Utilizing Recycled Carbon Fiber-Based Composites for Sustainable Manufacturing

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Carbon Fiber Composites are Becoming More Cost Effective

<table>
<thead>
<tr>
<th>Advanced Software Tools</th>
<th>Affordable Precursors</th>
<th>Production Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation tools</td>
<td>Textile grade PAN</td>
<td>Automation</td>
</tr>
<tr>
<td>Cost modeling</td>
<td>Lignin based</td>
<td>Faster cycle times</td>
</tr>
<tr>
<td>Design integrated</td>
<td>Polyolefin based</td>
<td>Out of autoclave</td>
</tr>
<tr>
<td>manufacturing simulation</td>
<td>Recycled CF</td>
<td>processes</td>
</tr>
</tbody>
</table>

As the price of carbon fiber (CF) decreases, the demand of CF will increase

Can create less stability on CF supply chain
Stabilizing Carbon Fiber Supply Chains for OEMs

How can OEMs stabilize their own CF supply chains?

Replace CF with an alternative reinforcing filler

- Glass Fibers
- Aramid Fibers
- Natural Fibers

Utilize recycled content

- Recycled feedstocks
  - End of Life part
  - Mechanical Recycling
  - Recycled material

- Recycled CF
  - CF composites
  - Pyrolysis

Goal: Implement Strategies without Sacrificing Mechanical Performance
Replacing CF Content with Alternative Fiber

**Base CF Composite**
Polyamide-6,6’ (PA66) + 40wt% CF

**Example CF-base Composite**
Polyamide-6,6’ (PA66) + 30wt% CF + 10wt% Alternative Fiber (XF)

Substitute some portion of CF content with alternative fiber

**Effect of Substituting 10wt% of CF Content**
- Decrease in tensile modulus
- Relatively consistent strength
- Substitution ratio depends on application and replacement fiber type

![Tensile Modulus and Strength Graph](chart.png)
Utilizing Mechanically Recycled Content

- Reinforcing Fillers
- Compounding
  - Polymer Matrix
  - Injection Molding
  - Compression Molding
  - Additive Manufacturing
- Processing Technique
- Mechanical Recycling
  - Processing Technique
  - Injection Molding
  - Compression Molding
  - Additive Manufacturing
- Virgin Material
Considerations When Determining Mechanical Properties of Recycled Materials

What are the mechanisms that cause mechanical properties to change?

Potential Mechanisms

1) Loss in Fiber Content
2) Fiber Length Attrition
3) Polymer Degradation

* Processing/Recycling * Pathway Dependent

### How do mechanical properties change with respect to amount of recycled content?

<table>
<thead>
<tr>
<th>Recycled Material</th>
<th>Virgin Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>100%</td>
</tr>
<tr>
<td>33%</td>
<td>67%</td>
</tr>
<tr>
<td>67%</td>
<td>33%</td>
</tr>
<tr>
<td>100%</td>
<td>0%</td>
</tr>
</tbody>
</table>

* Processing/Recycling * Pathway Dependent
Where Mechanisms Occur During Processing/Recycling

- CF + AltF

Compounding

- PA66

Processing Technique (Injection Molding)

- Fiber length attrition
- PA66 degradation

Mechanical Recycling (Shredding and Granulating)

- Loss of Fiber Content

Processing Technique (Injection Molding)

- Fiber length attrition
- PA66 degradation
Case Study for Recycling of PA66/30CF/10AltF

Virgin Pellet Material

Injection Molding

Dogbones (0% Recycled)

Testing And Analysis

Thermal Polymer Structure Fiber Length

Shredding/Granulating

Recycled Material

Testing And Analysis

Thermal Polymer Structure Tensile Fiber Length

Injection Molding

Dogbones (33%, 67%, 100% Recycled)

Dry Blend

Testing And Analysis

Thermal Polymer Structure Tensile Fiber Length

Scrap

Recycled Material

OR

Virgin Pellet Material

4mm

3d-tulostus.fi
Mechanical Characterization of Recycled PA66/30CF/10AltF

- Tensile strength and tensile modulus decreased as recycled content percent increased
- What Mechanisms are causing a reduction in mechanical properties?

Knock Down Factor (KDF)

\[ KDF = \left(1 - \frac{P_r}{P_v}\right) \times 100 \]

- \( P_r \) - average property value of material with recycled content
- \( P_v \) - average property value of material with 0% recycled content

<table>
<thead>
<tr>
<th>Recycled Content</th>
<th>Strength (MPa)</th>
<th>Strength KDF (%)</th>
<th>Modulus (GPa)</th>
<th>Modulus KDF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>221.2 ± 4.82</td>
<td>0</td>
<td>22.7 ± 1.26</td>
<td>0</td>
</tr>
<tr>
<td>33%</td>
<td>207.2 ± 6.90</td>
<td>6.3</td>
<td>21.3 ± 0.66</td>
<td>6.2</td>
</tr>
<tr>
<td>67%</td>
<td>195.7 ± 3.57</td>
<td>11.6</td>
<td>21.3 ± 1.69</td>
<td>6.2</td>
</tr>
<tr>
<td>100%</td>
<td>181.3 ± 9.35</td>
<td>18</td>
<td>19.8 ± 0.41</td>
<td>12.7</td>
</tr>
</tbody>
</table>

Adding fibers (compounding) reduces crystallinity and increased crystallization temperature.

Processing pathway has no effect on melting temperature.

PA66 crystallinity not a factor in reduction of mechanical properties.

Differential Scanning Calorimetry:
1) Heat to 300°C at 10 °C/min
2) Cool to 30°C at 5 °C/min
Assessing Loss in Fiber Content Along Processing Pathway

**Thermogravimetric Analysis:**
- Heat to 600°C at 10°C/min in argon
- Processing pathway reduces degradation temperature
- Fiber content remains relatively consistent
- Loss of fiber content not likely a mechanism for reduction in mechanical properties
Assessing Fiber Length Attrition Along Processing/Recycling Pathway

- Virgin Pellets have broader distribution
- Fiber length stabilizes after recycling
- Fiber length attrition not likely a mechanism for reduction in mechanical properties
Assessing Polymer Degradation Along Processing/Recycling Pathway

Nuclear magnetic resonance (NMR) used to determine any PA66 degradation.

Peaks at 169 ppm in $^{13}$C spectra and 8.88 ppm in $^1$H for 100% recycled sample indicates degradation.
## Processing/Recycling Steps That Affect Mechanical Properties

<table>
<thead>
<tr>
<th>Processing/Recycling Steps</th>
<th>Loss in Fiber Content</th>
<th>Fiber Length Attrition</th>
<th>Polymer Degradation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential Causes</td>
<td>None</td>
<td>Injection Molding</td>
<td>Injection Molding</td>
</tr>
<tr>
<td>Considerations</td>
<td>N/A</td>
<td>High Shear Forces</td>
<td>High Shear Forces High Temperatures</td>
</tr>
</tbody>
</table>

### Processing/Recycling Steps
- **Injection Molding**
- **Injection Molding**
- **Injection Molding**
- **Injection Molding**
- **Injection Molding**

### Potential Causes
- **N/A**
- **High Shear Forces**
- **Initial fiber lengths**
- **Processing method and parameter selection**

### Considerations
- **Dust generation in scale-up**
- **Initial fiber lengths**
- **Processing method and parameter selection**

### Processing Method and Parameter Selection
- **Processing method and parameter selection**

### Fiber Length Attrition

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Frequency</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cycle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 cycles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 cycles</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fiber Length</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 μm</td>
<td></td>
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</tbody>
</table>

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**compositesworld.com**

**indiamart.com**
Conclusions and Future Work

Conclusions:
• Although recycling reduced the tensile strength and modulus, the decrease was not dramatic
• Loss of fiber content and fiber length attrition did not cause mechanical property reduction
• Polymer degradation is likely the cause for the decrease in mechanical properties
• The selected processing/recycling pathway directly affects mechanical properties when utilizing recycled material

Future Work:
• Determine which processing step(s) is causing polymer degradation
• What impact does the 10wt% AltF have on the mechanical performance when utilizing recycled material?
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