Correlation Study Using Moldflow MuCell® for Lightweighting

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This class focuses on a correlation study done using Moldflow's Microcellular (or, MuCell®) Injection Molding simulation module. After establishing a reasonable correlation, a strategy for using the analysis module is offered.
Why Did I Want to Do This?

- CAE Services in the Automotive Industry
- MuCell important for lightweighting
  - CAFE (Corporate Average Fuel Economy) 54.5 mpg by 2025
- Getting requests to do MuCell analysis
- Trexel recommends using a makeshift method using standard module
- Wanted to understand the differences between using the standard and MuCell modules
Key learning objectives

At the end of this class, you will:

- Learn how the MuCell molding process works
- Learn the MuCell methodology to determine weight savings
- Learn how to setup a MuCell analysis in AMI
- Learn how well AMI MuCell analysis correlates with molded samples
- Understand relationships among common inputs and results
- Understand the differences between using the standard and MuCell modules
The MuCell Process
What is MuCell?
Why use MuCell?
Who invented it and who owns it now?
When / Where was it invented?
How is MuCell done?
Current developments in MuCell
What is MuCell?

- Microcellular injection molding
- Mechanical (not chemical) foaming method to impart a microcellular structure to molded parts
- Millions of cells created on order of 5-100 microns
Why Use MuCell?

- Weight reduction (commonly up to 15%)
- Reduced viscosity = reduced pressures to fill
- Reduced clamp force requirement (foaming = packing)
- Improved warpage
- Reduced sink marks
- Reduced cycle times
Advantages Over Chemical Foaming

- Chemical foaming requires significantly thicker walls = increased weights
- MuCell can be done at any wall thickness
Foundations based on work done by Dr. Nam Suh (MIT) in the 1980s
- Formation of microcellular structures in plastic parts
- 1995: Trexel, Inc. obtained exclusive license
- Continued development & commercialization up to today
The MuCell Process

- Molding machine is modified or comes pre-fit with gas-injection unit
- A super-critical fluid (SCF) is injected into the melt stream
- SCFs include $N_2$ and $CO_2$
- Typical dosage = 0.2% - 1.0%
- The Trexel unit injects SCF into screw / barrel area
- 2/3 of way down barrel
- Pressurized, single-phase, SCF-polymer solution injected into part cavity
- Shot size reduced from equivalent solid shot (say 90%)
- Drop in material pressure initiates immediate cell nucleation
Molding Machine Modifications (MMU or OEM)

- Molding machine is modified or comes pre-fit with gas-injection unit
Super-Critical Fluid (SCF) Formation
Mold Modifications

- Hot runner molds require valve gates to prevent material drooling
- Molds where machine nozzle breaks contact need shutoff
  - E.g., Stack Molds
- Use larger gates due to typically faster injection speeds
  - Exception: Sub gates may not de-gate well with larger size
MuCell Molding Strategy
MuCell Molding Strategy

- SCF dosing % determined based on polymer
- Gradually reduce stroke (reduced shot volume)
- Gradually increase injection speed at each stroke setting until filled (promotes cell nucleation)
- Faster filling speeds possible due to reduced viscosity
- Little to no packing time needed (0.5 seconds)
- Pack at least as high as back pressure to maintain screw balance
MuCell in Moldflow (AMI 2014)
Step 1 - Microcellular Injection Molding Module
Step 2 – Part Modeling

- Midplane or Dual Domain (no 3D)
- No special modeling considerations
Step 3 – Mold Modeling

- Hot Runners need Valve Gates!
- Pressurized material prevented from seeping into mold prematurely
Step 3 – Material Modeling

- MuCell reduces the viscosity of the material up to 30%
  - 12 – 15% reduction is typical
- Viscosity reduction model testing
  - PS material (Styron 666D) from an in-mold rheometer
- Moldflow materials database
  - Correction factors based on these tests
- You must actively turn on the viscosity modification
- Different viscosity modification, gas solubility and diffusion coefficients are used for N₂ and CO₂
Step 3 – Material Modeling

Give it Some Gas!

<table>
<thead>
<tr>
<th>Description</th>
<th>N2</th>
</tr>
</thead>
</table>

**Select MuCell® Material Properties**

- Select

**Select MuCell® material properties**

- Select

*Image of a green race car with the number 1.*
Step 3 – Material Modeling

**N₂ Coefficients**

- Molecular weight of the gas: 28
- Surface tension: 5e-005 N/mm
- Viscosity coefficients for gas:
  - v1: 1
  - v2: -58.381
  - v3: 3520
- Solubility coefficients for gas:
  - k1: 1.3489e-009
  - k2: -1.7089e+005
- Diffusion coefficient for gas:
  - d1: 3.819e-007
  - d2: -2830.5

**CO₂ Coefficients**

- Molecular weight of the gas: 44
- Surface tension: 5e-005 N/mm
- Viscosity coefficients for gas:
  - v1: 1
  - v2: -17.135
  - v3: 186.55
- Solubility coefficients for gas:
  - k1: 1.5361e-009
  - k2: 1.9829e+005
- Diffusion coefficient for gas:
  - d1: 8.741e-008
  - d2: -2830.5

Name: N₂

Name: CO₂
Step 3 – Material Modeling

Gas/Polymer Viscosity Model

\[ \eta = \eta_r + \phi v_1 \eta_3 \]

Where:

- \( \eta \) = viscosity of gas/polymer system
- \( \eta_r \) = viscosity of the base resin without gas
- \( \phi \) = volume fraction of the nucleated gas bubble
- \( c \) = initial gas concentration
- \( v_1, v_2, \) & \( v_3 \) = data-fitted coefficients
Step 3 – Material Modeling

During 1st Stage Injection: \( \varphi = 0 \); (i.e., no bubble growth)

- \( \text{N}_2 \)
- \( \text{CO}_2 \)

- 12 - 17% viscosity reduction
- Foaming Stage
  - \( 0 < \varphi < 1 \) = reduction in viscosity
  - But flowfront slowdown means \( \eta_r \) dominates
Step 3 – Material

\[ \kappa = \frac{d_1}{d_2} \left( \frac{T_2}{T_1} \right) \]

**Gas Diffusion Model**

\( d_1, d_2 \) are data-fitted coefficients

\[ \kappa = \frac{k_1}{k_2} \left( \frac{T_2}{T_1} \right) \]

**Gas Solubility Model**

\( k_1, k_2 \) are data-fitted coefficients
Step 4 – Process Modeling

Key Assumption – Cell Nucleation

- Nucleation = the birth of a bubble
- MuCell
  - Nucleation occurs during 1st stage
  - Nucleation is non-uniform
- Moldflow
  - No nucleation during 1st stage
  - Nucleation is uniform
Step 4 – Process Modeling

MuCell Process

- Bubbles nucleate and grow during 1st stage
- Foaming is non-uniform
- Foaming reduces viscosity
- Foaming continues during brief packing – 0.5 sec. typical
- Packing helps stabilize the start of screw rotation
- Foaming continues until cavity is filled
Step 4 – Process Modeling

Moldflow MuCell – 1\textsuperscript{st} stage
- No nucleation during 1\textsuperscript{st} stage
- Viscosity modified
  - \(N_2\) constants
  - Cells/volume setting
- 1\textsuperscript{st} stage filling ends at user-specified shot %

Moldflow MuCell – 2\textsuperscript{nd} stage
- Foaming starts at user-specified shot %
- Foaming replaces packing
  - Exception: Packing told to start before foaming
- Nucleation starts at user-defined bubble radius
  - 0.001 mm typical (1 micron)
- Bubble growth calculated due to:
  - Hydrodynamic Growth
  - Gas Diffusion
Step 3 – Material Modeling – Other Assumptions

- Foam is divided into spherical microscopic unit cells of equal and constant mass
- Number of cells = number of nuclei
- Bubble radius is calculated at each time step
Step 4 – Process Modeling

- Faster filling is typical
  - More shear = better nucleation
  - Lower viscosity
Step 4 – Process Modeling

NOT USED UNLESS IT OCCURS BEFORE FOAMING
### Step 4 – Process Modeling

#### Why do we have these?

- **No nucleation model**
- **Viscosity modification**
- **Starting point for bubble growth**

<table>
<thead>
<tr>
<th>Setting</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume filled at start of foaming</td>
<td>89 % (0:100)</td>
</tr>
<tr>
<td>Initial bubble radius</td>
<td>0.001 mm (0:1)</td>
</tr>
<tr>
<td>Number of cells per volume</td>
<td>2e+005 1/cm^3 (0:1e+014)</td>
</tr>
<tr>
<td>Initial gas concentration</td>
<td>0.4 % (0:10)</td>
</tr>
</tbody>
</table>
Step 5 – Analyze

### Filling phase:

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Volume (%)</th>
<th>Pressure (psi)</th>
<th>Clamp Force (ton(US))</th>
<th>Status</th>
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</thead>
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<td>0.04</td>
<td>2566.85</td>
<td>0.26</td>
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</tbody>
</table>

Execution time in Filling Phase = 1172.45 s

### Packing phase:

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Packing (%)</th>
<th>Pressure (psi)</th>
<th>Clamp Force (ton(US))</th>
<th>Status</th>
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<td>51.08</td>
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<td>58.62</td>
<td>F</td>
</tr>
<tr>
<td>4.10</td>
<td>9.30</td>
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<td>58.46</td>
<td>F</td>
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<td>4.45</td>
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<td>F</td>
</tr>
<tr>
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<td>F</td>
</tr>
<tr>
<td>12.30</td>
<td>49.30</td>
<td>520.19</td>
<td>36.85</td>
<td>F</td>
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<td>18.81</td>
<td>F</td>
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<td>F</td>
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<tr>
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<td>89.33</td>
<td>595.13</td>
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<td>F</td>
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<tr>
<td>22.70</td>
<td>100.00</td>
<td>608.01</td>
<td>2.05</td>
<td>F</td>
</tr>
</tbody>
</table>

Status: V = Velocity control
F = Foaming
U/P = Velocity/Pressure switch-over
Case Example - Correlation
The Part – Oil Pan

30.0” x 10.0” x 4.8”
762 x 254 x 122 mm
The Part – Moldflow Model

Two Models:
40,000 elements
8,000 elements
The Mold – Manifold Design

Hot Manifold:
- Synventive 16E
- Inlet – 16.0 mm
- Main Bore – 16.0 mm
- Nozzle Bore – 16.0 mm
- Valve Pins – 6.0 mm
- Gate Orifices – 5.0 mm
The Material

Molded Material
- Polifil T-20
- 20% talc-filled PP
- 8-12 MFI @ 230°C

Moldflow Material
- Hi-Prene MT42HS
- 20% talc-filled PP
- 12 MFI @ 230°C
- Quality Standard = Gold

<table>
<thead>
<tr>
<th>PHYSICAL</th>
<th>ASTM / Method</th>
<th>Units</th>
<th>Polifil® T-10</th>
<th>Polifil® T-20</th>
<th>Polifil® T-30</th>
<th>Polifil® T-40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinforcement Content</td>
<td>TPG WI</td>
<td>%</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>D 792</td>
<td>-</td>
<td>0.98</td>
<td>1.05</td>
<td>1.15</td>
<td>1.24</td>
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<tr>
<td>Melt Flow (230/2.16)</td>
<td>D 1238</td>
<td>g/10 min</td>
<td>8-12&quot;</td>
<td>8-12&quot;</td>
<td>8-12&quot;</td>
<td>8-12&quot;</td>
</tr>
<tr>
<td>Water Absorption, 24 Hours</td>
<td>D 570</td>
<td>%</td>
<td>nil</td>
<td>nil</td>
<td>nil</td>
<td>nil</td>
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<tr>
<td>Mold Shrinkage – 1/8” Specimen</td>
<td>D 955</td>
<td>in/in</td>
<td>0.015</td>
<td>0.010</td>
<td>0.009</td>
<td>0.008</td>
</tr>
</tbody>
</table>

MECHANICAL @ 73°F
- Tensile Strength: D 638, psi, 4,900, 4,900, 4,750, 4,600
- Elongation @ Yield: D 638, %, 7.0, 6.0, 5.0, 4.5
- Elongation @ Break: D 638, %, 20, 15, 14, 10
- Tensile Modulus: D 638, kpsi, 240, 280, 330, 380
- Flexural Modulus (tangent): D 790, kpsi, 270, 300, 350, 400
- Flexural Strength: D 790, psi, 5,800, 6,500, 7,000, 8,000
- Izod Impact (notched): D 256, ft-lbs/in, 0.80, 0.60, 0.50, 0.60
- Gardner Impact (1/2” tup): D 5420, in-lbs, 12, 9, 5, 5
- Hardness, Shore: D 1415, D-Scale, 72, 74, 75, 77

THERMAL
- Deflection Temperature, 86psi: D 648, °F, 238, 255, 270, 280

* melt flow may be specified
The Process

Solid Shot
- Shot Stroke – 11.0”
- Fill Time – 3.8 sec.
- Fill Pressure – 8373 psi
- Part Weight – 950g

Final MuCell Shot
- Shot Stroke 9.8”
- Fill Time – 2.0 sec.
- Fill Pressure – 11,500 psi
- Part Weight – 845 g
Molded Parts

Solid Shot

MuCell Shot
Solid Shot – Part Weight Results

Total Part Weight

Predicted - 945.5 g
Actual - 950 g
The Analysis Setup – MuCell Shot

Process Settings Wizard - Fill+Pack Settings - Page 1 of 3

Mold surface temperature: 140 F
Melt temperature: 475 F

Filling control:
- Absolute ram speed profile
- Velocity/pressure switch-over: 0.2 in (0.1968)

Pack/holding control:
- Packing pressure vs time
- Cooling time: 20 s

Fiber orientation analysis if fiber material

Filling Control Profile Settings

<table>
<thead>
<tr>
<th>Ram position</th>
<th>Ram speed in (0.1968)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.798</td>
</tr>
<tr>
<td>2</td>
<td>9.15</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Starting ram position:
- Cushion warning limit: 0.02 in
- Starting ram position: 9.798 in

Pack/Holding Control Profile Settings

<table>
<thead>
<tr>
<th>Duration s (0.580)</th>
<th>Packing pressure psi (0.72520)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4000</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>4000</td>
</tr>
</tbody>
</table>

OK Cancel Help
MuCell Shot – Part Weight Results

Total Part Weight

Predicted – Huh?
Actual - 845 g
MuCell Shot – Part Weight Results

- Reduce Pack Time
- Shut Valve Pins
- Correct SCF %
- Use Fill Time