UD Prepregs for Load Carrying Structures in Infused Blades

A presentation by Dr Chris Shennan
R&T Manager
Hexcel Corporation
Agenda

- Introduction to Hexcel in Wind Energy
- Prepreg and infusion technologies
- Combinations of prepreg and infusion
- Examples
  - Prepregs in thick laminates
  - Comparison of mechanical properties from prepreg and infusion
  - Case study – large scale trial
- Conclusions
Introduction to Hexcel in Wind Energy
**Hexcel: Company Profile**

- Leading global provider of advanced composites
- Primary markets: aerospace, defence and wind energy
- Net Sales of $1.108 billion in 2009
- 4,000 employees worldwide
- Headquarters in Stamford, CT, USA
- Listed on NYSE
- Manufacturing in nine countries, 18 locations
Hexcel - Vertically Integrated

<table>
<thead>
<tr>
<th>Key RM</th>
<th>Technologies</th>
<th>Applications</th>
<th>Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylonitrile</td>
<td>Carbon Fiber</td>
<td>Carbon Fiber for Prepregs reinforcements for aerospace, wind blades,</td>
<td>Prepregs, Honeycomb Core Block, Resin Systems</td>
</tr>
<tr>
<td></td>
<td></td>
<td>recreation, and infrastructure</td>
<td>for wide range of products</td>
</tr>
<tr>
<td>Aramid Fiber</td>
<td>Reinforcements</td>
<td>Reinfomercement for composites (RFC)</td>
<td>Component assemblies</td>
</tr>
<tr>
<td>Carbon Fiber</td>
<td></td>
<td></td>
<td>for aerospace</td>
</tr>
<tr>
<td>Glass Fiber</td>
<td></td>
<td></td>
<td>HexMC Parts, Shaped/Machined Core</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Composites</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aramid Paper</td>
<td>Prepreg</td>
<td></td>
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<tr>
<td>Carbon Fiber</td>
<td>Honeycomb</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glass Fiber</td>
<td>Structures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resins</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
Hexcel in Global Wind Energy

- Market Leader for prepreg materials in Wind Energy
- More than 65000 tons of prepreg products supplied since early 1990s
- Global Supply, Sales, Technical Support and R&T
- Product development in close cooperation with key accounts

New plant for wind energy at Windsor, Colorado 2009
Infusion and Prepreg Technologies

What are prepregs?
How do prepreg and infusion processes compare?
Impregnation of Fibre and Fabrics from Resin

Prepreg production is now highly industrialised for optimum cost and quality.
Typical Prepreg Systems in Wind Energy

- **Resin systems**
  - M9 290 J/g
  - M9F 250 J/g
  - M19 190 J/g

- **Product forms (UD)**
  - Carbon 500-600 gsm
  - Glass 1000-3000 gsm

- **Cure cycles (ramps, dwells + cure times)**
  - ~4 (M19) to ~8 (M9) hours when optimised

- **Storage at +5°C (6 month shelf life)**

Typical prepregs combine high areal weights, full impregnation, and low reaction enthalpies.
Prepreg and Infusion in Wind Energy

Worldwide Cumulative MW Installed
160,000 total (2009)

The split between prepreg and infusion for blade manufacture is similar
### Blade technology: Infusion versus Prepreg

<table>
<thead>
<tr>
<th></th>
<th>Infusion</th>
<th>Prepreg</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Raw Material Cost</strong></td>
<td>€/kg ~ 3.0 (resin + glass NCF)</td>
<td>€/kg UD: 2.8 to 3.3/ Glass NCF ~ 4.0</td>
</tr>
<tr>
<td></td>
<td>Foam: 1600</td>
<td>Foam: 1800</td>
</tr>
<tr>
<td><strong>Tooling Cost</strong></td>
<td>++</td>
<td>- -</td>
</tr>
<tr>
<td><strong>Capex Requirements</strong></td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td><strong>Layup</strong></td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td><strong>Cure Cycle</strong></td>
<td>- Up to 20 hours</td>
<td>+ Up to 10 hours</td>
</tr>
<tr>
<td><strong>Blade Finishing</strong></td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td><strong>Health &amp; Safety</strong></td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td><strong>Waste &amp; Scrap</strong></td>
<td>- -</td>
<td>-</td>
</tr>
<tr>
<td><strong>Throughput &amp; Quality Control</strong></td>
<td>- -</td>
<td>++</td>
</tr>
<tr>
<td><strong>Mechanical Performance</strong></td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>

Both technologies have their pros and cons.
Why not combine Prepreg and Infusion Technologies?
Combinations of Prepreg and Infusion Technologies

Proposal
Use prepreg in load critical structures (spar caps or girders)

Benefits
Full impregnation (even in thickest structures, even with carbon)
Choice of chemistry (reaction enthalpy) to suit cycle
Low exotherm

Benefits (to be demonstrated)
Low porosity in laminate
Fast cure cycle
Maximum mechanical properties from pure UD
Combinations of Prepreg and Infusion Technologies

Three examples

1. Prepregs in thick laminates
2. Comparison of mechanical properties from prepreg and infusion
3. Case Study: Large scale trial of prepreg in a spar cap
Prepregs in Thick Laminates

Example 1
Cure Cycles Using Low Exotherm Prepregs

M(1)9.1/32%/1200/G

5 plies \{\text{Dry BB450}\} \times 10

60 prepreg plies
11 biax layers
\sim 6 \text{ cm thick}
Cure Cycles: Layup Configuration

**Thermocouples**

Top
Middle
Bottom
Left
Middle
Right

After cure

Vacuum bag
Bleeder (2 plies)
Perforated film (P3)
Peel ply
Prepreg stack
**Cure Cycles: Results**

<table>
<thead>
<tr>
<th></th>
<th>Tool surface</th>
<th>In the middle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum temperature (°C)</td>
<td>M9.1 125</td>
<td>M19.1 112</td>
</tr>
<tr>
<td></td>
<td>M9.1 166</td>
<td>M19.1 138</td>
</tr>
<tr>
<td>Exotherm after (hours)</td>
<td>4</td>
<td>6</td>
</tr>
</tbody>
</table>

Peak exotherm can be reduced by optimisation of matrix and cure cycle.

Cure cycles not optimised.
Low Porosity in Thick Laminates

4 plies

9 plies

X 5

Dry BB600

M9.6F/32%/1600+CV/G

53 prepreg plies

6 biax layers

~ 6 cm thick
Very low porosities can be achieved with standard prepregs even in thick laminates

<table>
<thead>
<tr>
<th>Fiber volume (%)</th>
<th>Air content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>51,9</td>
<td>0,2</td>
</tr>
</tbody>
</table>
Comparison of Mechanical Properties from Prepreg and Infusion

Example 2
Mechanical Evaluation - Overview

Prepreg panel cured at 100°C

Mechanical comparison

Infusion panel cured at 100°C

Reference prepreg panel cured at 120°C under pressure (gives ultimate performance)

<table>
<thead>
<tr>
<th>Test</th>
<th>Plies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile 0°</td>
<td>2</td>
</tr>
<tr>
<td>Tensile 90°</td>
<td>2</td>
</tr>
<tr>
<td>Compression 0°</td>
<td>4</td>
</tr>
<tr>
<td>ILSS/ SBS</td>
<td>2</td>
</tr>
<tr>
<td>IPS</td>
<td>2</td>
</tr>
</tbody>
</table>
Mechanical Evaluation - Trial Layup

**Top view**
- 1300 mm
- 1700 mm
- 1000 mm
- 4 Plies
- 2 Plies
- 2 Plies
- 1000 mm

**Side view**
- TC Air temp
- 0°
- 90°
- TC

Sandia 210710
Mechanical Evaluation - Trials

Infusion:
- Reinforcement: LT1218 (stitched UD)
- Resin: Hexion RIM 135

Prepreg:
- M9.1/32%/1200/G

Prepreg and infusion panels given the same cure of 6 hours at 100°C
Mechanical Evaluation – Reference

→ M9.1/32%/1200/G
→ 8 bars
→ Cure cycle:

Defines ultimate performance of prepreg
# Mechanical Evaluation: Results

## Panel Characterisation:

<table>
<thead>
<tr>
<th></th>
<th>Reference</th>
<th>Prepreg</th>
<th>Infusion</th>
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</thead>
<tbody>
<tr>
<td>Fiber volume (%)</td>
<td>70,1</td>
<td>65,3</td>
<td>58,9</td>
</tr>
<tr>
<td>Air volume (%)</td>
<td>0</td>
<td>1.55</td>
<td>1.45</td>
</tr>
<tr>
<td>Tg (DSC) (°C)</td>
<td>127,1</td>
<td>124,8</td>
<td>74,2</td>
</tr>
</tbody>
</table>

## Mechanical results:

<table>
<thead>
<tr>
<th>Test</th>
<th>Standard test method</th>
<th>Plies</th>
<th>Prepreg reference</th>
<th>Prepreg</th>
<th>Infusion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Strength (MPa)</td>
<td>Modulus (GPa)</td>
<td>Strength (MPa)</td>
</tr>
<tr>
<td>Tensile 0° *</td>
<td>EN ISO 527</td>
<td>2</td>
<td>1241</td>
<td>48.7</td>
<td>1109</td>
</tr>
<tr>
<td>Tensile 90°</td>
<td></td>
<td>2</td>
<td>48</td>
<td>16.9</td>
<td>28.93</td>
</tr>
<tr>
<td>Compression 0° *</td>
<td>ISO 14126</td>
<td>2</td>
<td>1144</td>
<td>51.8</td>
<td>771.3</td>
</tr>
<tr>
<td>ILSS/ SBS</td>
<td>ISO 14130</td>
<td>4</td>
<td>75.3</td>
<td>53.4</td>
<td>51.7</td>
</tr>
<tr>
<td>Flexural 0° *</td>
<td>ISO 14125</td>
<td>4</td>
<td>1557</td>
<td>42.7</td>
<td>1315</td>
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<tr>
<td>IPS</td>
<td>EN 6031</td>
<td>2</td>
<td>45.1</td>
<td>6.4</td>
<td>36.5</td>
</tr>
</tbody>
</table>

* normalised to FV=60%

100MPa = 14.5ksi
Prepreg consistently delivers superior mechanical performance.
Case Study
Large Scale Trial of Prepreg in a Spar Cap

Example 3
Use of Prepreg for Spar Cap Construction

Pre-cured spar cap infused to form the complete shell
Case Study: Carbon Girder at Half Scale

Carbon spar cap length 25 m
Carbon spar cap width 0.40 m
Carbon spar cap thickness 22 mm
Number of plies 43
Material M9.6/32%/500 + 8P/C

UD prepregs are ideally suited to automated layup
Case Study: Results

Spar cap Tg 106°C
Average porosity 0,24 %
Highest porosity value 0,8 % (1 point out of 135)
Lowest porosity value 0 % (19 points out of 135)
Resin content 30 %

Typical cross section of cured laminate

Porosity level 0,27 %

Cohesive break

Good adhesion of infused glass on prepreg carbon laminate
Conclusions

- Typical prepregs in wind energy combine high areal weights, full impregnation and low enthalpy

- These result in the following:
  - Fast lay down of heavy weight structures, ideally suited to automation
  - Reliable low porosity, even in thick laminates
  - Short cure cycles

- The same is true of both carbon and glass

- Typical UD prepregs can have significantly higher mechanical properties than their infused equivalents

The use of UD prepregs in load bearing structures enhances mechanical properties, reliability and productivity