Thermal Conductivity of High Pressure Cross Ply Carbon Fiber

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My research is focused on the materials science of these “Dees” Jim Alexander spoke about at the intro lecture.
The Apparatus & Procedure

Spring clamp to ensure equal pressure at thermal interfaces
- Resistive heating element
- Heating flux-meter made of copper with 6 thermistors
- Test material
- Cooling flux-meter
- Peltier element with water cooling

How do we mitigate convective and radiative losses from the sample?

- Ensure heat flow entering sample is equal to heat flow exiting sample. Requires tweaking heater voltage and Peltier voltage with realtime estimation of the fluxes.
- Residual difference of ~ 5% is one of the dominant uncertainties.

Six equidistant thermistors placed at the center of copper rod and sealed with adequate thermal grease to create a heat flux-meter

Contact surfaces of the flux-meter milled flat with very high tolerance

How do we eliminate contact conductance from our measurements?

- By carrying out four independent measurements with varying thicknesses of TIM
- By using the same amount of MX4 between sample and fluxmeters across all measurements
- By using the same force across all measurements
Motivation for High-pressure cross-ply K13D2U/EX1515 Measurement

Trying to improve through-plane thermal conductivity using high pressure. Unidirectional or Cross-ply?

<table>
<thead>
<tr>
<th>K13D2U+EX1515 carbon fiber composite</th>
<th>(Unidirectional)</th>
<th>(Cross-ply)</th>
<th>0.65</th>
<th>410 [7]</th>
</tr>
</thead>
<tbody>
<tr>
<td>x-axis</td>
<td>(376 ± 31)</td>
<td>(1.7 ± 0.3) · 10^{-5}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>y-axis</td>
<td>(7.5 ± 4.4)</td>
<td>(3.9 ± 3.5) · 10^{-4}</td>
<td></td>
<td>0.01</td>
</tr>
<tr>
<td>z-axis</td>
<td>(1.44 ± 0.24)</td>
<td>(1.4 ± 1.4) · 10^{-4}</td>
<td>0.44</td>
<td>0.53 [7]</td>
</tr>
<tr>
<td>z-axis (cured at 20 bar)</td>
<td>(2.79 ± 0.46)</td>
<td>(2.0 ± 9.0) · 10^{-5}</td>
<td>0.43</td>
<td>1.2 [7]</td>
</tr>
</tbody>
</table>

- K13D2U/EX1515 cured at 20 bar, unidirectional, $k = 2.8 \pm 0.5$ W/mK
- K13D2U/EX1515 cured at 20 bar, cross-ply, $k =$ ?
1. Lay up is done as a 2-inch x 6-inch slab of material
2. Debulking done for every 4 plies of lay up
3. The samples are cured in a press with environmental chamber at the recommended cure temperature at 20 bar pressure
4. Post cured as per manufacturer recommendations
5. Water jet cut into 5 discs of 1 inch diameter and same thickness
6. The 5 pucks are mounted on a flat surface using parallels and CNC machined to different thicknesses
7. The samples are cleaned using IPA and dried at 80°C for 4 hours and then sent to PSDL for measurement
Fabrication for High-pressure cross-ply K13D2U/EX1515

Micrograph for EX1515/K13D2U high pressure 20 bar cure cross ply [0/90]_ns

Sushrut Karmarkar^6
TC8_CF1

Sample ID = “TC8_CF1.” Measurements:

- Sample Thickness = 2000 ± 10 μm
- Temperature difference across the sample, $\Delta T = 13.284 \pm 0.001$ K (Uncertainty dominated by fit uncertainties)
- Heat flux through the sample, $I = 8.5 \pm 0.4$ W (Uncertainty dominated by heat balancing accuracy)

We infer the total thermal resistance: $R_{TC8\_CF1} = \frac{\Delta T}{I} = 1.57 \pm 0.08$ K/W
Sample ID = “TC8_CF2.” Measurements:

- Sample Thickness = 2450 ± 10 μm
- Temperature difference across the sample, $\Delta T = 16.2122 \pm 0.001$ K (Uncertainty dominated by fit uncertainties)
- Heat flux through the sample, $I = 8.6 \pm 0.5$ W (Uncertainty dominated by heat balancing accuracy)

We infer the total thermal resistance: $R_{TC8\_CF2} = \Delta T/I = 1.9 \pm 0.1$ K/W
Sample ID = “TC8_CF3.” Measurements:

- Sample Thickness = 2750 ± 10 μm
- Temperature difference across the sample, $\Delta T = 16.011 \pm 0.001$ K (Uncertainty dominated by fit uncertainties)
- Heat flux through the sample, $I = 8.4 \pm 0.3$ W (Uncertainty dominated by heat balancing accuracy)

We infer the total thermal resistance: $R_{TC8\_CF3} = \Delta T/I = 1.92 \pm 0.08$ K/W
Sample ID = “TC8_CF4.” Measurements:
- Sample Thickness = 3020 ± 10 μm
- Temperature difference across the sample, $\Delta T = 20.354 \pm 0.001$ K (Uncertainty dominated by fit uncertainties)
- Heat flux through the sample, $I = 8.99 \pm 0.09$ W (Uncertainty dominated by heat balancing accuracy)

We infer the total thermal resistance: $R_{TC8\_CF4} = \Delta T/I = 2.26 \pm 0.02$ K/W
Sample ID = “TC8_CF5.” Measurements:

- Sample Thickness = 3300 ± 40 μm
- Temperature difference across the sample, $\Delta T = 21.630 \pm 0.002$ K (Uncertainty dominated by fit uncertainties)
- Heat flux through the sample, $I = 9.42 \pm 0.07$ W (Uncertainty dominated by heat balancing accuracy)

We infer the total thermal resistance: $R_{TC8\_CF5} = \Delta T/I = 2.30 \pm 0.02$ K/W
Result: High-pressure cross-ply K13D2U/EX1515

Cross-ply layup does increase through-plane thermal conductivity compared to unidirectional layups in high-pressure cures of carbon fiber pre-preg.

$k_{\text{Undirectional}} = 2.8 \pm 0.5 \text{ W/mK}$

$k_{\text{Cross-Ply}} = 3.9 \pm 0.5 \text{ W/mK}$