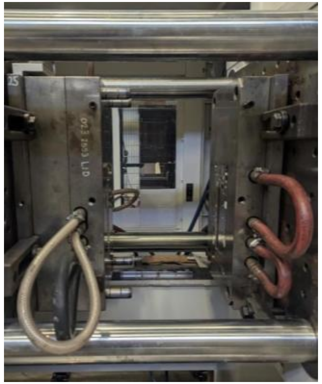
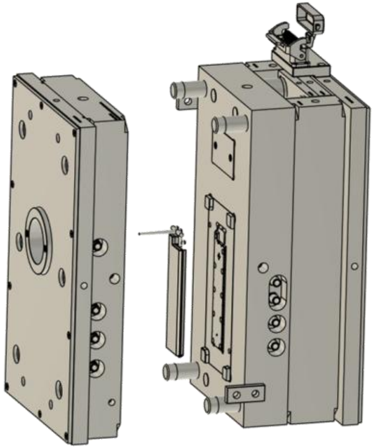
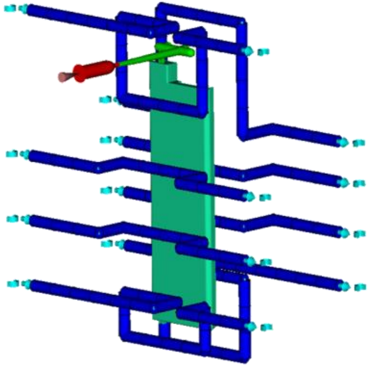
Can STAMP Move Us Closer to a Digital Twin?







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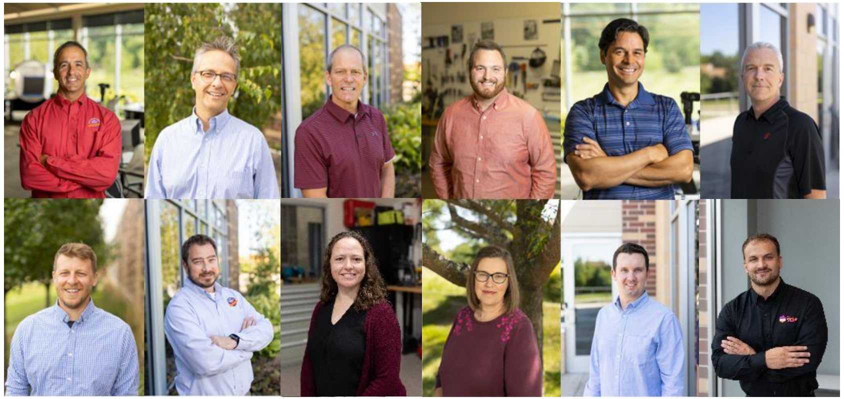
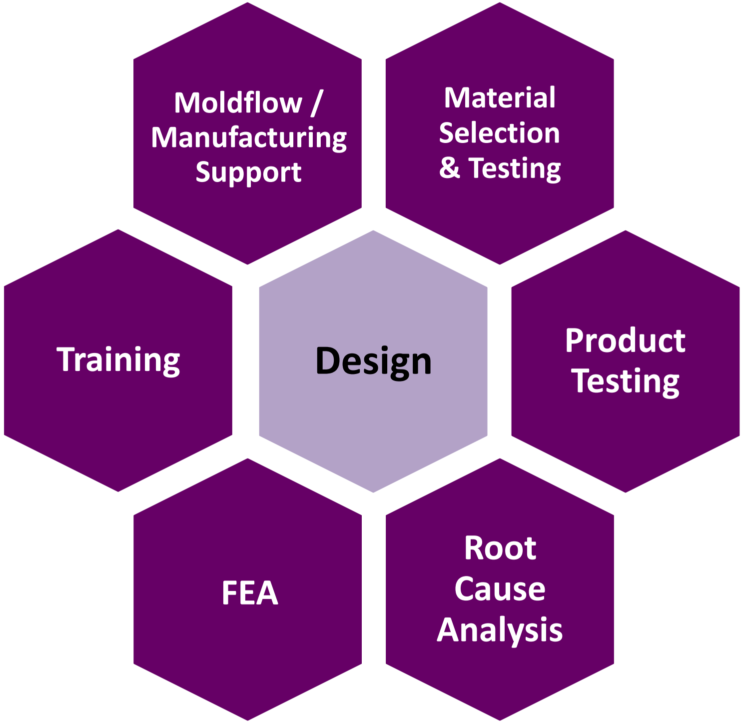
The Madison Group

- Offices in Madison, Milwaukee and Pittsburgh.
- Engineering company focused on plastics and polymeric materials.
  - Founded in 1993.
- Your partner throughout the entire product development process.



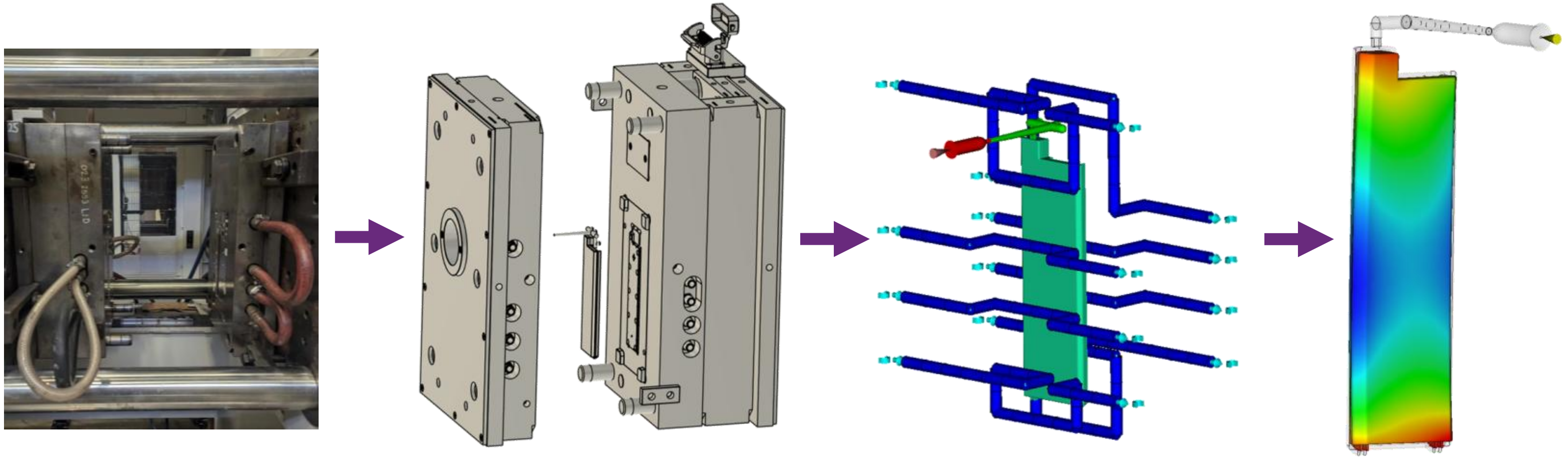


Agenda

- We will cover:
  - When is it appropriate to create a digital twin vs. analyzing a simpler model?
  - What is needed to create an injection molding digital twin?
    - Focused on accurate warpage predictions.
  - Common pitfalls or missing pieces when creating your model.
    - Risks associated with these pissing pieces.
  - What is STAMP?
    - Why do we need STAMP; benefits over other warpage solvers.
  - Analysis of a “Golden Case”, taking a look at the performance of the new STAMP shrinkage (and warpage) solver in a perfectly controlled digital twin model.

What Is A Digital Twin?

- **A "digital twin" is a high-fidelity virtual replica of an injection mold, material and process conditions, created in Autodesk Moldflow.**
- A digital twin integrates real-world geometry, material behavior, machine parameters, and processing conditions to accurately simulate and predict how the part will fill, pack, cool, and deform—enabling engineers to evaluate performance, optimize the process, and reduce risk before physical trials and production.



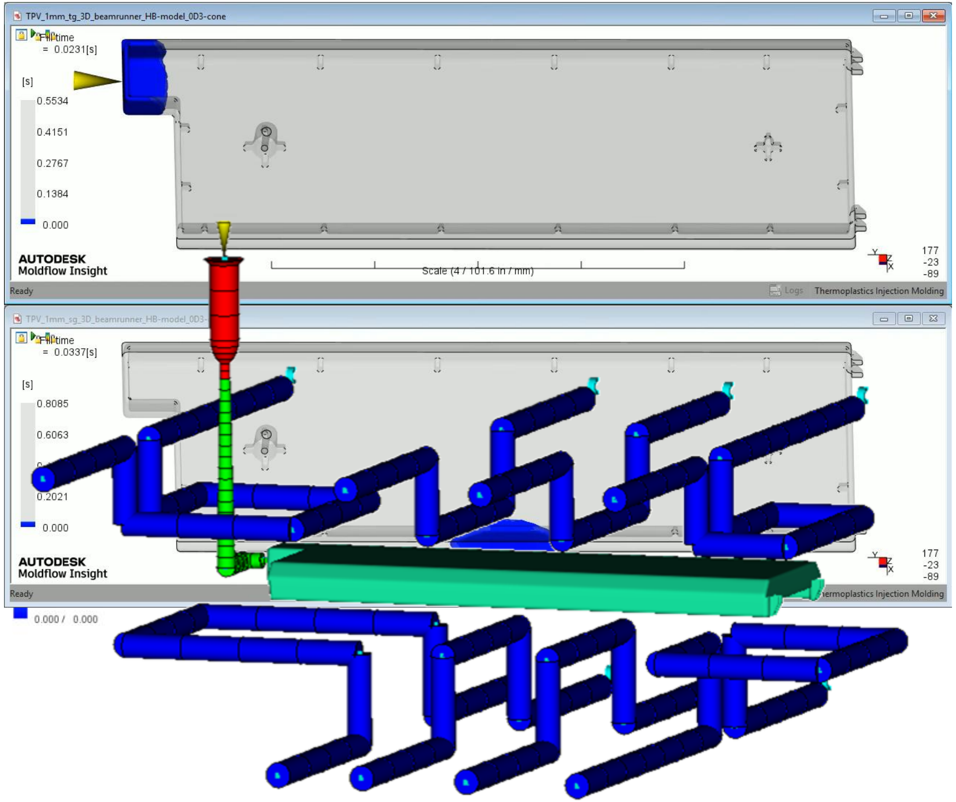
When Do You Need To Create A Digital Twin?

- At what point in the design or product lifecycle do you need a digital twin?

	Part Design	Material	Gating	Feed System Details	Cooling	Venting	Molding Machine
Product Design/ DFM	X	X	X				
Initial Tooling/Quoting	X	X	X				X
Tooling Optimization and Validation	X	X	X	X	X	X	X
Troubleshooting or Root Cause	X	X	X	X	X	X	X

Are All Digital Twins Requirements The Same?

- Many different objectives for running injection molding simulations:
  - Part Design
    - Can I fill my part?
    - What material should I use?
    - Where should I place my gates?
    - What is my cycle time?
    - **<u>What will my part look like after ejection?</u>**
  - Processing:
    - How fast should I fill my mold?
    - What feed system should I use? What dimensions?
    - What mold and melt temperature should I select?
    - How sensitive will my process be to these variables?
    - **<u>How will my part look after ejection?</u>**
  - Mold Design:
    - What cooling strategy should I use?
      - Conventional vs conformal cooling
      - High conductivity inserts
    - **<u>How will my part look like after ejection?</u>**

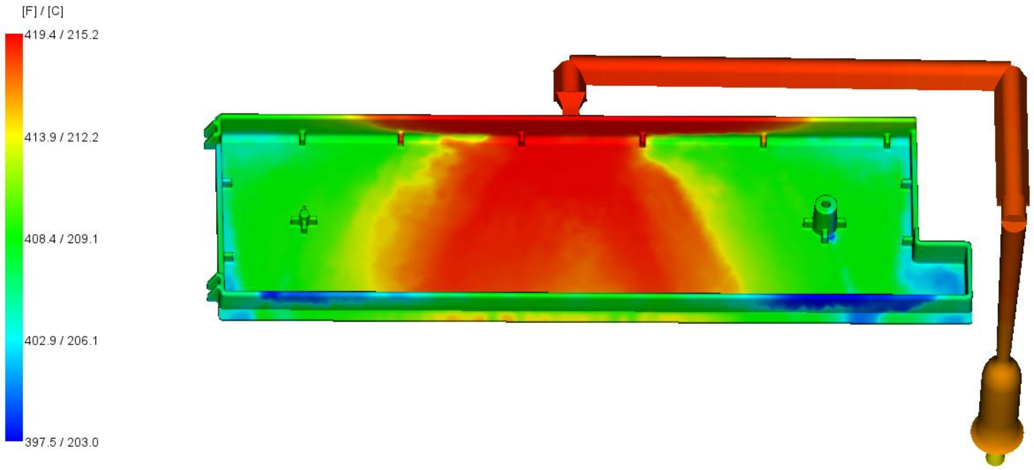


What is Needed for Accurate Warpage?

- One of the most common objectives is how will my part shrink and warp?
- In order to get good warpage results, a good representation of the pressure and thermal history of the material is needed.
- Therefore, we need good digital twins of mold filling stage and cooling stage?
  - Warpage is a result of these inputs!

What is Needed for Accurate Mold Filling?

- To Get Realistic Injection Pressure Predictions We Need:
  - Good Model Definition (Good Analyst):
    - Part Design
    - Feed System
    - Correct Solver
  - Good Process Settings
    - Fill Time/Flow Rates
    - Packing Pressures and Time
    - Melt and Mold Temperature
    - Cycle Time.
  - Good Material Data
    - Measured Viscosity Data (Shear and Elongation)
    - Multi-Point Thermal Data



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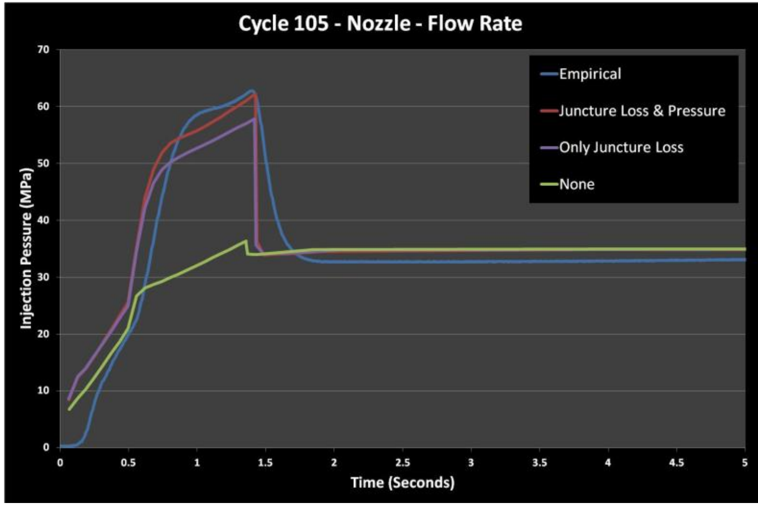

What is Needed for Accurate Cooling?

- To Get Realistic Warpage Predictions We Need:
  - Good Model Definition (Good Analyst):
    - Part Design
    - Feed System
    - **Cooling Line Layout**
    - **Mold Material Details**
      - **High Conductivity Inserts**
  - Good Process Settings
    - **Coolant Conditions:**
      - **Coolant Inlet Temperatures**
      - **Flow Rate**
    - Melt and ***<u>Mold Temperature</u>***
    - **Cycle Time**
  - Good Material Data
    - **Multi-Point Data (Thermal)**

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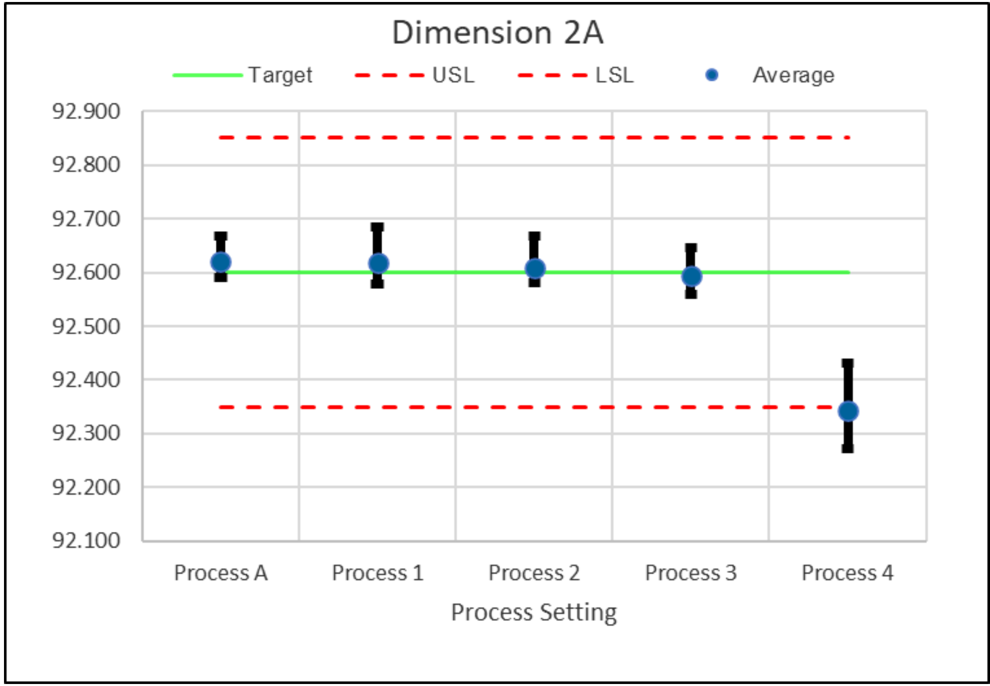

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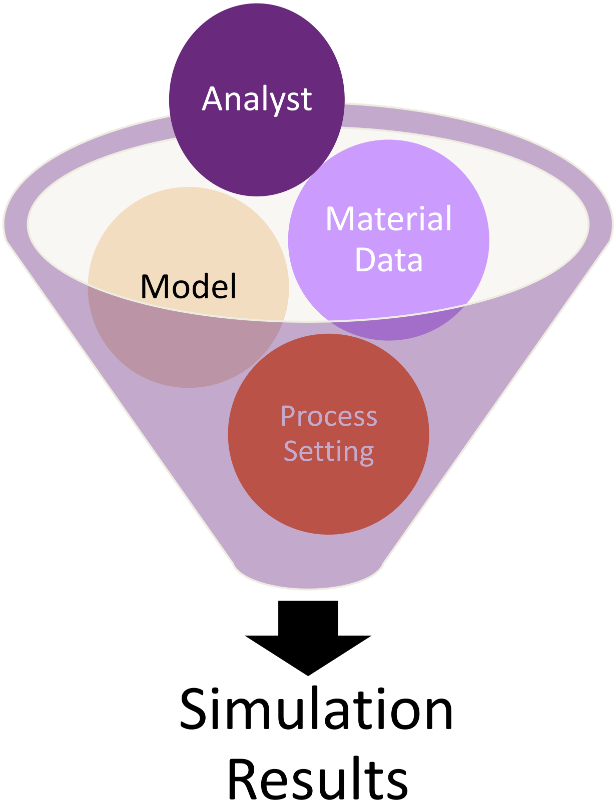
  - Good Material Data
    - Multi-Point Data (Thermal)
    - Shrinkage Data (CRIMS/STAMP)



So What is Missing? What is the Risk?

- To Get Realistic Warpage Predictions We Need:
  - Good Model Definition (Good Analyst):
    - Part Design
    - Feed System
    - Cooling Line Layout
    - Mold Material Details
      - High Conductivity Inserts
  - Good Process Settings
    - Fill Time/Flow Rates
    - Packing Pressures and Time
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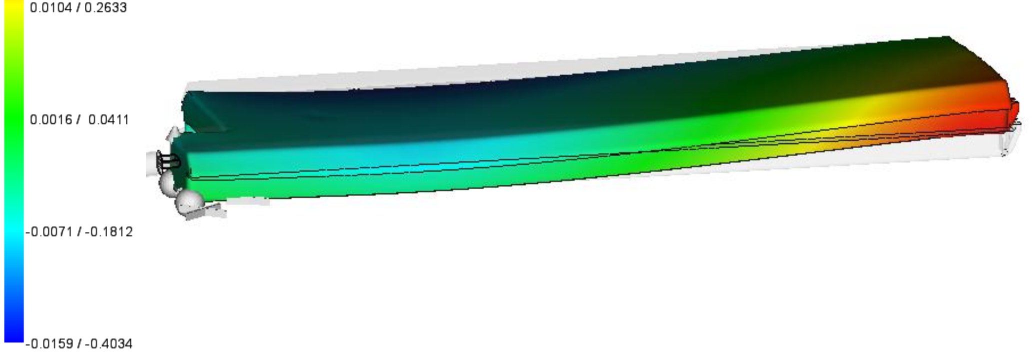
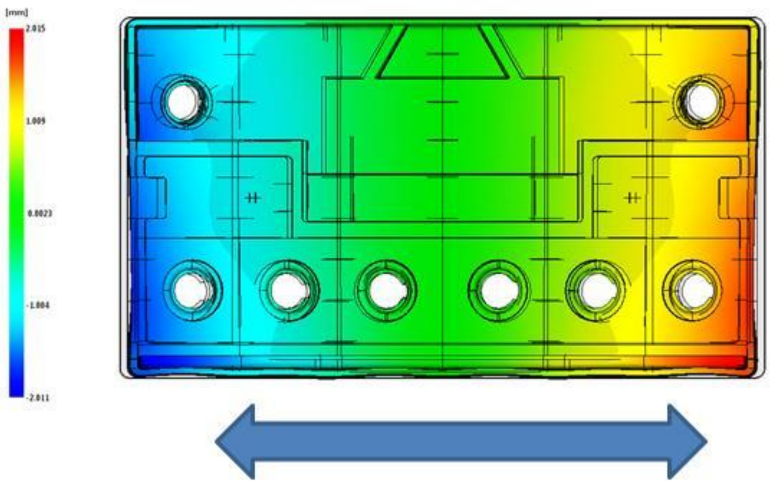
    - Multi-Point Data (Thermal)
    - *Shrinkage Data (CRIMS/STAMP)*



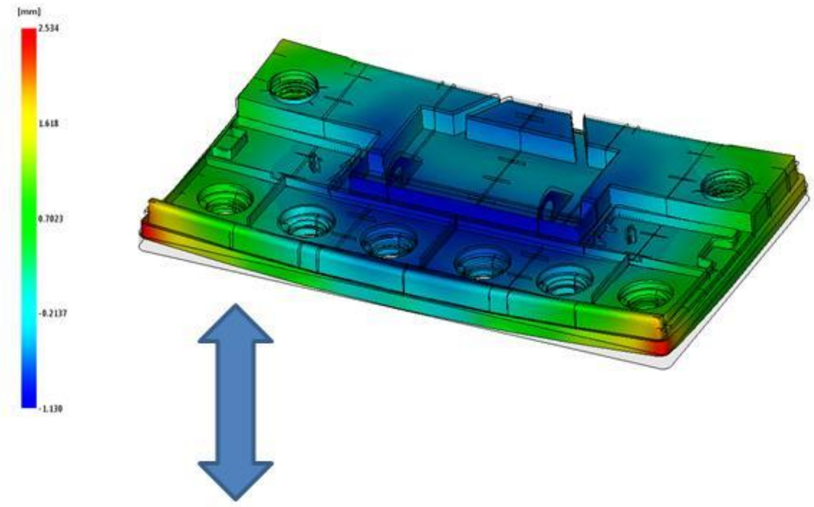
What Is Shrinkage?

- Shrinkage vs Warpage
  - Shrinkage – Linear change in dimensions of the part after ejection
  - Warpage – Out-of-plane deflection of the part

Shrinkage

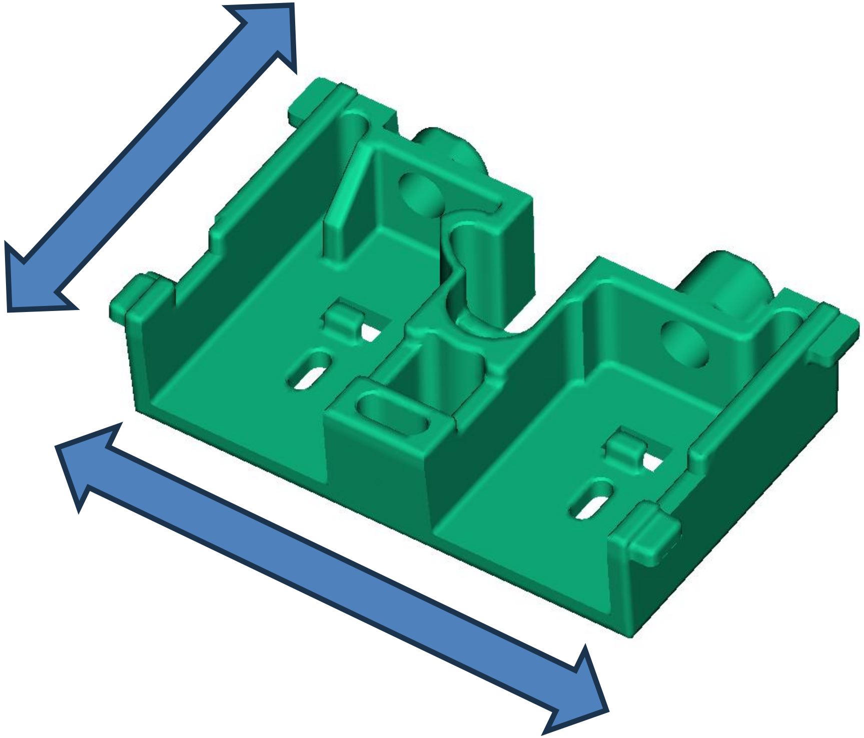


Warpage



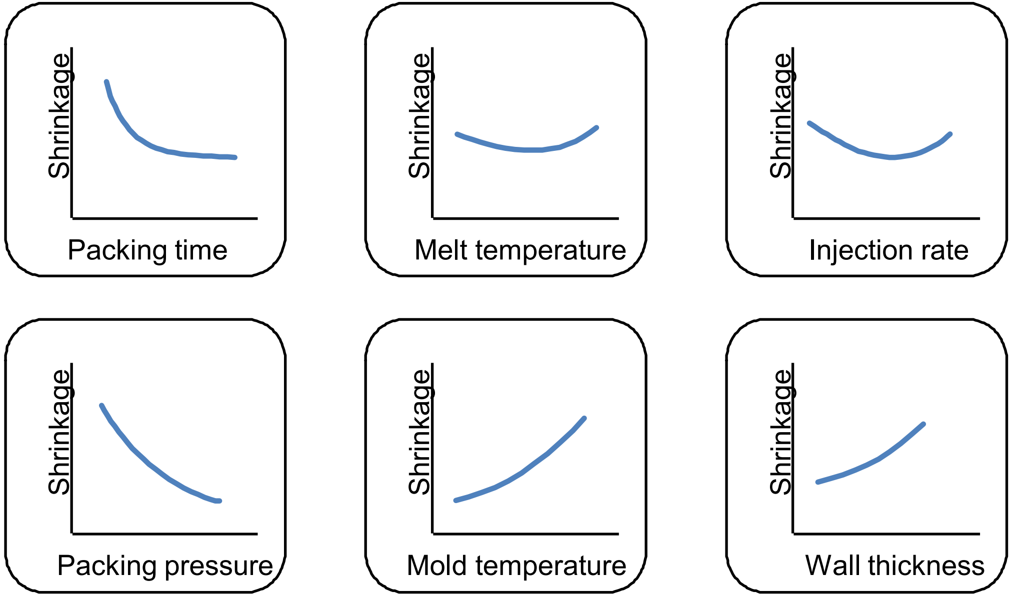
What Is Shrink Rate?

- Ideally, The Part Will Shrink Uniformly in All Directions
- Could Simply Scale Final Part Dimensions Uniformly to Make the Part to Print



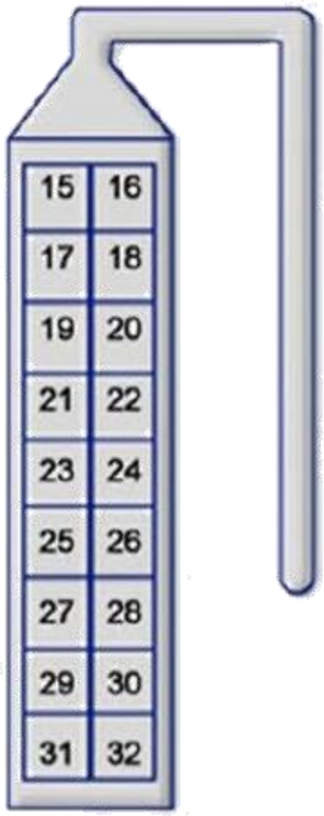
What Influences Shrink Rate?

- Examining Factors That Typically Influences Shrinkage (Warpage) Comes Back to Design Decisions!



Shrinkage Accuracy – CRIMS / STAMP

- How do we account for this in simulation?
- Autodesk Moldflow is Only Software To Have Shrinkage Data (CRIMS/STAMP) That Improves Warpage Correlation and Accounts for Post-Mold Shrinkage
  - **Part Thickness**
  - Melt Temperature
  - Mold Temperature
  - Fill Time
  - Packing Pressure
  - **Packing Time**
  - Cooling Time
  - **Post Mold Shrinkage**



Shrinkage Accuracy – CRIMS / STAMP

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- Autodesk Moldflow is Only Software To Have Shrinkage Data (CRIMS/STAMP) That Improves Warpage Correlation and Accounts for Post-Mold Shrinkage

Shrinkage Experimental Data

Process Condition	Melt Temperature (°C)	Mold Temperature (°C)	Flow Rate (cc/sec)	Part Thickness (mm)	Packing Pressure (MPa)	Packing Time (sec)	Cooling Time (sec)
1	193.9	43.5	40.9	3.0	88.4	16.0	10
2	194.4	44.9	40.0	3.0	112.6	16.0	10
3	194.5	45.3	40.9	3.0	136.6	16.0	10
4	194.4	45.3	20.4	3.0	112.6	16.0	10
5	194.5	45.1	64.1	3.0	112.7	16.0	10
6	211.7	43.8	39.2	3.0	88.2	16.0	10
7	213.0	43.9	39.2	3.0	112.5	16.0	10
8	212.7	44.1	39.2	3.0	136.5	16.0	10
9	212.9	44.1	19.4	3.0	112.9	16.0	10
10	213.0	44.4	64.1	3.0	112.7	16.0	10
11	213.1	43.1	33.4	2.0	103.2	11.0	10
12	213.0	44.1	32.6	2.0	127.2	11.0	10
13	213.1	44.4	32.6	2.0	151.1	11.0	10
14	212.9	43.6	17.2	2.0	127.4	11.0	10
15	213.0	44.5	50.8	2.0	127.5	11.0	10
16	212.9	42.2	49.0	5.0	82.8	24.0	10
17	212.8	44.3	49.8	5.0	102.4	24.0	10
18	213.0	43.7	49.0	5.0	121.9	24.0	10
19	212.9	43.0	24.7	5.0	102.3	24.0	10
20	212.9	44.0	74.1	5.0	102.7	24.0	10
21	235.5	43.5	40.0	3.0	83.5	18.0	10
22	235.3	44.3	39.2	3.0	102.6	18.0	10
23	235.3	44.4	39.2	3.0	132.2	18.0	10
24	235.1	43.6	19.8	3.0	102.8	18.0	10
25	235.1	44.4	62.0	3.0	102.9	18.0	10

Part Shrinkage

Process Condition	Average Measured Parallel	Average Measured Perpendicular	Average Predicted Volumetric
1	2.873%	1.202%	2.586%
2	2.647%	0.884%	1.677%
3	2.403%	0.638%	0.961%
4	2.559%	0.950%	1.696%
5	2.707%	0.819%	1.670%
6	2.896%	1.136%	2.531%
7	2.650%	0.834%	1.624%
8	2.417%	0.652%	0.917%
9	2.594%	0.892%	1.627%
10	2.759%	0.701%	1.615%
11	2.414%	1.269%	2.983%
12	2.250%	0.968%	1.895%
13	1.983%	0.752%	1.093%
14	2.182%	1.071%	1.859%
15	2.312%	0.941%	1.884%
16	3.818%	2.345%	6.597%
17	3.653%	2.044%	5.991%
18	3.440%	1.783%	5.130%
19	3.477%	2.104%	4.941%
20	3.833%	1.992%	6.326%
21	2.977%	1.201%	2.653%
22	2.821%	0.906%	1.908%
23	2.551%	0.633%	0.995%
24	2.763%	0.854%	1.909%
25	2.882%	0.876%	1.893%

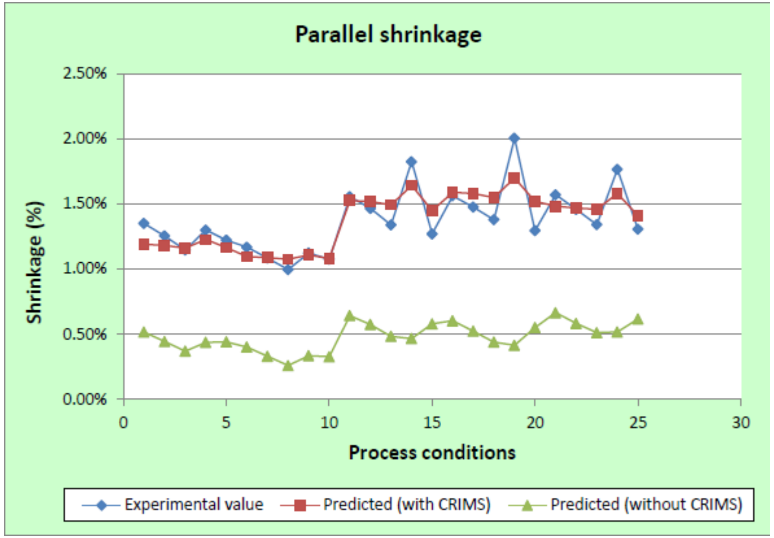
Shrink Data

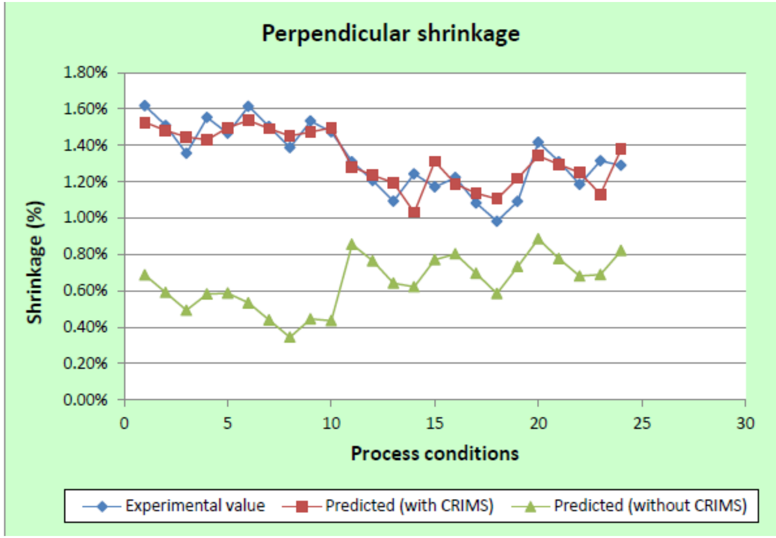
- Shrinkage Can Vary Greatly Based on Processing and Additives
  - Datasheet May not Provide Representative Values
  - Optimizing Packing Becomes Important (Gate Location and Size!)

Material	Prospector Flow Direction	Prospector Across-Flow Direction	Minimum Flow Direction	Maximum Flow Direction	Minimum Across - Flow Direction	Maximum Across - Flow Direction
Zytel 101L (PA66)	1.4%	1.4%	0.986%	2.084%	1.204%	2.444%
Zytel 70G33 (33% GF PA66)	0.30%	1.1%	0.193%	0.2832%	1.353%	1.866%
Lexan 121R (PC)	0.5-0.7%	0.5-0.7%	0.7238%	0.9815%	0.7515%	1.065%
Makrolon GF9018 (PC w/10% Glass)	0.45%	0.50%	0.09%	0.112%	0.320%	0.0406%

Shrinkage Accuracy – CRIMS / STAMP

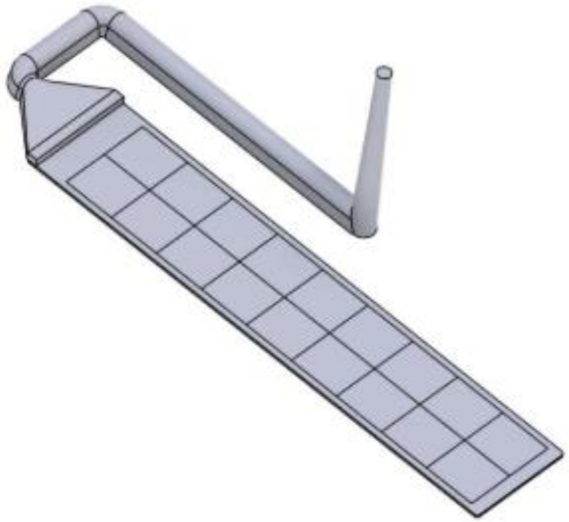
- Autodesk Moldflow is Only Software To Have Shrinkage Data (CRIMS/STAMP) That Improves Warpage Correlation and Accounts for Post-Mold Shrinkage





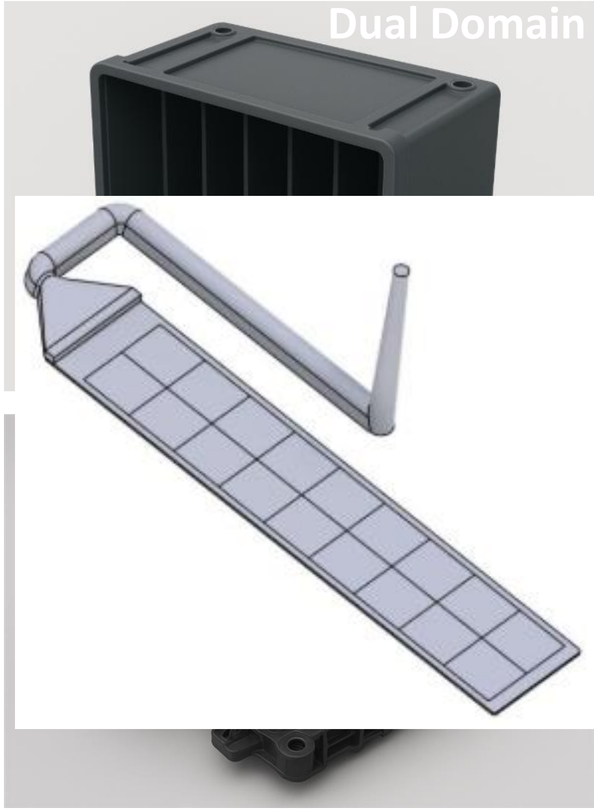
What is STAMP?

- Shrinkage Test Adjusted Mechanical Properties
  - STAMP is a corrective shrinkage model.
  - Continued improvement from the dual domain CRIMS model.
    - Uses the same measured shrinkage data to calibrate mechanical properties such as CTE Poisson's ratio and modulus.
      - Done using a compressibility factor to compensate for the viscoelastic and orientation effects of plastics.



Why Did We Need STAMP?

- "We already have CRIMS"
  - Not Suitable for All Part Geometries.
    - Midplane and Dual Domain
- With part designs becoming more and more complex we are leaning on 3D analyses for accurate Cool, Fill and Pack results.
- Same testing as CRIMS.



CRIMS vs. STAMP

- Corrected Residual In-Mold Stress (CRIMS)
  - Dual Domain and Midplane models.
  - Residual stress is calculated and then corrected based on molded part data.
- Shrinkage Test Adjusted Mechanical Properties (STAMP)
  - Used to more accurately represent 3D models.
  - Built from compressibility factors relating actual measurements and cavity pressure.

CRIMS vs. STAMP

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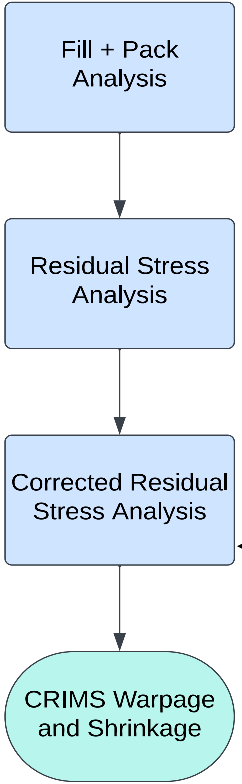
CRIMS (MP/DD)



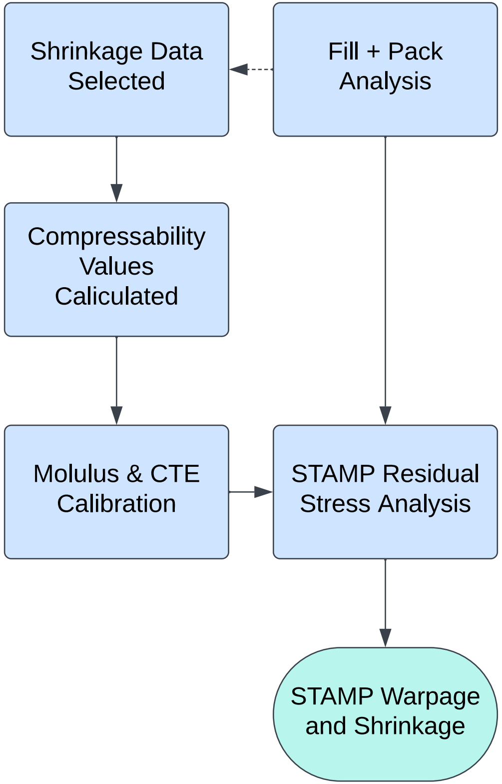
Material Characterization (Shrinkage Data)

Process Condition	...	Packing Pressure (MPa)	Shrinkage (flow)	Shrinkage (transverse)
1		88.4	2.873%	1.202%
2		112.6	2.647%	0.884%
3		136.6	2.403%	0.638%
...		...	...	...
25		102.9	2.882%	0.876%

CRIMS Coefficients

A_1	0.8273
...	...
A_6	0.0003

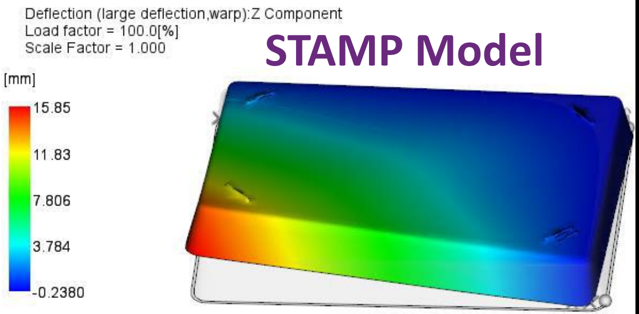
STAMP (3D)

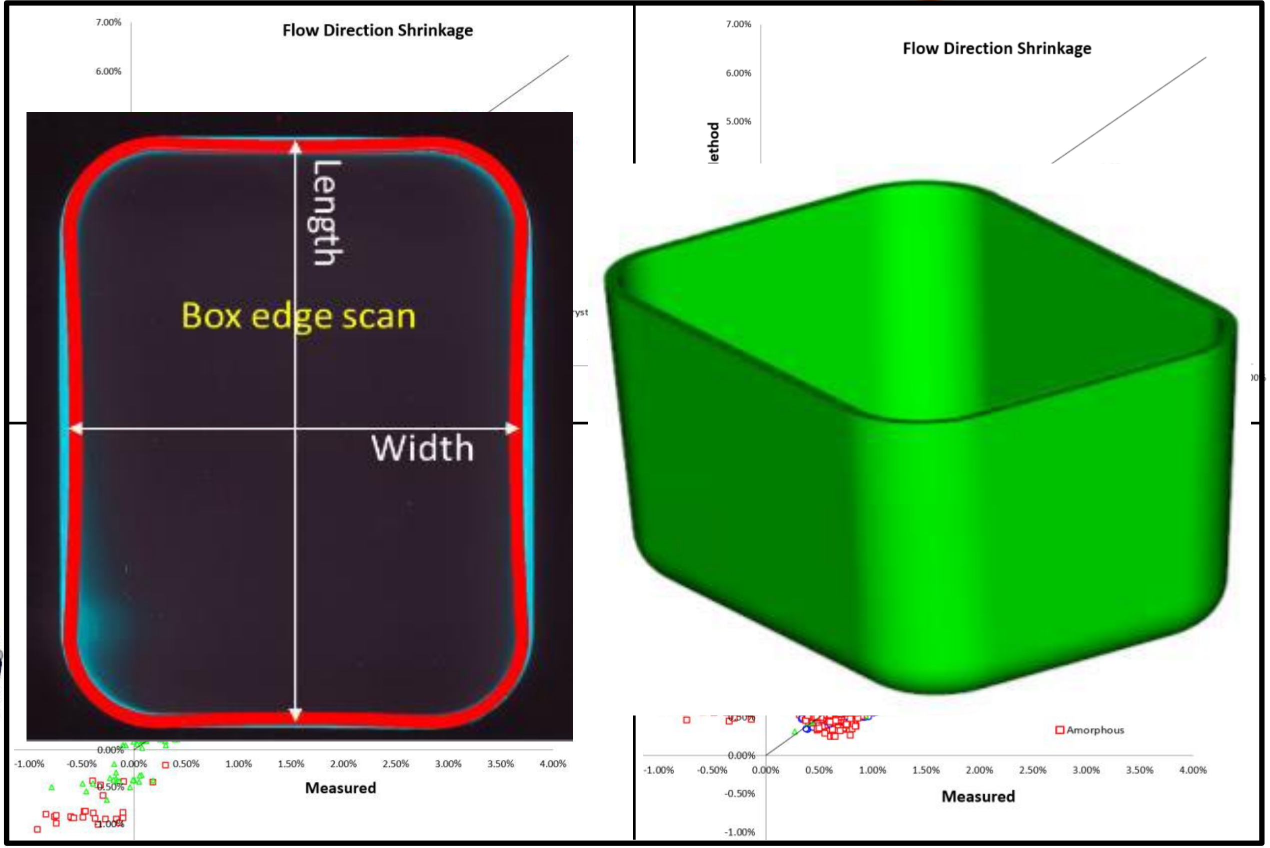


STAMP Validation Study

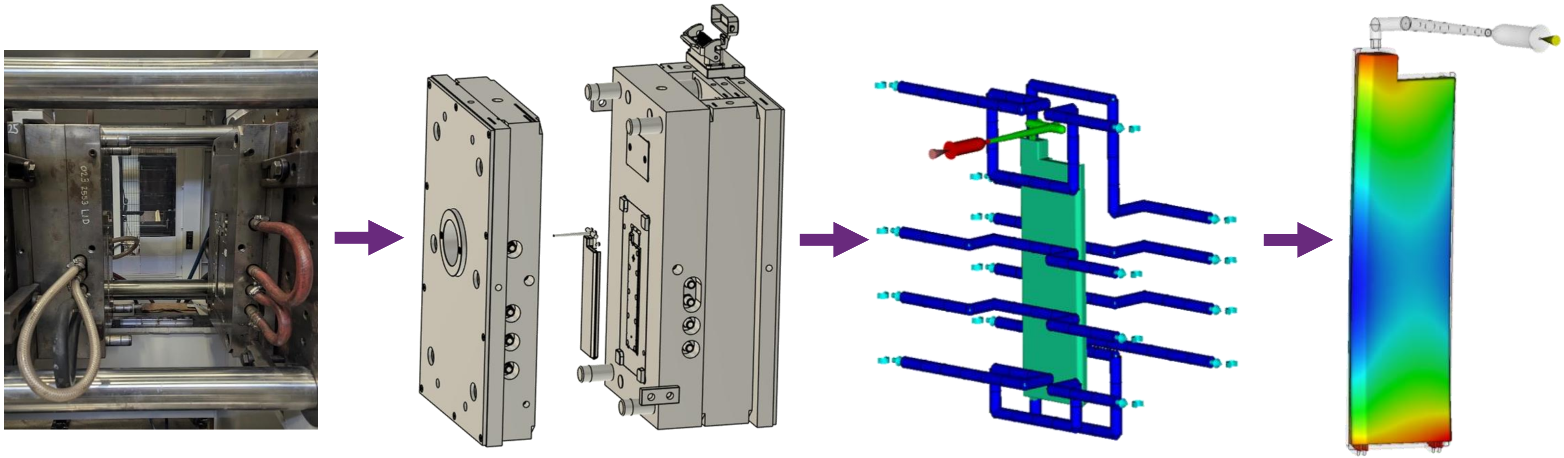
- 171 Different Resins
- Mixed Correlation
- Simple Geometries

STAMP Model



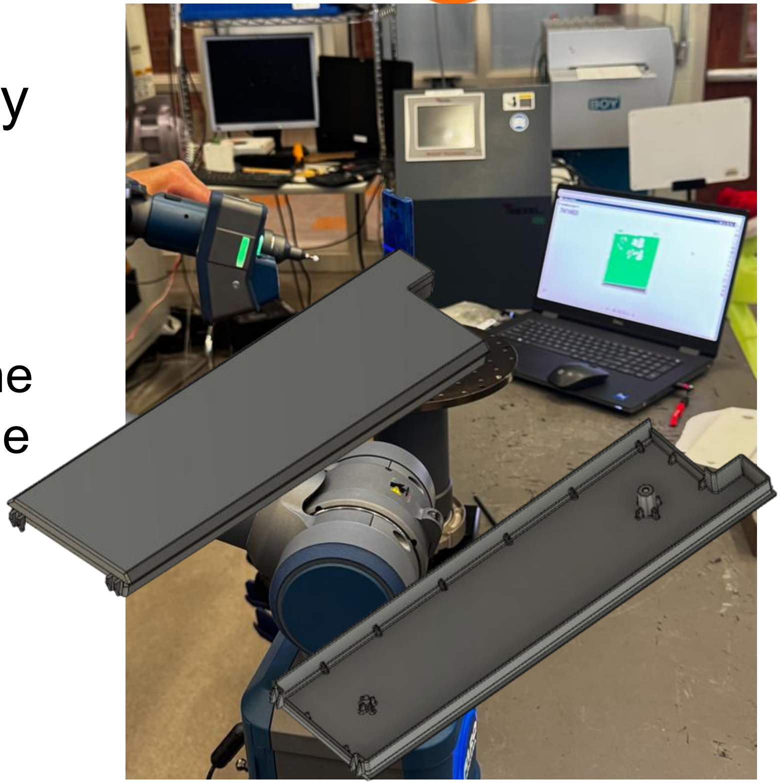


Case Study: Lutron Lid Digital Twin Analysis of the STAMP Model



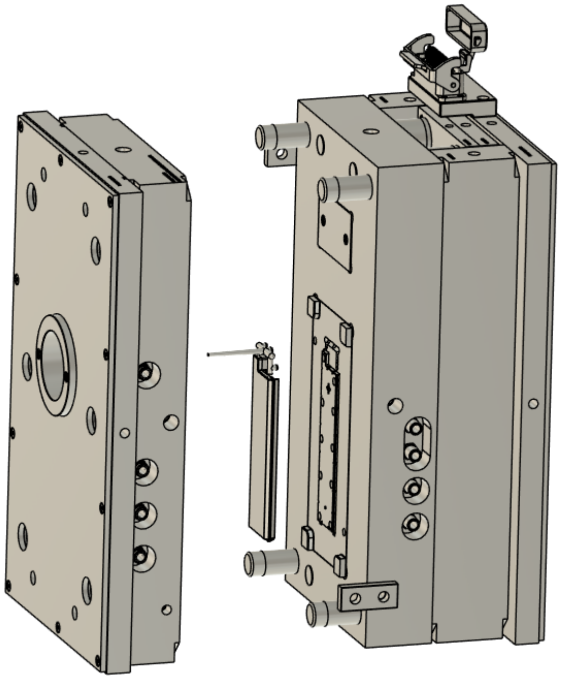
Project Overview

- Independent Warpage Validation Study
  - Building a digital twin of a real-world part application.
    - Cover/housing style part
  - Scanning molded parts and comparing the deflection (vs CAD) to Moldflow's warpage prediction.
    - Stamp vs Uncorrected Residual Stress
- Looking to Explore the Limits of the STAMP Model.



Why is This Study Important?

- Digital Twin Tool Validation
  - Helping Our Clients Build Robust Tools
    - Identify Any Potential Risks
    - Provide a Good Starting Point for Their Production Process
    - **Accurately Predict Shrinkage and Warpage**
  - Minimize Costly Rework
- What Does the Customer Want to Know?
  - "What's my shrink rate?"
  - "Will this fit in my assembly?"
  - "Can I use this to cut windage?"
- Building a Library of Very Precise Data



Material Models

Acceptable Materials for Testing				
Family + additives	**TPV**	**PP+FR MINERAL**	**PE**	**PP+GF30**
Mold Temperature (°C)	30.0 (10.0-52.0)	50.0 (32.0-66.0)	45.0 (21.0-65.0)	50.0 (30.0-65.0)
Melt Temperature (°C)	220.0 (193.0-232.0)	210.0 (191.0-232.0)	215.0 (193.0-232.0)	210.0 (190.0-230.0)
Elastic Modulus [E1] (MPa)	128.8	3,331	1,311	5,541
Elastic Modulus [E2] (MPa)	128.8	3,209	1,649	3,395
Alpha1 (1/°C)	8.68E-05	6.91E-05	2.01E-04	2.81E-05
Alpha2 (1/°C)	1.17E-04	7.33E-05	1.03E-04	6.52E-05

ID	ν_{12}	ν_{23}	T_{sol} (°C)
TPV	0.491	0.491	116
PE	0.423	0.423	119
PP+FRM	0.331	0.331	127
PP+GF	0.408	0.533	121

Measured Poisson's ratios and transition temps.

ID	Poisson's Ratios ν_{12} and ν_{23} (Test Lab Comments)
TPV	Derived from bulk modulus (PvT) and tensile test data.
PE	ν_{23} tested below ν_{12}. To eliminate errors in the .udbs, ν_{23} was made equal to ν_{12}.
PP+FRM	Inconsistent results seen for ν_{23}. ν_{23} made equal to ν_{12} for isotropic behavior.
PP+GF	No lab comment.

Material Models

- Four Polyolefin Materials Supplied by RTP
  - All were fully CRIMS/STAMP characterized
    - Also with additional pressure-depended viscosity models
  - All Materials are Readily Available and Published Publicly in the Database
  - The Materials Process Similarly
  - The Type of Materials That STAMP was Developed For
    - Low TG (post-mold shrinkage)
  - Different Filler/Additive Packages Looking to Test Different Areas of the Model

- **Parts Were Molded From the Same Lot That Was Characterized**
  - Minimizing lot-to-lot variations from characterization to molding

Lutron Lid Mold

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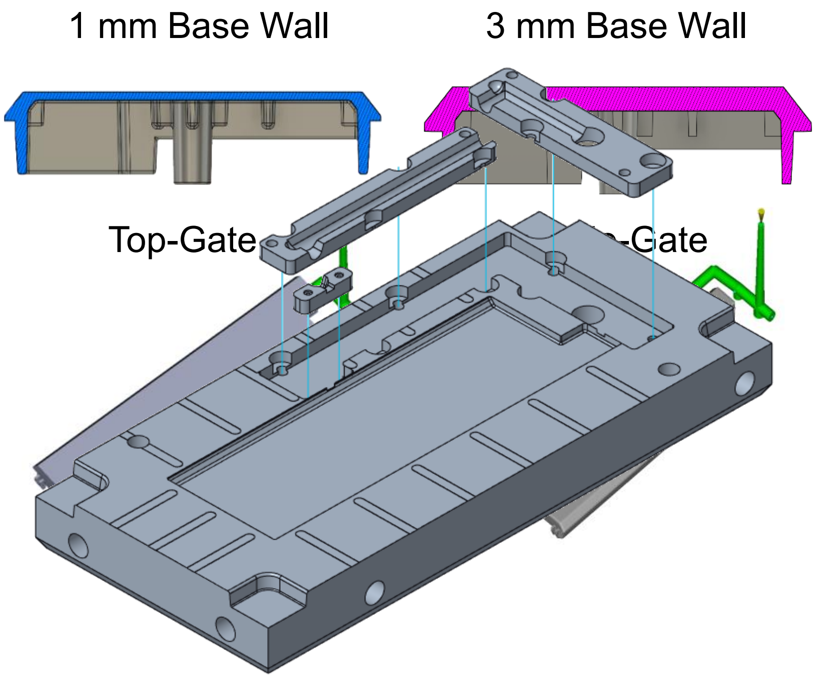
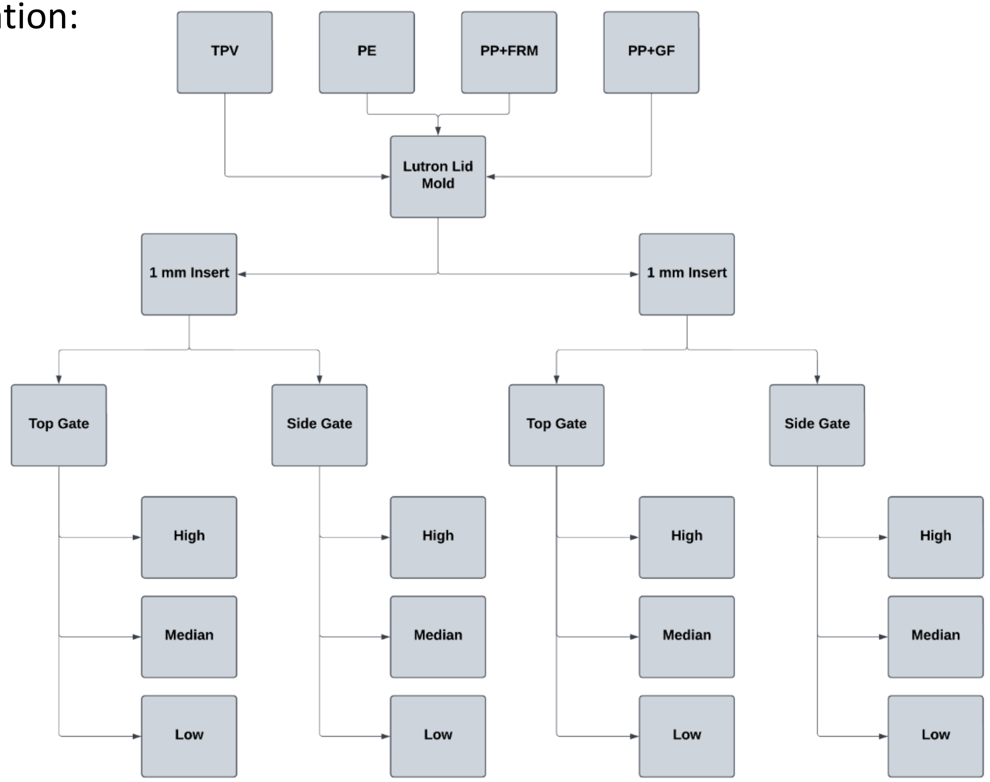
- Two Cavity Inserts
  - 1mm and 3mm Part Thickness
- Two Gate Locations
  - Top and Side-Gates
- In-Mold Sensors
  - Cavity Eye Pressure Transducers
  - RJG IR Sensors
- Running in a Krauss Maffei Px81-100



Sample Populations: Lutron Lid

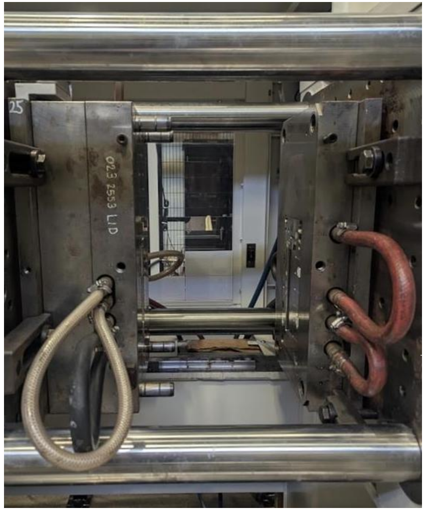
- The following populations were created for evaluation:
  - Four Materials
  - Two Shrink Models
    - Uncorrected Residual Stress (URS) and STAMP
  - Two Wall Thicknesses
  - Two Gate Locations
  - Three Pressure Levels
    - Low, Median and High pressure
- Number of unique populations: 96
- Number of specimens per population: 3

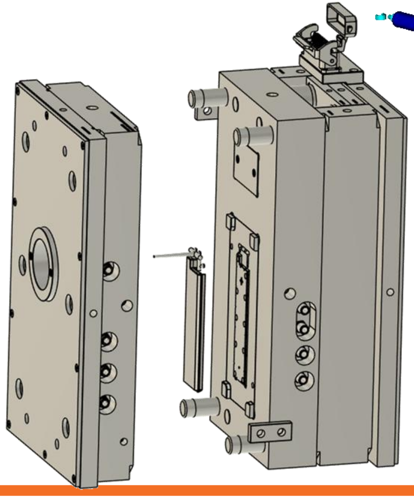
Thickness	Gate	Hold Pressure
1mm	Top Gate	High
		Median
		Low
	Side Gate	High
		Median
		Low

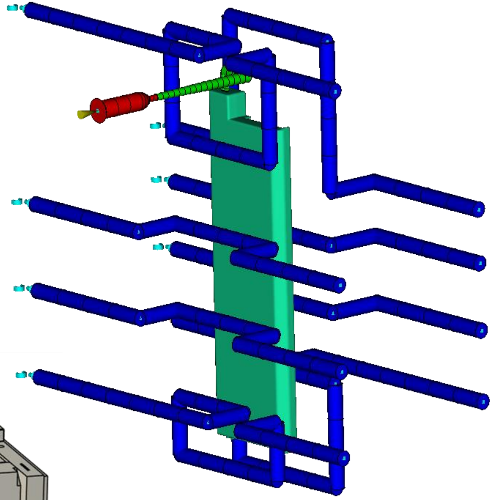


Digital Twin Setup

- Lutron Lid Mold
  - Part geometry (3D)
    - Built from measured steel dimensions
  - Feed system (Beam)
    - Machine nozzle
    - Runner and gates
  - BEM cooling lines
    - Centerlines from mold CAD
  - Process settings
    - From molding matrix







Process Settings

	A	B	C	D	F	G	J	K	L	N	P	V
1	**Material**	TPV (RTPRENE)			PP+FR (B Black)		PP GF30 (A Black)			E Blend (ABR Natura		
2	**Insert Configuration**	1mm TG	1mm SG	3mm TG	1mm TG	1mm SG	1mm TG	1mm SG	3mm TG	1mm TG	3mm TG	
3	**Part Weight (g)**											
4	95% Full Part	15	15	28	20.57	18.68	0	16.4	31.8	13.15	24.6	
5	Final Part	16.3	16.3	32.1	23.1	23.29	0	19	37.1	16.52	30.1	
6	Runner Weight	2	6.3	2.1	2.82	8.66	0	7.1	2.4			
7	**Times (s)**	**11.63**	**22.76**	**26.65**	**11.72**	**14.09**	**8.15**	**12.56**	**22.75**			
8									0.9			
9									0.75			
10									14			
11									8			
12									0.5			
13									12			
14									5.8			
15									23.97			
16									**1.22**			
17									6410			
18									8410			
19									6410			
20									3500			
21									2000			
22									5000			
23									1000			
24									50			
25												
26									**3.5**			
27									0.5			
28									0.116			
29									0.15			
30												
31									6.4			
32									360			
33									4.83			
34												
35	Nozzle (set)	415	415	415	415	415	415	415	415			
36	Nozzle (act)	415	415	415	415	415	415	415	415			
37	Front - Back (set)	415	415	415	415	415	415	415	415	415	415	Front - Back (set)
38	Front - Back (act)	415	415	415	415	415	415	415	415	415	415	Front - Back (act)
39	Feed (set)	120	120	120	140	140	120	120	120	120	120	Feed (set)
40	Feed (act)	120	120	120	120	120	120	120	120	120	120	Feed (act)

	X	Y	Z	AA	AC	AD	AG	AH	AI	AK	AM
1		RTPrene			B Black		A Black			(ABR Natural	
2		1mm TG	1mm SG	3mm TG	1mm TG	1mm SG	1mm TG	1mm SG	3mm TG	1mm TG	3mm TG
3	**Part Weight (g)**										
4	95% Full Part	15.00	15.00	28.00	20.57	18.68	--	16.40	31.80	--	24.60
5	Final Part	16.3	16.3	32.1	23.1	23.29	--	19	37.1	--	30.10
37	Front - Back (set)	212.78	212.78	212.78	212.78	212.78	212.78	212.78	212.78	212.78	212.78
38	Front - Back (act)	212.78	212.78	212.78	212.78	212.78	212.78	212.78	212.78	212.78	212.78
39	Feed (set)	48.89	48.89	48.89	60.00	60.00	48.89	48.89	48.89	48.89	48.89
40	Feed (act)	48.89	48.89	48.89	48.89	48.89	48.89	48.89	48.89	48.89	48.89

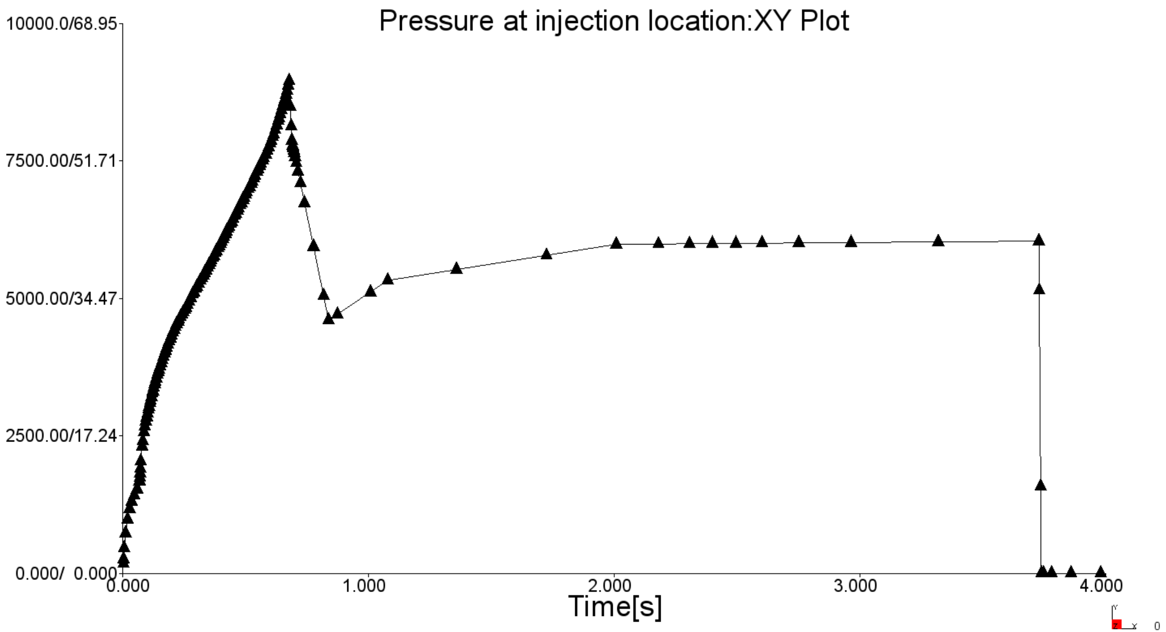
Pack/Holding Control Profile Settings

Packing pressure vs time

	Duration s [0:]	Packing pressure psi [0:72520]
1	0	7865.37
2	0.16	4601.97
3	0.24	5323.4
4	0.93	5980
5	1.72	6038.02
6		

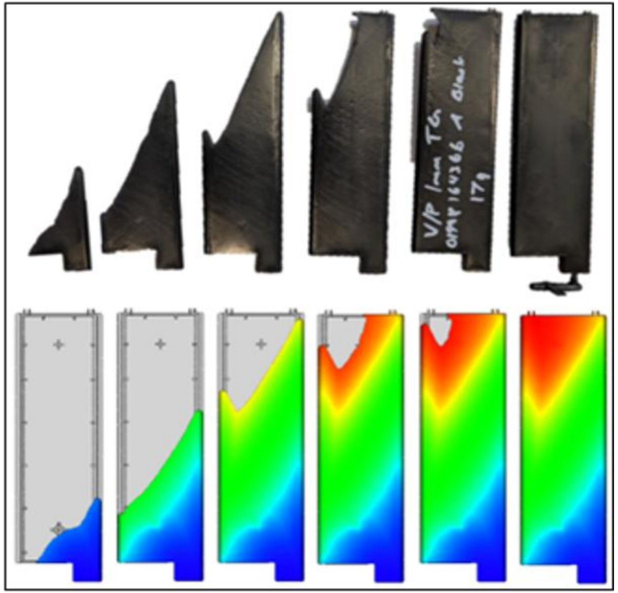
Import Profile... | Plot Profile...

OK | Cancel | Help



Digital Twin Verification

- Short shot progressions verify the fill pattern and minimizing false results



Comparison of short shots for 1mm TG PP+GF at nominal pressure

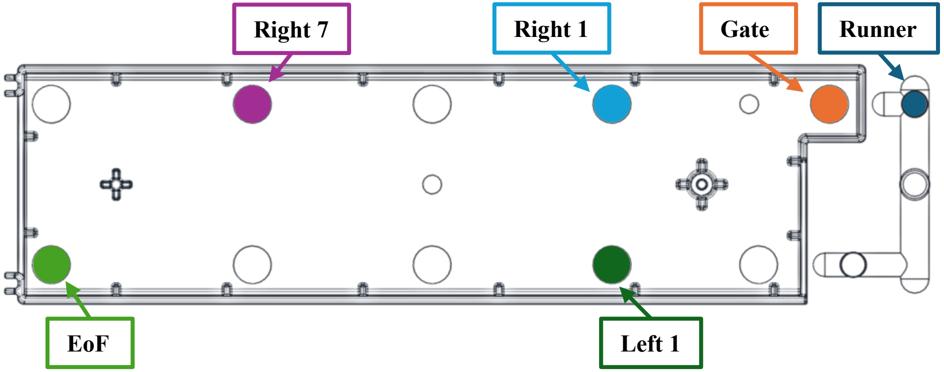
- Transfer pressure comparisons indicate the precision and repeatability in pressure dependent results

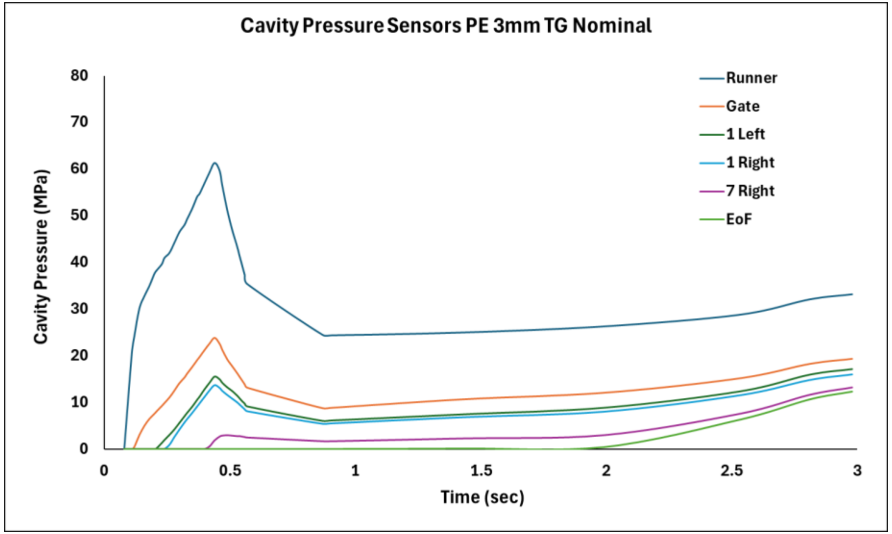
Material	ID	Transfer Pressure (MPa)	
		As Molded	Simulated
TPV	1 mm TG	56	67
	1 mm SG	62	59
	3 mm TG	43	40
PE	1 mm TG	*171	183
	3 mm TG	133	132
PP+FRM	1 mm TG	76	80
	1 mm SG	82	83
PP+GF	1 mm TG	55	62
	1 mm SG	61	54
	3 mm TG	41	38
		*Pressure-Limited Process	

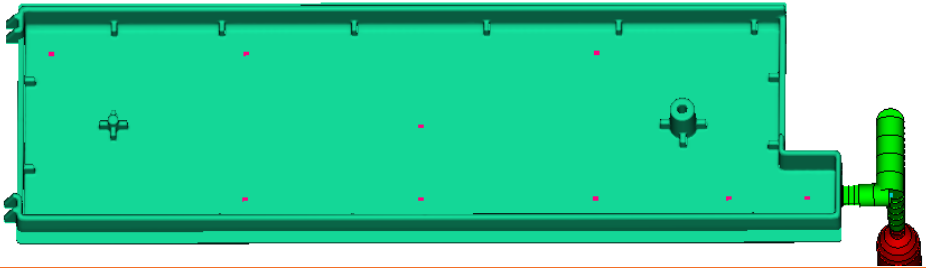
As-Molded and Simulated Transfer Pressure Comparison

Digital Twin Verification: PE

- 8 pressure transducers (E-Dart RJG)
  - 6 were used to create pressure profiles

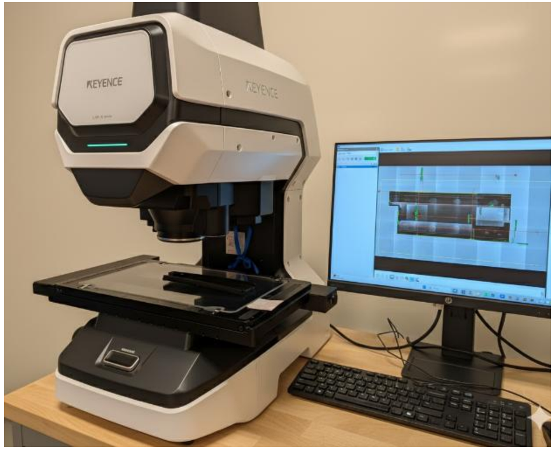


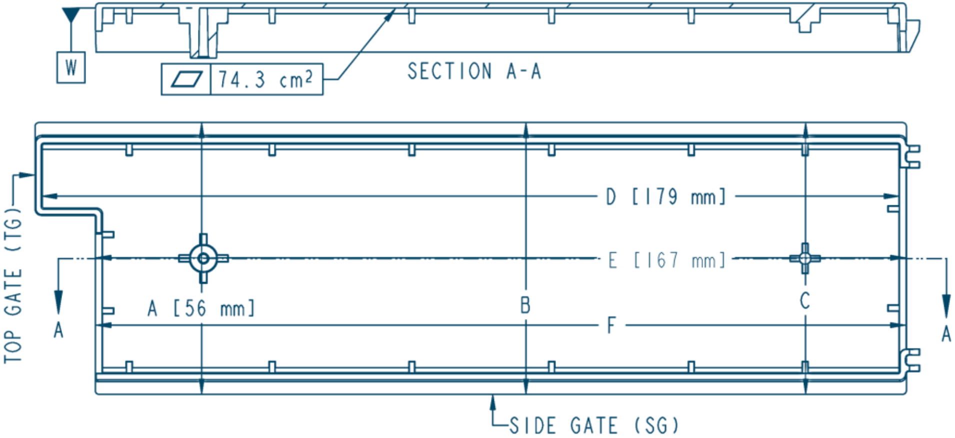




Shrinkage Measurements

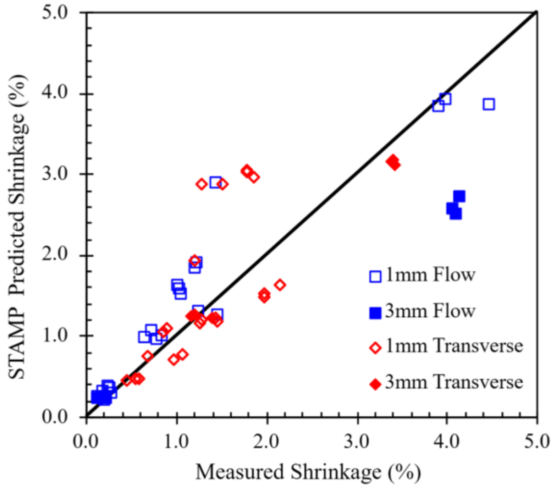
- Keyence 100LM Visual CMM
  - Top Gate:
    - Flow: D, E, and F dimensions
    - Transverse: A, B, and C dimensions
  - Side Gate:
    - "Flow": A, B, and C dimensions
    - "Transverse": D, E, and F dimensions

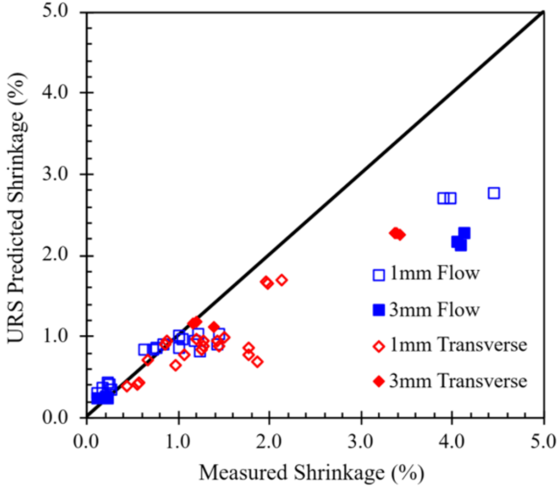




Shrinkage Results: PE and TPV

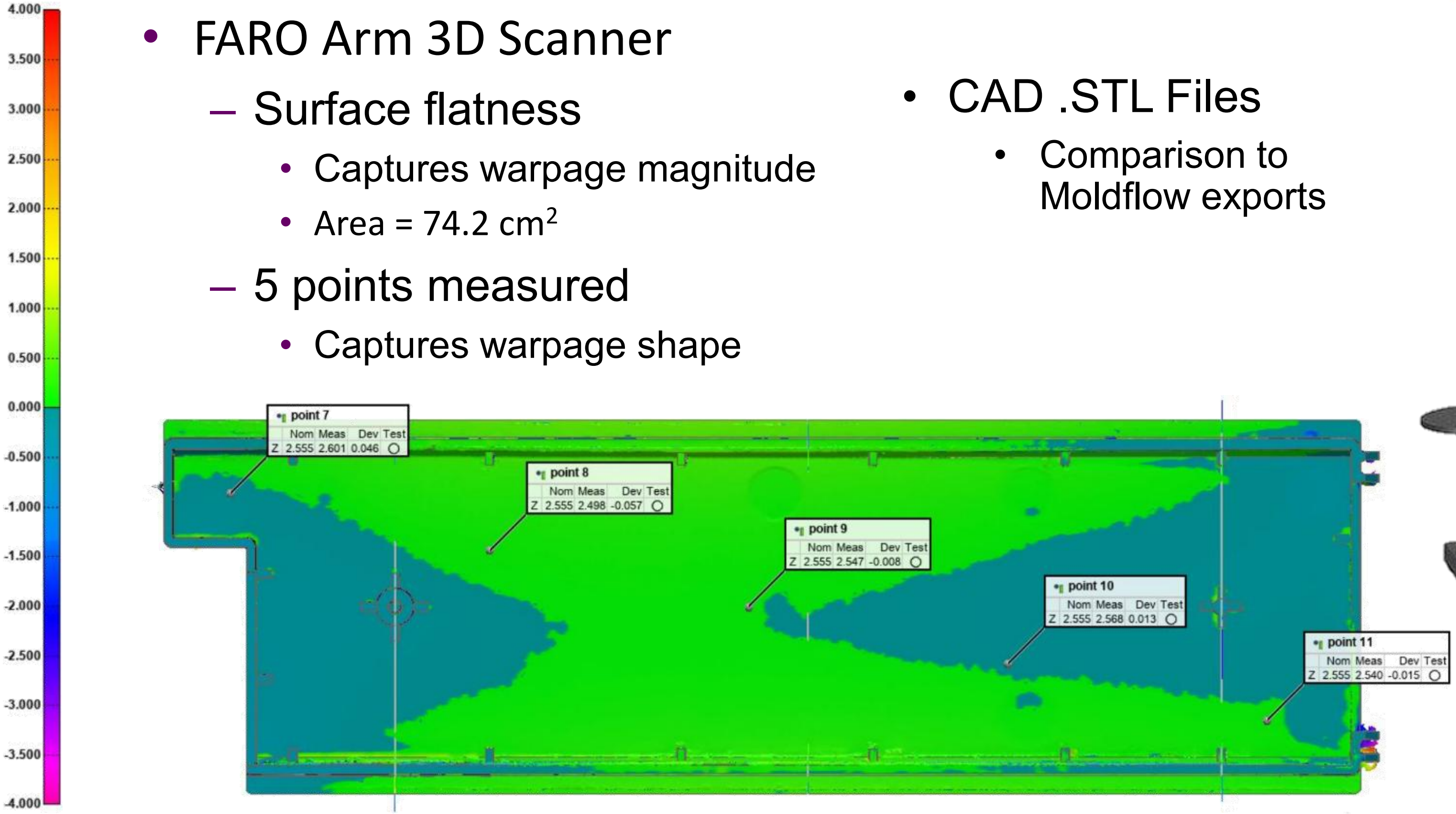
- TPV
  - Prediction error increased with STAMP
    - Flow: -56% accuracy
    - Transverse: -64% accuracy
- PE
  - Predictions improved with STAMP
    - Flow: +88% accuracy
    - Transverse: +36% accuracy
- PP+FRM
  - No significant change, minimal shrinkage overall
  - All shrink. predictions within 1%
- PP+GF
  - No significant change
  - All shrink. predictions within 1%





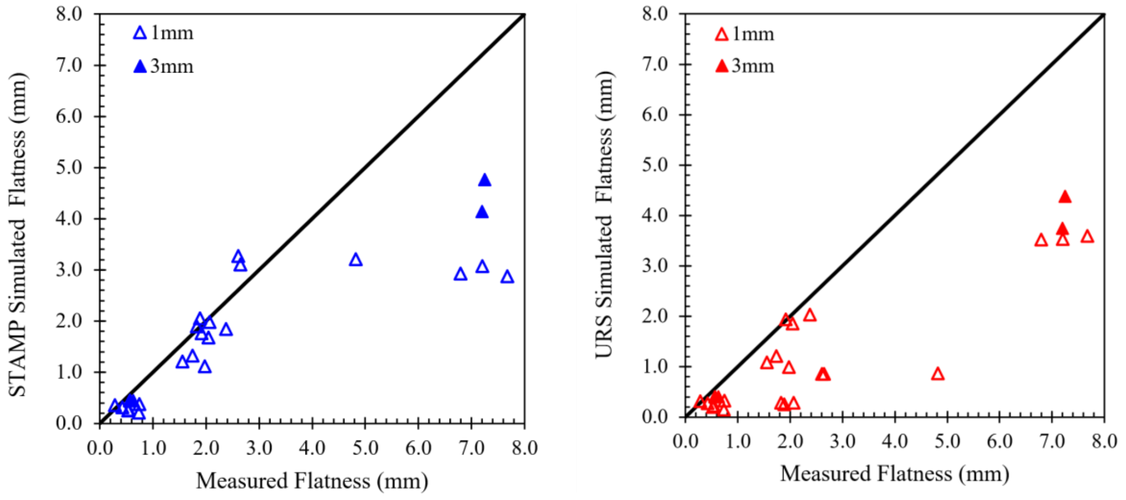
Out-of-Plane (Warpage) Measurements

- FARO Arm 3D Scanner
  - Surface flatness
    - Captures warpage magnitude
    - Area = 74.2 cm^2
  - 5 points measured
    - Captures warpage shape
- CAD .STL Files
  - Comparison to Moldflow exports



Warpage Results

- TPV
  - 1.82 - 4.82 mm Flatness
  - +73% Improvement w/STAMP
- PE
  - 6.80 - 7.68 mm Flatness
  - +13% Improvement w/STAMP
- PP+FRM
  - 0.28 - 0.74 mm Flatness
  - Negligible change between models
- PP+GF
  - 0.56 - 2.37 mm Flatness
  - No statistically significant change in prediction between models
  - Error is approximately 0.3 mm across measured face



Warp Comparisons – 1 mm TG

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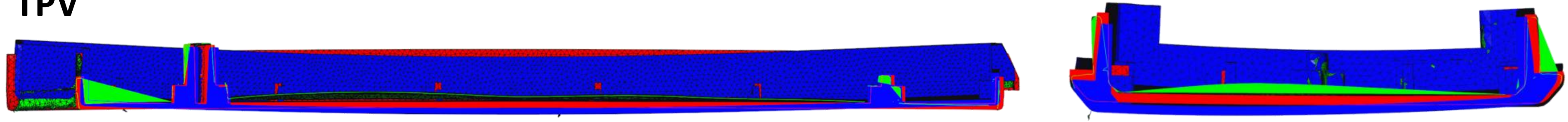
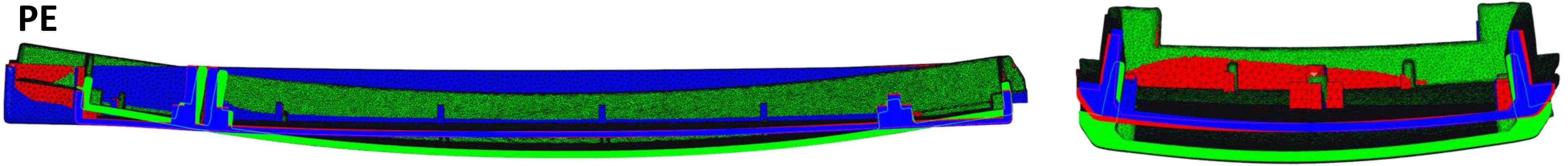
STAMP | **URS** | **Empirical**

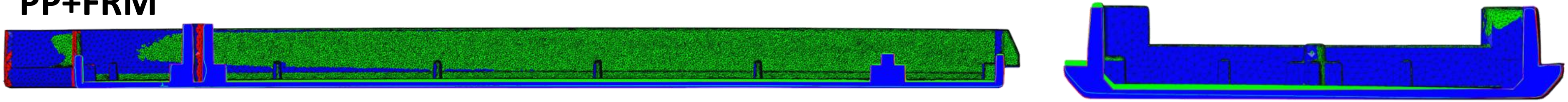
TPV



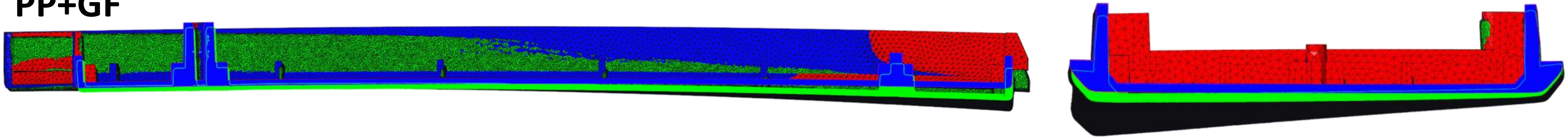
PE



PP+FRM

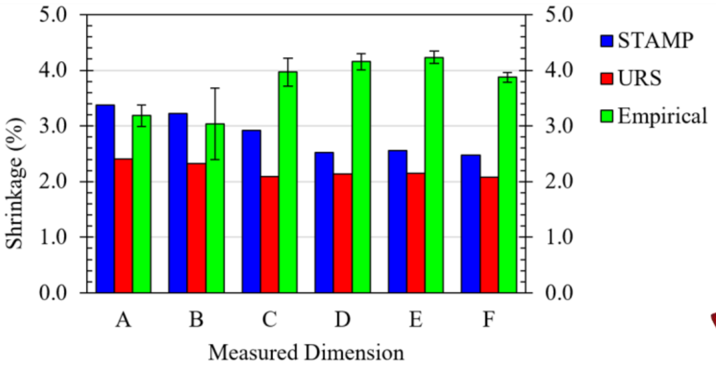


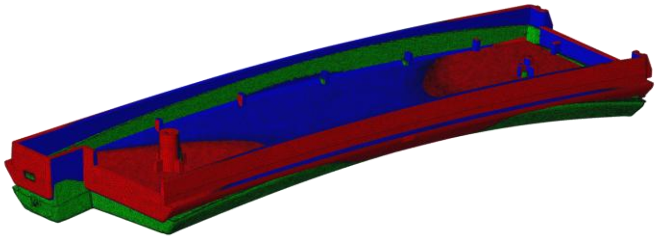
PP+GF

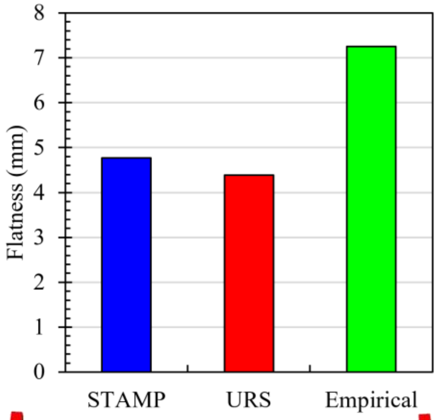


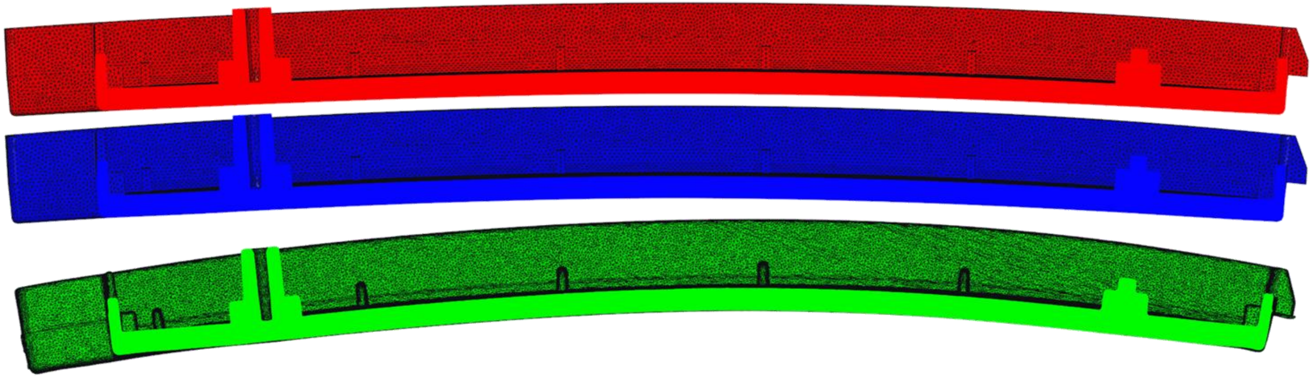
Case Study: Results

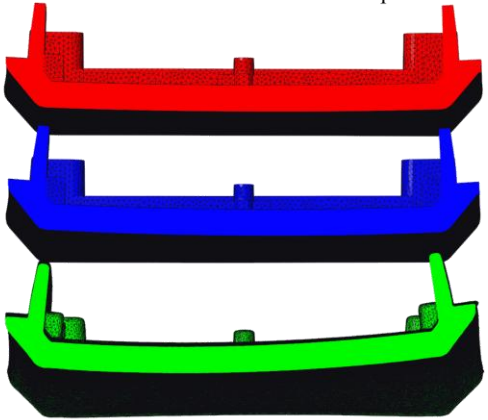
PE 3mm TG High Pressure





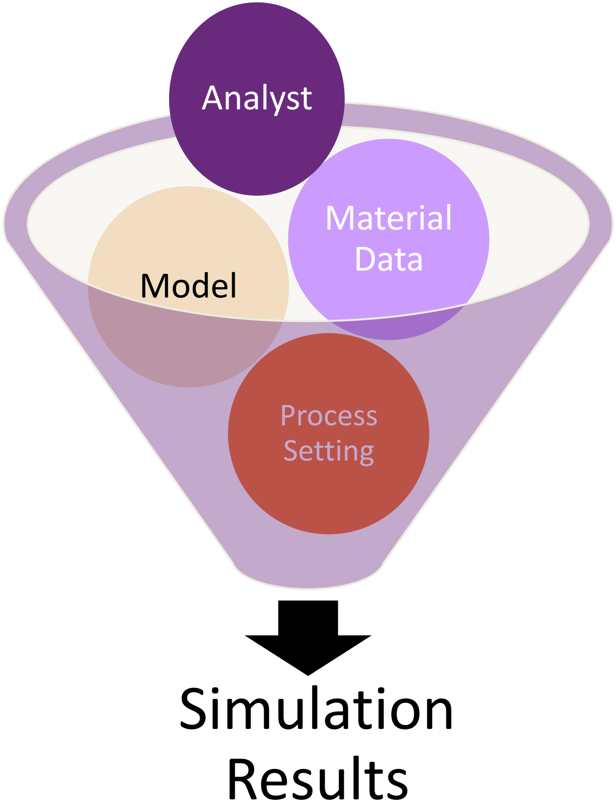






CONCLUSIONS

- The Key to Accurate Simulations Are:
  - Having Correct Inputs to Achieve Objective
    - Model Data
    - Process Data
    - Material Data
    - Warpage Data
  - STAMP improvements can vary significantly based on the material being simulated.
    - Over the aggregate, there is a benefit to using STAMP.
  - Significant improvements were observed in both shrinkage and warpage for PE samples.
  - No significant benefits were found for materials with lower shrink.



Questions?

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- For Further Discussion Please Reach Out To Our Team!
- For Future Training for Both Moldflow Insight and Adviser Check Out
  - https://madisongroup.com/customized-training/
  - https://madisongroup.com/manufacturing-support/
- For Software Demonstration Reach Out!

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CERTIFIED EXPERT

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