HTCMC 5 Abstract

The Effect of Fiber Architecture on Matrix Cracking in SiC/SiC CMC's

Gregory N. Morscher, Ohio Aerospace Institute, Cleveland, OH

Applications incorporating silicon carbide fiber reinforced silicon carbide matrix composites (CMC's) will require a wide range of fiber architectures in order to fabricate complex shapes. The stress-strain response of a given SiC/SiC system for different architectures and orientations will be required in order to design and effectively life-model future components. The mechanism for non-linear stress-strain behavior in CMC's is the formation and propagation of bridged-matrix cracks throughout the composite. A considerable amount of understanding has been achieved for the stress-dependent matrix cracking behavior of SiC fiber reinforced SiC matrix systems containing melt-infiltrated Si. This presentation will outline the effect of 2D and 3D architectures and orientation on stress-dependent matrix-cracking and how this information can be used to model material behavior and serve as the starting point for mechanistic-based life-models.
The Effect of Architecture on Matrix Cracking in SiC/SiC CMC's

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Objective

• To understand the effect of architecture on matrix cracking in CMC's
  – Cause of non-linearity – necessary for modeling $\sigma$/$\epsilon$ behavior
  – Access for ingress of oxidation species that lead to strength-degrading embrittlement mechanisms
• To stimulate the use of architecture-based designs for composite applications
  – Architectures offer the potential to enhance matrix cracking stress, interlaminar strength, thermal conductivity, etc...
Outline

- Matrix cracking in 2D Woven systems when stressed in orthogonal directions
  - The standard MI system
  - Ways to improve matrix cracking
- Matrix cracking in some 3D Woven MI systems when stressed in orthogonal directions
- Matrix cracking in 2D woven and braided architectures when stressed in off-axis directions
- Summary and conclusions

Standard Slurry Cast Melt-Infiltrated (MI) 2D Woven Composites

- Sylramic Fiber
- Weaving
- Fabric
- Reactor
- Slurry Cast SiC Matrix
- Slurry Cast SiC Matrix
- For Syl-IBN, special treatment prior to CVI Si-BN
- Silicon Melt Infiltration
- Furnace
- MI SIC/SIC
2D Woven Systems When Stressed in Orthogonal Direction

HN and Sylramic (iBN) Fiber-types
MI and CVI SiC Matrix

Stress-Strain and AE for Different Composite Panels

- Acoustic Emission used to monitor matrix crack density and derive a matrix crack distribution
  - Excellent source location coupled with a near direct proportion between cumulated AE energy and matrix crack density
- Applied to Sylramic-based and Hi-Nicalon-based composite systems that vary by a factor of two in number of plies, thickness, tow ends per cm, and number of fibers per woven tow
For Orthogonal Composites, the 90° Fiber-Tows are the Source for Matrix Crack Formation

- The stress that acts on the 90° fiber-tows is the stress in the composite "outside" of the load-bearing fiber, BN, CVI SiC minicomposite, i.e., the “mini-matrix” stress:

\[
\sigma_{\text{min matrix}} = \frac{(\sigma_c + \sigma_{\text{th}})}{E_c} \left( \frac{E_c - f_{\text{min}} E_{\text{min i}}}{1 - f_{\text{min}}} \right)
\]

Composite modulus

All the information required is obtained from RT stress-strain test (or sound techniques) and processing data sheet.

A very simple relationship for matrix cracking in 2D MI SiC/SiC Composites

\[
\rho_c = \text{final crack density} \sim 2.5/\text{mm for Hi-Nicalon} \sim 10/\text{mm for Syricular}
\]

\[
\sigma_o = 150 \text{ MPa}; \quad m = 5
\]

\[
\rho_c \left( \sigma_{\text{min matrix}} \right) = \rho_c \left[ 1 - \exp \left( -\left( \frac{\sigma_{\text{min matrix}}}{\sigma_o} \right)^m \right) \right]
\]
Effect of Tow Size and Shape:
Single-Tow vs. Double-Tow Woven Composites
- Identical fiber volume fraction; Both five-harness satin

3D-Orthogonal Composites With Different Z-Fiber Types

X- and Y-direction Fibers = Syrlamic or Syl-iBN
MI Composites
Woven 3D-Orthogonal Composites with *Different* Z-Fiber Types

**Z-Direction:**
- ZMI (800 fiber/tow)
- **T300** (1000 fiber/tow)
- Rayon (400 fiber/tow)

**X-Direction:**
- Two Syrlamic Tows (1600 fibers)
- 10 epi
- 7 plies

**Y-Direction:**
- One Syrlamic Tow (800 fibers)
- 18 or 20 epi
- 8 plies

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**3D Orthogonal σ/ε Behavior**

<table>
<thead>
<tr>
<th>Strain, %</th>
<th>Stress, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>50</td>
</tr>
<tr>
<td>0.1</td>
<td>100</td>
</tr>
<tr>
<td>0.2</td>
<td>150</td>
</tr>
<tr>
<td>0.3</td>
<td>200</td>
</tr>
<tr>
<td>0.4</td>
<td>250</td>
</tr>
<tr>
<td>0.5</td>
<td>300</td>
</tr>
</tbody>
</table>

- **Y-direction**
  - Rayon
  - T300
  - ZMI

- **ZMI (X-direction)**
Loading in the Y-Direction

Stress Distributions For Three Y-Direction Oriented 3D Composites and Standard 2D Composite

- Wide range of matrix cracking stress-distributions
- XPLY cracking stresses always higher than UNI cracking stresses
- Rayon > T300 > ZMI
Minimatrix Stress Dependence for Matrix Cracking in 3D Composites

Good correlation for XPLY regions

UNI regions unaffected

UNI Regions Dependent on Height of Z-Tow: Griffith-type Relationship

* Tow height measured 0.5 mm from surface
Ways to Increase Matrix Cracking Strength

Using the 2D Woven System

Ways to improve matrix cracking stress

- Optimize constituent contents
  - E.g., increase fiber volume fraction in loading direction
- Unbalanced weaves

![Graph showing stress-strain relationship with different CVI and epcm values](image-url)
Ways to improve matrix cracking stress

- Improve strength of 90° minicomposites
  - E.g., "fluffed" fabric (A. Calomino, NASA Glenn)

<table>
<thead>
<tr>
<th>Composite</th>
<th>$h$, mm</th>
<th>$w$, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-produced</td>
<td>0.13 ± 0.01</td>
<td>1.10 ± 0.14</td>
</tr>
<tr>
<td>Mechanical-spread</td>
<td>0.11 ± 0.01</td>
<td>1.22 ± 0.06</td>
</tr>
</tbody>
</table>

Relax the Matrix Via Creep

- Holmes et al, Widaja et al. (See Morsch-Pujari Poster)
- HNS/MI 1315°C Tensile $\sigma/t$ history
Relax the Matrix Via Creep

- Holmes et al, Widaja et al. (See Morscher-Pujar Poster)
- HNS/MI *room temperature* tensile $\sigma/\varepsilon$ after creep

<table>
<thead>
<tr>
<th></th>
<th>As-Produced</th>
<th>After Creep</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.002% Offset</td>
<td>125 MPa</td>
<td>142 MPa</td>
</tr>
<tr>
<td>Significant AE</td>
<td>115 MPa</td>
<td>140 MPa</td>
</tr>
<tr>
<td>Matrix Compression</td>
<td>20 MPa</td>
<td>60 MPa</td>
</tr>
</tbody>
</table>

Off-Axis 2D Woven and Braided Architectures

Syl-iBN MI Composites
Matrix Cracking in Off-Axis Direction and for Braided Structure is Equivalent if not Better than Orthogonal Direction

- Limited data so far
- Note, double-tow woven, 0/±60 braided composite tested in the 90° direction

Summary and Conclusions

- The stress-distribution for matrix cracking in 2D and 3D orthogonal dense SiC matrix composites is dependent on architecture and can be effectively modeled with simple "minimatrix" approach
  - Mechanical behavior of 90° minicomposites and matrix-rich regions
- The stresses for matrix cracking in these systems can be optimized via architecture/processing enhancements
  - Fiber loading in desired direction
  - 90° tow dimension
  - Matrix relaxation via creep
- Onset of matrix cracking in off-axis directions is similar to orthogonal directions and is potentially superior for some architectures such as a braided structure
  - More optimization needed