Development of PCM* technology

* Prepreg Compression Molding

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MITSUBISHI RAYON CO., LTD.
CFRP Molding Process

Mechanical Properties

- Low
- High

Productivity

- Low
- High

Moldability

- Low
- High

Small Volume

- Autoclave
- Oven
- RTM
- VaRTM

Mid Volume

- PCM
- Advanced RTM

High Volume

- CFRP Mass Production
- GMT
- LFT-D
- LFP
- Injection

Remark

- Thermoset
- Thermoplastic

Mass Production

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MITSUBISHI RAYON CO., LTD.
High cycle CFRP molding process

- PCM has a potential for CFRP mass production.

**PCM (Prepreg Compression Molding)**

Newly developed fast curing prepreg is preformed, and then cured in heated steel tool. Short mold cycle times.

**Advanced RTM**

Dry fabric is charged in heated tool, then resin is injected into the mold. Cycle time can be shortened with fast curing resin system.
## Comparison between PCM and RTM

<table>
<thead>
<tr>
<th></th>
<th>PCM (Prepreg Compression Molding)</th>
<th>Advanced RTM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material</strong></td>
<td>Compression moldable fast curing prepreg</td>
<td>Fabric (NCF, multi-axial F etc.)</td>
</tr>
<tr>
<td></td>
<td>Co-molding with SMC is possible</td>
<td>Chopped fiber mat, Resin</td>
</tr>
<tr>
<td><strong>Typical Fiber content (Vf)</strong></td>
<td>Up to 65%</td>
<td>Up to 45%</td>
</tr>
<tr>
<td><strong>Typical Resin system</strong></td>
<td>Epoxy resin</td>
<td>Epoxy resin</td>
</tr>
<tr>
<td><strong>Parts Geometry</strong></td>
<td>PCM; Relatively simple shape</td>
<td>Relatively complex geometry</td>
</tr>
<tr>
<td></td>
<td>Uniform thickness</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hybrid; Relatively complex geometry</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ribs and bosses etc.</td>
<td></td>
</tr>
<tr>
<td><strong>Preform</strong></td>
<td>Prepreg; Near net shape preform</td>
<td>Fabric; Net shape preform</td>
</tr>
<tr>
<td><strong>Tool</strong></td>
<td>Steel tool</td>
<td>Steel tool</td>
</tr>
<tr>
<td><strong>Molding pressure</strong></td>
<td>3-10MPa</td>
<td>0.5MPa (5MPa for HP RTM)</td>
</tr>
<tr>
<td><strong>Typical cycle time</strong></td>
<td>5 minutes or longer</td>
<td>10 minutes or longer</td>
</tr>
<tr>
<td><strong>Equipments</strong></td>
<td>Preforming system</td>
<td>Preforming system</td>
</tr>
<tr>
<td></td>
<td>High tonnage press</td>
<td>Injection machine</td>
</tr>
<tr>
<td></td>
<td>Preforming system</td>
<td>Press (High tonnage for HP RTM)</td>
</tr>
<tr>
<td><strong>Metal Insert</strong></td>
<td>Possible in hybrid molding</td>
<td>Possible</td>
</tr>
<tr>
<td><strong>Core Insert molding</strong></td>
<td>Possible in simple parts geometry</td>
<td>Possible (Difficult in HP-RTM)</td>
</tr>
</tbody>
</table>
Cost comparison

- Total manufacturing cost using PCM / Advanced RTM is lower than the one using autoclave where production volume is over 200 parts per a month.
- PCM has cost advantage over advanced RTM in higher volume production.

Cost index vs Production Volume

Cost index comparison
@2400 part per month

Cost study
The size of parts; 1200X700, thickness; 1.1mm
Cycle time; Autoclave 120 min., Advanced RTM 15 min., PCM 10 min.
PCM (Prepreg Compression Molding)

- Newly developed fast curing prepreg
  - 2 minute cure at 150°C (302°F) (the shortest cure time condition) or 3 minutes at 140°C (284°F).
  - Product shelf-life is minimum 40 days < 20°C (68°F) storage.
  - Resin system optimized for both preform and compression molding processes.
    - Controlled Viscosity at elevated temperature
    - Suitable tackiness at room temperature
  - Equivalent mechanical properties compared to conventional autoclave technology with standard Prepreg
    - Tg > 160°C.
PCM (Prepreg Compression Molding)

- Molding process development
  - Preform design matched for compression molding
  - Quick preform process
  - Optimized tool design for PCM
  - Molding condition optimized for PCM
  - PCM/CF-SMC co-molding

- Application development studies
  - Automotive outer body panels
  - Automotive structural parts
# Prepreg for PCM

<table>
<thead>
<tr>
<th>Properties</th>
<th>Developed prepreg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R 02</td>
</tr>
<tr>
<td><strong>Resin type</strong></td>
<td>Bisphenol A type Epoxy resin</td>
</tr>
<tr>
<td><strong>Gel time @ 140 C min.</strong></td>
<td>2.0</td>
</tr>
<tr>
<td><strong>Minimum cure time @ 140 C min.</strong></td>
<td>5.0</td>
</tr>
<tr>
<td><strong>CF reinforcement</strong></td>
<td>Typical grade</td>
</tr>
<tr>
<td>1)</td>
<td>UD</td>
</tr>
<tr>
<td>2)</td>
<td>Fabric 2)</td>
</tr>
<tr>
<td><strong>FAW g/m²</strong></td>
<td>250 or 125</td>
</tr>
<tr>
<td><strong>Resin Content wt%</strong></td>
<td>30</td>
</tr>
<tr>
<td><strong>CF Vf vol%</strong></td>
<td>59</td>
</tr>
<tr>
<td><strong>Specific Gravity</strong></td>
<td>1.54</td>
</tr>
<tr>
<td><strong>Other advantage</strong></td>
<td>Good Surface</td>
</tr>
</tbody>
</table>

1) TR50S carbon fiber from Mitsubishi Rayon Co., Ltd. is used for all prepgels
   Tensile strength; 4900 MPa, Modulus; 240 GPa, Elongation; 2.0%

2) Plain, twill and Satin fabric can be used.
Viscosity control

- Resin viscosity at elevated temperature was optimized for compression molding.
  - Low viscosity of conventional materials at elevated temperature results in excessive resin flow

Viscosity at elevated temperature

Problem caused by low resin viscosity
- Bleed out of cavity
- Inconsistent mechanical results
- Fiber distortion
- Poor thickness uniformity
- Poor cosmetics
- Demolding issue
Fast curing formulation

- Resin formulation has been optimized for fast curing
  - Optimized combination of resins and curing agents
  - Curing behavior are evaluated by Curelastometer
    - Curelastometer can measure/monitor resin behavior under conditions similar to actual molding.

![Graph showing torque vs. time for different resins: R 03 and R 02.](chart)

Curelastometer test

- Press
- Heated Dice (140°C)
- Resin sample
- Detect Torque

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### Mechanical properties

<table>
<thead>
<tr>
<th></th>
<th>General Grade</th>
<th>R 02</th>
<th>R 03</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flexural Properties</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 degree</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strength (MPa)</td>
<td>1720</td>
<td>1631</td>
<td>1558</td>
</tr>
<tr>
<td>Modulus (GPa)</td>
<td>125</td>
<td>126</td>
<td>126</td>
</tr>
<tr>
<td>Strain (%)</td>
<td>1.40</td>
<td>1.29</td>
<td>1.24</td>
</tr>
<tr>
<td>0 degree</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strength (MPa)</td>
<td>2570</td>
<td>2820</td>
<td>2659</td>
</tr>
<tr>
<td>Modulus (GPa)</td>
<td>124</td>
<td>127</td>
<td>127</td>
</tr>
<tr>
<td>Strain (%)</td>
<td>2.50</td>
<td>2.64</td>
<td>2.36</td>
</tr>
<tr>
<td>90 degree</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strength (MPa)</td>
<td>120</td>
<td>123</td>
<td>102</td>
</tr>
<tr>
<td>Modulus (GPa)</td>
<td>9.1</td>
<td>9.3</td>
<td>8.6</td>
</tr>
<tr>
<td>Strain (%)</td>
<td>1.33</td>
<td>1.37</td>
<td>1.03</td>
</tr>
<tr>
<td><strong>Tensile Properties</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 degree</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strength (MPa)</td>
<td>2650</td>
<td>2421</td>
<td>2096</td>
</tr>
<tr>
<td>Modulus (GPa)</td>
<td>138</td>
<td>141</td>
<td>138</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>1.90</td>
<td>1.80</td>
<td>1.70</td>
</tr>
<tr>
<td><strong>Shear strength</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ILSS</td>
<td>104</td>
<td>98</td>
<td>84</td>
</tr>
</tbody>
</table>

**Notes**

1) UD test specimens were molded at 140 C and 10 MPa. Cure time is 5 minutes. General purpose prepreg is molded by autoclave with standard curing condition.

2) measured at room temperature RT. n=5

3) 90 degree Flexural test. ILSS were not normalized. 0 degree flexural was normalized to Vf 60%.
0 degree Flexural strength/modulus

![Graph showing flexural strength and modulus for different samples.]

- Strength (MPa):
  - Control: ~1500 MPa
  - R02: ~1500 MPa
  - R03: ~1500 MPa

- Modulus (GPa):
  - Control: ~140 GPa
  - R02: ~140 GPa
  - R03: ~140 GPa

Legend:
- Strength
- Modulus
90 degree Flexural strength/modulus

- **Strength (MPa)**: Control, R02, R03
- **Modulus (GPa)**

- **Legend**: Strength - Solid, Modulus - Dashed Line
0 degree Tensile strength/modulus

![Graph showing 0 degree Tensile strength/modulus for Control, R02, and R03. Strength is measured in MPa, and Modulus is measured in GPa. The graph compares the strength and modulus of the materials.]
Mechanical Properties of Laminates

- Mechanical properties of R03 laminates
  - R02 laminates showed similar properties

<table>
<thead>
<tr>
<th></th>
<th>Mechanical Test</th>
<th>Unidirectional</th>
<th>Cross ply</th>
<th>Quasi-isotropic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>Average</td>
<td>Average</td>
</tr>
<tr>
<td>Tensile</td>
<td>Strength MPa</td>
<td>2096</td>
<td>1128</td>
<td>700</td>
</tr>
<tr>
<td>0 deg.</td>
<td>Modulus GPa</td>
<td>138</td>
<td>73</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td>Elongation %</td>
<td>1.70</td>
<td>1.53</td>
<td>1.46</td>
</tr>
<tr>
<td>Flexural</td>
<td>Strength MPa</td>
<td>1558</td>
<td>1195</td>
<td>795</td>
</tr>
<tr>
<td>0 deg.</td>
<td>Modulus GPa</td>
<td>126</td>
<td>89</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Strain %</td>
<td>1.24</td>
<td>1.34</td>
<td>1.50</td>
</tr>
<tr>
<td>90 deg.</td>
<td>Strength MPa</td>
<td>102</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Modulus GPa</td>
<td>8.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Strain %</td>
<td>1.03</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: Thickness of unidirectional test specimen is 2.0mm
Cross plies test specimen is laminate of (0/90/0/90)s, thickness is 1.6 mm
Quasi-isotropic test specimen is laminate of (45/0/-45/90)s, thickness is 1.6 mm
Thermal Analysis

- E’ Tg of R 03 is over 160° C
  - R 03 can be used for high temperature applications

### DMA

- **Prepreg Control R 02 R 03**
  - G’-Tg (℃): 127, 125, 165
  - tan δ (℃): 148, 154, 186

<table>
<thead>
<tr>
<th>Prepreg</th>
<th>Control</th>
<th>R 02</th>
<th>R 03</th>
</tr>
</thead>
<tbody>
<tr>
<td>G’-Tg (℃)</td>
<td>127</td>
<td>125</td>
<td>165</td>
</tr>
<tr>
<td>tan δ (℃)</td>
<td>148</td>
<td>154</td>
<td>186</td>
</tr>
</tbody>
</table>

Molding Condition: 140 C×5min  8MPa
Control prepreg is cured by autoclave
Temperature Dependence of Mechanical Properties

- R 03 maintains high mechanical properties at elevated temperatures.

### Flexural Properties of UD sample

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>-30</th>
<th>25</th>
<th>80</th>
<th>100</th>
<th>120</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>R 02</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strength (MPa)</td>
<td>2140</td>
<td>1631</td>
<td>1468</td>
<td>1321</td>
<td>989</td>
</tr>
<tr>
<td>Modulus (GPa)</td>
<td>126</td>
<td>126</td>
<td>128</td>
<td>128</td>
<td>123</td>
</tr>
<tr>
<td><strong>R 03</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strength (MPa)</td>
<td>2047</td>
<td>1558</td>
<td>1352</td>
<td>1338</td>
<td>1195</td>
</tr>
<tr>
<td>Modulus (GPa)</td>
<td>125</td>
<td>126</td>
<td>128</td>
<td>127</td>
<td>126</td>
</tr>
</tbody>
</table>

### Flexural Properties of Laminate (Cross Ply; 0/90/0/90/0)

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>-30</th>
<th>25</th>
<th>80</th>
<th>100</th>
<th>120</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>R 02</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strength (MPa)</td>
<td>1570</td>
<td>1248</td>
<td>1230</td>
<td>1053</td>
<td>955</td>
</tr>
<tr>
<td>Modulus (GPa)</td>
<td>90</td>
<td>88</td>
<td>91</td>
<td>89</td>
<td>91</td>
</tr>
<tr>
<td><strong>R 03</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strength (MPa)</td>
<td>1671</td>
<td>1195</td>
<td>1070</td>
<td>955</td>
<td>988</td>
</tr>
<tr>
<td>Modulus (GPa)</td>
<td>90</td>
<td>89</td>
<td>91</td>
<td>91</td>
<td>92</td>
</tr>
</tbody>
</table>
0 degree Flexural Strength of UD test specimens at various temperatures.
Temperature Dependence of Flexural Modulus

- 0 degree Flexural Strength of laminate at various temperatures

![Graph showing the relationship between strength and temperature for laminate samples R02 and R03. The graph indicates a decrease in strength with increasing temperature.](image-url)
PCM Molding Process

100% mold coverage, preform recommended

Charge

Press

De-mold

PCM
UD and/or Fabric Prepreg

Hybrid Molding
UD and/or Fabric Prepreg + SMC

Molds complex shape with SMC

SMC
**Preform process**

- Cutting patterns, preform, and compression molding are consecutive processes.
  - It is possible to produce one piece every 10 minutes.

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**Process simulation:**
Deck lid outer panel  
750X1200mm  
UD Prepreg 5 plies, 1.1mm  
Cure time; 5 minutes

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<table>
<thead>
<tr>
<th>Process</th>
<th>Cycle Time (minute)</th>
<th>Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prepreg Pattern Cut</td>
<td>10</td>
<td>Cutting plotter</td>
</tr>
</tbody>
</table>
| Preform               | 10                  | Light press (such as air cylinder press)  
|                       |                     | Chemical wood tool  
|                       |                     | IR heater  
|                       |                     | Vacuum bagging system (if necessary)                                       |
| Compression Molding   | 10                  | High Tonnage hydraulic press  
|                       |                     | (Typical Molding Pressure; 4-10MPa)  
|                       |                     | Steel tool                                                               |
Deck lid model development

CFRP deck lid model parts was designed.
- Outer panel; R 02 UD prepreg
  - Cross ply (0/90/0/90/0) 1.1mm thickness
- Inner panel; CF-SMC
  - 1.5 mm thickness vinyl ester carbon fiber SMC parts
  - Volume fraction of carbon fiber 45%
- Bonded with epoxy structural adhesive
Example of FEM Analysis

- **Stiffness**
  - Load: 196 kN, Area of load: 300X400mm
    - CFRP-Sample: Max. Displacement: 0.61mm
    - Aluminum: Max. Displacement: 2.59mm

- **Anti-dent**
  - Load: 686 N, Area of load: 50 mm²
    - CFRP-Sample: Max. Displacement: 12.4mm
    - Aluminum: Max. Displacement: 14.6mm
Evaluation of CFRP Deck Lid

- CFRP deck lid can reduce weight by 38% comparing with aluminum model
  - Stiffness, torsion rigidity, anti-dent, etc. are equal to aluminum model by FEM analysis.
  - CFRP deck lid were evaluated in several different durability tests and showed similar results to aluminum part.
  - Bonded parts was 2.4 kg and achieved 38% weight saving comparing with aluminum deck lid.
A quarter part of engine hood was developed to demonstrate feasibility of PCM body panels.

- PCM outer and CF-SMC inner panels were bonded to produce a body panel structure consisting of two parts.
- CFRP engine hood is 63% lighter than steel hood.

SUBURU Impreza
Steel hood;  14.5 kg
CFRP hood;  5.3 kg
(Whole hood)
Engine hood model part development

- Outer panel molded by PCM has very smooth surface and no porosity
  - Good paintability and no paint blisters were observed

- Body color painted part
  - R 02 UD Prepreg
  - Cross ply (0/90/0/90/0) 1.1mm thick
  - Paint; Primer/Base/Clear Top
    - Totally 100 micrometer thick
    - Three bake at 120°C for 30 minutes

- Clear coat painted carbon fabric look part
  - R 02 3K twill prepreg
  - Twill + Cross ply totally 1.3mm thick
  - Paint: Clear Primer/Clear Top
    - Totally 70 micrometer thick
    - One bake at 120°C for 30 minutes
Surface Quality of PCM parts

- R 02 UD Prepreg can achieve Class A surface.
  - Wave scan index of parts molded by PCM is similar to that of typical class A SMC parts.

UD PCM; Body color paint
Fabric PCM; Clear coat paint

Wave scan index was measured by Wave Scan-T from BYK-Chemie
PCM/SMC hybrid molding process

- Co-molding of Prepreg and CF-SMC
  - High performance of Prepreg and moldability of SMC
  - Good adhesion between Prepreg and SMC

CF-SMC was charged on the net shape preform.

Molded part

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Test specimens were prepared by several different laminate designs.

Flexural properties were evaluated by ASTM D790
- Load was applied on specimens as shown in Figure below.
- Sample size; 25.4X110mm, L/D: 40

Sample name; SMC, SMC/PP, PP/SMC, PP

<table>
<thead>
<tr>
<th></th>
<th>SMC</th>
<th>SMC/PP/SMC</th>
<th>SMC/PP</th>
<th>PP/SMC</th>
<th>PP</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMC</td>
<td>2mm</td>
<td>0.45+0.45mm</td>
<td>0.9mm</td>
<td>0.9mm</td>
<td>–</td>
</tr>
<tr>
<td>Prepreg</td>
<td>–</td>
<td>1.1mm</td>
<td>1.1mm</td>
<td>1.1mm</td>
<td>2.2mm</td>
</tr>
<tr>
<td>Laminate</td>
<td>–</td>
<td>0/90/0/90/0</td>
<td>0/90/0/90/0</td>
<td>0/90/0/90/0</td>
<td>(0/90/0/90/0)</td>
</tr>
</tbody>
</table>

(Note) PP; R 02 UD prepreg (Vf 59%), SMC; CF-SMC (Vf 45%)
PCM / CF-SMC molded parts property

- Prepreg on crosshead side of specimens increase modulus.
- Prepreg on support side of specimens increase strength.
- Prepreg reinforcement minimizes variation of mechanical properties.
- 90 degree flexural properties become a little higher using Prepreg as reinforcement.

0 degree Flexural

90 degree Flexural
Core material inserted molding process

- Core (Foam) material can be used in PCM process to make light weight parts.
  - Foam material was wrapped in near net shape preform as a core.
  - Tool was designed not to apply excessive molding pressure on the core material.
  - Applied molding cycle is the same as the one used for PCM process without core material.
  - High stiffness can be achieved without significant weight increase on the parts

Large electric equipment housing
Size; 480X160mm
Thickness; Shell 0.4mm, Core 5mm
Structural model parts development

- Structural floor model parts was developed by PCM
  - Hybrid molding of Prepreg and CF-SMC
    - Prepreg; R 03 cross ply 2.0mm thickness
    - SMC; 0.5mm thick to mold ribs and a boss

**Structural floor model**
Size: 500X500mm

- Hollow section can be molded with PCM technology

Prepreg assures high strength and parts quality consistency
CF-SMC covers complex shape
Summary

- PCM (Prepreg Compression Molding) technology was developed as a high cycle CFRP molding process.
  - Fast curing Prepreg has been developed for compression molding
    - Cured in two minutes at 150° C
    - Minimum resin bleed during compression molding
    - High mechanical properties thanks to CF Prepreg
  - Preform and molding process have been also studied and developed.

- Model parts development suggests capability of PCM technology as highly suitable for high volume automotive parts production. Examples:
  - Class A outer body panel (quality surface) with painted finish
  - Cosmetic part with carbon fabric appearance
  - Structural parts by PCM/CF-SMC Hybrid molding
To a world standard.

Mitsubishi Rayon is one of the world’s leading suppliers of carbon fibre. Our driving force is our integrated production system – raw material to finished product – which enables us to respond quickly to changing market needs. Our new range of P330 carbon fibres is an example of this response in action with a fibre that offers high strength and resilience plus volume production. The standards set by Mitsubishi are endorsed by customers throughout the world.

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