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

Gregory N. Morscher
Ohio Aerospace Institute
NASA Glenn Research Center
Cleveland, OH

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
2D Woven Systems When Stressed in Orthogonal Direction

HN and Syramic (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 Syramic-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:

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

Composite modulus

Net residual stress

Applied composite stress

0° minicomposite modulus

(rule of mixtures)

Fraction of minicomposite in 0° direction

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

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

\[
\rho_c = \text{final crack density}
\]

- 2.5/mm for Hi-Nicalon
- 10/mm for Sylramic

\[
\sigma_0 = 150 \text{ MPa; } m = 5
\]

\[
\rho_c \left( \sigma_{\text{min matrix}} \right) = \rho_c \left[ 1 - \exp \left( - \left( \frac{\sigma_{\text{min matrix}}}{\sigma_0} \right)^m \right) \right]
\]
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 = Sylramic 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 Sylramic Tows (1600 fibers)
- 10 epi
- 7 plies

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

3D Orthogonal σ/ε Behavior

Stress, MPa

0 100 200 300 400

Strain, %

0 0.1 0.2 0.3 0.4 0.5

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
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>
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<tbody>
<tr>
<td>As-produced</td>
<td>$0.13 \pm 0.01$</td>
<td>$1.10 \pm 0.14$</td>
</tr>
<tr>
<td>Mechanical-spread</td>
<td>$0.11 \pm 0.01$</td>
<td>$1.22 \pm 0.06$</td>
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</tbody>
</table>

- Mechanically spread

Relax the Matrix Via Creep

- Holmes et al, Widaja et al. (See Morsch-Pujar Poster)
- HNS/MI $1315^\circ C$ Tensile $\sigma$/$\varepsilon$ history
Relax the Matrix Via Creep

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

![Graph showing stress vs. strain for panel A3 and A2 with creep data]

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<thead>
<tr>
<th></th>
<th>As-Produced</th>
<th>After Creep</th>
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</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° mini-composites 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