Forged Molding Compound™
High Performance Chopped Carbon Fiber Composites

Steven Wusterbarth
Mitsubishi Chemical America
Steven_Wusterbarth@m-chem.com

Koichi Akiyama
Gemini Composites LLC | A subsidiary of
Mitsubishi Chemical Carbon Fiber and Composites
Koichi.Akiyama@mccfc.com
Agenda

• Traditional Carbon Fiber SMC
• Forged Molding Compound™ (FMC™) Technology
• FMC™ Material
• FMC™ Process
• FMC™ Design
• Conclusion
Carbon Fiber Sheet Molding Compound (CF SMC)

- CF SMC is a chopped fiber molding compound
  - Relatively large tow size of carbon fiber is commonly used
  - Small tow carbon fiber is too expensive for industrial applications
  - Vinyl ester resin is typical matrix resin system

- CF SMC is usually molded by traditional compression molding
  - Cure time is relatively short; suitable for high cycle molding
  - SMC is normally squeezed to flow and fill complex geometry

<table>
<thead>
<tr>
<th>SMC Production</th>
<th>Compression Molding</th>
</tr>
</thead>
<tbody>
<tr>
<td>![SMC Production Image]</td>
<td>![Compression Molding Image]</td>
</tr>
</tbody>
</table>
Example of Carbon Fiber SMC applications

- 2017 Toyota Prius Prime Rear hatch inner panel
- 2018 KTM Skid plate
- 2018 Lexus LC500 Door inner panel
- 2018 Lexus LC500 Decklid inner panel
Suitable application for CF SMC and limitation

- Suitable for secondary structural or aesthetical applications
  - Most of those applications are designed for stiffness
  - Complex geometry can be molded
  - Snap cure material enables high cycle molding for high volume applications

- Limitations for use in primary structural applications
  - Material can’t keep isotropic fiber orientation and mechanical properties during traditional compression molding process
  - Mechanical properties of common CF SMC are insufficient
  - Large variation of mechanical properties
  - Sophisticated FEM analysis and design technique were unavailable
Forged Molding Compound™ (FMC™) technology

- Forged Molding Compound™ (FMC™) is the integrated technology of chopped carbon fiber composites

- FMC™ technology consists of three factors.
  - Advanced material
  - Optimized molding process
  - Dedicated design

- The ideal combination of the three factors of FMC™ enables metal replacement with carbon fiber composites, achieving significant weight reduction of structural applications.
Advanced Chopped Carbon Fiber Composites

- FMC™ technology was developed for primary structural applications
  - FMC™ material is high performance sheet molding compound made with advanced chopped carbon fiber, which provides higher strength and specific modulus than light-weight metal
  - Snap cure material enable high cycle molding for high volume applications
  - Properties of advanced materials can be fully utilized in the molded part by optimizing the molding process
  - Dedicated FMC™ design replaces metal design
  - FEM analysis technique specialized for FMC™ is available
Smaller CF tow provides ideal structure

- Homogeneous structure provide excellent mechanical properties and dimensional stability
  - More fiber layers exist in the same thickness of 3K material than larger tow
  - Less resin-rich area is observed in 3K material
Effect of Carbon Fiber Tow Size on Mechanical Property

- Fiber bundle size has strong influence on mechanical properties
  - The smaller and thinner bundles give higher and more homogeneous mechanical properties
  - Property variation significantly lowers the value used for parts design
Small Tow CF SMC Provides Excellent Properties; However...

- Small tow CF SMC is good for certain applications, but there are limitations for use in industrial applications
  - The SMC cost is high due to the high expense of smaller tow carbon fiber
  - Limited moldability of complex geometries
FMC™ material is high performance sheet molding compound made with advanced chopped carbon fiber to provide an economic solution with excellent properties.

- The chopped fiber has tow size distribution providing excellent mechanical performance and good moldability.
- Split tow-based advanced chopped fiber provides an affordable solution.

FMC™ material contains many thin layers of carbon fiber tow.

- Homogeneous structure without the resin-rich portion also provides excellent properties.
A variety of FMC™ products are available:
- Fiber contents and length can be chosen depending on application requirements
- Both vinyl ester and epoxy matrix resin systems are available
- Flame retardant and high Tg grades are under development and will be available soon

<table>
<thead>
<tr>
<th>Material</th>
<th>15K / Vinyl Ester</th>
<th>3K / Vinyl Ester</th>
<th>Vinyl Ester</th>
<th>Epoxy</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Regular Carbon Fiber</strong></td>
<td>Lower Cost</td>
<td>Excellent Mechanical Property</td>
<td>Excellent Mechanical Property</td>
<td>Excellent Mechanical Property</td>
</tr>
<tr>
<td>Easy to mold</td>
<td>Good Aesthetics</td>
<td>Cost Effective</td>
<td>Good Moldability</td>
<td>No odor</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Carbon Fiber Tow</th>
<th>15K</th>
<th>3K</th>
<th>Adjustable distribution</th>
<th>Adjustable distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Fiber Length</td>
<td>1/2&quot;, 1&quot;, 2&quot;</td>
<td>1/2&quot;, 1&quot;, 2&quot;</td>
<td>1&quot;, 2&quot;</td>
<td>1&quot;, 2&quot;</td>
</tr>
<tr>
<td>Fiber Content</td>
<td>45 - 60%</td>
<td>45 - 60%</td>
<td>45 - 60%</td>
<td>45 - 60%</td>
</tr>
<tr>
<td>Suitable Application</td>
<td>Secondary structure</td>
<td>Aesthetic parts</td>
<td>Primary Structure</td>
<td>Primary Structural</td>
</tr>
</tbody>
</table>
FMC™ Material | Excellent Mechanical Properties

- FMC™ made with advanced carbon fiber provides higher strength than 3K CF SMC with the same fiber content

Mechanical Properties of 60% fiber content vinyl ester material

### Tensile Strength & Modulus

<table>
<thead>
<tr>
<th></th>
<th>Tensile Strength (MPa)</th>
<th>Tensile Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15K</td>
<td>300</td>
<td>20</td>
</tr>
<tr>
<td>3K</td>
<td>400</td>
<td>40</td>
</tr>
<tr>
<td>FMC™</td>
<td>410</td>
<td>20</td>
</tr>
</tbody>
</table>

### Flexural Strength & Modulus

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<td>40</td>
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<tr>
<td>FMC™</td>
<td>410</td>
<td>20</td>
</tr>
</tbody>
</table>
• FMC™ can be made with any fiber content from 40% to 65%
  – The resin system and fiber content can be specified depending on desired mechanical properties or other application requirements

FMC™ Material | Carbon Fiber Content

- Tensile Strength & Modulus
- Flexural Strength & Modulus

### Tensile Strength & Modulus
- **Vinyl Ester**
  - Tensile Strength
  - Tensile Modulus
- **Epoxy**
  - Tensile Strength
  - Tensile Modulus

### Flexural Strength & Modulus
- **Vinyl Ester**
  - Tensile Strength
  - Tensile Modulus
- **Epoxy**
  - Tensile Strength
  - Tensile Modulus
FMC™ Moldability | Spiral Flow

- FMC™ made with advanced carbon fiber flows better than 3K CF SMC
  - FMC™ flows well even though tow size is small to provide higher property than 3K CF
  - Low flow molding is essential for FMC™, however good moldability is still quite important to mold complex geometry.

### Spiral Flow

<table>
<thead>
<tr>
<th>Material</th>
<th>CF Content</th>
<th>Spiral Flow (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>53% 3K</td>
<td></td>
<td>400</td>
</tr>
<tr>
<td>53% FMC</td>
<td></td>
<td>500</td>
</tr>
</tbody>
</table>

MCC Standard Test Method
- Width of channel: 5cm, Thickness of Channel: 2mm
- Plunger pressure: 10Mpa, Mold Temp: 140 °C

### Spiral Flow of Vinyl Ester Material

<table>
<thead>
<tr>
<th>Material</th>
<th>CF Content 53%</th>
<th>CF Content 60%</th>
</tr>
</thead>
<tbody>
<tr>
<td>15K</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>3K</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>FMC™</td>
<td>500</td>
<td>600</td>
</tr>
</tbody>
</table>
FMC™ Moldability | Deep Rib Part Molding

- FMC carries carbon fiber better into complex geometry such as ribs.
  - Advanced CF keeps isotropic fiber orientation better than regular CF during molding
  - Advanced CF retains 85% and 66% of nominal tensile strength in top and rib specimens respectively

**Deep Rib Molding Condition**
- Mold Coverage: 95% charge only on top, no insert in rib
- Part Thickness: Top 2.0 mm, Rib root 3.0mm, Rib top 2.0mm
- Rib Height: 43mm, Rib Draft angle: 1 degree
- Molding pressure: 10Mpa, Mold Temp: 140 °C

**Tensile Strength Retention of Top & Rib Specimens**

**Material**
- FMC™ carries carbon fiber better into complex geometry such as ribs.
- Advanced CF keeps isotropic fiber orientation better than regular CF during molding.
- Advanced CF retains 85% and 66% of nominal tensile strength in top and rib specimens respectively.
• Minimizing material flow during molding process
  – Minimal material flow prevents sacrificing mechanical properties
  – Optimizing the change pattern by shape and weight distribution is the key
  – Utilizing a preformed charge pattern is recommended
  – Low flow molding-friendly part design makes a large impact on properties
Material Flow During Compression Molding

**FMC ™ Low Flow Molding**
Low-flow specimen shows more uniform strain distribution and parallel tow/fiber breakage

**Traditional High Flow Molding**
High flow specimen show high strain concentration area, swirling ad fiber bunching, single fracture point
Fiber orientation after material flow during molding

- Material flow orientates carbon fiber and makes a swirl of fiber
  - Fiber aligns along to direction of material flow
  - At the flow front of material, a swirl of fiber occurs and creates defects
Mechanical Properties | After Material Flow During Molding

- Material flow significantly changes mechanical properties
- Fiber orientation creates anisotropic and inhomogeneous properties

### Mechanical Properties After Material Flow During Molding

<table>
<thead>
<tr>
<th>Process</th>
<th>% Coverage</th>
<th>Tensile Strength (MPa)</th>
<th>Tensile Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0º</td>
<td>95%</td>
<td>300</td>
<td>50</td>
</tr>
<tr>
<td>90º</td>
<td>95%</td>
<td>300</td>
<td>50</td>
</tr>
<tr>
<td>0º</td>
<td>50%</td>
<td>200</td>
<td>40</td>
</tr>
<tr>
<td>90º</td>
<td>50%</td>
<td>200</td>
<td>40</td>
</tr>
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300x300mm flat panel
- Material: CF SMC PTO130N127
- Vinyl ester matrix resin
- 1” 53% 3K CF
- Panel Thickness: 3.2–3.4mm
- Molding Temperature: 140 °C
- Molding Pressure: 10 MPa
- Cure time: 3 minutes
- Charge pattern: 95% coverage, 50% coverage
Design philosophy of FMC™ technology is completely different from that for either metal or continuous carbon fiber composites.

• FMC™ parts design is dedicated to chopped fiber material.
• Parts should be designed as material flow can be minimized during compression molding. So the parts can keep isotropic fiber orientation and mechanical property.
• FEM analysis and simulation optimized for FMC™ material should be used.
• Holes, thickness change, molded-in inserts can be used, which is difficult in the case of traditional continuous carbon fiber composites.
FMC™ Design Example | Suspension Prototype

- FMC™ design was developed for suspension prototype part.
  - Size: 362(L)x63(W)x70(H)mm
  - Thickness: 3–13 mm
  - Prototype parts were manufactured and its property was evaluated
FMC™ Design Improvements

• FMC™ design can make composite part stronger than metal part
  – Example: Automotive suspension part

• Compression property
  – Rev II: FMC™ design with the right material and process achieved higher load than ultimate failure of aluminum part.

• More than 40% weight reduction

<table>
<thead>
<tr>
<th>Rev 0</th>
<th>Rev I</th>
<th>Rev II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>Aluminum part design</td>
<td>Aluminum part Design</td>
</tr>
<tr>
<td>Material</td>
<td>15K CF SMC</td>
<td>FMC™</td>
</tr>
<tr>
<td>Molding Process</td>
<td>Traditional High Flow</td>
<td>FMC™ Low Flow</td>
</tr>
<tr>
<td>Weight Reduction from Aluminum Part</td>
<td>47%</td>
<td>47%</td>
</tr>
</tbody>
</table>
FMC™ Cost Competitiveness to Aluminum

- Cost of compression molding is normally lower than metal forging
  - FMC™ material is more expensive than aluminum.
    - However mass of FMC™ part is 60% of aluminum part.
    - 40% of impact can be deducted.
  - Molding cycle of FMC™ is short.
  - FMC™ can mold complex geometry, so most of machining can be eliminated.
  - Total process cost is lower than metal forging

![Parts cost comparison chart](image-url)

(Anonymous primary structural part. Cost is index, not dollar amount)
In Conclusion...

• FMC™ technology has been developed as the lightweight solution for primary structural applications with high production volumes.

• The advanced chopped carbon fiber is the key technology of FMC™ material, which provides high mechanical performance and excellent moldability at an affordable cost.

• FMC™ technology consists of not only advanced material, but also optimized molding process and dedicated design. The combination of those three factors enables utilization of chopped carbon fiber composite to primary structural applications that require high mechanical performance.

• FMC™ technology can be utilized in a variety of structural applications such as large body structure, suspension, power train, crash box, EV battery enclosure and more.
Contact us! We can design the parts, supply the advanced material and build optimized process depends upon your needs.
Thank you.