Understanding the Effects of Gravity and Inertia on Heavily Filled Polymers

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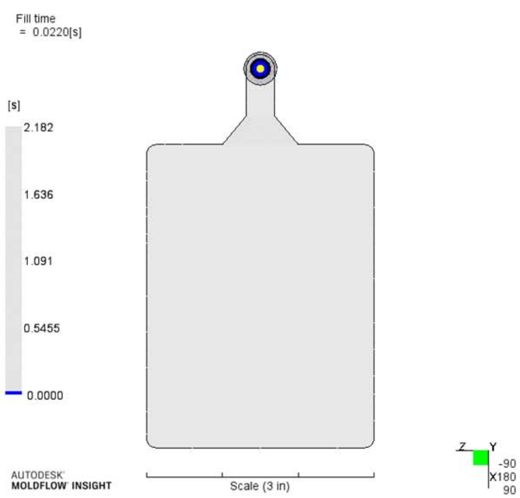
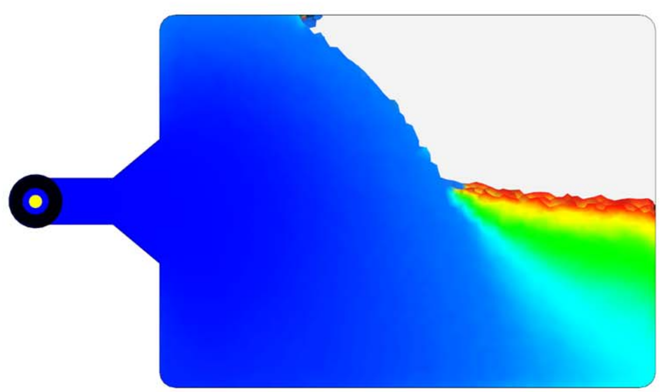
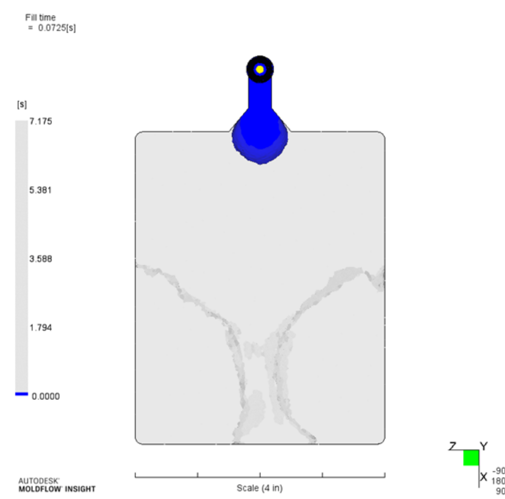
Objective

To explore and explain the effects inertia and gravity can have on heavily filled systems such as those used in powder injection molding (PIM)

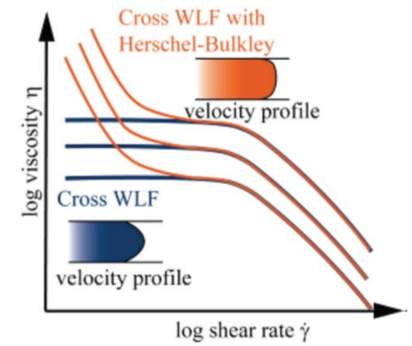






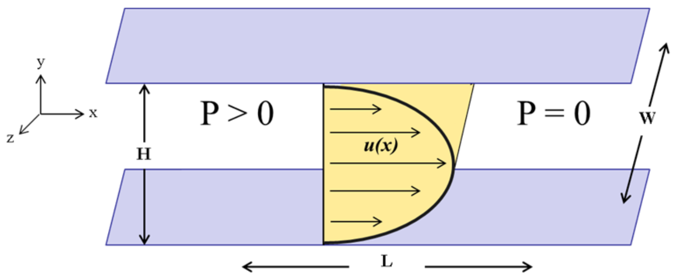
Theory

- Standard assumptions for thermoplastic behavior neglects gravity, inertia, and wall slip
  - Flow typically modelled using a Cross WLF model
- PIM feedstock cant always use the standard assumptions
  - Inertia forces increased with the increased density
  - Feedstocks are effected by gravity due to the heavy fillers
  - Flow could be modelled using a Herschel-Bulkley model

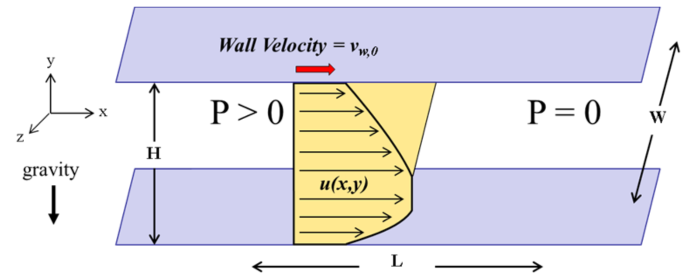


Integratred filling, packing, and cooling CAE analysis of powder injection moulding parts by S. Ahn, S.T. Chung, S.V. Atre, S.J. Park, R.M. German. (2008) Powder Metallurgy vol.51, no.4, pg.318-326

Steady State	L >> H
Fully developed	Negligible gravity and inertia
Laminar	Power law fluid
Isothermal	No wall-slip

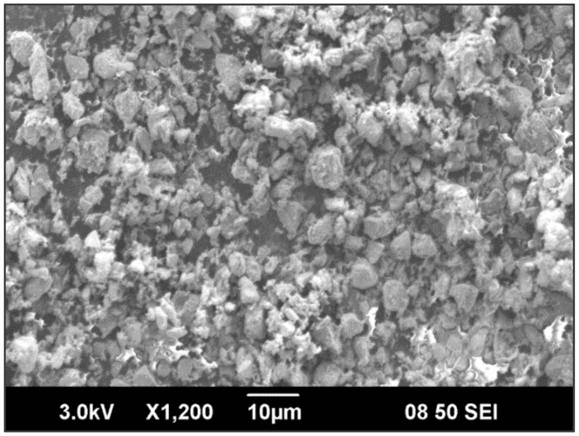


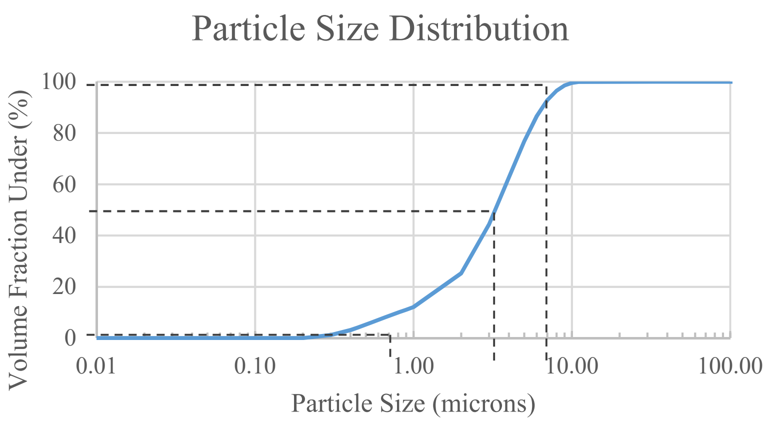
Steady State	L >> H
Fully developed	Herschel-Bulkley modified Cross-WLF
Laminar	

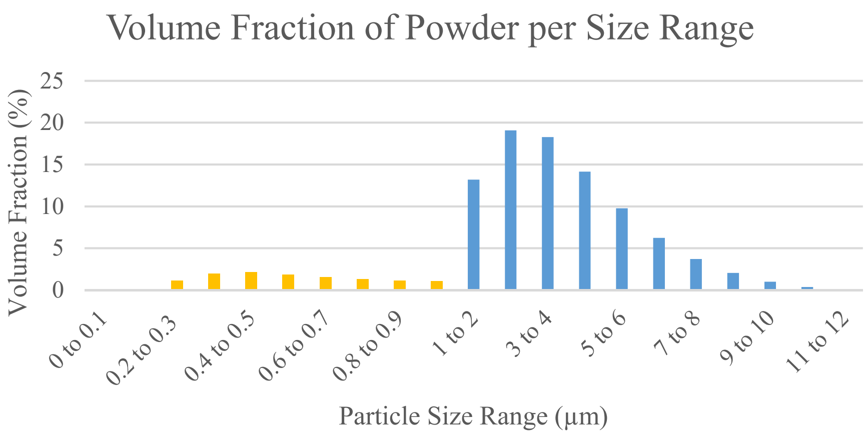


Material

- Powder injection molding feedstock
  - Silicon powder in a wax based binder system
  - 58.4% silicon by volume
- Feedstock
  - Average particle size: 4-5µm
  - Aspect ratio: 1.4
  - Feedstock density: 1.72 g/cc

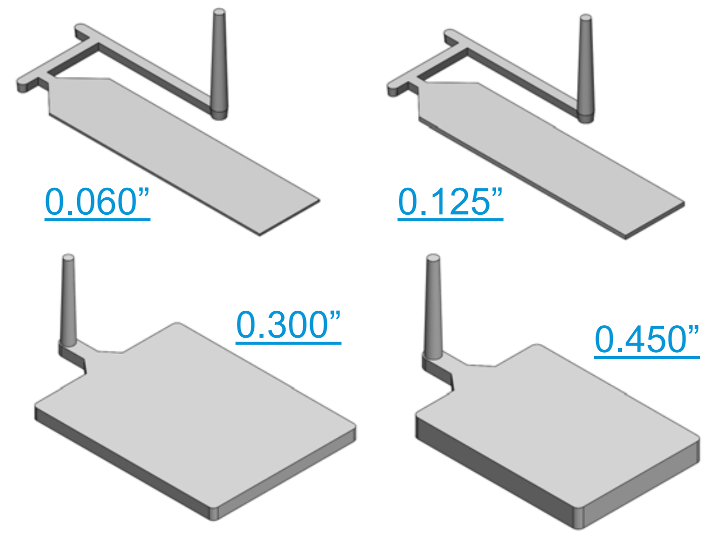






Experimental Methodology

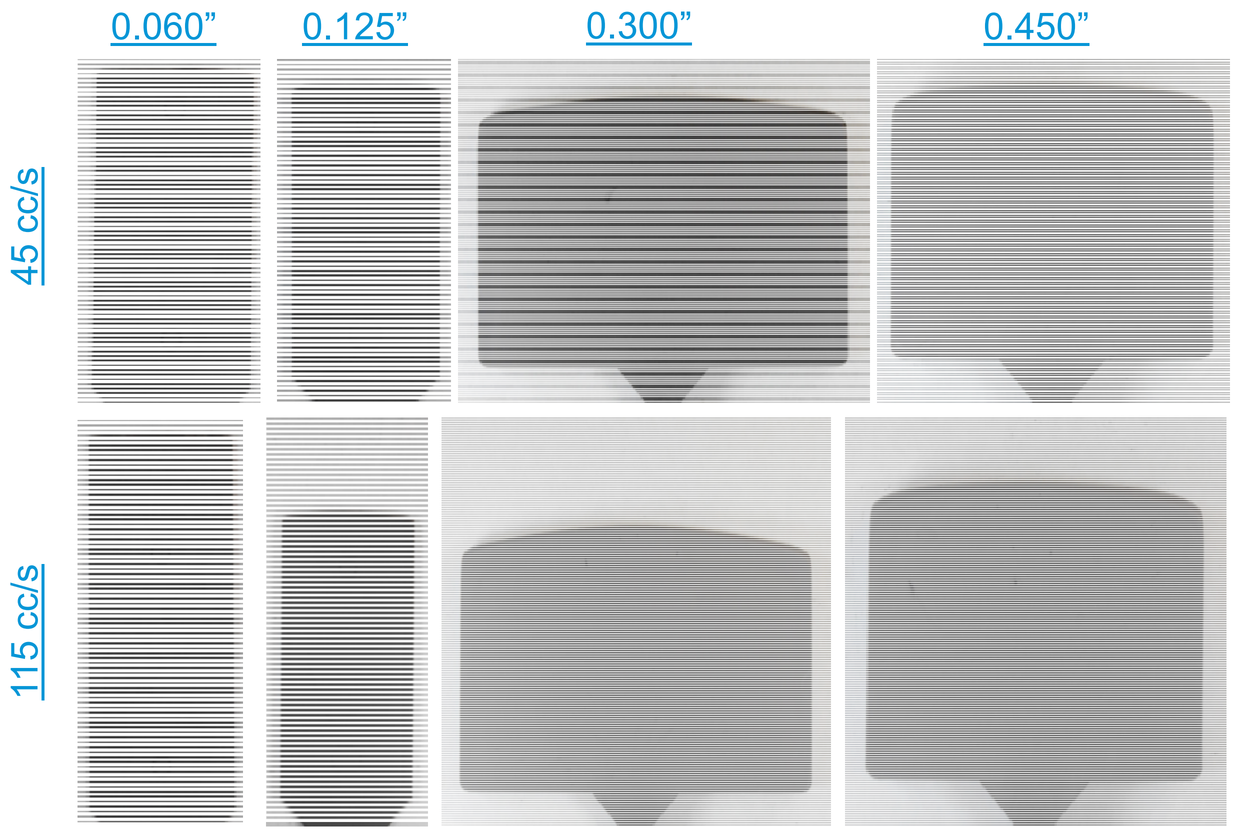
- Molded PIM feedstock on Arburg Allrounder 470E
- Characterized PIM feedstock
- Ran simulations that mimic molding trial
- DOE Layout
  - Flow through cavity is in three directions to gravity:
    - Against, With, and Transverse
  - Molded at two speeds:
    - Slow at 45 cc/s and Fast at 115 cc/s
  - Molded 4 different thicknesses:
    - 0.060” (1.5mm), 0.125” (3.2mm),
      0.300” (7.6mm), and 0.450” (11.4mm)



Molding Results

Against Gravity

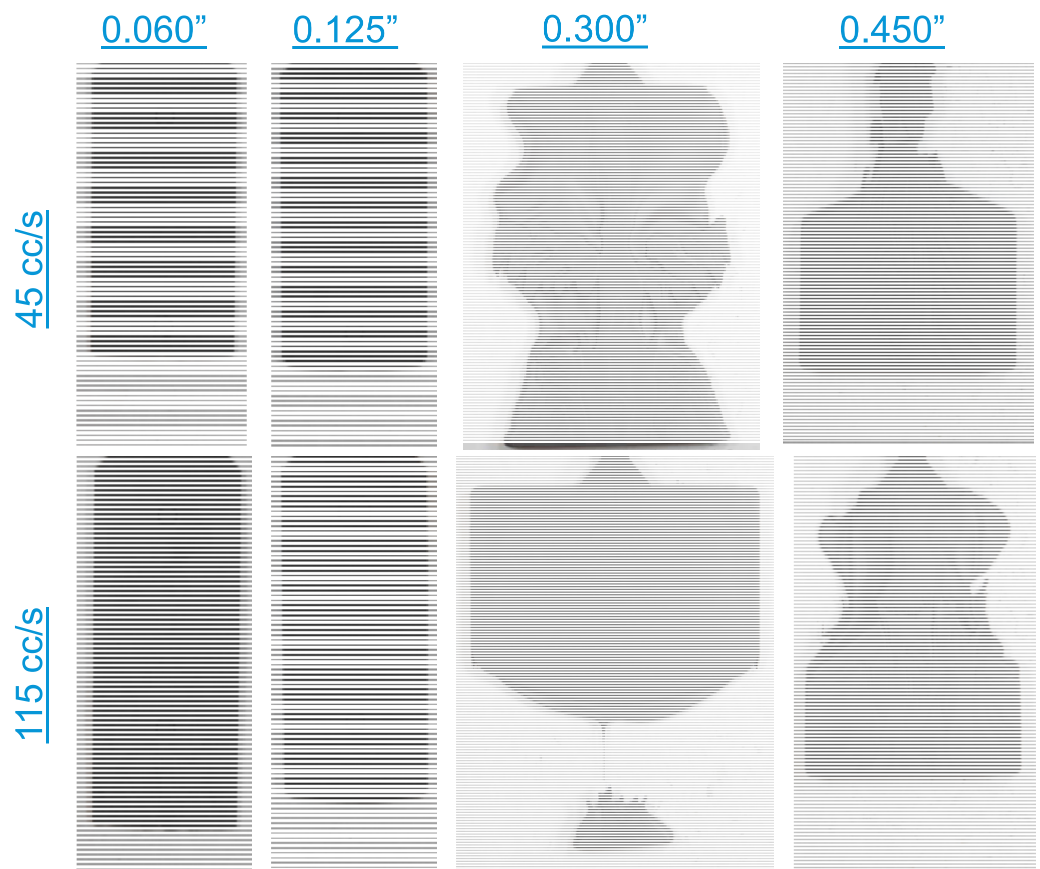
- Flow pattern looks as excepted for a typical thermoplastic process
- Gravity isn't observed to effect the flow front
- Increased injection velocity provides the melt with more inertia and fills more of the cavity
  - Machine dynamics
  - Compressibility of melt



Molding Results

With Gravity

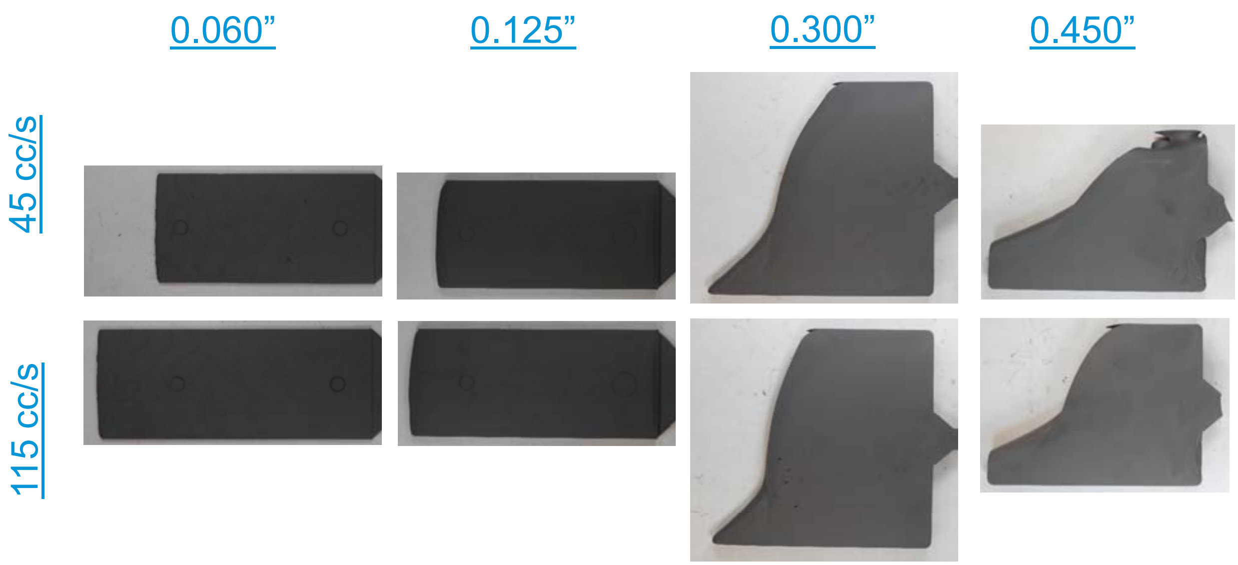
- Flow patterns look as excepted for a typical thermoplastic process for the 0.060” and 0.125” parts
- Gravity and inertia induce unpredictable flow for the two thicker plaques
  - Wall slip
  - Jetting/puddling
- There is evidence of post fill stage movement of the melt



Molding Results

Transverse Gravity

- Flow patterns look as excepted for a typical thermoplastic process for the 0.060” and 0.125” parts
- Thick plaques show two movements of the melt
  - Initial fill stage profile
  - Post fill stage slumping
- Fill stage profiles
  - Parts seem to accelerate across the bottom
  - Molten polymer still able to flow due to gravity

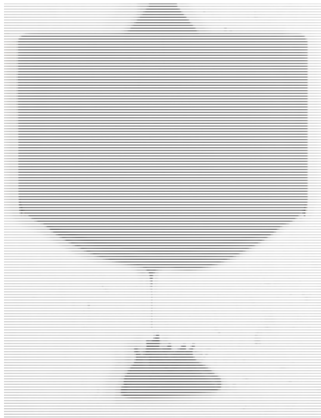


Molding Results

Conclusions

- Comparable thicknesses to typically injection molding parts seem to have little to no effect of gravity on its fill pattern
- Inertia on the other hand effects the end of fill location of the melt
- As thicknesses are increase the effects of gravity are easily observed
  - Movement of flow front curvature is changed
  - Molten inside still able to flow post fill

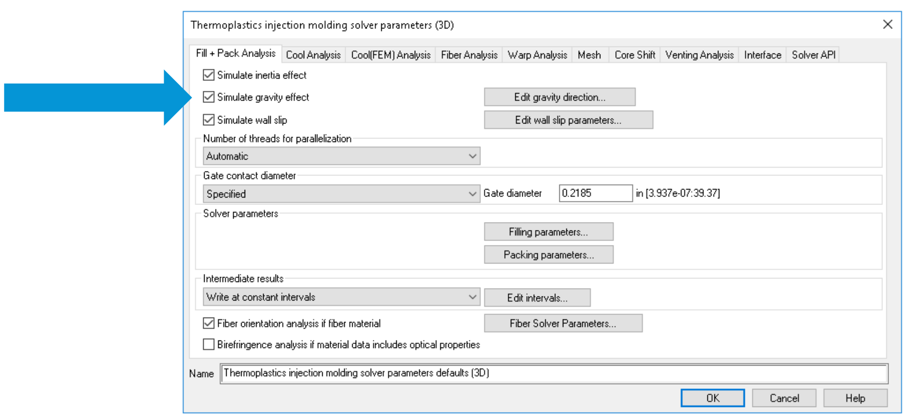
Can we simulate this behavior?

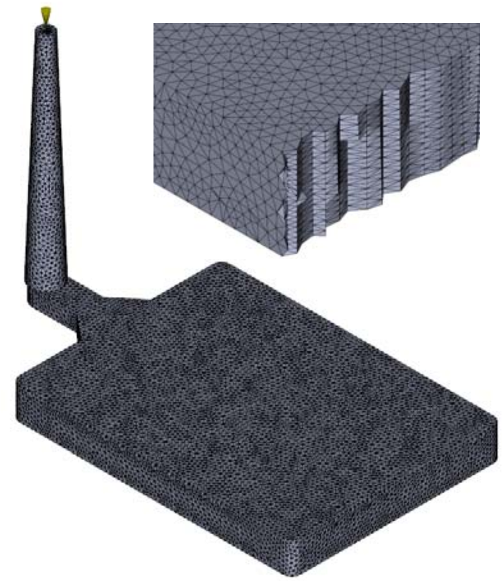


Simulation Set-Up

- Models meshed as a 3D mesh
  - Global edge length of 0.060”
  - 20 layers through the thickness

- Solver Parameters in the Advanced settings are changed to include Inertia, Gravity, and Wall Slip
  - Gravity direction was assigned per model
  - Default wall slip parameters were used





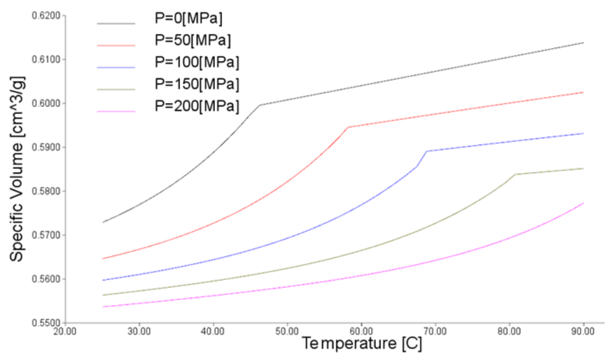
Parameter	0.060”	0.125”	0.300”	0.450”
Tetrahedral	972,121	961,653	1,117,234	687,696
Aspect ratio				
Maximum	68.26	48.42	42.56	102.68
Average	13.34	7.18	3.66	3.08
Minimum	1.15	1.12	1.10	1.11

Material Characterization

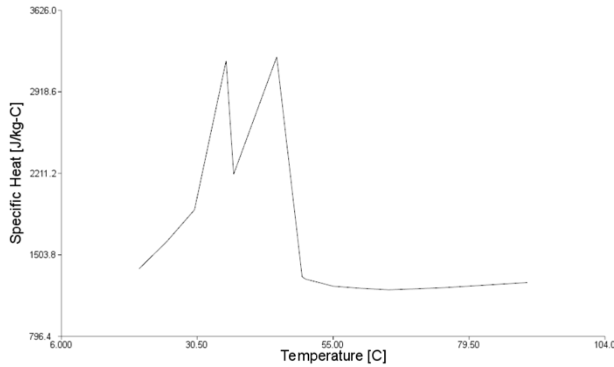
- Testing performed to generate custom material model
  - Rheology: Ares-G2 cone and plate overlaid with Dynisco LCR7000 capillary
  - Specific heat: TA Discovery Series DSC
  - PVT and thermal conductivity: tested at external labs
- Semi-crystalline behavior of wax based binder system
  - Two distinct melting peaks at 35C and 50C
  - Melt temperature 80C, mold temperature 26.6C
- Very low viscosity material <10 Pa-s
  - Slight shear thinning behavior, minimal temperature dependence
- Material model generated using Autodesk Moldflow Data Fitting 2018 software

Parameter	Value	Units
K	2.76	W/m*k
n	0.8632	
Tau*	7.364e-18	Pa
D1	716473	Pa-s
D2	263.15	K
D3	0	K/Pa
A1	7.1207	
A2~	51.6	K

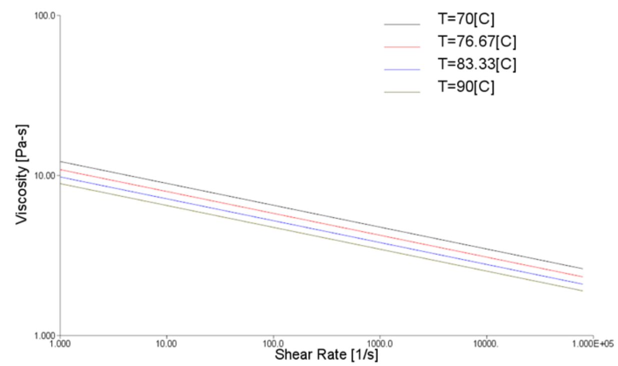
PVT Behavior



Specific Heat



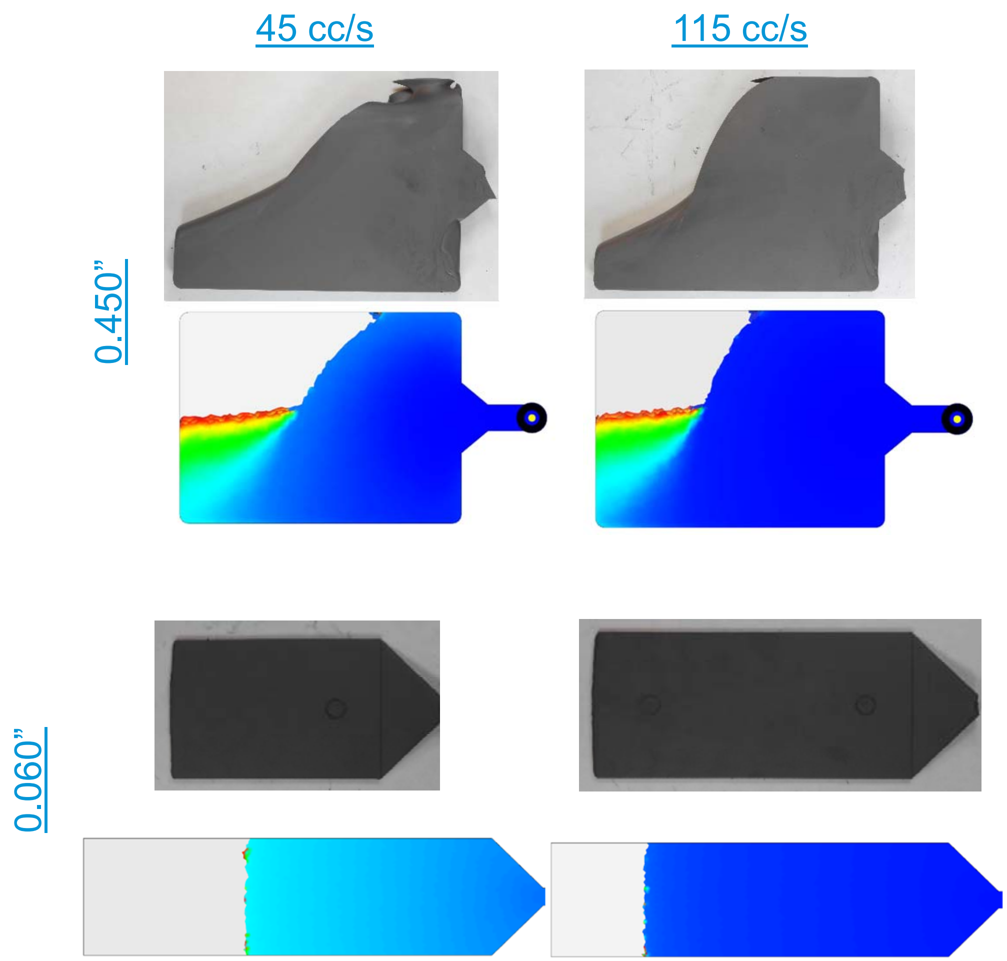
Rheology



Simulated Short Shots

PIM vs Simulation: Transverse Gravity

- Flow rate changes how the cavity fills
  - Faster flows changes end of fill stage
  - Faster flows changes curvature of flow front
- Molding shows a post filling movement of feedstock in thicker parts
  - Middle of part is still molten and gravity promotes material flow into the empty space
- Cooling effects the amount of post fill movement
  - 0.060” cools fast enough that there is negligible movement

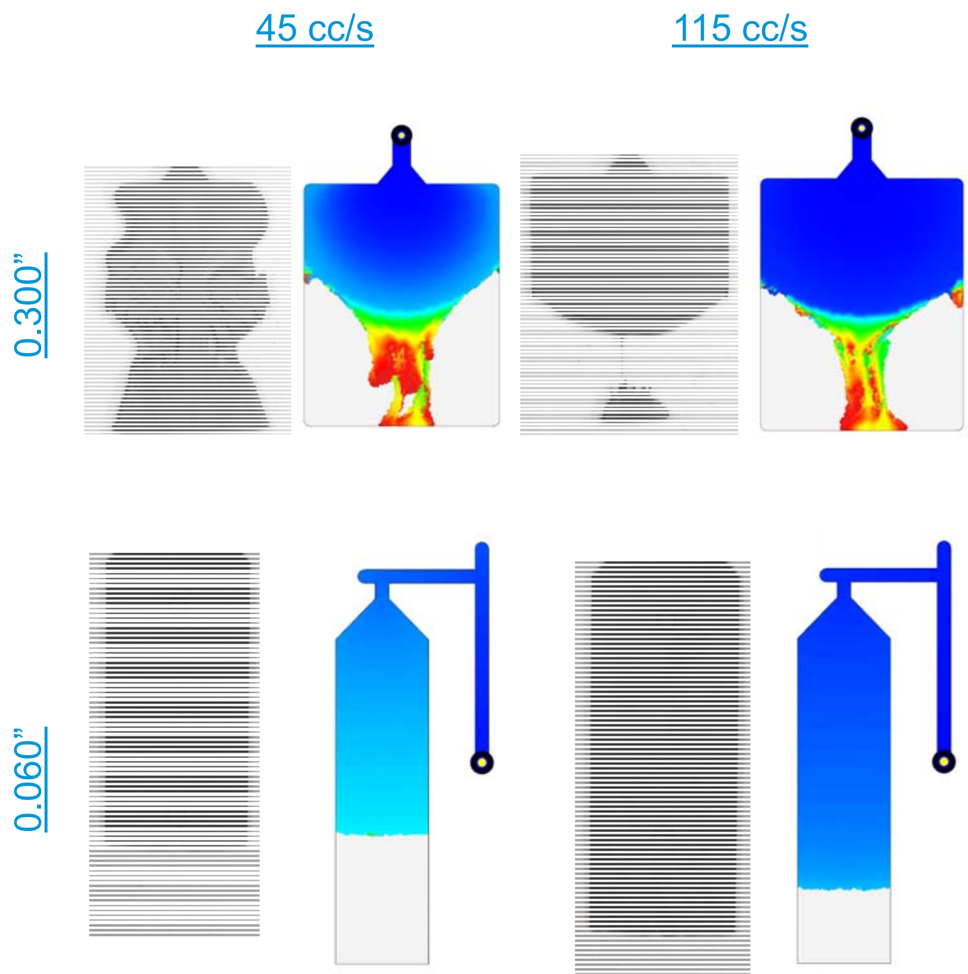


Simulated Short Shots

PIM vs Simulation: With Gravity

- Gravity and inertia is captured by the simulation however there is evidence of wall slip which created unpredicted flow
  - Flow with gravity imparts enough energy that slip is more likely than the other directions
  - With wall slip conditions on it is clear the default setting need further refinement to capture behavior

- Molding shows a post filling movement of feedstock in thicker parts
  - Middle of part is still molten and gravity promotes material flow into the empty space below

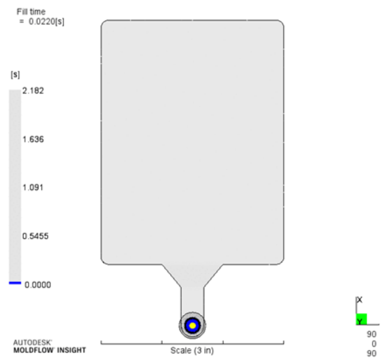


Simulation Results

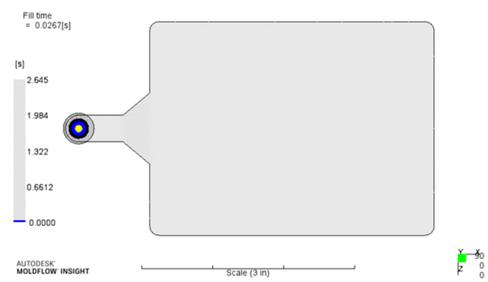
Effect of Gravity and Viscosity

- LDPE ran w/ gravity and inertia effects
  - High viscosity, low density
  - Flow pattern mimics standard molding
- PIM ran w/ gravity and inertia effects
  - Low viscosity, high density
- Gravity influences flow
  - Flattens the flow front moving up
  - Fills the bottom of the cavity first moving horizontal
  - Elongates flow front filling the middle irregularly

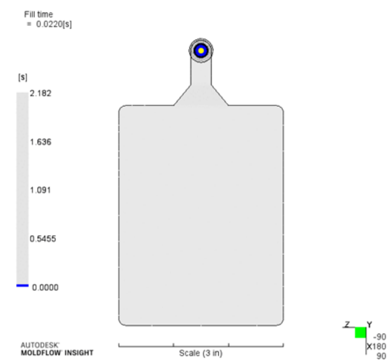
LDPE – 0.450” - Up



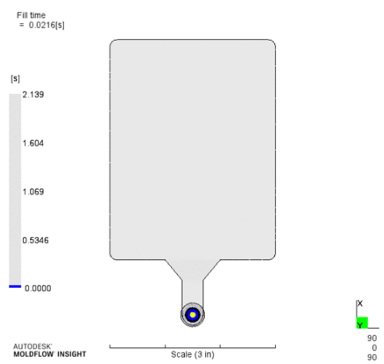
LDPE – 0.450” - Horiz



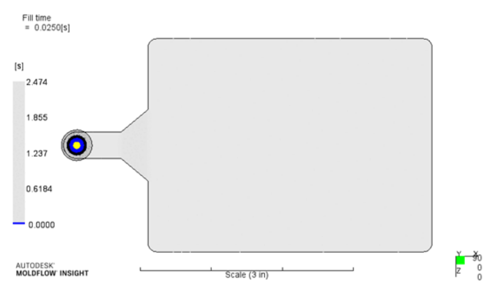
LDPE – 0.450” - Down



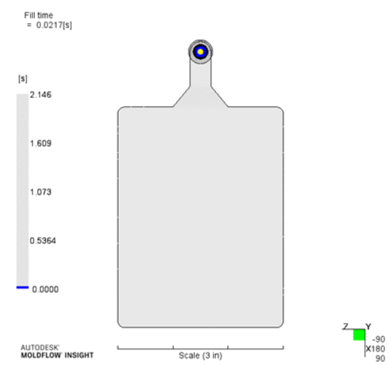
PIM – 0.450” - Up



PIM – 0.450” - Horiz



PIM – 0.450” - Down

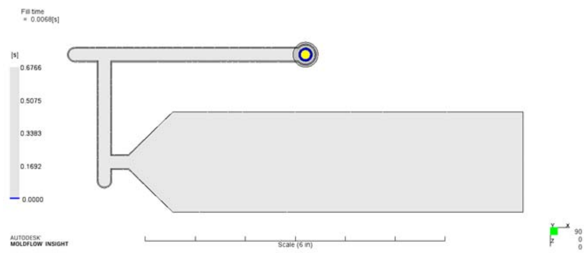


Simulation Results

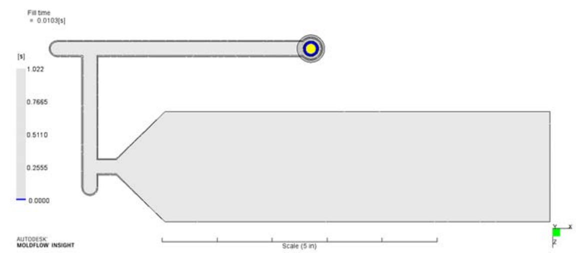
Effect of Thickness

- All thicknesses ran w/ gravity and inertia effects
- As thickness increases a change to the flow front curvature can be observed
  - Gravity promotes flow across the bottom of the cavity
  - As parts get thinner the flow front is effected less

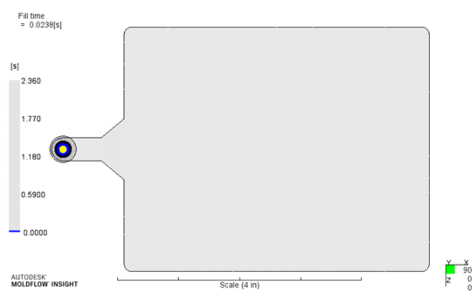
PIM – 0.060” - Horiz



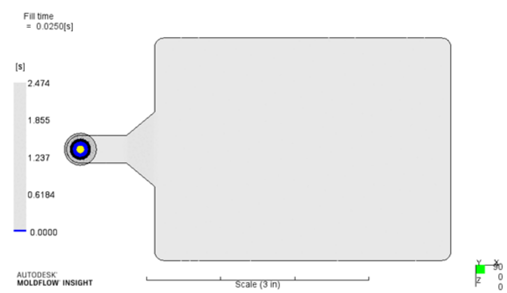
PIM – 0.125” - Horiz



PIM – 0.300” - Horiz



PIM – 0.450” - Horiz



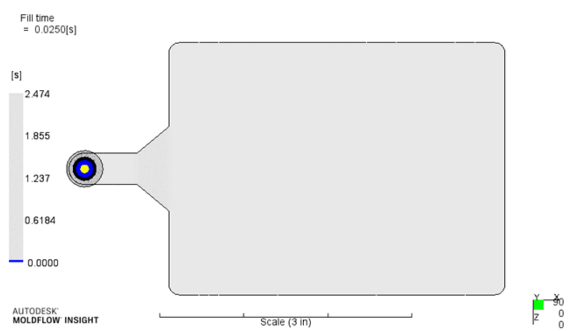
Simulation Results

Effect of Gravity and Speed

- All thicknesses ran w/ gravity and inertia effects
- Faster speeds produces more inertia in the system
  - Flow with gravity at faster speeds helps promote flow more uniformly
  - Flow transverse to gravity flattens out with increase inertia

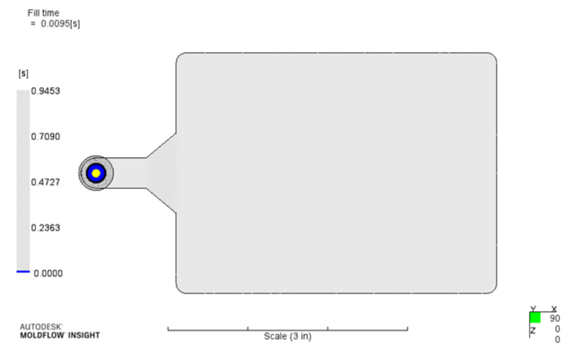
45 cc/s

PIM – 0.450” - Horiz

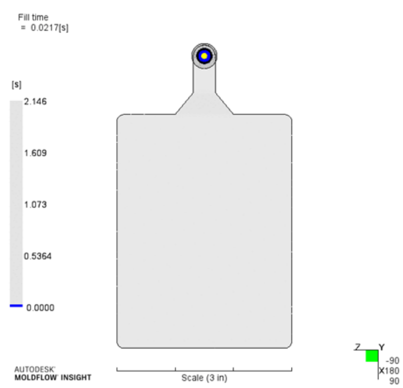


115 cc/s

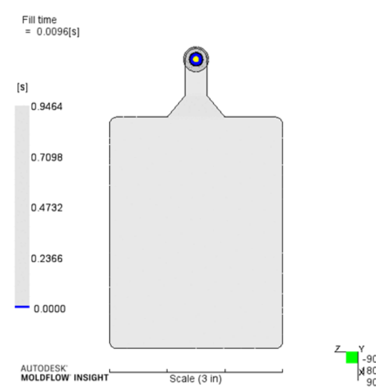
PIM – 0.450” - Horiz



PIM – 0.450” - Down



PIM – 0.450” - Down

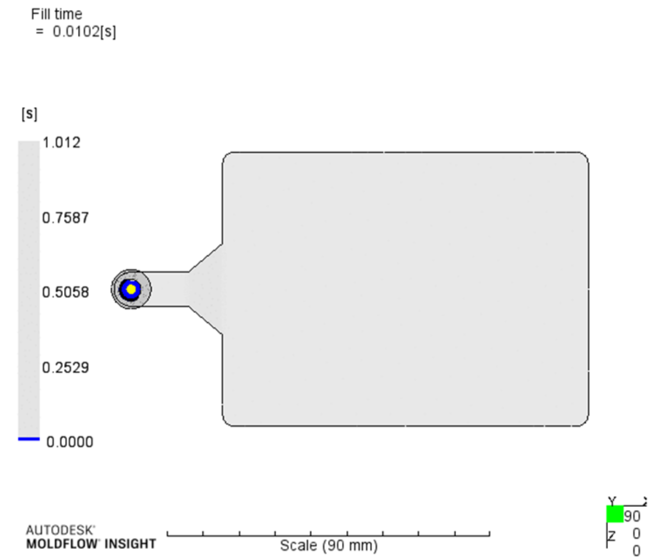


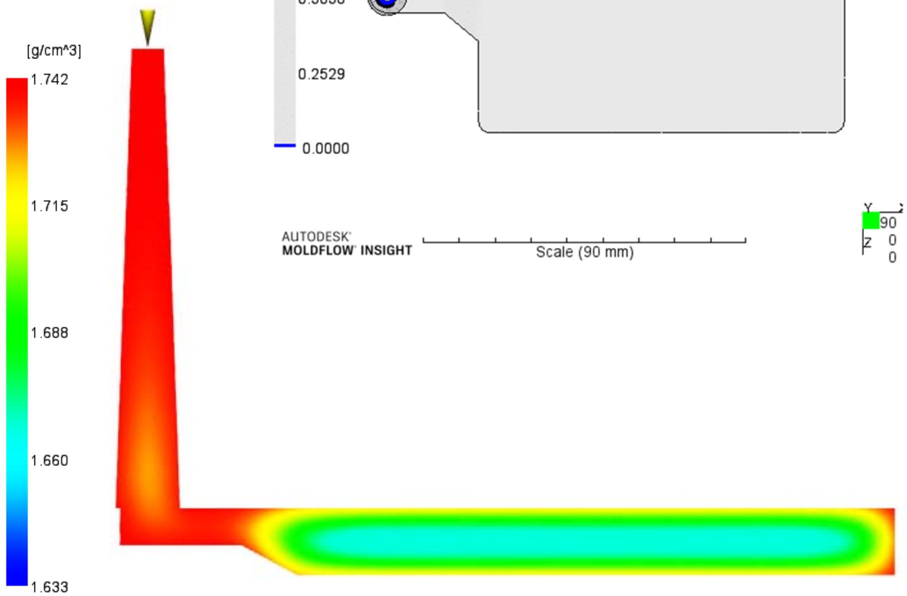
Conclusion

- Inertia and Gravity play a significant role in the filling behavior of PIM systems
  - Recommended to fill against gravity to minimize effects
  - Thickness played a key role on whether gravity or inertia would have an effect on polymer flow
- Autodesk Moldflow Insight™ did a great job on simulating low viscosity PIM systems
  - Simulated short shots predicted correct post filling movements
  - Against gravity filled comparable to typically thermoplastic behavior
  - Transverse to gravity has good agreement
  - With gravity accurately shows jetting and puddling of melt
    - Wall slip parameters need fine tuning

Future Work

- Fully understanding the wall slip parameters and how to characterize them for different feedstocks
- Work with the PIM solvers to start understanding powder migrations that is observed in heavily filled systems
  - Leads to density gradients in the part





Acknowledgements

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- Prof. Stephen Johnston: Advising and project support
- Gregory Pigeon: Experiment trials and feedstock characterization
- Stephen Esposito and Jordan Dorff: Lab assistance

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