Material Properties of Injection Molded Glass and Carbon Fiber Reinforced Thermoplastic Composites – A Review

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Mark Cieslinski, BASF - Advanced Materials & Systems Research
Outline

1 About BASF

2 Why Composites?

3 What Influences Composite Properties?

4 Summary

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1 About BASF

2 Why Composites?

3 What Influences Composite Properties?

4 Summary
BASF – We create chemistry

- Our chemistry is used in almost all industries
- We combine economic success, social responsibility and environmental protection
- Sales 2015: €70,449 million
- EBIT 2015: €6,739 million
- Employees (as of December 31, 2015): 112,435
- 6 Verbund sites and 376 other production sites
Research and development at a glance

Research for the future: With our innovative products and processes, we provide sustainable solutions for global challenges.

- Expenditures for research and development €1,953 million, world leader in chemical industry
- Around 3,000 research projects
- Strongest innovation power in the chemical industry (No.1 in the Patent Asset Index™)
- Target 2015 achieved: around €10 billion sales with new and improved products or applications that had been on the market since 2011
Advanced Materials & Systems: Global research Verbund

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Metal replacement: comparison with engineering plastics compounds

Steel and Al-alloys: Data taken from Hütte (1996)

<table>
<thead>
<tr>
<th>Material</th>
<th>( \rho ) g/cm³</th>
<th>( T_m ) °C</th>
<th>E GPa</th>
<th>( \sigma ) MPa</th>
<th>( K_{IC} ) MN/m³²</th>
<th>( \lambda ) W/mK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel (ferritic, austenitic)</td>
<td>7.8</td>
<td>1150 (FeC4)</td>
<td>195 - 210</td>
<td>440 - 750</td>
<td>50 - 200</td>
<td>30 - 60</td>
</tr>
<tr>
<td>Steel (High-strength)</td>
<td>7.8</td>
<td>-</td>
<td>195 - 210</td>
<td>1300 - 2100</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Al alloys</td>
<td>2.7</td>
<td>577 (AlSi12)</td>
<td>60 - 80</td>
<td>300 - 700</td>
<td>23 - 45</td>
<td>121 - 237</td>
</tr>
<tr>
<td>PA66 GF50 (23 °C, dry conditions)</td>
<td>1.56</td>
<td>260</td>
<td>16.8</td>
<td>240</td>
<td>5 - 10</td>
<td>(~ 0.5)</td>
</tr>
</tbody>
</table>

- Low density even for highly glass fiber filled PA compound is advantageous
- Tensile strength of PA compound is high and comparable to “soft“ Al alloys
- Stiffness and fracture toughness as well as melting point and thermal conductivity much lower compared to metals

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Specific tensile strength & stiffness of PA66 compounds

- Specific tensile strength of highly GF-filled PA compounds similar to Al-alloys and higher than steel
- Specific stiffness of PA/GF compounds further enhanced by carbon fibers

Comparison of glass & carbon fibers

- Specific tensile strength
- Specific stiffness

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Question: What injection molding material do we use for our application?

- Short or Long fiber?
- Glass or Carbon fiber?
- Resin?

How do these variables transfer to mechanical properties?

- Modulus
- Strength
- Impact
- Fatigue
Designations of Fiber Lengths

- **Short fibers** – incorporated into thermoplastic via extrusion compounding, typical average fiber length < 0.5 mm
- **Long fibers** – composites retain fiber length in molded part > 1.0 mm, pultrusion or wet-lay processes are used
- Extrusion/Injection molding reduces fiber length to a log-normal distribution, described by:
  - Number average fiber length, \( L_n = \frac{\sum N_i L_i}{\sum N_i} \)
  - Weight average fiber length, \( L_w = \frac{\sum N_i L_i^2}{\sum N_i L_i} \)
  - Aspect Ratio = \( \frac{\text{Length}}{\text{Diameter}} \)
Fiber Length Trends

Modulus – Cox model
Strength – Kelly-Tyson Model
Impact – Thomason-Vlug model

10-40 wt% glass – Polypropylene produced via wet-lay process
Normalization trend appears independent of concentration for Flexural and Tensile data


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Injection Molded Composites  
Long Glass Fiber - Polypropylene

Fiber length decreases with increasing concentration

Modulus linearly increasing with concentration (except >65wt%)

### Ultramid® Polyamide Glass Fiber Materials

#### Modulus

<table>
<thead>
<tr>
<th>Material</th>
<th>15% Short Glass</th>
<th>25% Short Glass</th>
<th>30% Short Glass</th>
<th>35% Short Glass</th>
<th>40% Short Glass</th>
<th>50% Short Glass</th>
<th>40% Long Glass</th>
<th>50% Long Glass</th>
<th>60% Long Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA66</td>
<td>15</td>
<td>25</td>
<td>30</td>
<td>35</td>
<td>40</td>
<td>50</td>
<td>40</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>Ultradim® A</td>
<td>15</td>
<td>25</td>
<td>30</td>
<td>35</td>
<td>40</td>
<td>50</td>
<td>40</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>Ultradim® B</td>
<td>15</td>
<td>25</td>
<td>30</td>
<td>35</td>
<td>40</td>
<td>50</td>
<td>40</td>
<td>50</td>
<td>60</td>
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#### Strength

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<td>50</td>
<td>60</td>
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</tbody>
</table>

**Parallel trends in flexural and tensile moduli and strength**

**Modulus independent of fiber lengths in test specimens**

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Ultramid® Impact properties

Ultramid® A

Ultramid® B

Long fiber advantage → Impact performance

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Short/Long Creep Performance
Ultramid® A - 50% glass fiber

Creep performance differences more pronounced at higher time scales and higher loadings
Fatigue Behavior

Short Glass Fibers

- Parallel to Flow Direction in Injection Molded Plaque
- Fracture Toughness

Increasing fiber content increases toughness while inhibiting crack growth

Short & Long Glass Fibers

- Ultramid® A 50% glass fiber

Fatigue performance extend due to long fibers creating a fiber network

### Fiber Diameter Effects (PA66-30wt% glass)

<table>
<thead>
<tr>
<th>Fiber Diameter, µm</th>
<th>Average Length</th>
<th>Average Aspect Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ln, mm</td>
<td>Lw, mm</td>
</tr>
<tr>
<td>10</td>
<td>0.34</td>
<td>0.55</td>
</tr>
<tr>
<td>11</td>
<td>0.4</td>
<td>0.65</td>
</tr>
<tr>
<td>14</td>
<td>0.49</td>
<td>0.73</td>
</tr>
<tr>
<td>17</td>
<td>0.56</td>
<td>0.79</td>
</tr>
</tbody>
</table>

**Strength** – some decrease (14%)

**Modulus** – no change (2%)

**Notched Impact** – slight increase (7%)

**Unnotched Impact** – significant decrease (72%)

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Ultramid® A3W - 40 wt% Short/Long, Glass/Carbon Fiber

Typical properties of glass and Carbon fiber

<table>
<thead>
<tr>
<th></th>
<th>Glass</th>
<th>Carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, g/cm³</td>
<td>2.5 – 2.6</td>
<td>1.7 – 1.8</td>
</tr>
<tr>
<td>Tensile Modulus, GPa</td>
<td>70 – 80</td>
<td>225 – 275</td>
</tr>
<tr>
<td>Tensile Strength, GPa</td>
<td>1.5 – 3.5</td>
<td>2.5 – 5</td>
</tr>
<tr>
<td>Elongation at Break, %</td>
<td>0.5 – 2</td>
<td>1.8 – 3.2</td>
</tr>
</tbody>
</table>
Relative specific properties to 40% Short Glass Fiber – Ultramid® A

Advantages of carbon fiber become more pronounced for light-weighting applications.

Long glass fiber impact properties not as significant improvement.

Specific [Property] = \frac{[Property]}{Composite Density}
Glass and carbon fiber at equal volume% in polypropylene

<table>
<thead>
<tr>
<th>Property</th>
<th>Carbon</th>
<th>Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter, µm</td>
<td>7.5</td>
<td>13.8</td>
</tr>
<tr>
<td>Tensile Strength, MPa</td>
<td>3950</td>
<td>1956</td>
</tr>
<tr>
<td>Tensile Modulus, GPa</td>
<td>238</td>
<td>78.5</td>
</tr>
</tbody>
</table>

Stiffness – translated from fiber properties
Strength & Impact – less driven by fiber properties more likely aspect ratio & sizing


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Fiber network from long fibers improves modulus at elevated temperatures
Resin Formulation - Ultramid® A

General trends of property improvement with concentration appear to be universal

Some additives necessary for the end-use application can negatively effect properties
## General Summary

<table>
<thead>
<tr>
<th>Property</th>
<th>Modulus</th>
<th>Strength</th>
<th>Strain at Break</th>
<th>Notched Impact</th>
<th>Creep</th>
<th>Fatigue</th>
<th>Performance at Higher Temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase Concentration</td>
<td>🔺</td>
<td>🔺</td>
<td>🔻</td>
<td>🔺</td>
<td>🔺</td>
<td>🔺</td>
<td>🔺</td>
</tr>
<tr>
<td>Increase Fiber Length</td>
<td>-</td>
<td>🔺</td>
<td>🔻</td>
<td>🔺</td>
<td>🔺</td>
<td>🔺</td>
<td>🔺</td>
</tr>
<tr>
<td>Carbon Fiber (relative to glass)</td>
<td>🔺</td>
<td>🔺</td>
<td>🔻</td>
<td>-</td>
<td>🔺</td>
<td>🔺</td>
<td>🔺</td>
</tr>
</tbody>
</table>

*Concentration, length and fiber type are not completely independent variables*

Properties in the end-use part are largely influenced by **processing**:
- Fiber Orientation
- Fiber Length (aspect ratio)
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