GRC High Temperature Ceramic Matrix Composites (HTCMC)- Current Thrusts, Capabilities, & Challenges/Gaps

Dr. Jon Goldsby, Chief

Ceramic and Polymer Composites Branch

AFRL- NASA GRC High Temperature Materials Technical Interchange Mtg

Apr 18, 2024

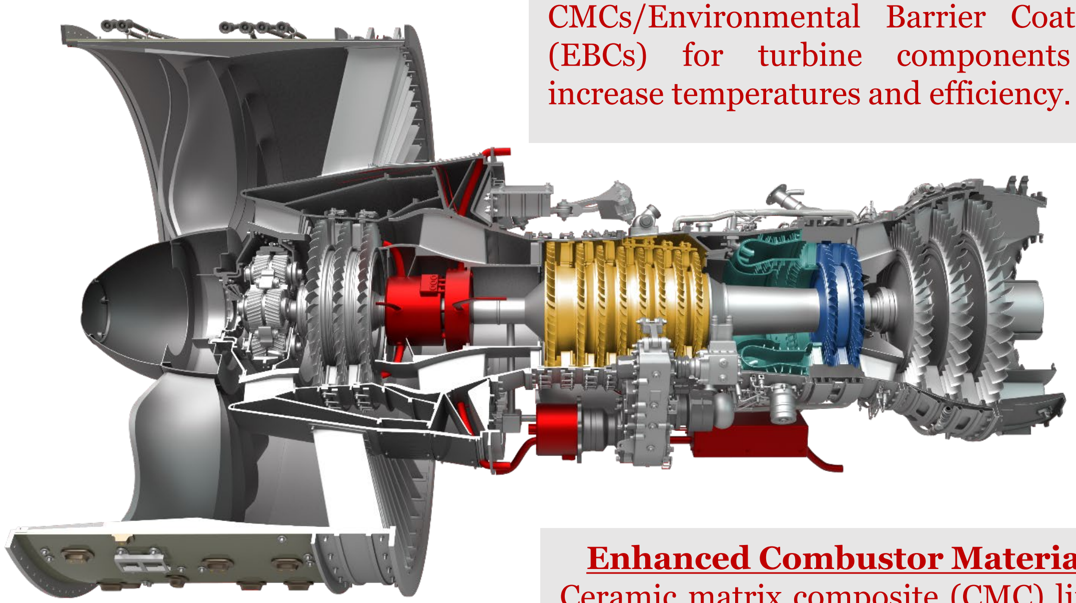
Current Thrusts

Ceramic Matrix Composite (CMC) Components for Turbine Engine Applications

Turbine Engines - Targeted Components (CMCs)

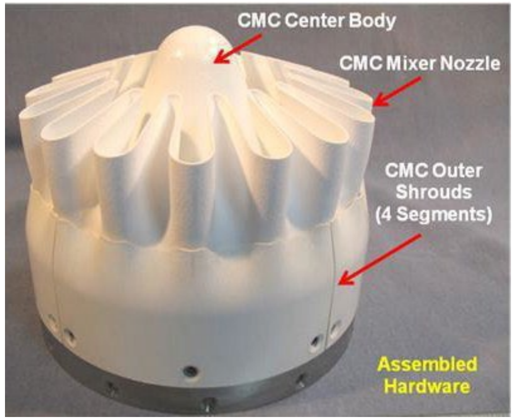
High Pressure Turbine (HPT) Materials

CMCs/Environmental Barrier Coatings (EBCs) for turbine components to increase temperatures and efficiency.

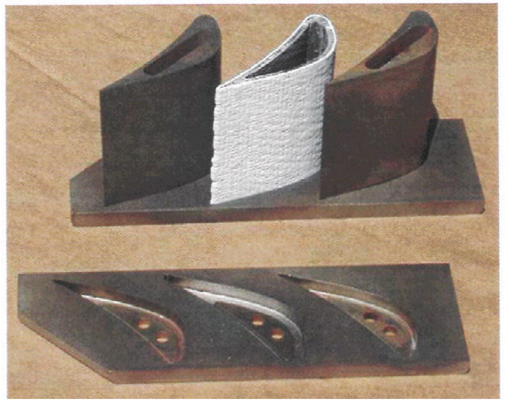


Enhanced Combustor Materials

Ceramic matrix composite (CMC) liners for combustors to increase performance and durability.



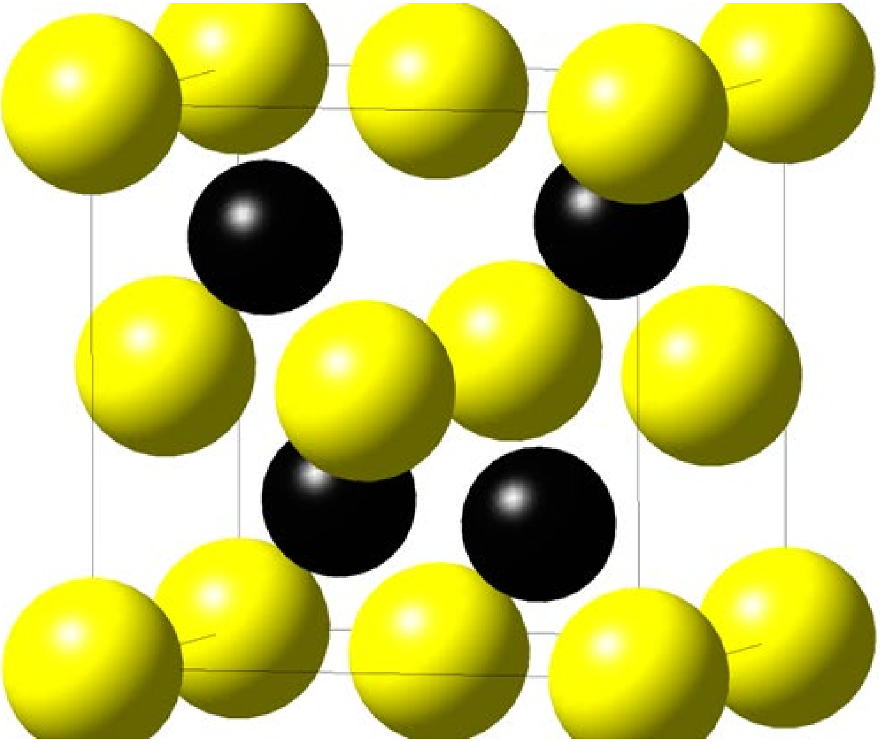
Oxide/Oxide Mixer Nozzle



EBC Coated SiC/SiC Vanes

SiC/SiC Combustor Liners: Outer Liner and EBC Coated Inner Liner

Silicon Carbide



Melting point: 2830 ^{o}C
Young's Modulus: 415 GPa
Density: 3.16 g/cm^3
Hardness: 32 GPa (Vickers's)
Fracture Toughness: 3.160.3 MPa*m$^{1/2}$
Tensile Strength: 250 MPa
Thermal Conductivity: 114 W /m*K
Crystal Structure: Fm-3m

Journal of Physical and Chemical Reference Data 26, 1195 (1997)

Applications

- Combustion and turbine section components.
- Heat exchangers, reformers, reactors, and filters for the chemical industry.
- Preheaters, recuperators, and radiant tubes.
- Thermal protection systems, thruster nozzles, reusable rocket nozzles, and turbopump components for space vehicles.
- Nuclear fission and fusion reactors as fuel cladding and radiation blankets.

Current Approaches for Manufacturing of Ceramic Matrix Composites

Preforming and Interface

Hand lay-up and tooling of ceramic fibers or woven shapes

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.

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 prepregs 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)

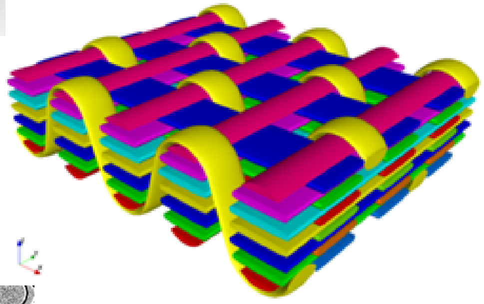
→ **Joining**
(brazing and attachments)

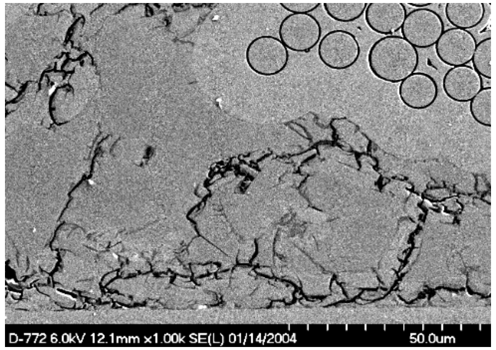
→ **Coating and Finishing**
NDE

GRC Has Extensive Expertise and Capabilities in High Temperature CMCs

NASA 2700° F CMC combines three technology advancements

- Creep-resistant Sylramic-iBN fiber
- Advanced 3D fiber architecture
- Hybrid CVI-PIP SiC matrix

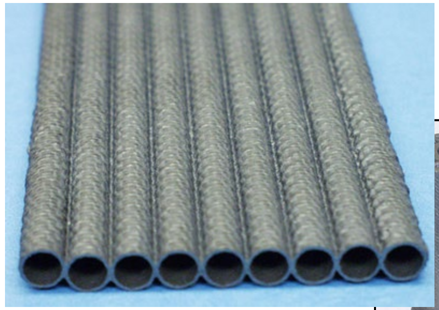


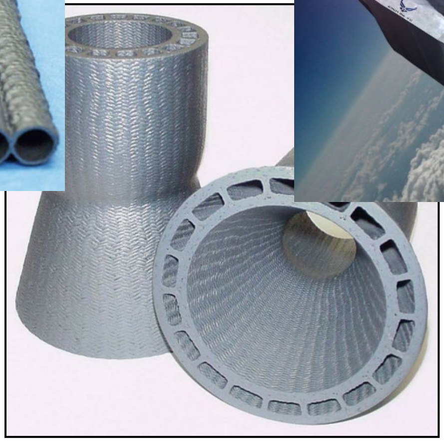


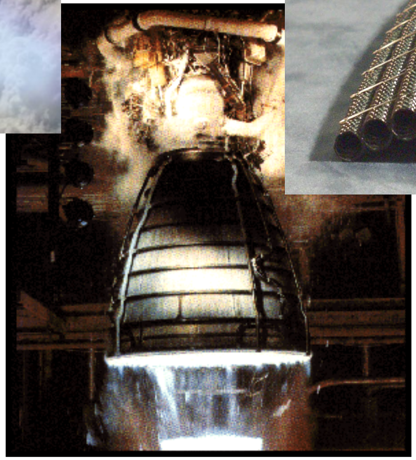
CMC research includes material development, life prediction and experimental validation

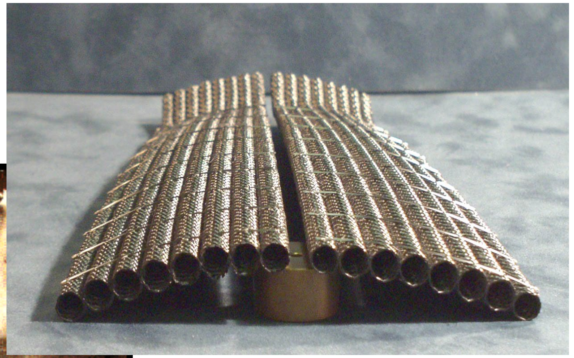
Cooled CMC Development at NASA

Test capabilities include actively cooled CMC subelements with built-in coolant channels







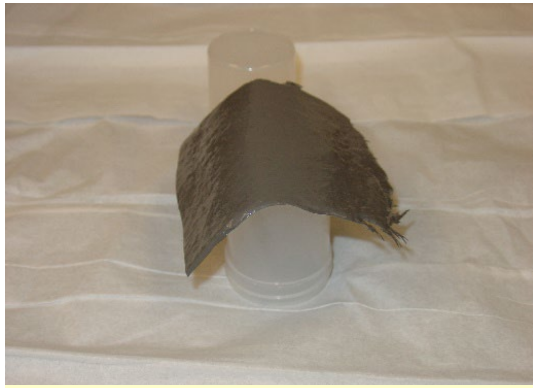


- **Lighter weight than metallic designs: up to 50% weight reduction**
- **Increased operational margin: enhanced range and/or payload**

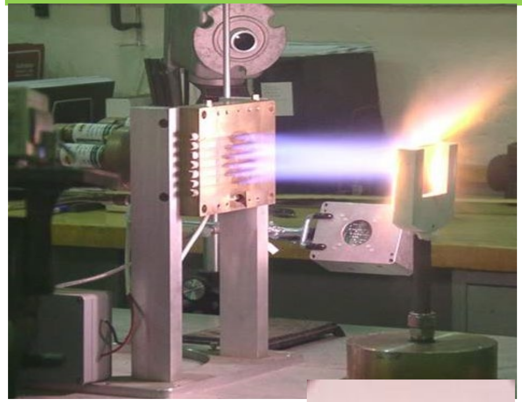
Flexible Gaskets for Hypersonic Applications


GRC 11 Gaskets made from RTV foam

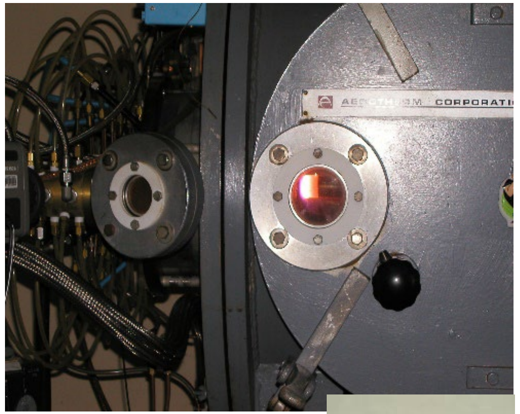

GRC 16 Gaskets made from Ablative polymer


GRC 17 Gaskets made from silicone based RTV polymer

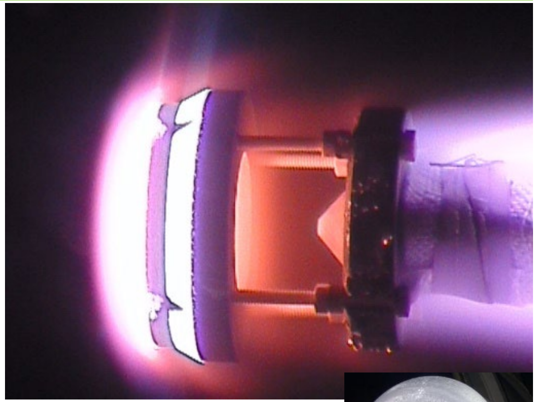
These gaskets have shown excellent plasma performance in various facilities under re-entry and hypersonic conditions.




QARE Testing at GRC




HYMETS (LaRC)



ArcJet Testing at ARC and LCAT

In-Space Manufacturing, Assembly, and Repair Technologies (I-SMART) for Space Structures

Developing refurbishment approaches for extending the reusability and for reducing the replacement and maintenance costs for the high-performance ceramic matrix composite (CMC) materials that are utilized for propulsion and airframe applications in hypersonic and aerospace vehicles

Project Objective(s)

- Develop and optimize materials and processing for CMC repair approaches.
- To enable 2x the reusable life in repaired versus unrepaired CMC components.
- Demonstrate the ability to prolong CMC life so that mechanical properties and environmental durability are maintained.

Integration of Metals to Ceramics and Composites Using Metallic Interlayers

Active Metal Brazing

Soldering

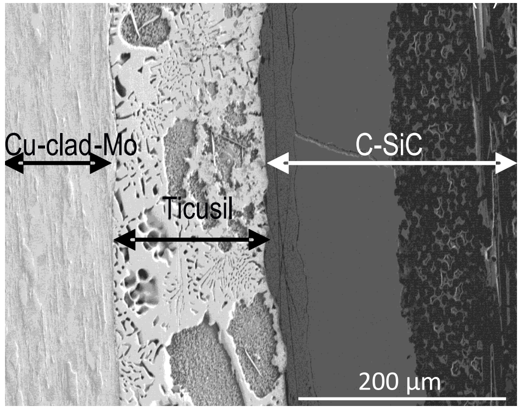
Metallic Systems
- Titanium
- Inconel and Other Ni-Base Superalloys
- Kovar, Cu-Clad Mo,
- Stainless Steels, W

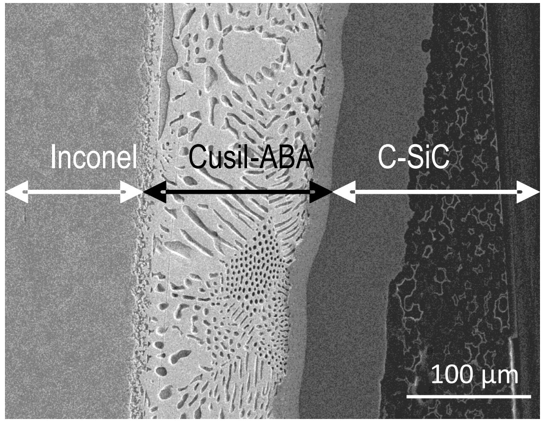
Ceramics/Composite
- SiC, Si_3N_4
- YSZ, Alumina
- UHTCs and UHTCMCs
- C/C Composites
- C/SiC, SiC/SiC

Interlayer Systems
- Active Metal Brazes (Ag, Cu, and Pd based)
- Metallic Glass Ribbons
- Solders (Zinc based)

Technical Issues
- **Melting range / behavior**
- **Wetting characteristics**
- **Atmosphere compatibility**
- **Compositional compatibility**
- **Cost & availability**

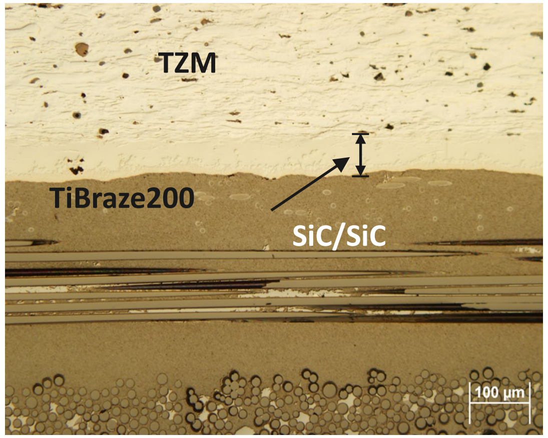
Joining and Integration of Composites to Metals for Applications in Hypersonic Systems





Objectives:

- Develop joining and integration technologies for incorporating high temperature carbon-carbon and ceramic matrix composite components with metallic systems.
    - Thermal protection,
    - Hot structures,
    - Control surfaces,
    - Heat exchangers, and combustor walls

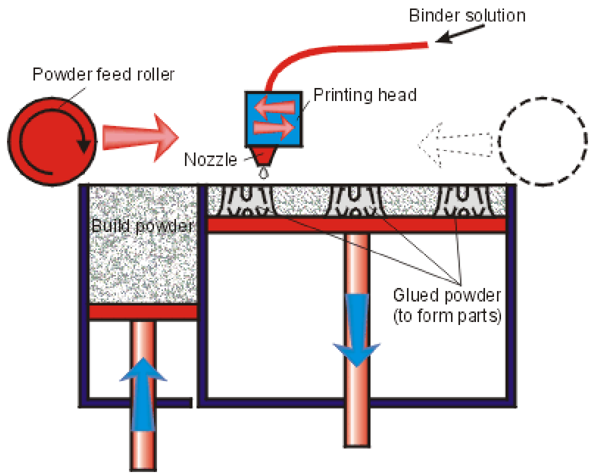


Approach:

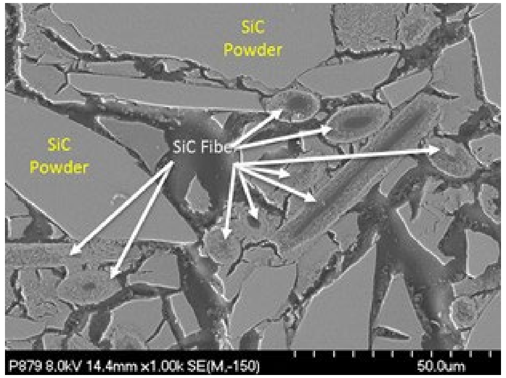
- Develop brazing for relevant material pairings (e.g. SiC/SiC, C/SiC, or C/C to Kovar, TZM, Inconel, or others) with proper selection of joining interlayer(s) and optimized brazing conditions. Develop tailored and functionally graded brazes. Conduct braze design and stress analysis.
- Address challenges in brazing more complex shapes such as tube to tube and complex geometries.

Capabilities

Additive Manufacturing of Ceramics Using Binder Jetting



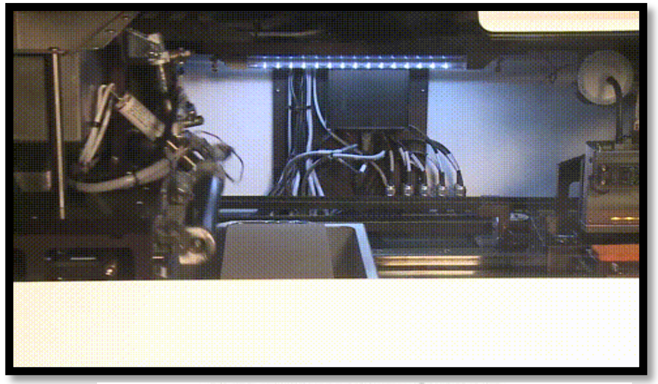
Binder Jetting process

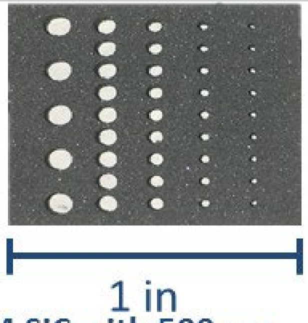


Chopped Fiber Reinforced Ceramic Matrix Composite

ExOne's Innovent System

High pressure turbine nozzle segments: cooled doublet vane sections.

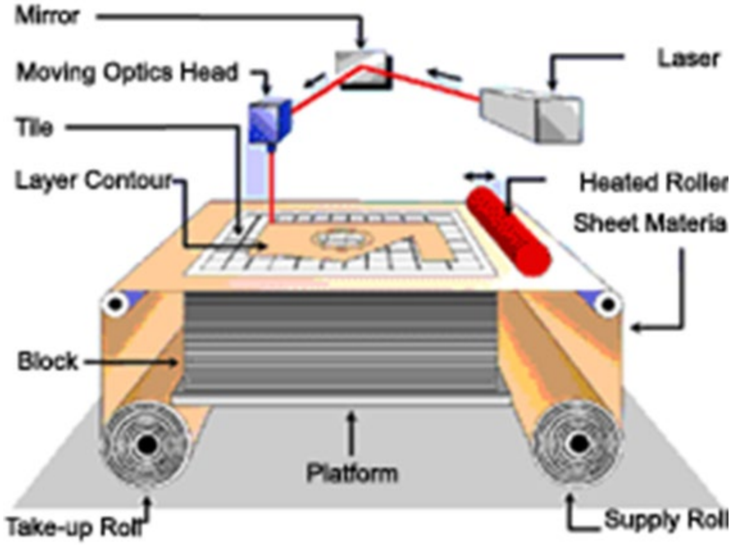




AM SiC with 500 µm diameter holes

AM SiC with 1.5 mm channels

Laminated Object Manufacturing (LOM) For Silicon Carbide-Based Composites

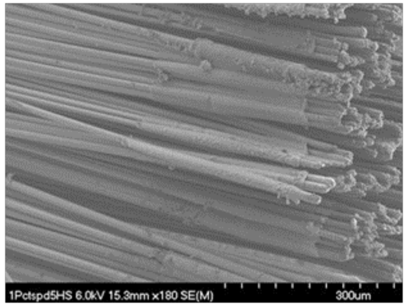


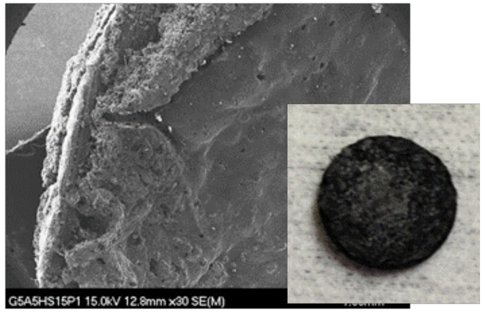
LOM allows for continuous fiber reinforced CMCs.

Universal Laser System (Two 60 watt laser heads and a work area of 32"x18")

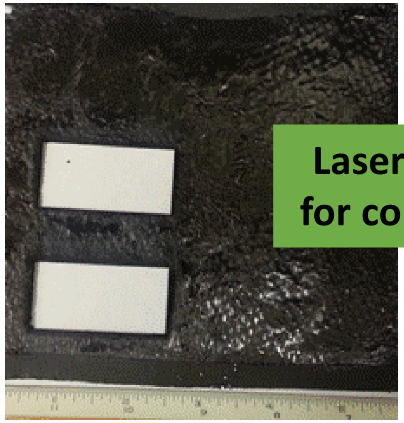
Prepregs for Composite Processing

- A number of SiC (Hi-Nicalon S, uncoated) fabrics (~6"x6") were prepregged.
- These prepregs were used for optimization of laser cutting process.
- Baseline laser cutting data was also generated for different types of SiC fabrics (CG Nicalon, Hi-Nicalon, and Hi-Nicalon S)

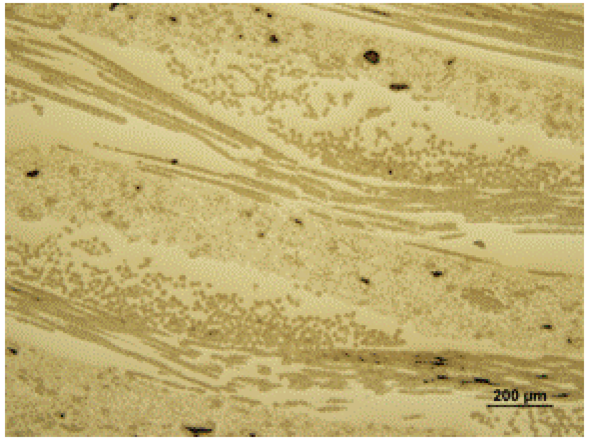




Fabrics and Prepregs cut at different laser powers/speeds



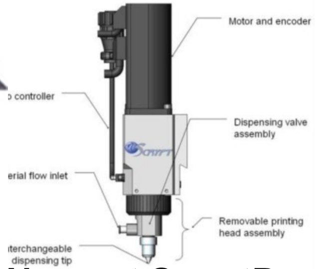
Laser cut prepregs used for composite processing



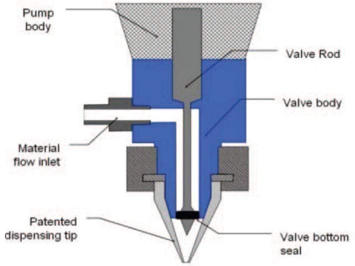
Silicon Infiltration:
1475°C, 30 minutes in vacuum

Direct Writing Technologies for Sensors/Embedded Systems

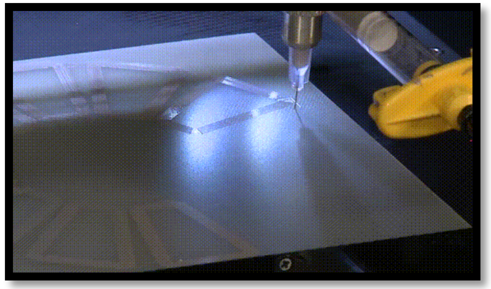
NScrypt Direct Write Printer

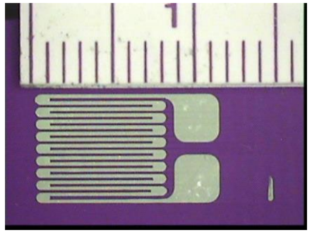


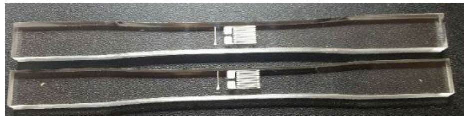
Nscrypt SmartPump



SmartPump Valve Assembly

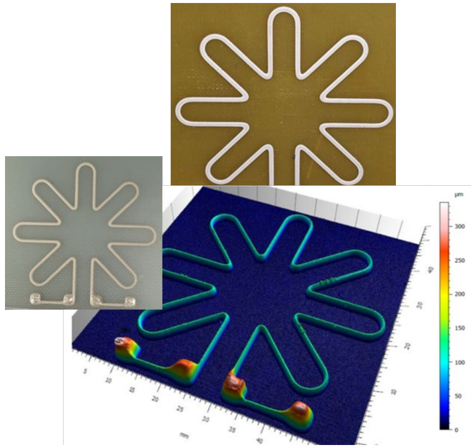






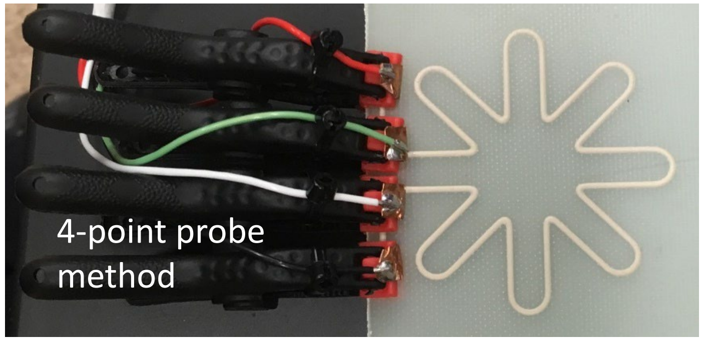
Printed strain gages.

Keyence VR 3200 Profilometer



NScrypt Capabilities and Benefits

- 300x 300x 150mm Gantry XYZ Platform
- SmartPump with 100 Picoliter Volumetric Control
- Ability to host up to four separate materials.
- Print on curved surfaces and 3D structures.
- Precise motion control and micro-dispensing of materials.
- Direct writing with clean starts and stops (no contact or masks as for screen printing).
- Ability to print a wide variety of ceramic pastes (structural and functional), electronic pastes, adhesives, solders, bio-materials.



Thin Surface and Imbedded Thick 4-Pt Probe Windings

ARCJoinT: Joining of Ceramic Components Using Affordable, Robust Ceramic Joining Technology (ARCJoinT)

Apply Carbonaceous Mixture to Joint Areas

Cure at 110-120°C for 10 to 20 minutes

↓

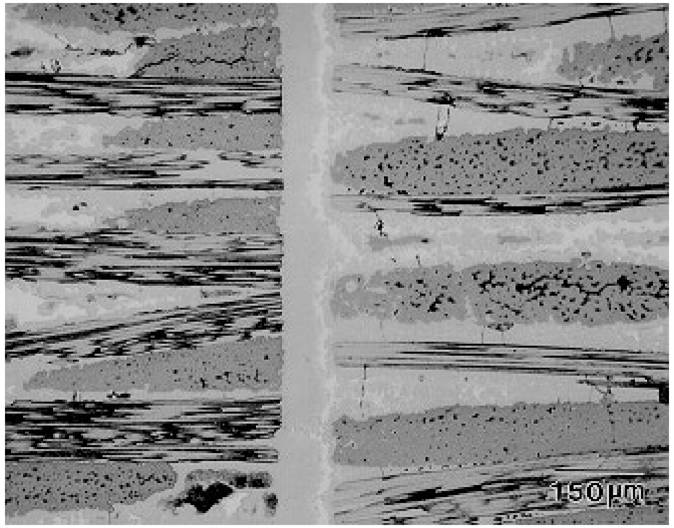
Apply Silicon or Silicon-Alloy (paste, tape, or slurry)

Heat at 1250-1425°C for 10 to 15 minutes

↓

Affordable and Robust Ceramic Joints with Tailorable Properties

1999 R&D 100 Award
2000 NorTech Innovation Award



Joined MI C/SiC Composite

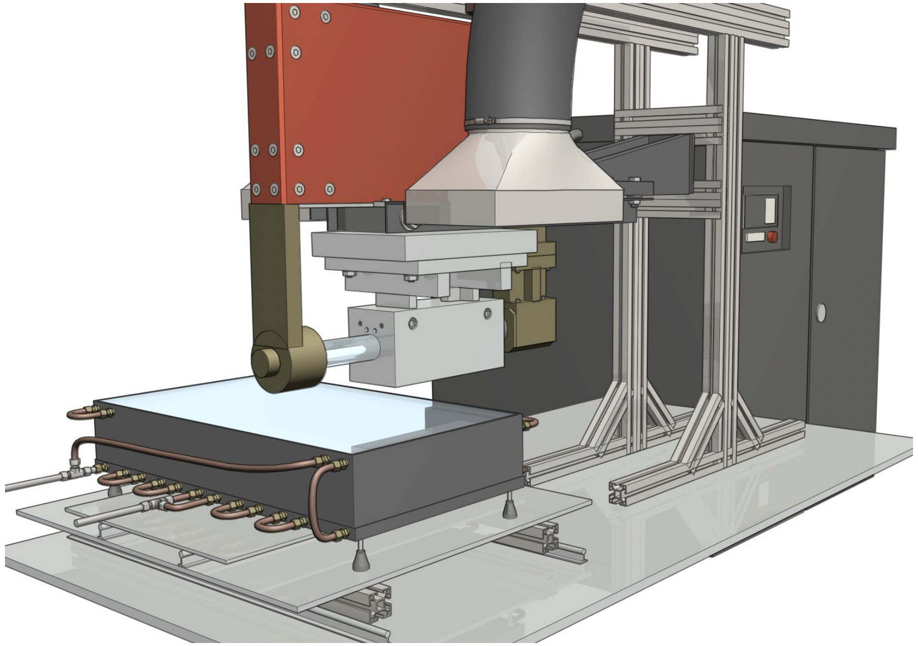
Advantages

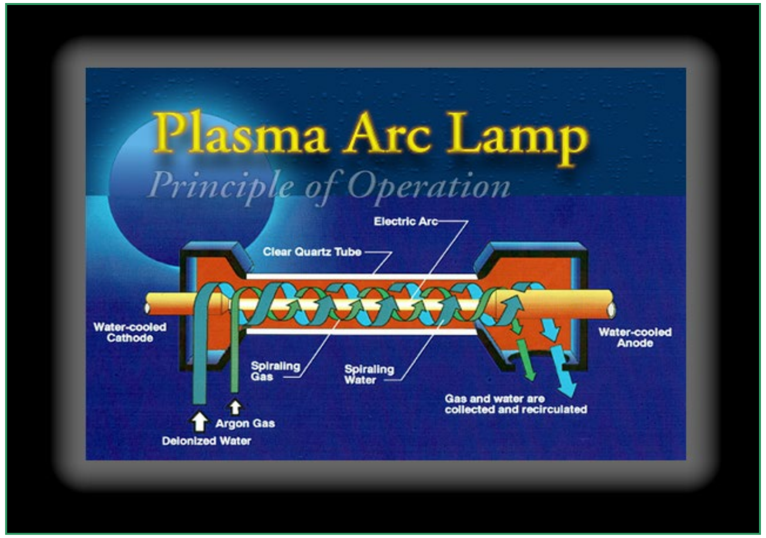
- Joint interlayer properties are compatible with parent materials.
- Processing temperature around 1200-1450°C.
- No external pressure or high temperature tooling is required.
- Localized heating sources can be utilized.
- Adaptable to in-field installation, service, and repair.

Very good quality, high strength bonds are obtained.

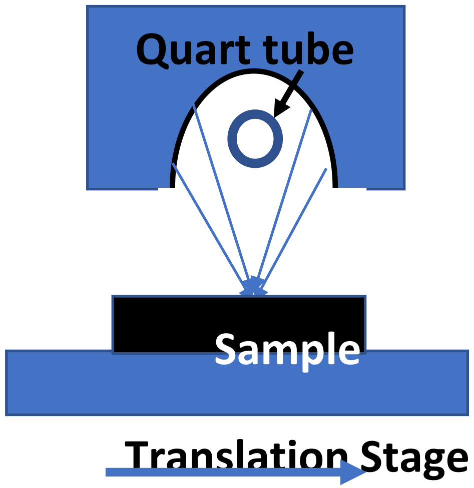
200kW Plasma Arc Lamp (Artificial Sun)

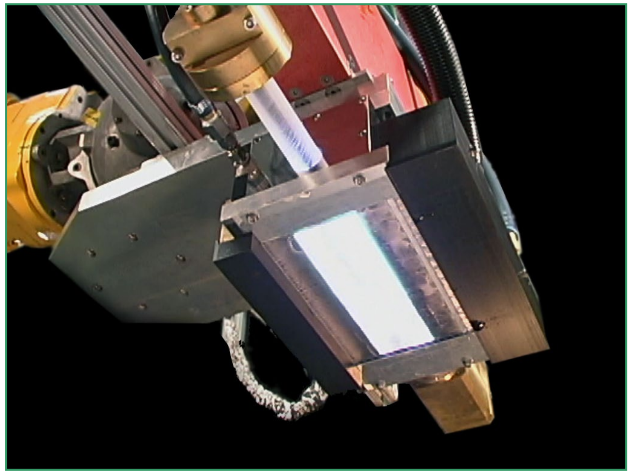
- Full spectrum stabilized arc generated within quartz tube.
- Reflector focuses radiant energy.
- Generates radiate 4000°F surface temperature
  - Durability testing
  - Material processing
  - Thermal gradients





Reflector focuses Radiant Energy



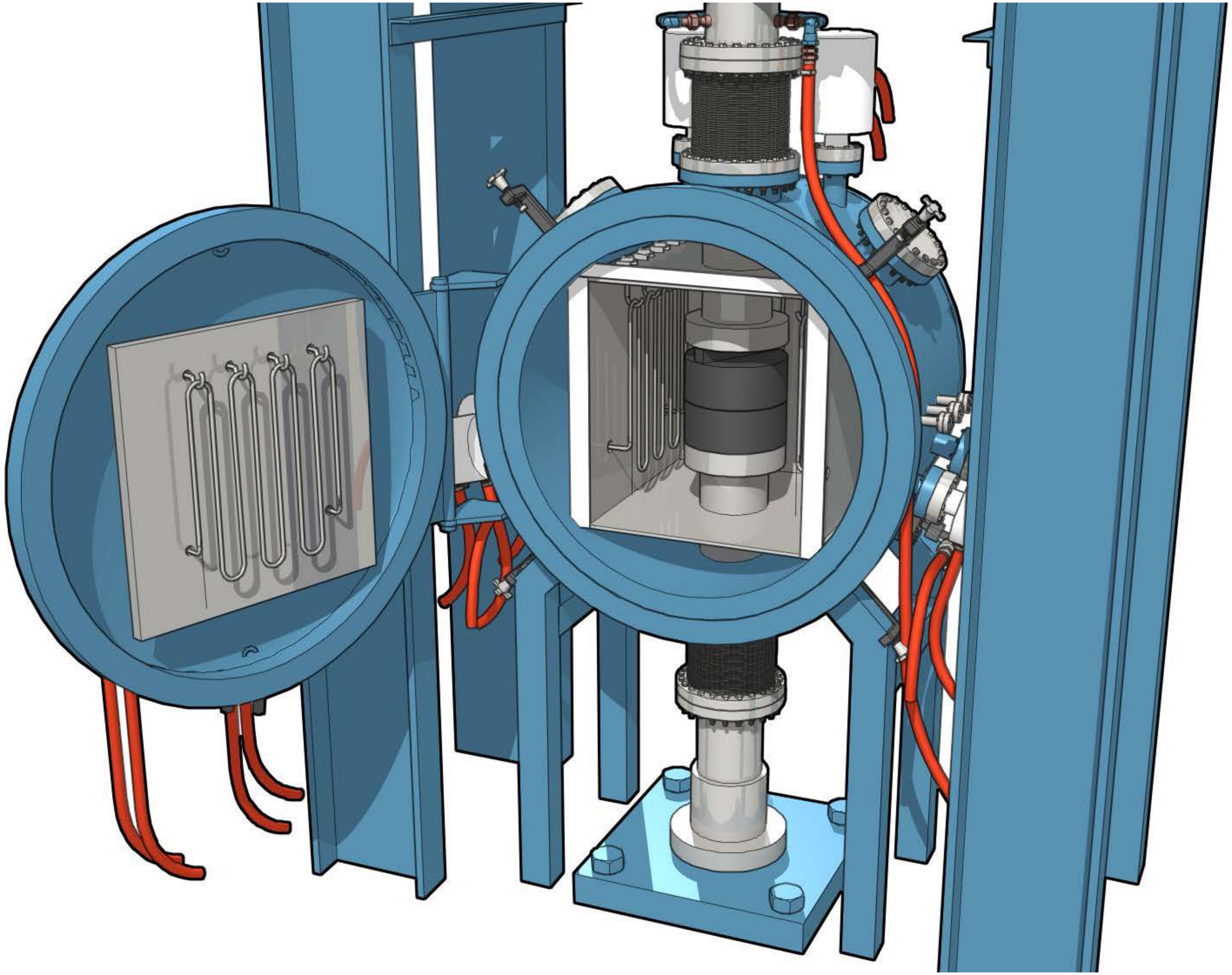


Advanced Vacuum Systems (AVS)

Vacuum Hot- Press
Tungsten heating 2000°C (max)
Ram force 110 tons
9-inch diameter die

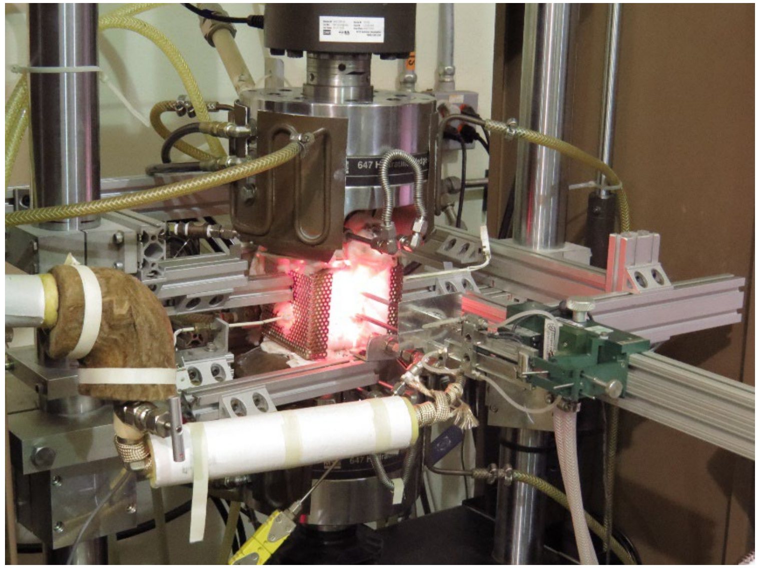
- Diffusion Bonding
- Ceramic Processing
- Metal Processing
- Powder Densification
- Powder Metal Forming
- Thermal Forging
- Super Plastic Forming
- Refractory Metal Forming
- Thermal Sizing.

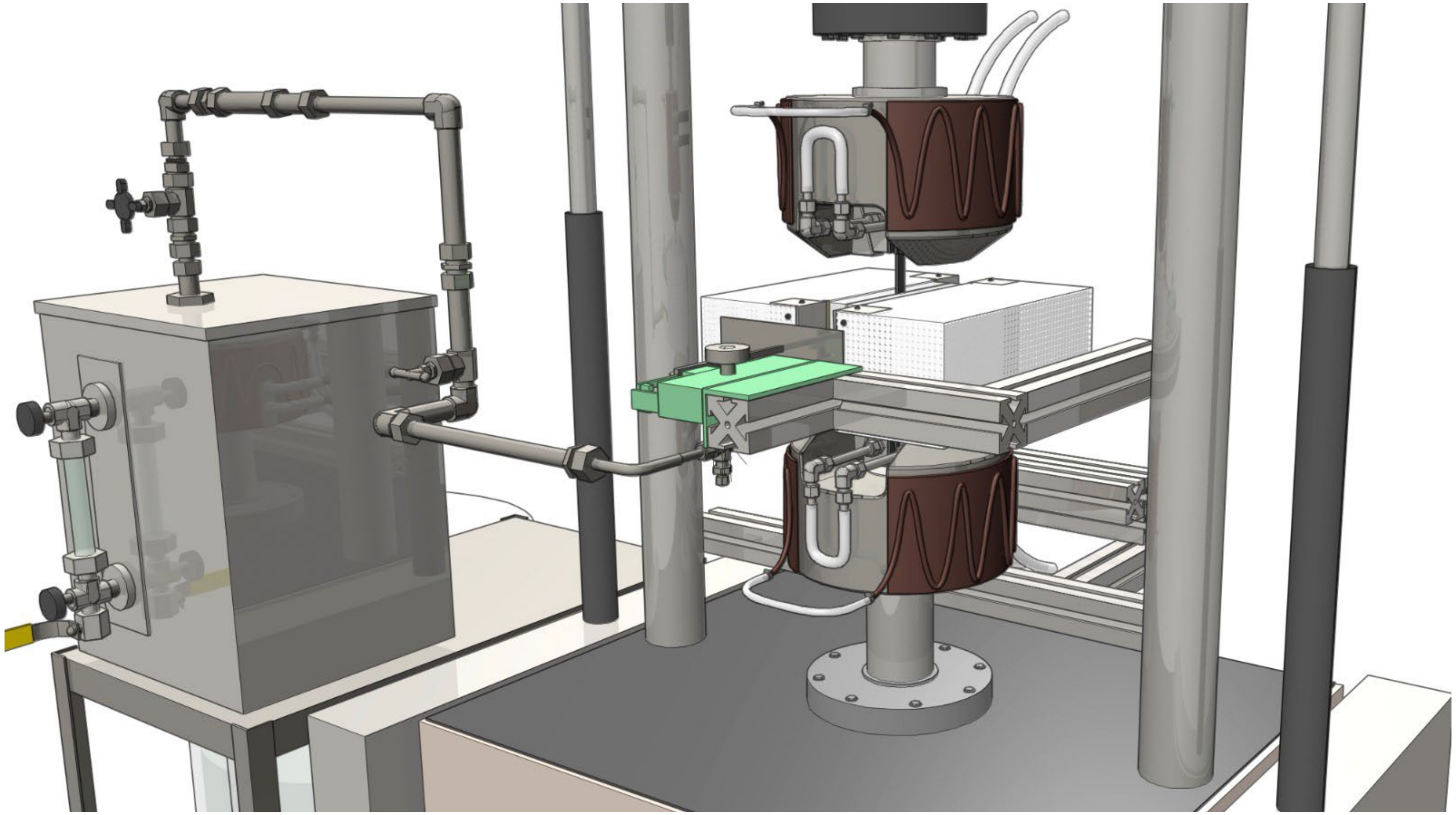
ATMOSPHERES
Vacuum, Inert, or Reducing Gas;
Partial Pressure to 5 PSI



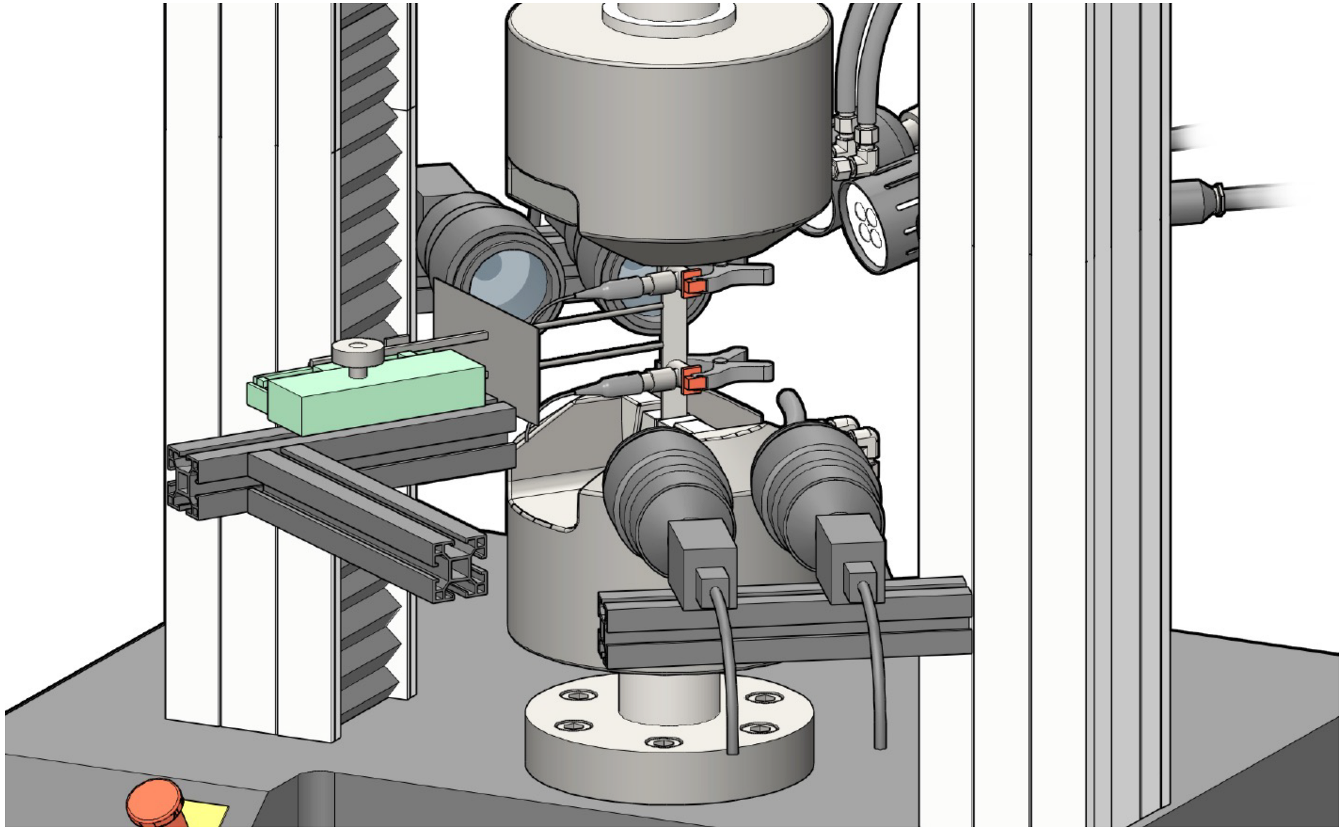
Elevated temperature, tensile-dwell fatigue tests in steam environment

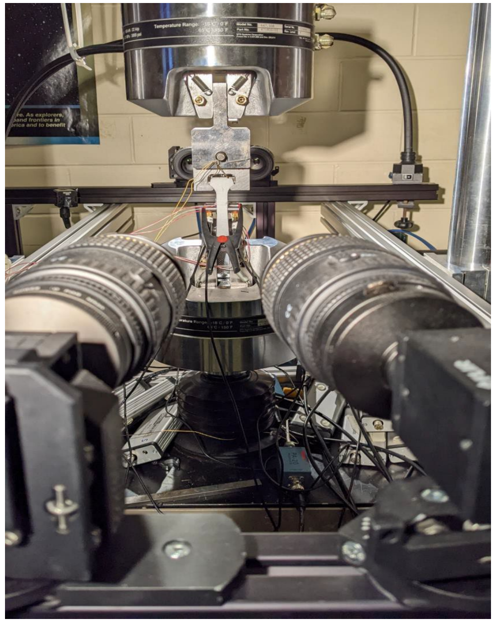
- Demonstrated capability to perform long duration (up to 300 hours) Sustained-Peak Low-Cycle Fatigue (SPLCF) tests in steam environment at 2400 °F.

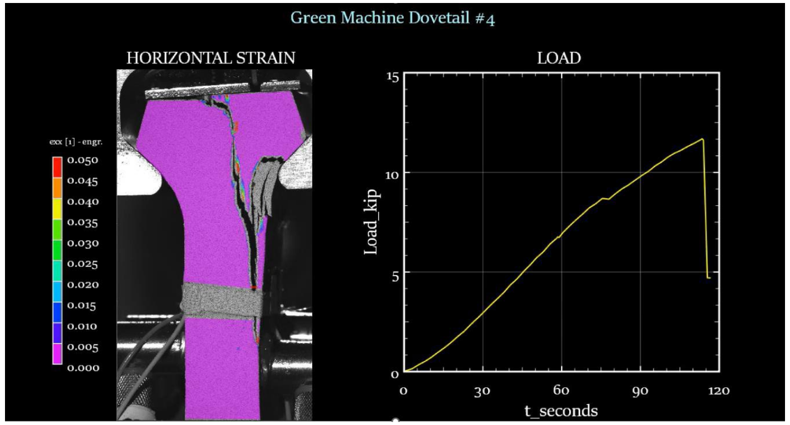




Digital Image Correlation Measurement

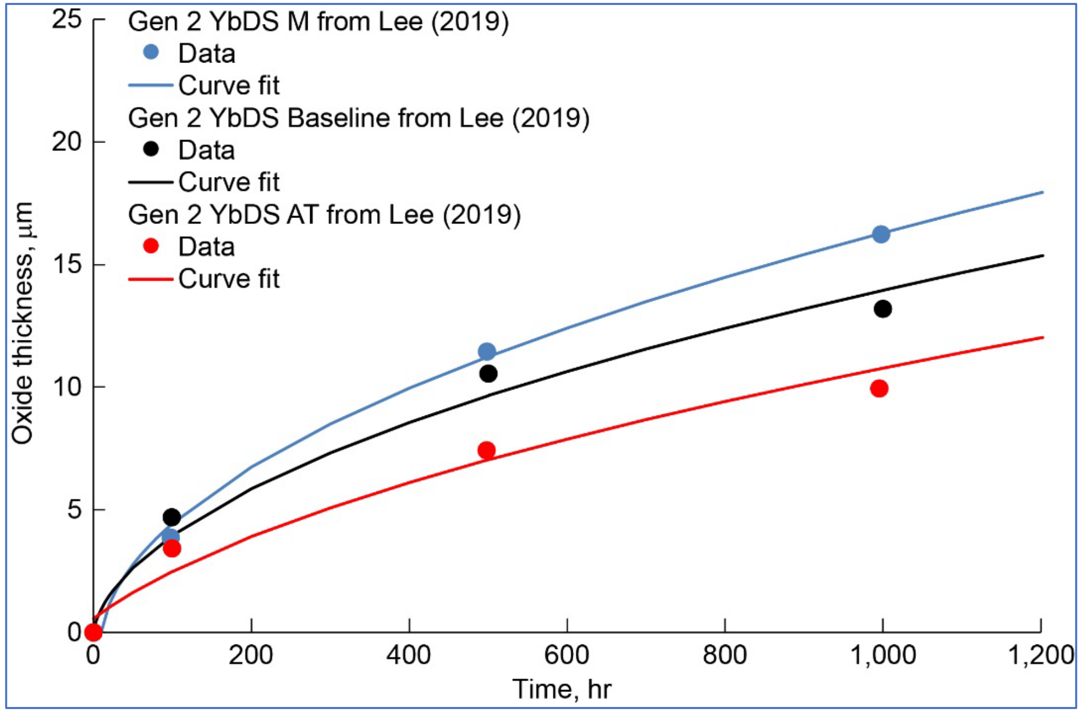






Estimates of the Permeability of Water in Rare Earth Silicates

This work is significant as no direct measurements of the permeability of water in rare earth silicates have been reported in the literature and steam oxidation is one of the greatest threats to the durability of EBC coated ceramic matrix composites in engine applications.



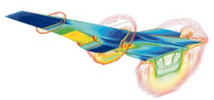
Gaps and Challenges

Development of an Ultra- High Temperature Ceramic Fiber

- Polymer base precursor
- Small diameter to allow weaving
- Interphase coatings
- Temperature and time dependent characterization

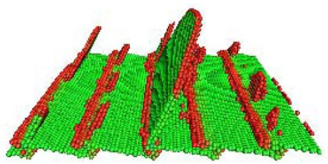
GRC High Temp CMC – Current Thrusts, Life Prediction, Capabilities, & Challenges/Gaps

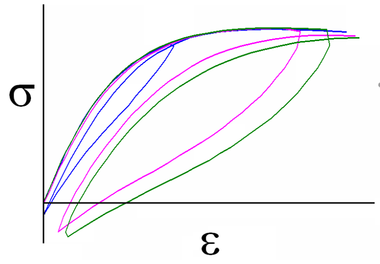
Steven M. Arnold, PhD, FASM
Technical Lead: Multiscale Multiphysics Modeling
T^3 Project: Material and Structures Discipline Lead

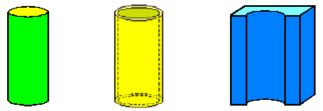


NASA GRC's Multiscale Analysis Approach Links the Behavior Of A Composite Material/Structure To The Behavior Of Its Constituents

Constituent Response





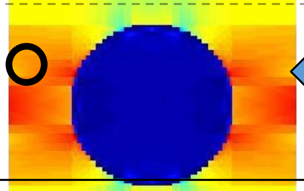


Atomistic Informed

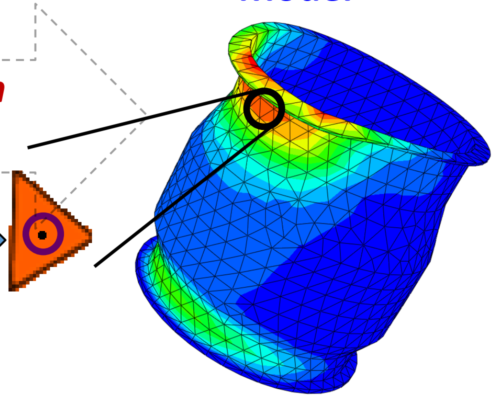
Continuum Deformation and damage models

Composite Micromechanics Repeating Unit Cell

Micromechanics Provides the Link Between Structures and Materials



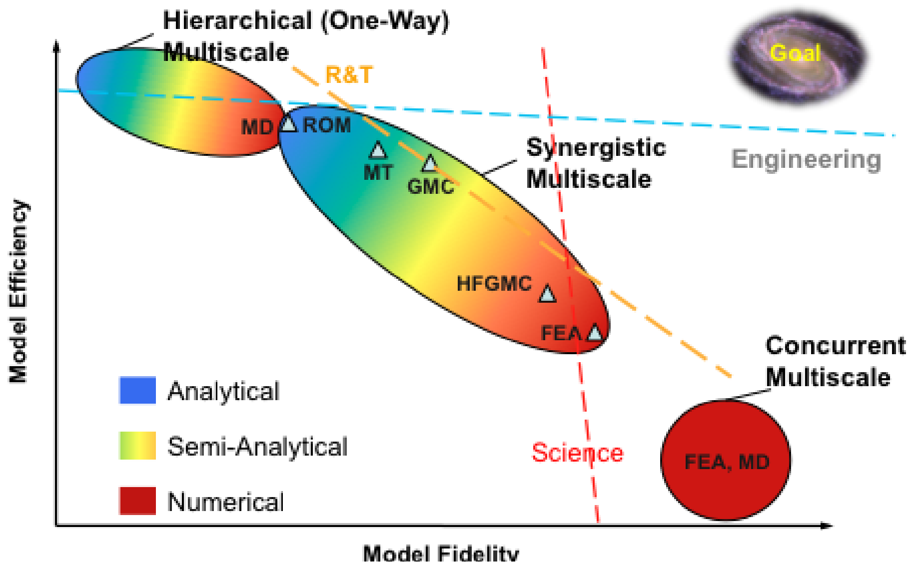
Structural Model



Fully coupled (Synergistic)

Computational Efficiency Required

Ultimate Goal: Balance Efficiency vs Fidelity

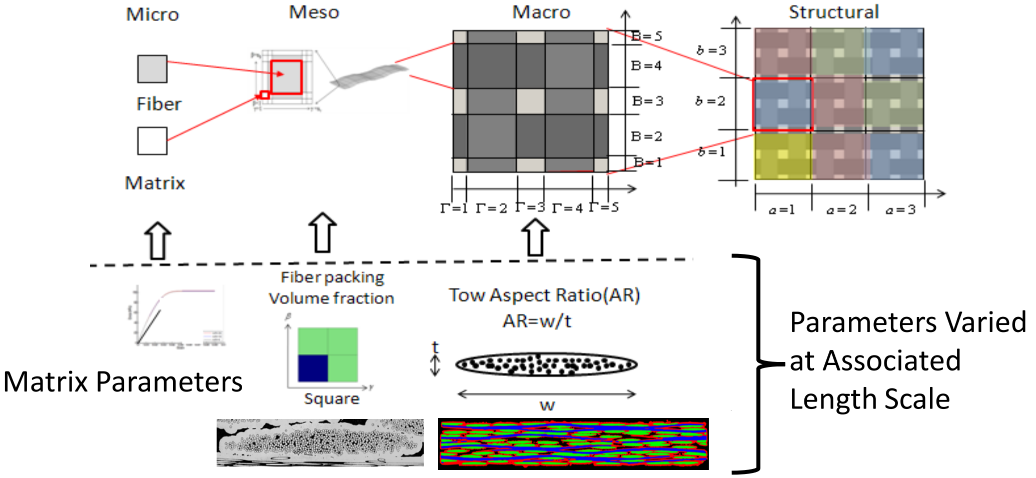


Framework Admits Nonlinear Constitutive and Damage Models

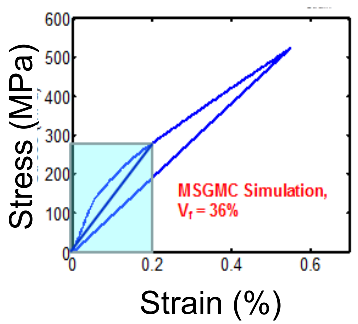
Aboudi, J., Arnold, S.M., and Bednarcyk, B.A. (2013) *Micromechanics of Composite Materials: A Generalized Multiscale Analysis Approach*, Elsevier, Oxford, UK., pp 1-984.

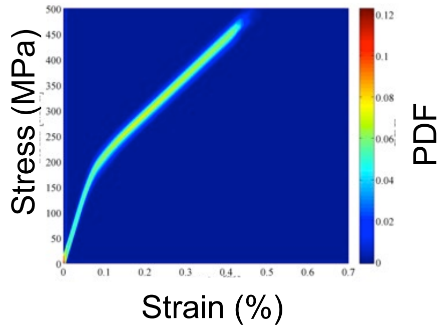
Multiscale Modeling of CMC Behavior

Stochastic Nonlinear Response of Woven CMCs Using MSGMC

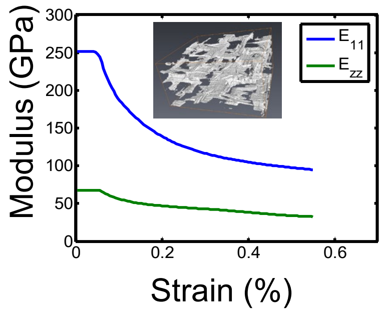


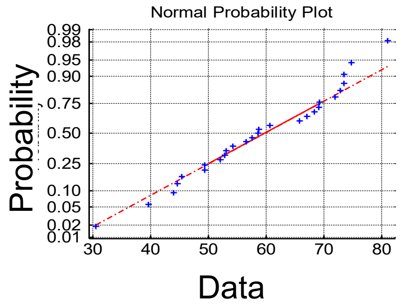
Liu, K.C. And Arnold, S.M. (2013),"Statistical Influence of Scale Specific Features on the Progressive Damage of Woven Ceramic Matrix Composites (CMCs)", Computers, Materials and Continua. Vol.35, No. 1, pp. 35-65.





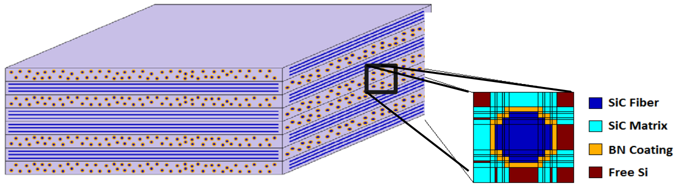
Stochastic simulation of a 5HS weave composite



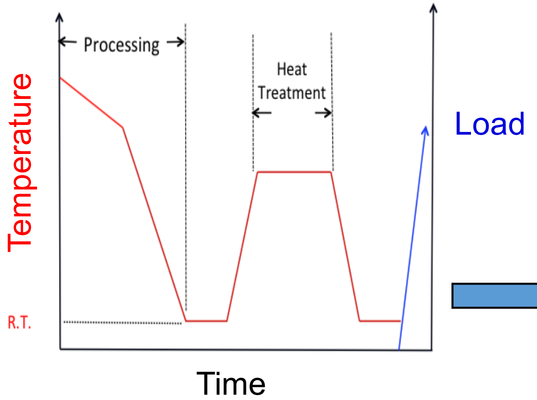


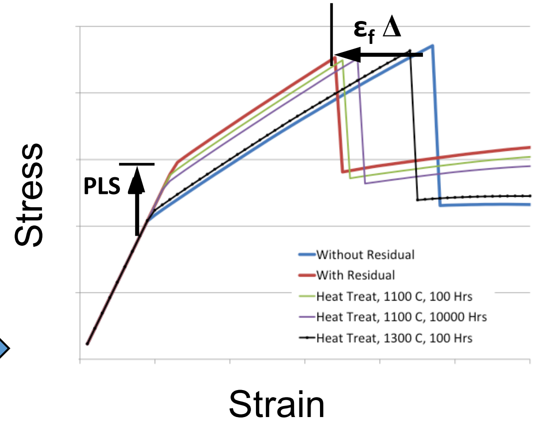
History Dependent Response of Laminated CMCs Using GMC

Mital, S. K., Arnold, S.M., Bednarcyk, B.A. and Pineda E.J..; "Micromechanics-based Modeling of SiC/SiC Ceramic Matrix Composites and Structures", Special Issue: Ceramic Matrix Composites: Performance Evaluation and Application, Recent Progress in Materials, Vol. 5, No. 2, June 2023



$$\varepsilon^{I}_{fiber} << \varepsilon^{I}_{matrix} << \varepsilon^{I}_{free\ Si}$$





PLS: Proportional Limit Stress

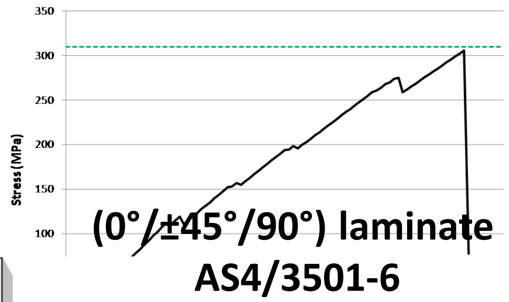
ImMAC Enables Multiscale Failure / Progressive Damage

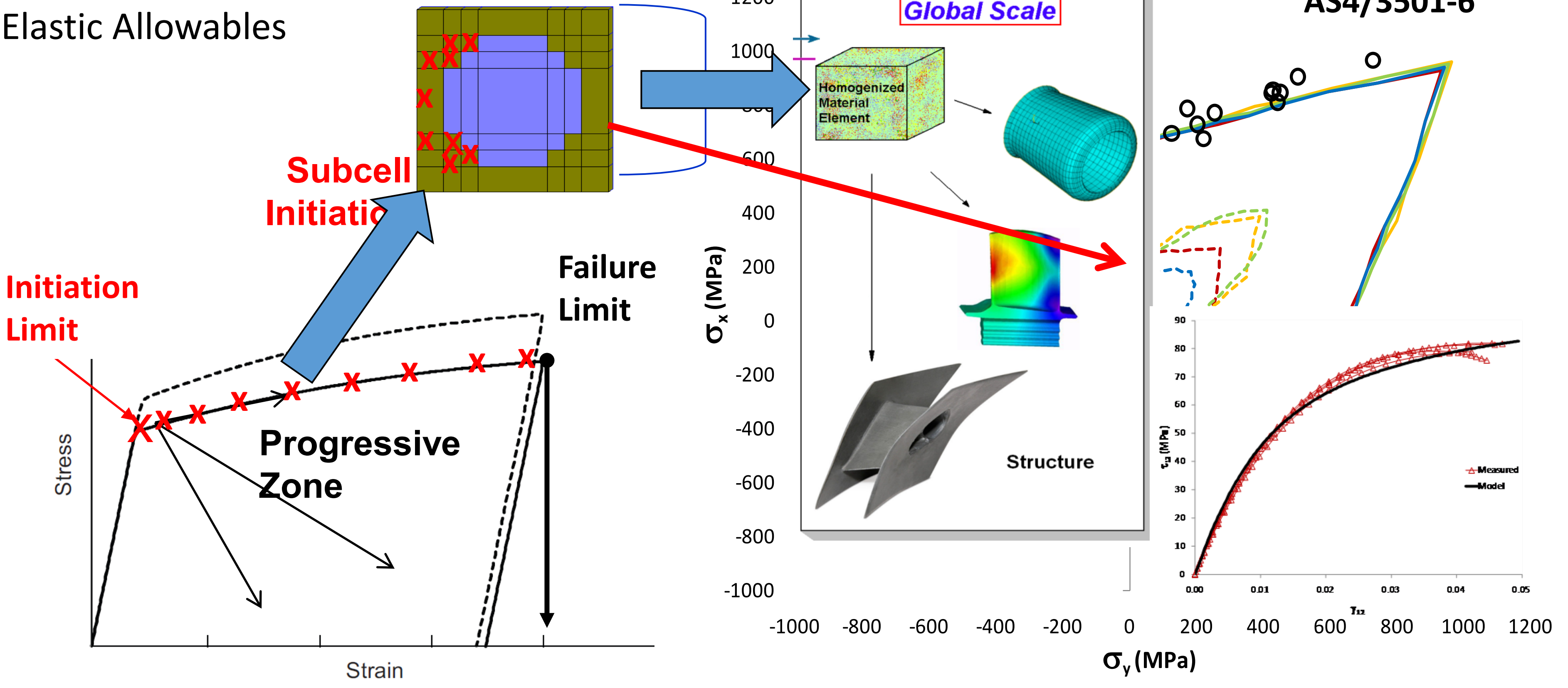
Subcell Elimination Criterion

- Max. Stress Theory
- Max. Strain Theory
- Tsai-Hill Theory
- Tsai-Wu
- SIFT
- Elastic Allowables

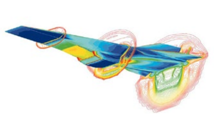
Progressive Damage Criterion

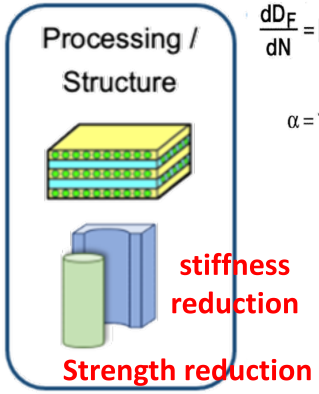
- *Scalar Damage (Triaxial)*
- *MMCDM*
- Smeared Crack Band





Coupled Deformation and Damage Methodology Utilized For Fatigue Life Prediction

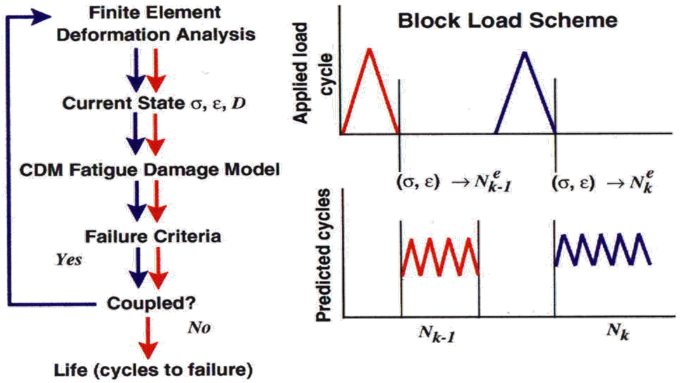




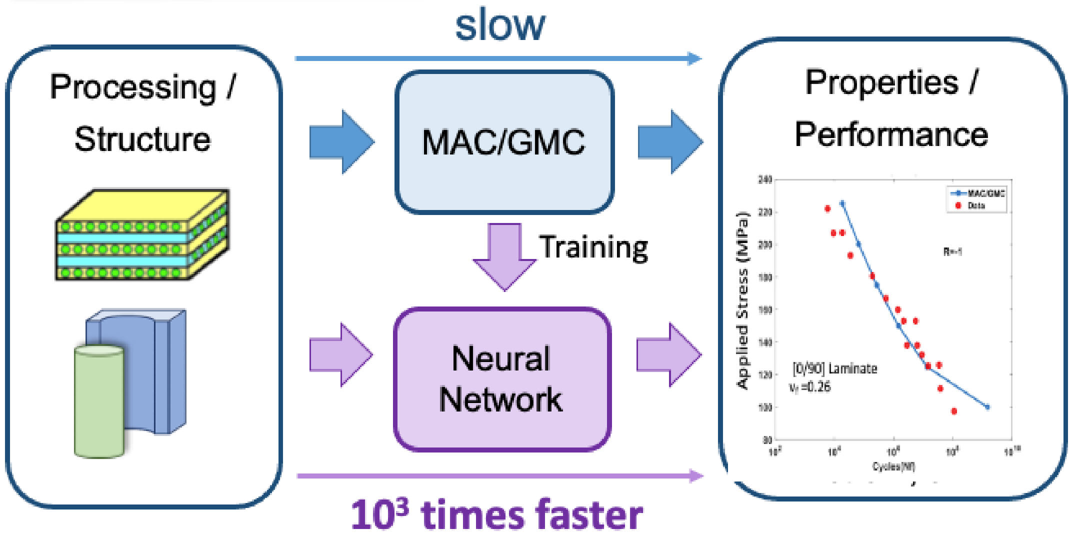
$$\frac{dD_F}{dN} = [1-(1-D_F)^{\beta+1}]^{\alpha}\left[\frac{\hat{F}_m}{(1-D_F)}\right]^{\beta}$$

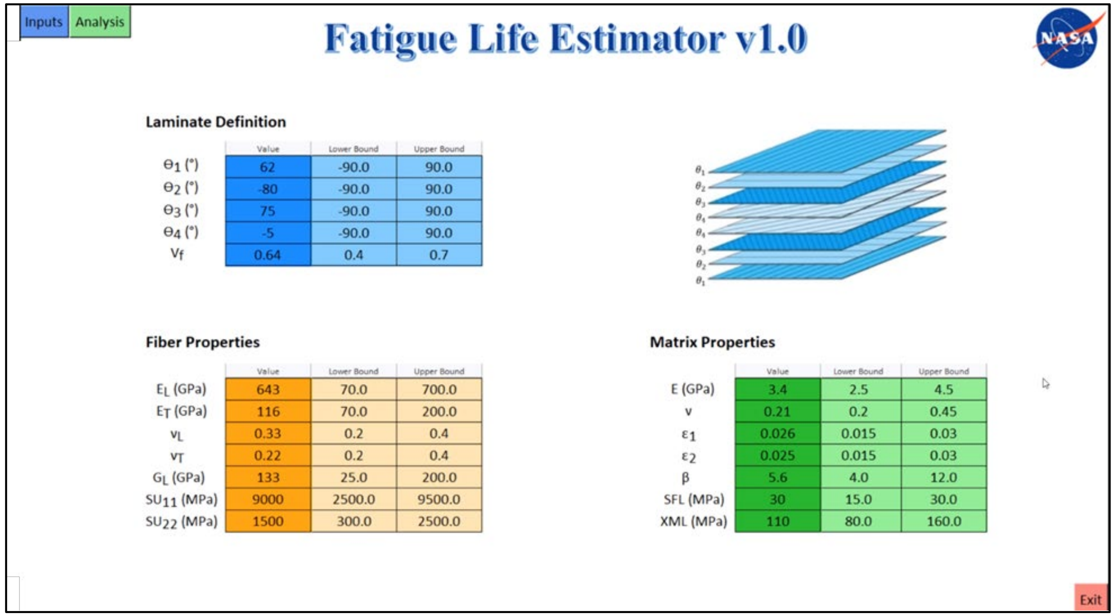
$$\alpha = 1 - a\frac{\langle \hat{F}_{fl} - 1\rangle}{\langle 1-\hat{F}_u\rangle}$$

Life Prediction Scheme



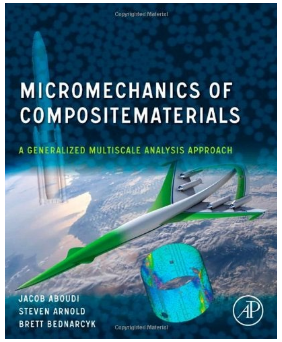
- MAC/GMC offers macroscale fatigue life prediction by degrading the stiffness of the matrix and strength of the fiber (microscale damage) – **Physics based Model**
- Created a Recurrent Neural Network surrogate model to improve computational efficiency **(1000X Speedup)**
  - Currently restricted to 8-ply, symmetric CMC
  - Trained on both laminates with random angles and industry-standard layups (5k laminates; > 15K hrs generate training data





Key References

Aboudi, J., Arnold, S.M., and Bednarcyk, B.A. (2013) *Micromechanics of Composite Materials: A Generalized Multiscale Analysis Approach*, Elsevier, Oxford, UK., pp 1-984.

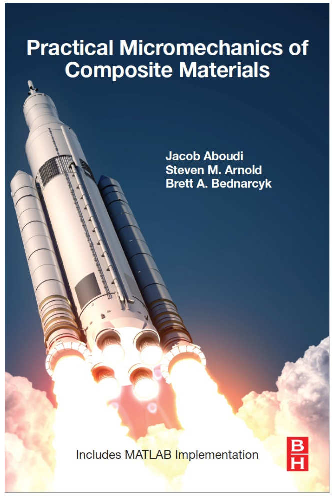


<u>Outline</u>

1) Introduction
2) Constituent Material Modeling
3) Fundamentals of the Mechanics of Multiphase Materials
4) The Method of Cells Micromechanics
5) The Generalized Method of Cells Micromechanics
6) The High Fidelity Generalized Method of Cells Micromechanics
7) Multiscale Modeling of Composites
8) Fully Coupled Thermomechanical Analysis of Multiphase Composites
9) Finite Strain Micromechanical Modeling of Multiphase Composites
10) Micromechanical Analysis of Smart Composite Materials
11) Higher-Order Theory for Functionally Graded Materials
12) Wave Propagation in Multiphase and Porous Materials
13) Micromechanics Software

Published July 2021

"Written with both ***students and practitioners*** in mind and is coupled with a fully functional MATLAB code to enable solution of technologically relevant micromechanics problems. The many illustrative example problems and exercises highlight key concepts and rely heavily on the MATLAB code"



<u>Table of Contents</u>

1. Introduction
2. Lamination Theory Using Macromechanics
3. Closed Form Micromechanics
4. Failure Criteria and Margins of Safety
5. The Generalized Method of Cells (GMC) Micromechanics Theory
6. The High-Fidelity Generalized Method of Cells (HFGMC) Micromechanics Theory
7. Progressive Damage and Failure

Features:

- Thermoelastic Material Behavior
- Emphasis on Local fields via Strain and Stress Concentration Tensors;
- General MATLAB open-source code provided
    - four micromechanics theories MT, MOC, GMC, HFGMC
    - four failure criteria, along with consistent treatment of Margins of Safety (MoS)
    - Emphasis on PMC & CMC, order and disorder microstructures
    - https://github.com/nasa/Practical-Micromechanics
- Extensive Practical Examples; ~ 15 Exercises /Chapter (Solution Manual available to professors)