Simulation of the MuCell® Microcellular Foaming Process in AMI 2016

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Class summary

This class focuses on the basics of the microcellular foam injection molding process and the key differences to standard solid molding and on the advances in simulation of this process through the use of the MoldFlow Insight simulation package.

Key learning objectives

At the end of this class, you will understand:

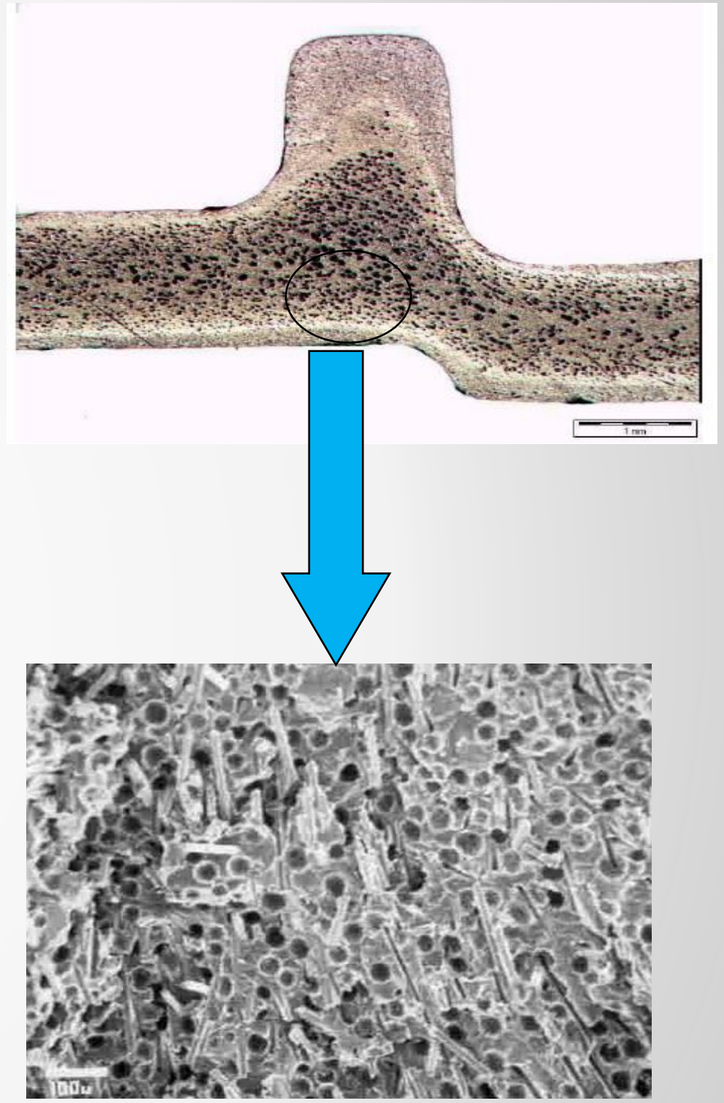
- The fundamental mechanics of the MuCell® microcellular foam injection molding process
- The key differences between microcellular foam molding and tradition solid injection molding
- The simulation issues related to bubble nucleation and cell growth
- The advances MoldFlow is making in the simulation of microcellular foam injection molding

Outline

- What is the MuCell Process
- The MuCell Process vs Solid Molding
- Design Optimization for MuCell
- Challenges to Simulation
- Mucell simulation enhancements in AMI 2016
  - Bubble nucleation model
  - 3D simulation
  - Input data changes
- Case studies

What is MuCell®?

- MuCell is a foaming Technology
  - Putting small cells into a thin wall plastic part
- Primarily using nitrogen as the foaming agent
  - Sometimes carbon dioxide



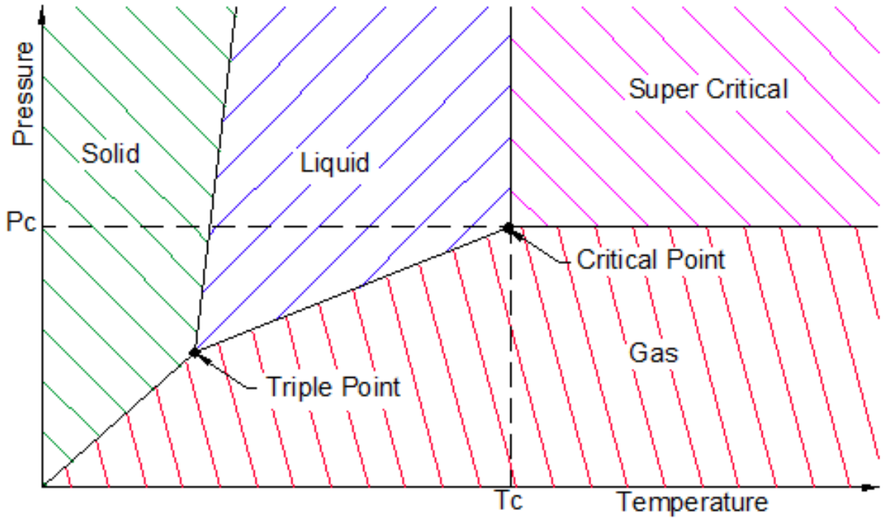
Fundamentals of Microcellular Foam Molding

- Create a single phase solution
  - Dissolution of foaming agent into the polymer
- Homogeneous Cell Nucleation
  - Controlled during injection
- Cell Growth
  - Controlled during filling and cooling

Production hardware must be capable of controlling these steps

Gas Dissolution (Creating a Single Phase Solution)

- Create a single phase solution
  - Introduction of a physical foaming agent in supercritical state
  - Appropriate conditions to dissolve the supercritical fluid (SCF) into the polymer melt (Time/Temp/Pressure/SCF Level)



CO_2: Pc = 72 bar Tc = 31^{O}C

N_2: Pc = 34 bar Tc = -147^{O}C

Supercritical Fluid (SCF)

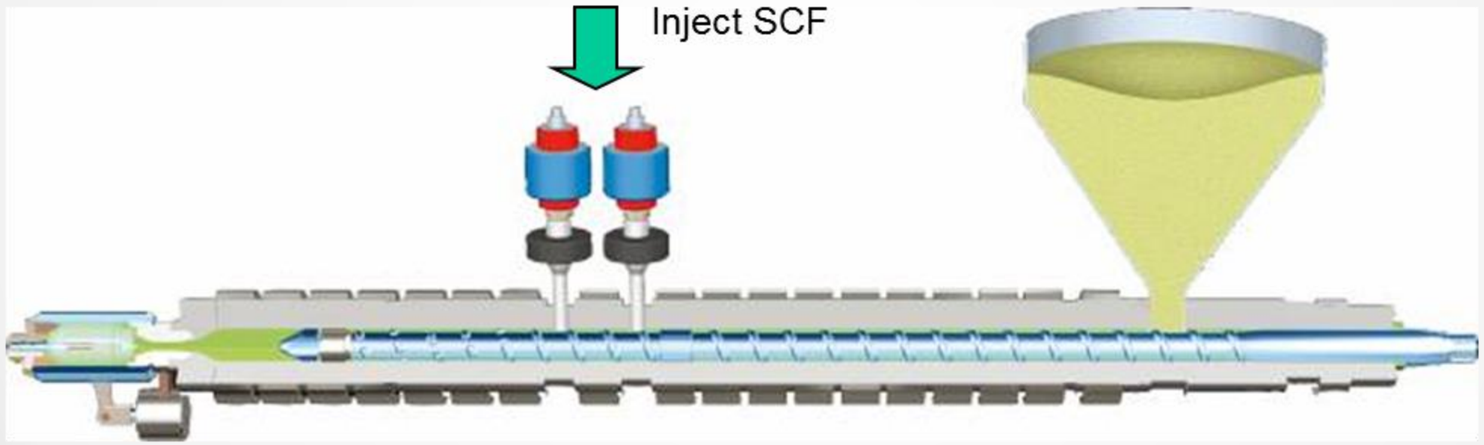
- Matter at pressure and temperature where it has properties of both liquid and gas
  - Solubility of liquid
  - Diffusion properties of a gas
- End result of using SCF
  - High rates of diffusion
  - Unique levels of solubility
  - Precise metering

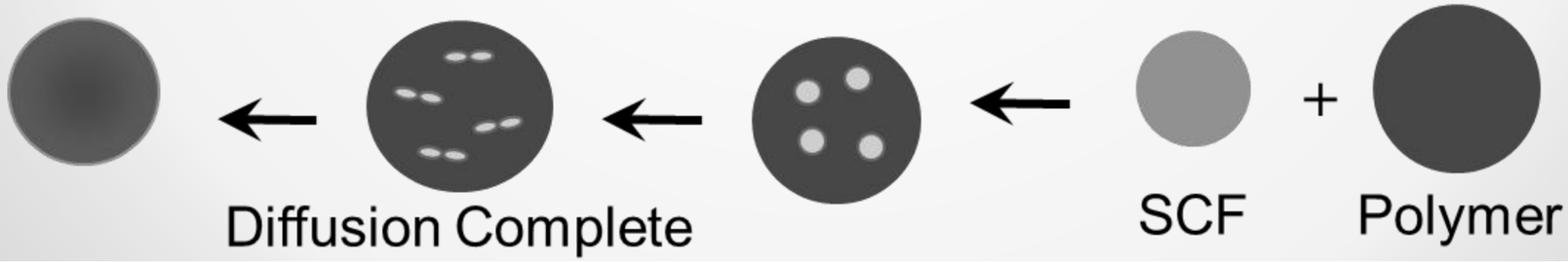
Creating the Single Phase Solution

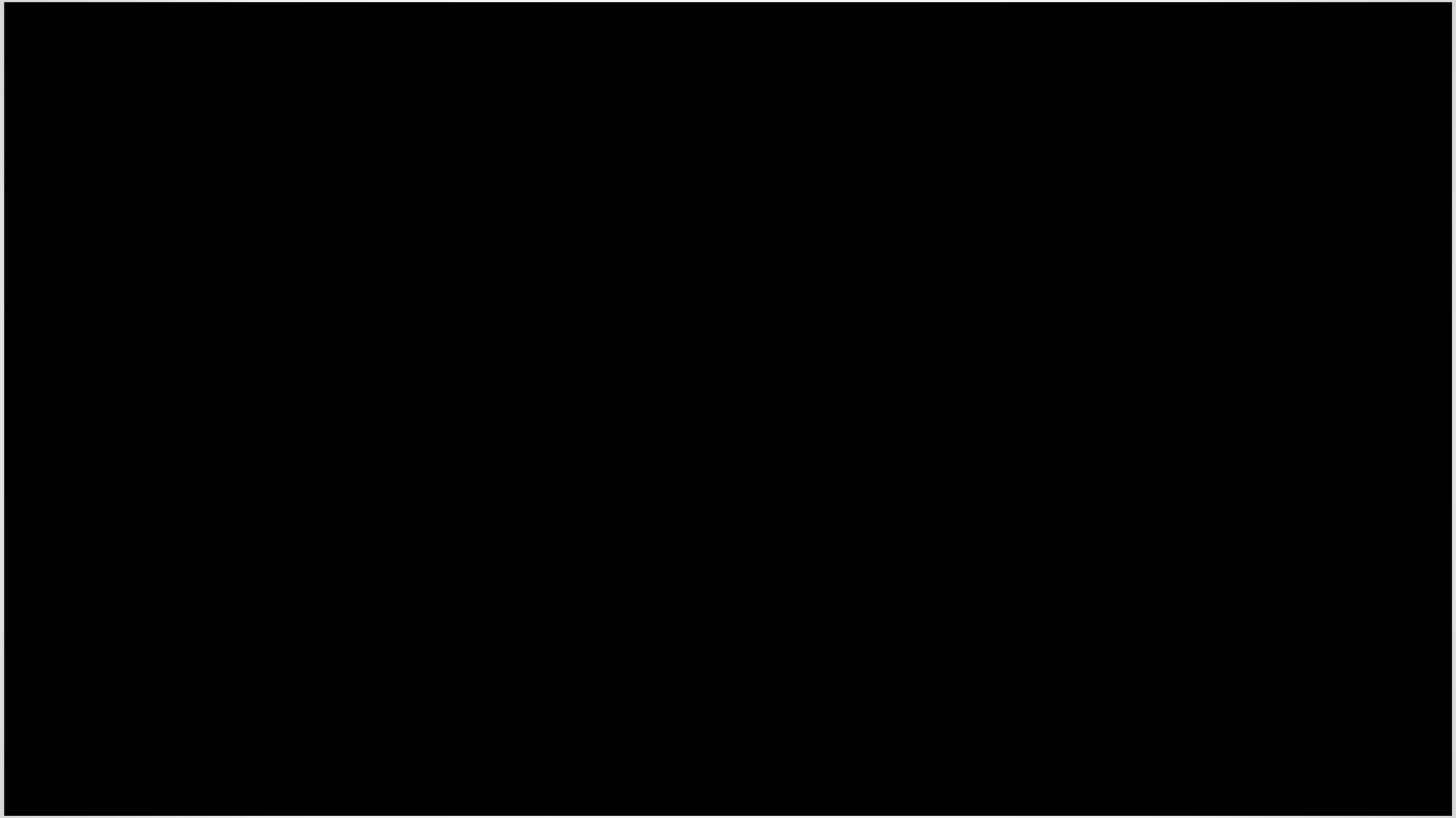
- SCF must be added under proper barrel conditions
  - Screw cannot be static
  - Barrel must be at a stable pressure
  - Barrel pressure must be appropriate for polymer/SCF level
    - Between 1500 and 3000 psi
  - Eliminate pressure surges
  - Maintain pressure on all SCF laden polymer

MuCell Process

- Basic Steps
  - Melt plastic prior to SCF injection
  - Inject SCF during screw rotation
  - Dissolve SCF into the polymer melt (single phase solution







MuCell Process

- Once the SCF is dissolved into the molten polymer it must be kept under pressure
  - In the molding machine this means
    - Screw position control
    - Shutoff nozzle
  - In the mold
    - Valve gates for hot runner molds

Nucleation

- **Cell Nucleation occurs when a single phase solution undergoes a rapid pressure drop**
  - **(Pressure drop) / (Time duration)**
- **This occurs at the machine nozzle (cold runner) or valve gate (valve gated hot runner)**
- **Cell nuclei are site where cells can form, & grow**

Nucleation

- **Homogeneous nucleation is an ideal situation under which all cell sites form at exactly the same time**
- **Shorter injection times comes closest to this ideal situation**
- **The higher the driving force creates more cells (higher cell density)**
  - **Increased rate of pressure drop**
  - **High foaming agent level**

Cell Growth Control

- Factors that affect cell growth
  - The surface tension of the bubble surface
  - The stress in the visco-elastic cell wall
  - The number of cells nucleated
  - Gas wt% saturated in the melt
  - The rate at which this occurs depends on the stiffness of the material
  - Cooling rate
  - Gas pressure in the cells

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The MuCell Process vs Solid Molding

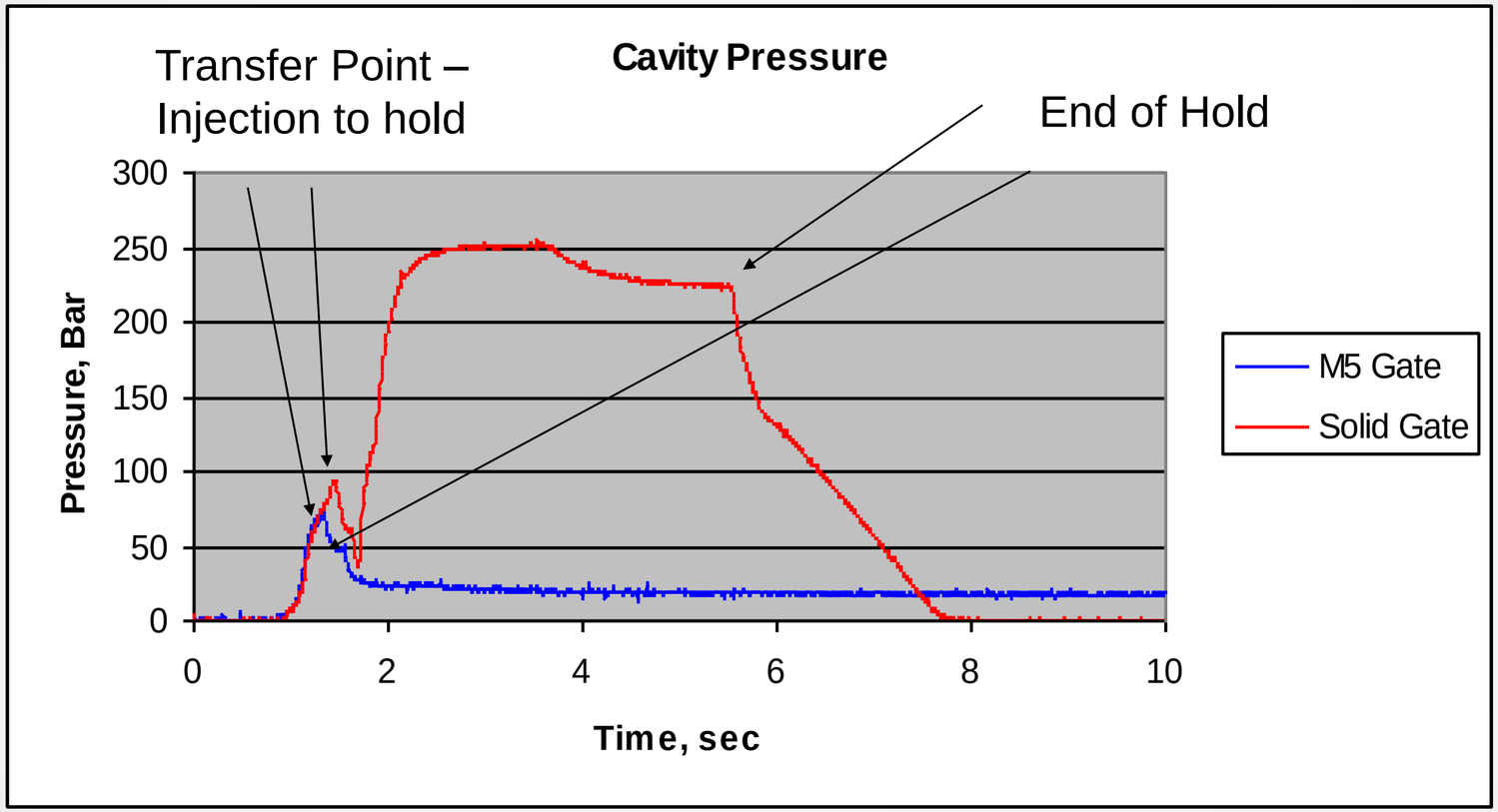
- Dissolving an SCF into a polymer reduces the material viscosity
- Viscosity changes
  - 5% to 8% for polyolefins
  - 10% to 15% for a 30% glass fiber reinforced semi-crystalline engineering resin
  - 15% to 25% for an amorphous resin
- Cell growth provides final packing of the part
  - Reduces residual stress patterns by eliminating traditional pack and hold phase
  - Results in improved part dimenstions
- Cycle time reduction due to shorter pack/hold and increase mold contact

The MuCell Process vs Solid Molding

- Pack phase of tradition molding introduces non-uniform pressure in the mold cavity
  - Higher pressure near the gate, lower pressure at the end of the fill
  - Pressure does not transfer uniformly through semi-molten polymer
- Cell growth provides packing pressure uniformly throughout the mold cavity
  - Uniform pack pressure results in uniform pressure conditions in the final part

The MuCell Process vs Solid Molding

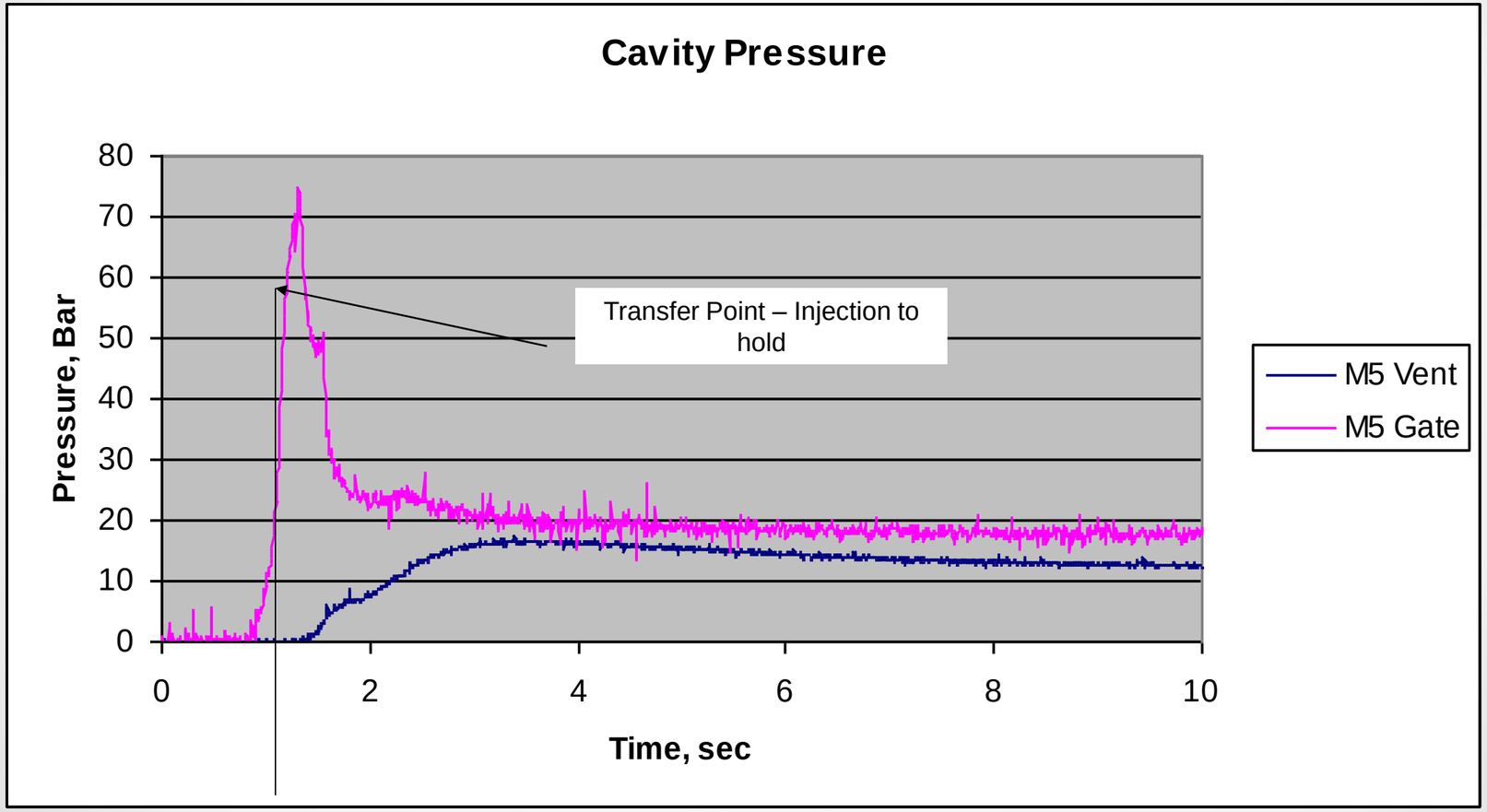
- Pressure curve – solid vs the MuCell process
  - Sensor at the gate



- Reduced cavity pressures translates to reduced clamp tonnage
  - At 8% weight reduction – clamp tonnage of 1 ton/in 2

The MuCell Process vs Solid Molding

- Typical MuCell process pressure curves



The MuCell Process vs Solid Molding

- Weight reduction
  - Material density reduction
- Reduced clamp force requirement (foaming = packing)
- Improved warpage
  - Reduced Residual Stress
- Reduced sink marks
- Reduced cycle time

Outline

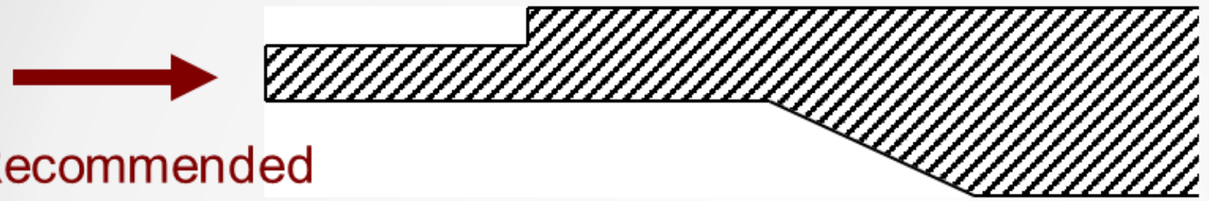
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Designing for Function

- Weight reduction by designing part for function and not process
  - Wall thickness optimized for performance requirements not for packing requirements
    - Means thinner nominal wall and higher L/t ratios
      - ❖ Viscosity reduction due to SCF
      - ❖ Pack pressure is applied through foaming
    - How is this applied
      - ❖ 2.5mm wall thickness at 150:1 (375mm flow)
        - ✓ 8-10% density reduction
      - ❖ 2.0mm wall at 375mm flow (188:1 L/t)
        - ✓ 20% weight reduction (design) / 6-8% density reduction

Designing for MuCell

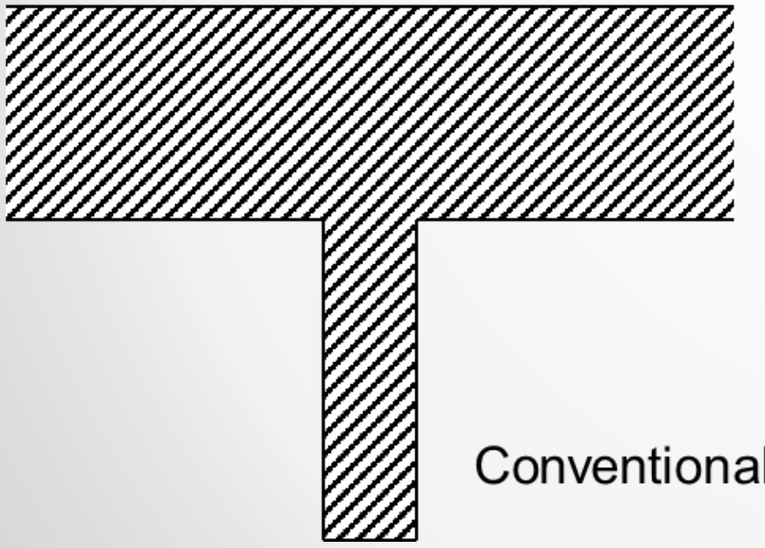
⇨ **Filling from “thin to thick“**



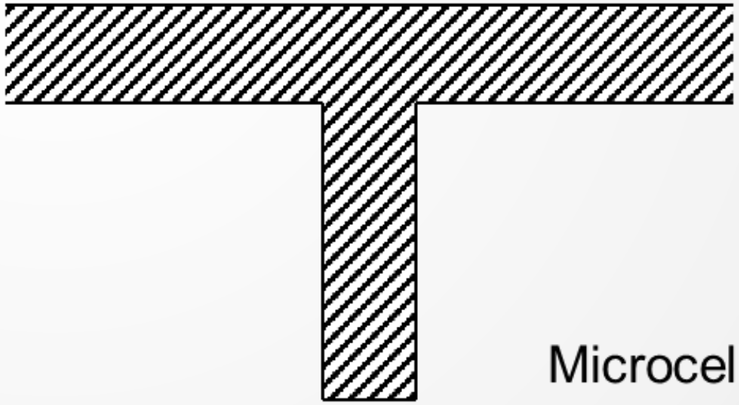
Recommended injection with Microcellular Foam

Injection in solid (with MuCell® still possible)

⇨ **Wall to rib ratio 1:1 possible**

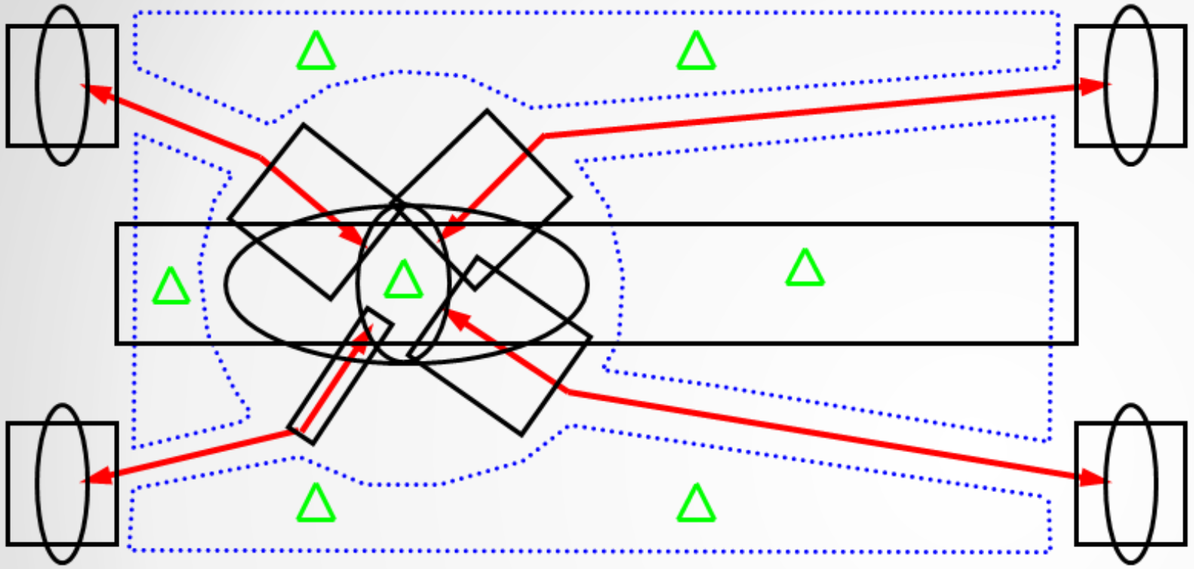


Conventional design



Microcellular design

Applied Design – Fan Shroud BMW



Design Drivers:

- ⇨ Mechanical strength for hubs and stators
- ⇨ Minimal wall thickness for air deflection

- ⇨ Hub and stators 2 mm
- ▯ Reduced wall to 1 mm

Conventional Design:

⇨ Base thickness: 2.0 mm

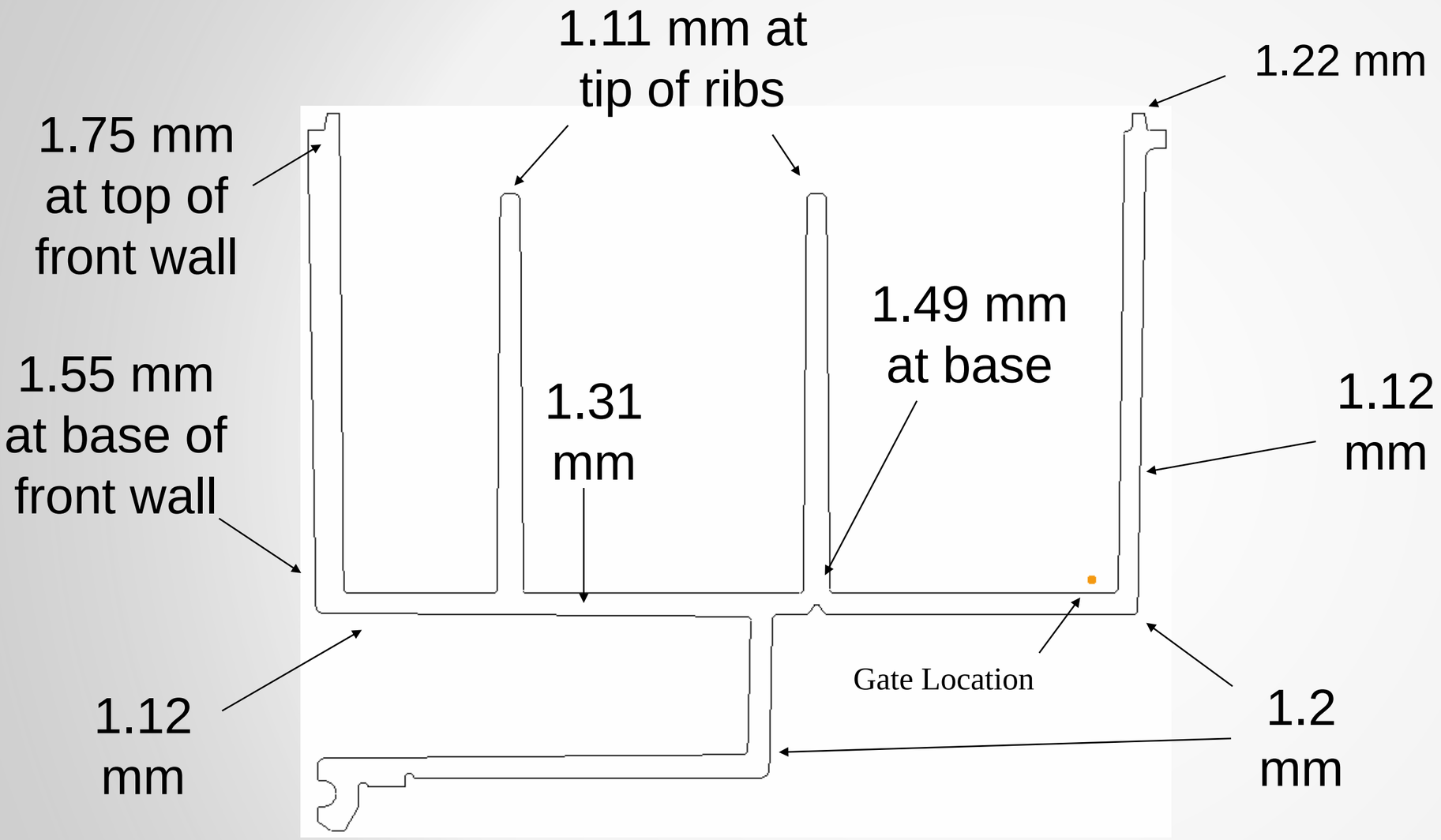
MuCell-Design:

⇨ Hub & stators: 2.0 mm

⇨ Air deflection: 1.0 mm

Weight Savings per Shroud: 410 gr/0.9 lbs.

Applied Design – Printer Cartridge



Weight Savings per Cartridge: 15% Design/6% density

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Challenges to Simulation

- Accounting for changes to viscosity and Tg
- SCF acts as a temporary plasticizing agent
  - Reduces viscosity and suppresses the Tg of the material
  - Only during the fill phase of the process
- Predicting cell structure and the effects of cell structure.
  - Cell nucleation models
  - Cell growth models
  - Density reduction
  - Reductions in residual stress
  - Enabling prediction of advanced design methods.

Challenges to Simulation

- Validation Studies
- Run multiple materials at multiple conditions and correlate to simulation
  - Not all conditions produced optimum parts
  - Goal was to simulate result achieved
- Materials:
  - 30% glass filled PA6
  - Unfilled PP Homopolymer
  - PP Homopolymer with 20% glass fiber
  - PP Copolymer with 20% calcium carbonate
- Process variables:
  - Injection velocity
  - % Nitrogen
  - Part Weight
  - All other conditions constant across samples

Challenges to Simulation

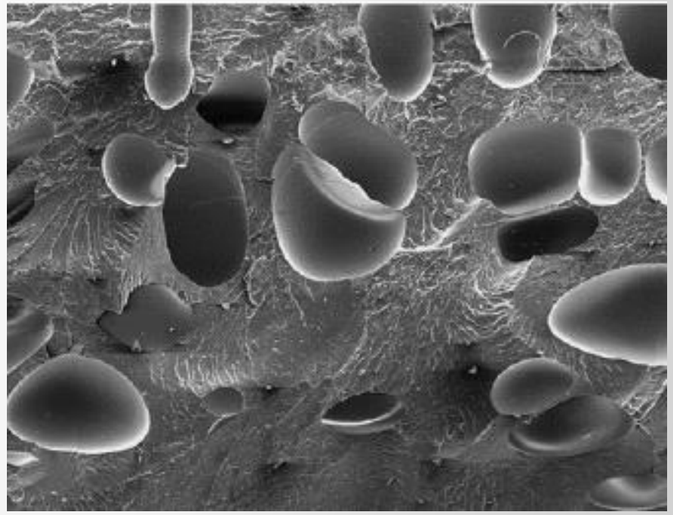
- Validation Studies
- Process variables except for % nitrogen constant across all materials:
  - Injection velocity: 50 mm/sec, 100 mm/sec and 150 mm/sec
  - Part Weight: 96% of solid, 92% of solid, 88% of solid
  - % Nitrogen:
    - 0.15%, 0.3% and 0.45% for glass filled PA6 and glass filled PP
    - 0.2%, 0.4% and 0.6% for calcium carbonate filled PP and unfilled PP
    - Unfilled PP had an additional level of 0.8% nitrogen
- Molding Equipment
  - Krauss Maffei KM500/3400

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Topics

- **Enhancements in Microcellular Injection Molding (Mucell ®) Simulation in AMI 2016**
  - **Implementation of bubble nucleation model**
  - **Input data changes**
  - **3D microcellular simulation developments**
- **Examples**



Constant Nucleation Density

- **In the previous release, only “constant nucleation density” model was available**
  - **The user has to input the number of cells per volume**
  - **The number of cells per volume is the same at all locations**
  - **Cannot simulate the effect of process condition on the number of cells**

Bubble Nucleation Model

- Bubble nucleation model was added in the new release
- Nucleation model for Microcellular Injection Molding → Classical nucleation model
  - Homogeneous nucleation model
  - Heterogeneous nucleation model
  - Fitted nucleation model

- Limitations of the model
- Material data
- Implementation of the bubble nucleation model in Moldflow

Bubble Nucleation Model

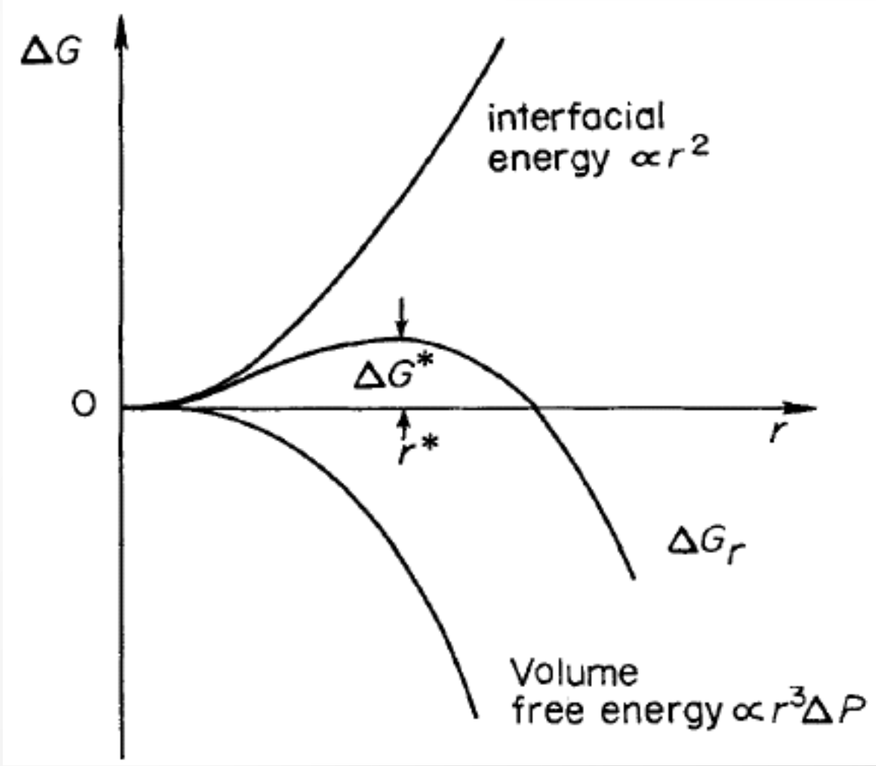
- **Bubble nucleation in boiling water**
- **Classical nucleation model**
- **A similar model can be used for the bubble nucleation in polymer foaming**



Homogeneous Nucleation Model

- Nucleation occurring interior of polymer
- Nucleation occurs when critical amount of gas dissolved in polymer comes together to form a critical size bubble
- Nucleation rate ~ Probability to reach the critical bubble size (r^*)

$$J \sim exp[\frac{-\Delta G}{kT}]$$



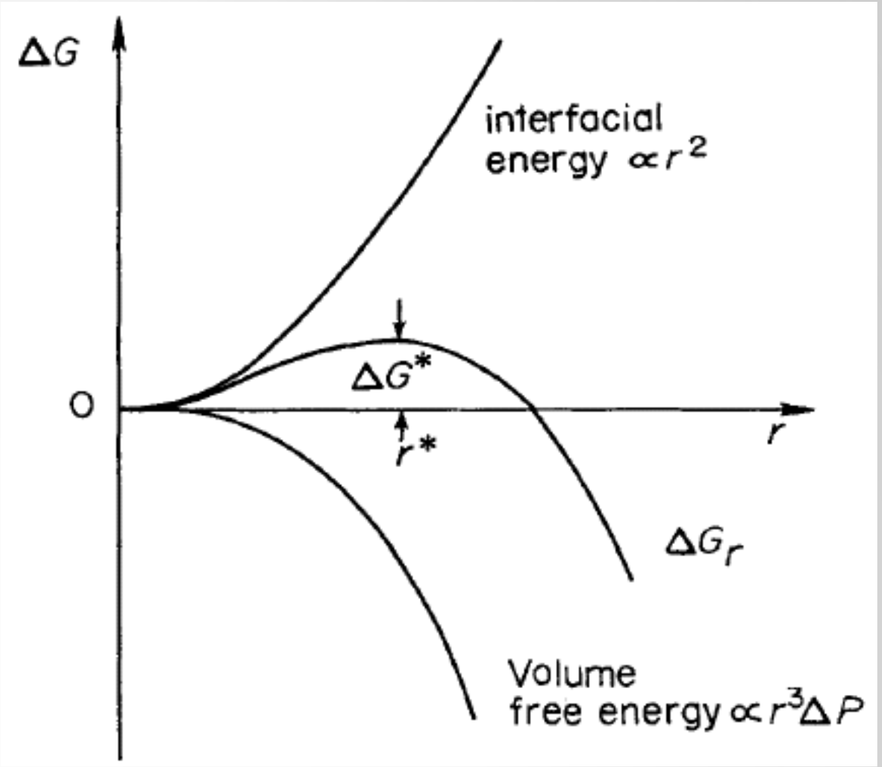
J: Nucleation rate (per volume per time)
ΔG: Energy required to form a critical bubble
T: Temperature
k: Boltzmann constant

Homogeneous Nucleation Model

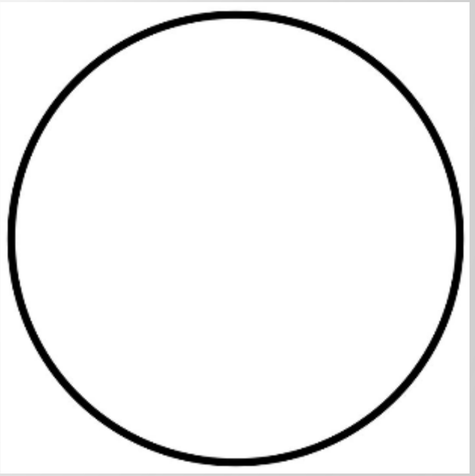
- **Probability to reach the critical bubble size**

$$\Delta G = -V_b \Delta P + A_b \sigma = \frac{16\pi\sigma^3}{3(\Delta P)^2}$$

$$r^* = \frac{2\sigma}{\Delta P}$$



ΔG: Change in free energy
r^*: Critical bubble radius
σ: Surface tension
ΔP: Pressure difference between the gas and the polymer
V_b: Bubble volume
A_b: Bubble surface area

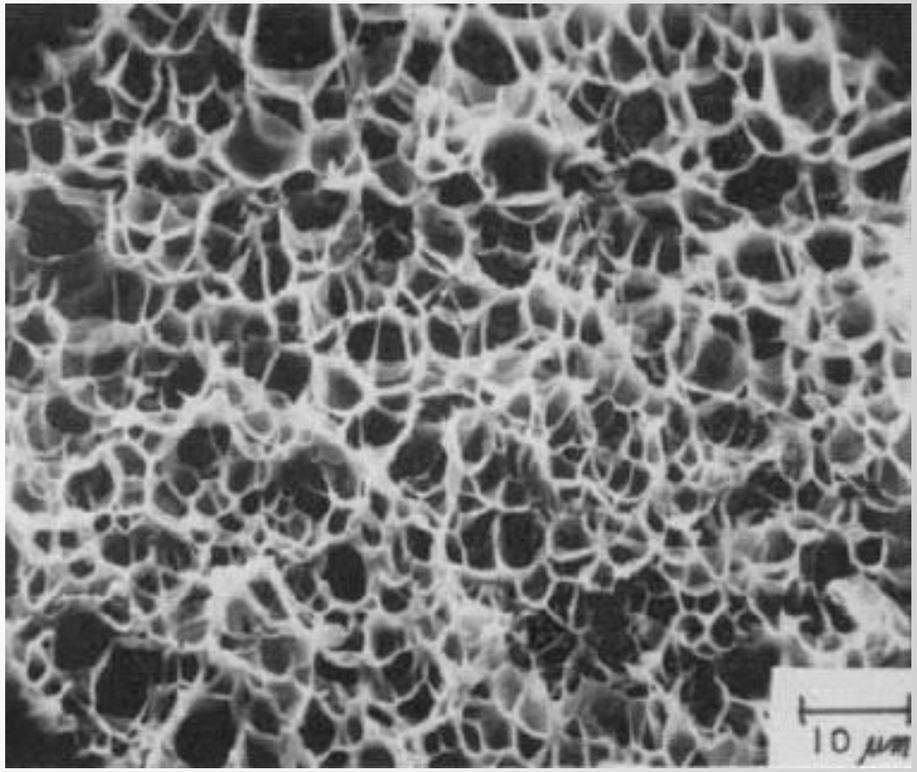


Colton & Suh, Blander & Katz

Homogeneous Nucleation Model (Continued)

Nucleation rate

$$J = N\left[\frac{2\sigma}{\pi m}\right]^{\frac{1}{2}} exp\left[\frac{-16\pi\sigma^3}{3kT[P_v - P_l]^2}\right]$$



J: Nucleation rate (per volume per time)
N: Number of gas molecules (per volume)
m: Molecular mass
σ: surface tension
k: Boltzmann constant
T: Temperature
P_v: Gas pressure
P_l: Polymer resin pressure

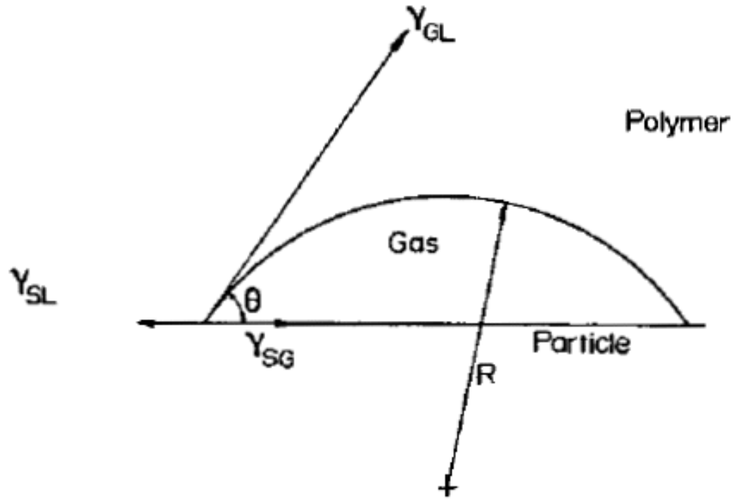
- Generally, nucleation rate is too small with this model

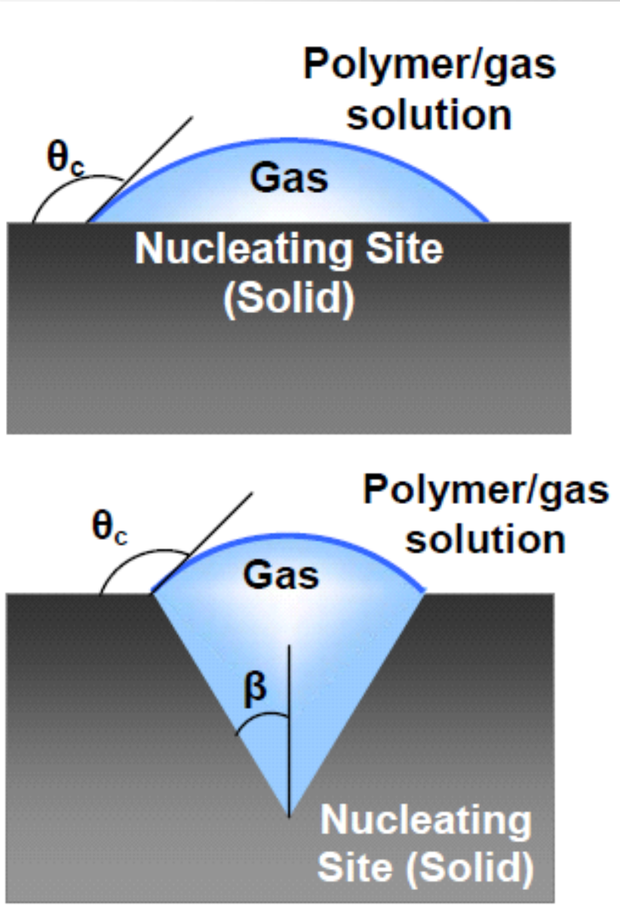
Heterogeneous Nucleation Model

- **Nucleation occurring at interface with solid surface, filler, polymer imperfection**
- **Bubble volume and area are smaller at critical radius**

$$J \sim exp[\frac{-\Delta G}{kT}]$$

$$\Delta G = -V_b \Delta P + A_b \sigma = \frac{16\pi\sigma^3 F(\theta)}{3(\Delta P)^2}$$





Heterogeneous Nucleation Model

- **F(θ) < 1 → Enhances nucleation rate**
- **Generally, nucleation rate is faster with this model**

$$J_{het} = N_{het} Q \left[\frac{2\sigma}{\pi m B}\right]^{\frac{1}{2}} exp\left[\frac{-16 F(\theta) \pi \sigma^3}{3kT[P_v - P_l]^2}\right]$$

$$Q = \frac{1 + cos(\theta)}{2}, \qquad F = \frac{2 + 3\,cos(\theta) - cos^3(\theta)}{4}$$

N_{het}: Number of heterogeneous sites

Sample Calculations

- **Calculate nucleation rate for a typical case with N_2 as a foaming agent**

- $J = N[\frac{2\sigma}{\pi m B}]^{\frac{1}{2}} exp[\frac{-16\pi\sigma^3}{3kT[P_v - P_l]^2}]$ **: Homogeneous nucleation**

- $J_{het} = N_{het} Q[\frac{2\sigma}{\pi m B}]^{\frac{1}{2}} exp[\frac{-16F(\theta)\pi\sigma^3}{3kT[P_v - P_l]^2}]$ **: Heterogeneous nucleation**

κ_h = 1.0e^{-9} (solubility constant), c= 0.5%, P_v = c / κ_h (5 MPa), P_l=0, T = 500 K
σ = 0.02 N/m

J= 1.32x10^{-299} for homogeneous nucleation

J_{het} = 6.68x10^{4} for heterogeneous nucleation with F = 0.1

Sensitivity of Nucleation Rate on Material Data (Heterogeneous)

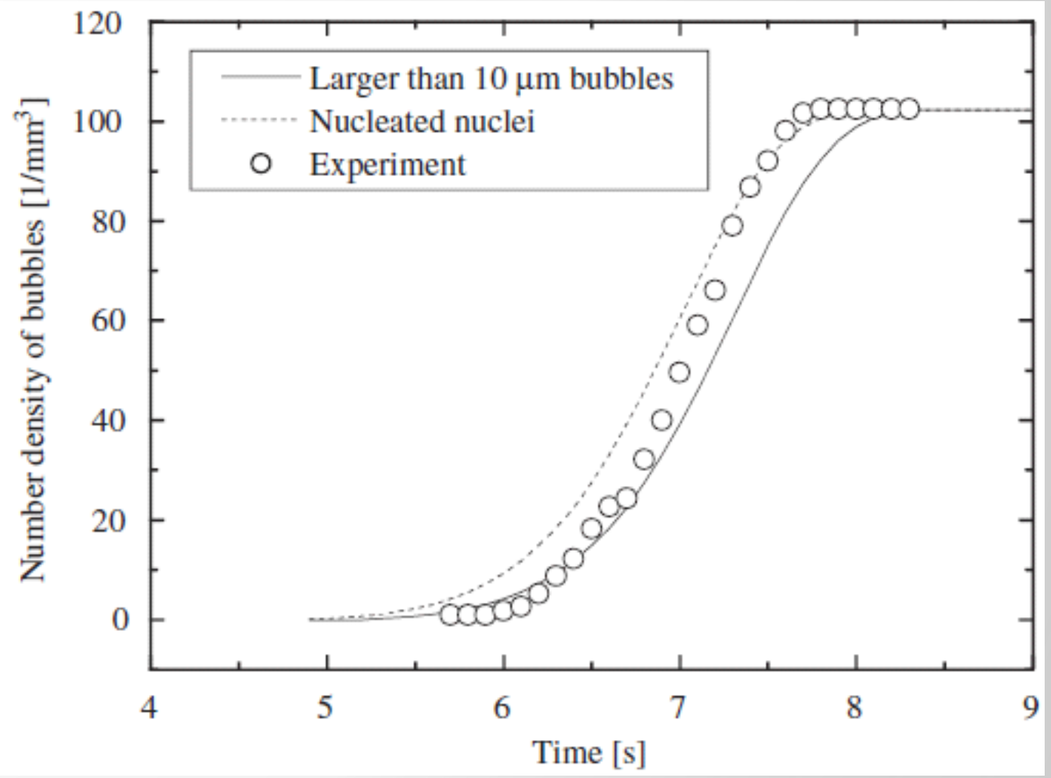
- For a typical case, P_v = 5 MPa, P_l=0, T = 500 K, σ = 0.02, N_2 , F = 0.1
- $J_{het} = N_{het} Q [\frac{2\sigma}{\pi m B}]^{\frac{1}{2}} exp[\frac{-16F(\theta)\pi\sigma^3}{3kT[P_v - P_l]^2}]$: Heterogeneous nucleation
- J_{het} = 6.68x10^{4} for σ = 0.02, κ_h = 1.0e^{-9} (P_v = c / κ_h)
- J_{het} = 1.86x10^{24} for σ = 0.015, κ_h = 1.0e^{-9}
- J_{het} = 6.97x10^{-15} for σ = 0.02, κ_h = 1.25e^{-9}
- Nucleation rate is very sensitive to material properties and process conditions → Difficult to use in practice

Fitted Nucleation Model

- Fit the nucleation model to the actual nucleation density measurement data from the molding experiment
- Reduce the sensitivity of the nucleation rate calculation
- Currently being used in Moldflow

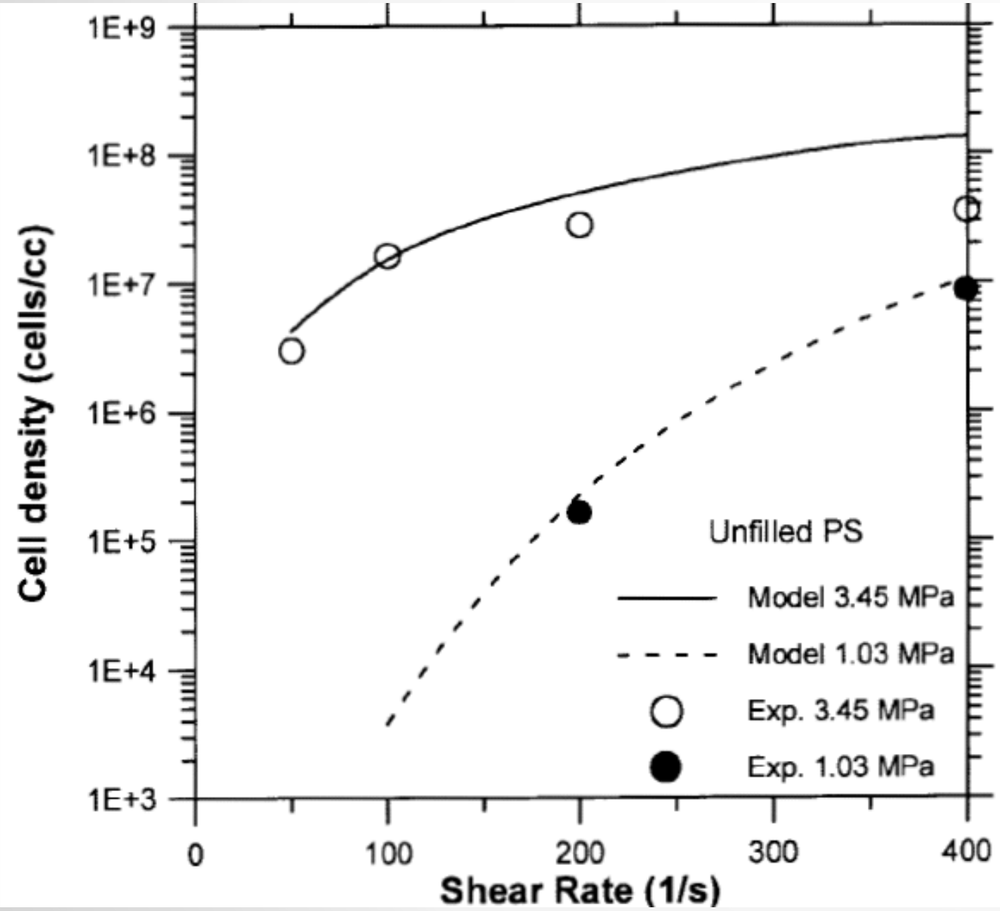
$$J = F_1 N \left[\frac{2\sigma}{\pi m B}\right]^{\frac{1}{2}} exp\left[\frac{-16 F_2 \pi \sigma^3}{3kT[P_v - P_l]^2}\right]$$

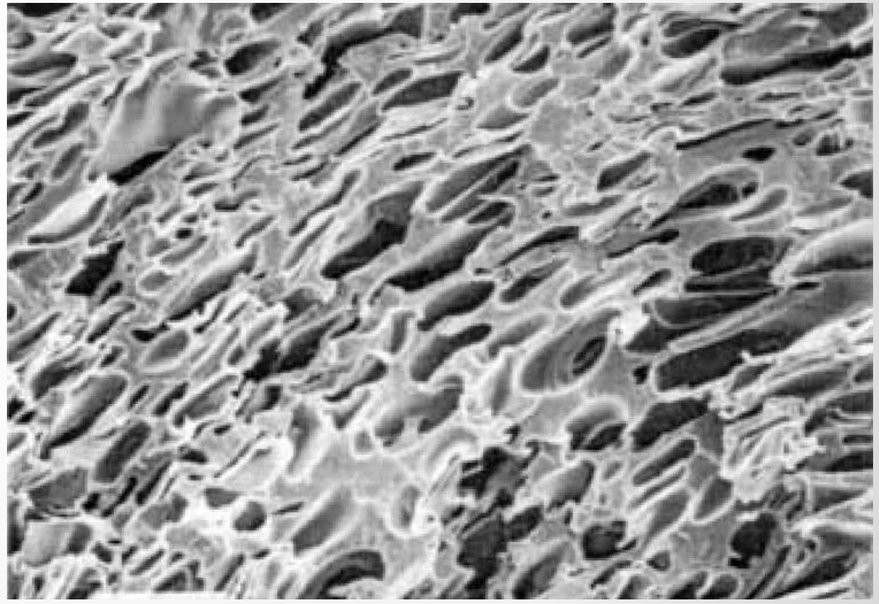
- F_1, F_2: Determined from fitting
- Proposed by Taki
  - ($F_1 = 3.5 \times 10^{-25}$, $F_2 = 0.01408$ for his case)



Limitation: Flow Effect on Nucleation

- **Flow enhances the nucleation rate**
- **Flow can also change the shape of the bubble (elongated bubble)**





Limitation: Crystallization, Filler Effect and Others

- **Crystals and fillers act as a heterogeneous nucleation site → change the nucleation**
- **Other limitations: local stress variation (around bubble), viscoelasticity, fountain-flow**

Material Data Model

- **Accurate material data is needed for accurate nucleation calculation**
- **Surface tension**

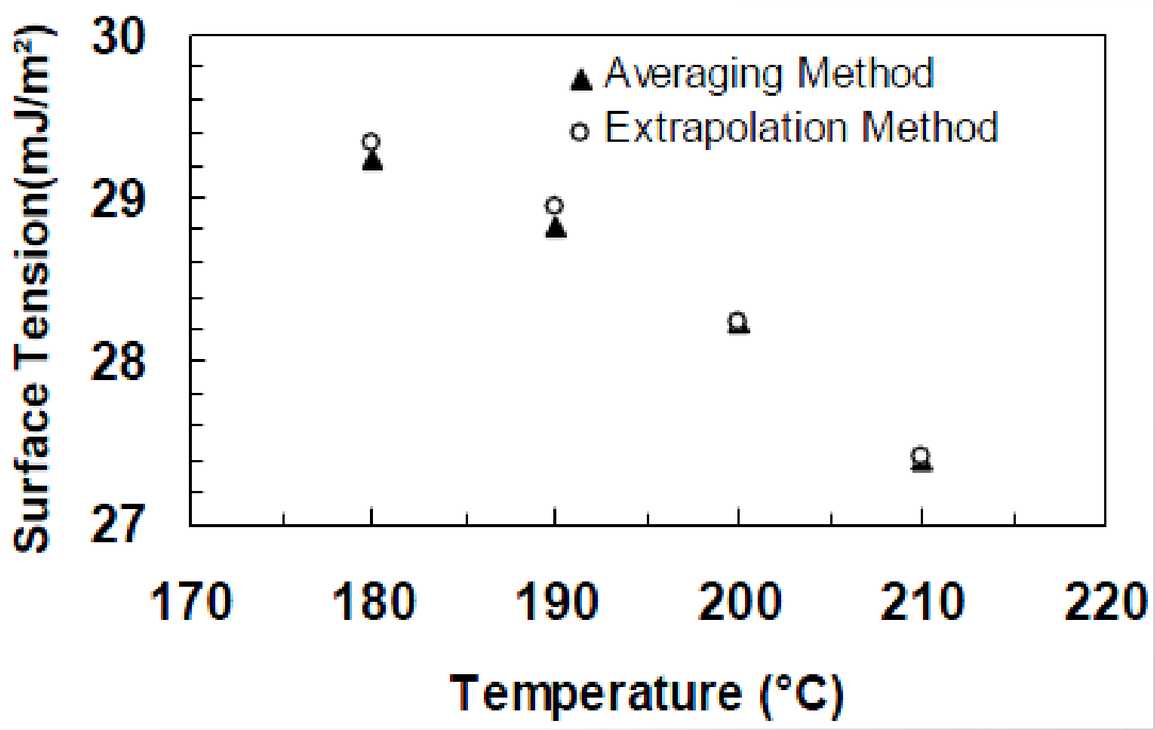
$$\sigma = \sigma_0\left(1 - \frac{T}{T_C}\right)^{11/9} \quad \text{or} \quad \sigma = \sigma_0\left(\frac{\rho}{\rho_0}\right)^4$$

- **Solubility**

$$\kappa_h = \kappa_{h0} exp\left(\frac{\kappa_{h1}}{T^2}\right)$$

- **Diffusivity**

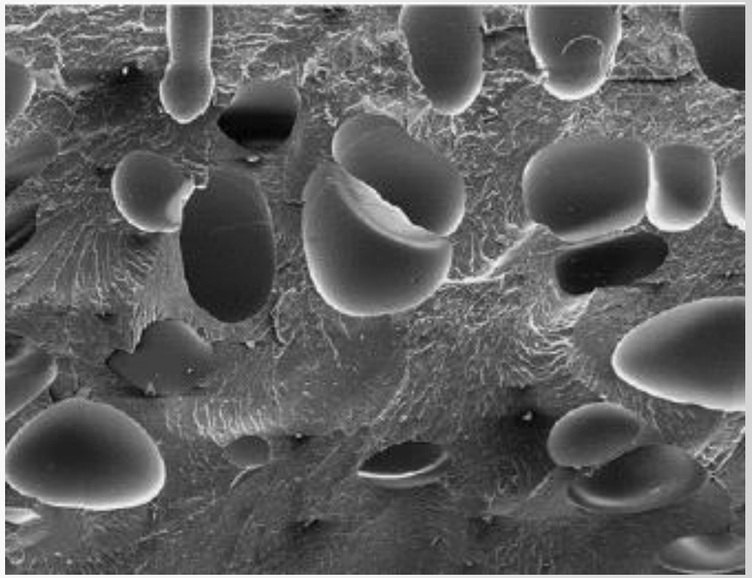
$$D = D_0 exp\left(\frac{D_1}{T}\right)$$



Bubble Nucleation Model Implementation

- **Added bubble nucleation model to mid-plane, dual-domain & 3D**
  - **Calculate bubble number density**
  - **Nucleation rate depends on**
    - **Material properties**
    - **Local temperature and pressure**

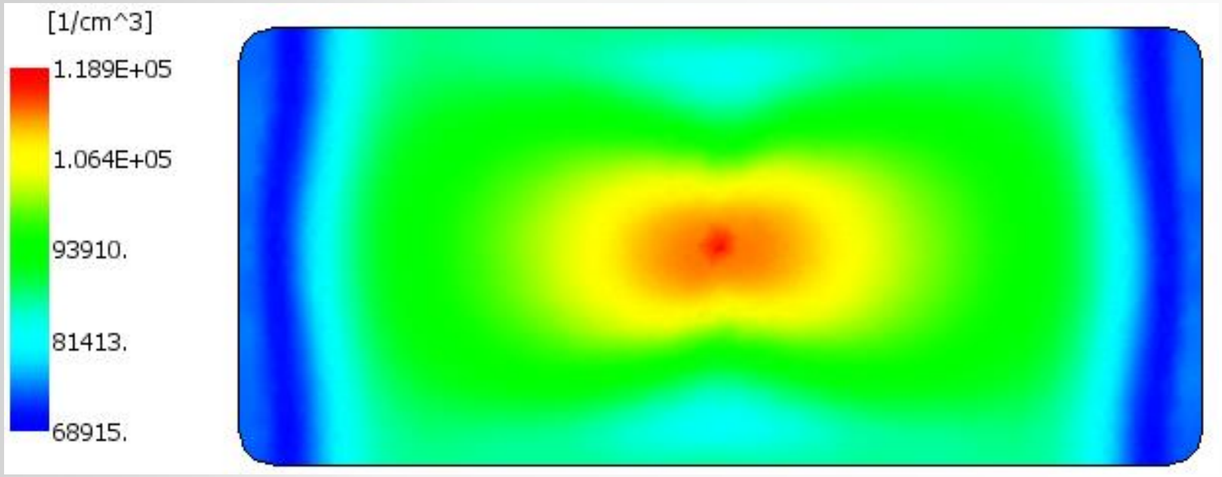
$$J = F_1 N \left[\frac{2\sigma}{\pi m}\right]^{\frac{1}{2}} exp\left[\frac{-16F_2\pi\sigma^3}{3kT[P_v - P_l]^2}\right]$$



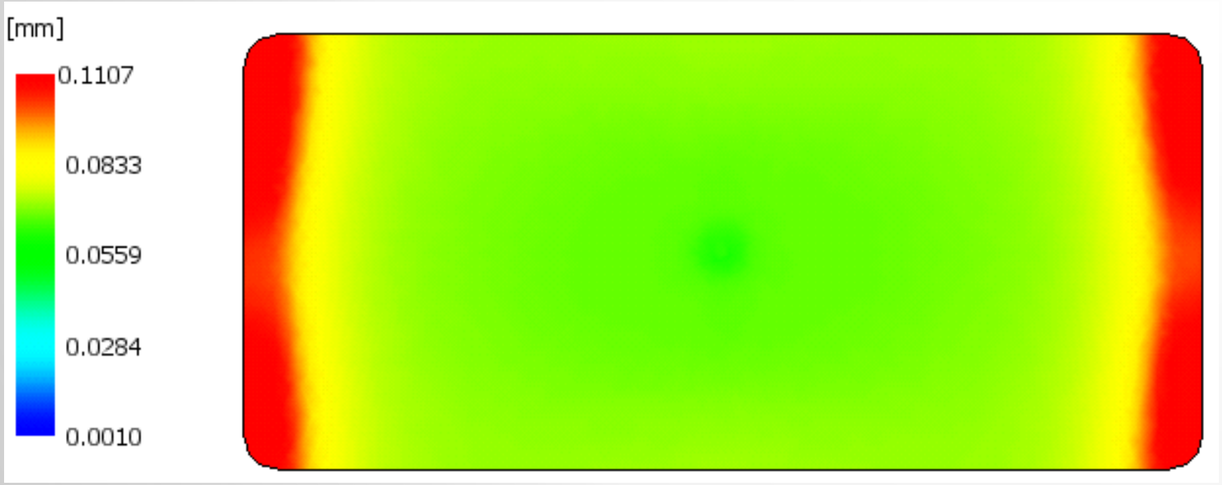
- **Results is non-uniform nucleation prediction**
- **User can select either constant nucleation density option or nucleation model**

Calculation Results for Mid-plane

- **A mid-plane case for a rectangular plate**



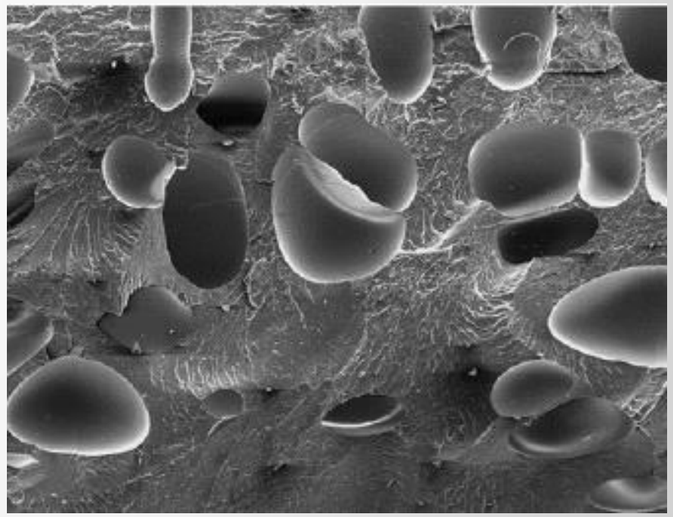
Bubble number density



Bubble radius

Topics

- Bubble nucleation model
- **Input data changes**
- 3D microcellular simulation developments
- Case studies

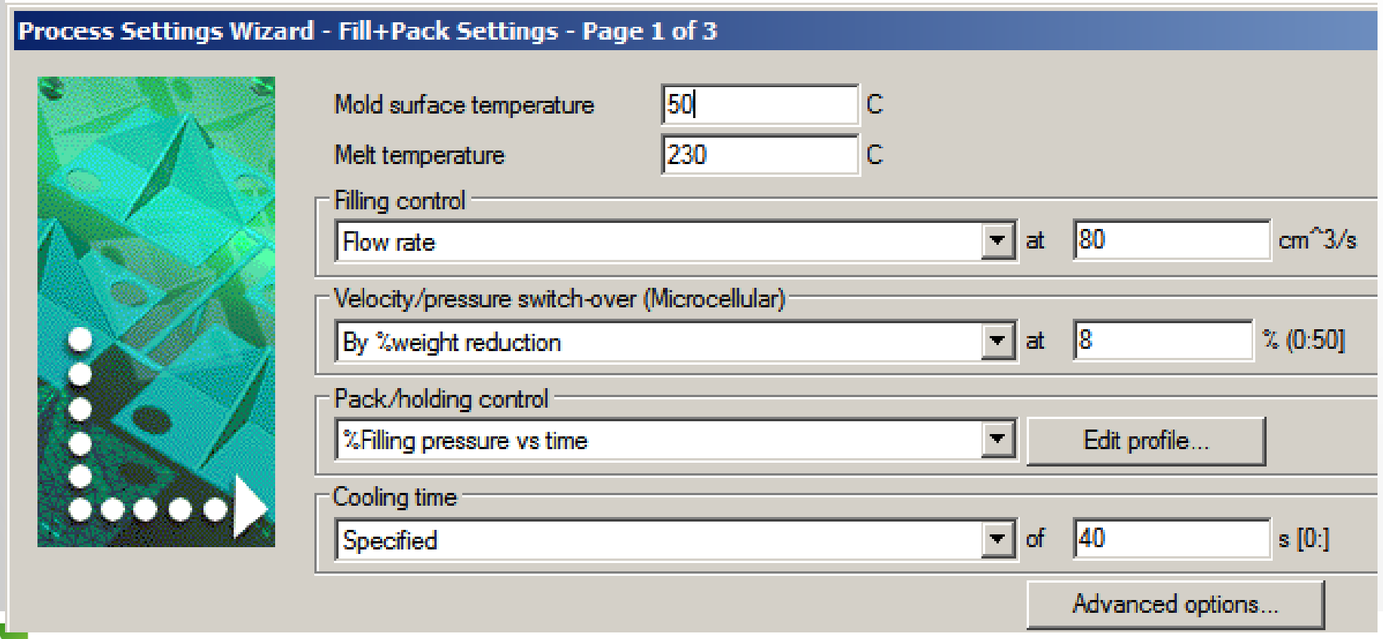


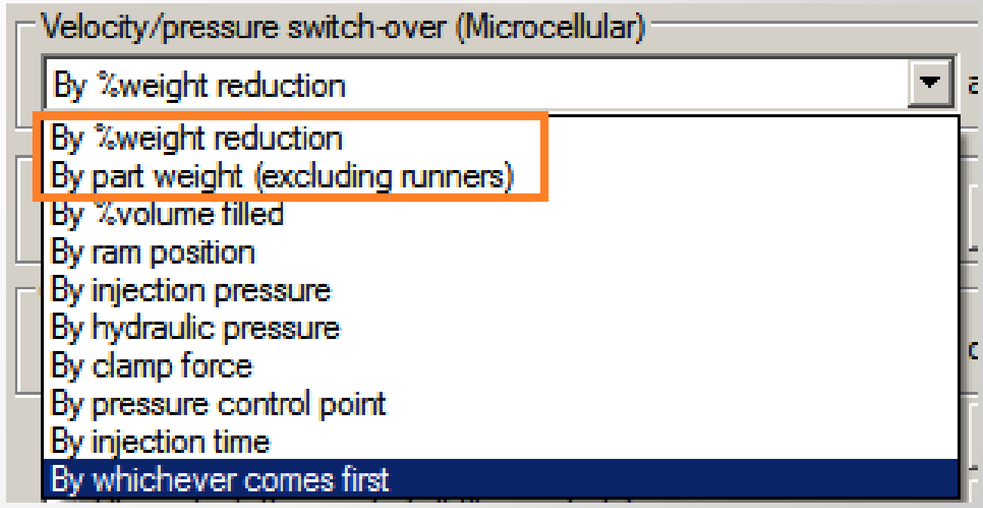
Input Data Change Microcellular Injection Molding

- Input data changes were made
  - To make it easier
  - To make it more realistic
- Changes include
  - Removal of “volume filled at start of foaming”
  - Removal of “initial bubble radius”
  - Changes in V/P switch-over
  - Foaming gas selection
  - Initial gas amount input option
  - Bubble nucleation model
  - Microcellular material data
- Some old mid-plane/DD study files: May not be compatible

Input Data Change for Microcellular Injection Molding

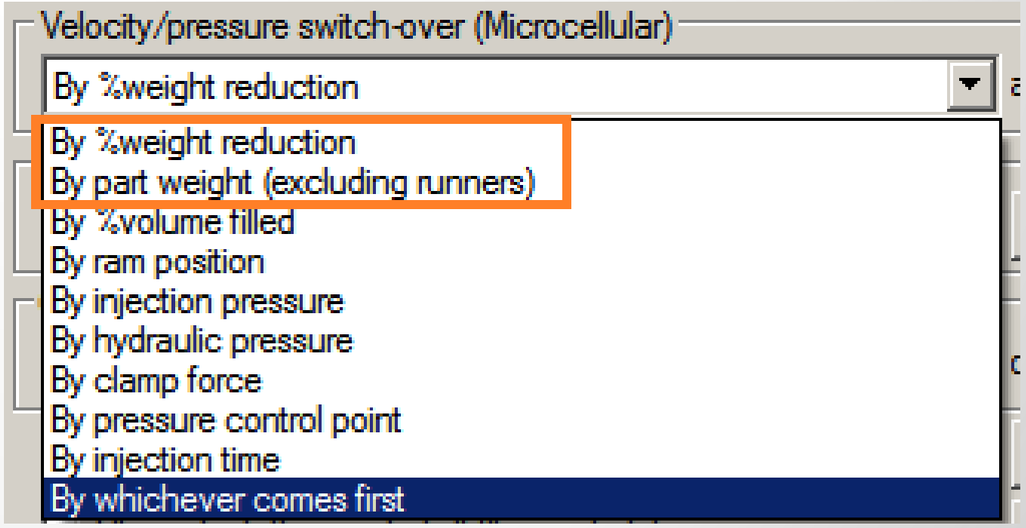
- **“Volume filled at start of foaming”: Replaced by V/P switch-over**
- **“Initial bubble radius”: Removed**
- **Special V/P switch-over options for Microcellular process**
  - **By %weight reduction**
  - **By part weight**





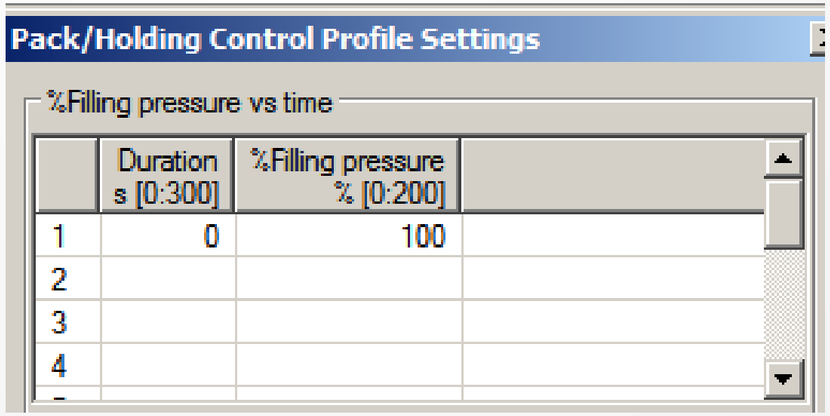
V/P Switch-over by Weight Reduction (or Weight)

- **% Weight reduction: Reduction of the part weight produced by Microcellular process compared to regular injection molding**
- **Weight of the injection molded part: Estimated from part volume and material data (PVT, transition temperature) → Can have some error**
- **Can also input the target part weight directly**

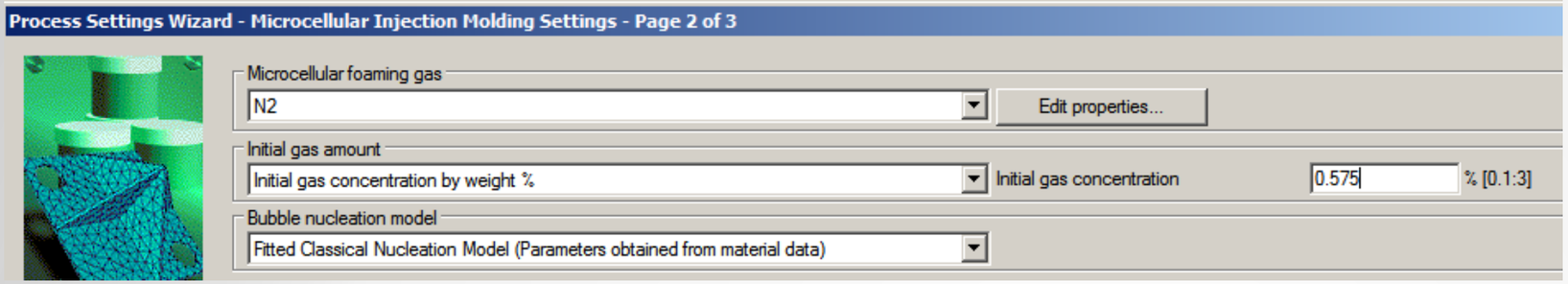


Packing Pressure

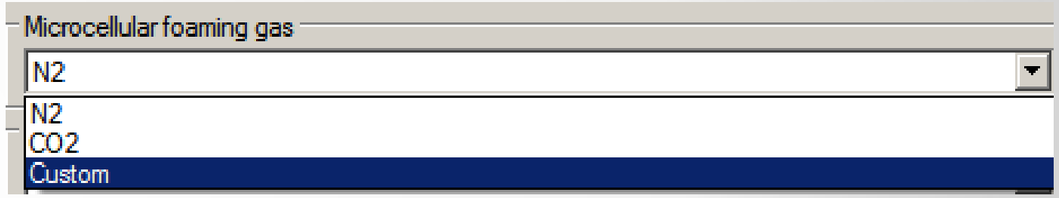
- **Typically no packing or a short and low packing for a Microcellular process**
- **Default is 0 packing time**
- **Use of packing time will reduce the weight reduction from the specified value**

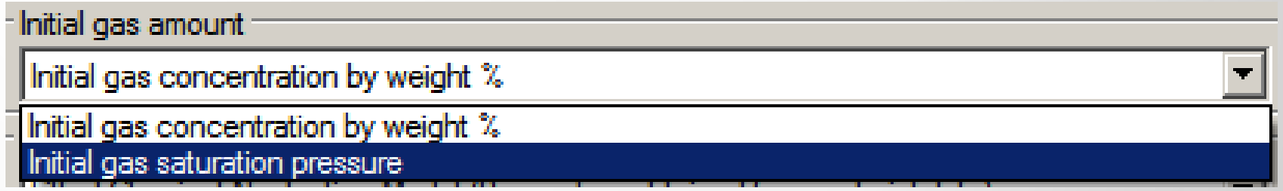


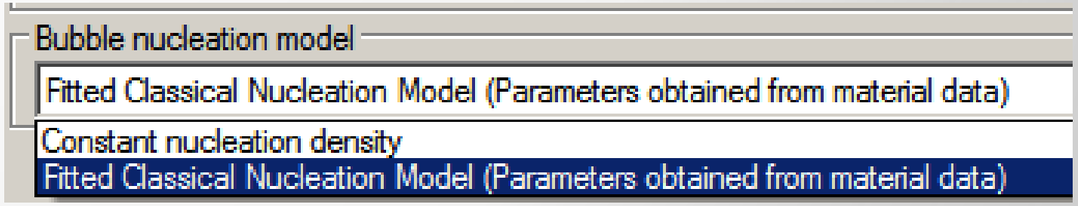
Microcellular Process Setting



- **Foaming gas**
  - **N2, CO2, Custom**
- **Initial gas amount**
  - **By weight %**
  - **By saturation pressure**
- **Bubble nucleation model**
  - **Constant nucleation density**
  - **Fitted classical nucleation model**

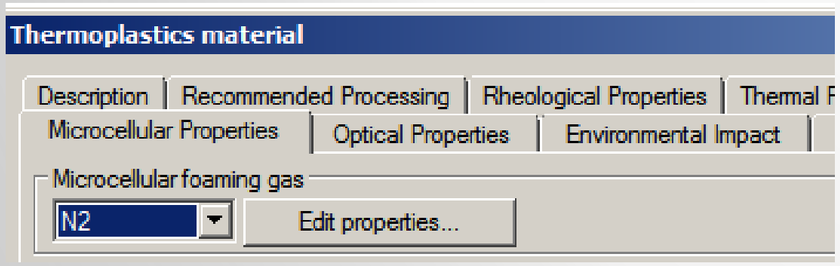


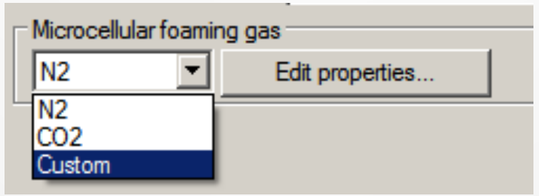


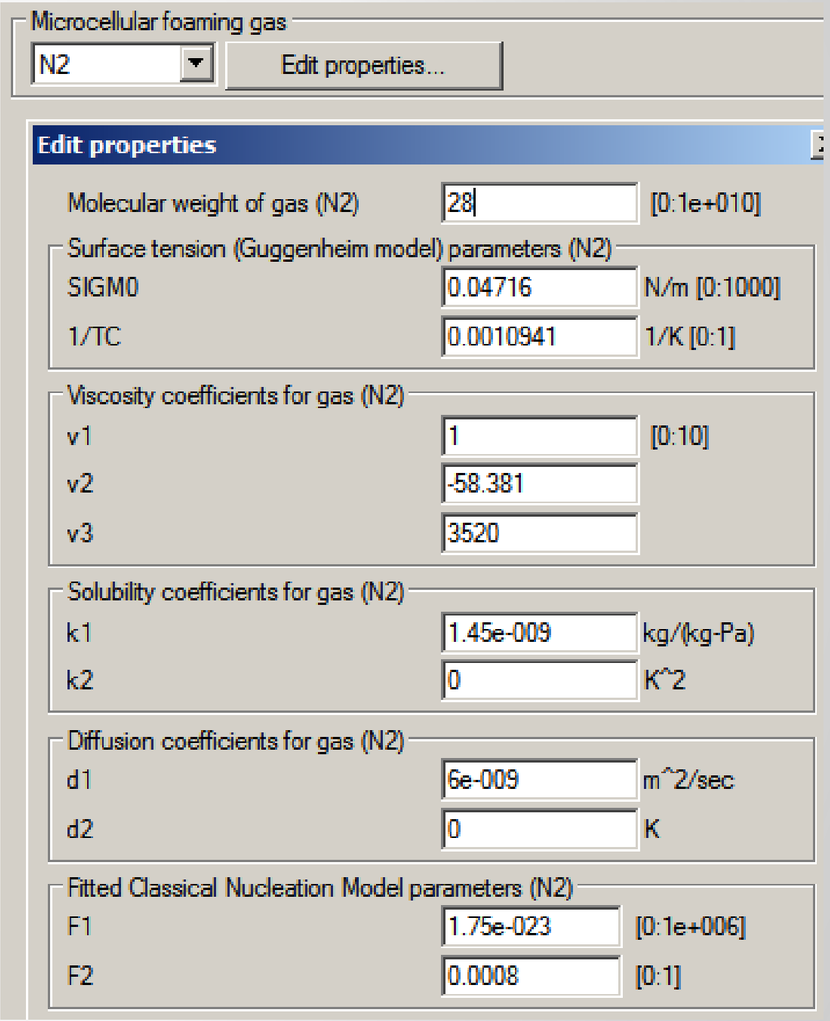


Microcellular Material Data

- **Microcellular material data for 3 types of foaming gas**
  - **N2, CO2, Custom**
- **Data needed**
  - **Molecular weight**
  - **Surface tension**
  - **Viscosity coefficients for gas**
  - **Solubility**
  - **Diffusion coefficient**
  - **Nucleation model parameters**

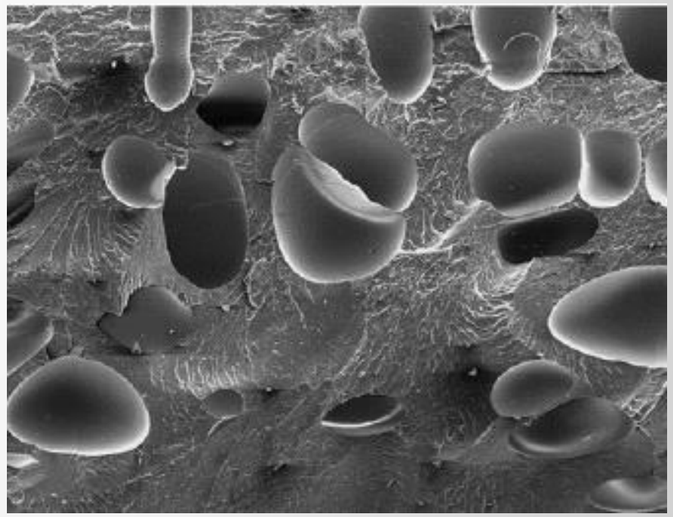






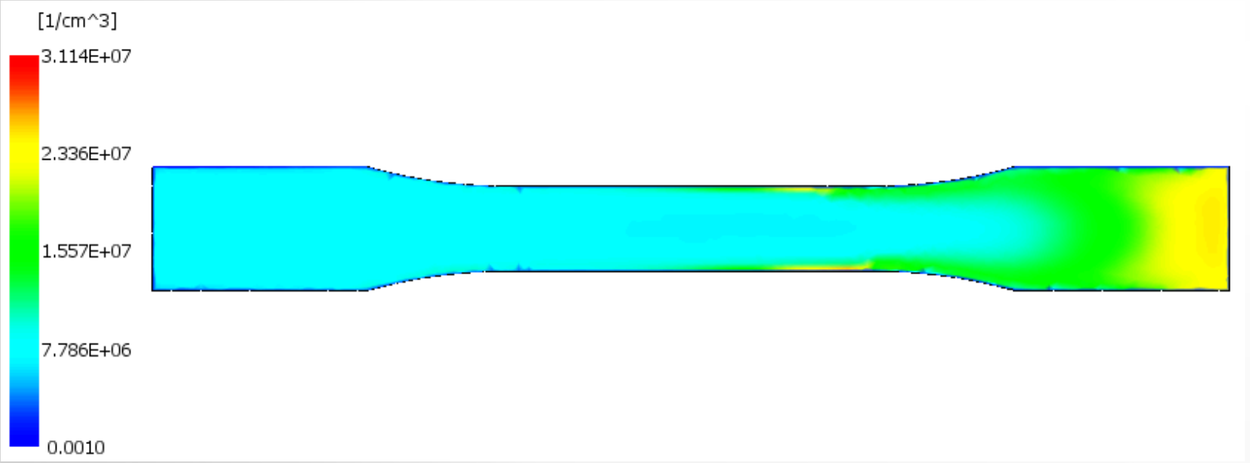
Topics

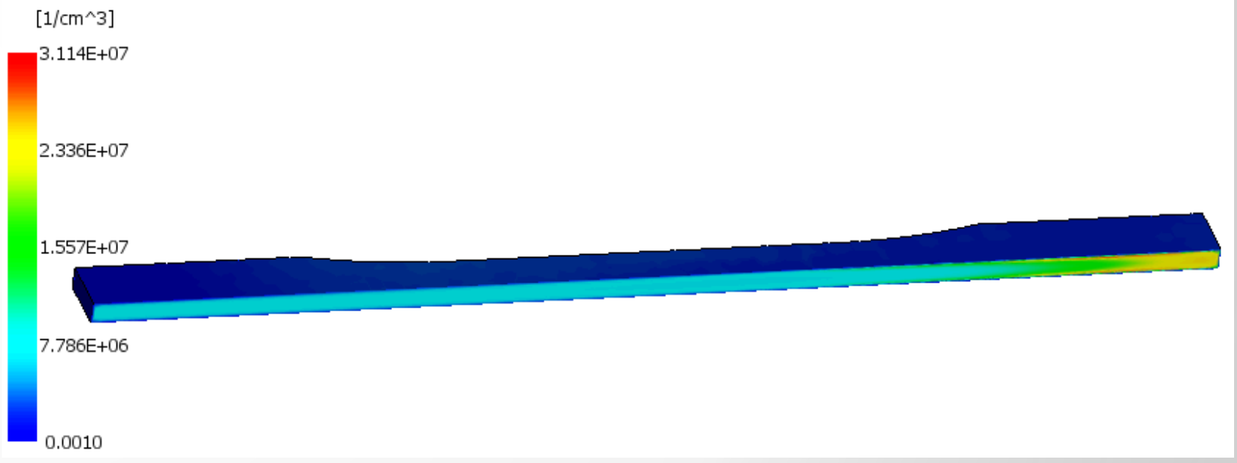
- Bubble nucleation model
- Input data changes
- **3D microcellular simulation developments**
- Case studies



3D Microcellular Injection Molding Simulation

- **Extend microcellular foaming simulation to 3D**
  - **Bubble radius / pressure / number density calculation**
- **Bubble nucleation calculation result for 3D**
- **Adequate for thick parts or complicated geometry parts**

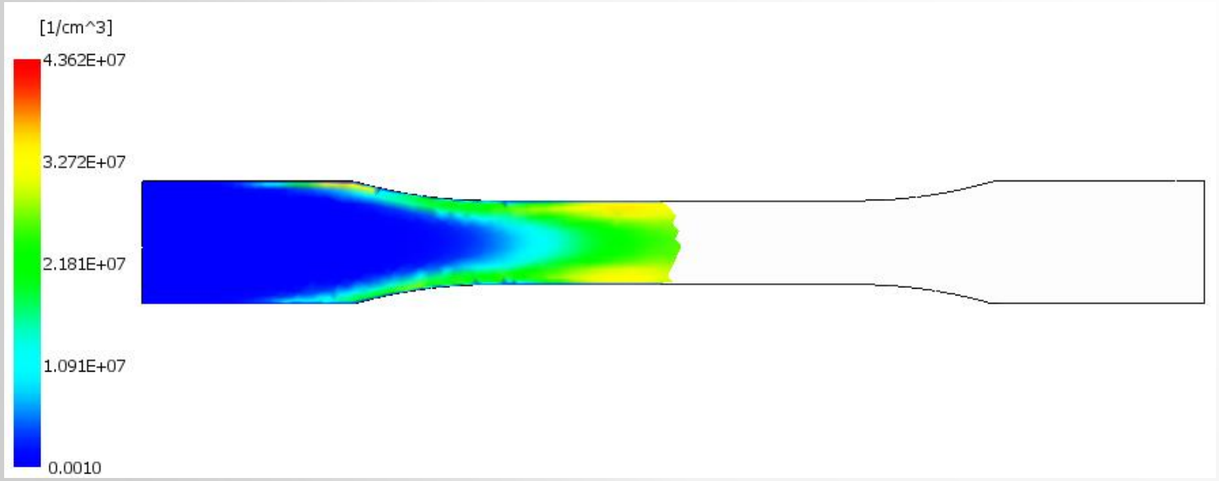


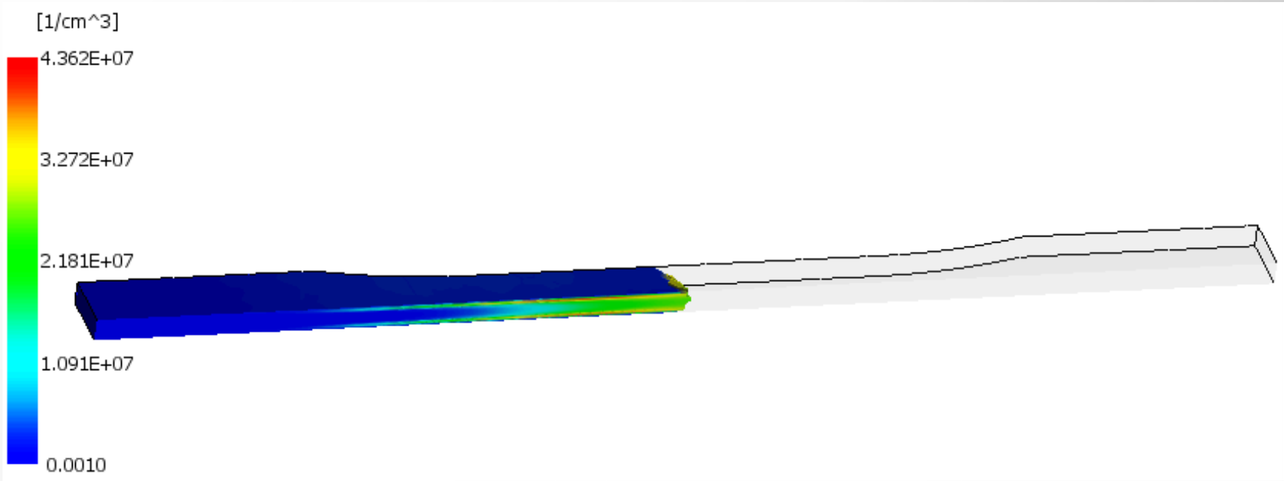


PP with N_2
0.575% gas weight

3D Microcellular Injection Molding Simulation

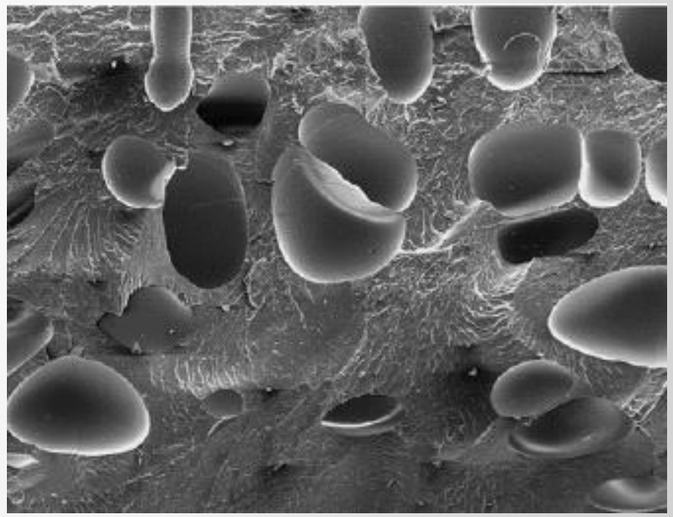
- In 3D, bubble nucleation / growth simulation starts from the start of filling
  - In mid-plane/dual-domain, it starts at the end of V/P switch-over / packing
- Bubble nucleation calculation result for 3D
- More 3D results in examples





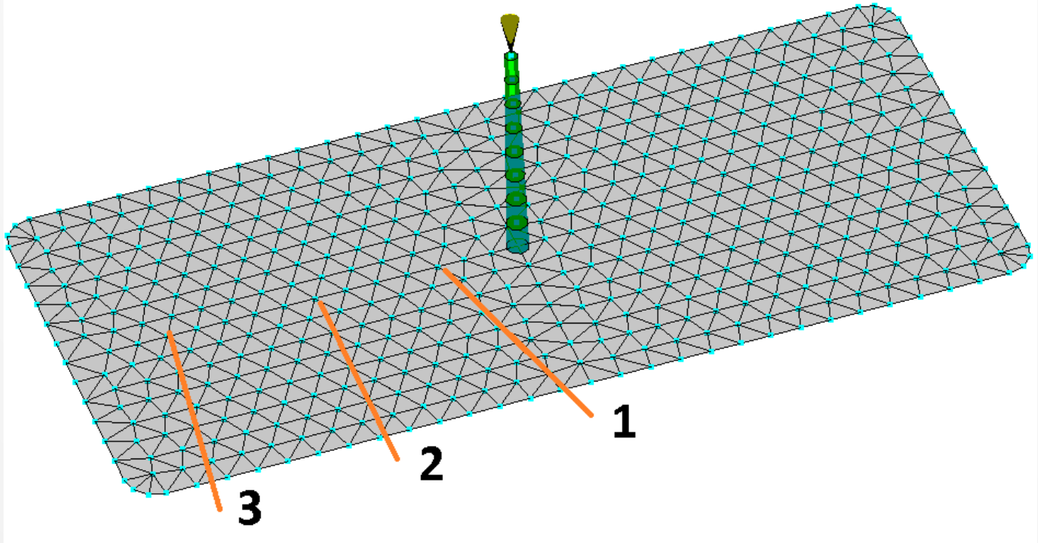
Topics

- Bubble nucleation model
- Input data changes
- 3D microcellular simulation developments
- **Examples**



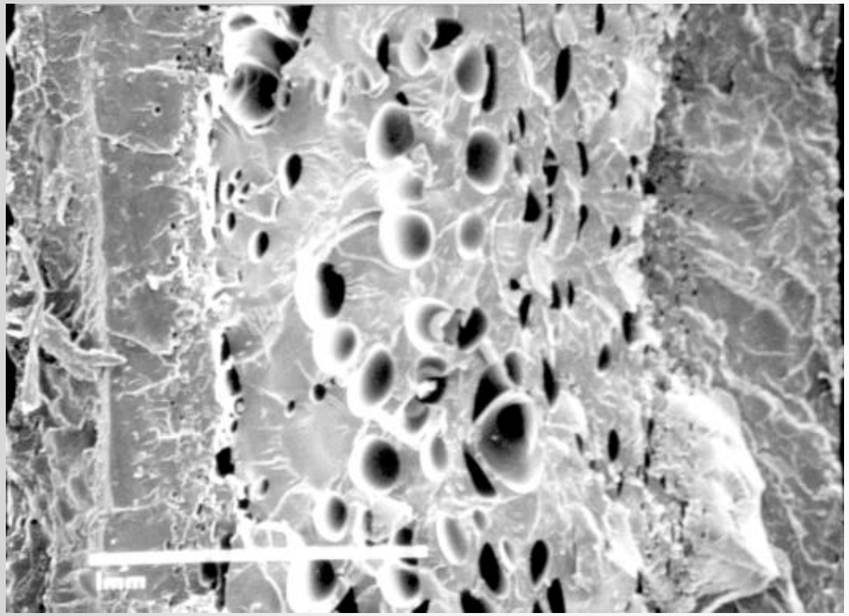
Example 1

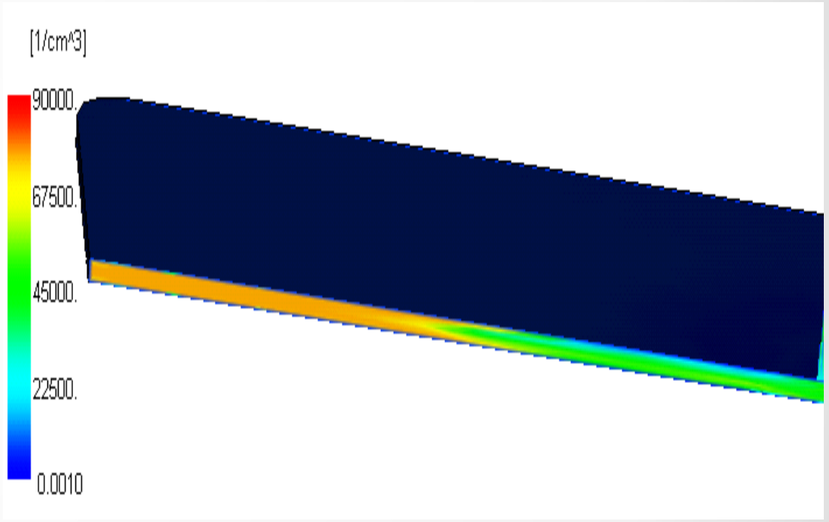
- **Microcellular injection molding of a rectangular plate**
  - **Material: Polystyrene, N2**
  - **Weight reduction: 5%**
  - **SEM pictures were taken at 3 locations (1, 2, 3) and bubble number densities were determined**

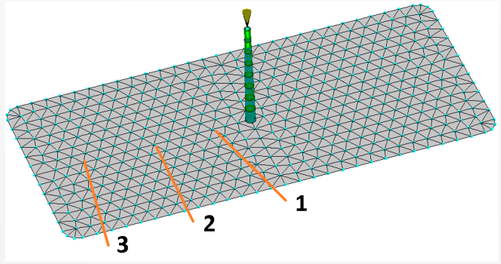


Bubble Number Density

- Comparison of experiment and simulation
- Simulation done for 3D model

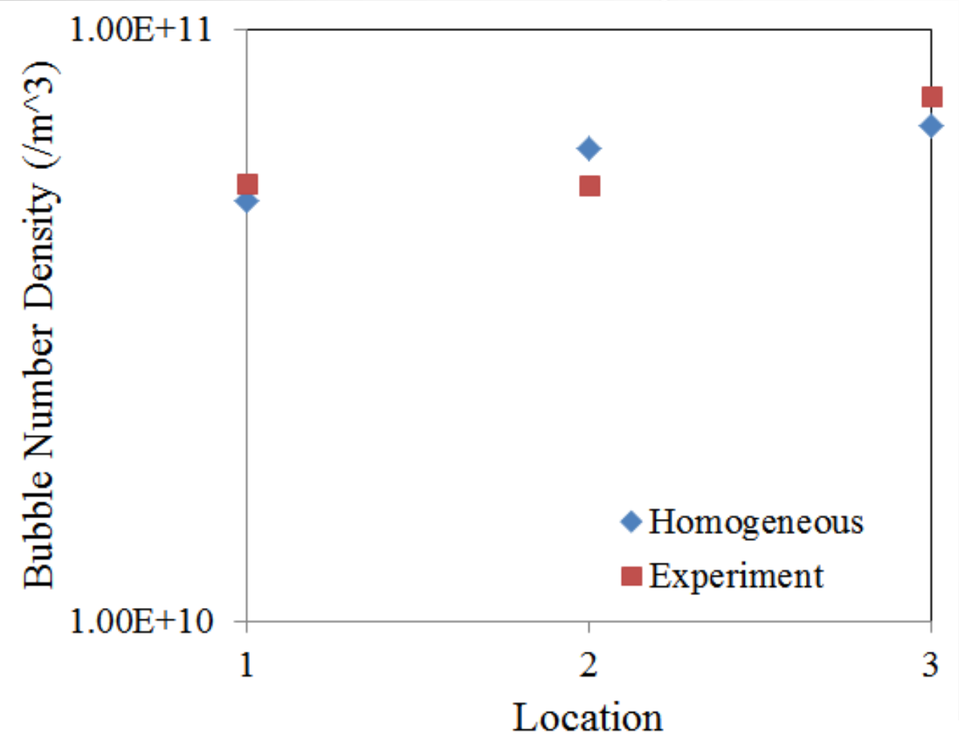


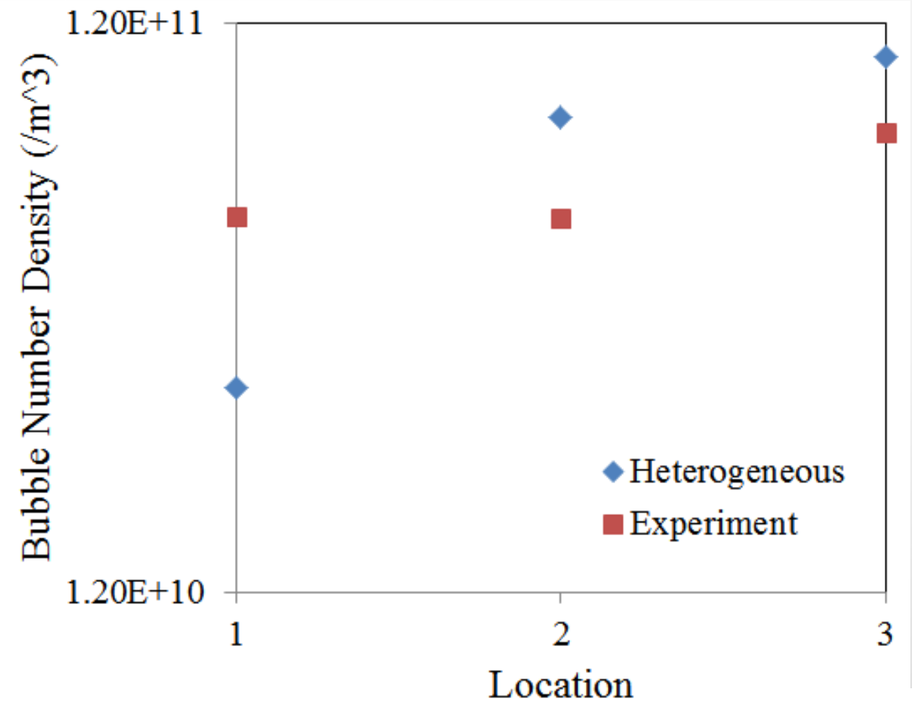


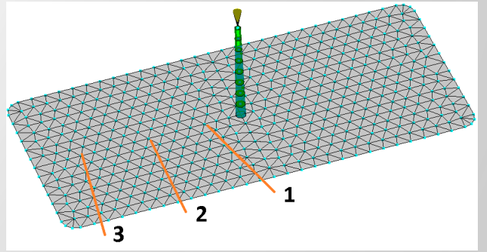


Bubble Number Density: Experiment & Simulation

- **Homogeneous model & Heterogeneous model (not in commercial release)**
  - **Can match the experimental data by optimizing the nucleation parameters**
  - **Nucleation very sensitive to parameter changes and difficult to be**

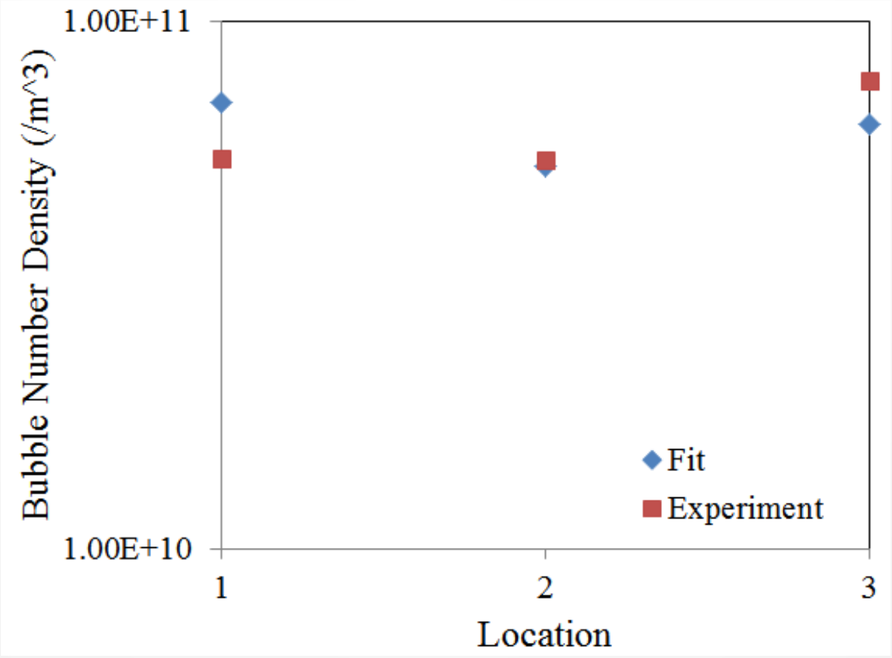


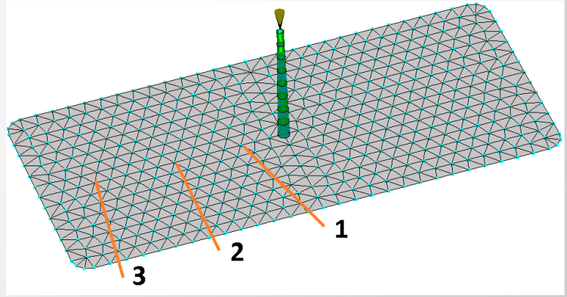




Bubble Number Density: Experiment & Simulation

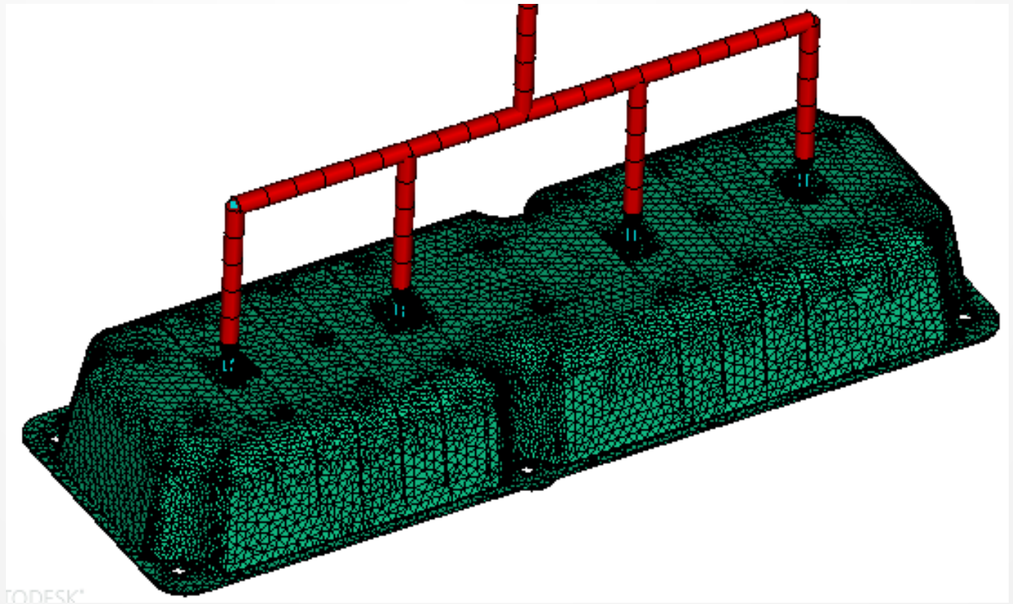
- **Fitted nucleation model**
  - **Can match the experimental data by optimizing the nucleation parameters**
  - **Nucleation not vey sensitive to parameter changes and can be used for similar cases in practice**





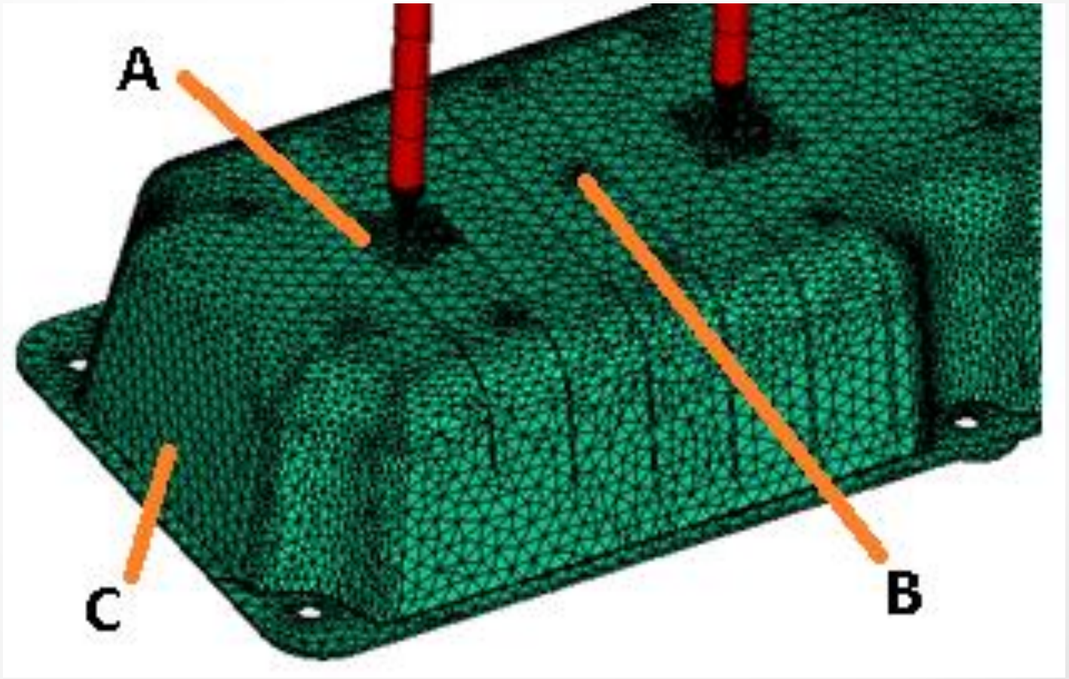
Example 2

- **Microcellular injection molding of a more complicated part**
  - **Material: Polypropylene, N2**
  - **Weight reduction: 8%**
  - **Injection speed: 2 “ / sec**
  - **SEM pictures were taken at various locations for the morphology**



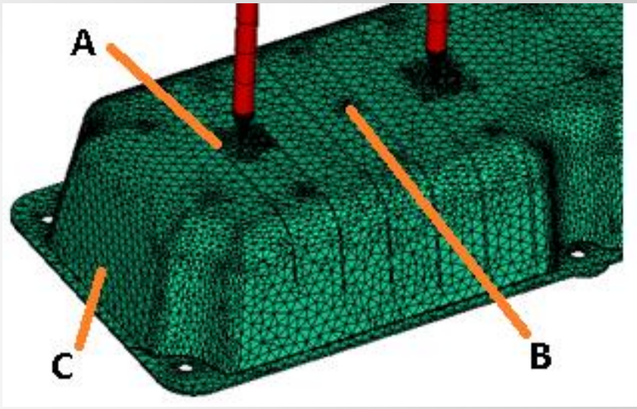
SEM Locations

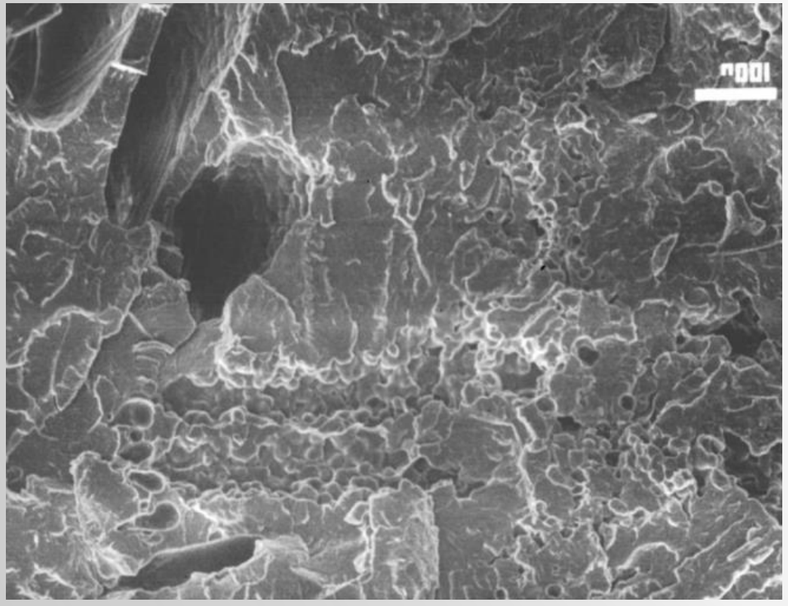
- SEM pictures taken at 3 locations will be used for the comparison with simulation
- Simulation done for 3D model

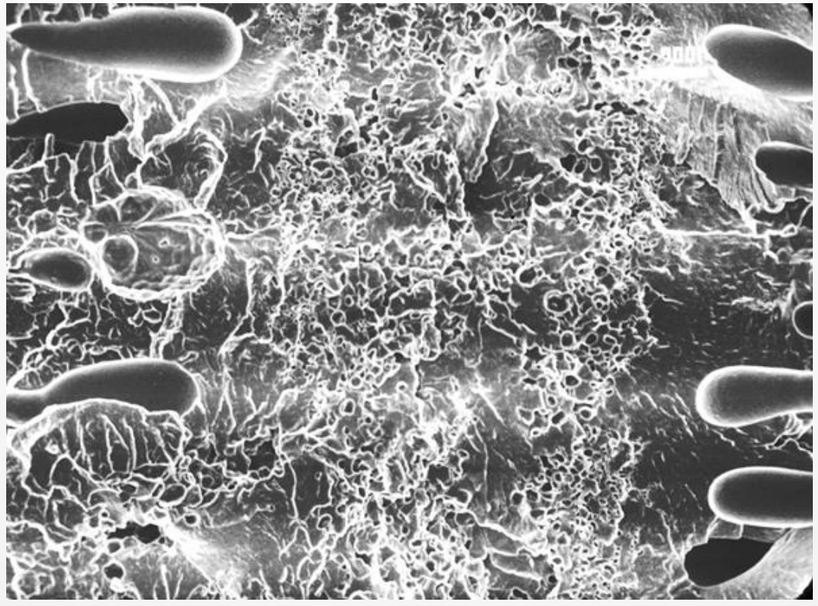


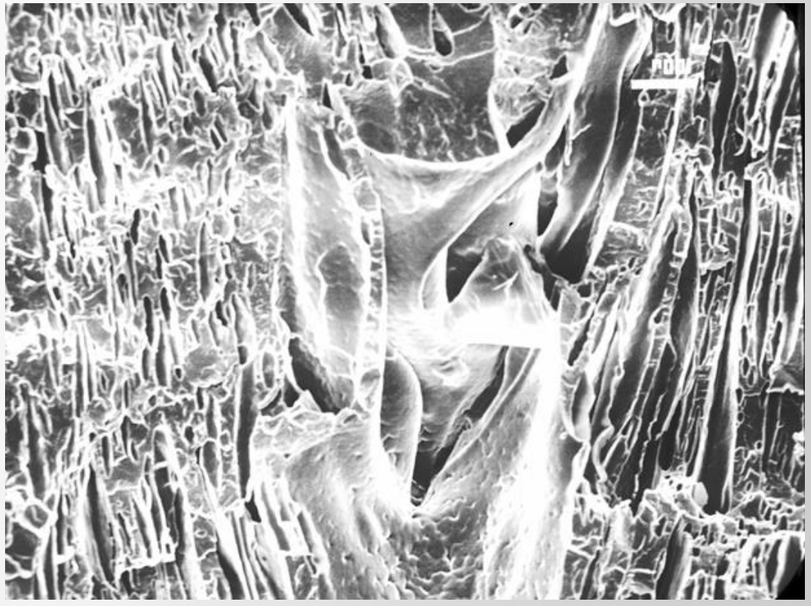
Bubble Morphology

- SEM pictures taken at locations A, B, C
  - A: Near gate: Small number of bubbles
  - B: Between gates: Large number of small bubbles near core, large bubbles near surface
  - C: Near flow end: Elongated bubbles



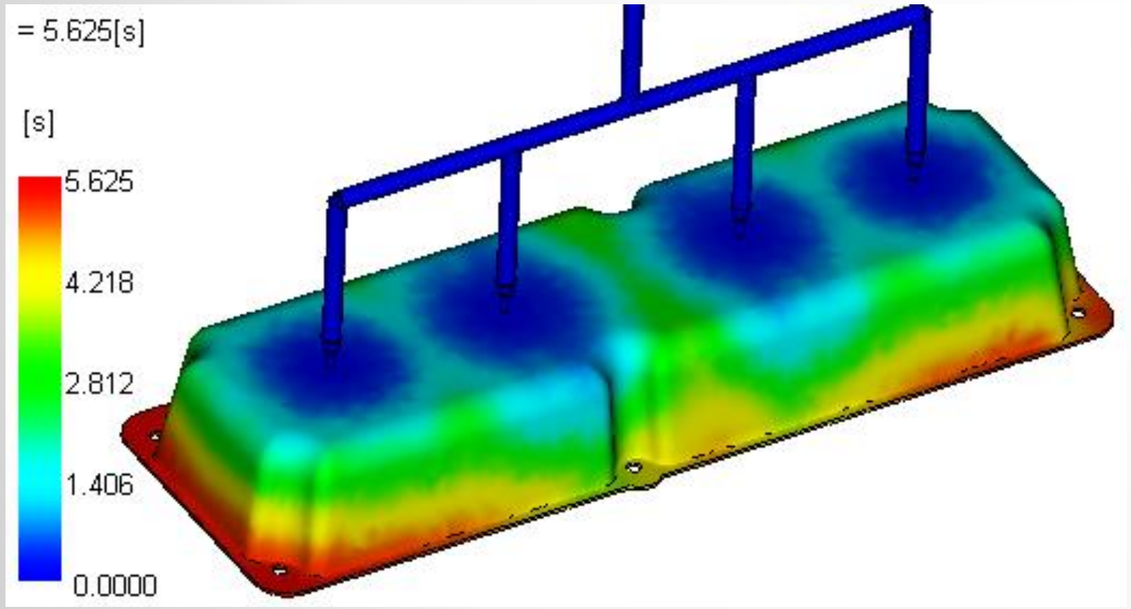


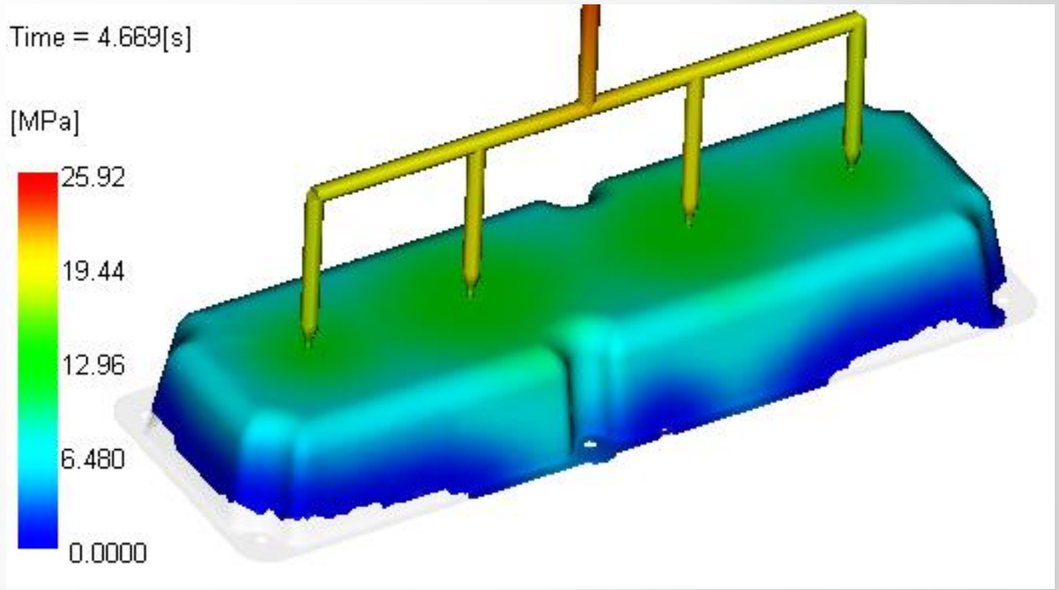




Simulation Results

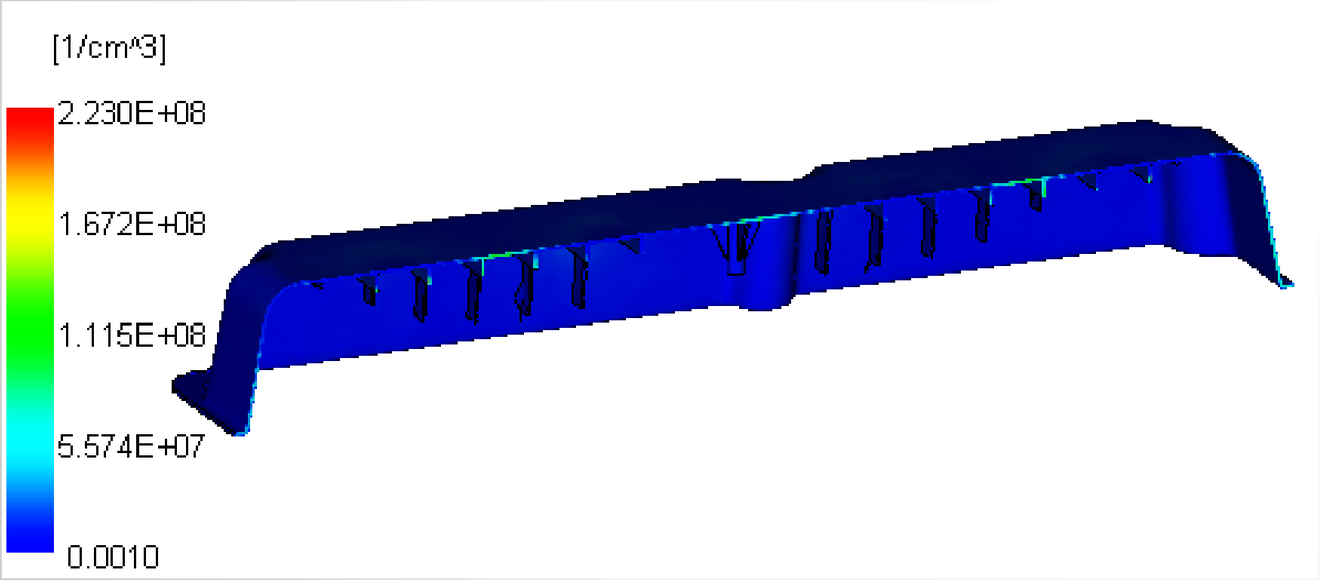
- **Fill time and pressure during filling**

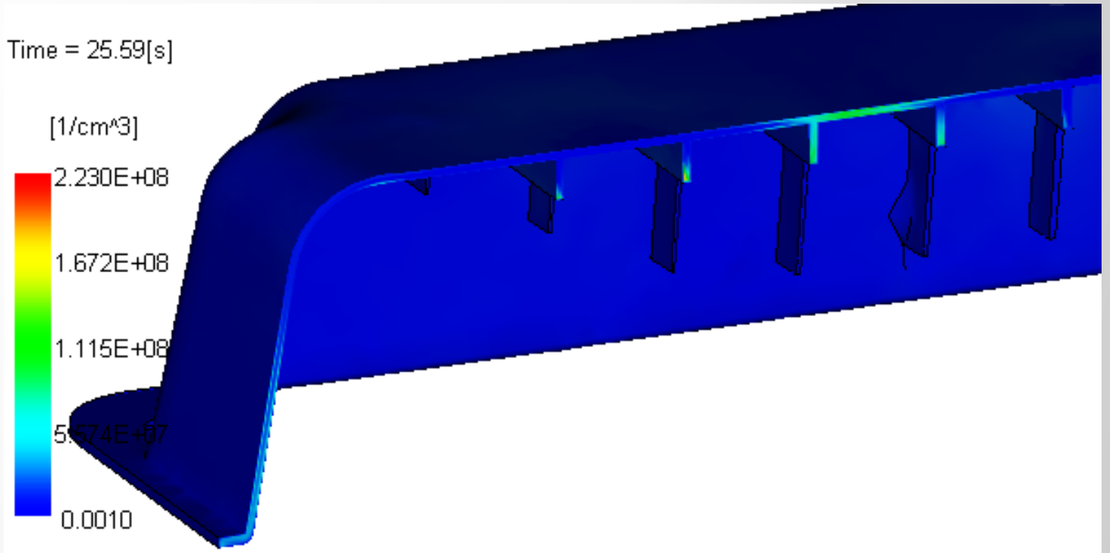




Simulation Results

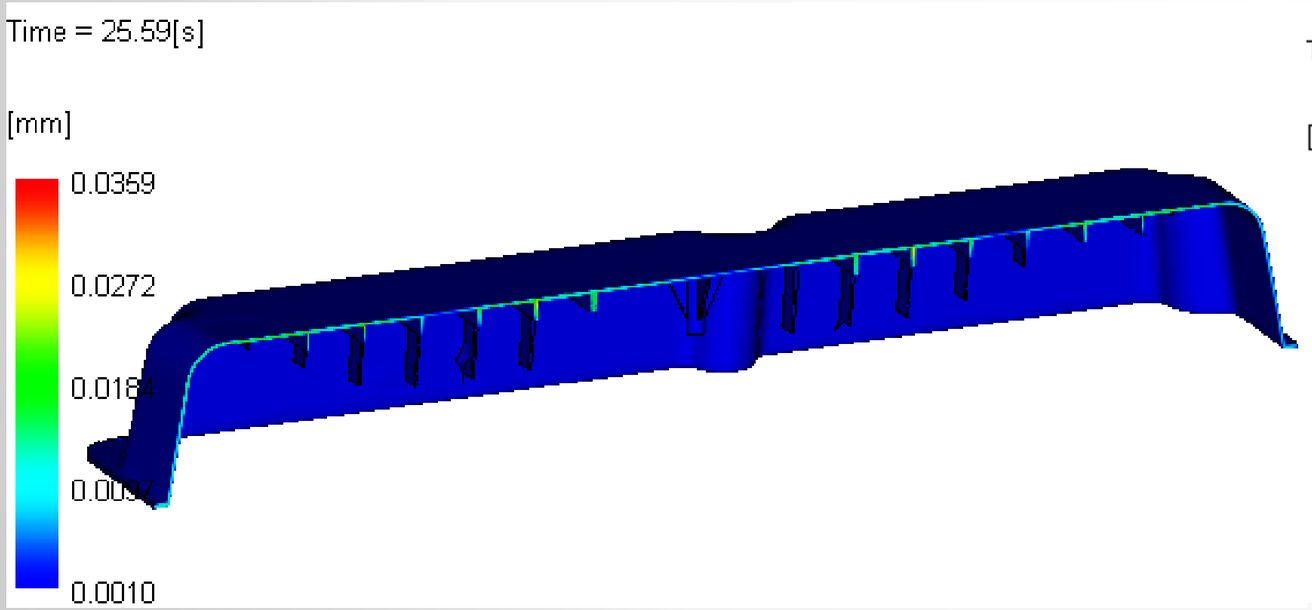
- **Calculated bubble number density**
- **Observations:**
  - **Small number density near gate**
  - **Large number density between gates and end of flow**

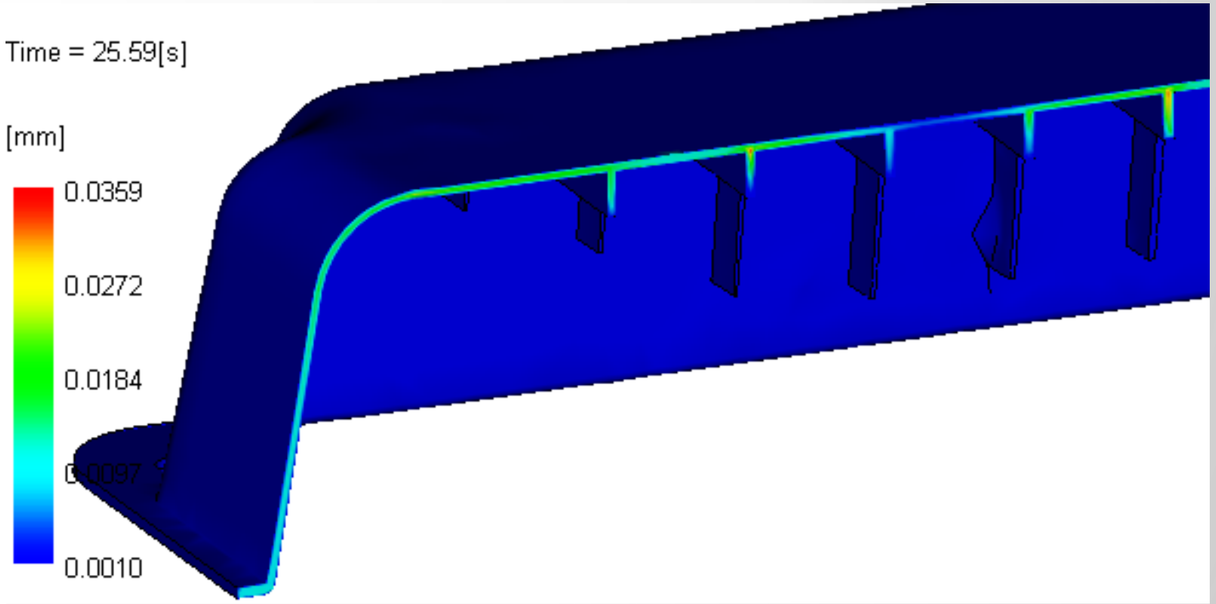




Simulation Results

- Calculated bubble radius
- Observations
  - Large bubble near gate and end of flow
  - Small bubble between gates





Experiment and Simulation

- Simulation can predict some qualitative behaviors
  - Low bubble number density near gate
  - High bubble number density between gates and end of flow
  - Small bubble size at the core between gates
- Limitations
  - Simulation cannot predict elongated (non-spherical) bubble shapes
  - Simulation cannot predict large variations in bubble number density and bubble size in thickness direction

Conclusion

- **The current bubble nucleation model can predict some qualitative behavior, but it needs improvements in the future**
- **The nucleation parameters may need to be adjusted for different cases**
- **3D Microcellular simulation may provide more realistic simulation than mid-plane simulation for some cases**

Future Work

- More research on better nucleation models
  - Flow effect, filler effect, crystallization effect
- Improvement of material property models (surface tension, solubility, density)
- More material data
- More research on bubble growth and collapse model
- Research on the effect of non-spherical bubble shape
- Other microcellular process simulation

Outline

- What is the MuCell Process
- The MuCell Process vs Solid Molding
- Design Optimization for MuCell
- Challenges to Simulation
- Mucell simulation enhancements in AMI 2016
  - Bubble nucleation model
  - 3D simulation
  - Input data changes
- Case studies

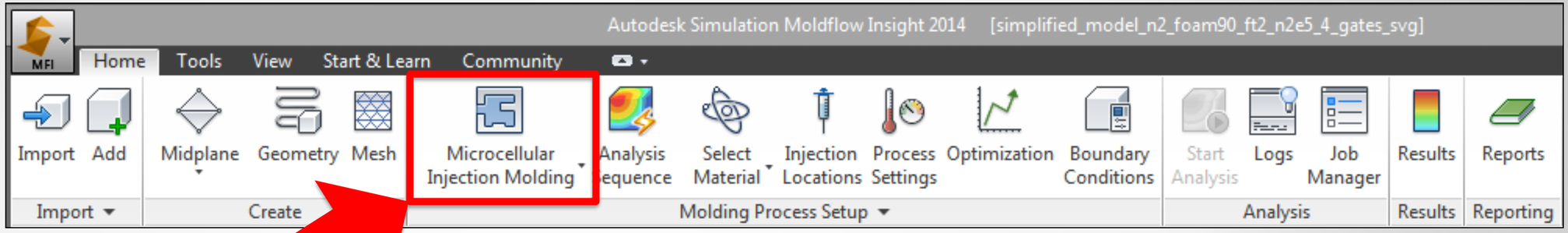
Kudos to Autodesk!

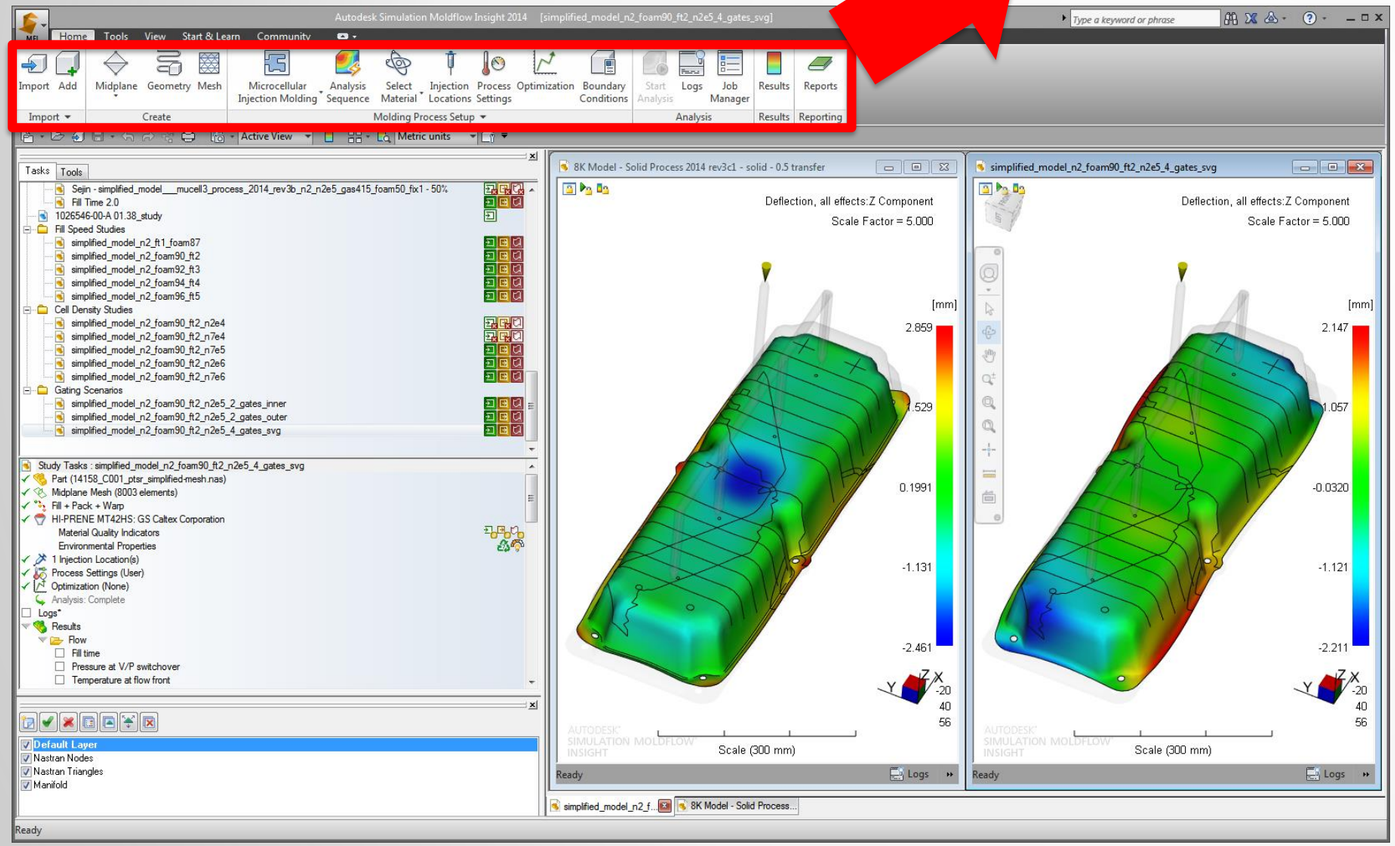
MuCell in Moldflow (Beta 2016)

Moldflow Strategy

- **Balance gate locations**
- **Run simulations with increasing levels of weight reduction**
- **Increase injection speed until filled (promotes cell nucleation)**
- **If full shot is not possible, decrease weight reduction slightly and repeat**

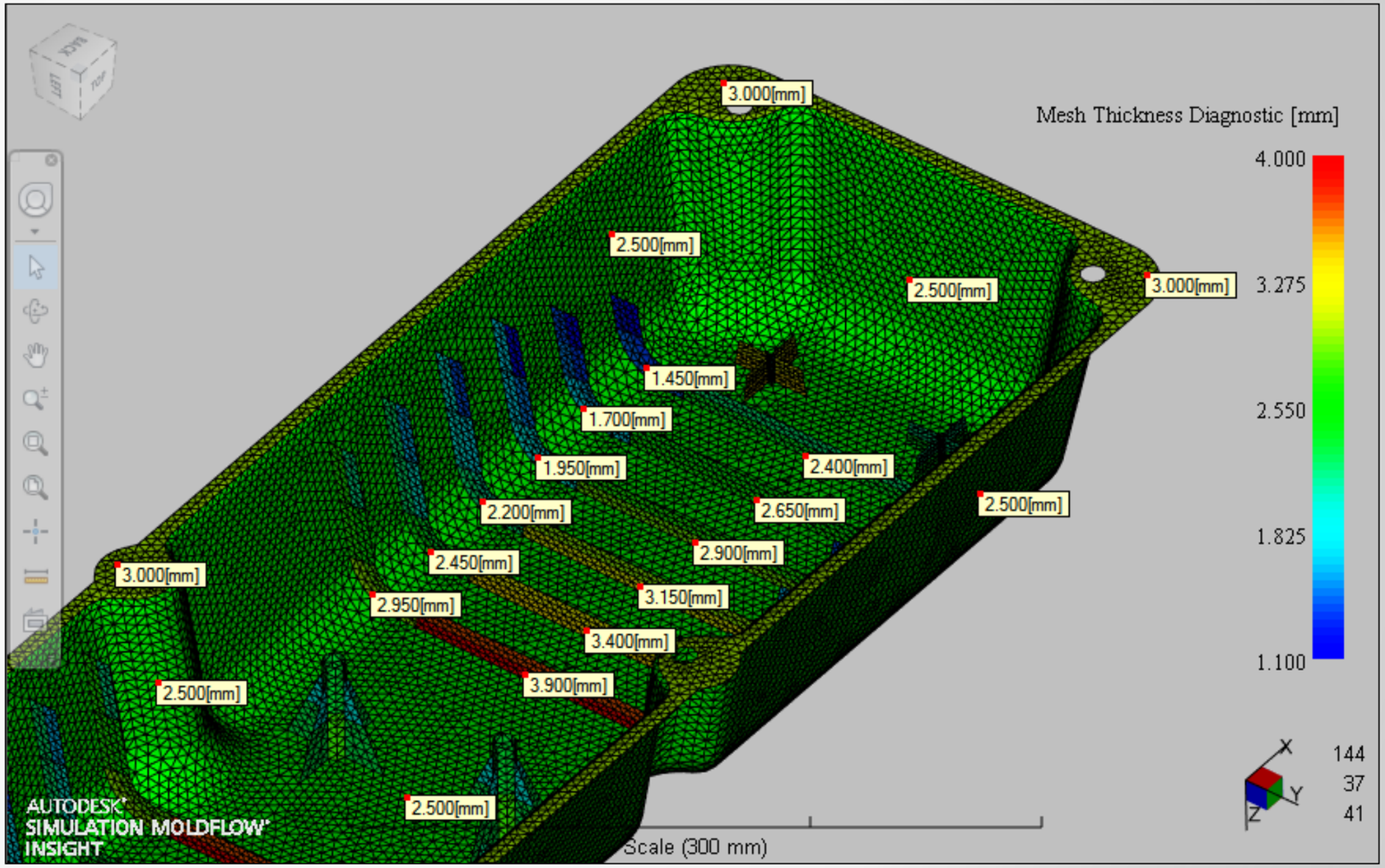
Step 1 - Microcellular Injection Molding Module





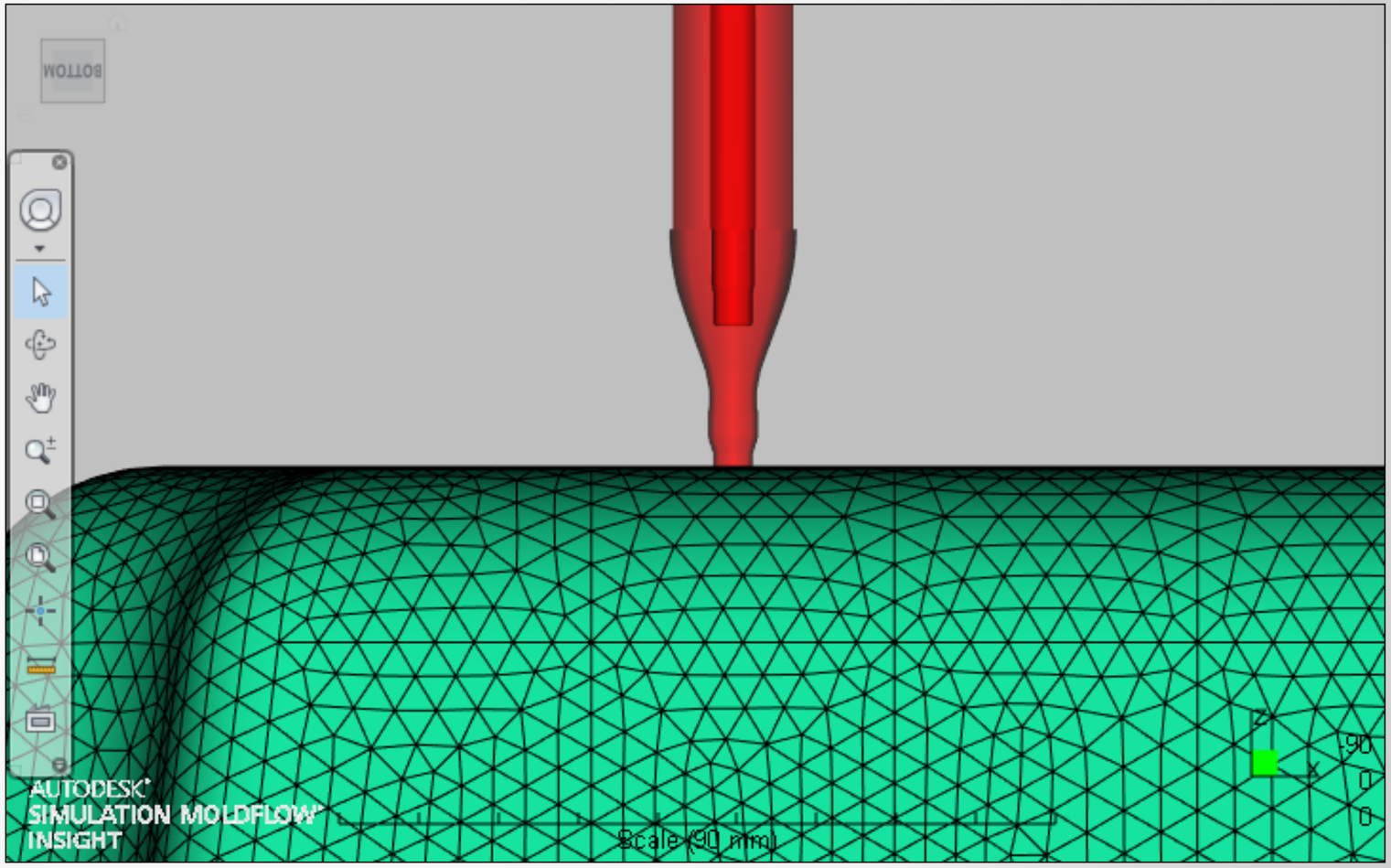
Step 2 – Part Modeling

- Midplane
- Dual Domain
- **3D Added!**
- No other special modeling considerations



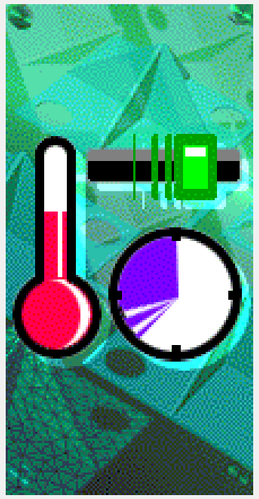
Step 3 – Mold Modeling

- Hot Runners need Valve Gates!
- Pressurized material prevented from seeping into mold prematurely
- No other special considerations



Step 4 – Process Modeling – The Old Way

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



Mold surface temperature 60 C

Melt temperature 246.11 C

Filling control

Injection time of 2 s [0:]

Velocity/pressure switch-over

By %volume filled at 89 % [0:100]

Pack/holding control

Packing pressure vs time Edit profile...

Cooling time

Specified of 20 s [0:]

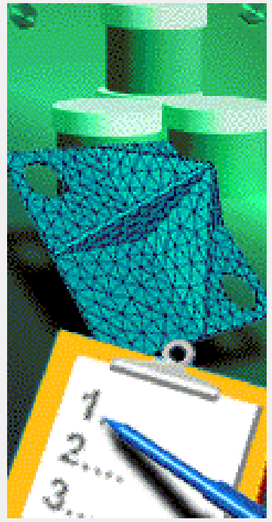
Advanced options...

Fiber orientation analysis if fiber material

< Back Next > Cancel Help

Step 4 – Process Modeling – The Old Way

Process Settings Wizard - Microcellular Injection Molding Settings - Page 2 of 3



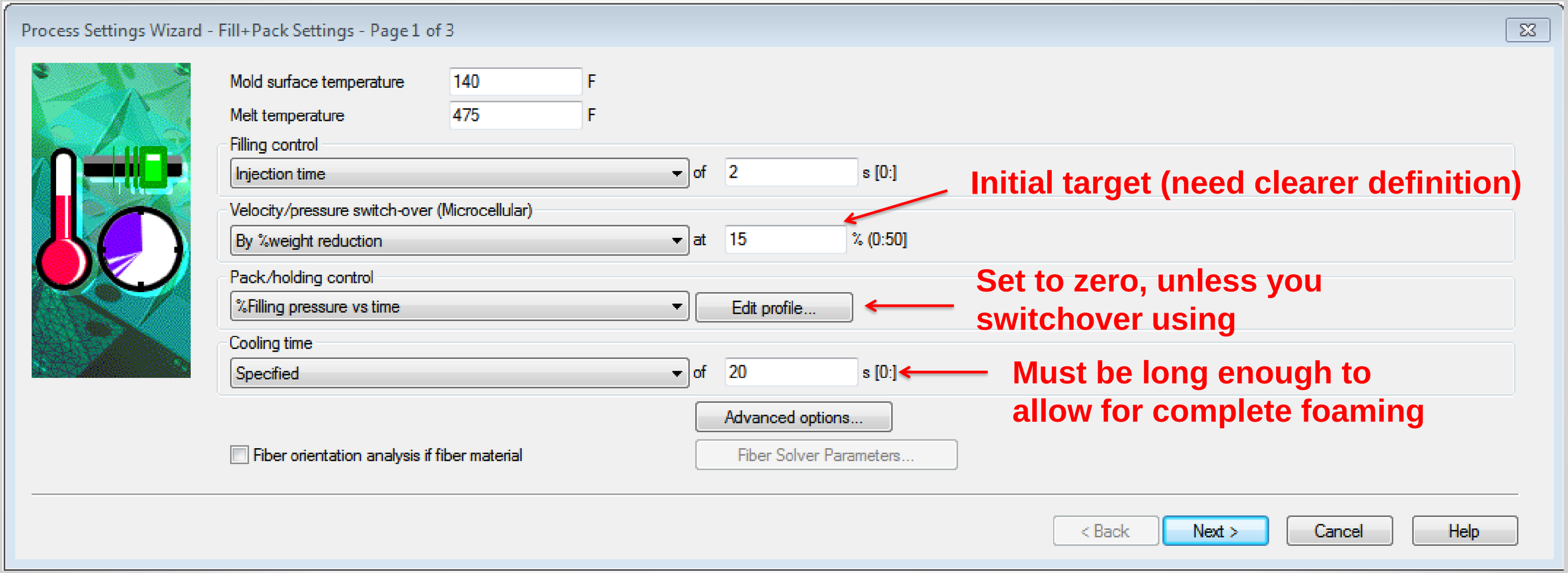
Volume filled at start of foaming	89	% [0:100]
Initial bubble radius	0.001	mm [0:1]
Number of cells per volume	2e+005	1/cm^3 [0:1e+014]
Initial gas concentration	0.4	% [0:10]

Why did we have these?

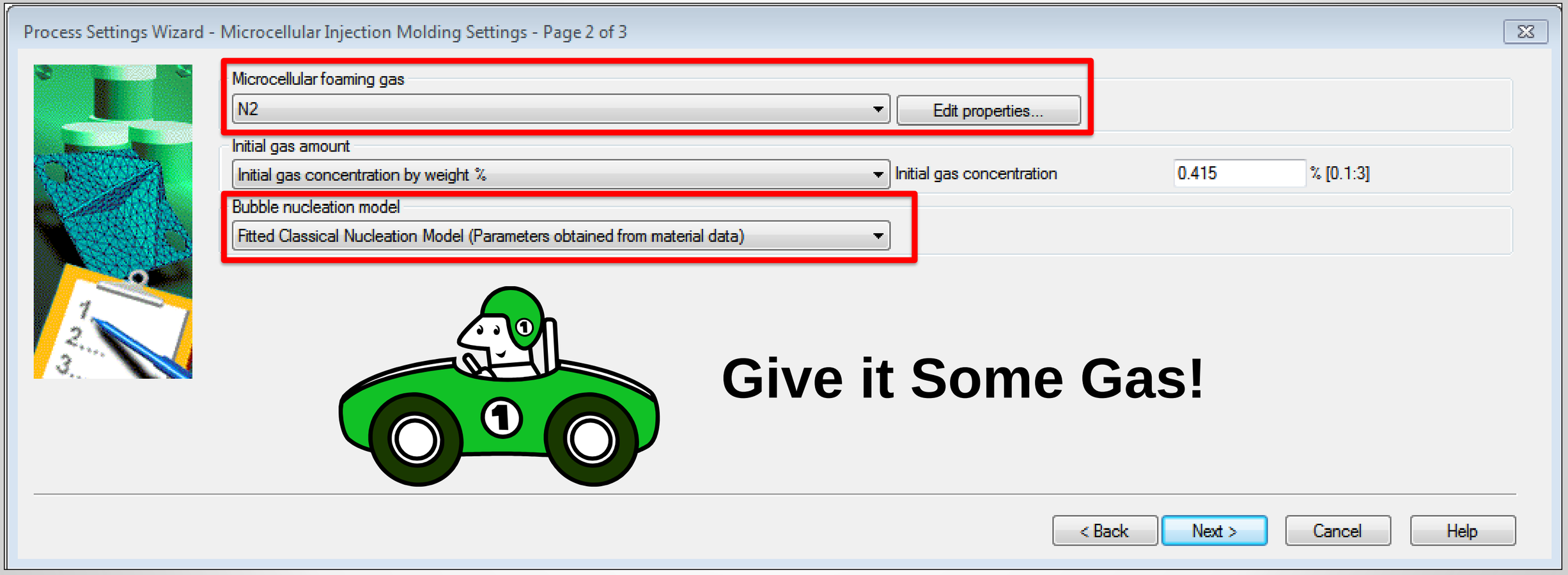
- **No nucleation model**
- **Viscosity modification**
- **Starting point for bubble growth**

< Back | Next > | Cancel | Help

Step 5 – Process Modeling – The New Way



Step 5 – Process Modeling



Step 6 – Analyze

Midplane / Dual Domain	3D
Reference solid part weight is calculated (pvT & T_{trans} & 80% pack)	Reference solid part weight is calculated
Filling progresses with viscosity modification until calculated weight reduction is reached	Bubble nucleation calculated immediately during filling
Viscosity is modified using N_2 or CO_2 constants & SCF dosing %	Filling continues until calculated V/P switchover
Foaming starts at calculated V/P switchover	Packing conditions same as in midplane/dual-domain
V/P switchover calculated based on calculated weight of solid part	

Step 6 – Analyze (Midplane)

Filling phase:

Status: V = Velocity control
P = Pressure control
F = Foaming
V/P= Velocity/pressure switch-over

Time (s)	Volume (%)	Pressure (MPa)	Clamp force (tonne)	Flow rate (cm^3/s)	Status
0.001	0.04	"Valve gate controller defaults" # 1 (Elem# 70231) opened.			
0.001	0.04	"Valve gate controller defaults" # 1 (Elem# 70268) opened.			
0.001	0.04	"Valve gate controller defaults" # 1 (Elem# 70305) opened.			
0.001	0.04	"Valve gate controller defaults" # 1 (Elem# 70342) opened.			
0.102	1.49	17.39	0.31	394.40	V
0.201	5.93	19.90	1.33	473.59	V
0.300	10.71	20.72	3.09	478.56	V
0.406	15.80	21.39	5.65	479.82	V
0.506	20.66	21.90	8.41	481.39	V
0.605	25.46	22.33	11.26	483.04	V
0.701	30.08	22.73	14.53	483.46	V
0.807	35.20	23.27	20.25	482.17	V
0.904	39.84	23.82	26.00	483.17	V
1.011	44.90	24.47	34.35	482.71	V
1.107	49.46	25.05	42.20	482.77	V
1.204	54.11	25.59	49.87	483.41	V
1.311	59.17	26.24	59.35	483.67	V
1.404	63.56	26.84	68.32	484.36	V
1.510	68.52	27.64	81.64	483.72	V
1.611	73.27	28.46	94.42	484.78	V
1.700	77.43	29.12	104.82	485.52	V
1.802	82.19	29.94	118.47	485.79	V
1.900	86.76	30.75	132.09	486.19	V
1.953	89.19	31.28	141.40	446.00	V/P(M)
1.954	89.21	1.46	35.84	201.14	F
2.001	93.57	1.70	23.98	673.67	F
2.101	97.36	1.92	28.22	233.35	F
2.201	98.79	2.01	29.98	88.52	F
2.300	99.54	2.06	30.90	65.24	F
2.374	99.92	2.08	31.36	39.14	F
2.375	100.00	2.08	31.24	31.93	Filled

Packing phase:

Time (s)	Packing (%)	Pressure (MPa)	Clamp force (tonne)	Status
2.375	2.11	1.90	31.57	F
3.916	9.81	2.09	36.44	F
5.876	19.61	2.09	35.29	F
7.832	29.39	2.12	33.37	F
9.789	39.18	2.14	27.94	F
11.747	48.97	2.15	25.93	F
13.706	58.76	2.17	19.04	F
15.667	68.57	2.20	13.52	F
17.622	78.34	2.23	6.60	F
19.582	88.15	2.27	2.63	F
21.541	97.94	2.27	0.95	F
21.957	100.00	2.27	0.94	F

Filling phase results summary :

Maximum injection pressure (at 1.9532 s) = 31.2782 MPa

End of filling phase results summary :

Time at the end of filling = 2.3753 s
Total weight (part + runners) = 791.4841 g
Maximum Clamp force - during filling = 132.0934 tonne

Step 6 – Analyze (3D)

1.422	69.300	3.259e+01	7.42e+01	479.655	6.48	V
1.478	71.108	3.301e+01	8.11e+01	479.671	6.65	V
1.503	72.695	3.319e+01	8.44e+01	479.661	6.69	V
1.540	74.549	3.345e+01	8.89e+01	479.513	6.77	V
1.574	76.354	3.370e+01	9.30e+01	479.630	6.85	V
1.629	78.080	3.408e+01	9.87e+01	480.127	7.02	V
1.647	79.219	3.421e+01	1.01e+02	480.357	7.04	V
1.669	80.358	3.437e+01	1.04e+02	480.092	7.09	V
1.702	82.007	3.461e+01	1.08e+02	480.069	7.15	V
1.734	83.610	3.485e+01	1.12e+02	480.156	7.21	V
1.765	85.412	3.511e+01	1.17e+02	480.113	7.26	V
1.818	87.023	3.553e+01	1.23e+02	480.446	7.41	V
1.843	88.604	3.577e+01	1.28e+02	480.414	7.43	V
1.898	90.208	3.634e+01	1.38e+02	480.206	7.58	V

Velocity/pressure switch-over by %weight reduction = 20.0000 %

1.910	91.180	3.650e+01	1.42e+02	479.376	7.58	V/P
1.933	91.320	1.763e+01	1.10e+02	0.000	7.80	F
1.945	91.914	1.509e+01	9.01e+01	0.000	7.92	F
1.963	92.211	1.146e+01	7.16e+01	0.000	8.11	F
1.992	92.650	8.254e+00	5.39e+01	0.000	8.40	F
2.028	93.322	5.843e+00	4.11e+01	0.000	8.74	F
2.073	93.645	4.149e+00	3.35e+01	0.000	9.18	F
2.127	93.951	2.990e+00	3.04e+01	0.000	9.69	F
2.198	94.456	2.242e+00	3.00e+01	0.000	10.30	F
2.298	94.955	1.819e+00	3.04e+01	0.000	11.12	F
2.398	95.594	1.674e+00	3.07e+01	0.000	11.87	F
2.498	96.193	1.818e+00	3.11e+01	0.000	12.60	F
2.598	96.718	1.912e+00	3.17e+01	0.000	13.30	F
2.698	97.320	1.960e+00	3.20e+01	0.000	13.99	F
2.798	97.800	1.992e+00	3.22e+01	0.000	14.67	F
2.883	98.543	2.012e+00	3.25e+01	0.000	15.18	F
2.983	98.576	2.051e+00	3.27e+01	0.000	15.91	F
3.083	99.009	2.073e+00	3.24e+01	0.000	16.55	F
3.183	99.668	2.103e+00	3.24e+01	0.000	17.12	F
3.283	99.999	2.138e+00	3.35e+01	0.000	17.74	F
3.383	100.000	2.156e+00	3.32e+01	0.000	18.44	Filled

Foaming is occurring here too

Case Example - Correlation

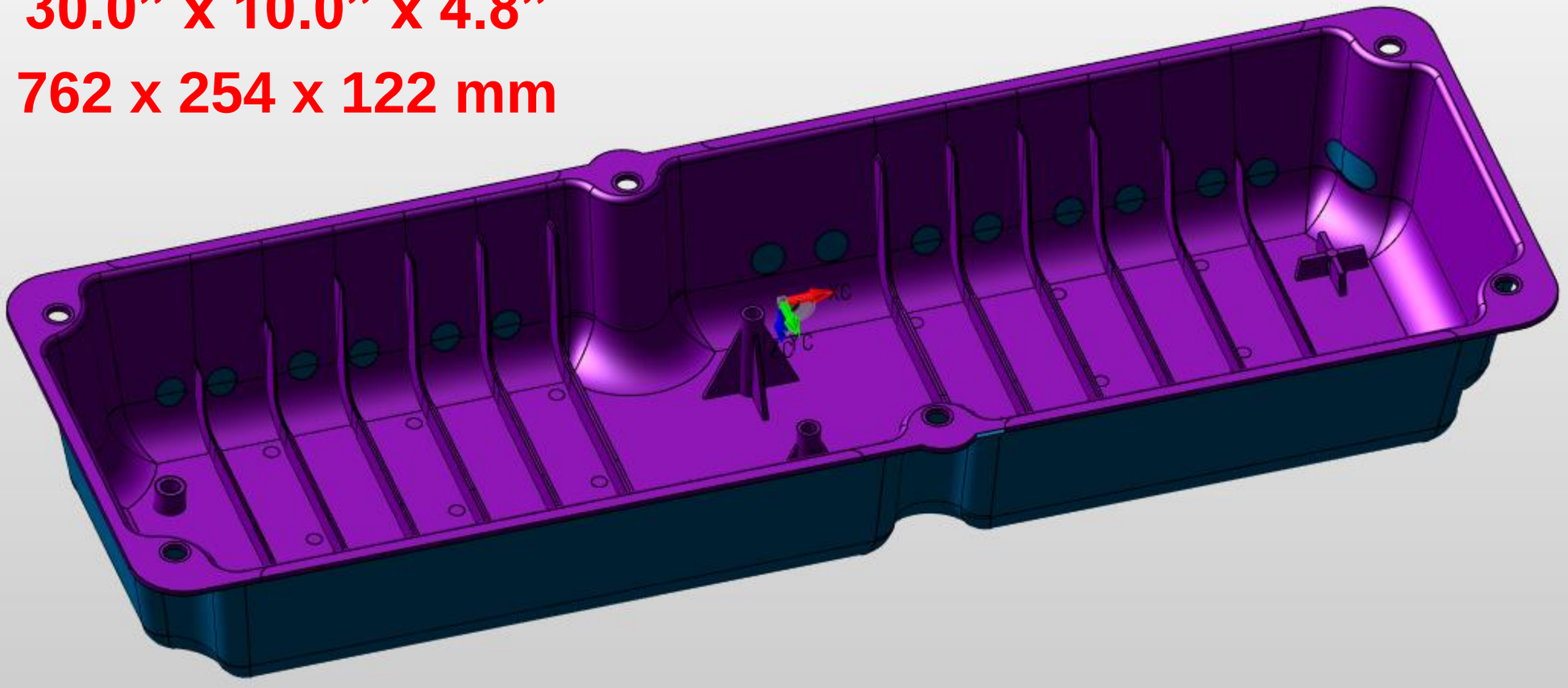
Correlation Limitations

- Limited resources
  - One mold trial session
  - Limited clamp tonnage
- More real-world studies needed
  - Material shortcomings
  - Viscosity reduction constants based on PS, not PP
  - PP constants show a different trend
- No instrumentation

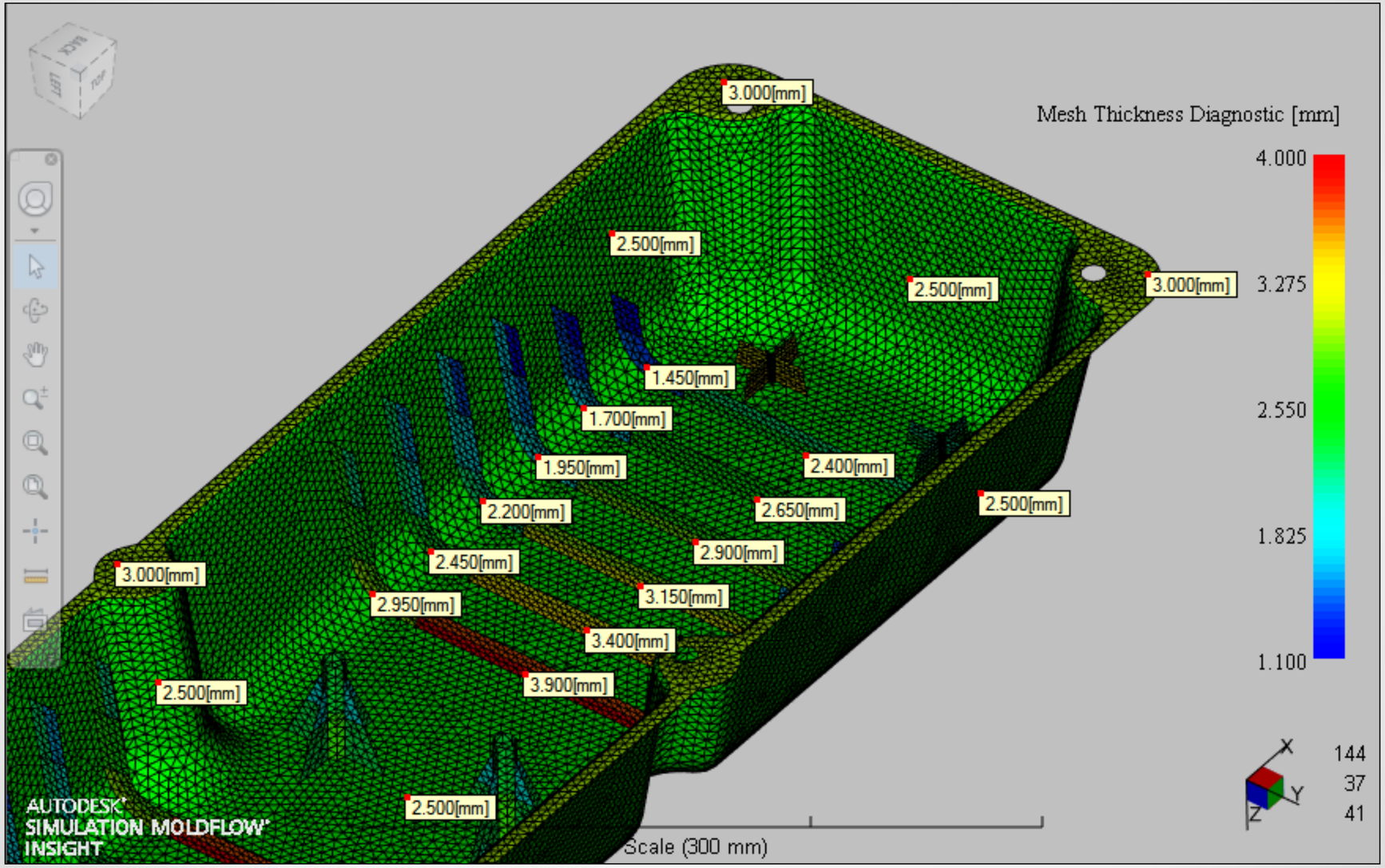
The Part – Oil Pan

30.0” x 10.0” x 4.8”

762 x 254 x 122 mm



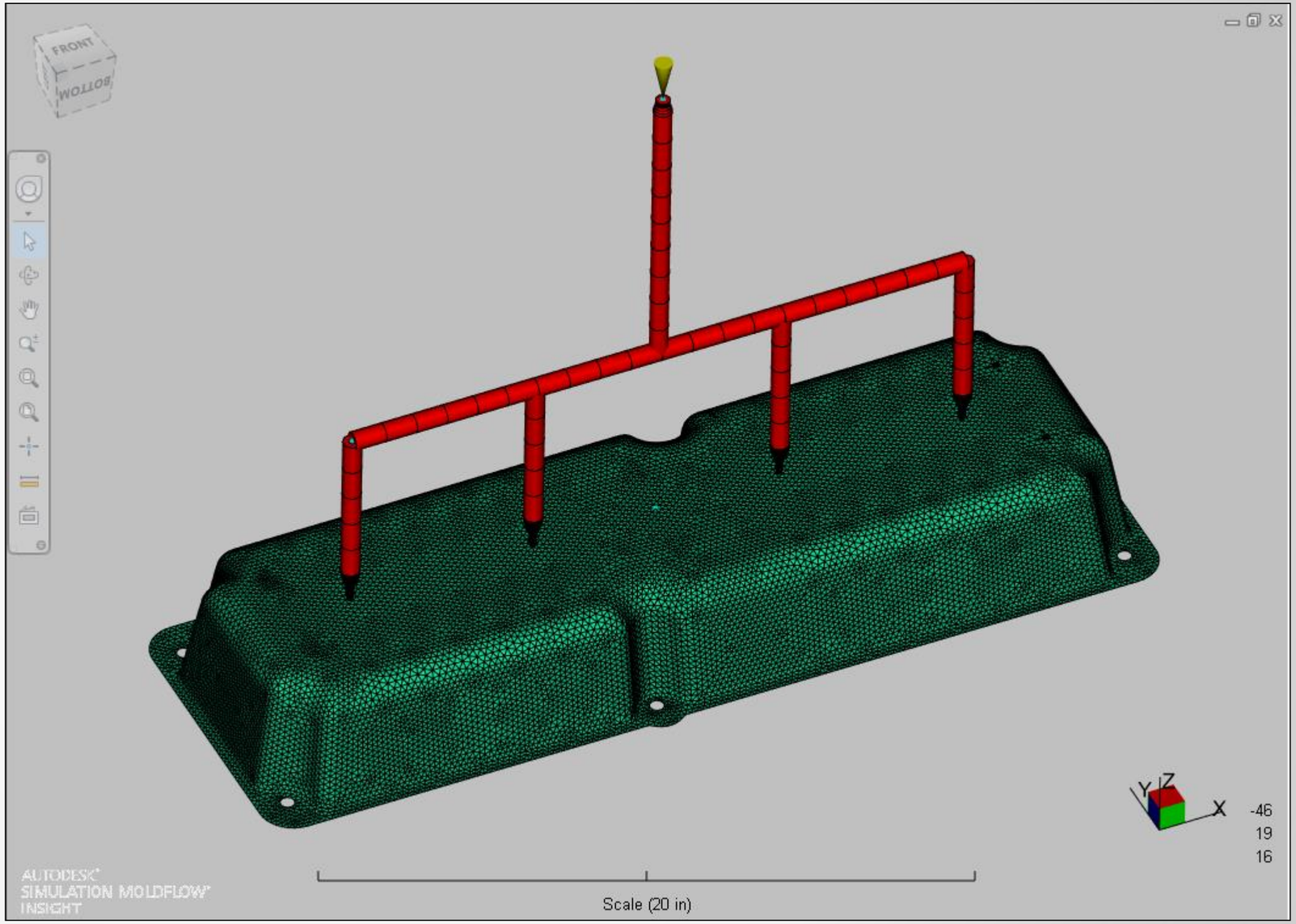
The Part – Moldflow Model



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

PHYSICAL	ASTM / Method	Units	Polifil® T-10	Polifil® T-20	Polifil® T-30	Polifil® T-40
Reinforcement Content	TPG WI	%	10	20	30	40
Specific Gravity	D 792	-	0.98	1.05	1.15	1.24
Melt Flow (230/2.16)	D 1238	g/10 min	8-12*	8-12*	8-12*	8-12*
Water Absorption, 24 Hours	D 570	%	nil	nil	nil	nil
Mold Shrinkage – 1/8" Specimen	D 955	in/in	0.015	0.010	0.009	0.008
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	3.5
Elongation @ Break	D 638	%	20	16	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	0.60	0.55	0.50	0.50
Gardner Impact (1/2" tup)	D 5420	in-lbs	12	8	5	5
Hardness, Shore	D 1415	D-Scale	72	74	75	77
THERMAL						
Deflection Temperature, 66psi	D 648	°F	235	255	270	280
Deflection Temperature, 264psi	D 648	°F	135	145	160	175

**melt flow may be specified*

The Process

Melt Temp (air shot) – 475 °F

Solid Shot

- Shot Stroke – 11.0”
- Fill Time – 3.8 sec.
- Fill Pressure – 7768 psi
- Part Weight – 950g

Final MuCell Shot

- Shot Stroke 9.8”
- Fill Time – 2.0 sec.
- Fill Pressure – 8799 psi
- Part Weight – 845g

MuCell Injection Molding Process Sheet

Mold/Part:	Oil Pan Mold
Material:	Polifil T-2010
Machine:	KM

Date:	29-Aug-13
Operator:	LAK
Process File Name:	

SCF Delivery System/Manifold

	MuCell 1	MuCell 2	MuCell 3	MuCell 4
System Pressure:				
Pre-Metering Pressure:				
Post-Metering Pressure:				
Flow Rate:	1.74	1.74	1.74	
SCF Inlet Pressure:				
SCF Delivery Pressure:				

SCF Injector Operation

	MuCell 1	MuCell 2	MuCell 3	MuCell 4
Inj 1 Open:	0.7	0.7	0.7	
Inj 2 Close:	5.5	5.5	5.5	
Open Time:	16	16	16	
MPP:				
Pressure Drop:				

Part Information	MuCell 1	MuCell 2	MuCell 3	MuCell 4
Shot Weight:	895	870	845	
% Red:	5.789474	8.42105	11.05263	100
Part Weight:	895	870	845	
% Red:	5.789474	8.42105	11.05263	100
% SCF:	0.391937	0.4032	0.415129	#DIV/0!
SCF Type:				

Solid Shot Weight:	950	grams
Solid Part Weight:	950	grams

Screw Speed:	Solid	MuCell 1	MuCell 2	MuCell 3	MuCell 4
Delay					
Speed 1	175	175	175	175	
Pressure	2200	2200	2200	2200	
Position					
Speed 2					
Pressure 2					

Recovery Time:	40	37.9	37	36	
Sprue Break:					

Machine Parameters

	Solid	MuCell 1	MuCell 2	MuCell 3	MuCell 4
Shot Size:	11	10.25	10.1	9.8	
Trans. Pt	0.5	0.5	0.2	0.2	
Trans. Pr.	7768	6409	6369	8799	
Cushion:	0.02	0.02	0.02	0.02	
Inj. Time	3.83	3.67	3.67	2.02	
Pk Inj. Pr.	8373	9600	10327	11500	

Mold Temperature	Solid	MuCell 1	MuCell 2	MuCell 3	MuCell 4
Stationary:	120	120	120	120	
Moving:	120	120	120	120	

Injection Profile

	Solid	MuCell 1	MuCell 2	MuCell 3	MuCell 4
Pos 1	11	10.25	10.1	9.8	
Spd 1	1.5	1.5	1.5	1.5	
Pos 2	10	9	9	9	
Spd 2	3	3	3	6	
Pos 3					
Spd 3					
Pos 4					
Spd 4					
Pos 5					
Spd 5					
Transfer	0.5	0.5	0.2	0.2	

Barrel Temperatures	Solid	MuCell 1	MuCell 2	MuCell 3	MuCell 4
Zone 1 (Feed)	365	365	365	365	
Zone 2	420	420	420	420	
Zone 3	430	430	430	430	
Zone 4	430	430	430	430	
Zone 5	430	430	430	430	
Zone 6	430	430	430	430	
Zone 7 (Nozzle)	430	430	430	430	
Zone 8 (Nozzle)	430	430	430	430	

Hold Profile

	Solid	MuCell 1	MuCell 2	MuCell 3	MuCell 4
Time 1	3	0.5	0.5	0.5	
Press 1	4000	4000	4000	4000	
Time 2					
Press 2					

Hot Runner Temps	Solid	MuCell 1	MuCell 2	MuCell 3	MuCell 4
Zone 1	440	440	440	440	
Zone 2	440	440	440	440	
Zone 3	460	460	460	460	
Zone 4	460	460	460	460	
Zone 5	440	440	440	440	
Zone 6	440	440	440	440	
Zone 7	440	440	440	440	
Zone 8	440	440	440	440	
Zone 9	440	440	440	440	
Zone 10	440	440	440	440	
Zone 11	440	440	440	440	

Melt Temperature:	475				
Clamp Tonnage:					
% Clamp Red:		#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!

Molded Parts – Achieved 11% weight reduction

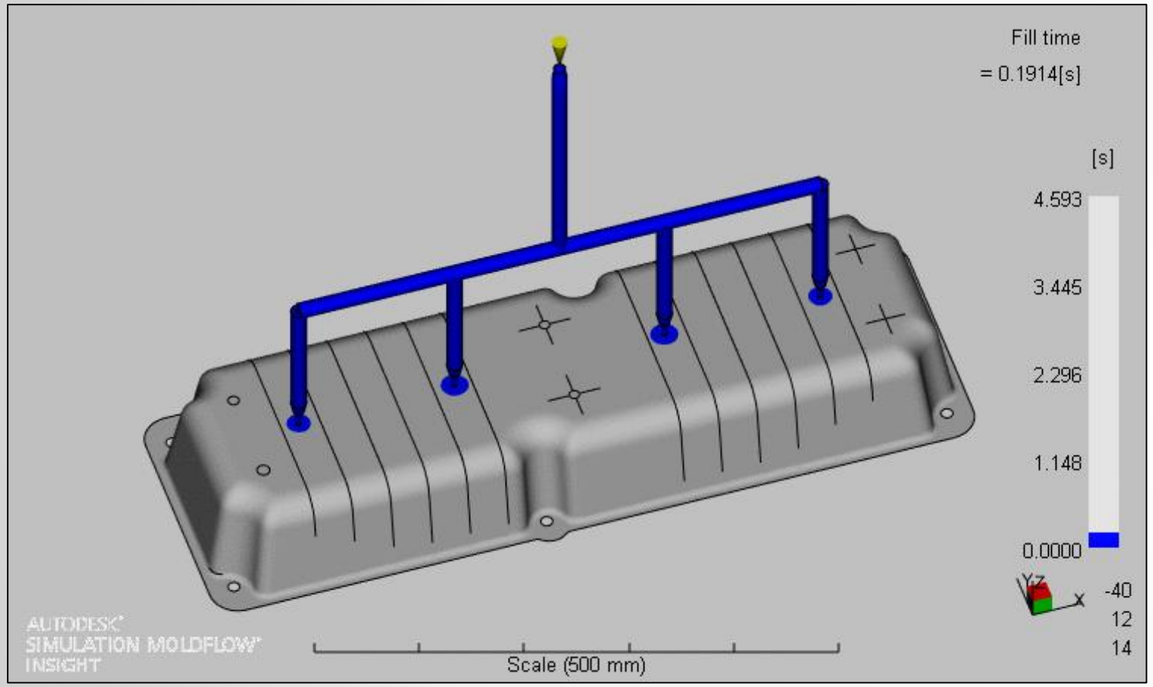


Molded Parts

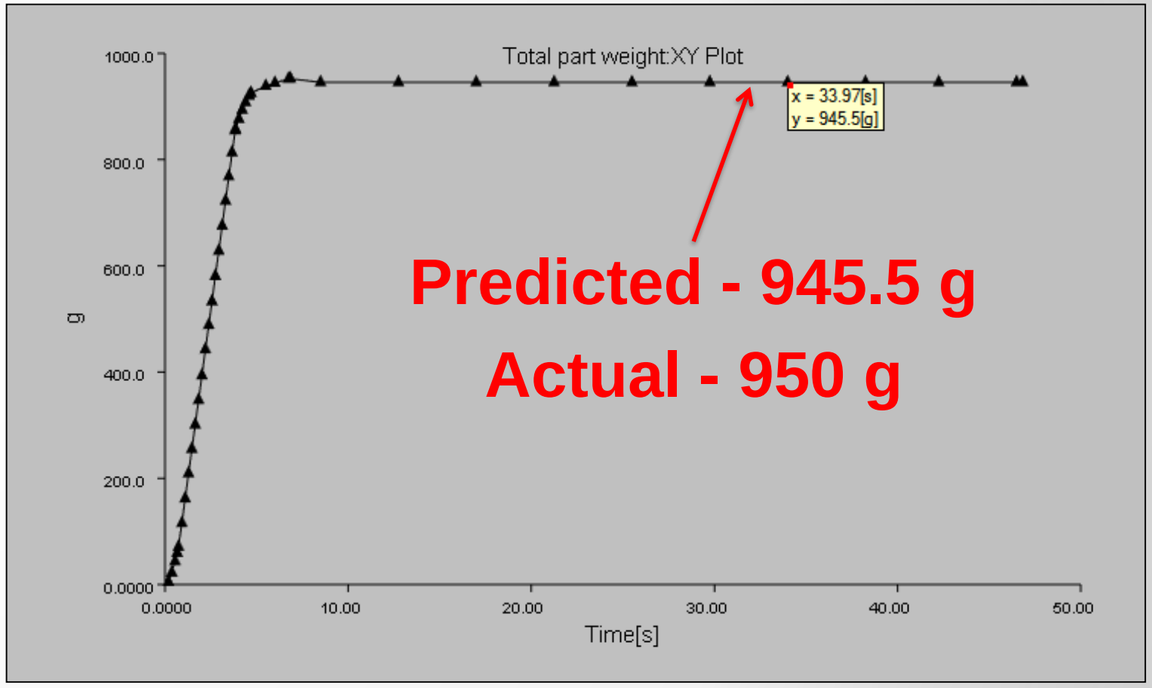
Full Shot **Short Shot**



Solid Shot – Part Weight Results



Total Part Weight



Predicted - 945.5 g

Actual - 950 g

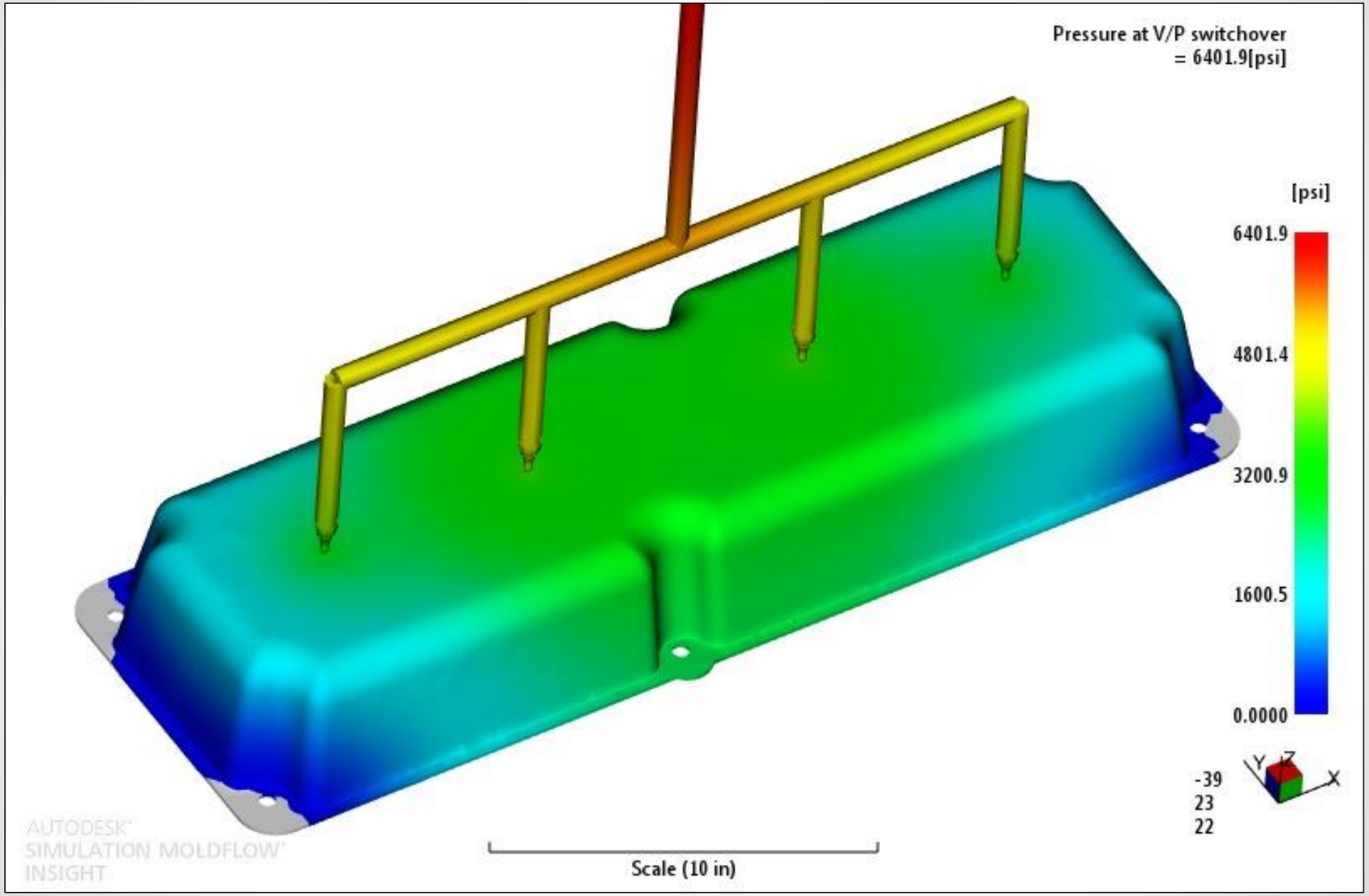
MuCell Shot – Weight Results

Fill Time (sec.)	V/P Switchover (By % Weight Reduction)	Predicted Part Weight (g)	Predicted Weight Reduction
2.0	11%	868.9	12.2%
2.0	15%	837.4	15.4%
2.0	20%	791.5	20.1%
2.0	25%	746.4	24.6%
2.0	30%	Short shot	

Calculated Reference Solid Part Weight = 990g

Pressure Prediction

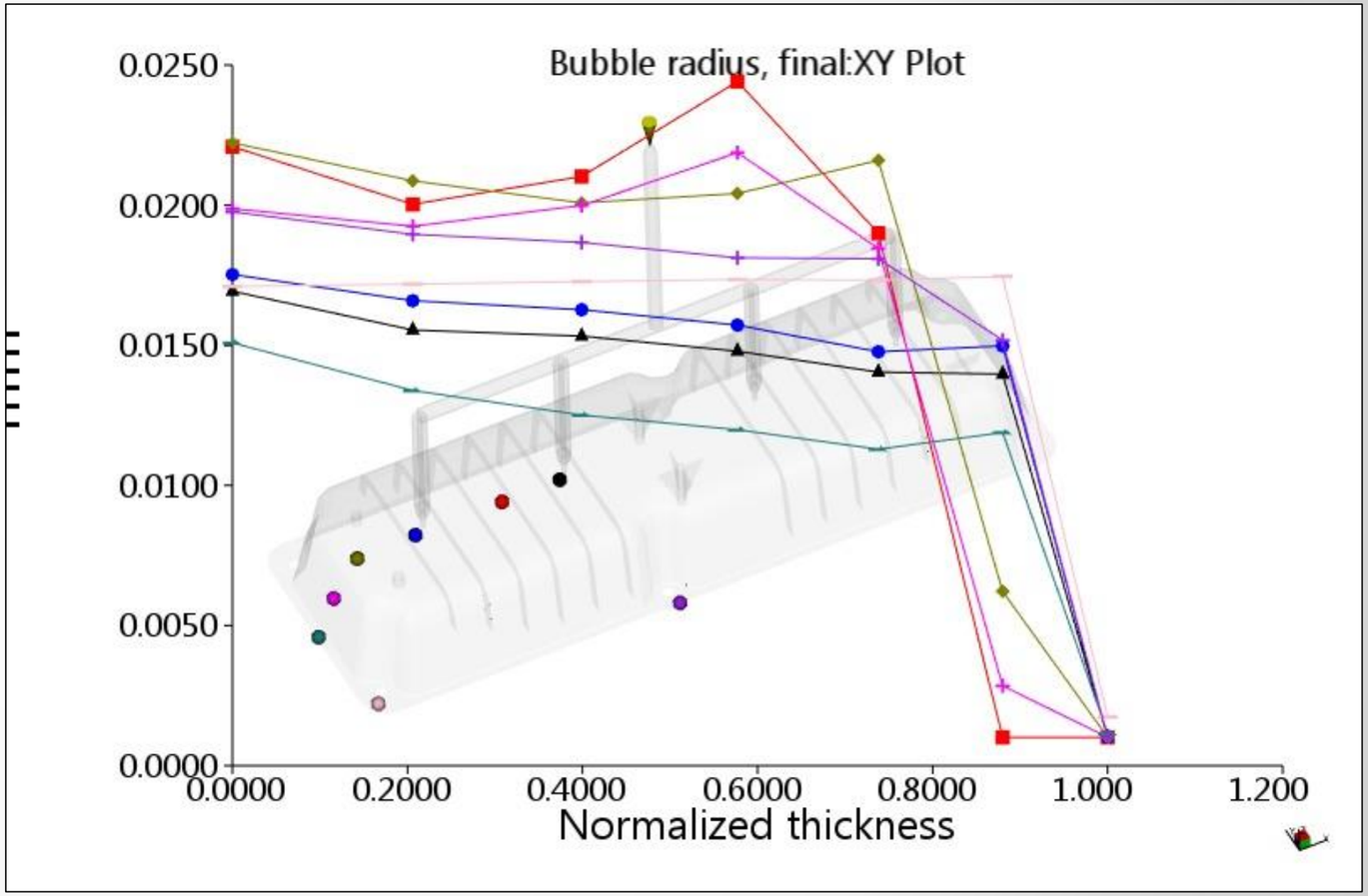
Predicted – 6401 psi (midplane)



Bubble Radius Results

Trends

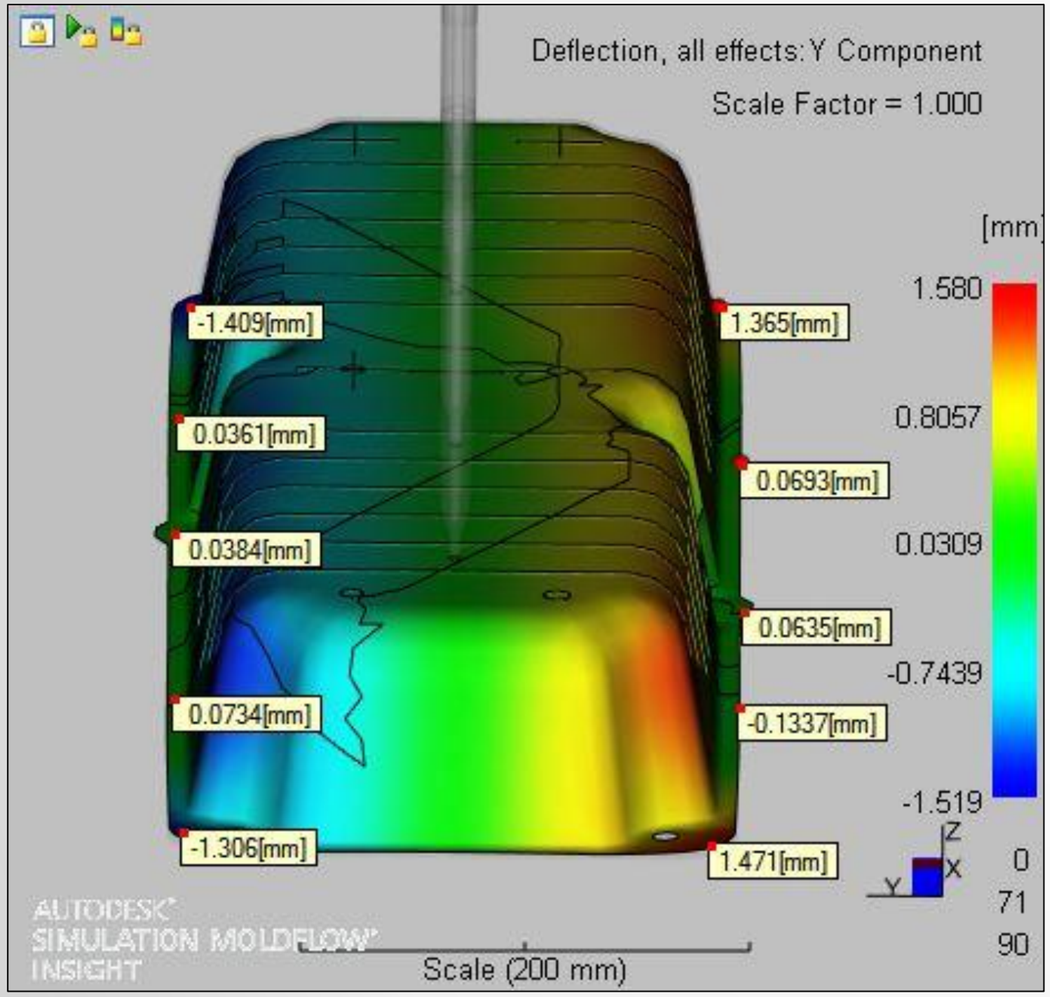
- **Higher pressure = small radius**
- **Higher temp = large radius**



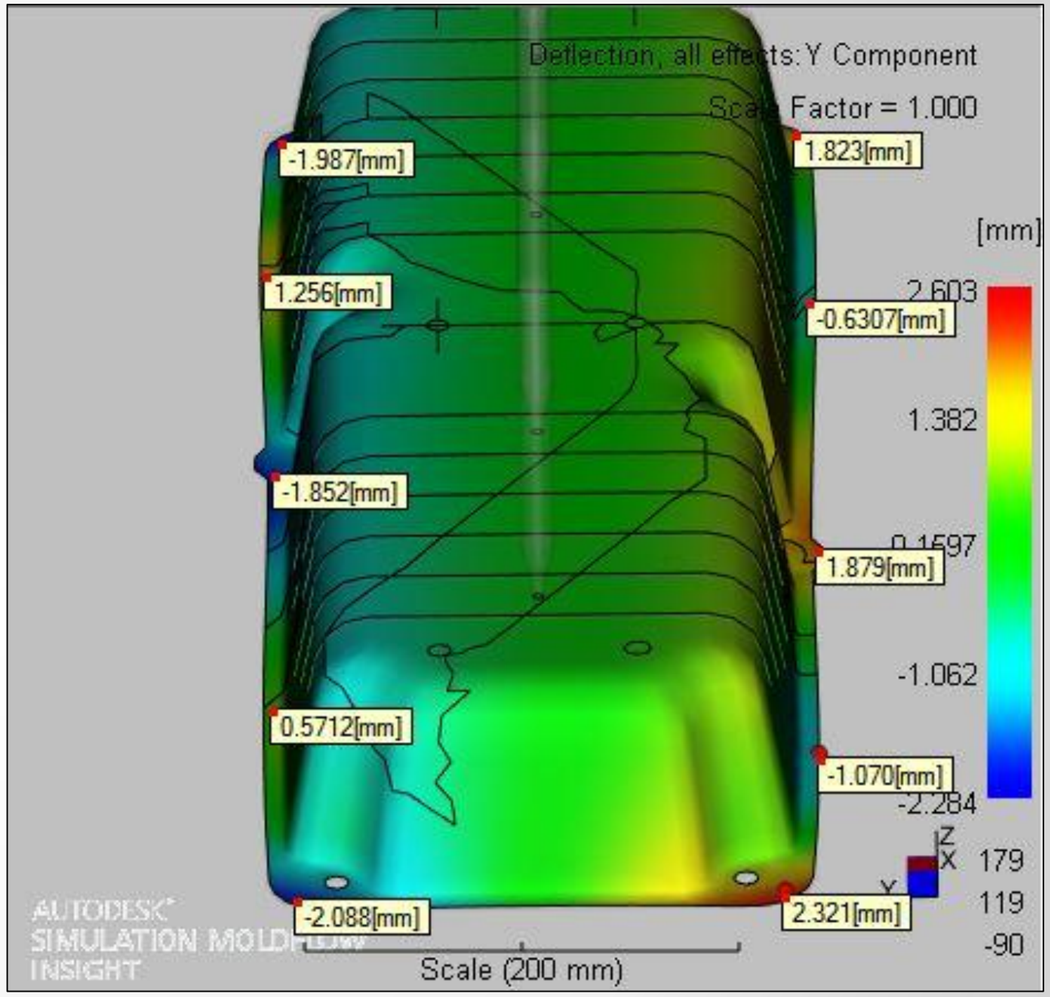
Warpage – Molded Samples



Predicted Warpage – (ASMI 2015)

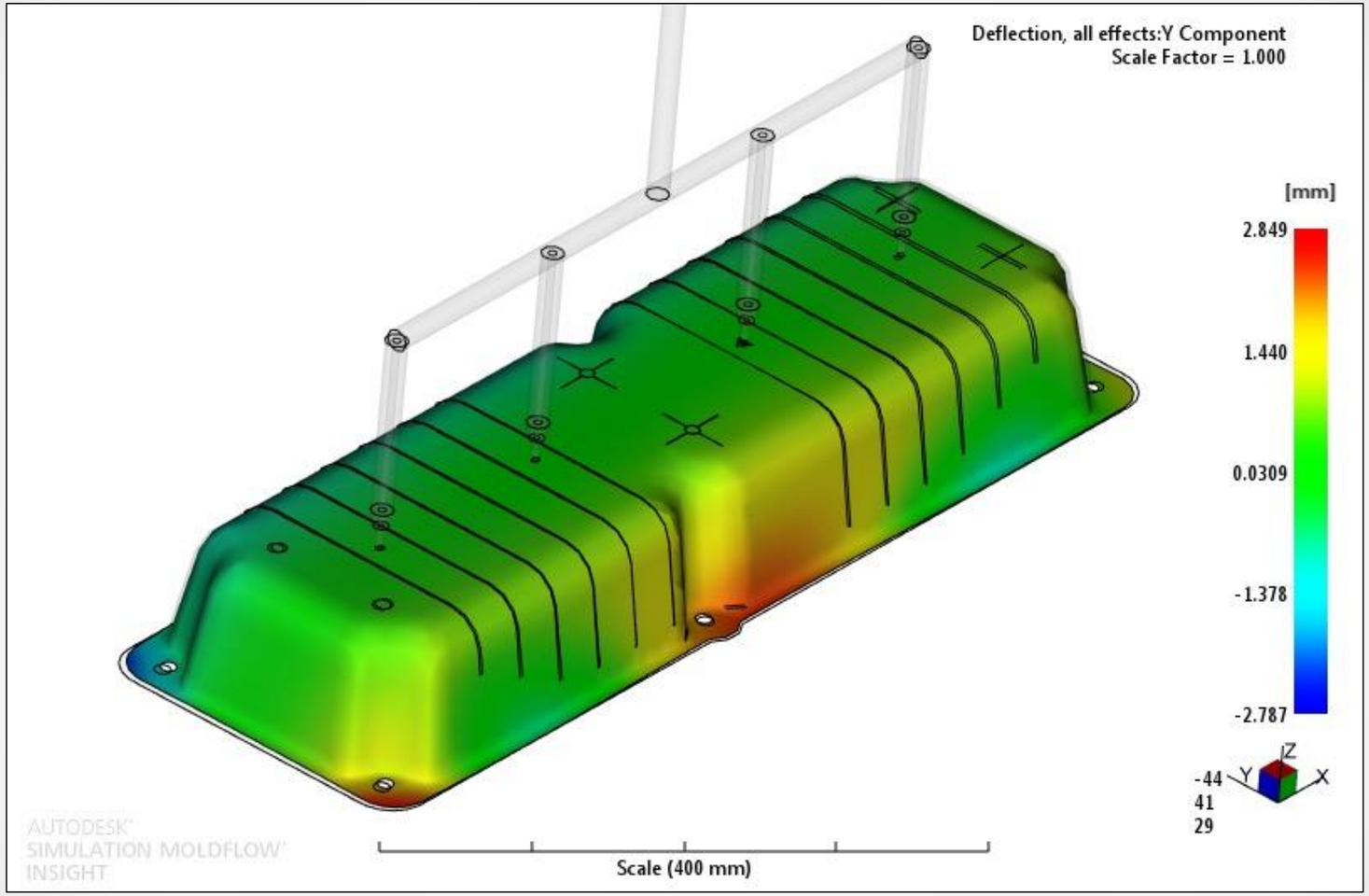


Solid



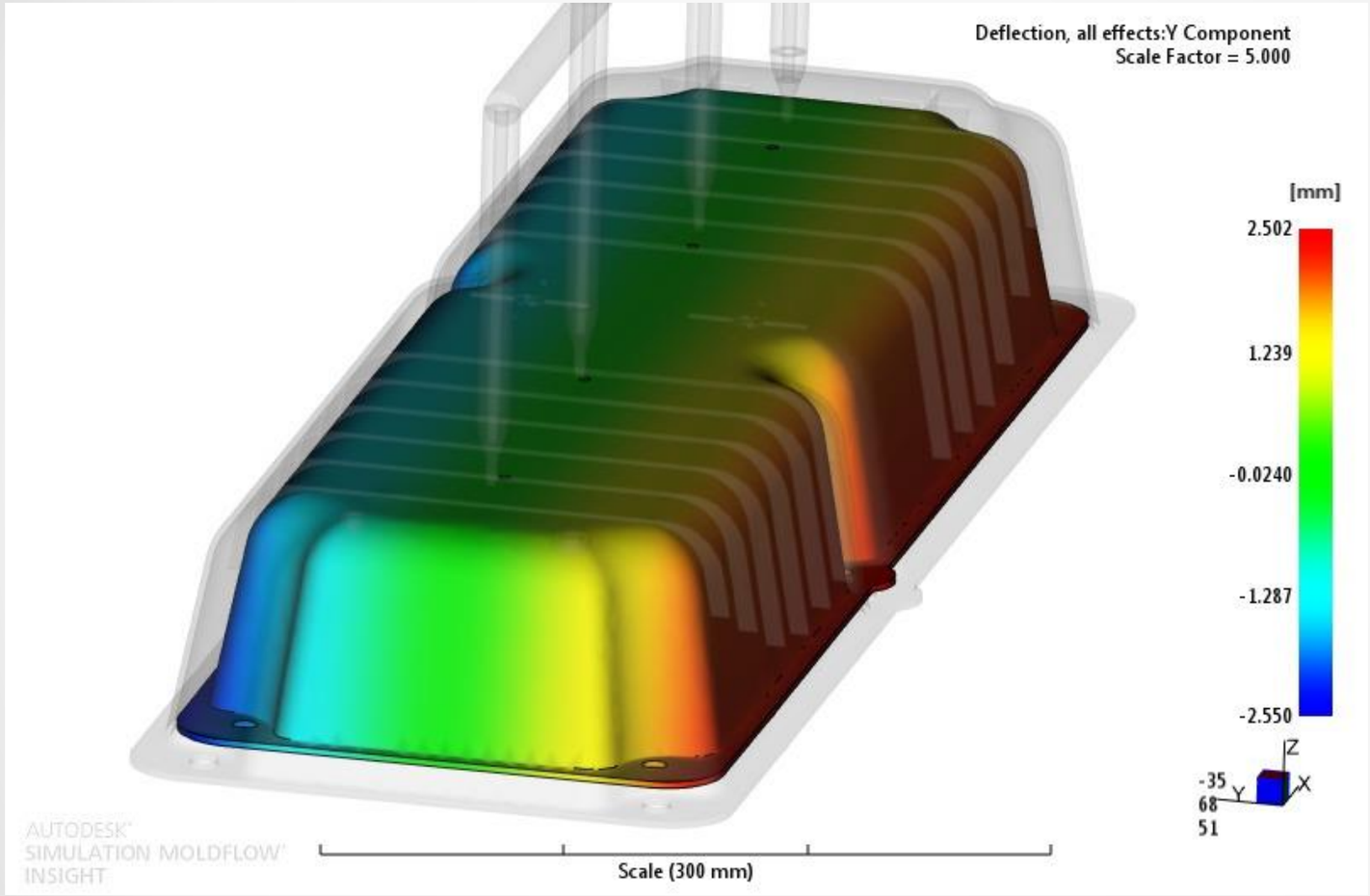
MuCell

Predicted Warpage – 2016 (no CRIMS)



MuCell

Predicted Warpage – 2016 (3D)



MuCell

Conclusions

Key learning objectives

- **Bubble nucleation directly calculated = no bubble concentration guesses**
- **Inputs are more clear**
- **Viscosity reduction calculation is sensitive to material properties – more materials need to be tested**
- **Cannot make conclusion about pressure**
  - **Substitute material**
  - **Viscosity, diffusivity, and solubility constants generated from PS material**



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