Modeling Creep-Induced Stress Relaxation at the Leading Edge of SiC/SiC Airfoils

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Abstract

Anticipating the implementation of advanced SiC/SiC composites into internally cooled airfoil components within the turbine section of future aero-propulsion engines, the primary objective of this study was to develop physics-based analytical and finite-element modeling tools to predict the effects of composite creep and stress relaxation at the airfoil leading edges, which will generally experience large thermal gradients at high temperatures. A second objective was to examine how some advanced NASA-developed SiC/SiC systems coated with typical EBC materials would behave as leading edge materials in terms of long-term steady-state operating temperatures. Because of the complexities introduced by mechanical stresses inherent in internally cooled airfoils, a simple cylindrical thin-walled tube model subjected to thermal stresses only is employed for the leading edge, thereby obtaining a best-case scenario for the material behavior. In addition, the SiC/SiC composite materials are assumed to behave as isotropic materials with temperature-dependent visco-elastic creep behavior as measured in-plane on thin-walled panels.

Key findings include: (1) without mechanical stresses and for typical airfoil geometries, as heat flux is increased through the leading edge, life-limiting tensile crack formation will occur first in the hoop direction on the inside wall of the leading edge; (2) thermal gradients through all current SiC/SiC systems should be kept below ~300°F at high temperatures to avoid this cracking; (3) at temperatures near the maximum operating temperatures of advanced SiC/SiC systems, thermal stresses induced by the thermal gradients will beneficially relax with time due to creep; (4) although stress relaxation occurs, the maximum gradient should still not exceed 300°F because of residual tensile stress build-up on the airfoil outer wall during cool-down; and (5) without film cooling and mechanical stresses, the NASA-developed N26 SiC/SiC system with thru-thickness Sylramic-iBN fiber reinforcement and a typical EBC coating has the potential of offering a maximum long-term steady-state operating temperature of ~3100°F at the surface of the EBC.

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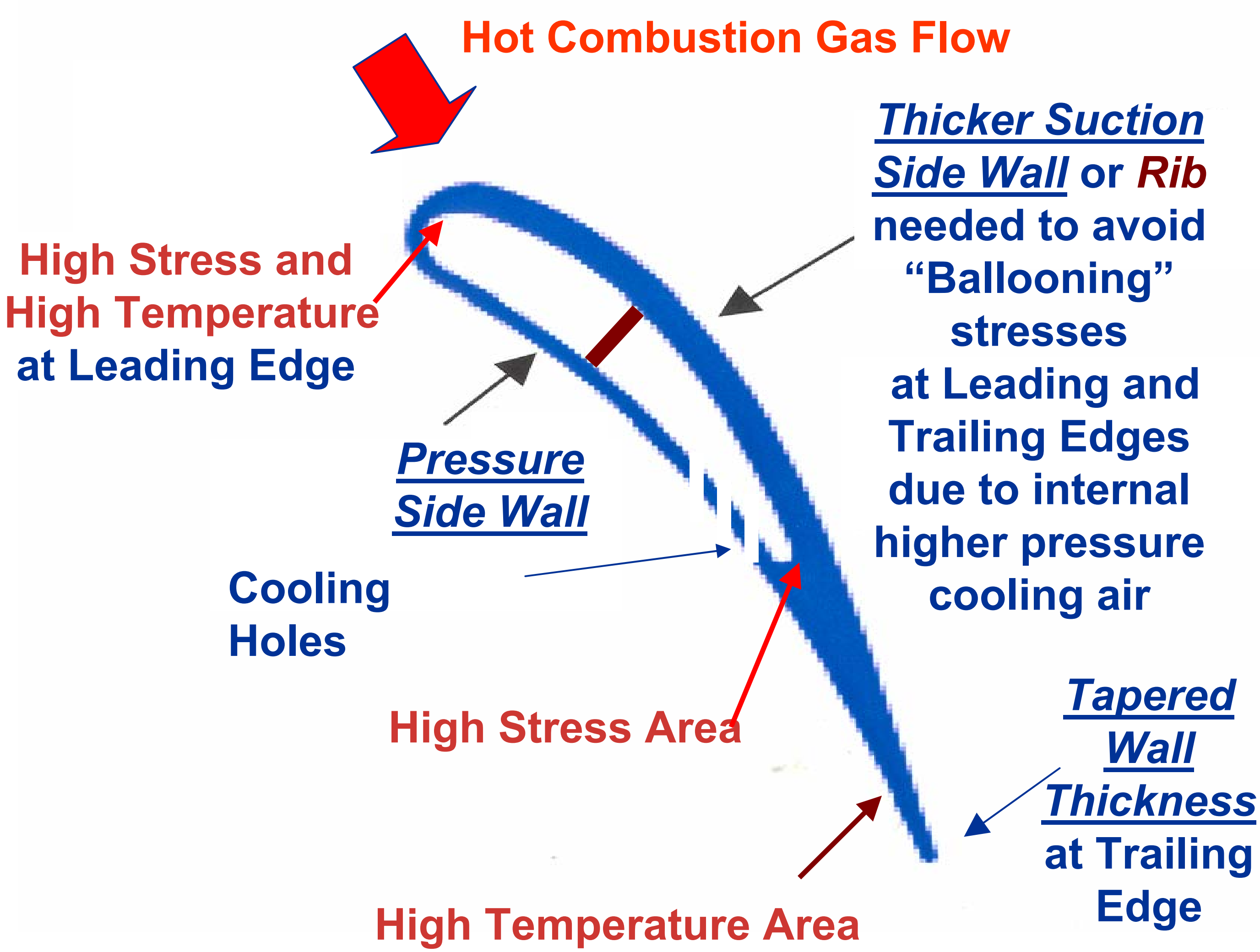
Background

Recently NASA Glenn has developed a variety of advanced SiC/SiC composite systems targeted for aerospace components that will experience long-term structural service to temperatures from ~2200 to over 2650^{o}F.

Under the new NASA Fundamental Aeronautics Program, one of Materials and Structures objectives is to develop basic tools that will allow these advanced CMC systems to be implemented in turbine section airfoils of future aero-propulsion engines for long-life supersonic vehicles.

Generic studies are now on-going at NASA Glenn to examine the capabilities of these SiC/SiC systems to (1) down-select the best materials, architectures, and processes for turbine airfoil applications and (2) to develop advanced technologies that will overcome current SiC/SiC implementation issues.

Shape and Thermo-Structural Requirements for Internally-Cooled Turbine Airfoils are Very Complex

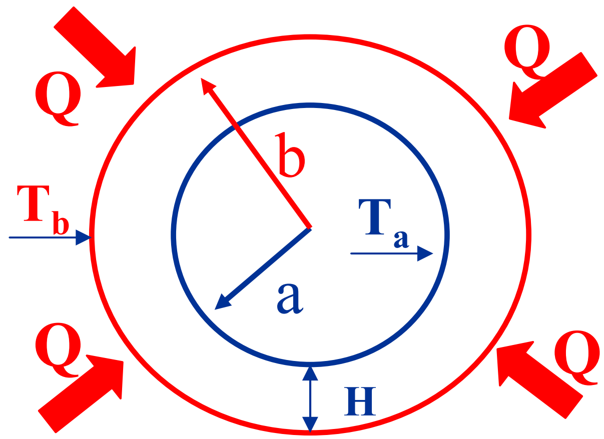


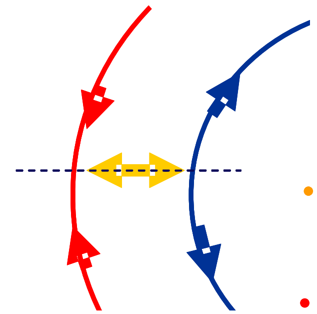
Objectives

This Study

- **Use simple tube model and property data for current NASA SiC/SiC systems to examine the generic effects of creep-induced stress relaxation on the leading edge of cooled SiC/SiC turbine airfoils, which will typically be subject to the highest temperatures and highest thermal stresses.**
- **Relate these effects to general guidelines for selecting the optimum SiC/SiC materials, processes, and architectures for a turbine airfoil leading edge.**

Simple Internally-Cooled Tube Model for Leading Edge of SiC/SiC Airfoil





Advantages

- Allows a best-case evaluation of SiC/SiC leading edge temperature and thermal stress capability by elimination of mechanical stresses that depend on specific airfoil designs
- Allows generic examination of effects due to thermal stresses, curvature, wall thickness, creep, stress relaxation, and other properties of different SiC/SiC systems
- Allows both analytical and finite element analyses
- Useful also for analyzing SiC/SiC tubular heat exchangers

Four Key Properties of Airfoil Technical Interest Using Internally Cooled Tube Model

1. T^* = Max Material Temperature for microstructural stability
2. $\Delta T^* = T_b - T_a$ = Max Allowable Thermal Gradient across Wall in order to avoid life-limiting matrix cracking:

$$\Delta T^* = S^* \{ 2(1-\nu) / \alpha E F \}$$

S^* = max allowable in-plane or thru-thickness tensile stress

F = geometry factor

3. Q^* = Max Allowable Heat Flux Thru Wall w/o matrix cracking:

$$Q^* \approx K_3 \Delta T^* / H$$

4. T^*_{EBC} = Max Allowable Surface Temperature for EBC coating w/o cracking of SiC/SiC matrix:

$$T^*_{EBC} = T^* + \beta Q^*$$

β dependent on EBC thickness and thermal conductivity

Key Thermo-Structural Properties of High-Performance NASA SiC/SiC Systems

- **TYPE 1 (N24): Sylramic-iBN fiber, CVI + Slurry SiC + Si matrix**

  T* ~ 2400°F (1315°C)

- **TYPE 2 (N26): Sylramic-iBN fiber, CVI + PIP SiC matrix**

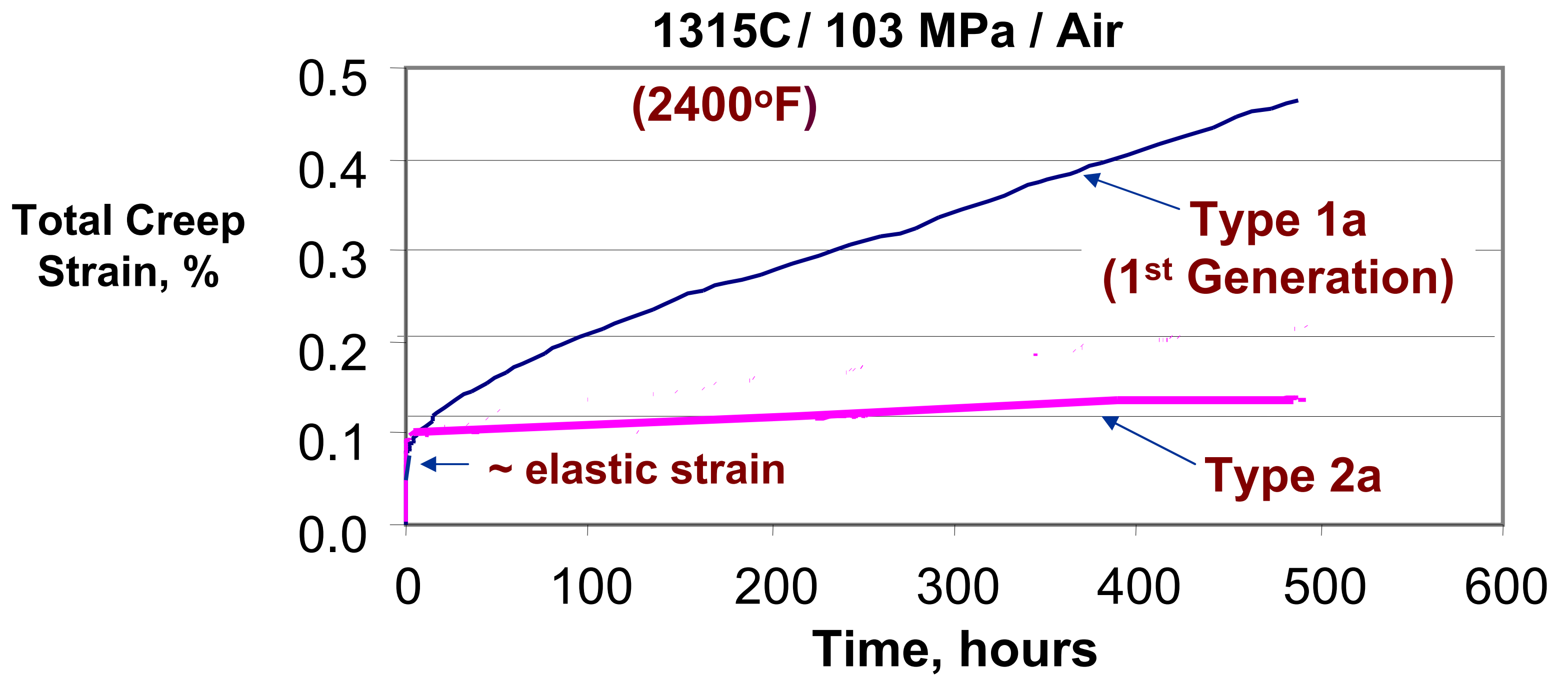
  T* > 2650°F (1450°C)

Nominal SiC/SiC Property Data from 2200 – 2700°F:

TYPE	1a	1b	2a	2b
Architecture	2D	2.5D	2D	2.5D
E_1, GPa	230			
ν_{13}	0.13			
α_1, 10^{-6} $^\circ C^{-1}$	5.9			
S^*_1 (t = 0), MPa	150			

S^*_3, MPa	15	25	15	25
K_3, W / m .°K	18	23	12	25
Creep Param A_1	< 2.0		0.08	

Typical In-Plane Tensile Creep for Type 1a and Type 2a SiC/SiC Systems



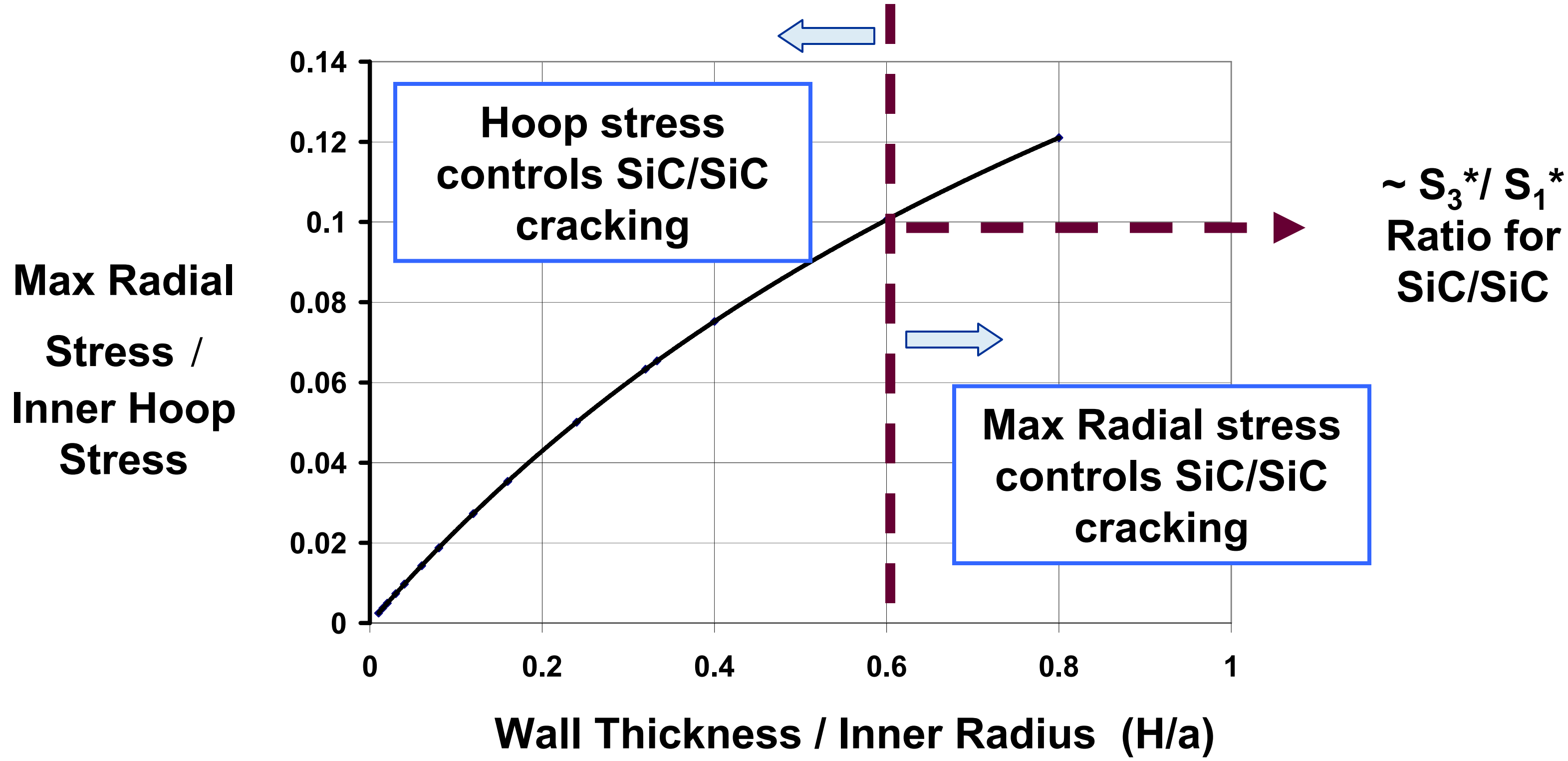
***<u>NASA models assuming linear stress dependence</u>*:**

Creep: $\varepsilon_1(t) / \varepsilon_1(0) = 1 + A_1 \{ 1 - \exp - t/\tau(T) + t/8\tau(T) \}$

Prony Series: $G(t)/G(0) = 0.30 \exp(- t/C) + 0.70 \exp(- t/D)$

(Parameters C and D = functions of A_1 and T)

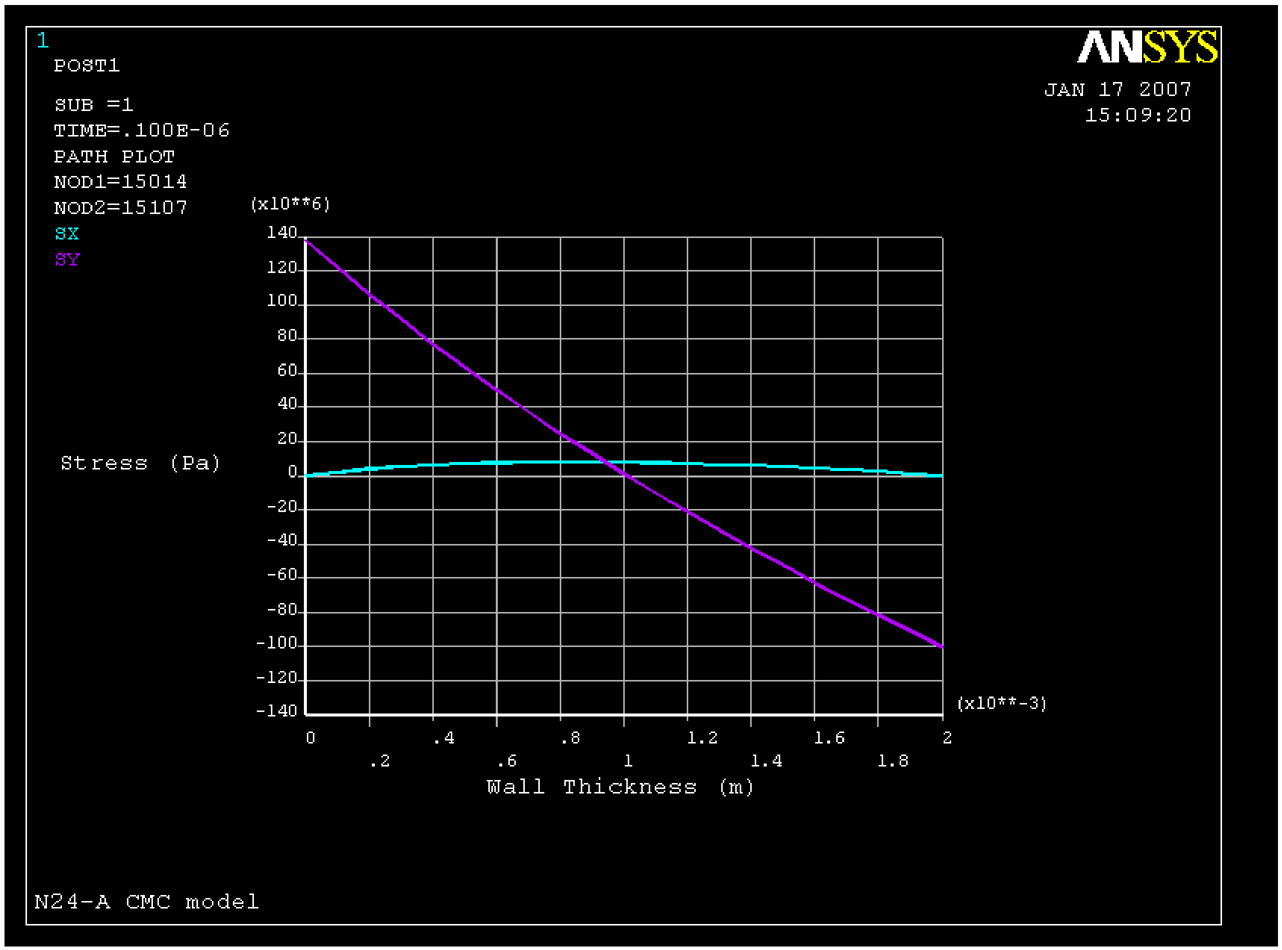
Curvature and Wall Thickness Effects on Thermal Stresses at t = 0 in Leading Edge Tube Model



- ***For typical airfoil leading edges with H/a ratios < 0.6, max radial tensile stresses are less than 10% of hoop tensile stresses at inner wall surface. Thus based on thermal stresses alone, the upper thermal gradient of a airfoil leading edge with current SiC/SiC systems will be limited by their hoop stress allowable of ~150 MPa.***

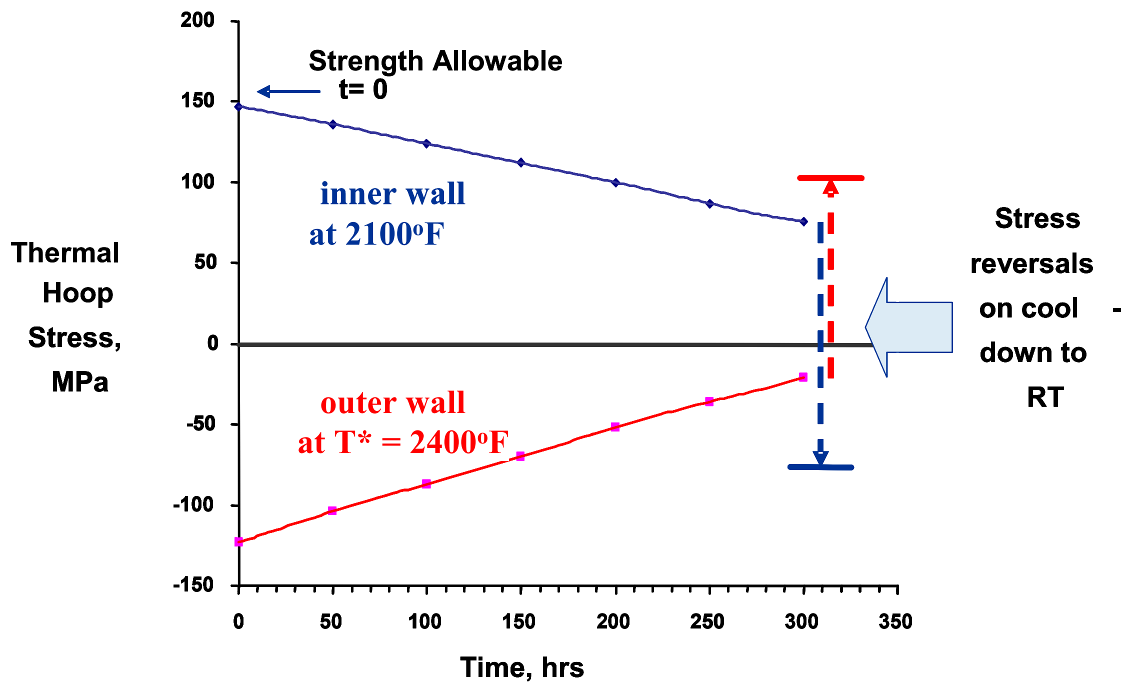
Thermal Stress Distribution in Types 1 and 2 SiC/SiC Tubes at t = 0 (Elastic) and at ΔT^* that Avoids Cracking

Conditions: ΔT^* = 300°F, a = 6 mm, H = 2 mm, H/a = 0.33



Hoop Stress Relaxation at Max Thermal Conditions for Type 1 SiC/SiC Tube Model

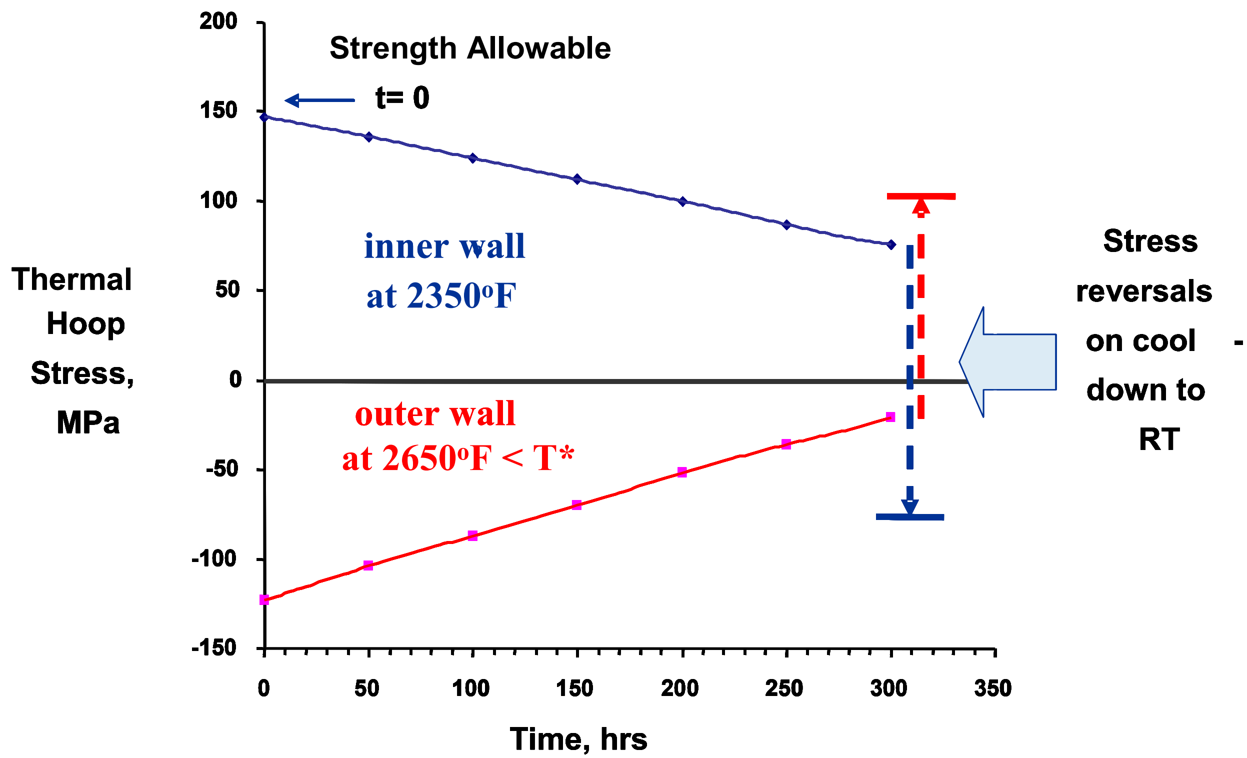
Conditions: ΔT^* = 300°F, H/a = 0.33, Linear Creep, A_1 = 2.0



- *Inner wall tensile stress relaxes with time, thereby increasing material reliability at temperature. Outer wall compression decreases faster due to higher temperature.*
- *Residual stress build-up during cool down indicate ΔT^* should be kept below ~300°F at all times to avoid cracking of outer wall.*

Hoop Stress Relaxation Near Max Thermal Conditions for Type 2 SiC/SiC Tube Model

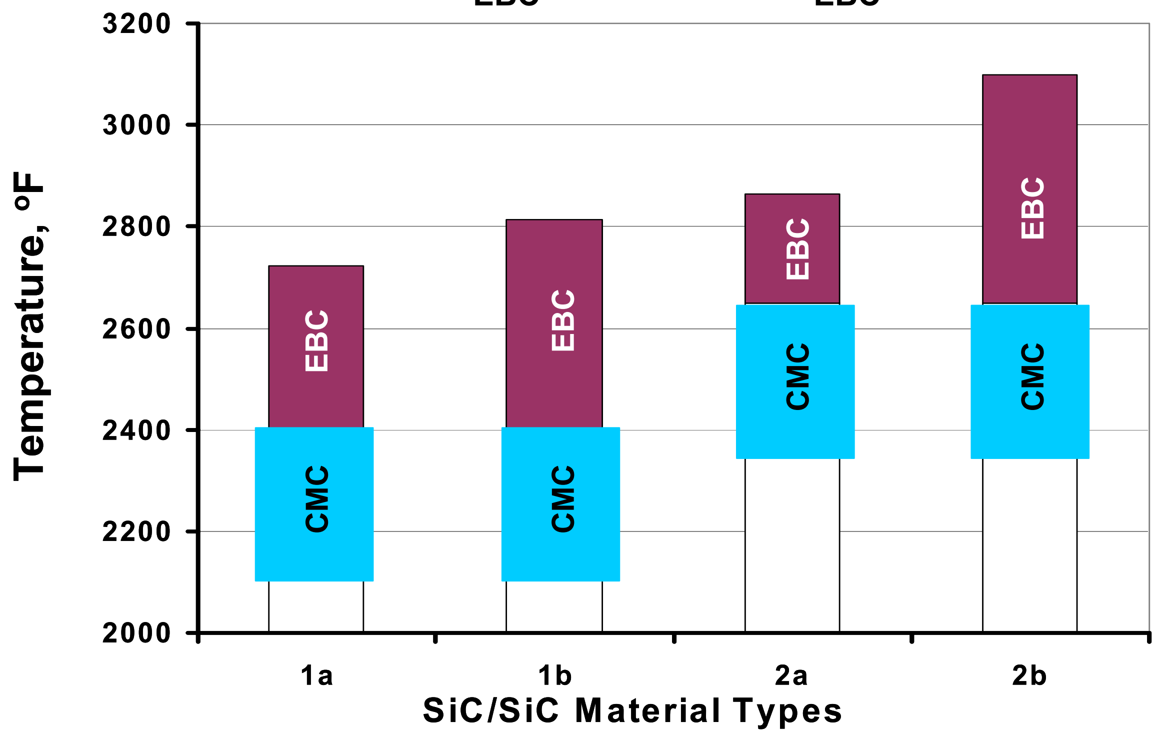
Conditions: ΔT^* = 300°F, H/a = 0.33, Linear Creep, A_1 = 0.08



- *Stresses relax with time similarly to Type 1, but at 300°F higher wall temperatures due to the enhanced creep resistance of Type 2.*
- *Higher temperature capability of Type 2 suggests that stresses can be relaxed even <u>faster</u> by higher service or pre-conditioning temperatures.*

Maximum Temperature Predictions from Tube Model of SiC/SiC Airfoil Leading Edges

Assumptions: $\Delta T^* = 300^oF$, $H_{CMC} = 1.5$ mm, $a_{CMC} = 6$ mm, $H_{EBC} = 0.2$ mm, $k_{EBC} = 2$ W/m.°K



- ***Type 2b SiC/SiC material offers the highest range of thermal capability, which will be needed when operating ΔT^* for CMC and EBC are reduced by the presence of mechanical stresses.***

Summary and Conclusions

- **Using a simple tube model for a SiC/SiC airfoil leading edge and assuming best case behavior with only thermal stresses within the tube wall, it is shown by analytical and NASA-developed FE methods that under maximum use temperature conditions, tensile and compressive stresses will relax with time, approaching zero values under steady-state conditions.**
- **Even though stresses relax, the maximum temperature gradient for all current NASA SiC/SiC systems should be kept below 300°F to avoid life-limiting cracking due to residual stress build-up during airfoil cool down.**
- **Type 2b SiC/SiC with no free silicon and high-conductivity thru-thickness reinforcement appears to offer the most thermo-structural capability, which will be needed when mechanical stresses are introduced into the airfoil leading edge.**
- **Higher temperature capability of Type 2 SiC/SiC suggests that pre-conditioning under simulated thermal gradients can reduce the failure risk of SiC/SiC airfoils during service.**

On-Going and Future Studies

- **From a *modeling point-of-view*, significantly more data and micro-mechanical models are needed to account for effects due to fiber architectures, stress transfer from matrix to fiber, airfoil geometries, and mechanical service conditions. Of particular concern is the need to model and down-select fiber architectures that will simultaneously meet airfoil requirements for shape, fabrication, thermal-structural performance, and surface roughness.**
- **From a *materials point-of-view*, both CMC and EBC constituents and architectures need to be developed to enhance stress, temperature, and thermal gradient allowables for current SiC/SiC systems. The relaxation results of this study suggest that the quest for higher creep resistant constituents needs further examination.**
- **These needs as well as others required for the implementation of SiC/SiC components in the turbine sections of supersonic vehicles are now being addressed under the new NASA Fundamental Aeronautics Program.**