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 σ/ε 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:

\[
\sigma_{\text{min matrix}} = \frac{(\sigma_c + \sigma_{\text{th}}) \left( E_c - f_{\text{mi}} E_{\text{mi}} \right)}{E_c \left( 1 - f_{\text{mi}} \right) E_{\text{mi}}} \quad \text{Composite modulus} \quad \text{0° minicomposite modulus} \quad \text{(rule of mixtures)} \quad \text{Fraction of minicomposite in 0° direction}
\]

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

\[ \rho_c = \text{final crack density} \]
\[ \sim 2.5/\text{mm for Hi-Nicalon} \]
\[ \sim 10/\text{mm for Syramic} \]
\[ \sigma_0 = 150 \text{ MPa; } m = 5 \]

\[ \rho_c (\sigma_{\text{min matrix}}) = \rho_c \left[ 1 - \exp \left( - \left( \frac{\sigma_{\text{min matrix}}}{\sigma_0} \right)^m \right) \right] \]

Regression fit "linear" region

Critical Design Parameter (matrix-cracking enables environmental ingress, strength degradation)

Norm Cum AE Energy

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Glenn Research Center at Lewis Field
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)

Y-Direction:

One Syrramic Tow (800 fibers)
18 or 20 epi
8 plies

X-Direction:

Two Syrramic Tows (1600 fibers)
10 epi
7 plies

3D Orthogonal $\sigma/\varepsilon$ Behavior
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

![Stress-Strain Curve Diagram]

- CVI: 9.4 epcm
  - 7 ply (001)
  - f=0.22
  - E=291 GPa

- CVI: 9.4 epcm
  - 8 ply (002)
  - f=0.21
  - E=293 GPa

- CVI: 5.5 epcm
  - f=0.12 (002)
  - E=281 GPa

- CVI: 6.3 epcm
  - f=0.14 (001)
  - E=285 GPa

Stress, MPa

Strain, %
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>$h_i$, mm</th>
<th>$w_i$, mm</th>
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<tbody>
<tr>
<td>As-produced</td>
<td>0.13 ± 0.01</td>
<td>1.10 ± 0.14</td>
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<tr>
<td>Mechanical-spread</td>
<td>0.11 ± 0.01</td>
<td>1.22 ± 0.06</td>
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</table>

**Mechanically spread**

**Syl-MI**

8.7 epcm

Relax the Matrix Via Creep

- Holmes et al, Widaja et al. (See Morsch-Pujar Poster)
- HNS/MI 1315°C Tensile $\sigma$/$\epsilon$ history

<table>
<thead>
<tr>
<th>Panel</th>
<th>Experiment</th>
<th>Creep Stress, MPa</th>
<th>0.002% offset stress, MPa</th>
<th>1315°C Initial Loading, MPa</th>
<th>1315°C After Creep, MPa</th>
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<tr>
<td>A1</td>
<td>1315FF</td>
<td>70</td>
<td>127</td>
<td>NA</td>
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<tr>
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<td>1315creep</td>
<td>160</td>
<td>99</td>
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</table>
Relax the Matrix Via Creep

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

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