Abstract, CIMTEC 2006, June 2006
Invited Lecture

ADVANCES IN SiC/SiC COMPOSITES FOR AEROSPACE APPLICATIONS

James A. DiCarlo
Senior Technologist, Ceramics
NASA Glenn Research Center

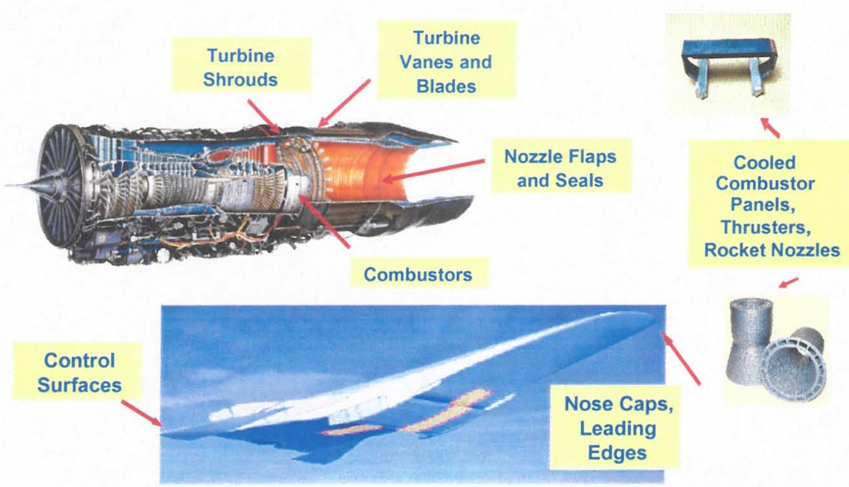
In recent years, supported by a variety of materials development programs, NASA Glenn Research Center has significantly increased the thermostructural capability of SiC/SiC composite materials for high-temperature aerospace applications. These state-of-the-art advances have occurred in every key constituent of the composite: fiber, fiber coating, matrix, and environmental barrier coating, as well as processes for forming the fiber architectures needed for complex-shaped components such as turbine vanes for gas turbine engines. This presentation will briefly elaborate on the nature of these advances in terms of performance data and underlying mechanisms. Based on a list of first-order property goals for typical high-temperature applications, key data from a variety of laboratory tests are presented which demonstrate that the NASA-developed constituent materials and processes do indeed result in SiC/SiC systems with the desired thermal and structural capabilities. Remaining process and microstructural issues for further property enhancement are discussed, as well as on-going approaches at NASA to solve these issues. NASA efforts to develop physics-based property models that can be used not only for component design and life modeling, but also for constituent material and process improvement will also be discussed.

ADVANCES IN SiC/SiC COMPOSITES FOR AEROSPACE APPLICATIONS

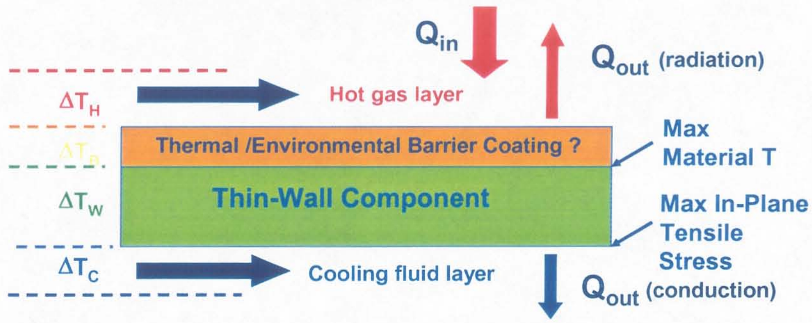
James A. DiCarlo
Materials and Structures Division
NASA Glenn Research Center
Cleveland, OH 44135
USA

Presented at CIMTEC 2006
June, 2006, Acireale, Sicily

Advanced Lightweight High-Temperature Structural Materials are Needed for Multiple Aerospace Applications



Typical Function of a Structural Material In a Hot Aerospace Application



Key Material Property Requirements:

- ***Low Density, Low Permeability, High Emissivity***
- ***Microstructural Stability at Maximum Temperature***
- ***High Tensile Stress Capability In-Plane and Thru-Thickness***
- ***High Thermal Conductivity Thru-Thickness to reduce thermal gradients and stresses***

Advantages of SiC Fiber / SiC Matrix (SiC/SiC) Ceramic Matrix Composites (CMC)

versus Superalloys:
- Lower density (~30% metal density)
- Higher temperature capability (>1100°C)
- Lower thermal expansion

versus Monolithic Ceramics:
- Non-catastrophic failure
- Higher toughness, better damage tolerance
- Capability for larger and more complex shapes

versus Carbon Fiber Composites (C/SiC, C/C):
- Higher oxidative durability, more predictable life
- Lower permeability

versus Oxide/Oxide Ceramic Composites:
- Higher strength, temperature capability, creep-rupture resistance, thermal conductivity, emissivity
- Lower permeability

Objective / Outline

- Present brief review of recent NASA efforts aimed at developing *Advanced Constituent Materials and Processes* for SiC/SiC composites to better meet the thermal, structural, and conductivity requirements for aerospace components.
  - NASA developments to 2002:
    - *Sylramic-iBN SiC Fibers*
    - *SiC Matrices based on Silicon melt infiltration*
  - More recent developments:
    - *Silicon free Matrices*
    - *Special Post-production Treatment*
    - *Advanced Fiber Architectures*

Acknowledgements

SiC/SiC Development Team at NASA Glenn

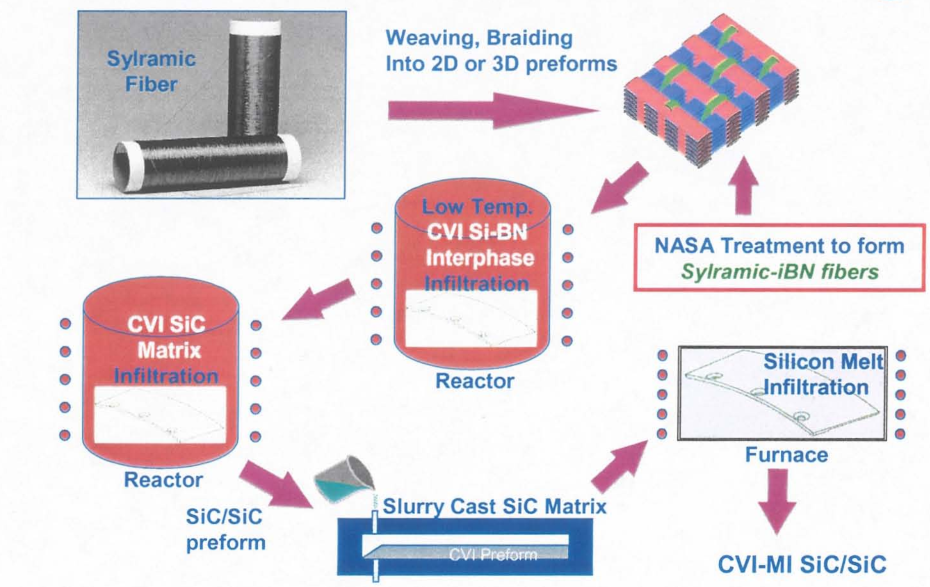
- Fibers/Architectures: *Hee Mann Yun* (now at MATECH/GSM)
- Matrices: *Ram Bhatt*
- Modeling: *Greg Morscher*, *Jerry Lang*

NASA Funding Programs

- Ultra Efficient Engine Technologies (UEET)
- Internal Research and Development

National Aeronautics and Space Administration

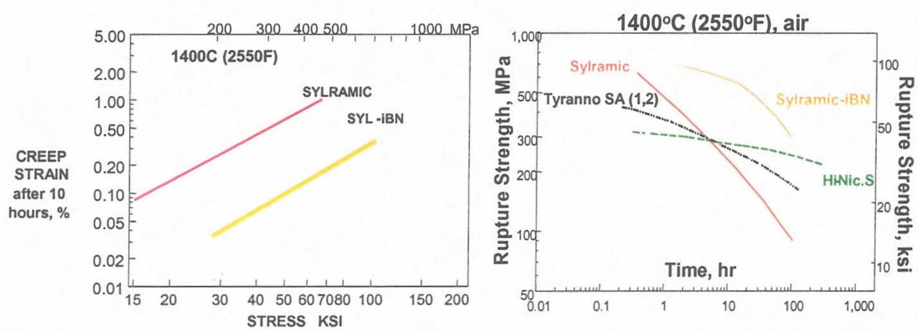
NASA 2002 Fabrication Route for SiC/SiC Components



National Aeronautics and Space Administration

NASA Advanced Process for Sylramic SiC Fibers

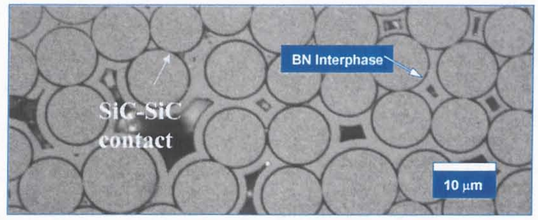
- In ~2000, NASA developed a high-temperature process for commercial Sylramic SiC fibers to produce the stoichiometric ***Sylramic-iBN fiber*** with a thermally stable in-situ grown BN (iBN) coating and ***state-of-the-art*** tensile strength and creep-rupture resistance.



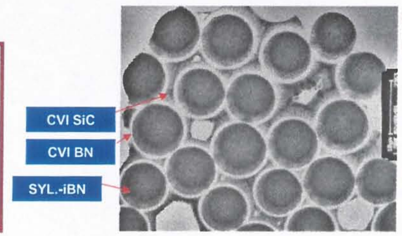
National Aeronautics and Space Administration

Durability Benefit of In-Situ BN Coating

Without NASA treatment, almost every Sylramic SiC fiber in each tow contacts another fiber, allowing rapid and detrimental fiber bonding upon oxygen ingress

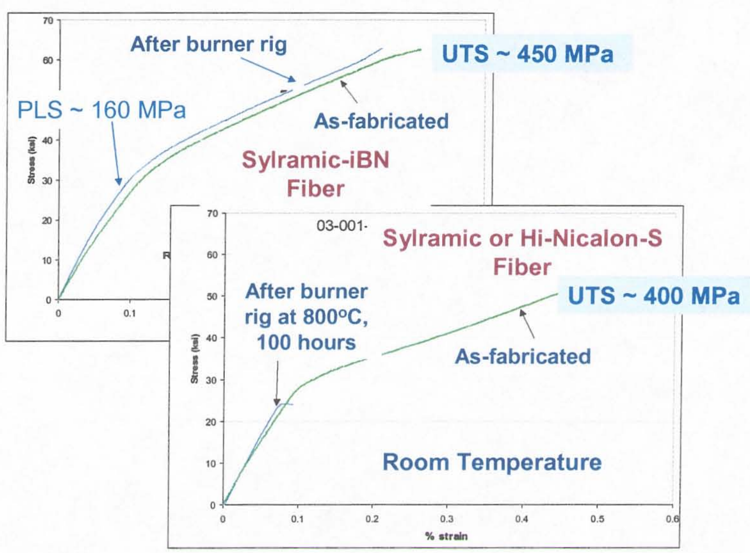


With NASA treatment, in-situ BN coating prevents SiC-SiC contact between Sylramic-iBN fibers, delaying oxide bonding and increasing SiC/SiC durability and reproducibility



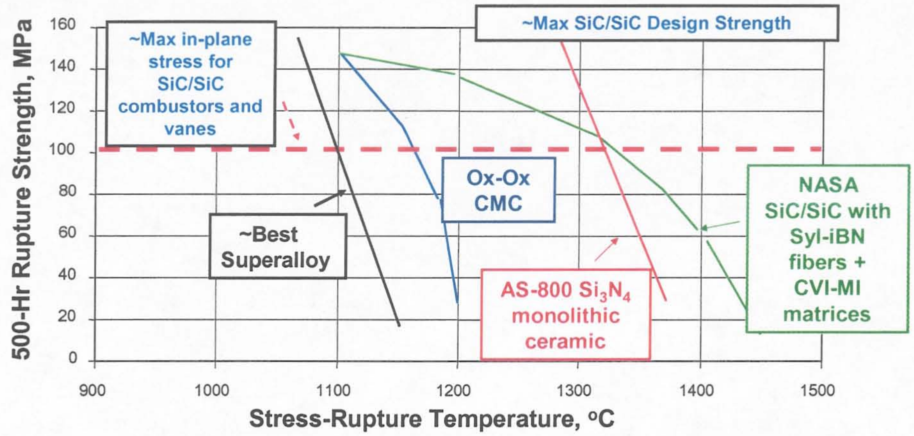
National Aeronautics and Space Administration

CVI-MI SIC/SIC Panels with Sylramic-iBN Fibers Show Improved In-Plane UTS and Burner Rig Durability



National Aeronautics and Space Administration

In-Plane 500-Hour Rupture Strength in Air for NASA CVI-MI SiC/SiC versus Competing Materials (~Yr 2002)



With upper use temperatures near ~1315°C , NASA 2002 SiC/SiC systems display higher thermostructural capability than competing materials

www.nasa.gov 11

National Aeronautics and Space Administration

CVI-MI SiC/SiC Properties Needed Further Improvement

- On *scientific* side, temperature capability, thermal conductivity, and design strength were less than the best SiC monolithic ceramics.
- On *technical* side, lifing risks still exist for SiC/SiC component failure due to unexpected hot spots and/or loss of the thermal barrier coatings.

NASA Activities:

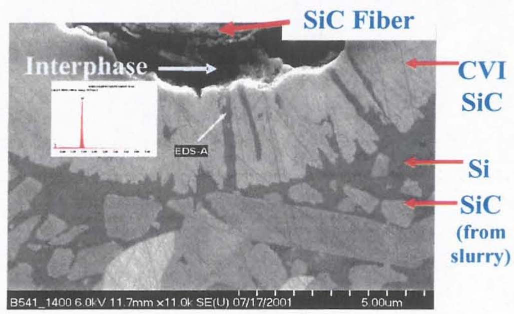
- Understand, mechanistically model, and minimize sources for property limitations.
- Key Concerns: Improving SiC/SiC
  - ***Microstructural Stability at higher temperatures***
  - ***Structural Capability at higher temperatures***
  - ***Thru-Thickness thermal conductivity***
  - ***Thru-Thickness strength*** (ILTS or interlaminar tensile strength for 2D composites)

www.nasa.gov 12

Stability Issues for CVI-MI SiC/SiC

Key Issues:

- For long times above 1300°C, ***free Si in matrix*** diffuses thru grain boundaries of initial CVI SiC matrix coating, attacks BN fiber coating and SiC fiber, and reduces UTS.



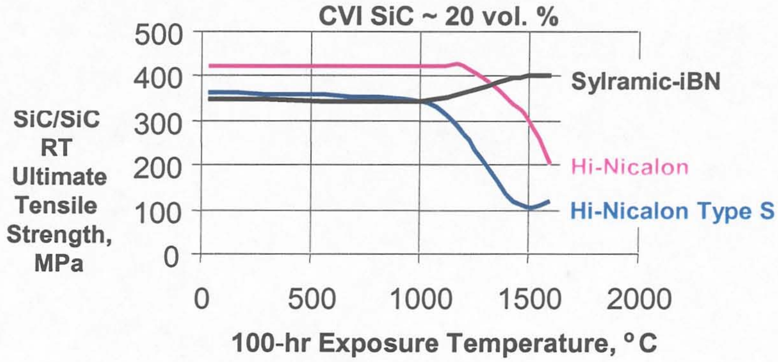
- ***Free Si*** in matrix also ***degrades composite creep-rupture resistance***, reducing CVI-MI SiC/SiC structural capability at high temperatures.
- ***CVI BN fiber coating***, which is deposited below 1000°C, ***densifies and shrinks at high temperatures***, reducing fiber-matrix load transfer, thru-thickness conductivity and tensile strength.

NASA Approaches to Microstructural Stability Issues

- ***Retain Sylramic-iBN SiC fiber*** because of its high strength, high creep-rupture resistance, high thermal conductivity, and microstructural stability to over 1650°C.
- Develop materials and processes for ***two advanced SiC/SiC systems with Si-free matrices:***
  - ***Full CVI SiC***
  - ***Partial CVI SiC + SiC*** derived from polymer infiltration and pyrolysis (hybrid CVI-PIP).
- Develop ***special annealing treatment*** that
  - Stabilizes BN coating, minimizing gap formation between fiber and matrix, and also
  - Removes process-related defects in the SiC matrix to improve CMC creep-rupture resistance and thermal conductivity

National Aeronautics and Space Administration

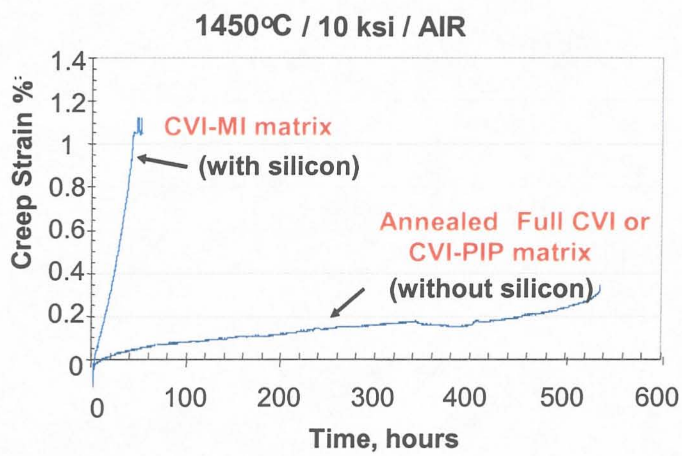
Annealing Effects on Partial CVI SiC Panels with Different Fibers



Intrinsic stability and in-situ grown BN coating for Sylramic-iBN fiber allows annealing of Si-free CVI SiC matrices to >1500°C <u>with NO loss in in-plane UTS</u>

National Aeronautics and Space Administration

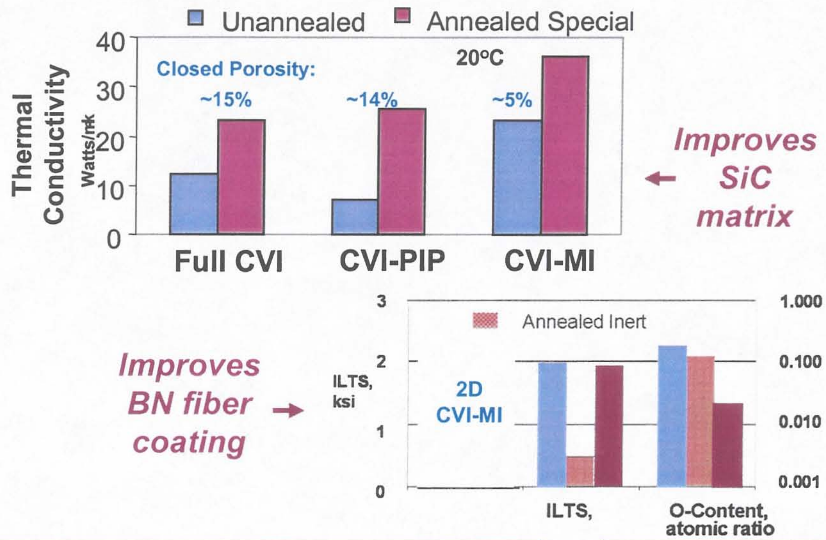
Creep-Rupture Behavior for NASA 2D SiC/SiC Systems



Si-free matrices with NASA special annealing treatment significantly improves creep rupture resistance of SiC/SiC

National Aeronautics and Space Administration

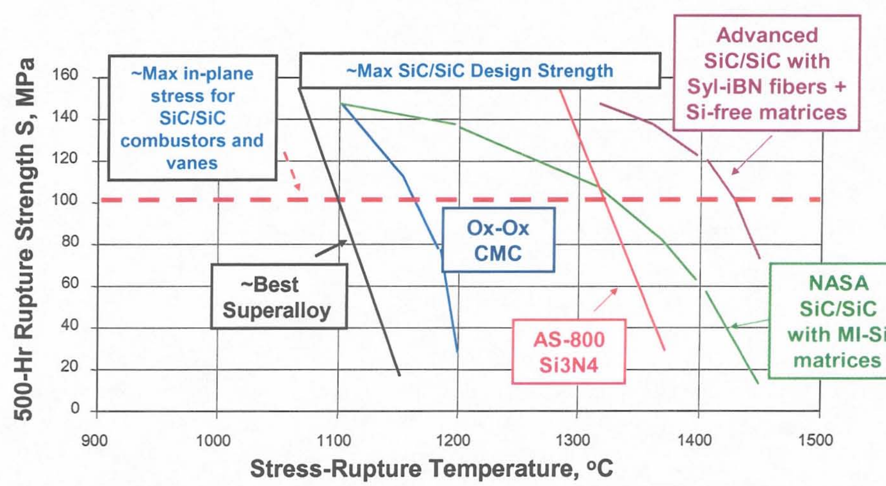
Effects of NASA Special Annealing Treatment on Thru-Thickness Properties for 2D Sylramic-iBN/SiC Systems



www.nasa.gov 17

National Aeronautics and Space Administration

In-Plane 500-Hour Rupture Strength in Air for NASA Advanced SiC/SiC versus Competing Materials (~Yr 2005)

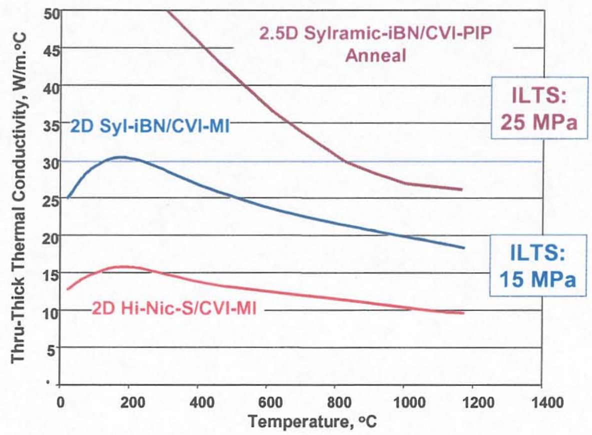


Thermostructural capability for advanced SiC/SiC system is state-of-the art with upper use temperatures of ~1450°C (2640°F)

www.nasa.gov 18

National Aeronautics and Space Administration

NASA Continues to Develop Improved SiC/SiC Using Alternate Fiber Architectures and Sylramic-iBN Fibers



2.5D angle-interlock architecture with low content of Sylramic-iBN fibers in z-direction (~3 vol. %) and NASA special anneal yields stoichiometric CVI-PIP SiC/SiC system with thru-thickness conductivity and 20°C thru-thickness tensile strength significantly improved over original CVI-MI system

National Aeronautics and Space Administration

Summary and Future Needs

- NASA SiC/SiC systems with high performance Sylramic-iBN fibers are ***capable of outperforming the best superalloys, Ox/Ox systems, and monolithic ceramics*** in in-plane strength capability at high temperatures (to 1450°C), while providing low density, high emissivity, high thermal conductivity, and high thru-thickness strength.
- Currently the SiC/SiC constituent materials and processes that provide the best combination of thermal and structural performance are:
  - ***Stoichiometric Sylramic-iBN SiC fiber***
  - ***CVI BN-based fiber coating after NASA special treatment***
  - ***Stoichiometric SiC matrix with partial CVI plus PIP SiC, again after NASA special treatment.*** (Future improvements are needed to reduce porosity in this matrix).
- Although 2D SiC/SiC systems offer simplicity in fabrication of aerospace components, ***3D systems*** reinforced by ***non-orthogonal high-strength high-conductivity fibers, such as Sylramic-iBN***, offer even higher thru-thickness conductivity and strength. (Future improvements are needed to increase Z-direction fiber content.)

Current SiC/SiC Commercialization Issues

Life-cycle cost-benefit analyses need to be conducted for each SiC/SiC component to determine economic viability, BUT

- High costs still exist for high-performance SiC fibers, for quality controls at every process step, and for generation of accurate design data bases
- Constituent vendors are often different and single organizations, complicating production time and resulting in multi-tiers of profit taking,
- Little or no experience exists demonstrating reliable performance under actual component service conditions
- SiC/SiC property and lifing models are complex, and approaches for converting models into Finite Element codes for component design are lacking.

Even at design stresses below matrix cracking, lifing analyses of SiC/SiC components at high temperatures can be very complex:

- Creep effects, residual stress development
- Environmental effects with and without barrier coatings.