Electrical Resistance Change of Ceramic Matrix Composites in Response to Applied Load and Microstructural Damage

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Why Electrical Resistance?

It would be beneficial to accurately detect small-scale transverse matrix cracks in a CMC coupon or component.

As cracks form, only bridging fibers can carry current → resistance increases.

For MI SiC/SiC, the matrix is more conductive than the fibers, which should give high sensitivity to crack formation.

This is a relatively simple technique compared to other inspection methods.
Experimental Procedure

- Resistance measured by four-point probe method
- Silver paint on surface for lower contact resistance
- Grip region wrapped with copper mesh (Used as electrical contact)
  - Offers a simple way of attaching electrical leads for elevated temperature tests
  - For select room-temperature samples, voltage of the contour gage section was also monitored
- Gripped with ceramic wedge grips (for electrical insulation)
- Capacitance strain gage used with 1% range over 25mm
- Resistance monitored with Agilent 34420A micro-Ohm meter
- Acoustic emission monitored by 50kHz to 2MHz sensors just outside the gage section
# Room Temperature Damage Characterization

## Syl-iBN/Slurry Cast MI Matrix Woven Composite ($f = 0.38$)

<table>
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<tr>
<th>Sample</th>
<th>Max Stress, MPa</th>
<th>Stiffness, GPa</th>
<th>Initial Resistivity, Ω-cm</th>
<th>Resistance change, %</th>
<th>Etched Crack Density, mm$^{-1}$</th>
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Note: all samples have eight plies with a BN interphase, 800 fibers per tow, and total fiber volume fraction of 0.38

* These samples were unloaded prior to failure to measure crack density
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**GE Hi-NicS/ Pre-preg MI Matrix Laminate composite ($f = 0.22$)**

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<td>248</td>
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<tr>
<td>0/90 balanced (+/-45°)</td>
<td>228</td>
<td>284</td>
<td>0.027</td>
<td>11.2</td>
<td>225</td>
<td>217</td>
<td>215</td>
</tr>
<tr>
<td>0/90 balanced (+20/-70°)</td>
<td>235</td>
<td>282</td>
<td>0.026</td>
<td>129</td>
<td>232</td>
<td>204</td>
<td>210</td>
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<tr>
<td>0/90 balanced (+70/-20°)</td>
<td>210</td>
<td>247</td>
<td>0.027</td>
<td>22.4</td>
<td>210</td>
<td>168</td>
<td>160</td>
</tr>
<tr>
<td>0/90 biased 2:1 in 0°</td>
<td>300</td>
<td>292</td>
<td>0.027</td>
<td>530</td>
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**0/90 Balanced**

- Stress vs. % Strain
- Acoustic Emission vs. % Strain
- Resistance vs. % Strain

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**0/90 2:1 Bias**

- Stress vs. % Strain
- Acoustic Emission vs. % Strain
- Resistance vs. % Strain
The Need for a Model

Key Benefits
• Can be measured in-situ
• Resistance changes permanently for inspection at zero load
• The deviation from linearity correlates with the proportional limit stress
• Resistance is sensitive to crack formation
• Can be used at elevated temperature
• Repeatable

Key Concerns
• The data needs to be related to the microstructural changes in the material
• Many variables at room temperature
  • crack formation, crack growth, fiber/interphase sliding, fiber breaks
• Even more variables at elevated temp
  • creep of constituents, oxidation, change in resistivity with temperature
• Need to understand what effect each mechanism has on resistance
Model Development

- Current is applied at the MI matrix surface.
- The matrix conductivity is an order of magnitude greater than the fibers (MI contains Si).
- Also, BN insulates the fibers from the matrix.
- When the matrix is cracked, current must be transferred to the fibers.
- The question is how?

Marshall, Cox, Evans 1985
The composite is treated as a series of concentric cylinders
- Fibers are surrounded by BN, then a Si rich region in the ply, then the bulk MI
- All the fibers are treated as one, while maintaining the same relative volume fractions for constituents
- 90° plies are neglected in this case, since the fibers will not bridge the cracks and they do not provide a continuous path (BN interphases in series)
- Each unit cell represents a specified length along the loading direction (10 μm)
• Resistance along the length of each constituent:

\[ R_c = \frac{\rho A_c}{L} \]

\( \rho \) is the constituent resistivity
\( A_c \) is the cross-sectional area
\( L \) is the length of the unit cell

• Similar equations describe the resistance of the constituents in the transverse (radial) direction:

\[ R_t = \frac{\rho A_s}{L} \]

\( A_s \) is \( \frac{1}{2} \) of the mean surface area of the cylinder
\( L_t \) is \( \frac{1}{2} \) of the thickness of the cylinder

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Current is applied to the first and last cells at the outer SiC layer.
Adjusting the BN resistivity has no effect on the un-cracked composite since the matrix resistivity is low.
Resistivity of the Si-rich region can be adjusted to fit the initial composite resistivity.

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Model Description

Un-cracked

\[ R_{\text{SiC}} \]
\[ R_{\text{Si}} \]
\[ R_{\text{BN(t)}} \]
\[ R_{\text{BN}} \]
\[ R_{f} \]

\[ \leftarrow L \rightarrow \]

Cracked

\[ R_{i} \]
\[ R_{i} \]
\[ R_{\text{fu}} \]
\[ \leftarrow L \rightarrow u \rightarrow L \rightarrow \]
Model Description

- The matrix and BN circuits are broken in the crack
- The fiber will de-bond from the BN and slide over a distance $x^1$
- An interfacial resistance is introduced between the BN and fiber
- The surrounding unit cells within the distance $x^1$ will all be affected

$$x^1 = \frac{r}{2\tau} \left[ \sigma_c \frac{v_m E_m}{v_f E_c} - \sigma_f^R \right]$$

Pryce, Smith 1993

$u = \frac{\sigma^2 R}{4\tau v_f^2 E_f \left( 1 + \frac{E_f v_f}{E_m (1 - v_f)} \right)}$

Marshall, Cox, Evans 1985

8 Stress profile in the fibres for a cracked laminate at an applied stress $\sigma_c$
Model Calibration

- Acoustic emission energy is used as an estimate of crack density as a function of stress
- The model introduces cracks at incremental stress levels, according to the AE data
- The cracks are randomly distributed and the overlap length can be specified
- The resistivity of BN is determined by setting $R_i=0$ and adjusting the BN
- If the value is too high, the model will be too sensitive to cracks
- The maximum BN resistivity was chosen such that the model would never overshoot the experiment in the extreme case of $R_i=0$

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• Interfacial resistance $R_i$ is assumed to be uniform over the slip length $x^1$, but changing with stress
• It is expected that the interfacial resistance increases due to relative sliding between fiber and matrix
• We see that $R_i$ must be proportional to $\sigma^2$ to fit the experimental data

Model Results

- Sliding distance of the fiber at the crack surface is proportional to $\sigma^2$

$$u = \frac{\sigma^2 R}{4\tau v_f^2 E_f \left( 1 + \frac{E_f v_f}{E_m (1 - v_f)} \right)}$$

Marshall, Cox, Evans 1985
The difference in magnitude of Ri for the two composites is likely due to fiber roughness.
Model Results

- By using the parabolic relationship for $R_i$, the model fits the experiment for the balanced 0/90 GE pre-preg composite at 98% of the strength.
- The same parabolic function generated from the balanced composite was used to model an unbalanced 0/90 sample with 2:1 bias in the loading direction.
- The model also fit this data, which indicates that the relationship is more than a mere curve fit.
Conclusion

• Electrical resistance offers a way of monitoring damage in CMC’s
• Several factors influence the electrical properties
• A discrete model has been developed to understand the mechanisms causing electromechanical changes
• The model verifies that the interfacial resistance is a function of stress squared, consistent with fiber sliding
Future Work

Examine the effect of the following:

- $R_i$ varying along the slip length
- Fiber breaks
- Load-unload-reload
- Varying cross-section along the sample
- Temperature
- Creep
- Environment