Designing with oxide-oxide CMCs: Understanding the price-performance relationship in new fabric designs

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Previous study

• Survey of new fabric designs for CMCs using AXC-610 Matrix

• Presented at the High Temperature Ceramic Matrix Composite conference in Jun 2016 (Toronto)

• Conclusions
  • Minimal changes in Nextel 610 and 720 CMC tensile and flex properties using fabrics with roving as high as 4500 denier
  • >40% cost savings in fabric input

• Available at www.3m.com/ceramics
Current study objectives

• Determine effects of high denier fabrics on CMC fabrication using AXC-610 Matrix

• Replicate results from previous study with larger sample set

• Focus on Nextel 610 and best performing fabric designs
  • **DF-11-27-1500 (baseline)**
  • DF-11-14-3000
  • DF-19-23-3000
  • DF-11-10-4500
  • DF-24-8-10000

• Expand analytical testing to include
  • Interlaminar shear properties
  • Tuning of composite properties with processing variations
  • Surface roughness
  • Part specific considerations – Bending radius
  • Cost savings – Fabric and CMC

Fabric naming convention

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Form</th>
<th>Thickness</th>
<th>Thread count</th>
<th>Denier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nextel 610</td>
<td>Woven fabric</td>
<td>11 mil</td>
<td>27 picks/in</td>
<td>1500 g/9000m</td>
</tr>
</tbody>
</table>
## 3M™ Nextel™ 610 Fabrics

<table>
<thead>
<tr>
<th>Fabric Type</th>
<th>Input Yarn</th>
<th>Weave</th>
<th>Thread Count (ppi)</th>
<th>Weight (oz/yd²)</th>
<th>Thickness (inch)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nextel 610</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(warp / fill)</td>
<td>Sized</td>
<td>Size Heat Cleaned</td>
</tr>
<tr>
<td>DF-11-27-1500</td>
<td>1500 d</td>
<td>8HS</td>
<td>27.5 / 27.5</td>
<td>11</td>
<td>0.012</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Heat</td>
<td>Cleaned</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DF-11-14-3000</td>
<td>3000 d</td>
<td>5HS</td>
<td>15 / 14</td>
<td>~11</td>
<td>~0.013</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>~0.010</td>
</tr>
<tr>
<td>DF-11-10-4500</td>
<td>4500 d</td>
<td>5HS</td>
<td>10 / 9</td>
<td>~12</td>
<td>~0.014</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>~0.011</td>
</tr>
<tr>
<td>DF-19-23-3000</td>
<td>3000 d</td>
<td>8HS</td>
<td>23.5 / 23.5</td>
<td>19</td>
<td>0.020</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.017</td>
</tr>
<tr>
<td>DF-24-8-10000</td>
<td>10,000 d</td>
<td>4HS</td>
<td>8 / 8</td>
<td>~ 22</td>
<td>~ 0.024</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>~ 0.019</td>
</tr>
</tbody>
</table>

### DF11-27-1.5K
- 8 HS Weave

### DF11-14-3K
- 5 HS Weave

### DF11-10-4.5K
- 5 HS Weave

### DF19-23-3.0K
- 8 HS Weave

### DF24-8-1000D
- 4HS Weave
## Laminate Physical Properties

<table>
<thead>
<tr>
<th>Fabric Style</th>
<th>Matrix</th>
<th># of Pies</th>
<th>Volume % Fiber</th>
<th>Volume % Matrix</th>
<th>Volume % Porosity</th>
<th>Density g/cc</th>
<th>Laminate Thickness (mm)</th>
<th>Per Ply Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DF-11-27-1500</td>
<td>AXC-610</td>
<td>12</td>
<td>40.8</td>
<td>36.4</td>
<td>22.8</td>
<td>2.82</td>
<td>2.84</td>
<td>0.24</td>
</tr>
<tr>
<td>DF-11-14-3000</td>
<td>AXC-610</td>
<td>12</td>
<td>40.7</td>
<td>34.7</td>
<td>24.6</td>
<td>2.76</td>
<td>2.85</td>
<td>0.24</td>
</tr>
<tr>
<td>DF-11-10-4500</td>
<td>AXC-610</td>
<td>12</td>
<td>38.5</td>
<td>37.6</td>
<td>23.9</td>
<td>2.77</td>
<td>3.10</td>
<td>0.26</td>
</tr>
<tr>
<td>DF-19-23-3000</td>
<td>AXC-610</td>
<td>8</td>
<td>41.8</td>
<td>34.7</td>
<td>23.5</td>
<td>2.80</td>
<td>3.04</td>
<td>0.38</td>
</tr>
<tr>
<td>DF-24-8-10000</td>
<td>AXC-610</td>
<td>6</td>
<td>38.3</td>
<td>34.0</td>
<td>27.7</td>
<td>2.64</td>
<td>2.84</td>
<td>0.47</td>
</tr>
</tbody>
</table>

5 Weaves of Nextel 610 were investigated. The denier of the fiber tow ranged from 1500D to 10000D. The number of plies per laminate were selected to produce approximately the same laminate thickness.
Test methods

- Tensile
  - ASTM C1275-15: Monotonic Tensile Behavior of Continuous Fiber-Reinforced Advanced Composites

- Flexure

- Interlaminar shear
  - ASTM C1292-10: Shear Strength of Continuous Fiber-Reinforced Advanced Ceramics
    - Double notched compression

- Bending strength
  - ASTM D6415: Measuring the Curved Beam Strength of a Fiber-Reinforced Polymer Matrix Composite
    - Modified to include variation in bending radius

- Thermal aging
  - 100 hrs at elevated temperatures

- Surface roughness
  - DIN EN ISO 4287: 1D profilometry
Room temperature tensile/flex modulus and strength

Across the weave styles the variation in strength and modulus is 10%, except for the laminate made using the 10000 denier fiber tow. All samples used the AXC-610 Alumina Silicate Matrix.
Room temperature interlaminar shear strength – SBS and DNC

Interlaminar shear strength (ILSS) follows the same trend as flexure strength and modulus. There is good correlation between short beam shear (SBS) and double-notch compression (DNC) measurements.
The long term service temperature of Nextel 610 is limited to 900-1000°C. For shorter durations, higher temperatures can be tolerated. Since the different weaves all use Nextel 610 fiber and AXC-610 Alumina Silicate Matrix, they all show similar thermal aging.
Many factors effect the quality of the final part. One key factor is the process (sintering) temperature. Higher sintering temperatures typically favor Shear and Modulus properties at the expense of the Tensile and Flexure properties.
DF-19-23-3000

Tensile Modulus v. Process Temperature

Tensile Strength v. Process Temperature
Surface roughness – Tool vs bag side

**Profilometry**

- **Tool**
  - Z Range: 78.21 µm
  - X Range: 9.23 mm

- **Bag**
  - Z Range: 128.0 µm
  - X Range: 10.00 mm

**Optical microscopy**

- **Tool**
  - Z Range: 120.0 µm
  - X Range: 8.70 mm

- **Bag**
  - Z Range: 149.8 µm
  - X Range: 10.00 mm

DF-11-27-1500

DF-11-10-4500
The surface texture of the composite laminate is affected by the tool surface texture or any release plies contacting the prepreg during the consolidation process.
Part layup

Infiltration

DF-11-27-1500

DF-19-23-3000
Part design – Bending radius

- Modified ASTM D6415
  - 4-pt bending fixture with MoS$_2$ lubricated dowels
  - Specimen inner radius varied

![Image of bending fixture](image1)

![Graph showing interlaminar strength](image2)

**Tight (R~0.8-1.0 mm) vs Broad (R~6.8-7.2 mm)**

![Tool side comparison](image3)
Cost analysis

Estimated cost reduction for the following weaves

<table>
<thead>
<tr>
<th>Fabric Style</th>
<th># of Plies</th>
<th>Cost reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DF11-27-1500</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>DF11-14-3000</td>
<td>12</td>
<td>19</td>
</tr>
<tr>
<td>DF11-10-4500</td>
<td>12</td>
<td>34</td>
</tr>
<tr>
<td>DF19-23-3000</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>DF24-8-10000</td>
<td>6</td>
<td>47</td>
</tr>
</tbody>
</table>

*Based on 2016 pricing
Summary / Conclusions

Laminate processing was equivalent for all laminates.

Variation in mechanical properties was less than 10% for all weave types except DF-24-8-10000. The variation was generally with in the normal scatter.

High temperature limits for long durations was confirmed.

Various mechanical properties can be enhanced through process modifications.

Surface roughness is controlled by the tool surface or release fabrics, localized measurements. Higher denier weaves can contribute to surface roughness when measured over larger areas.

Parts can be fabricated with broad or tight radii without damaging the fiber for all weave types.

AXC-610 Matrix is compatible with all fabric forms.

Significant cost reductions can be achieved with minimal variation in physical and mechanical properties. More work will be required to achieve both cost reduction and mechanical performance with fabrics made using 10000 denier yarns.

This presentation will be available soon at www.3m.com/ceramics

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