High Temperature Lightweight Self-Healing Ceramic Composites for Aircraft Engine Applications

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Introduction

- **Advanced aircraft engines require the use of reliable, lightweight, creep-resistant and environmentally durable materials.**

- **Silicon carbide-based ceramic matrix composite (CMC) technology is being developed to replace nickel-based superalloy blades and vanes.**

  - **Near term 1589 K (2400 ºF) (cooled).**
  - **Medium term 1755 K (2700 ºF) (cooled).**
  - **Long term 1922 K (3000 ºF) (uncooled).**

Rule of Mixtures (ROM) Composite Theory

$$P = P_{fiber}V_{fiber} + P_{matrix}V_{matrix}$$

$$V_{fiber} + V_{matrix} = 1$$

P_i = Property of the i^{th} component (e.g. strength).

V_i = Volume fraction of the i^{th} component .

- **Properties of the composite are determined by the properties of the fiber and the matrix and their relative volume fractions.**

Objectives

- **Develop a new class of ceramic composites –**

  Engineered Matrix Ceramics (EMCs).

  - **Design different engineered matrices.**
  - **Demonstrate thermal strain compatibility with SiC.**
  - **Evaluate oxidation and mechanical properties.**

- **Fabricate engineered matrix composites.**

  - **Evaluate self-healing properties.**

Current SiC/SiC CMC Fabrication Processes

(courtesy R. Bhatt)

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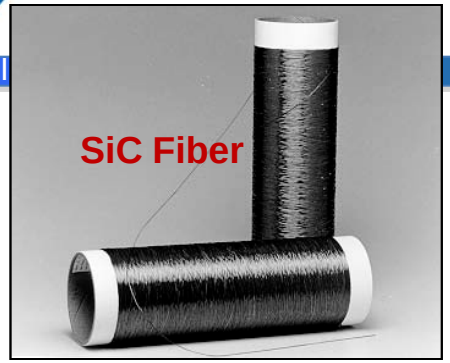


0/90 Fabric Weaving

Preform

Preform Compression

CVI BN Interface Infiltration

CVI SiC Matrix Infiltration

Reactor

Reactor

PIP

PIP or CVI-PIP CMC

Full CVI CMC

CVI SiC Preform

Slurry Infiltration

Si Melt Infiltration

CVI-MI CMC

Current Generation of CMCs: Matrix Microstructure

- **Silicon carbide (SiC).**
- **Unreacted or free carbon and silicon.**
- **Porosity:**

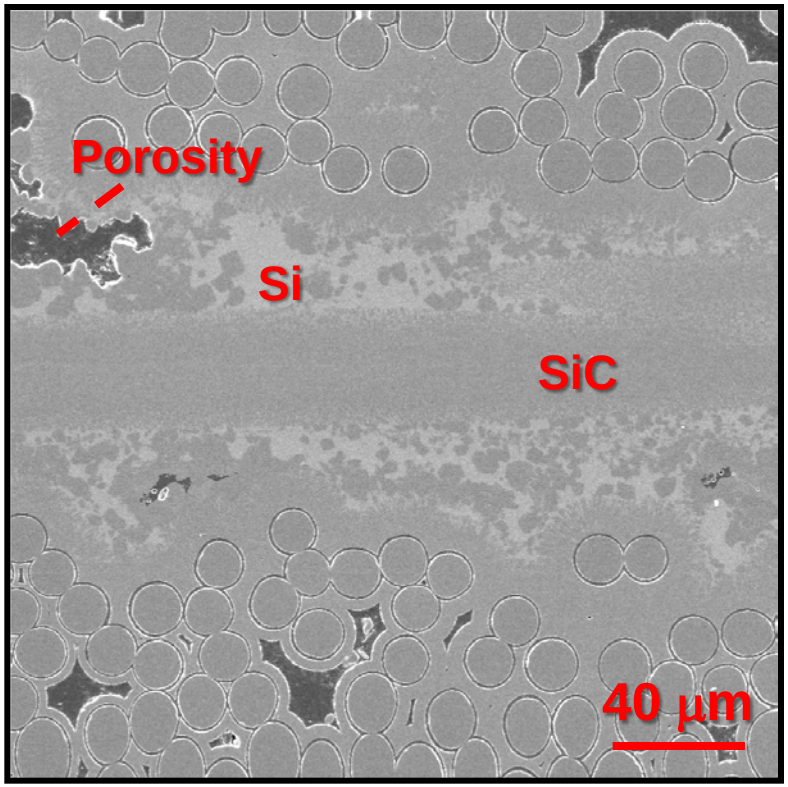
  ~10-25 vol.% for chemical vapor infiltration (CVI).

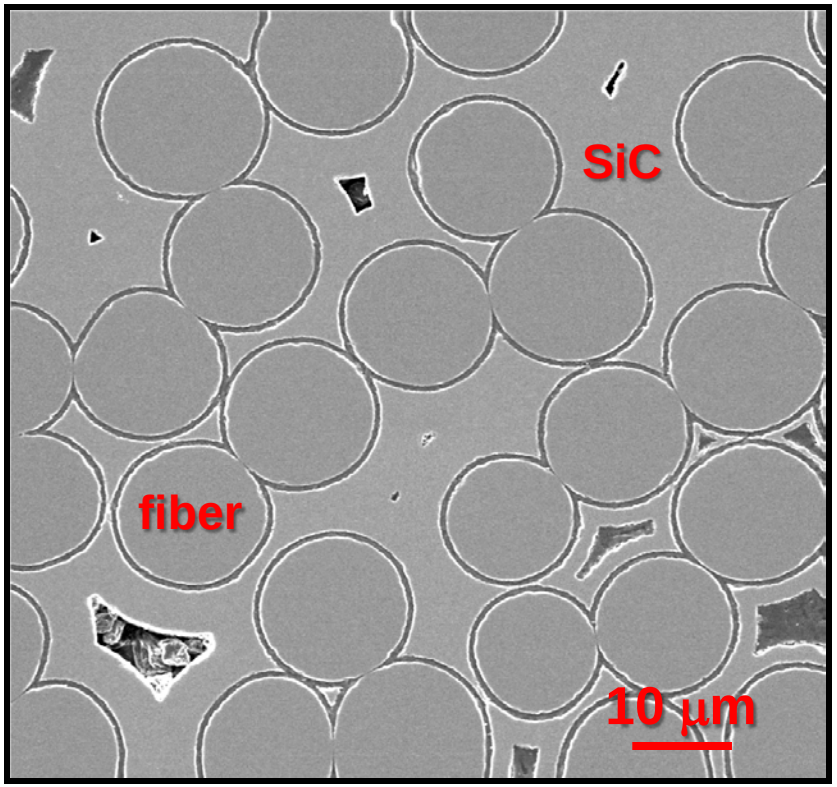
  ~10-25 vol.% for polymer infiltration and pyrolysis (PIP).

  ~3-10 vol.% for Melt Infiltration (MI).

Typical Microstructure of As-Processed BN-Coated Hi-Nicalon MI SiC Composites

(Courtesy M. Singh)





Density ~ 96-97 %

Current SiC/SiC CMC Matrix Capabilities

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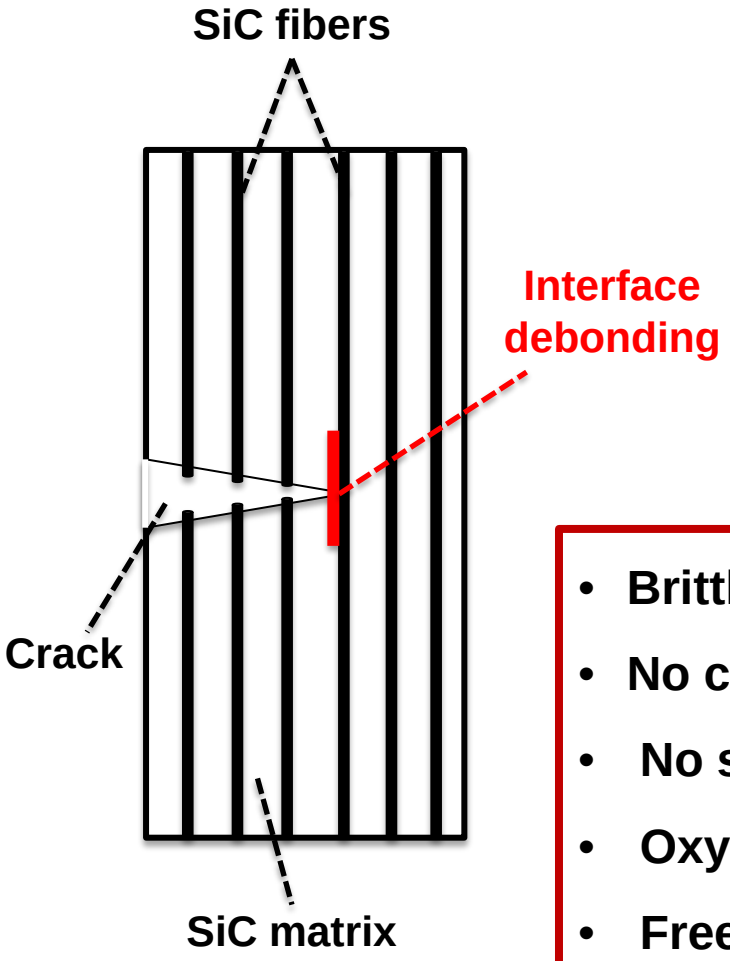

- Low matrix cracking strength (proportional limit - 69 MPa/10 ksi)
- Matrix fills space and provides a thermally conductive path.
- Fracture toughness due to crack bridging and interface debonding.

- Brittle at all temperatures.
- No crack tip blunting – fast crack propagation.
- No self-healing.
- Oxygen ingress to fibers shortens fiber life.
- Free Si in the matrix limits temperature usage to below 1588 K (2400 ºF).

Recession of BN and Formation of Glassy Phase in BN-Coated Hi-Nicalon MI SiC Composites

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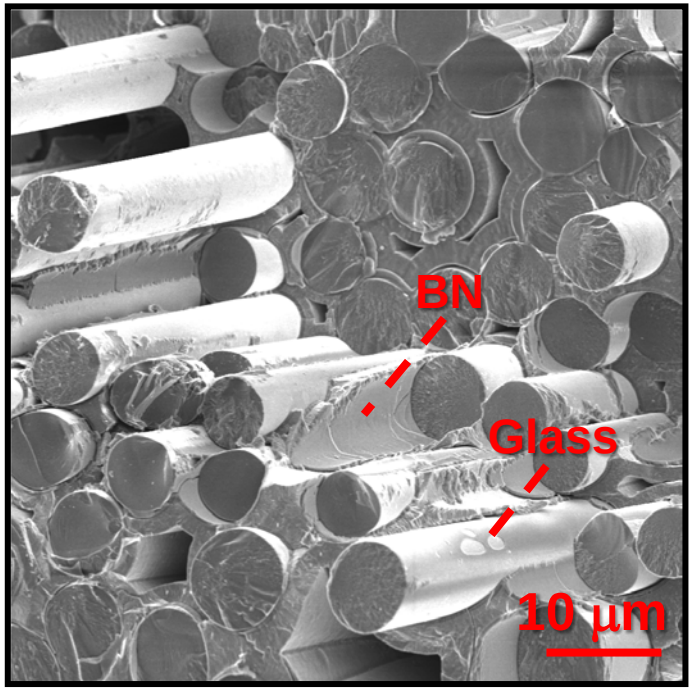
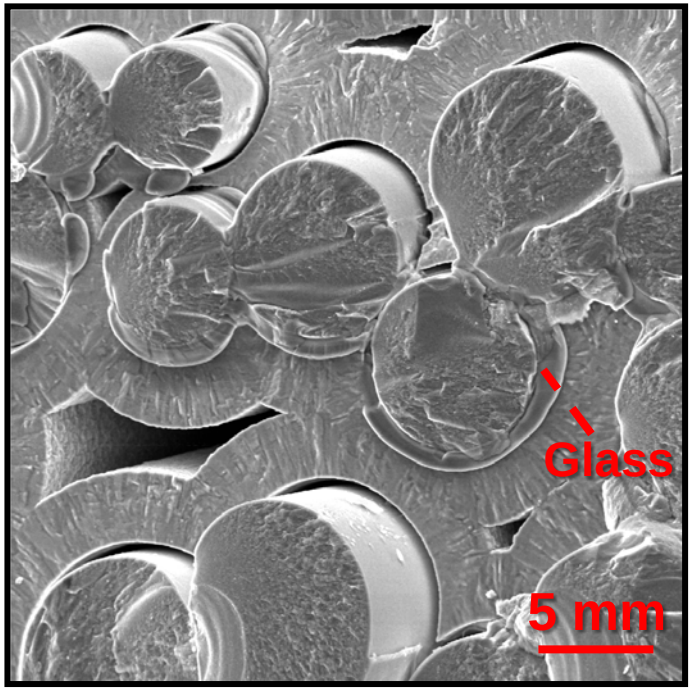
(Courtesy M. Singh)

T = 973 K; σ = 250 MPa;1000 h in air





$$2BN\,(s) + 3/2\,O_2\,(g) = B_2O_3\,(l) + N_2\,(g)$$

B_2O_3 - SiO_2: Low eutectic temperature of 372 °C

Important Question

Can the matrix properties be suitably engineered to ensure certain desirable characteristics?

Present Concept

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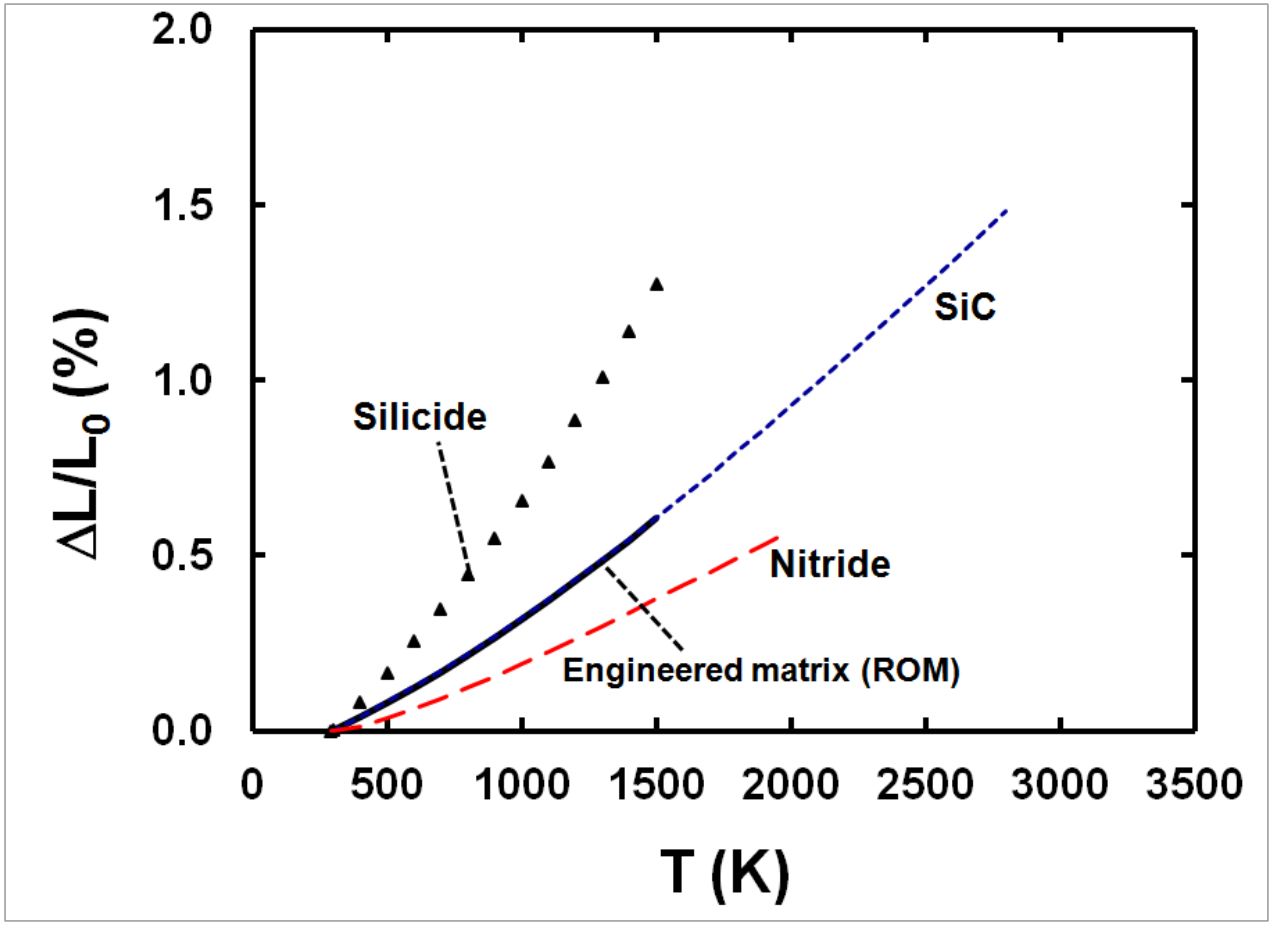

Crack Tip Blunting and Self-Healing

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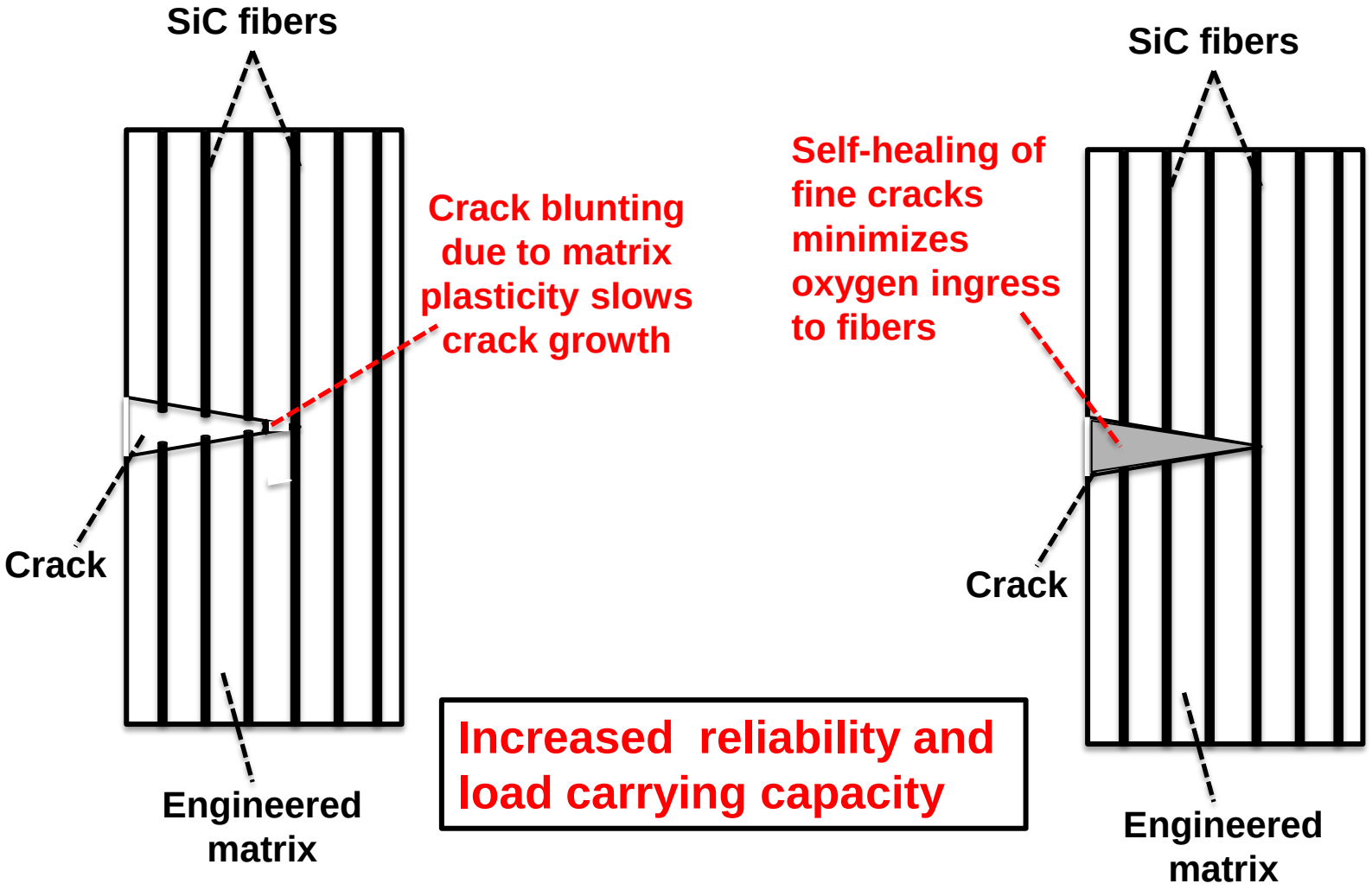

Increased reliability and load carrying capacity

Innovation: Desired Characteristics of the Engineered Matrix (EM)

- Thermal strain compatibility of the matrix with the SiC fibers.
- Plastically compliant matrix to blunt cracks.
- Self-healing crack capabilities to minimize ingress of oxygen.
- Minimize the volume fraction of unreacted silicon to prevent corrosive attack of fibers and incipient melting.
- Dense matrix to increase thermal conductivity.

Expected Impact of Innovation

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- **Matrix plasticity - increased reliability, compliant matrix.**
- **Self-healing matrix - prevents or minimizes oxygen ingress.**
- **Low free Si - reduces fiber attack, reduces incipient melting, increased high temperature capability.**
- **Dense matrix - High thermal conductivity.**

Fabrication and Testing of Engineered Matrix Composites (EMC)

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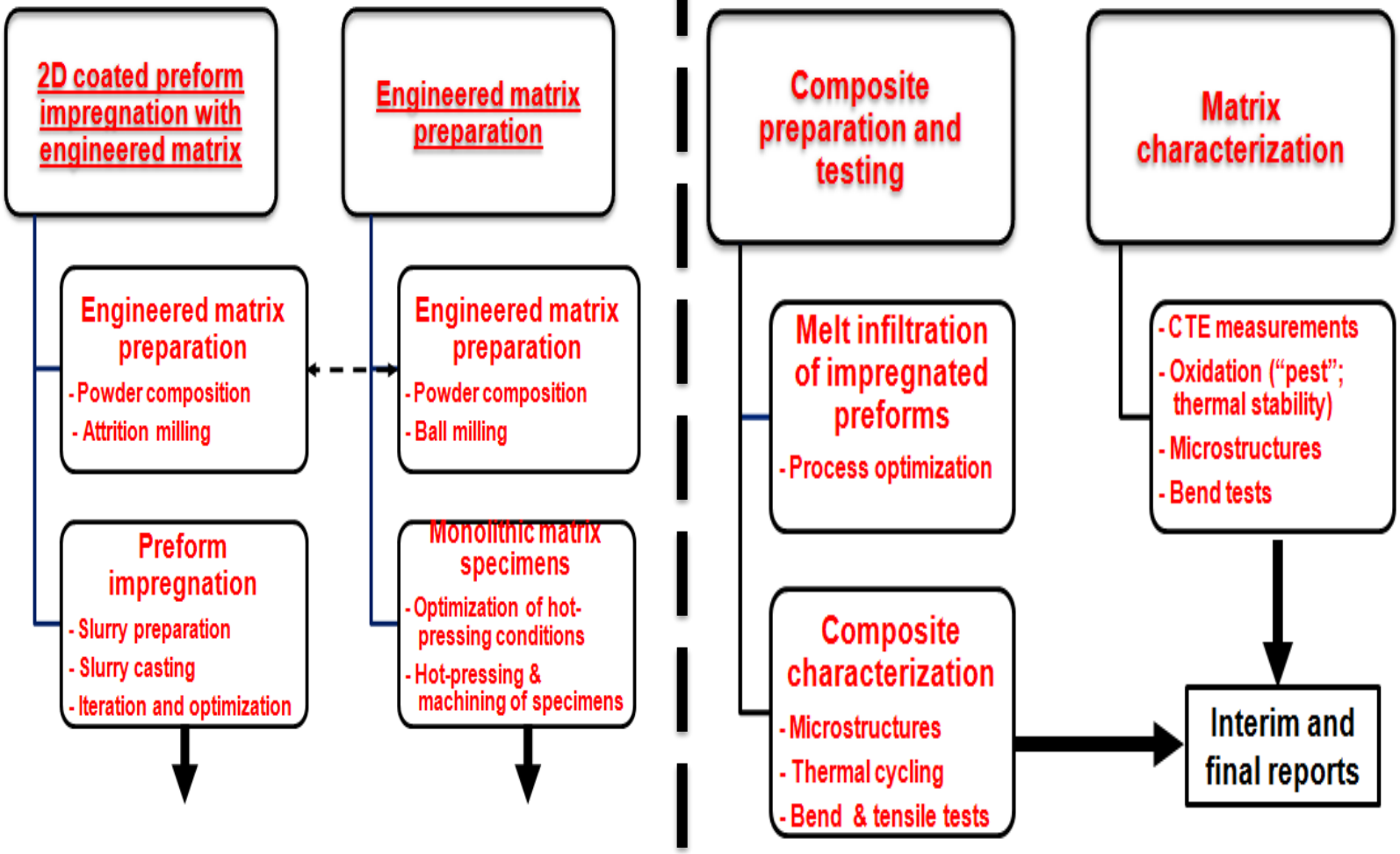
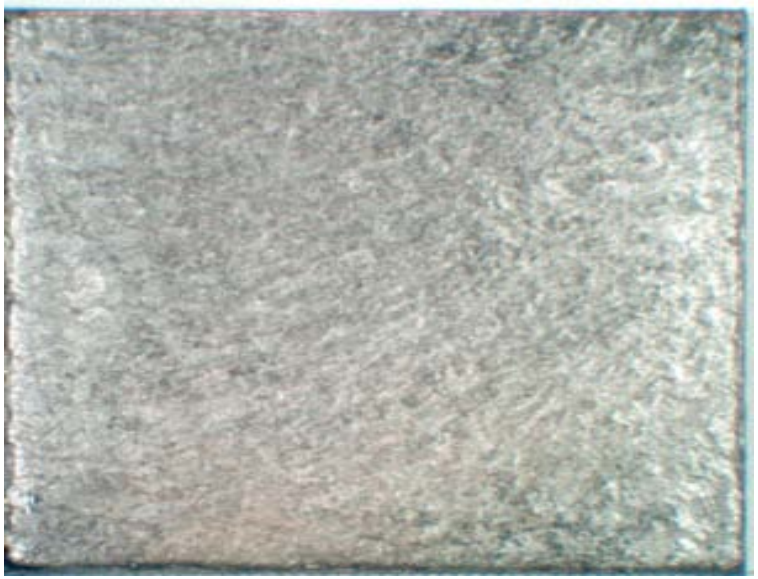


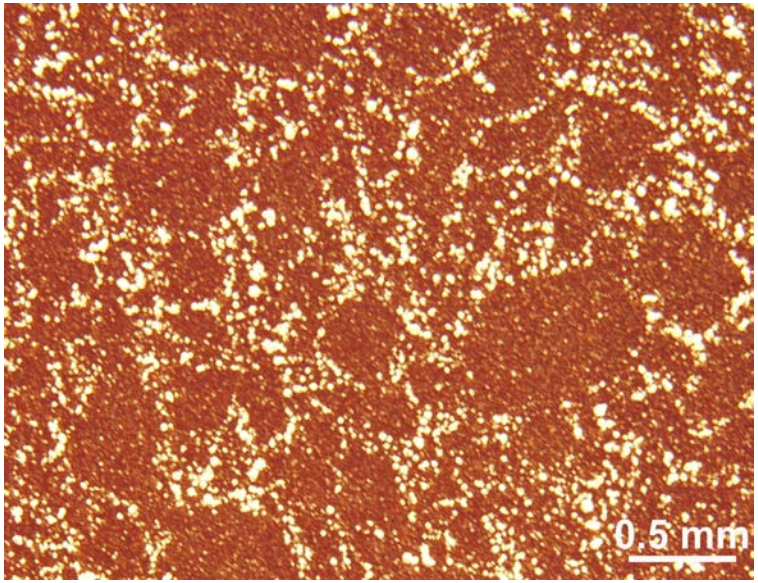
Hot-Pressed Plate and Optical Micrograph

CrMoSi-EM

50 x 50 x 4 mm



Optical micrograph



Proof-of-Concept: Thermal Strains

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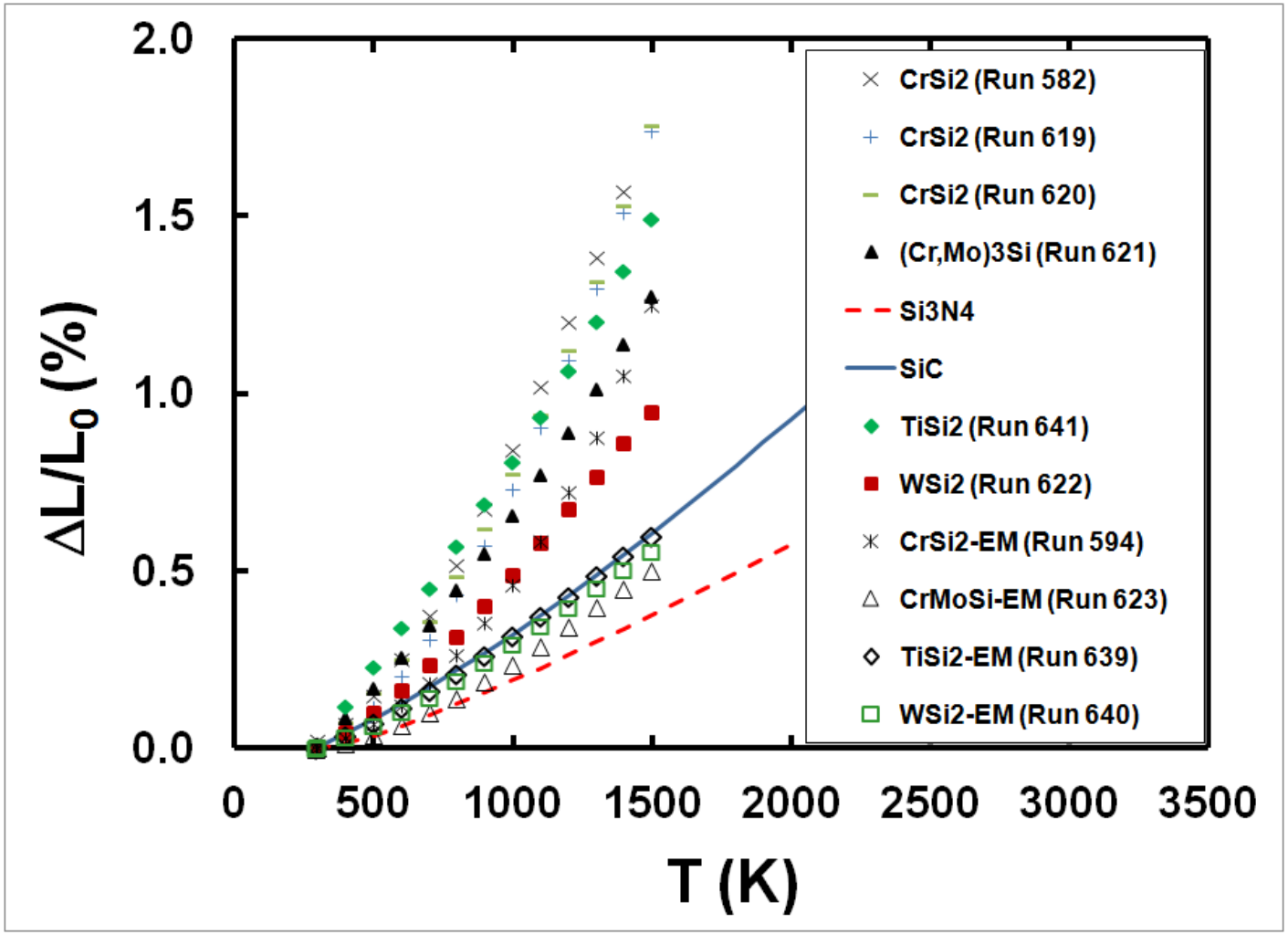

Optical Macrographs of $MoSi_2$ Engineered Matrix

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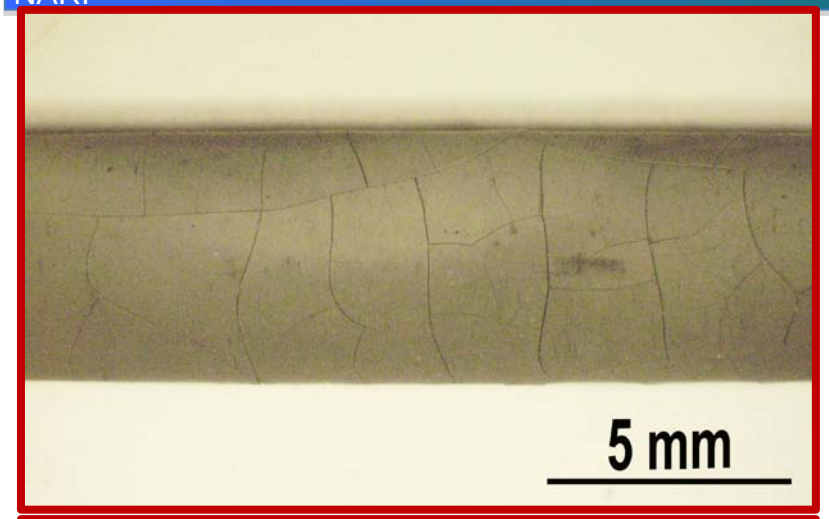

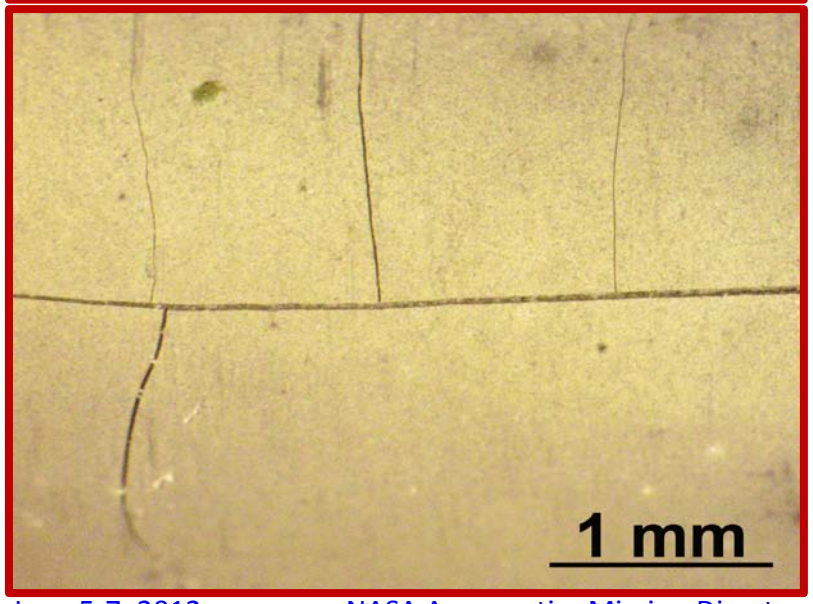

Thermally cycled between room temperature and 1500 K (2240 °F) three times.

- Thermal cycling resulted in cracking.
- No longer considered in the program.

Isothermal Oxidation Behavior

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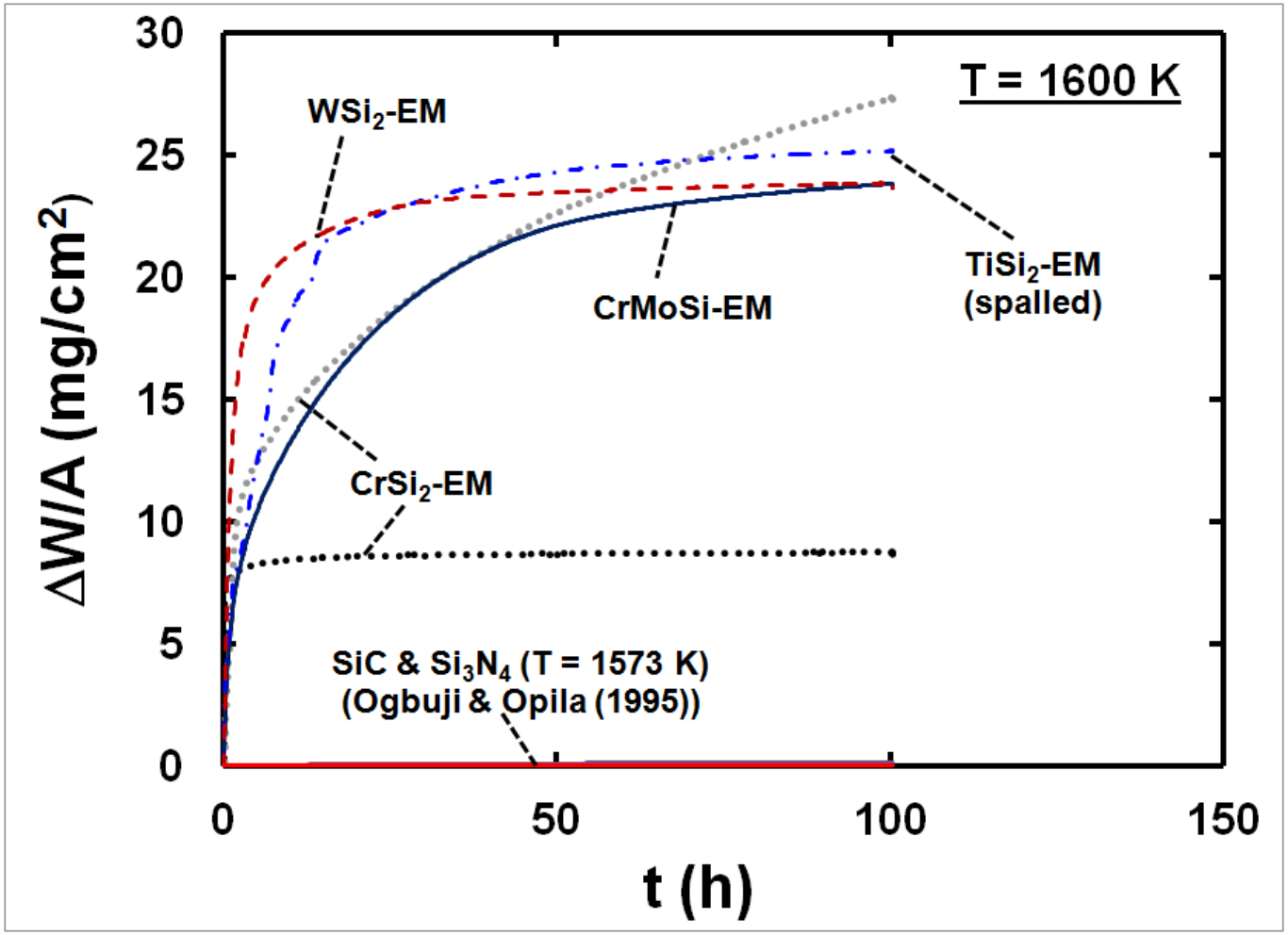
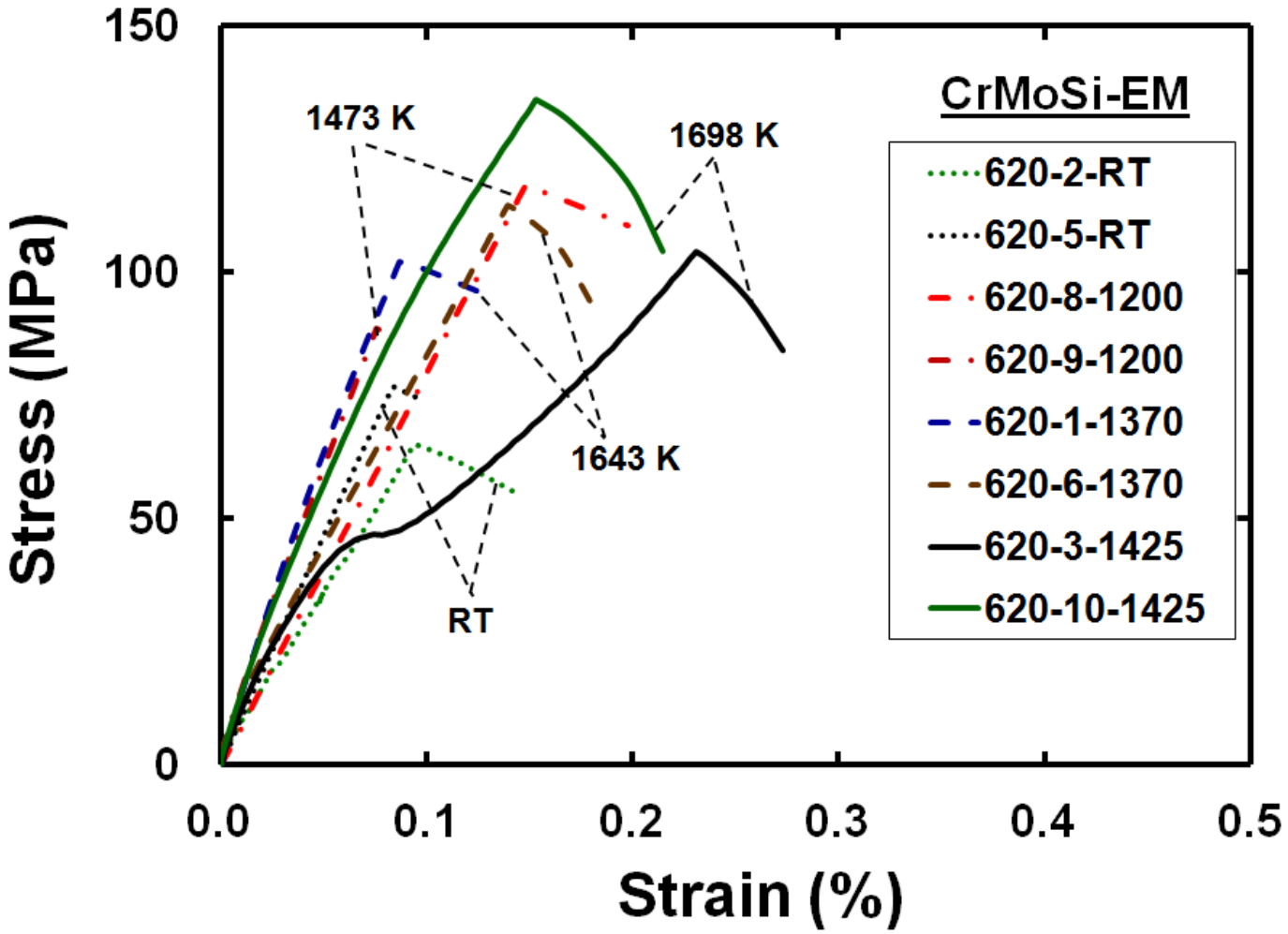


Bend Stress-Strain Curves for CrMoSi-EM



Bend Stress-Strain Curves for $CrSi_2$-EM

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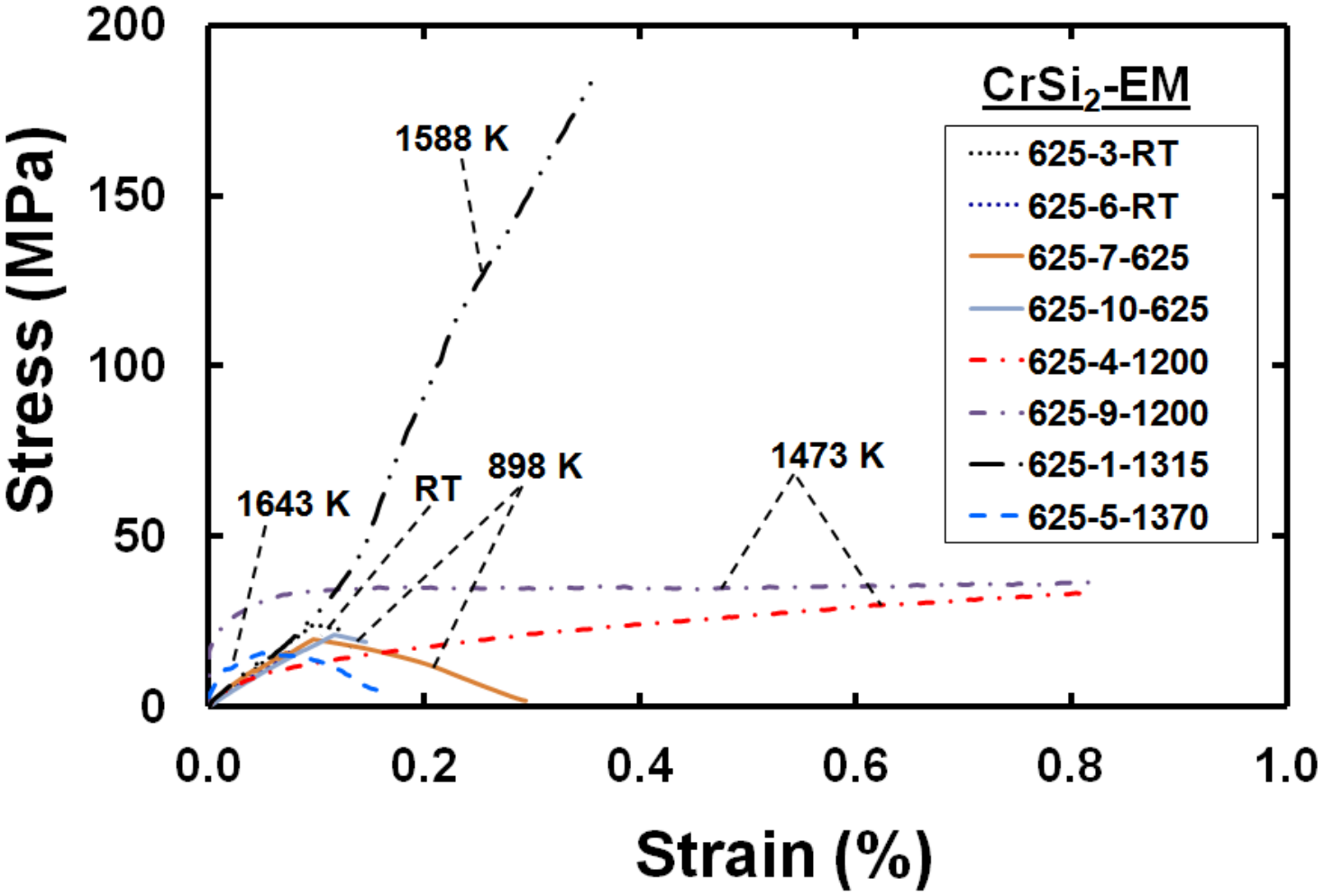

Bend Stress-Strain Curves for WSi_2-EM

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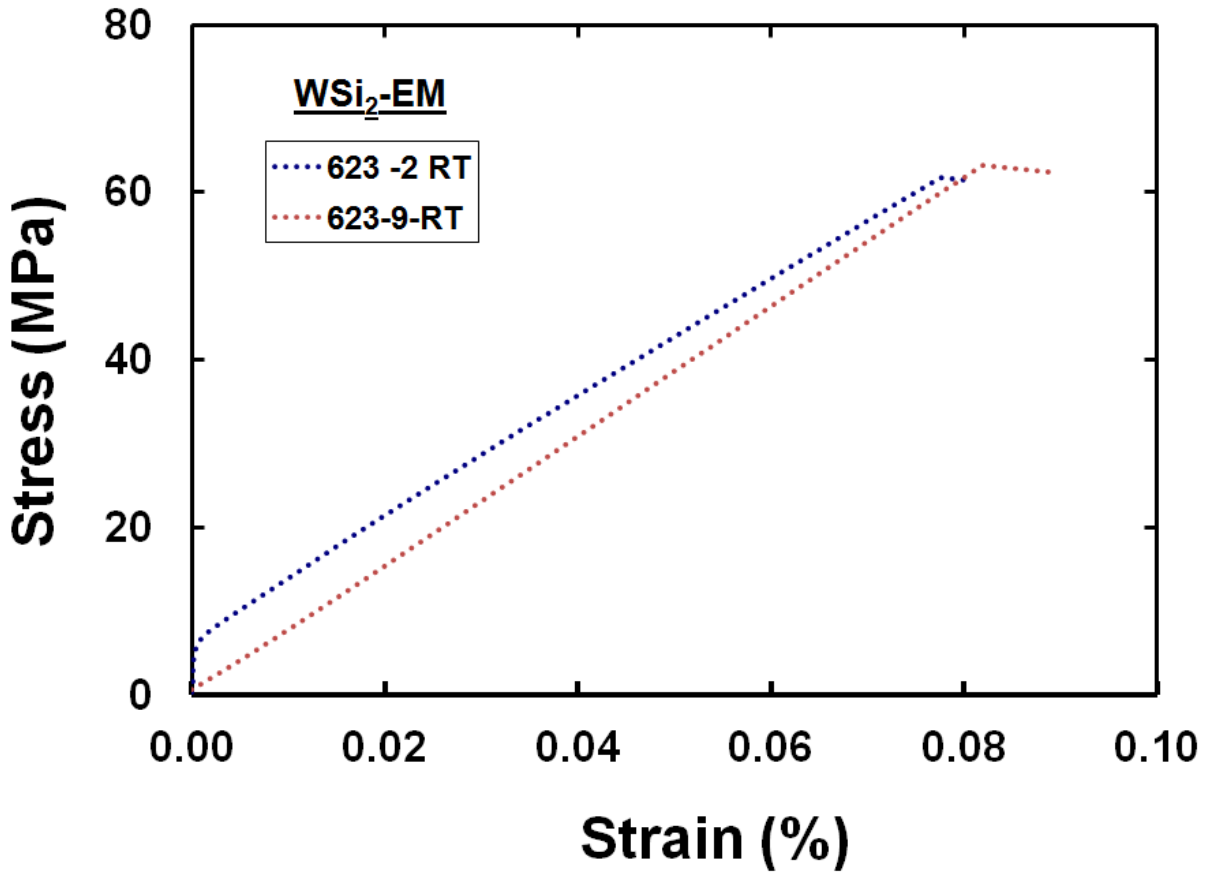

Catastrophic oxidation occurred during heat-up to 1473 K.

Engineered Matrix Composites Fabrication

(courtesy R. Bhatt)

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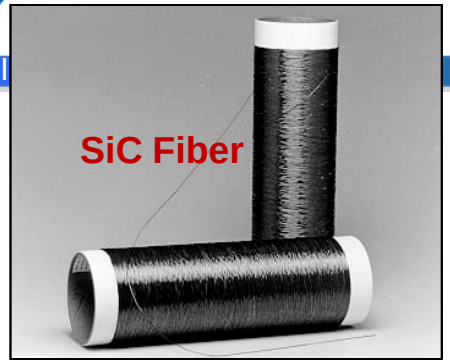
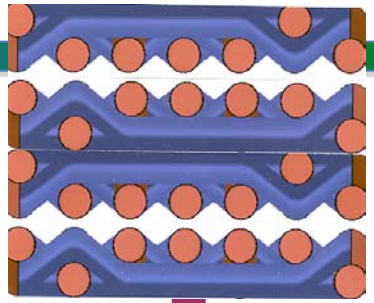
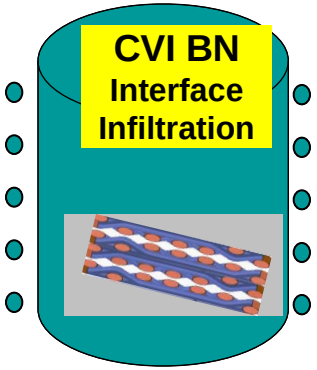


0/90 Fabric Weaving



SiC fiber Preform Fabrication

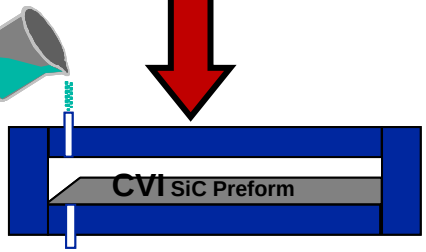
Reactor

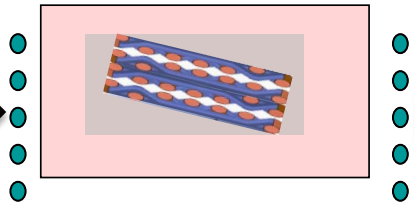


Reactor

Fiber coating

Engineered Matrix Infiltration





Melt Infiltration

EMC

Microstructures of Particulate-Infiltrated SiC Fiber Preform

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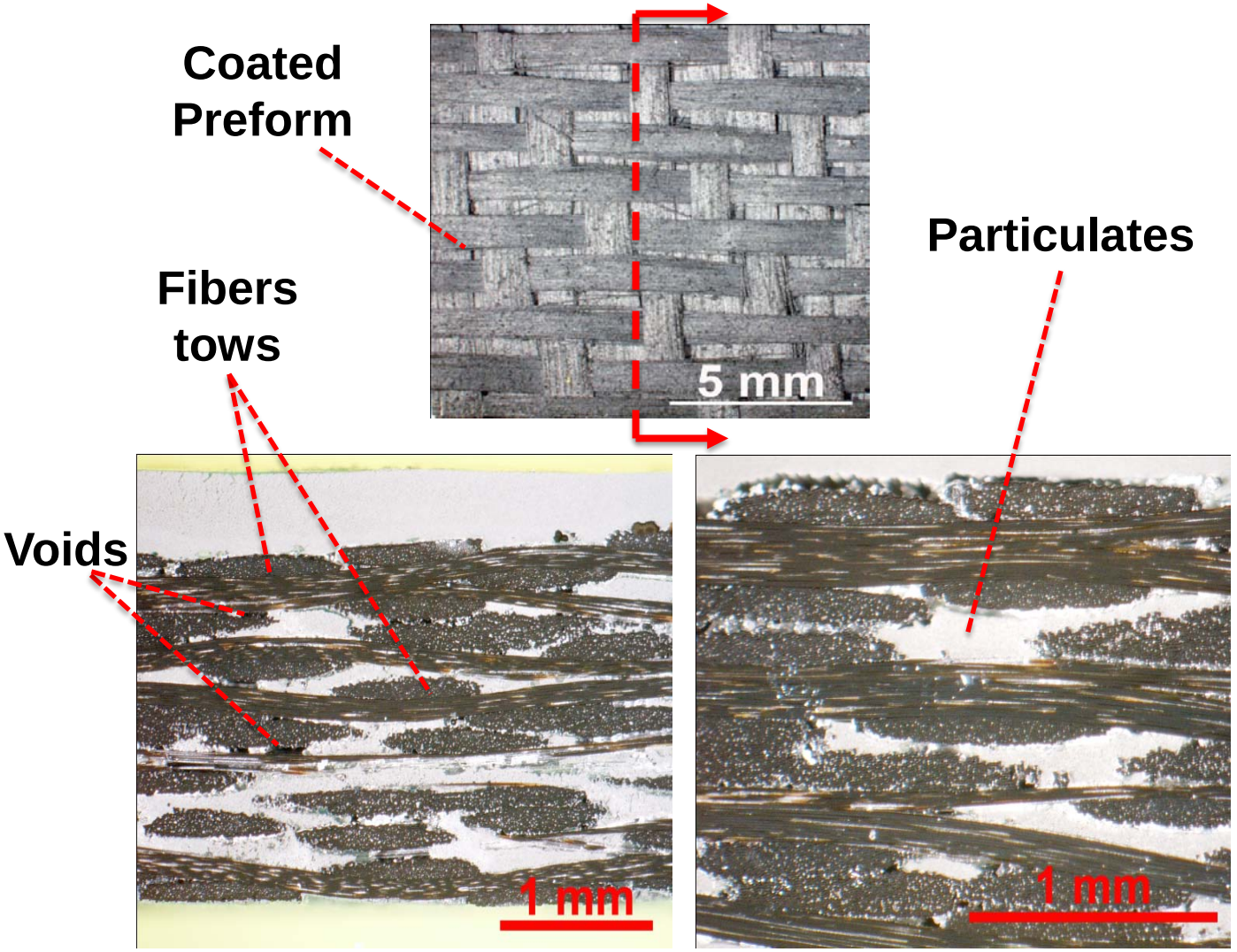

CT Scans of Particulate Infiltrated Preform

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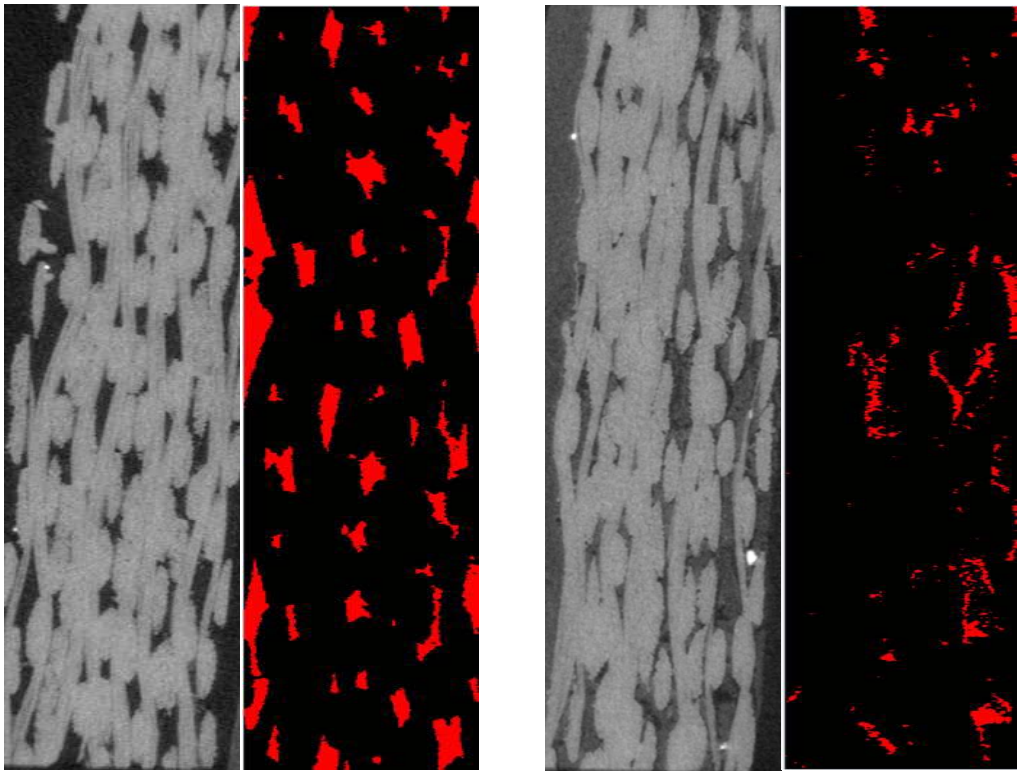
As-received Preform **Particulate Infiltrated**



Area fraction of porosity ~ 21-23%

Area fraction of porosity ~ 0.9%

The red regions are voids

Summary and Conclusions

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- **Bend, CTE, isothermal oxidation and thermal cycling tests were conducted on several engineered silicide/SiC/Si_3N_4 matrices.**
- **Two promising engineered matrix compositions were down-selected for further development.**
- **Trials to infiltrate one of these engineered matrices into SiC-coated fiber preforms have been completed. Microstructural analysis and CT scans demonstrated almost complete infiltration of the preform.**
- **Efforts are underway to produce Engineered Matrix Composites (EMCs) specimens to determine self-healing capabilities.**

Summary of Phase I Accomplishments: TRL 2

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Milestone	Status
Demonstrate thermal strains for engineered matrices match those of SiC.	Completed.
Generation of matrix properties and down-selection of promising compositions.	Completed.
Demonstrate high temperature matrix plasticity.	Completed.
Develop processing techniques for fabricating EMCs.	Particulate infiltration trials completed; melt infiltration trials to be completed.
Evaluate mechanical properties of EMCs and demonstrate self-healing capabilities.	To be completed.

Next Steps

- **Complete tensile tests of monolithic specimens.**
- **Particulate and melt infiltrate bend specimens.**
- **Mechanical testing of EMC bend specimens.**
- **Evaluate self-healing properties in EMCs.**
- **Write and submit final report.**
- **Submit Phase II proposal.**

Distribution and Dissemination

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- **Submitted NF 1679 to GRC patent attorney (LEW-18964-1).**
- **Submit papers to journals/NASA TMs after receiving approvals.**
- **Present papers at conferences after receiving approvals depending on the availability of travel funds.**