What's the Difference: Thermoset vs. Thermoplastic Carbon Fiber Composites?

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Presented by Allan James

With thanks to Pete Cate, Dave Bank, Rainer Koeniger, Mike Malanga, Jay Tudor, Jin Wang
Dow Automotive Systems

- A leading global provider of advanced material solutions, making vehicles lighter, safer, stronger, quieter and more comfortable

The Dow Chemical Company
- More than 5,000 products manufactured at 188 sites in 36 countries
- Selling to customers in 160 countries
- 6500 R&D staff globally
Thermoplastics & Thermosets

- Thermoplastics and thermosets are structurally different

**Amorphous Thermoplastics**
Molecular chains held together by weak van der Waals forces or by hydrogen bonds which reduce strength and stiffness with temperature, and cause the material to creep under load

**Polyamide**
Crystalline molecular groups connected by amorphous chains (which undergo changes at Tg), along with van der Waals forces or hydrogen bonds

**Epoxy**
Cross-linked molecular structure held together with strong covalent bonds, creating rigid, thermally-stable, creep-resistant materials which maintain strength and stiffness very well

**Semi-crystalline Thermoplastics**
Crystal lamella

**Thermosets**
Cross link

- **ABS**
- **Polyamide**
- **Epoxy**
Fibre Polymer Interface Detail

- The interaction between the polymer and the fibre determines the stability of the composite construction

Semi-Crystalline Polymers
- Fiber sizing reacts with **amorphous** region of the polymer to create the interface
- Amorphous regions are highly affected by changes in temperature, reducing interfacial strength and lateral stiffness between fibres

Thermosetting Polymers
- Fiber sizing reacts directly with the **epoxy network**, creating strong covalent bonds at the interface
- The cross linked network is rigid, and relatively unaffected by changes in temperature resulting in a more consistent structural performance
The Importance of Low Matrix Material Viscosity

- Excellent wet-out of the carbon fibre tows within the fibre weave is key to a strong, durable composite

Matrix Material Processing Viscosity Comparison

- RTM Epoxy: ~10 mPa.sec
- Polyamide 6 melt: 100,000-200,000 mPa.sec
Matrix Material Function in the Composite

- Structural composites must undergo a variety of short- and long-term load cases, generating interfacial forces which are managed by the polymer matrix material.

**Compressive Forces**
Matrix material must laterally support fibres and help to prevent fibre buckling.

**Shear Forces**
Matrix material must limit inter-laminar shear to preserve composite stiffness.

**Tensile Forces**
Matrix material must laterally connect fibres to prevent composite delamination.
Structural Composite Applications

- Different vehicle applications require different material properties

**Stiffness/Strength Relevance of Automotive Components**

Materials must maintain stiffness and strength over thermal / moisture / aging cycle

Original Source: “Stiffness Relevance and Strength Relevance in Crash of Car Body Components,” European Aluminum Association, May 2010
Thermal Stability of Different Polymer Types

- Thermal performance requirements of the application will influence response to load cases, and thus drive polymer choice.

![Graph showing thermal stability of different polymer types.](image)

- **Tg Epoxy** can be tuned via formulation.

Modulus (GPa) vs Temperature (°C)

Data source example: “Moisture absorption in polyamide-6...” by Vlasfeld, Groenewold, Bersee & Picken

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Thermal Stability of Different Polymer Types

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![Graph showing thermal stability of different polymer types.](image)

- Epoxy dry
- Semi-crystalline thermoplastic PA6 dry

PA6 Data source example: “Moisture absorption in polyamide-6...” by Vlasfeld, Groenewold, Bersee & Picken
Demo Part Simulation – Temperature Effect

• Comparison of short Carbon Fibre Epoxy and Polyamide 6 composites in a roof bow, showing overdesign required to achieve same stiffness at 80°C

Exterior Roof Panel

Roof Bows

Static loads

6 d.o.f. constrained

Thickness Increase Required to accommodate Modulus Loss at 80°C

Front Roof Bow

<table>
<thead>
<tr>
<th>Thickness Increase</th>
<th>CF Epoxy</th>
<th>CF PA6 Nylon</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20%</td>
<td></td>
<td></td>
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<tr>
<td>40%</td>
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<tr>
<td>60%</td>
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</tbody>
</table>

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Moisture Stability of Composites

• Typical structural automotive application conditions also involve moisture exposure to varying degrees

![Graph showing water absorption vs. water soak time](image)

Significant moisture absorption is an indication of property change in the matrix polymer and ultimately in the final composite, across the required temperature range.

PA6 Data sources: Vlasfeld, Bersee & Picken; BASF; Dupont

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Polymer Property Change after Moisture Exposure

- To predict composite performance, it is critical to understand the increase or decrease of all relevant matrix polymer properties as a result of exposure to application conditions.

Changes in stiffness and strength are typically addressed by proportional overdesign of the composite.
Demo Part Simulation – Moisture Conditioning Effect

- Short Carbon Fibre Epoxy and Polyamide 6 roof bow application, with overdesign to achieve same stiffness at 25°C after humidity exposure*

![Diagram of Exterior Roof Panel and Static loads]

**Thickness Increase Required at Room Temperature to accommodate Modulus Loss after 22hrs 90°C Moisture Exposure**

- Front Roof Bow
- Middle Roof Bow
- Rear Roof Bow

* 22hrs water immersion at 90°C, then tested at 25°C

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Moisture & Temperature Combination

• Typical automotive application conditions involve combined exposure to both temperature and moisture
Moisture & Temperature Combination

- Typical automotive application conditions involve combined exposure to both temperature and moisture

![Graph showing Modulus (GPa) vs. Temperature (°C)]

- Epoxy dry
- Epoxy wet
- Semi-crystalline thermoplastic PA6 dry
- Semi-crystalline thermoplastic PA6 wet

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Moisture & Temperature Combination

- Typical automotive application conditions involve combined exposure to both temperature and moisture.

Note: as carbon fibre reinforcement is added, the stiffness loss is reduced, down to <25% in high wt% continuous carbon fibre PA6 composites...

...and <5% in high wt% continuous carbon fibre Epoxy composites.
Component Cost & Mass Comparison

- Cost and Mass analysis including overdesign to accommodate composite stiffness decline at 80°C after 22hrs moisture exposure.

Cost Model Output for a Benchmark Carbon Fibre Composite Component

<table>
<thead>
<tr>
<th>Carbon Fibre Content and Format</th>
<th>Composite Material Cost*</th>
<th>Composite Material Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 wt%</td>
<td>CF Epoxy Composite Material</td>
<td>CF PA6 Composite Material</td>
</tr>
<tr>
<td>40wt% Chopped</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60wt% Woven</td>
<td></td>
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</tr>
</tbody>
</table>

Cost increases more for PA6 than Epoxy as overdesign adds more carbon fibre.

Original part mass before overdesign.

* Materials only. Processing cost analysis shows further disadvantage for PA6 due to high processing temperatures versus ultra-fast epoxy systems.

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So Why Thermoplastics?

• Traditionally Thermoplastics have been perceived to offer advantages of:
  - Lower cost polymers
  - Faster processing
  - Recyclability

• Advanced Thermoset epoxy chemistry and processing techniques are now:
  - Cost competitive in the final composite (by optimising carbon fibre utilization)
  - Fast enough to compete favourably with mid to high wt% carbon-fibre thermoplastics
  - Efficiently recyclable enabling recovery of high-value usable carbon fiber
Conclusion: ThermoSets The Benchmark

- After optimising cycle time to match volume targets, the key to competitive structural composites is to reduce the utilization of carbon fibre, as it is the most costly component.

**PRICE**

**MINIMISE CARBON FIBRE UTILIZATION!**

**PROCESSING**

Ensure low (~10mPa.sec) viscosity for excellent fiber wet out and maximum interfacial strength; accelerate demold times to <2mins and avoid high temperature processing.

**PERFORMANCE**

Ensure consistent mechanical performance (stiffness and strength) over temperature and humidity range, and sufficient chemical resistance for the application.
THANK YOU FOR YOUR ATTENTION!

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