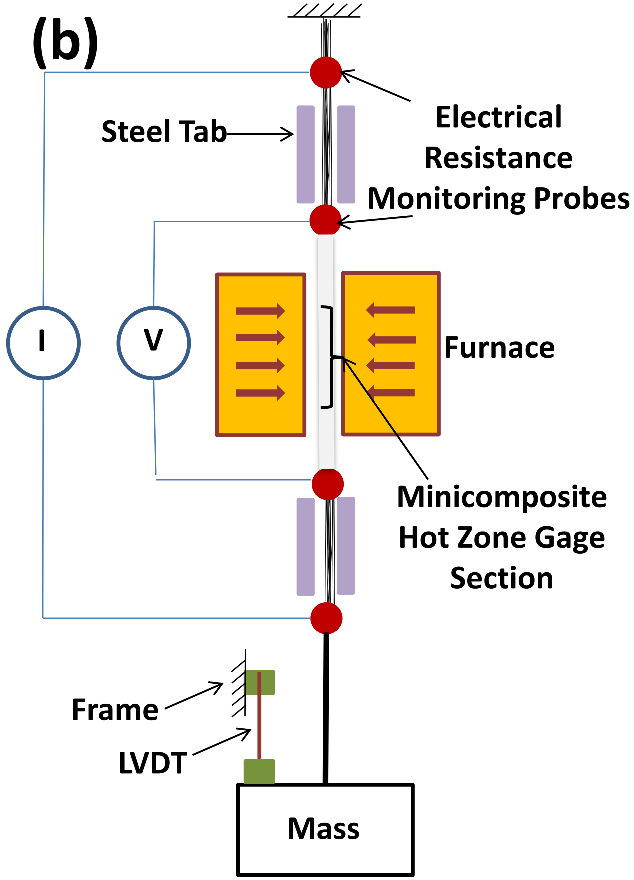




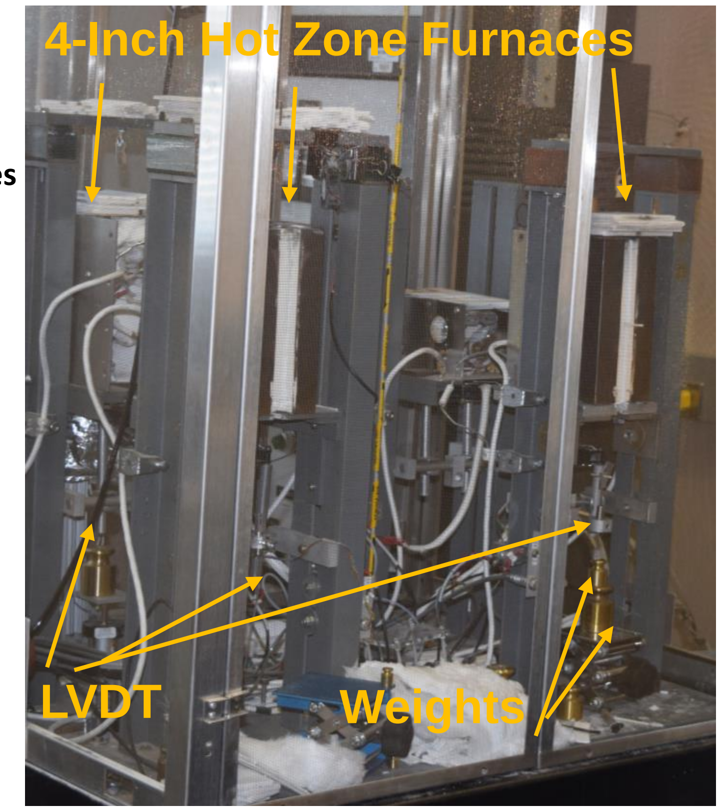


High Temperature Creep Test Setup in Air

Minicomposites Creep Test Rig

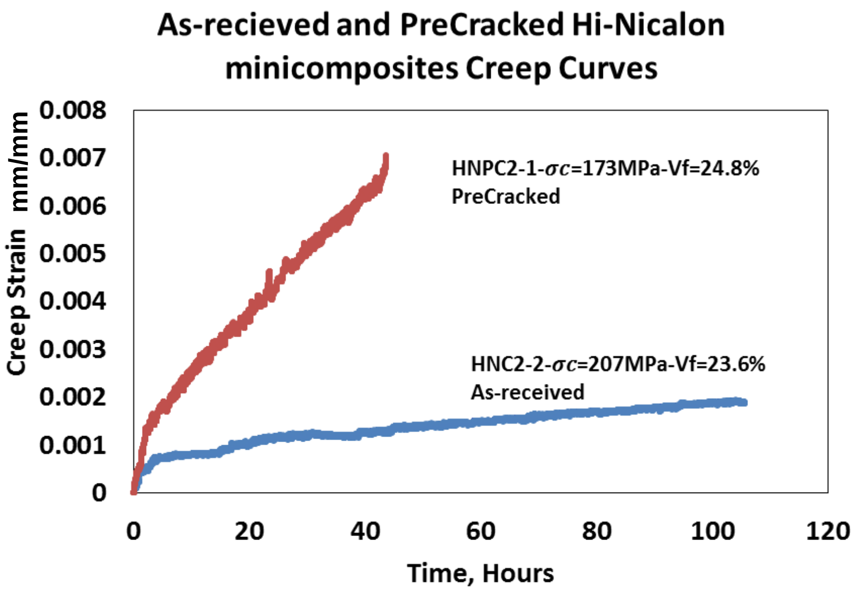


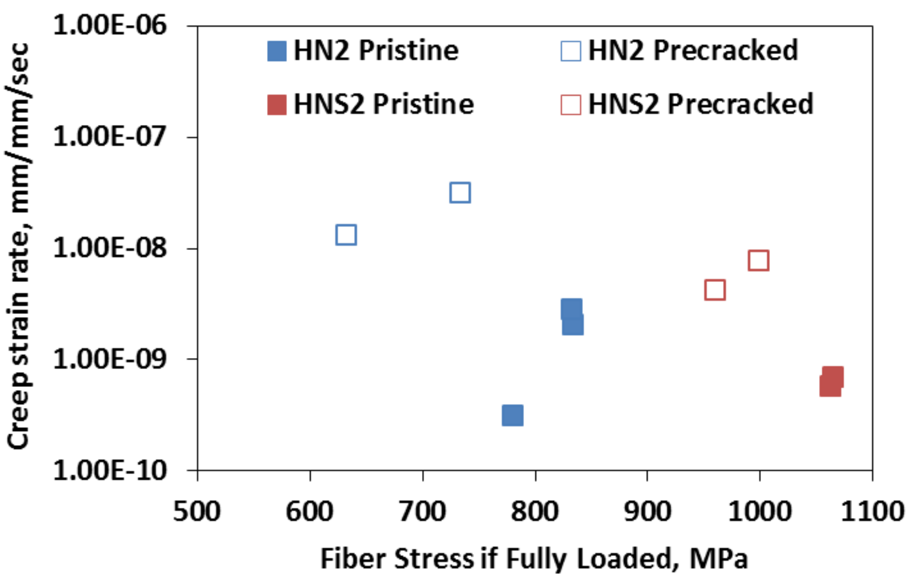
Single Fiber Creep Test Rig

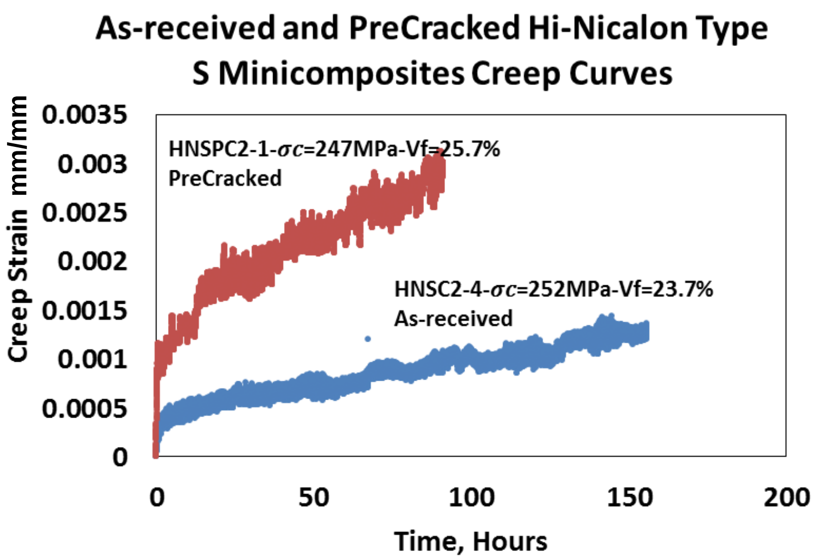


Uncracked Vs. Cracked Minicomposites'Creep Behavior

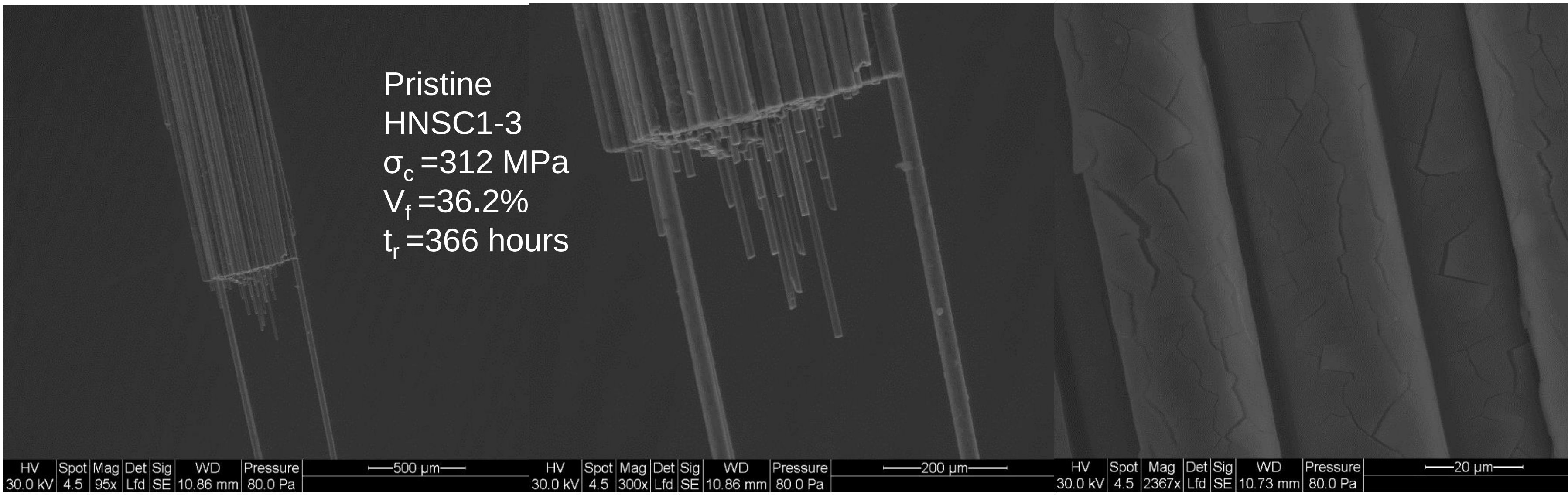
- Larger total strain and strain rates in Precracked HN and HNS due to longer lengths of fibers at higher stress and oxidation
- Smaller total strain in As-Produced HN and HNS due to load sharing (matrix carries some load – fiber stress isn't as high as for the precracked).
- Precracked samples failed earlier than the pristine samples under the same loading conditions.

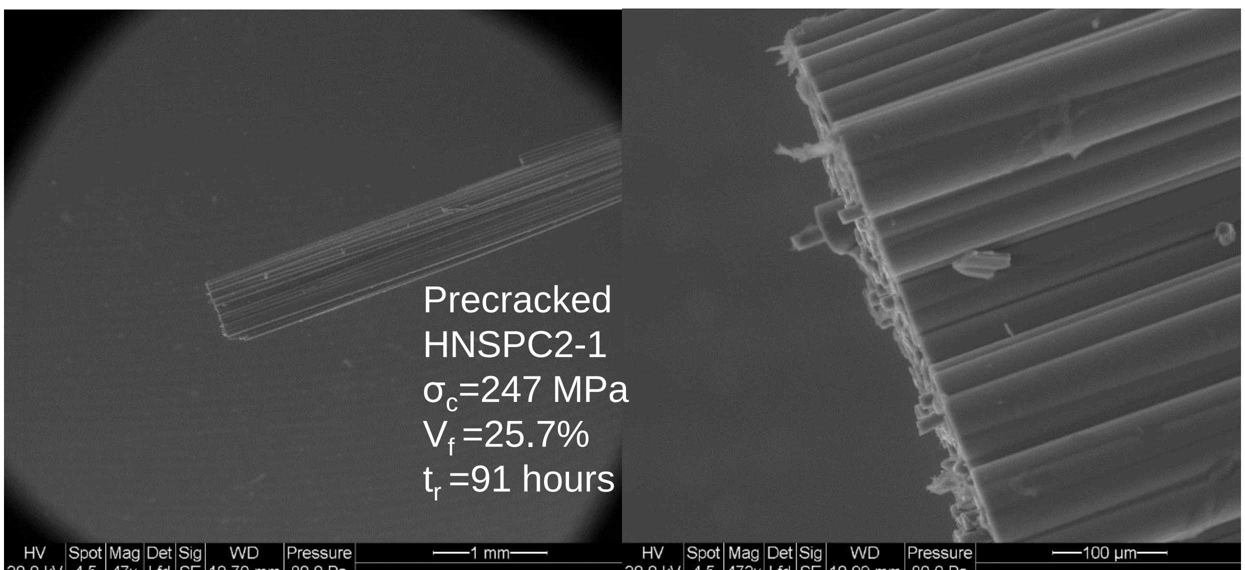






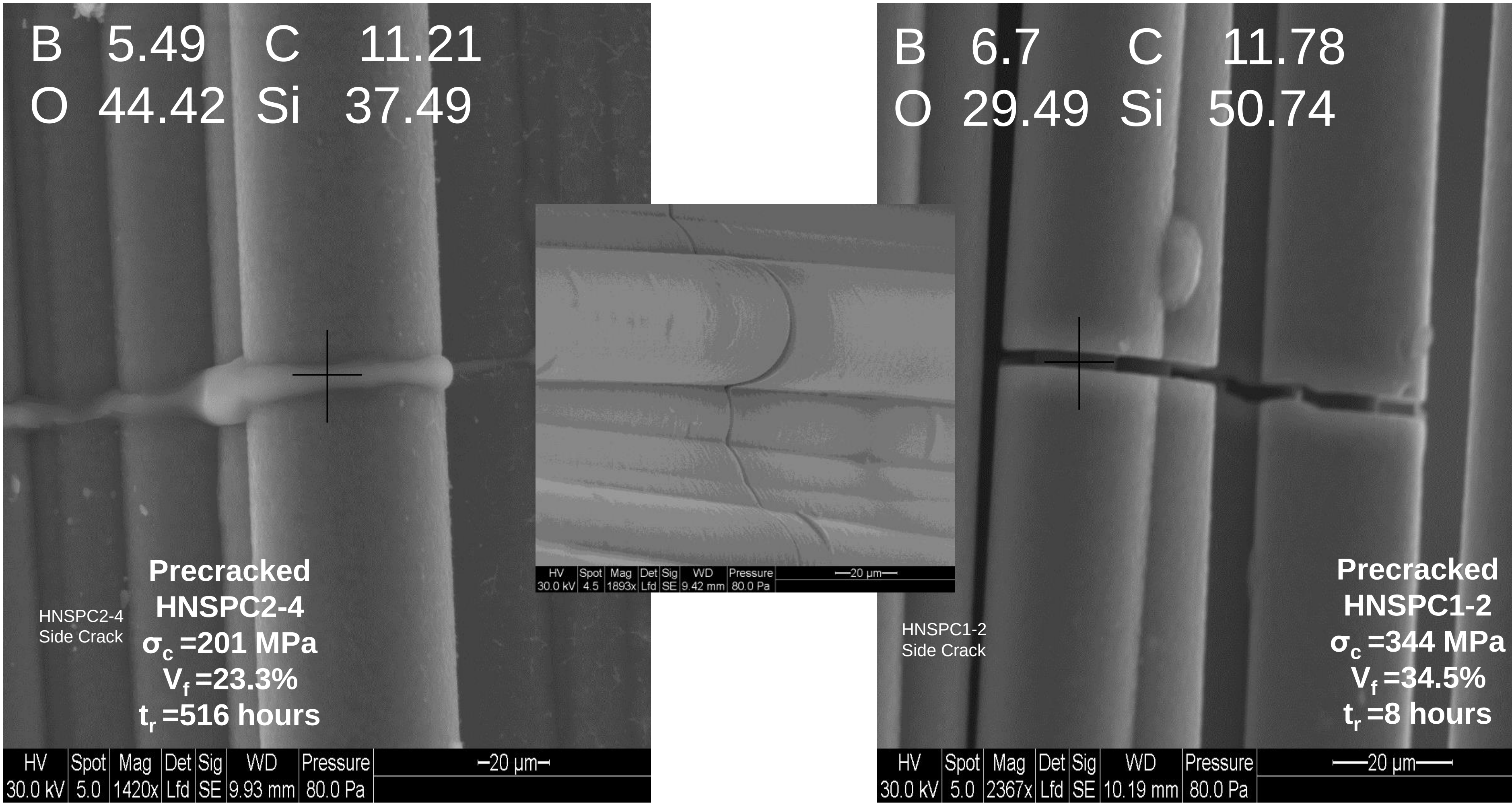
Post Creep Fracture Surface Morphology



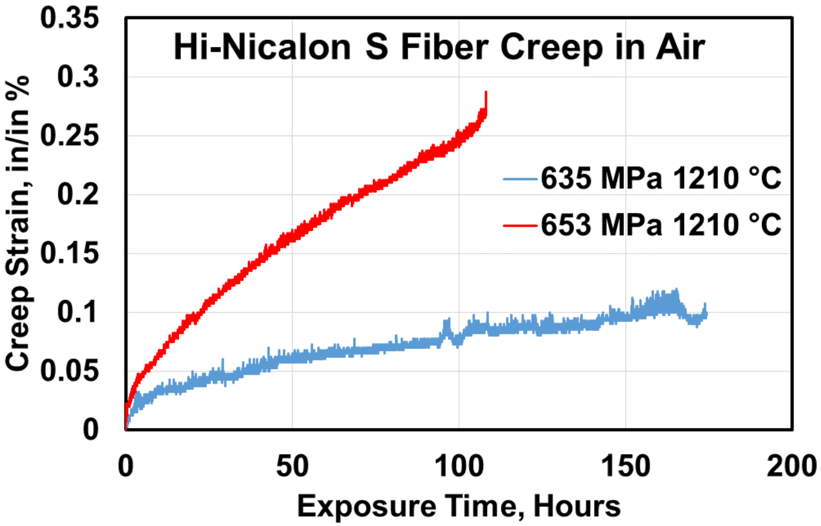


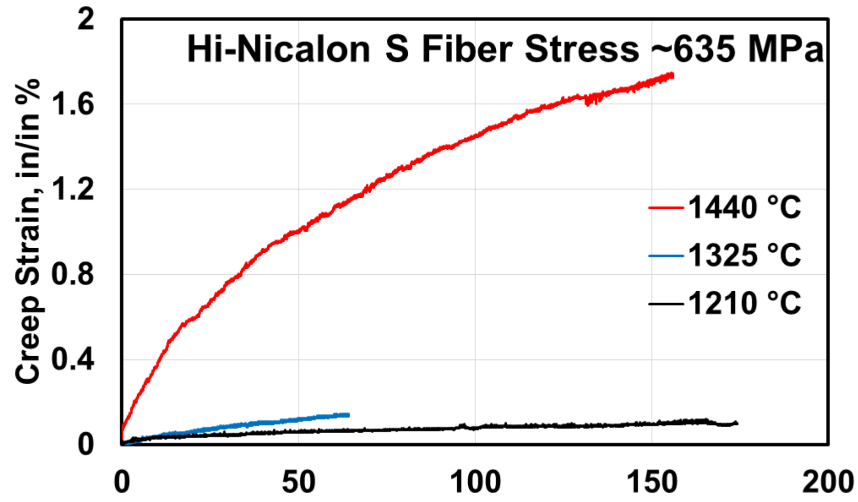
- Obvious fiber pull-out in pristine HNSC1-3 sample tested in creep.
- Also, cracked oxide layer on the surface of the pristine sample due to the long time it lasted in creep, thermal cycle and the surrounding air.
- Little to no fiber pull-out (brittle surface) due to fiber creep and oxidation degradation in precracked sample HNSPC2-1.

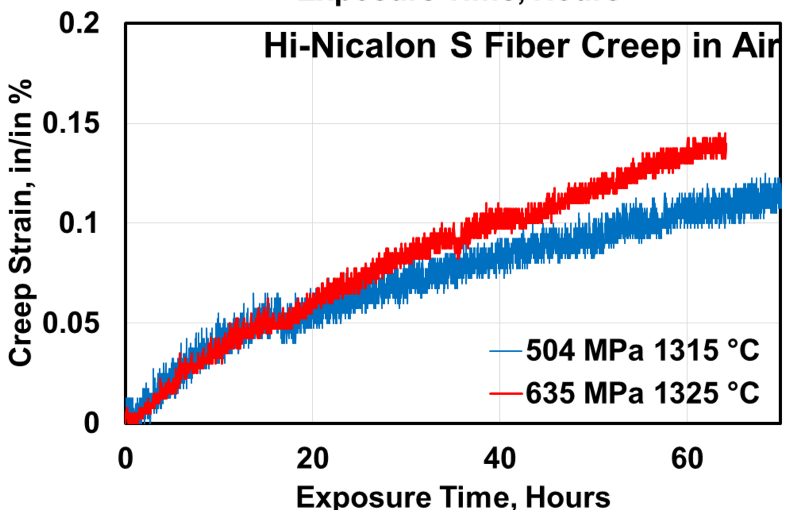
High Temperature Oxidation Behavior

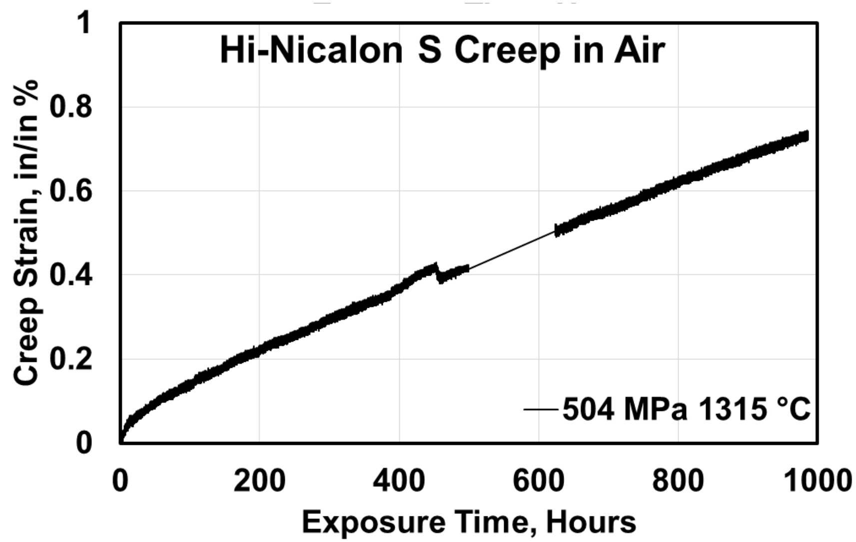


Hi-Nicalon S Single Fiber Creep in Air

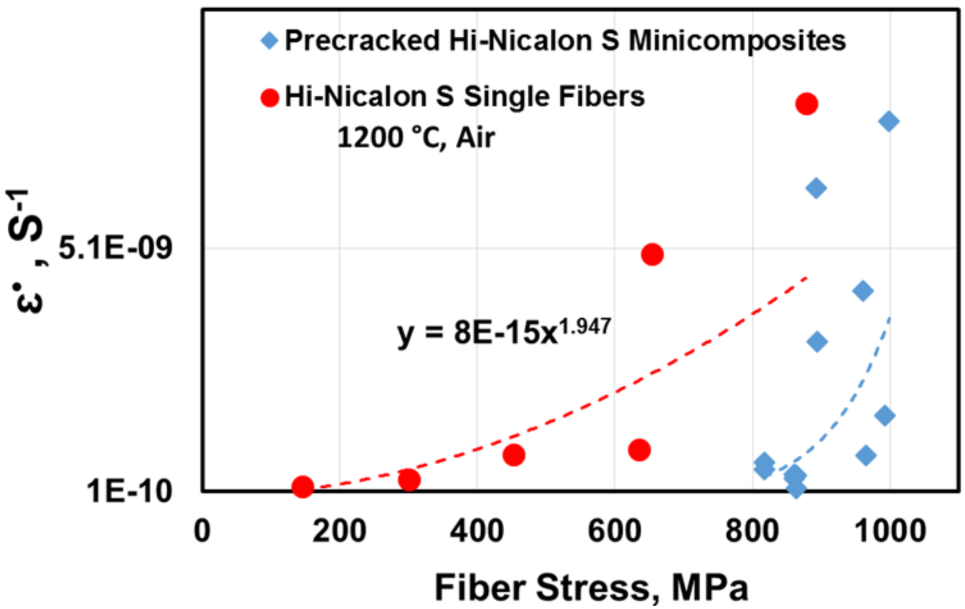


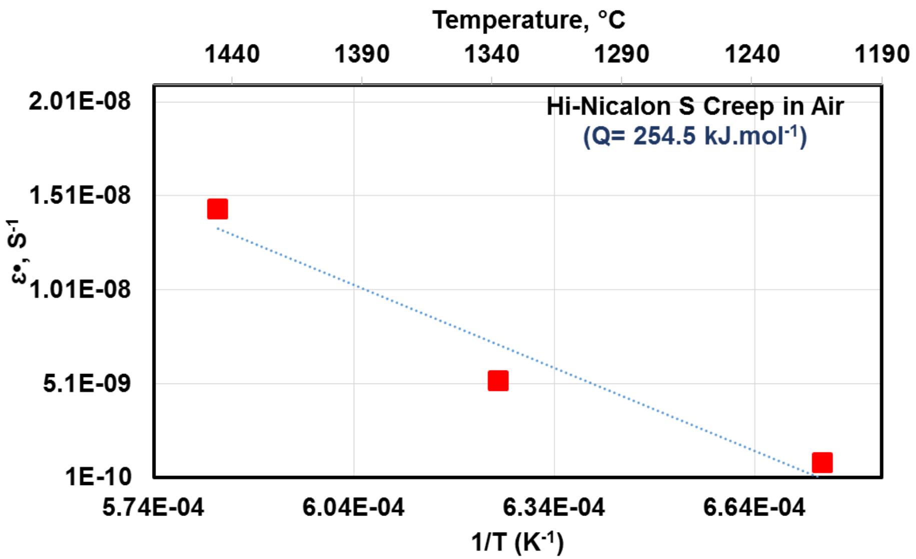


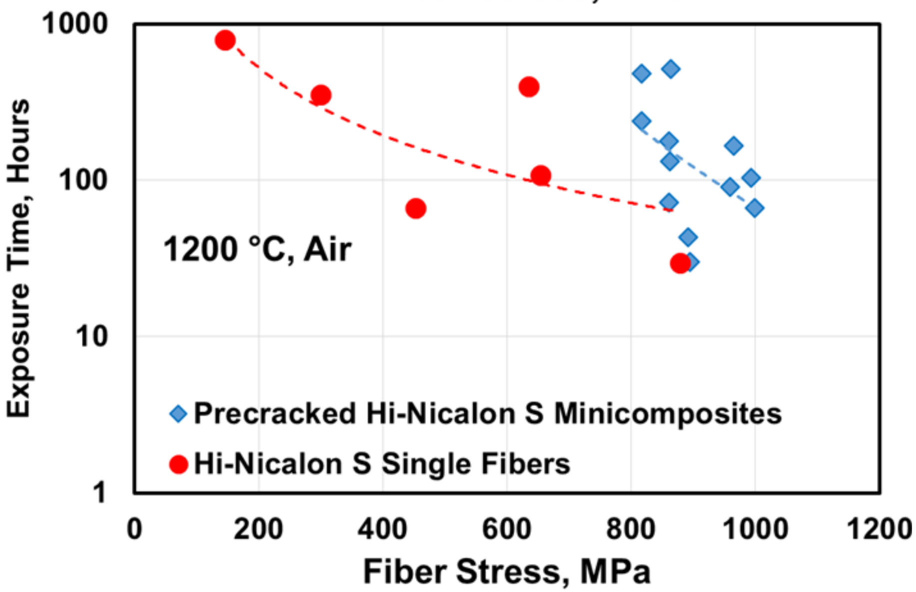


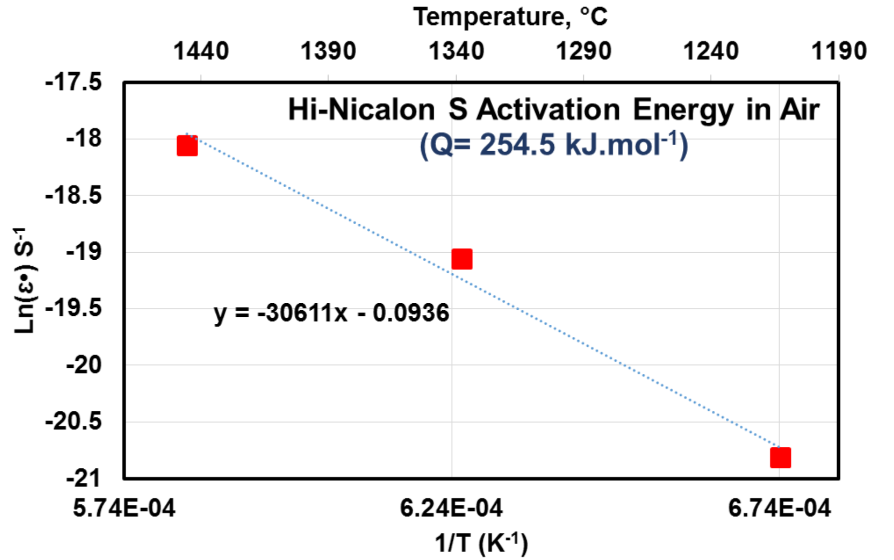


Hi-Nicalon S Single Fiber Creep in Air



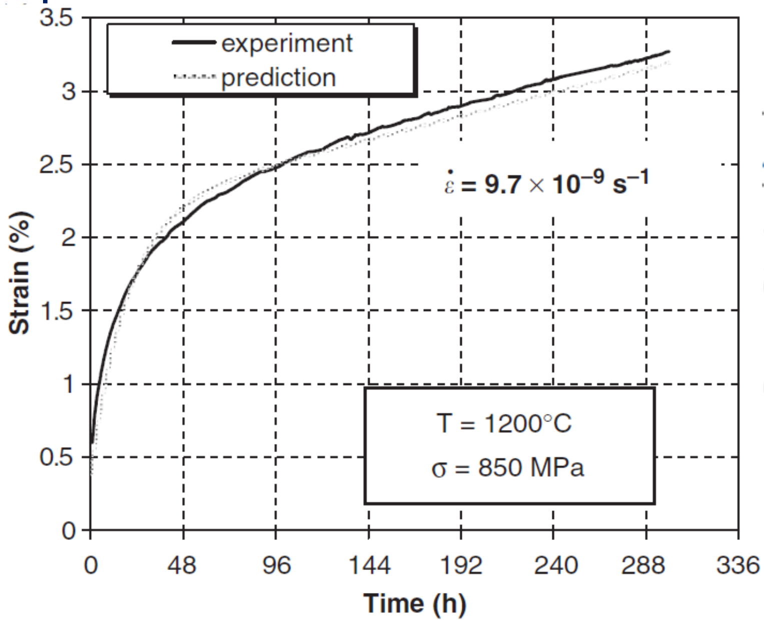




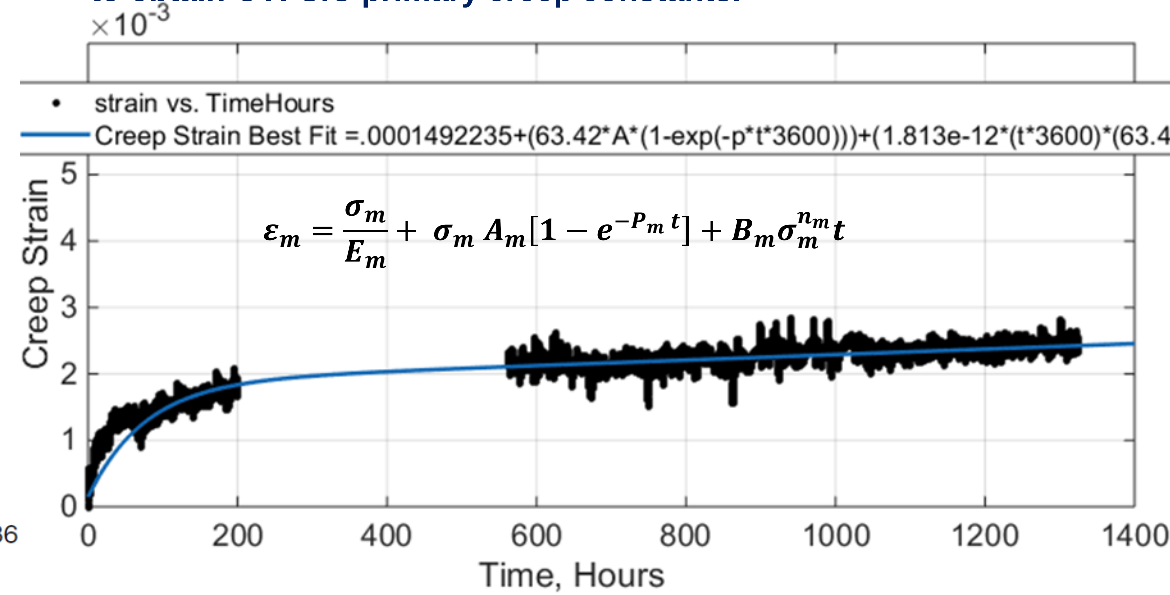


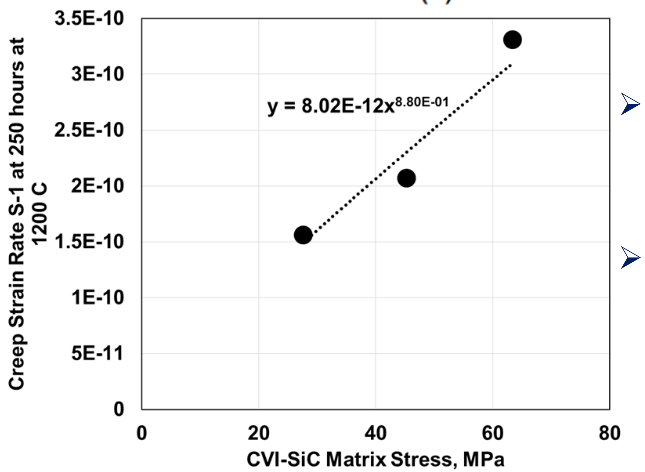
Fibers and Matrix Creep Properties at 1200 °C

Hi-Nicalon fibers primary and steady state parameters obtained from *Sauder&Lamon 2007*

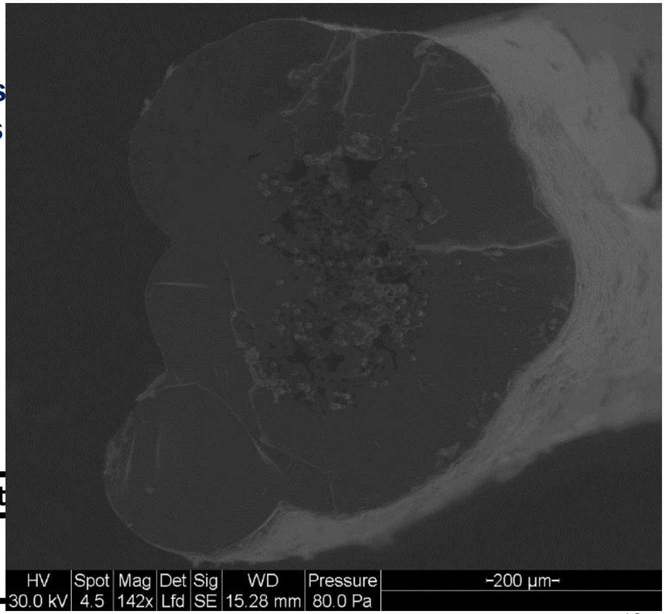


CVI-SiC matrix creep curve that lasted for more than 1350 hours in creep at 1200 C was best fitted using Matlab curve fitting application to obtain CVI-SiC primary creep constants.





- **CVI-SiC matrix steady state properties obtained from plotting 3 CVI-SiC tests strain rates at 1200 C as a function of stress.**
- **97% CVI-SiC matrix with 3% HNS fibers Minis were assumed to be pure CVI-SiC**



Constituent	A	p	B (s^{-1}/MPa)	n (Stress exponent
Hi-Nicalon Fibers	2.127×10^{-5}	1.485×10^{-5}	1.77×10^{-15}	2.3
CVI-SiC Matrix	2.59×10^{-5}	4.432×10^{-6}	1.81×10^{-12}	1

Creep Stress Transfer Model

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

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

$$\dot{\varepsilon}_f = \frac{\dot{\sigma}_f}{E_f} + \dot{\sigma}_f A_f - \dot{\sigma}_f A_f e^{(-P_f t)} + \sigma_f A_f P_f\left[e^{(-P_f t)}\right] + B_f \sigma_f^{n_f}$$

$$\dot{\varepsilon}_m = \frac{\dot{\sigma}_m}{E_m} + \dot{\sigma}_m A_m - \dot{\sigma}_m A_m e^{(-P_m t)} + \sigma_m A_m P_m\left[e^{(-P_m t)}\right] + B_m \sigma_m^{n_m}$$

$$\dot{\sigma}_m = \frac{\dot{\sigma} - \dot{\sigma}_f V_f}{V_m}$$

$$\dot{\sigma} = 0$$

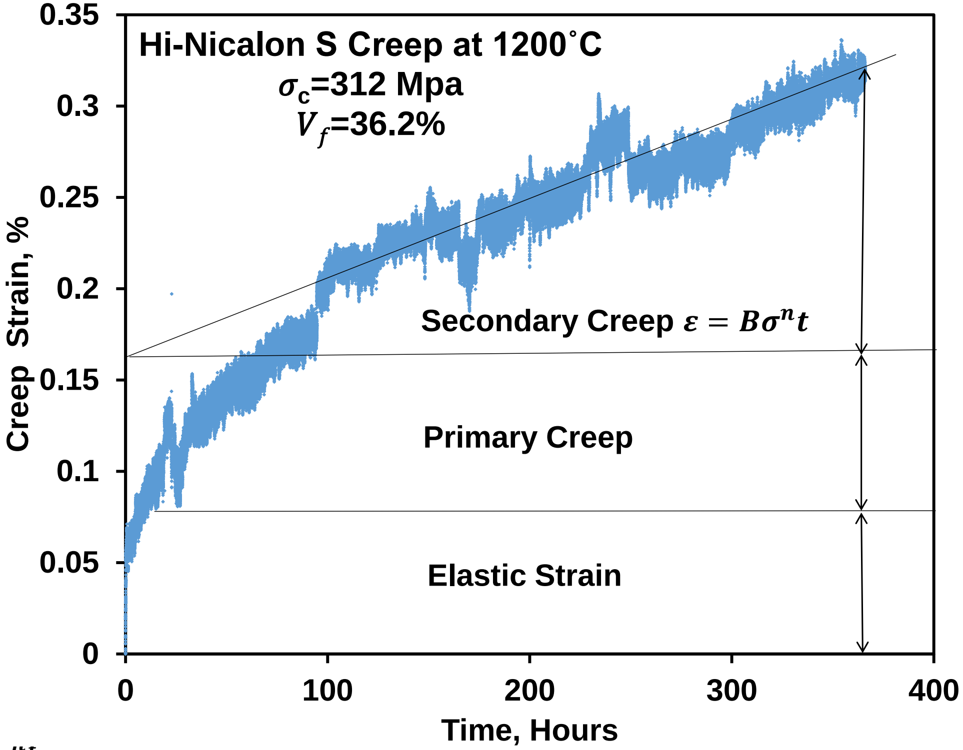
$$\varepsilon_f = \varepsilon_m$$

$$\dot{\varepsilon}_f = \dot{\varepsilon}_m$$

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

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

$$\sigma_{m(i)} = \sigma_{m(i-1)} + \Delta t\, \dot{\sigma}_{m(i-1)};\ \Delta t = t_i - t_{i-1}$$



Δt is 10 seconds in the model
Stress on the fibers and the matrix increased with the increase in V_f.

Creep Model Illustration

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

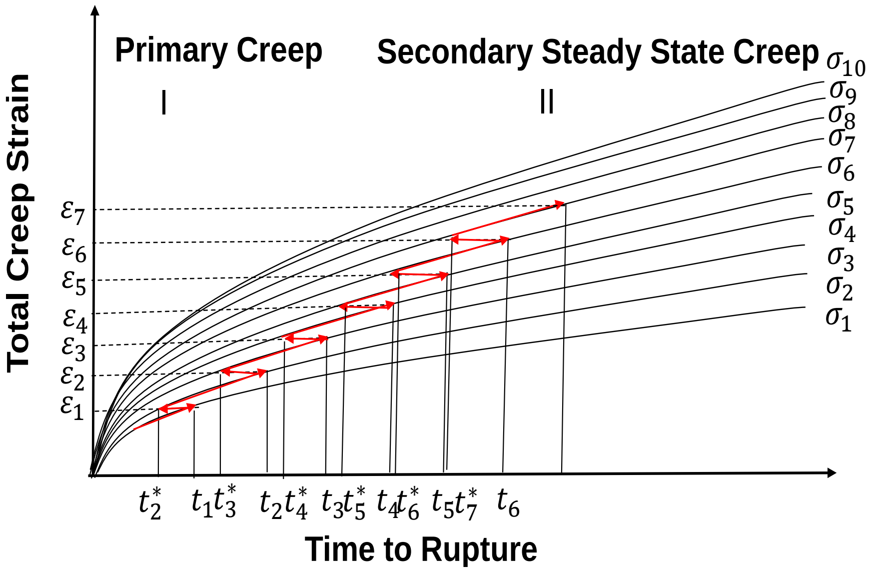
$$t_{i+1}^* = t_i - \frac{\varepsilon_f(t_i)}{\varepsilon_f'(t_i)}$$

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

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

with $\Delta = t_i - t_{i-1}^* = 10^{-8}$ sec and Error $< 10^{-6}$

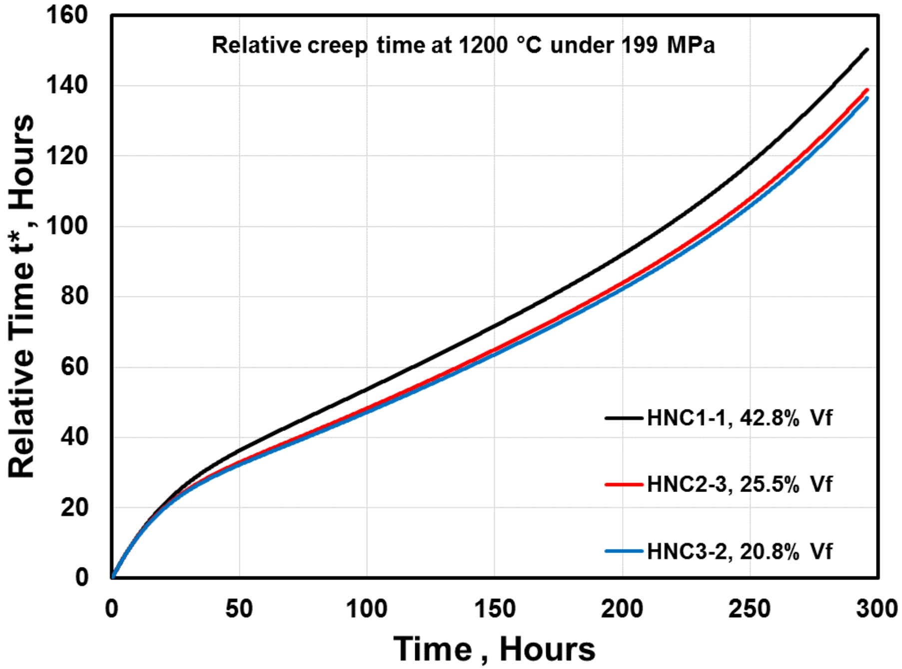
$$\varepsilon_{fi}(10 + t_{i+1}^*) = \frac{\sigma_{fi}}{E_f} + \sigma_{fi} A_f\left[1 - e^{-P_f (10 + t_{i+1}^*)}\right] + B_f \sigma_{fi}^{n_f}(10 + t_{i+1}^*)$$

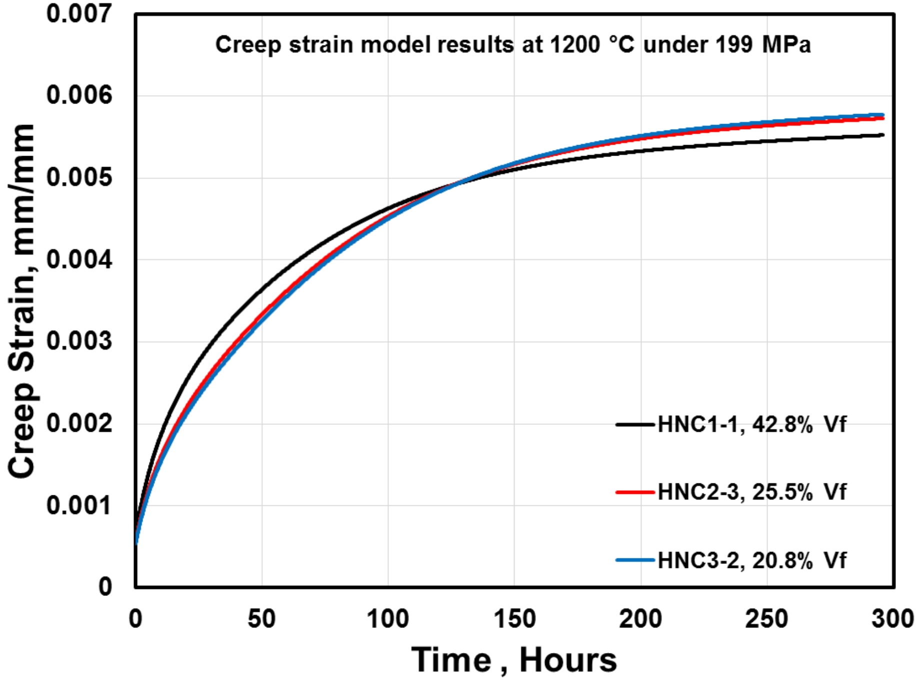


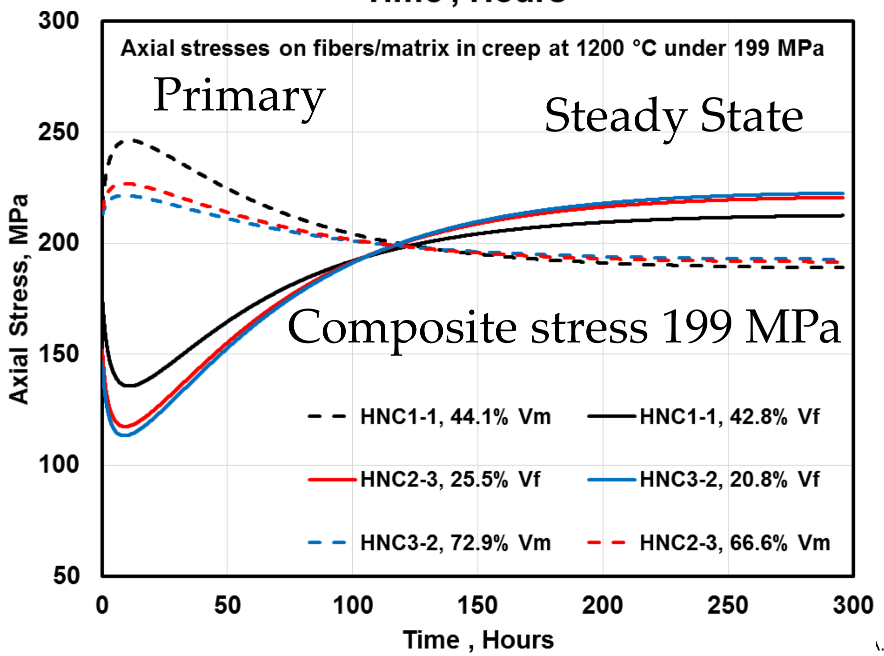
Real Time, t', Seconds	Stress on Fibers, σ_{fi}	Fibers Strain, $\varepsilon_{i-1}(\sigma_{fi}, t'_i)$	Relative time, $t_i^*(\sigma_{fi}, \varepsilon_{i-1})$	Cumulative Time, $t_i = \sum t_i^*$	Fibers Creep Strain $\varepsilon_{fi}(\sigma_{fi}, t_{i+1}^*+10)$
10	σ_1	ε_1	t_1^*	t_1	ε_{f1}
20	σ_2	ε_2	t_2^*	t_2	ε_{f2}
30	σ_3	ε_3	t_3^*	t_3	ε_{f3}
40	σ_4	ε_4	t_4^*	t_4	ε_{f4}
50	σ_5	ε_5	t_5^*	t_5	ε_{f5}
60	σ_6	ε_6	t_6^*	t_6	ε_{f6}

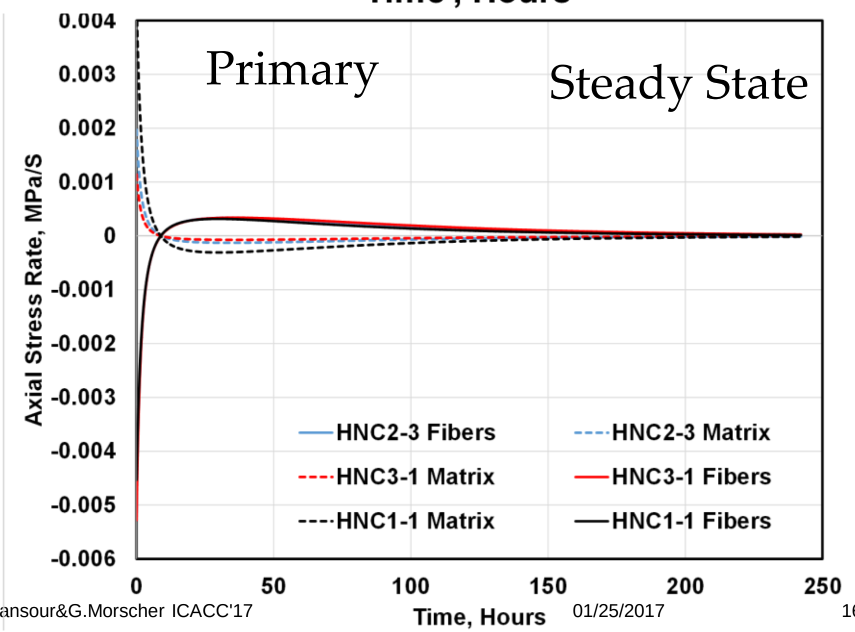
Where: $t' > t_n > t_n^*$
Time increment 10 Seconds

Creep Model Results for Constant Composite Stress & Different Fiber Content

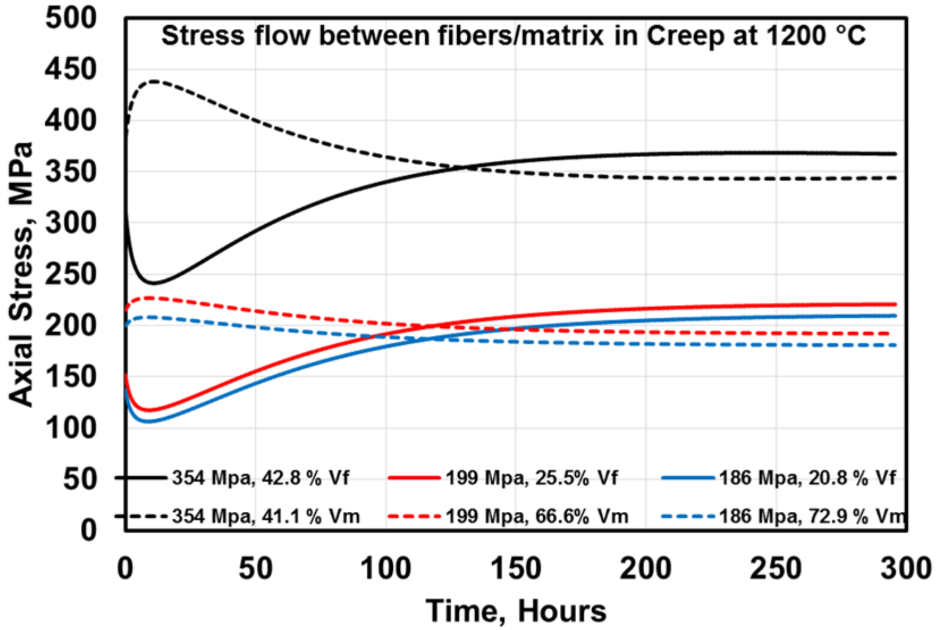


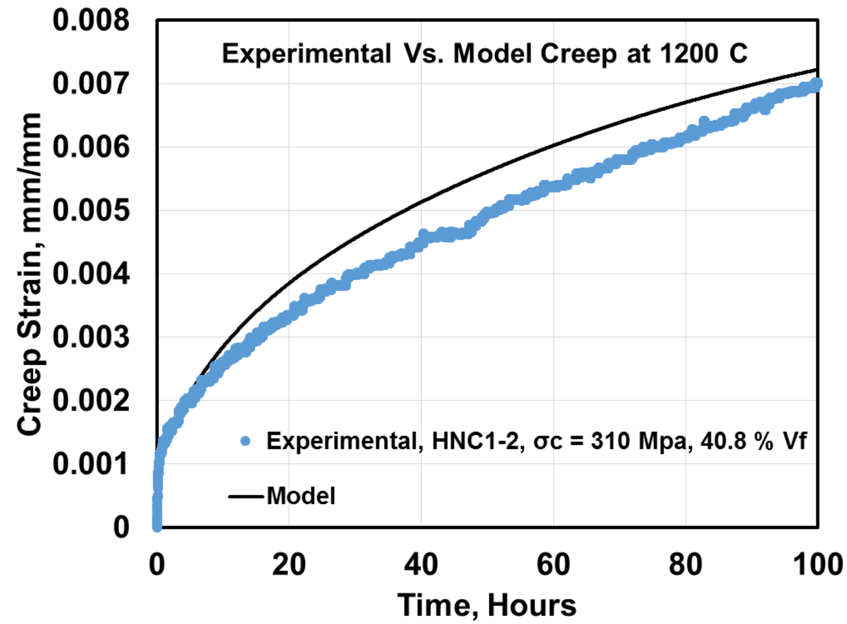


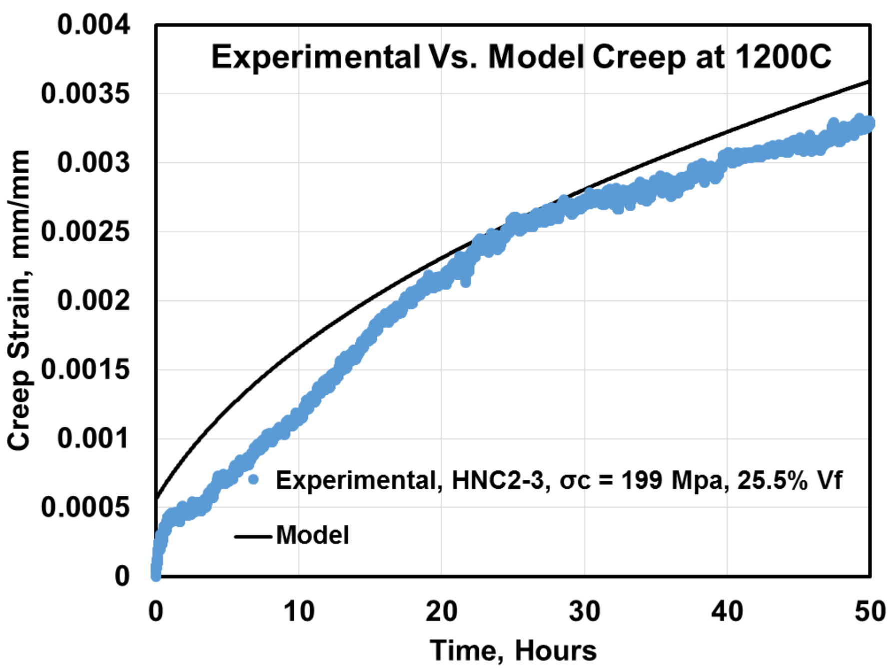


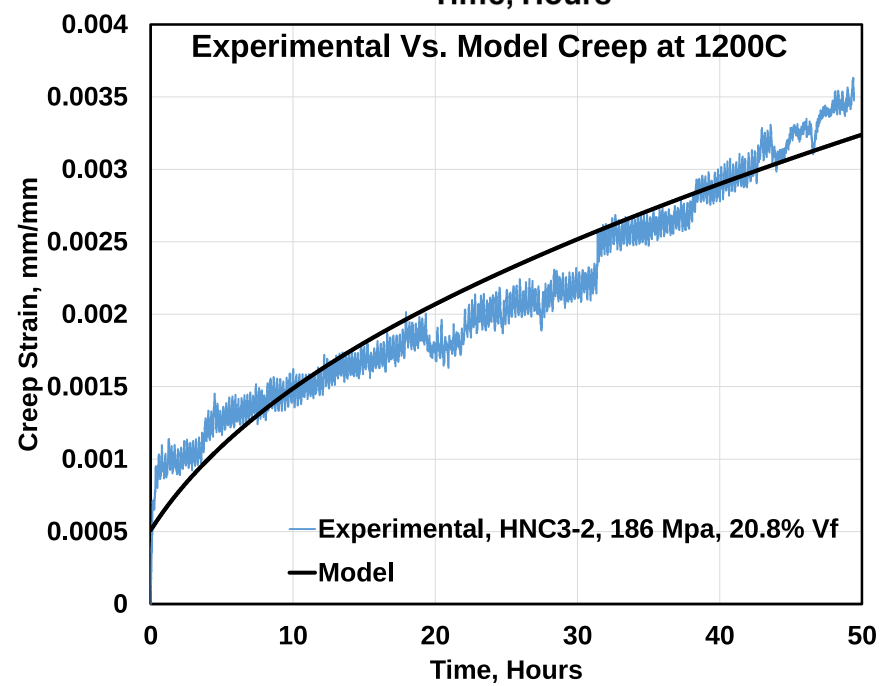


Creep Model Results for Different Composite Stress & Different Fiber Content

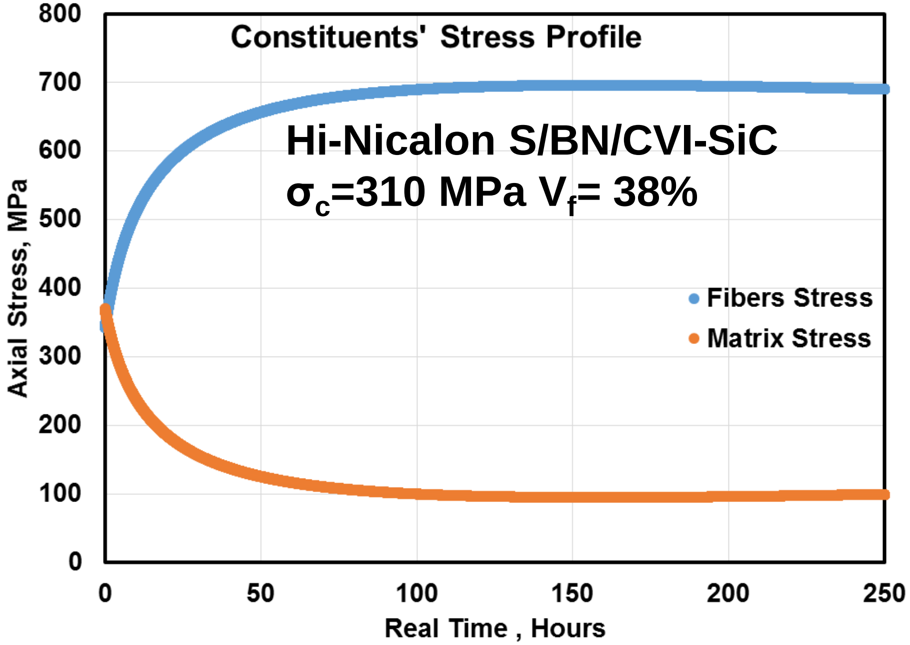


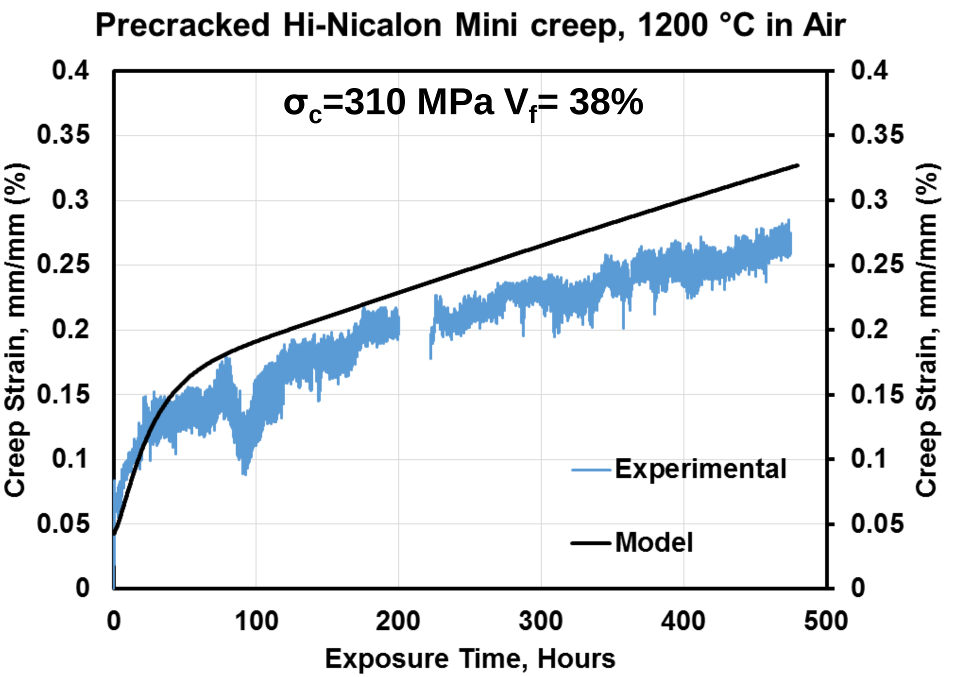






Creep Model Results for Precracked Hi-Nicalon S Minicomposite





- **Assumed extreme average fiber loading for precracked Hi-Nicalon S/BN/CVI-SiC (HNSPC1-5) σ_c=310 MPa V_f= 38% t_r=470 hours.**
- **Hi-Nicalon S fibers creep parameters in air were input to the creep model to study upper extreme creep condition.**
- **Overall model results overestimates creep strain but model evolution agrees with experimental data.**
- **This is due to lower stresses on the fibers in the debond region and regions where CVI-SiC is still intact.**

Conclusions

- CVI-SiC creep properties at 1200^oC determined.

- Derivation of creep equation generated a stress redistribution model between fibers and matrix in creep and helped to understand the effect of fiber content change on creep load sharing behavior.

- Load sharing model helped in constructing minicomposites' creep model.

- Similar model methodology can be used to predict/model true creep evolution within the same constituent (Oxidizing fibers).

- Single Hi-Nicalon S fibers creep data were compared to precracked minicomposites data with the same fiber type.

NASA