Tooling Options for Low Volume Programs: A Design of Experiments

SPE Thermoforming Division

R&D Committee: Munnoch, Short (Leads)

8/1/2023

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SPE Thermoforming Division R&D Committee

Introduction

It is an all-too common question among custom thick-gauge thermoformers, “What tooling material is right for this job?”

Historically, custom thermoformers have relied on their own experience level or regional/market know-how to make this decision, which might prevent a broader understanding of the pros & cons of each tooling material type when used with various common sheet materials.

This is especially true for newer, or more niche, tooling technologies. The thermoformer might be aware of these tooling types but feels the risk of the unknown is too great to take the leap and invest the time and money to try something new or unproven.

This dilemma is compounded by the fact that different plastic materials can behave differently with different tool types. Semi-crystalline materials such as polyethylene and polypropylene rely on more efficient heat transfer characteristics from the tool’s construction which almost automatically pushes the choice toward temperature-controlled aluminum. But what if the program/job’s volume cannot economically justify the premium of temperature-controlled aluminum?

Or, another common occurrence, what if the thermofomer acquires an existing program and “inherits” tools that are not necessarily ideal for the application’s quality requirements? Does the thermoformer struggle through trying to make someone else’s creation work or are there lower-volume, more affordable options?

The R&D Committee of the SPE Thermoforming Division, along with some key industry partners, decided to shed some light on potential options to this situation with the following design of experiments (DOE).

The Scope

When designing any experiment, the essential questions are, “What are we trying to learn?” and “What will be considered ‘in scope’ and ‘out of scope’”?

For the first question, we wanted to see how many good parts we could get out of limited-piece run, how quickly we could make them, and what the overall piece cost was using a variety of molds *of the same exact part,* preferably one that was a true production part for relevancy. The “good” part definition would come from our partnered thermoformer’s statement of requirements, which ideally would have a dimensional tolerance and aesthetic component.

The overall scope was a bit more challenging. What to include and exclude would determine how comprehensive a study that we would have to undertake. From the tooling perspective, we wanted to include both common tooling types and some of the newer tooling technologies that are being developed.

For materials, we decided to focus on two common - albeit at different ends of the polymer morphology spectrum for thick-gauge thermoformers – acrylonitrile butadiene styrene (ABS) and high molecular weight polyethylene (HMWPE).

At this point, we note that this study is not meant to be definitive, but instead just a start. Aside from generated data to share with readers of TQ, this study is meant to provoke additional curiosity and questions that will help drive further studies and shed scientific light on the cause and effect of the tooling vs. material dynamic in other materials and processes.

Below is a summary of the basic outline of the DOE. The number of tests required was 280 in total.

Tooling Types (7)	**Sheet Material** (2)	**Sheet Thickness** (1)	**Color/Texture** (1)	**Number of Parts** (20)
Aluminum (water cooled)*	HMWPE	0.125 in.	Black haircell	20
Aluminum (non-water cooled)	ABS			
Ceramic				
Polyurethane Machine Board (MB 3500)				
Aluminum/Epoxy (MetaPor)				
Syntactic Foam				
3-D Printed Silica				

**control*

For measurements, the following variables were documented:

<u>In Process</u>

- Tool Temperature – start
- Tool Temperature – demold
- Bottom side Sheet Temperature – demold
- Top Sheet Temperature – out of oven
- Bottom Sheet Temperature – out of oven

<u>After Process</u>

- Part Dimensions – width
- Part Dimensions – length
- Part Dimensions – height
- Part Detail – part number
- Part Detail – ridge
- Part Detail – inner

The Part

The original part and its corresponding production tooling (water-cooled aluminum) was generously provided by Electro General Corporation of Grove City, Ohio, who also was kind enough to donate the machine time and labor to conduct this study.

The part itself is a custom shoe insert mold that allows the shoe manufacturer to use a formed plastic mold to pour orthopedic foam in varying sizes for their product line. This mold was ideal for our study since the molds existed, the OEM allowed use for the study, other existing tool materials were available for this part, and we could affordably make the other various tool types and limit the amount of material and machine time and still get meaningful results.

The actual production part is designed for a thin-gauge (0.060”) polyolefin, but the materials and thickness we selected were ABS and HMWPE at 0.125”.

The Materials

As noted, there are several different plastic sheet options available to today’s thermoformer. We debated including packaging-related materials like PET or performance materials like TPO and PVC/acrylic flame-retardant grades.

The team decided on utility ABS and utility HMWPE due to the popularity in the industry, the fact that they would give two ends of the morphology spectrum (amorphous and semi-crystalline respectively), they were not proprietary grades or composition, and the costs would be minimal. Black color and haircell texture were selected as well for same reasons. Sheet size 0.125 x 17 x 20”.

The Process

For the process, we had to determine the ground rules, i.e., how we would specifically manage the necessary process temperatures and conditions in the study.

Putting ourselves in the shoes of a thermoformer who needs to make 20 good parts, we decided that the best method would be to start with the necessary start-up conditions to make a good part in each of the materials.

For parts that did not successfully form from these conditions, small tweaks were made to determine if the sheet exiting the oven was too hot or too cold. However, in the cases where the tools had built up too much heat and resulted in a bad part, then frames were skipped to allow the tool to cool off.

The machine used was a 3-station rotary using Solartech heater panels.

Machine	"R4"
Make	Brown
Type	3-Station Rotary
Heater Type	Solartech
Zones	3 top & bottom
Tool Location	Bottom Platen (A-surface up)
Vacuum	25 – 26 inches Hg

Material	HMWPE	ABS
Top Zone (%)	63%	57%
Bottom Zone (%)	70%	53%
Cycle Time (s)	180	120

The Tools

Each provider / manufacturer was asked to provide an overview of tooling composition, how it is made, specific lead time and costs for this shoe insert mold part, tooling dimensional capabilities, expected tool “life” (in parts), and overall perceived pros and cons from their perspective.

In no particular order:

Aluminum

Tool	ALUMINUM
Manufacturer	Borke Mold, Hamilton, OH
Composition	Aluminum (machined)
Time to produce	2-3 weeks
Tool Cost (for shoe mold)	$4,000 non-water-cooled; $5,500 water-cooled
Max. Tool Size	4” x 60” x 96” (depth, width, length)
Max. Tool Life	Unlimited
Cooling?	Yes (with cooling plate); 2nd condition cooling off
Pros	• Excellent heat conductor • Largest production runs • Easy to machine • 1 water plate can be used on multiple jobs
Cons	• Highest cost

Ceramic

Tool	CERAMIC
Manufacturer	PT Polymers, Middlebury, IN
Composition	Ceramic powder in a high-temp. vinyl ester resin with 1.5 oz chopped strand mat
Time to produce	3 weeks
Tool Cost (for shoe mold)	$1,975
Max. Tool Size	38” x 96” x 100” (depth, width, length)
Max. Tool Life	5,000 parts/year or 10 years
Cooling?	No
Pros	• Lower cost vs. aluminum • Successful with ABS, TPO, PMMA • Molds can be repaired • Light weight
Cons	• No temperature control • Slower cycle times for polyolefins • Not suitable for in-line thermoforming

Polyurethane-based Machine Board

Tool	MB 3500
Manufacturer	Polytek Development Corp, Easton, PA
Composition	Polyurethane-based machine board
Time to produce	2-4 days
Tool Cost (for shoe mold)	$2,000
Max. Tool Size	6” x 24” x 60” (depth, width, length)
Max. Tool Life	1,000 parts approximately
Cooling?	No
Pros	• Lower cost vs. aluminum • Easy to machine • Repairable
Cons	• No temperature control • Durability • Not suitable for in-line thermoforming

Aluminum / Epoxy Composite

Tool	METAPOR
Manufacturer	Portec, Switzerland
Composition	Aluminum Epoxy Resin Composite HD 210AL
Time to produce	2-4 days
Tool Cost (for shoe mold)	$7,700
Max. Tool Size	2.4” x 19.7” x 19.7” (depth, width, length)
Max. Tool Life	Variable - based temperature and material abrasiveness
Cooling?	Yes (with cooling plate); 2nd condition cooling off
Pros	• Porous material, allowing for air flow (no vacuum holes, no trapped air pockets) • Provides excellent detail • Machines easily
Cons	• Higher cost • Tool size limitations (can be bond several pieces together) • Limited cooling options (plate was used in this study) • Not as durable as Aluminum (degradation at higher temperatures)

Syntactic Foam

Tool	HYTAC-HTF
Manufacturer	CMT Materials, Inc, Attleboro, MA
Composition	Co-Polymer High Temperature Syntactic Foam HYTAC-HTF
Time to produce	2-4 days
Tool Cost (for shoe mold)	$3,034
Max. Tool Size	4” x 24” x 60” (depth, width, length)
Max. Tool Life	Unknown (as a plug-assist material, billions of cycles)
Cooling?	No
Pros	• Machines easily • Short time to produce molds • Easily polished • Easy to drill in vacuum holes
Cons	• No temperature control • Not as durable as aluminum • Typically used as a plug assist

3-D Printed Silica

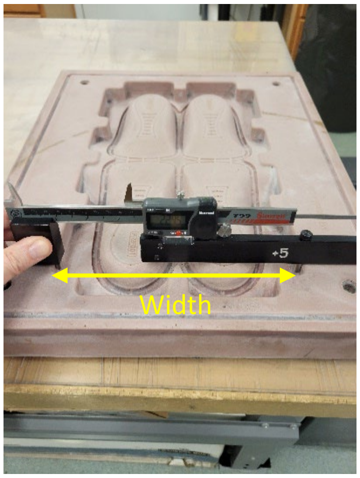
Tool	3-D PRINTED SILICA
Manufacturer	Catalysis, Columbus, OH
Composition	3-D printed silica sand, with a proprietary coating
Time to produce	3 – 4 days
Tool Cost (for shoe mold)	$550
Max. Tool Size	32” x 60” x 120” (depth, width, length)
Max. Tool Life	6,000 parts approximately (highest production data since 2016)
Cooling?	Yes (using air on demold process if available)
Pros	• Porous surface (minimal air-eject vacuum holes required) • Short time to produce molds • Complex mold designs at no additional cost • Post-form air demold functionality can cool the part / tool
Cons	• No water cooling • Longer cycle times in rotary machines • Not suitable for fine mold detail (i.e. lettering)

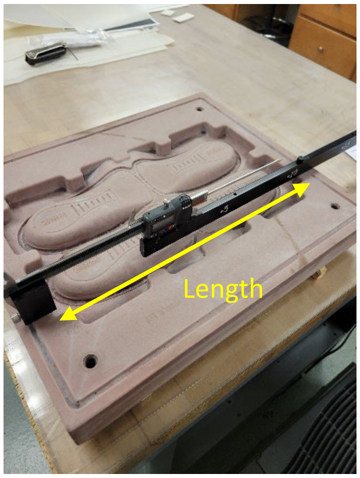
Data Collection & Methodology

The data collected can be categorized into 3 groups:

1. ***Temperature*** - Temperature of the sheet before and after forming; temperature of the tool before and after forming. Measured via IR guns. The sheet temperature (A & B sides) was captured but not graphed as it does not pertain to the performance or distinctness of the tool.

2. ***Part Dimensions*** – Part dimensions were measured on formed parts several days after forming to allow for proper cooling. The parts were not trimmed from the "hat" section to keep consistency. The specific areas of width and length were measured are illustrated below:





3. ***Part Detail or Aesthetics*** – Part detail was noted on a subjective scale from 1 – 5 (1 being the worst, 5 being the best) by one single observer using the following guidelines:

5 – perfect part (PASS)

4 – slight imperfections (actual examples), but still a good part (PASS)

3 – some imperfections – not a good part (FAIL)

2 – several imperfections – not a good part (FAIL)

1 – incomplete part – not a good part (FAIL)

The 3 areas noted for part detail were:

a) Part Detail – Part Number (PN).
   a. See below for examples of a 5, 3, & 1-rated part:

“5” PN Detail

“3” PN Detail

“1” PN Detail

b) Part Detail – Inner Area. See below for example of a 5, 3, & 1-rated part:

“5” Inner Detail

“3” Inner Detail

There were no “1” rated inner detail parts observed in the study

“1” Inner Detail

c) Part Detail – Ridge Area. See below for examples of a 5, 3, & 1-rated part:


“5” Ridge Detail


“3” Ridge Detail


“1” Ridge Detail

It should be noted on the graphs, that there are sometimes 21 datapoints and sometimes 20 datapoints. For temperature, there were 21 datapoints as the starting temps of the tooling was needed prior to forming.

Part-specific graphs only have up to 20 datapoints as the starting value was not necessary.

Notes

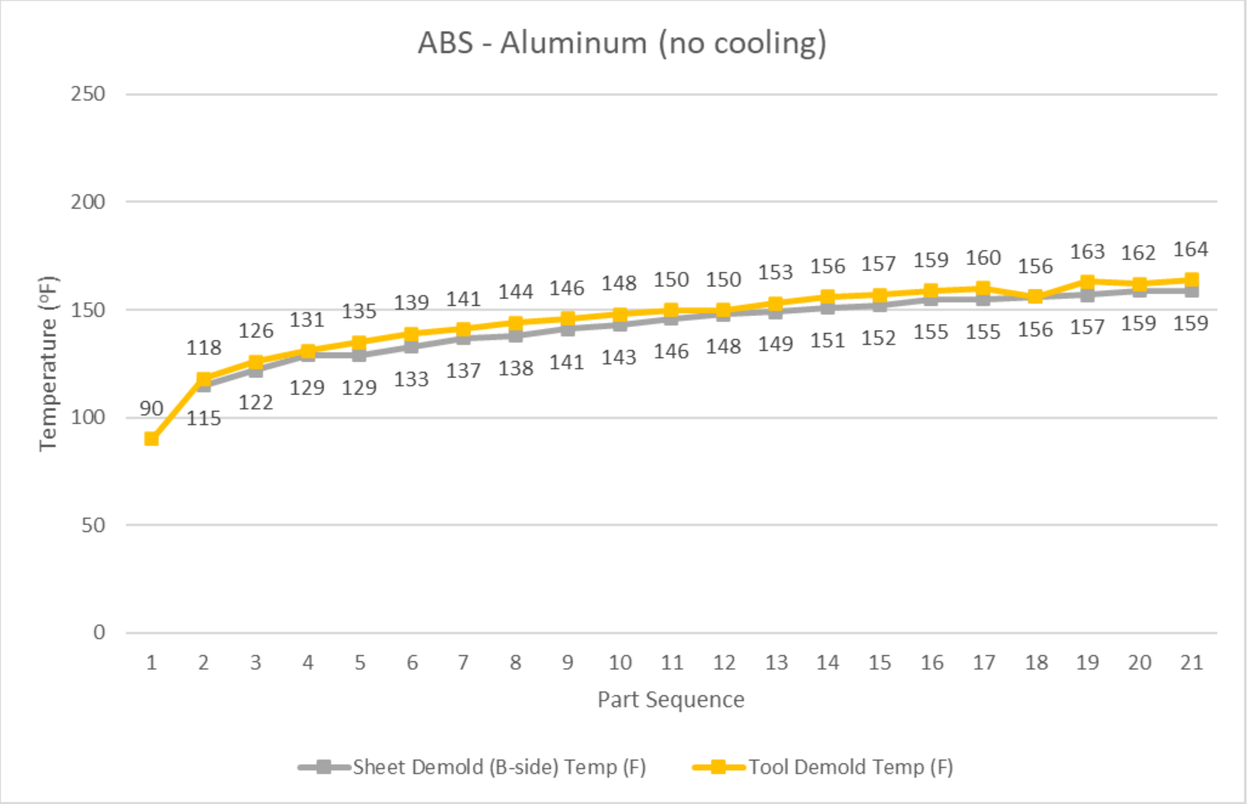
The reader will also note missing datapoints. These exist in the areas where parts were not formed (due to, say, the necessity to use an extra 1-2 cycles to cool down the tool) or were formed but did not yield a measurable part.

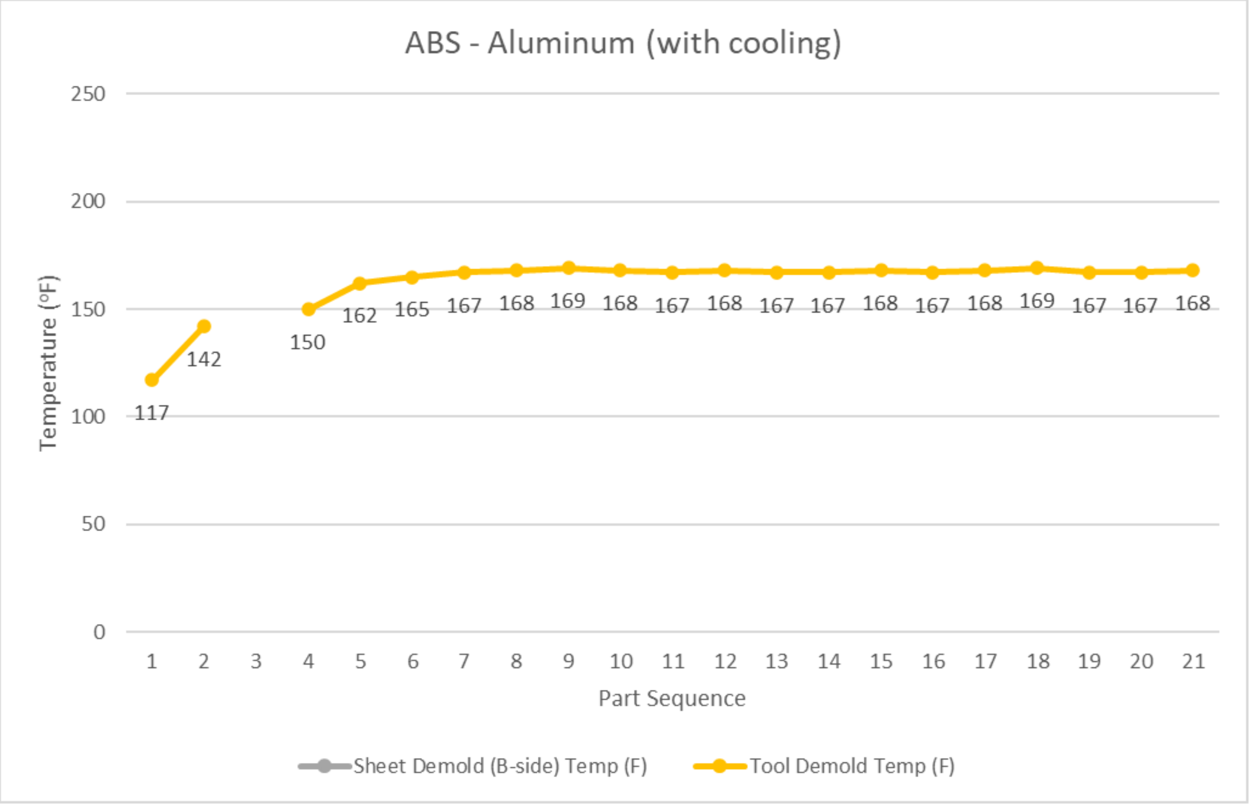
Lastly, as in all experiments, errors, omissions and just plain Murphy’s Law will happen. This study was no exception. There are some missing datapoints as the team traversed the learning curve in capturing datapoints in a live, production environment.

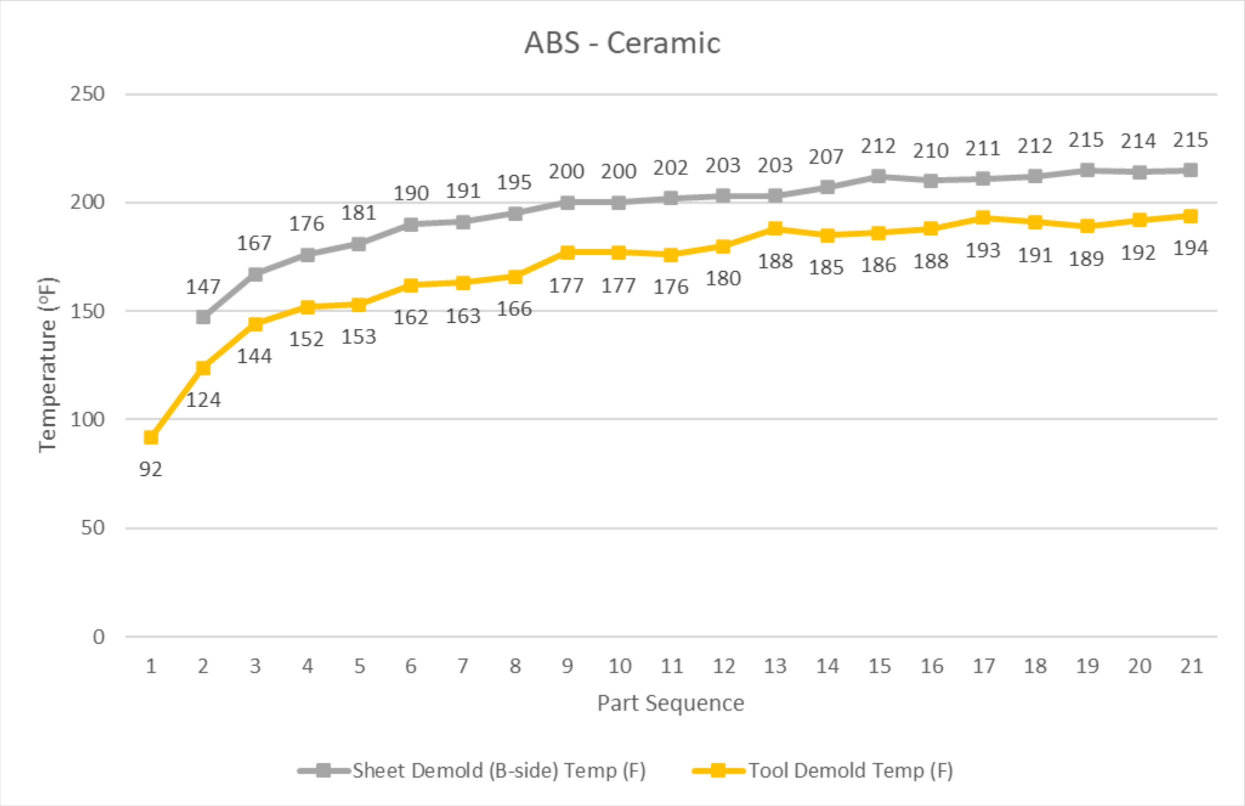
One example of this omission is in the sheet temperature after forming on the B-side for the Aluminum (with cooling) tooling in both ABS and HMWPE. The authors believe that this data would most likely follow the similar path for the Metapor tooling (cooled) and most likely the aluminum tooling (without cooling), especially in the earlier parts.

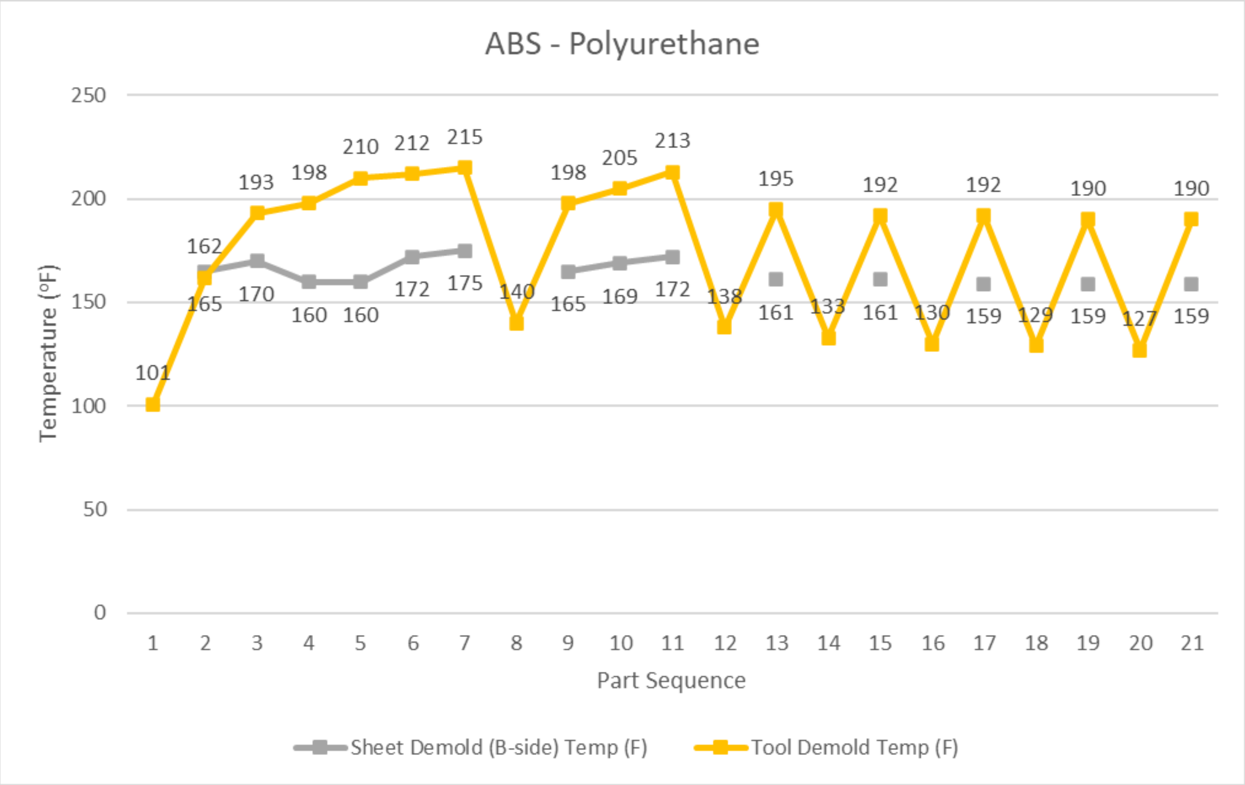
Data & Results

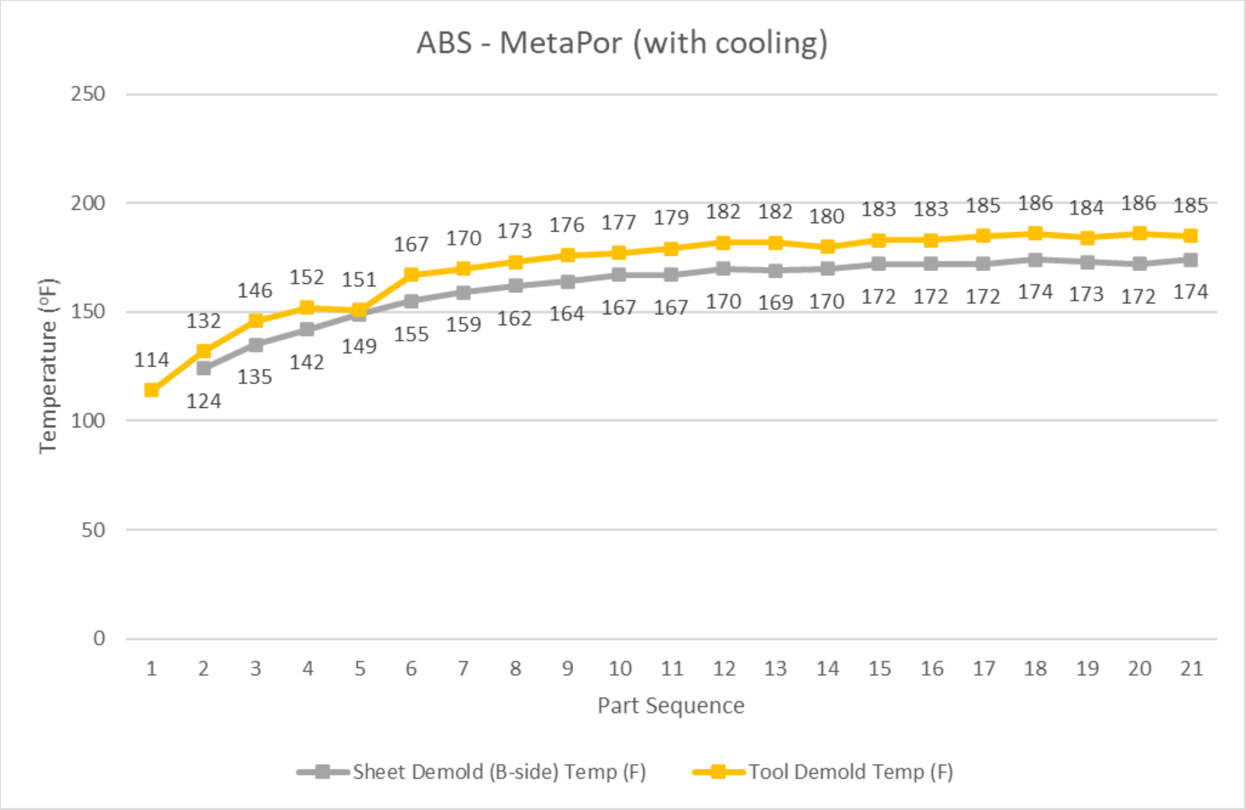
Results – Temperature by Each Tool (ABS)

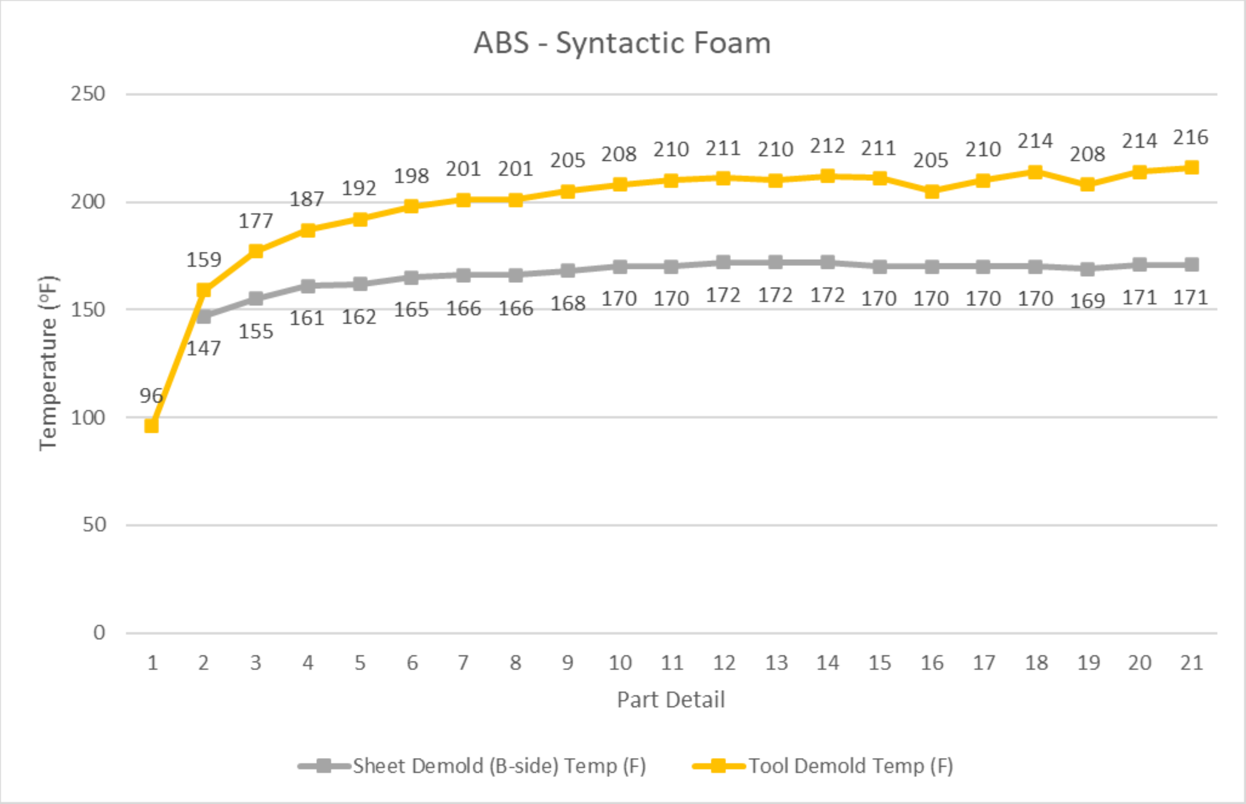


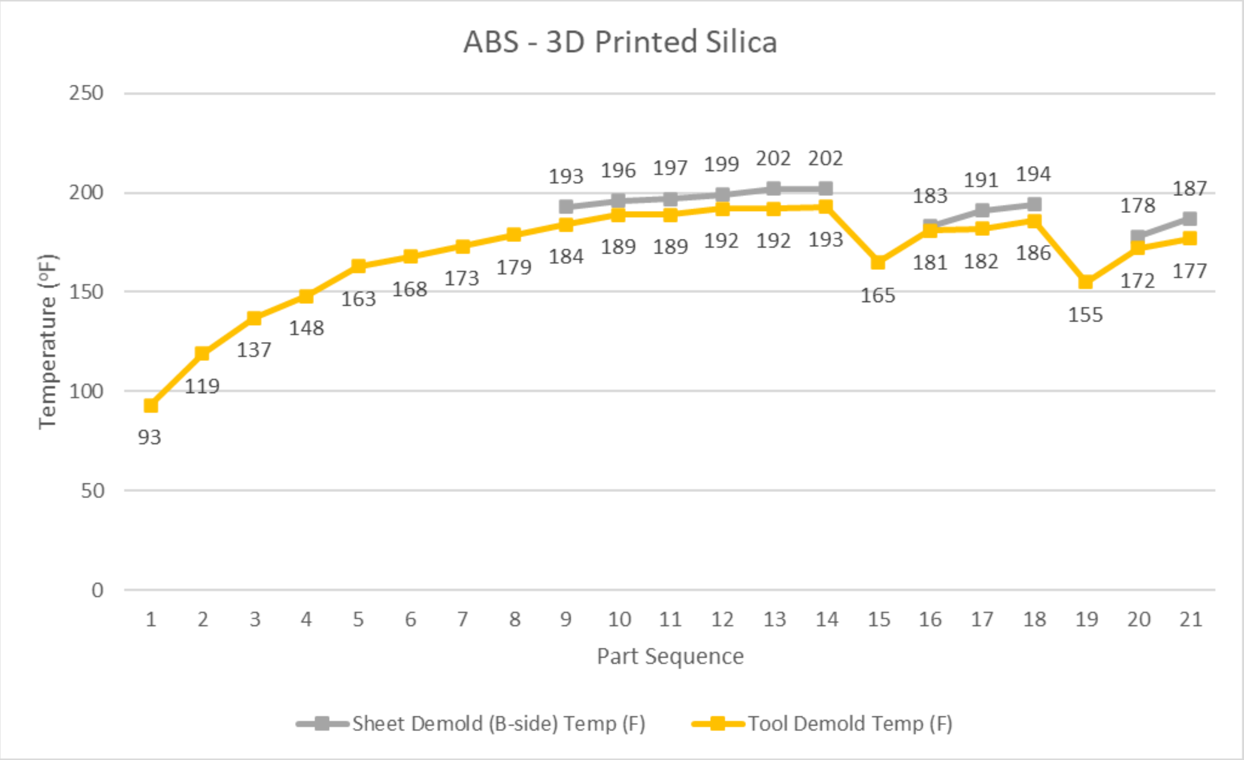



ABS - Ceramic
Temperature (ºF)
250
200
150
100
50
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Part Sequence
147
167
176
181
190
191
195
200
200
202
203
203
207
212
210
211
212
215
214
215
92
124
144
152
153
162
163
166
177
177
176
180
188
185
186
188
193
191
189
192
194
Sheet Demold (B-side) Temp (F)
Tool Demold Temp (F)


ABS - Polyurethane
Temperature (ºF)
250
200
150
100
50
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Part Sequence
101
162
193
198
210
212
215
140
198
205
213
138
195
133
192
130
192
129
190
127
190
165
170
160
160
172
175
165
169
172
161
161
159
159
159
Sheet Demold (B-side) Temp (F)
Tool Demold Temp (F)


ABS - MetaPor (with cooling)
Temperature (°F)
250
200
150
100
50
0
Part Sequence
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Tool Demold Temp (F): 114 132 146 152 151 167 170 173 176 177 179 182 182 180 183 183 185 186 184 186 185
Sheet Demold (B-side) Temp (F): 124 135 142 149 155 159 162 164 167 167 170 169 170 172 172 172 174 173 172 174
Sheet Demold (B-side) Temp (F)
Tool Demold Temp (F)

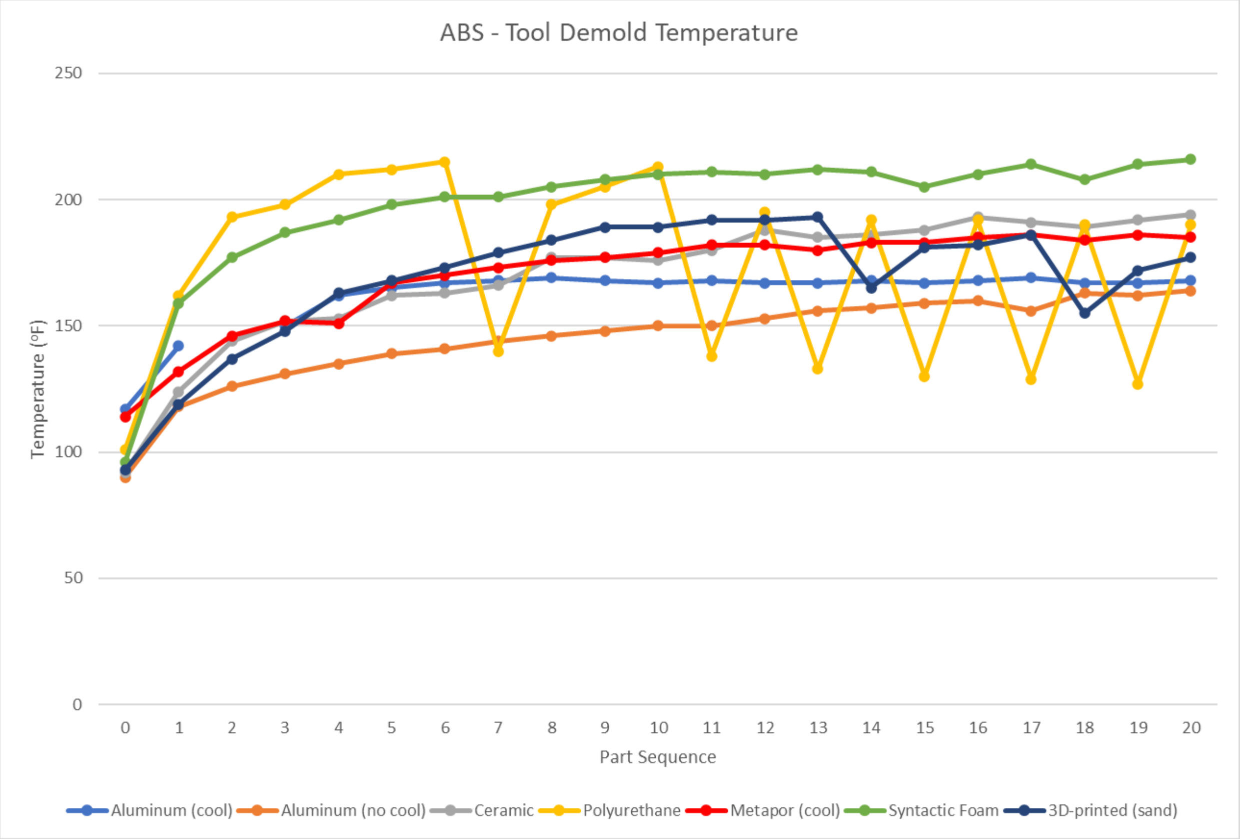

ABS - Syntactic Foam
Temperature (°F)
250
200
150
100
50
0
Part Detail
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Tool Demold Temp (F): 96 159 177 187 192 198 201 201 205 208 210 211 210 212 211 205 210 214 208 214 216
Sheet Demold (B-side) Temp (F): 147 155 161 162 165 166 166 168 170 170 172 172 172 170 170 170 170 169 171 171
Sheet Demold (B-side) Temp (F)
Tool Demold Temp (F)


ABS - 3D Printed Silica
Temperature (ºF)
250
200
150
100
50
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Part Sequence
193
196
197
199
202
202
183
191
194
178
187
93
119
137
148
163
168
173
179
184
189
189
192
192
193
165
181
182
186
155
172
177
Sheet Demold (B-side) Temp (F)
Tool Demold Temp (F)

Observations by Each Tool for Temperature

- **Aluminum (with cooling)** – as expected, the tool temperature on demold stayed steady per the mold temperature controller setting of 170 °F. Also noted that this was the very first data set gathered, and the B-side sheet demold temperature was missed. Two forms early in the run were “double-formed” and therefore omitted.
- **Aluminum (without cooling)** – also not a surprise to see even and steady temperature increase. Without having the mold temperature controller preconditioning the tool, the starting temperature was lower, and both tool and part temperature would have most likely risen higher with a longer run sequence.
- **Ceramic** – the first of the non-metallic tools, what is interesting to note is the sheet temperature is always higher than the tool temperature in this data set suggesting that the insulative properties of the ceramic do not allow for an efficient heat transfer from sheet to tool.
- **Urethane** – The Polyurethane machine board was the first tool that quickly climbed to that tool temperature “danger zone” of >200°F, and the first that we had to “skip” frames (not load sheet for that cycle in the rotary). By skipping 1 frame, the tool temperature dropped on average of 30 degrees, allowing a part to be produced.
- **MetaPor** – The cooled composite tool followed the same temperature slopes as both Aluminum tool conditions, but at roughly a 15–20-degree increase. Warmer, but still efficient.
- **Syntactic Foam** – This tooling material had a similar delta between tool and sheet as the Polyurethane but did not see as dramatic of heat gain in the tooling with each part and thus, no frames needed to be skipped.
- **3-D Printed Silica** – this trial suffered from lack of sheet temperature measurement early on, so despite the graph, only 2 frames had to be skipped later in the sequence (frame 15, 19). Tool temperature also demonstrated a very slow increase like the ceramic tool.

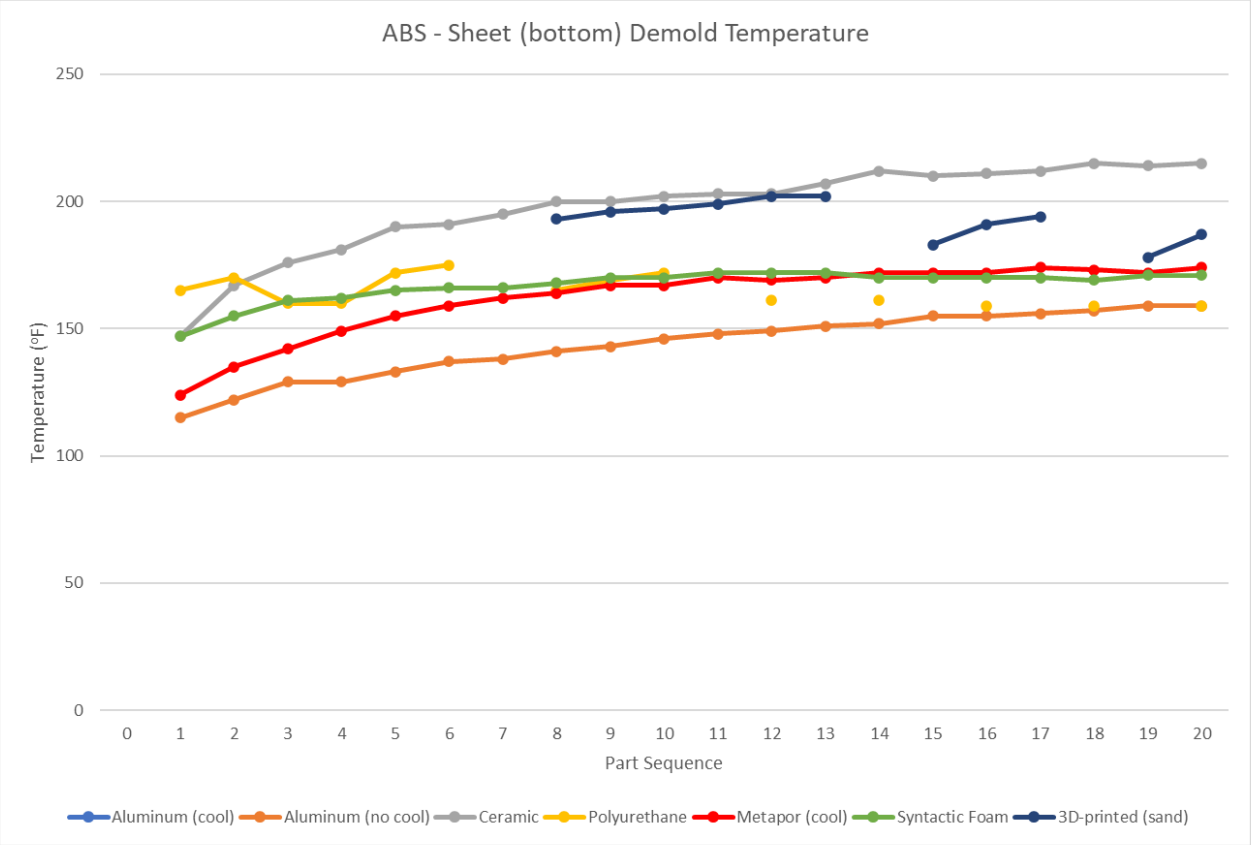
Data – Temperature Summary (ABS)



Observations by Temperature Summary

Tool Demold (ABS)

- **Aluminum (with cooling)** – flattest, almost level tool temperature for all 20 parts.
- **Aluminum (without cooling)** – unsurprisingly, the aluminum tool was consistently the lowest temperature values across the study
- **Ceramic** – the ceramic tool followed very closely to the Metapor tool until around the 12th part, eventually reading the 2nd highest temperature of the group by the 20th part
- **Polyurethane** – this tool had the fastest and highest tool heat increase rate & level of the study. Several frames had to be skipped to manage tool temperatures below 200°F.
- **MetaPor** – As noted, similar slope of temperature as the Aluminum (without cooling) tool but at roughly a 20-degree higher gap.
- **Syntactic Foam** – The syntactic foam had the 2nd highest tool "ramp up" temperature and eventually had the highest finishing tool temperature of the study (although no frames had to be skipped).
- **3-D Printed Silica** – early in the part sequence, this tool demonstrated similar heat rates as Metapor and ceramic, but then reached higher levels after the 7th part, eventually needing to skip a frame at shot 14 and 18).



Observations by Temperature Summary

Sheet Demold (ABS)

- **Aluminum (with cooling)** – too little data to comment.
- **Aluminum (without cooling)** – same as will tool demold, the aluminum tool was consistently the lowest temperature values across the study.
- **Ceramic** – interesting that the ceramic tool exhibited the highest level of sheet demold temperature, pointing to very little heat transfer between sheet and mold.
- **Polyurethane** – as with the tool demold, the Polyurethane was the highest sheet demold temperature right out the gate with part 1, before frame skipping was used to manage the sheet temp ~160°F
- **MetaPor** – Very even and gradual increase demolding temperature until leveling-out at ~172°F.
- **Syntactic Foam** – although the syntactic foam built up heat quickly in the tool, the sheet demolding temperature was low, even, and consistent, almost on par with the Metapor tool. This suggests that the syntactic foam was able to take heat out to the sheet efficiently possibly due to the air-pockets in the foam.
- **3-D Printed Silica** – again, limited data, but also follows the slope of ceramic from part 9 to 13, before frames are skipped

Data – Part Detail (ABS)

Part Detail-Part Number

Tool Material	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Count (Rating 4 or 5)	Total Parts
Aluminum (cool)	3	3	3	3	3	3	3	3	1	2	2	3	3	3	3	3	3	3	3	3	0	20
Aluminum (no cool)	3	*	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	0	19
Ceramic	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	0	20
Polyurethane	5	5	5	5	5	5		5	5	5		5		5		5		5		5	14	14
Metapor (cool)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	0	20
Syntactic Foam	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	20	20
3D-printed (sand)	3	3	3	3	3	3	3	3	3	3	3	3	3		3	3	3		3	3	0	18

Part Detail-Ridge

Tool Material	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Count (Rating 4 or 5)	Total Parts
Aluminum (cool)	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	20	20
Aluminum (no cool)	3	*	4	3	3	3	2	2	3	3	3	3	3	3	3	3	3	3	3	3	1	19
Ceramic	3	3	3	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	0	20
Polyurethane	3	3	3	3	4	3		2	2	2		2		2		1		1		1	1	14
Metapor (cool)	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	20	20
Syntactic Foam	3	3	3	3	3	2	3	2	2	3	2	2	3	2	2	2	2	2	3	2	0	20
3D-printed (sand)	2	2	2	2	2	2	2	2	2	2	2	2	2		2	2	2		2	2	0	18

Part Detail-Inner

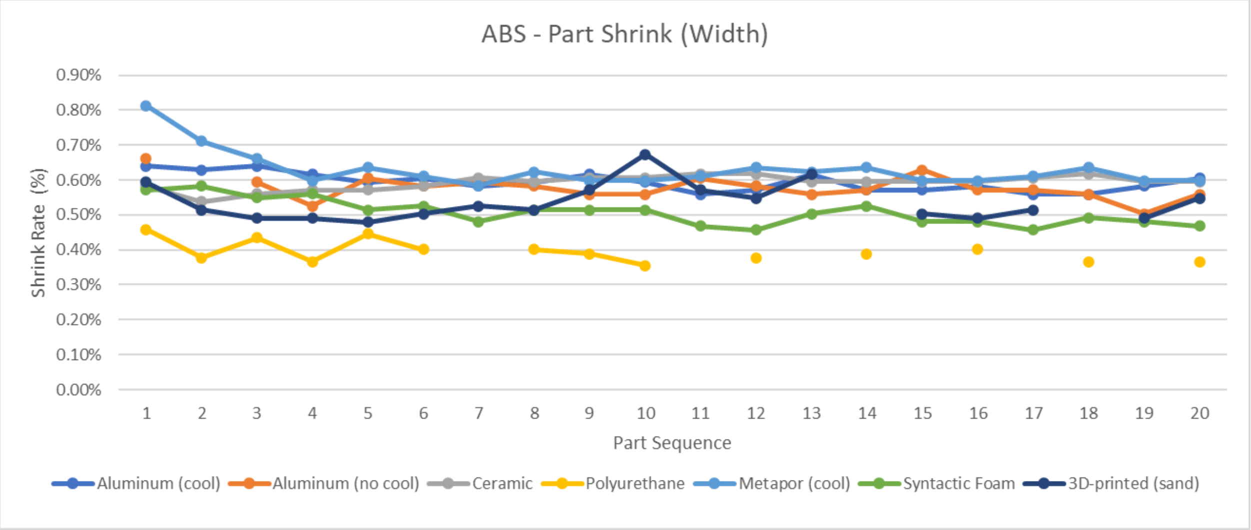
Tool Material	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Count (Rating 4 or 5)	Total Parts
Aluminum (cool)	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	18	20
Aluminum (no cool)	3	*	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	12	19
Ceramic	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	0	20
Polyurethane	5	5	5	4	5	4		5	5	5		5		5		4		5		5	14	14
Metapor (cool)	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	20	20
Syntactic Foam	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	20	20
3D-printed (sand)	2	3	3	3	3	3	3	3	3	3	3	3	3		3	3	3		3	3	0	18

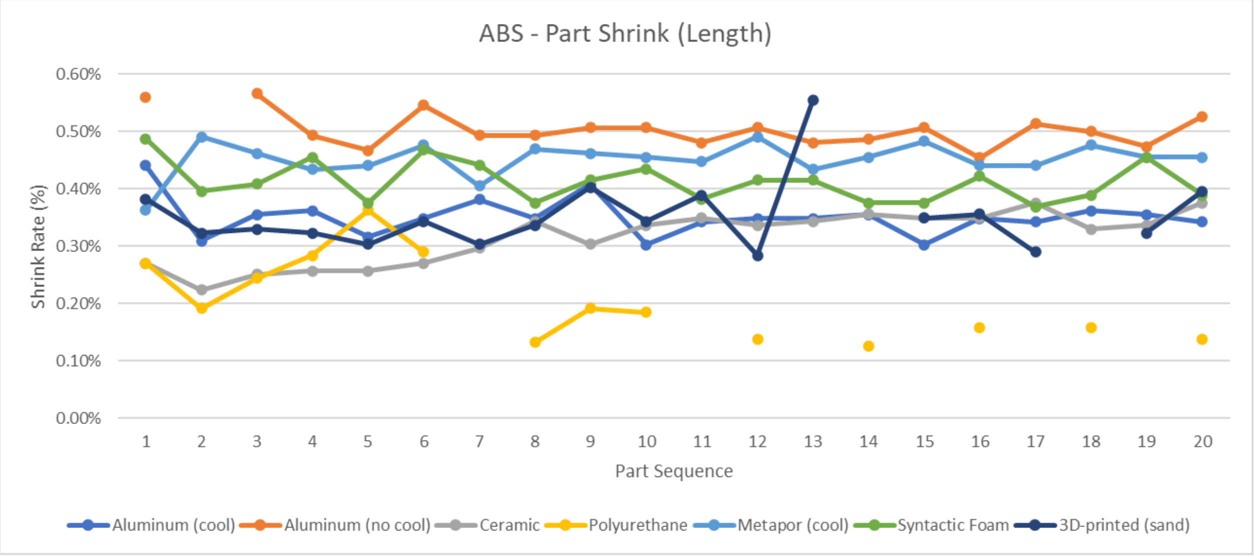
*-noted for the non-temperature-controlled Aluminum, Cycle #2 was lost due to machine error.

Observations by Part Detail (ABS)

- **Part Number (PN) Detail** – For part number detail, no parts passed in Aluminum, Ceramic, Metapor, or 3D-printed silica most likely due to the thickness of the trial materials versus actual production (0.125” vs. 0.060”). It is speculated that the 3D printed tool would not have excellent part number detail given the porous nature of the tool surface. The Polyurethane & Syntactic Foam tooling materials exhibited passable ratings.
- **Ridge Detail** – In terms of the quality of the Ridge Detail, only the temperature controlled metallic tools had acceptable ratings, suggesting that the buildup of temperature of the other tools either was too hot to form passing ridge detail, or the material didn’t have time enough to set up.
- **Inner Detail –** For the Inner Detail, the clear winners were the MetaPor & Syntactic Foam, both known to be ideal for providing lettering / fine feature details, so this was not surprising. What is interesting is the temperature-controlled Aluminum faltered a bit at the end, whereas the non-temperature-controlled Aluminum improved, suggesting increasing heat helped.

Data – Shrink (ABS)





ABS	**Part Width**				**Part Length**			
Shrink Rate	# of parts	Avg	Std Dev	CoV[1]	# of parts	Avg	Std Dev	CoV[1]
Aluminum (cool)	20	0.59%	0.03%	4.2%	20	0.35%	0.03%	9.1%
Aluminum (no cool)	19	0.58%	0.03%	5.9%	19	0.50%	0.03%	5.7%
Ceramic	20	0.59%	0.02%	3.3%	20	0.32%	0.04%	14.1%
Polyurethane	14	0.40%	0.03%	7.7%	14	0.21%	0.07%	34.5%
Metapor (cool)	20	0.63%	0.05%	8.1%	20	0.45%	0.03%	6.4%
Syntactic Foam	20	0.51%	0.04%	7.2%	20	0.41%	0.03%	8.3%
3D-printed (sand)	18	0.54%	0.05%	9.5%	18	0.35%	0.06%	17.0%

[1] Coefficient of Variance (CoV) equals the standard deviation divided by the average (mean). Lower values are favorable as this is an indication of minimal variation to the average.

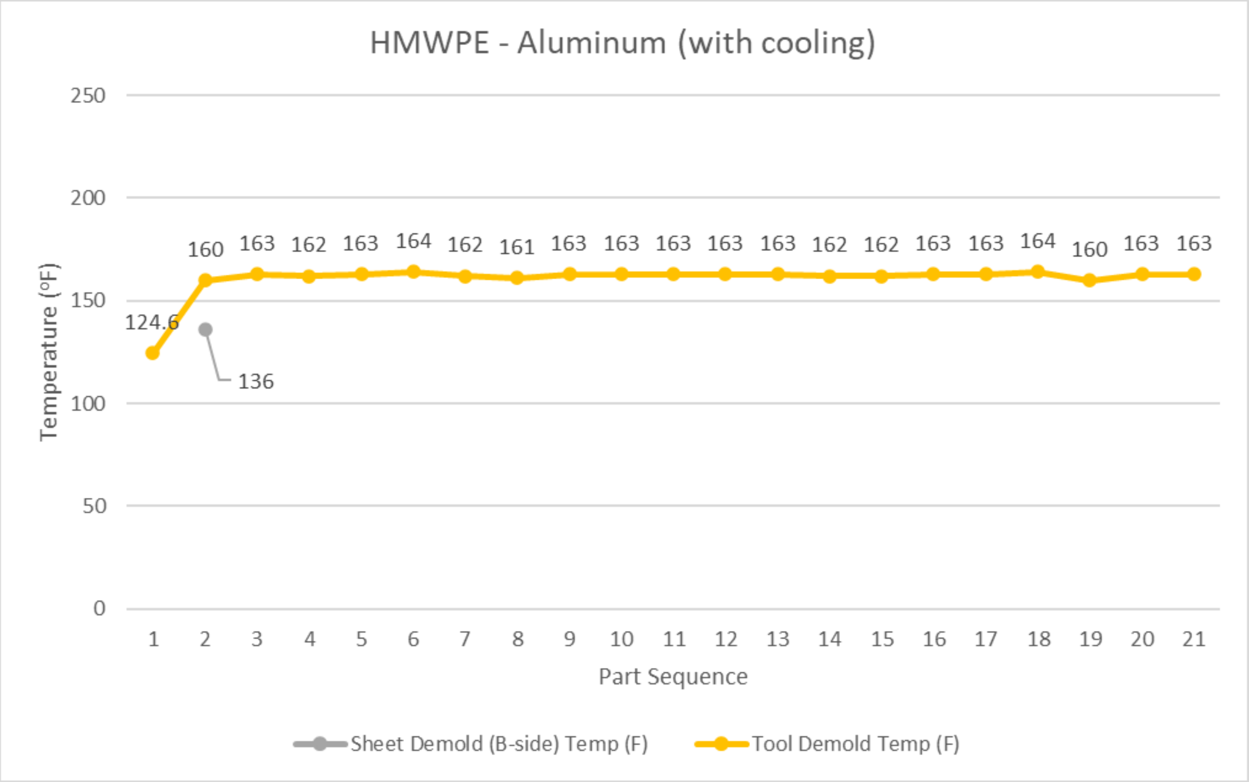
Observations of Part Shrink (ABS)

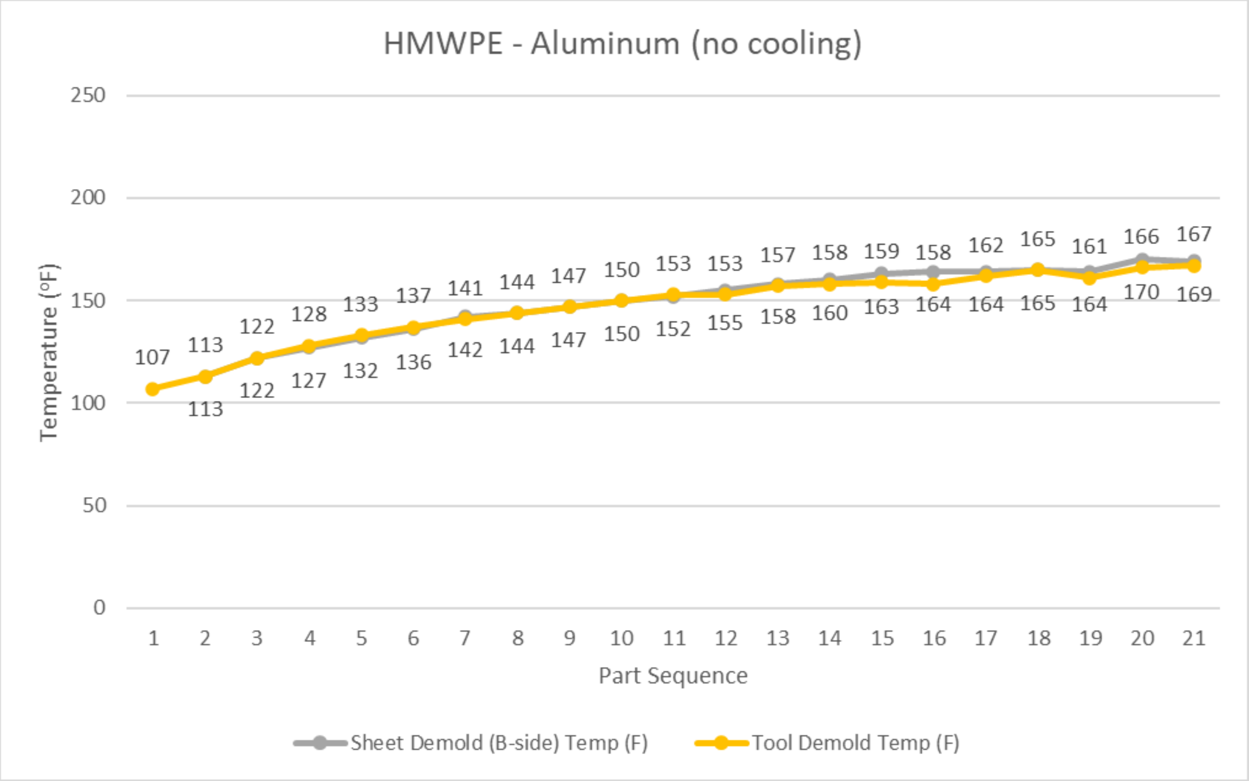
General comments on shrink rate before looking at the individual tooling materials:

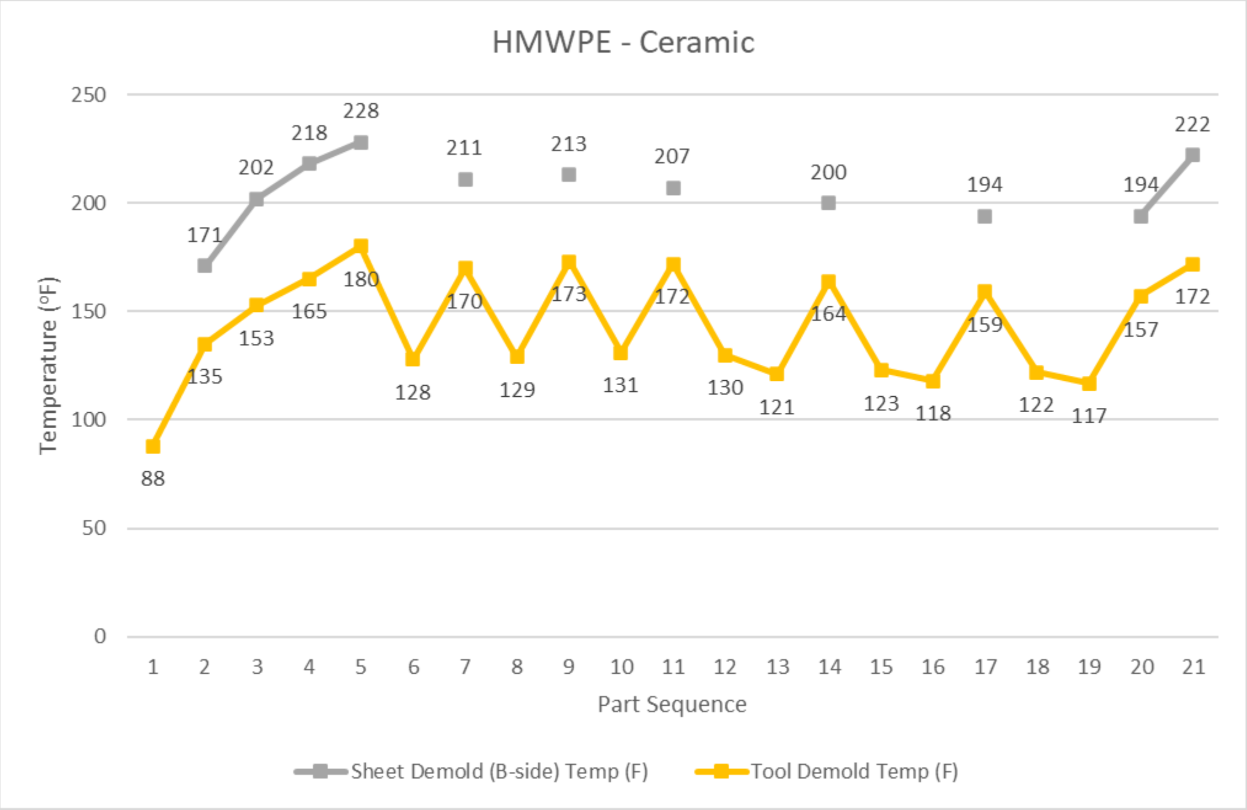
- All the tools were not cut to the same shrink rate, so the absolute shrink rate percentages are not comparative between tool to tool (except for the Aluminum tool since this was used for two conditions of temperature-controlled and non-temperature-controlled).
- Coefficient of variation was used to evaluate the shrink rate consistency from part to part.
- The width dimension (8.6”) is just under half the length dimension (15”), so one would expect a higher measurement error factor for the width.
- **Aluminum (with cooling)** – Interestingly that the Aluminum mold with cooling was not the most consistent condition, coming in as second & third best in CoV for width and length respectively. Given the minor differences in standard deviation, this is most likely the effect of measurement variation.
- **Aluminum (without cooling)** – the shrink rate in the length dimension increased by nearly 1.5 times without cooling versus with cooling, which is not surprising. This higher shrink rate, with fairly low standard deviation, yielded the best CoV for the width in ABS.
- **Ceramic** – for width the Ceramic tool yielded a 0.27% shrink rate and after a slight dip, increased steadily to finish at 0.38% on part 20. This is also not surprising as the successive formed parts elevated the tool temperature. CoV was middle of the pack at 14.1% in width but was the best at 3.3% for width.
- **Polyurethane** – even with the lowest number of saved parts from the ABS study, the Polyurethane had the highest amount of CoV in the width direction at 34.5%. This was largely impacted by the steady shrink rate increase during the early cycles, and then having to skip several frames to manage heat.
- **MetaPor** – MetaPor performed in between the two Aluminum conditions in CoV, which given the tool composition, is not surprising.
- **Syntactic Foam** – Syntactic Foam can claim the achievement of being the only non-metallic tool to produce 20 acceptable parts, but also the lowest CoV of the non-metallic tools as well at 8.3%.
- **3-D Printed Silica** – the 3-D Printed Silica tool for both shrink rate width and length started higher relatively for the first part, then dropped for the next eight or nine parts, only to increase dramatically at the thirteenth part which corresponded to the max tool demolding temperature of 193^{o}F. This contributed to the second-highest width CoV of ABS data set at 17.0%.

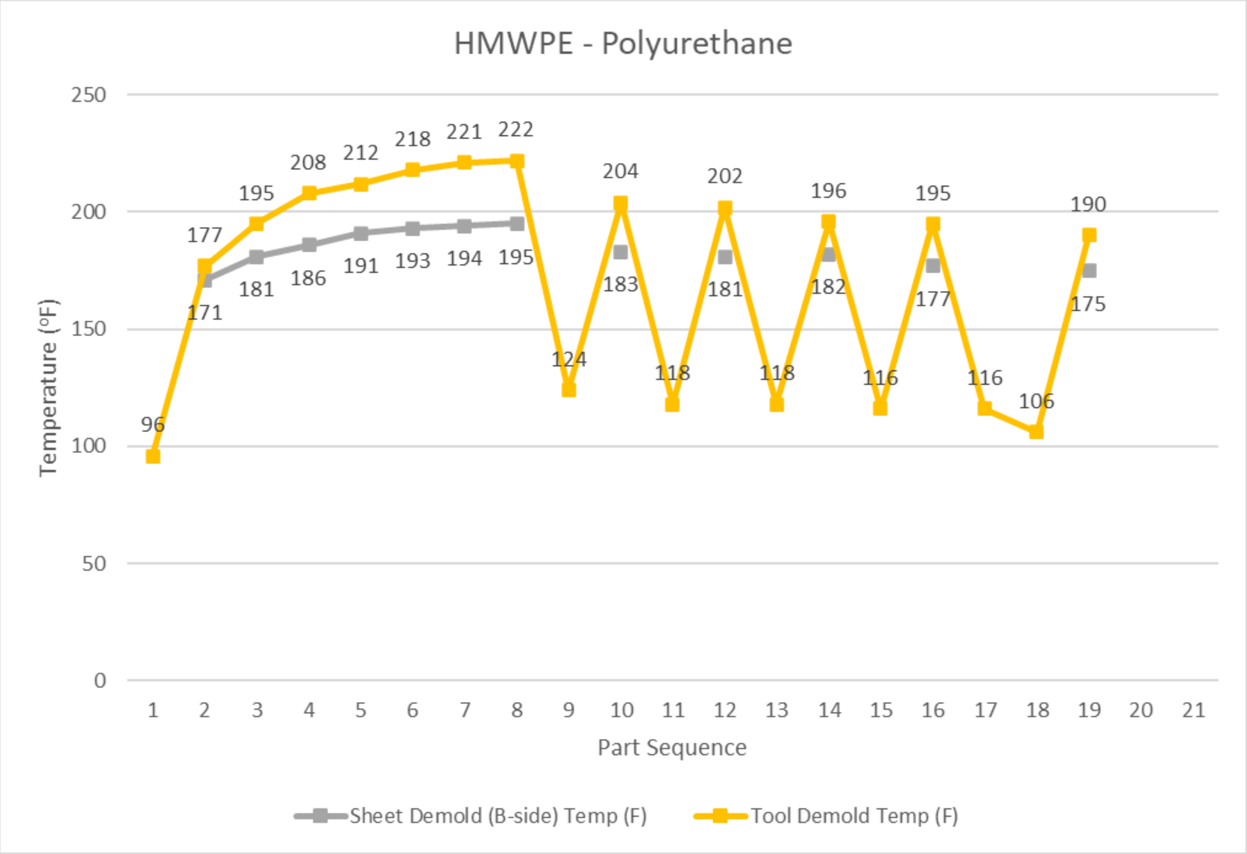
Results by Temperature

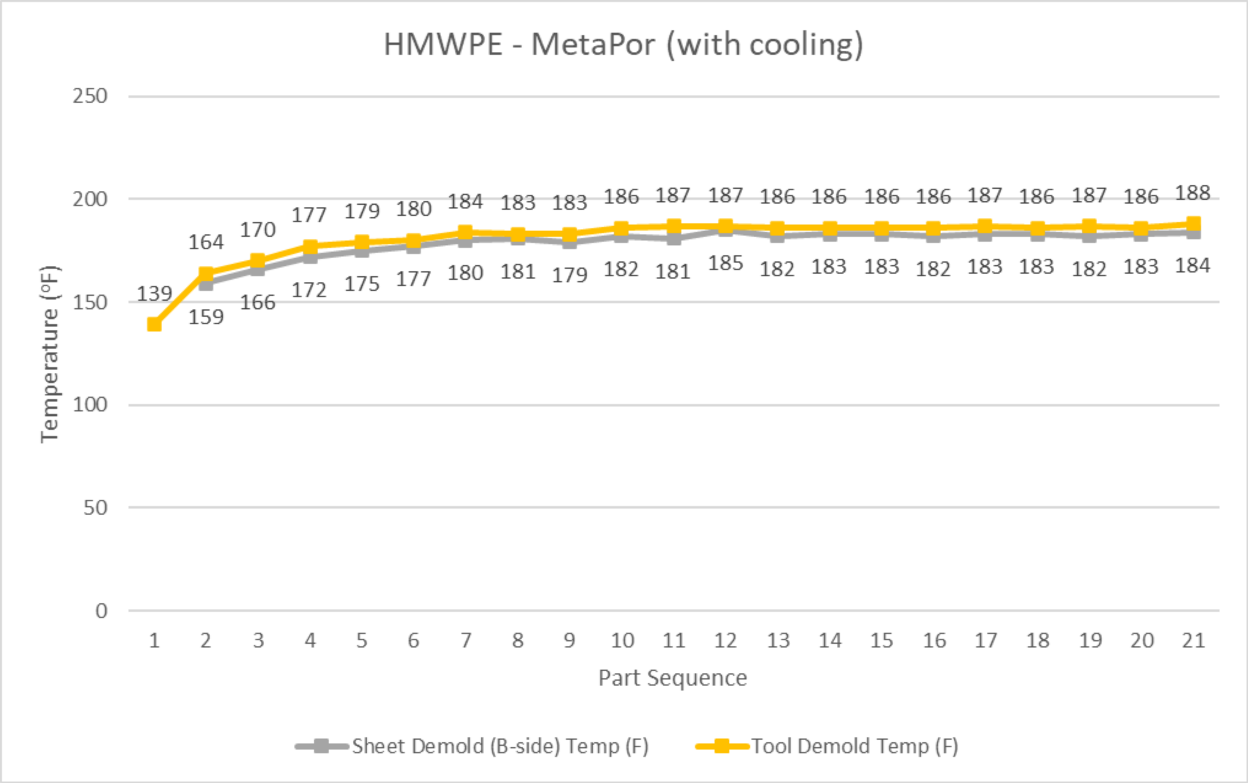
Temperature by Each Tool (HMWPE)

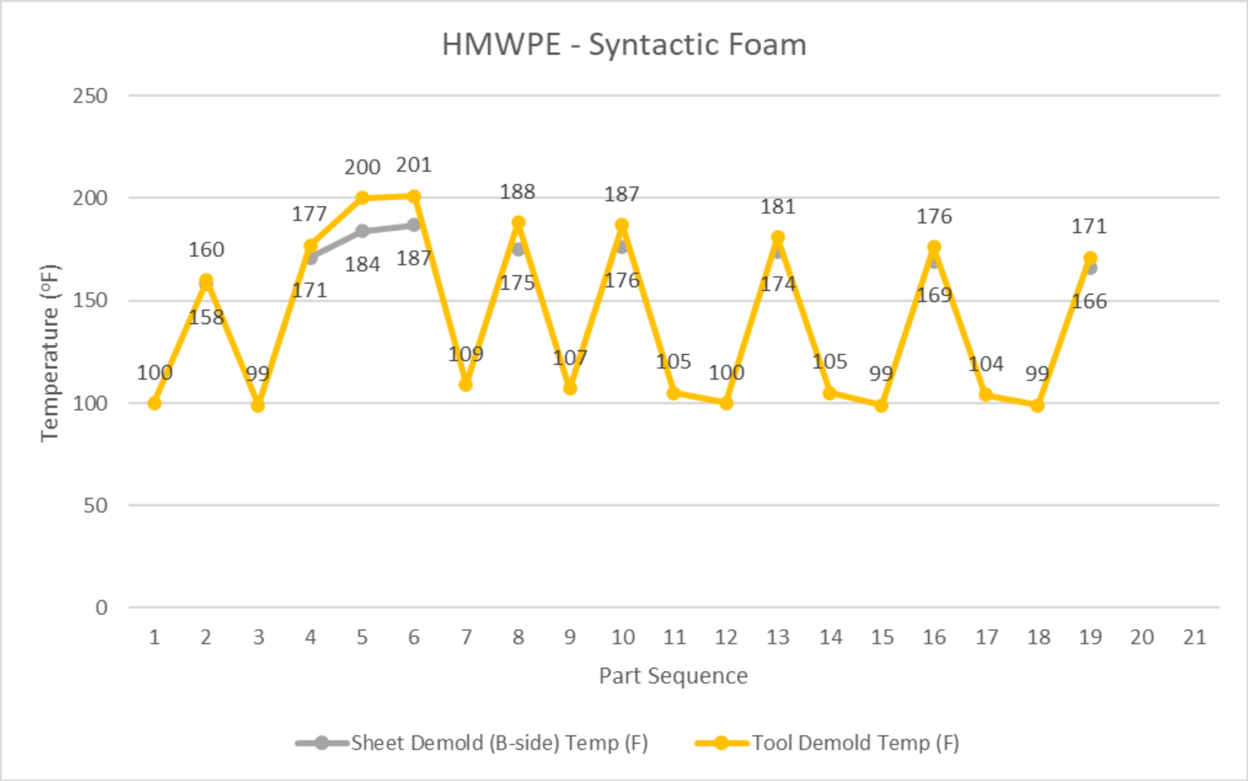


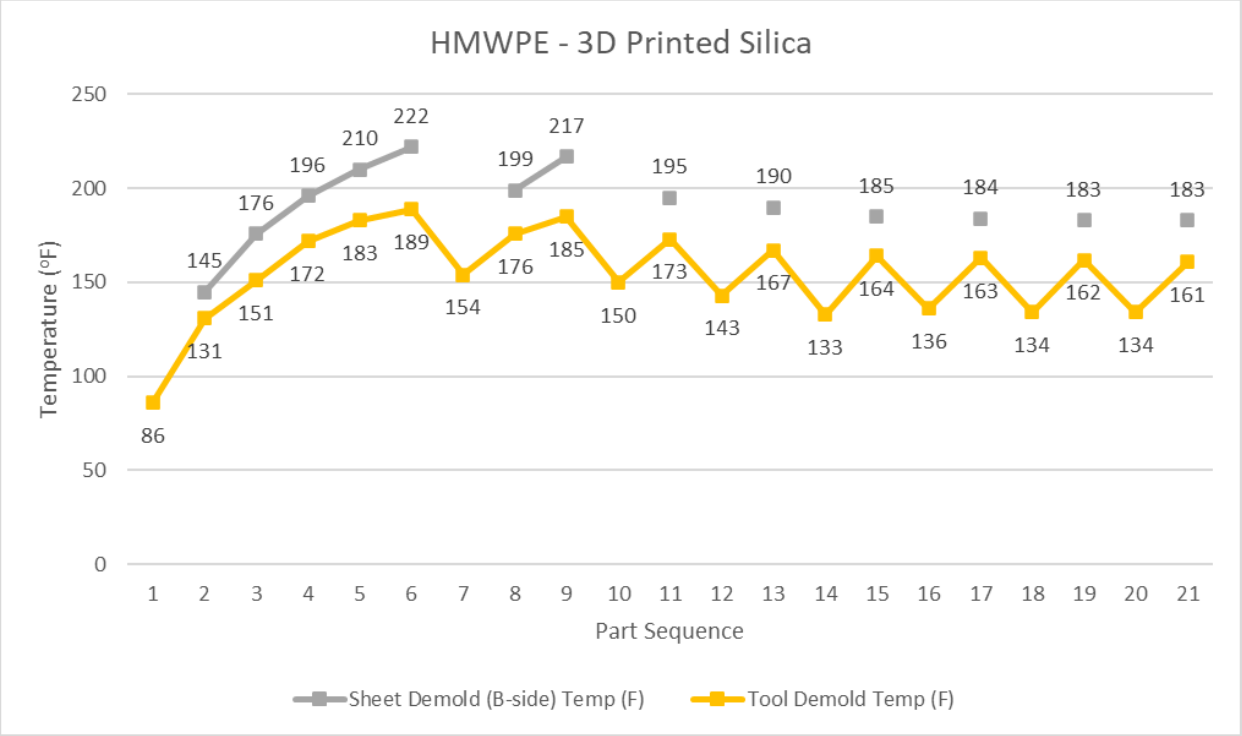



HMWPE - Ceramic
Temperature (°F)
250
200
150
100
50
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Part Sequence
171 202 218 228 211 213 207 200 194 194 222
88 135 153 165 180 128 170 129 173 131 172 130 121 164 123 118 159 122 117 157 172
Sheet Demold (B-side) Temp (F)
Tool Demold Temp (F)


HMWPE - Polyurethane
Temperature (°F)
250
200
150
100
50
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Part Sequence
96 177 195 208 212 218 221 222 124 204 118 202 118 196 116 195 116 106 190
171 181 186 191 193 194 195 183 181 182 177 175
Sheet Demold (B-side) Temp (F)
Tool Demold Temp (F)


HMWPE - MetaPor (with cooling)
Temperature (°F)
250
200
150
100
50
0
164 170 177 179 180 184 183 183 186 187 187 186 186 186 186 187 186 187 186 188
139
159 166 172 175 177 180 181 179 182 181 185 182 183 183 182 183 183 182 183 184
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Part Sequence
Sheet Demold (B-side) Temp (F)
Tool Demold Temp (F)

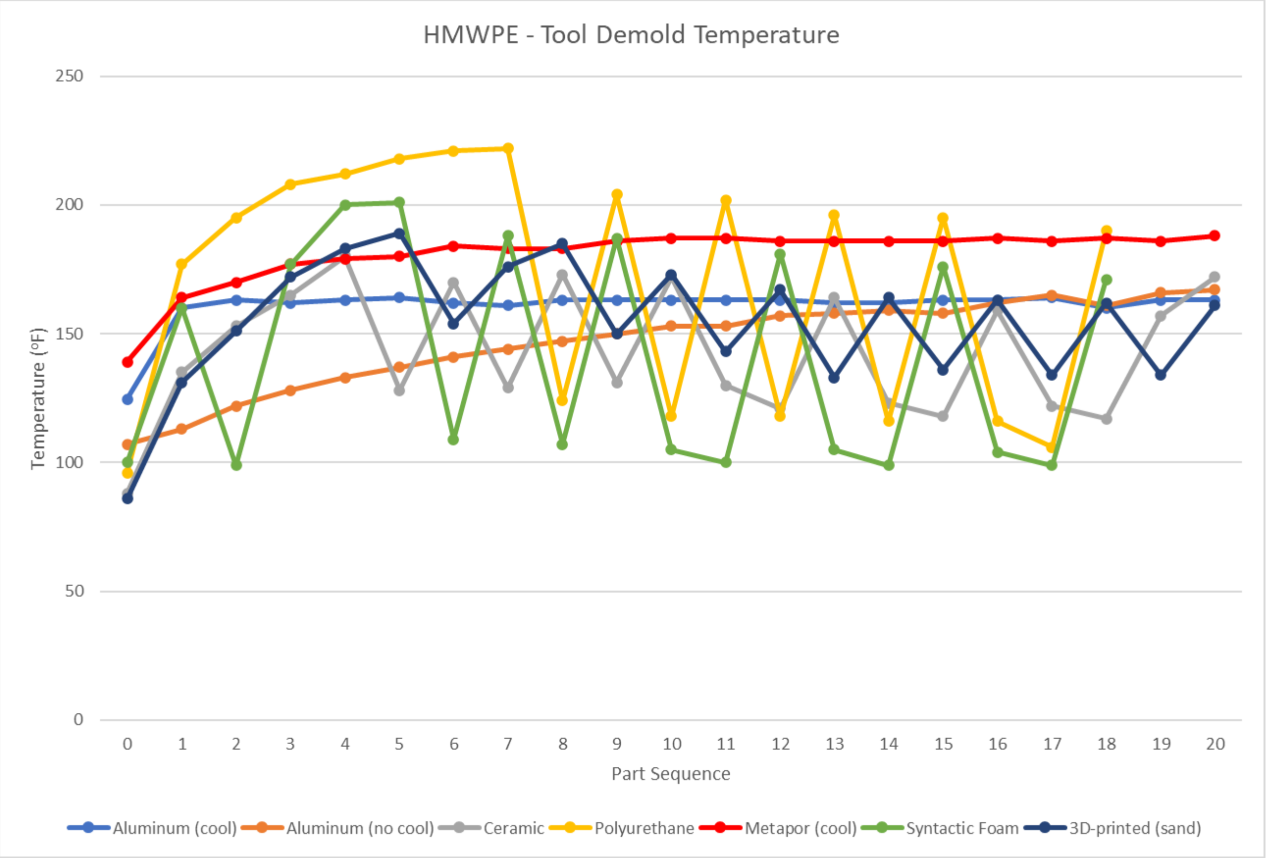

HMWPE - Syntactic Foam
Temperature (°F)
250
200
150
100
50
0
200 201
177
160
188
187
181
176
171
184 187
171
158
175
176
174
169
166
100 99 109 107 105 100 105 99 104 99
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Part Sequence
Sheet Demold (B-side) Temp (F)
Tool Demold Temp (F)


HMWPE - 3D Printed Silica
Temperature (ºF)
250
200
150
100
50
0
Part Sequence
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
145
176
196
210
222
199
217
195
190
185
184
183
183
86
131
151
172
183
189
154
176
185
150
173
143
167
133
164
136
163
134
162
134
161
Sheet Demold (B-side) Temp (F)
Tool Demold Temp (F)

Observations by Each Tool for Temperature

- **Aluminum (with cooling)** – like ABS, the HMWPE with the temperature-controlled aluminum, kept a near-consistent tool temperature near 163°F. Also noted that this was the very first data set gathered, and the B-side sheet demold temperature was missed.
- **Aluminum (without cooling)** – also like ABS, HMWPE with no cooling saw a steady rise to nearly 170°F. Without having the therm-o-later preconditioning the tool, the starting temperature was lower, and both tool and part temperature would have most likely risen higher with a longer run sequence.
- **Ceramic** – also observed in the ABS charts, the HMWPE sheet temperature is always higher than the tool temperature in this data set suggesting that the insulative properties of the ceramic do not allow for an efficient heat transfer from sheet to tool. Unlike the ABS, the ceramic mold had to skip frames for the HMWPE due to excessive part temperature.
- **Polyurethane** – The Polyurethane tool, after the third part exceeded the "danger zone" of >200°F and required the skipping of frames to manage tool temperature. By skipping 1 frame, the tool temperature dropped an average of 80 degrees, allowing a part to be produced.
- **MetaPor** – The cooled composite tool followed the same temperature slopes as both Aluminum tool conditions, but at roughly a 23-degree increase. Warmer, but still efficient.
- **Syntactic Foam** – This tooling material had the quickest need to skip a frame to manage heat, and also exhibited nearly an 80-degree drop in tool temperature after every skipped frame.
- **3-D Printed Silica** – the 3-D silica produced 5 forms before having to skip a frame, and then alternated through the 20 cycles. Tool temperature cooled and average of 20-30 degrees between from skipping 1 frame.

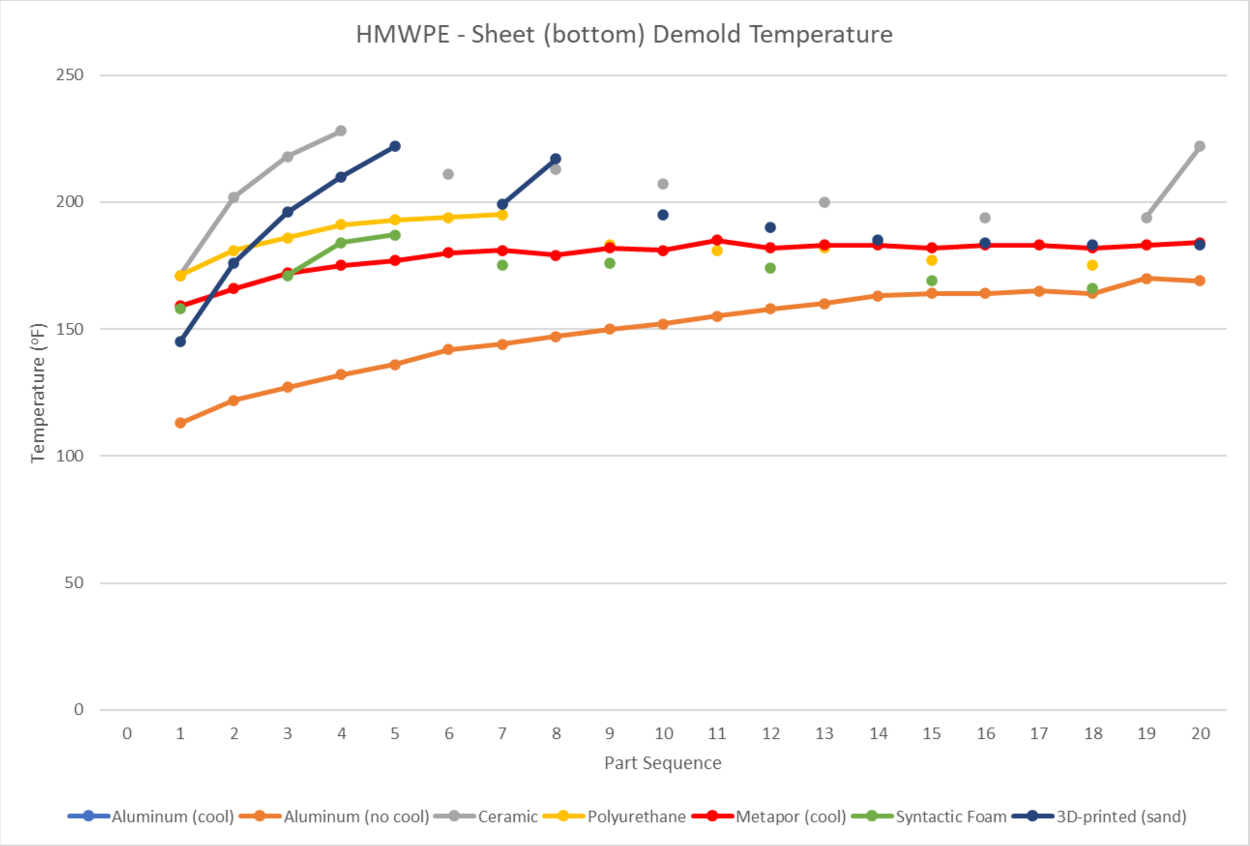
Data – Temperature Summary (HMWPE)



Observations by Temperature Summary

Tool Demold (HMWPE)

- **Aluminum (with cooling)** – flattest, almost level tool temperature for all 20 parts.
- **Aluminum (without cooling)** – unsurprisingly, the aluminum tool was consistently the lowest temperature values across the study, eclipsing the Aluminum with cooling at part 17.
- **Ceramic** – ceramic was the 2nd fastest to need frame-skipping, outperforming only the Syntactic Foam in that regard. After the skipped each frame, tool demold was fairly consistent.
- **Polyurethane** – As with ABS, Polyurethane with HMWPE exhibited the fastest and highest tool heat increase rate & level of the study. After the 7th consecutive part, every other frame had to be skipped to keep tool temperatures near or below 200ºF.
- **MetaPor** – The MetaPor tool exhibited the highest tool demold temperature of the metallic tools, but stayed below 200ºF, with a slope that was about 23-degrees warmer than the cooled aluminum after the 6th cycle.
- **Syntactic Foam** – The syntactic foam ramped up like the Polyurethane, but exhibited cooler demold temperature spikes and drops from the intermittent frame skips by almost 20-degrees.
- **3-D Printed Silica** – early in the part sequence, this tool demonstrated similar heat increase as the Polyurethane & Syntactic Foam. Interestingly, skipping 1 frame after the 8th cycle, showed a downward slope in temperature on the formed cycles (leveling out near 164ºF), with only a 30-degree average loss in between cycles (some of the lost "recovery" temperature of the group).



Sheet Demold (HMWPE)

- **Aluminum (with cooling)** – too little data to comment.
- **Aluminum (without cooling)** – same as will tool demold, the aluminum tool was consistently the lowest temperature values across the study.
- **Ceramic** – As with ABS, also with HMWPE with the ceramic tool exhibited the highest level of sheet demold temperature, pointing to very little heat transfer between sheet and mold.
- **Polyurethane** – sheet demold temperature followed the same slope as the Metapor tool, at roughly 15-degrees higher, until the 7th cycle, when frames were skipped, and then it was roughly identical to MetaPor.
- **MetaPor** – Very even and gradual increase in sheet demolding temperature until a near leveling-out at ~182°F (about 10-degrees higher than ABS on average).
- **Syntactic Foam** – syntactic foam was the first material to skip frames, and eventually needed 2-frames skipped in the latter half of the run. able to take heat out to the sheet efficiently possibly due to the air-pockets in the foam.
- **3-D Printed Silica** – after the 5th cycle, a skipped frame was necessary, but this cadence allowed the 3-D Printed Silica tool to reach nearly the same sheet demold temperature (183°F) as the MetaPor tool.

Data – Part Detail (HMWPE)

Part Detail-PN

Tool Material	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	Count (Rating 4 or 5)	Total Parts
Aluminum (cool)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	0	20
Aluminum (no cool)	1	1	1	1	1	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	0	20
Ceramic	1	2	2			2		2					1			1			1	2	0	9
Polyurethane	3	3	3	2	2	1	1		1		2		3		3			3			0	12
Metapor (cool)	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	0	20
Syntactic Foam	4		4	3	3		4		4			4			5			4			7	9
3D-printed (sand)	3	3	3	3	3		3	3		3		3		3		3		3		3	0	13

Part Detail-Ridge

Tool Material	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	Count (Rating 4 or 5)	Total Parts
Aluminum (cool)	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	20	20
Aluminum (no cool)	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	20	20
Ceramic	2	2	2			2		2					2			2			2	2	0	9
Polyurethane	3	3	3	3	3	1	1		3		3		3		3			3			0	12
Metapor (cool)	4	3	4	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	17	20
Syntactic Foam	2		3	1	3		1		1			1			4			3			1	9
3D-printed (sand)	1	1	1	1	1		1	1		1		1		1		1		1		1	0	13

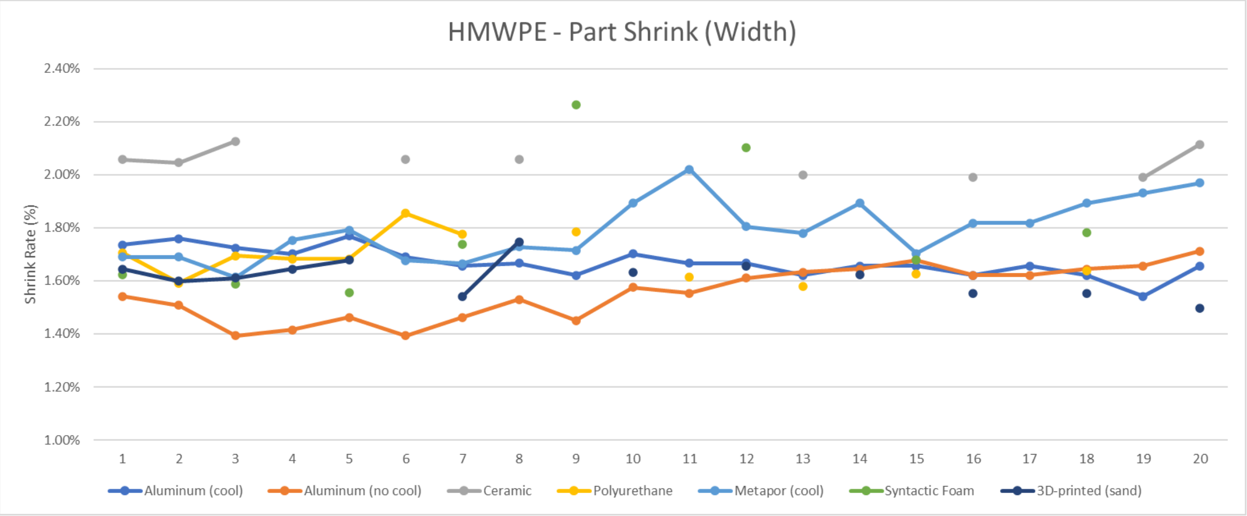
Part Detail-Inner

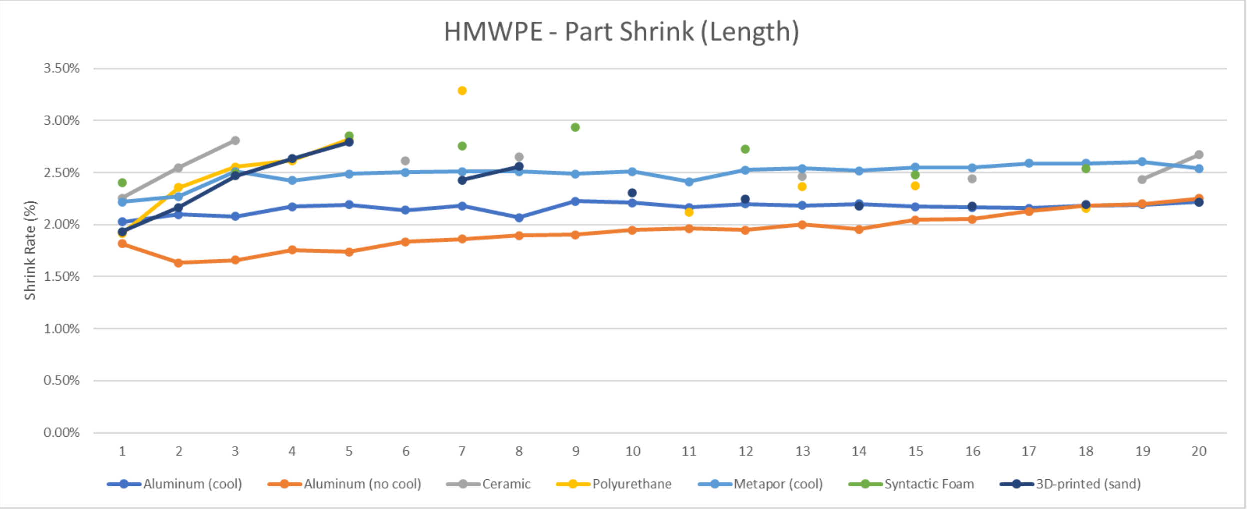
Tool Material	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	Count (Rating 4 or 5)	Total Parts
Aluminum (cool)	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	20	20
Aluminum (no cool)	4	4	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	18	20
Ceramic	3	3	3			2		3					2			2			2	2	0	9
Polyurethane	4	4	3	2	2	3	3		3		4		3		4			4			5	12
Metapor (cool)	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	20	20
Syntactic Foam	4		4	2	4		4		4			4			4			4			8	9
3D-printed (sand)	3	3	3	3	3		3	3		3		3		3		3		3		3	0	13

Observations by Part Detail (HMWPE)

- **Part Number (PN) Detail** – For part number detail, the only passing parts were from the Syntactic Foam tool. As noted, the thickness of the materials trialed was much greater than the production material, which would be counterproductive as it pertains to part detail or lettering.
- **Ridge Detail** – In terms of the quality of the Ridge Detail, and like the ABS parts, only the temperature controlled metallic tools had acceptable ratings, suggesting that the buildup of temperature of the other tools either was too hot to form passing ridge detail, or the material didn't have time enough to set up.
- **Inner Detail –** For the Inner Detail, and like the ABS, for the few Syntactic Foam parts, most received a passing grade. However, different from the ABS trial, the metallic molds yielded the highest number of parts that ranked a 4 or higher. Possibly the metallic molds allowed for improved crystallization rate for the HMWPE versus the other non-metallic tools.

Data – Shrink (HMWPE)





HMWPE	**Part Width**				**Part Length**			
Shrink Rate	# of parts	Avg	Std Dev	CoV[1]	# of parts	Avg	Std Dev	CoV[1]
Aluminum (cool)	20	1.67%	0.05%	3.1%	20	2.16%	0.05%	2.4%
Aluminum (no cool)	20	1.56%	0.10%	6.2%	20	1.94%	0.17%	8.7%
Ceramic	9	2.05%	0.05%	2.3%	9	2.54%	0.15%	6.1%
Polyurethane	12	1.69%	0.08%	4.8%	10	2.46%	0.37%	15.1%
Metapor (cool)	20	1.79%	0.11%	6.1%	20	2.49%	0.10%	3.8%
Syntactic Foam	8	1.79%	0.24%	13.4%	8	2.65%	0.18%	6.9%
3D-printed (sand)	13	1.61%	0.06%	3.9%	13	2.33%	0.22%	9.6%

[1] Coefficient of Variance (CoV) equals the standard deviation divided by the average (mean). Lower values are favorable as this is an indication of minimal variation to the average.

Observations of Part Shrink (HMWPE)

General comments on shrink rate before looking at the individual tooling materials:

- All the tools were not cut to the same shrink rate, so the absolute shrink rate percentages are not comparative between tool to tool (except for the Aluminum tool since this was used for two conditions of temperature-controlled and non-temperature-controlled).
- Coefficient of variation was used to evaluate the shrink rate consistency from part to part.
- The width dimension (8.6”) is just under half the length dimension (15”), so one would expect a higher measurement error factor for the width.
- **Aluminum (with cooling)** – The Aluminum tool with cooling yielded the full 20 parts and the lowest combination of CoV for width & length at 3.1% & 2.4% respectively.
- **Aluminum (without cooling)** – the shrink rate for the non-temperature-controlled Aluminum tool was less than when cooling was used, which is interesting and a bit counter-intuitive. Standard deviations were higher, and this resulted in a higher CoV when continuing to compare to the cooled version, which does follow conventional wisdom.
- **Ceramic** – Ceramic surprisingly yielded the lowest CoV at 2.3% and low for length at 6.1%, albeit with only 9 good parts formed. Also, the Ceramic tool, like the other non-metallic tools, demonstrates a steady shrink rate percent increase for each successive part, and only levels out after frames were skipped to manage tool temperature.
- **Polyurethane** – Polyurethane was middle of the pack for CoV in width but was the highest for CoV for length at 15.1%, likely attributed to the spike in shrink rate for part #7. This could be from measurement error, or that the tool retained simply too much heat. After part #7, three frames were skipped before the tool temperature could normalize suggesting it was heat related.
- **MetaPor** – Just as with ABS, the MetaPor tool performed in between the two Aluminum conditions in CoV for HMWPE, which again, given the tool composition, is not surprising.
- **Syntactic Foam** – Unlike with ABS, Syntactic Foam was not able to create the full complement of parts, and only 8 parts were procured with HMWPE. CoV for width was the highest of the study at 13.4%, but was surprisingly low for length, coming it at an average of 6.9%. This skipping of every-other frame for the first half of the run, and every two frames after the part #9 likely attributed to managing tool heat with less parts / longer cooling.
- **3-D Printed Silica** – the 3-D Printed Silica saw a steady increase in shrink rate through five consecutive parts, but this was controllably reduced by skipping every other frame, and eventually leveling out along the same level as the MetaPor HMWPE parts in the latter half of the run. A total of 13 parts were saved with a below average CoV of 3.9% for width and a slightly above average CoV of 9.6% for length.

Overall Summary

ABS

Tool Material	Tool Cost	Total Parts Produced	Cost per Part[1]	Shrink Coefficient of Variation Avg Width & Length	Passed Part Number Detail	Passed Inner Detail	Passed Ridge Detail
Aluminum (cooling)	$5,500	20	$278.53	6.7%	0%	100%	90%
Aluminum (no cooling)	$4,000	19	$214.24	5.8%	0%	5%	63%
Ceramic	$1,975	20	$102.28	8.7%	0%	0%	0%
Polyurethane	$2,000	14	$147.90	21.1%	100%	7%	100%
MetaPor	$7,700	20	$388.53	7.3%	0%	100%	100%
Syntactic Foam	$3,034	20	$155.23	7.7%	100%	0%	100%
3D Printed Silica	$550	18	$34.48	13.2%	0%	0%	0%

[1] cost per part = (Tool Cost+(max parts per hour*$100 hourly rate))/Total Parts produced

- **Aluminum (with cooling)** – Our control tooling material for ABS yielded the expected 20 parts and was toward the top in terms of cost per part, which is to be expected. Passing part number detail was elusive for most of the conditions, but the inner & ridge detail performed well. Aluminum is still an obvious choice for large volume programs, which is industry known.
- **Aluminum (without cooling)** – The cost for Aluminum without cooling was taken from an estimate if the tool was just a machined piece of aluminum without cooling channels, so the price per part was less than with cooling. It is noted that 19 parts were obtained, but for an extended run, the cost-benefit of better yield, inner & ridge detail would compel the user to invest in the cooling.
- **Ceramic** – Ceramic comes in as the second-lowest cost per part with the full yield of 20 parts, moderate coefficient of variance, but lacking in all the detail categories. Good option for low build ABS parts if detail is not a critical feature.
- **Polyurethane** – Polyurethane yielded the lowest number of ABS parts in the study at 14, which raised the price per part above that of Ceramic by $45. Coefficient of variation in shrinkage was the highest of the study at 21.1% but was excellent for part number and ridge detail. Almost as an antithesis to Ceramic, Polyurethane would be the solution to Ceramic's part detail deficiencies if the processor could take their time and overall productivity was a secondary concern.
- **MetaPor** – Although MetaPor yielded the full 20 ABS parts, it was still the priciest option of the group, but it was the only option that provided a 100% pass rate for ridge and inner detail. Given the limited tooling dimensions and higher cost, the MetaPor material would only be a fit for niche applications.
- **Syntactic Foam** – Typically known only as a plug-assist material, the Syntactic Foam tool held its own with the ABS portion of the study. Cost-wise, the tool was just under the aluminum options and above the other non-metallic tools. Full part yield, decent shrink CoV, and a leader with part number & ridge detail.
- **3-D Printed Silica** – the 3-D Printed Silica was the lowest tool cost of the study which translated to a significantly lower part cost with ABS and a solid part yield at 18. Shrink variation was on the higher end and detail, admittedly not a strong suit in the beginning, were noted drawbacks. Like Polyurethane, if the processor needed a few parts, and continuous cycling was not a concern, the 3-D Printed Silica tool would be an economical choice.

HMWPE

Tool Material	Tool Cost	Total Parts Produced	Cost per Part[1]	Shrink Coefficient of Variation Avg Width & Length	Passed Part Number Detail	Passed Inner Detail	Passed Ridge Detail
Aluminum (cooling)	$5,500	20	$280.19	2.8%	0%	100%	100%
Aluminum (no cooling)	$4,000	20	$205.19	7.5%	0%	100%	90%
Ceramic	$1,975	9	$230.99	4.2%	0%	0%	0%
Polyurethane	$2,000	12	$175.32	9.9%	0%	0%	42%
MetaPor	$7,700	20	$390.19	4.9%	0%	85%	100%
Syntactic Foam	$3,034	9	$348.65	10.1%	78%	11%	89%
3D Printed Silica	$550	13	$50.30	6.8%	0%	0%	0%

[1] cost per part = (Tool Cost+(max parts per hour*$100 hourly rate))/Total Parts produced

- **Aluminum (with cooling)** – As expected, the temperature-controlled Aluminum tool was able to secure all 20 parts, deliver 100% acceptable inner and ridge detail, and the lowest shrink coefficient of variation.
- **Aluminum (without cooling)** – Emulating a non-temperature-controlled Aluminum tool by turning the cooling off, this tool condition was also able to yield the full 20 parts, and theoretically saved $75/part, but also unsurprising, the shrink variation over doubled compared to its cooled version and suffered a bit with ridge detail.
- **Ceramic** – Ceramic struggles with temperature management hindered the yield, tying for last place with only 9 parts saved. Ceramic has been used successfully with another semi-crystalline material (TPO) in lower volume applications, so productivity and cycle time likely need to be traded for yield and part quality. Interestingly, the Ceramic tool delivered the lowest shrink CoV of the non-metallic tools, but this could also be the sample size was smaller.
- **Polyurethane** – Polyurethane wasn't much better with HMWPE than Ceramic, yielding 12 acceptable parts, but having the second highest shrink CoV. Ridge detail was better than zero.
- **MetaPor** – With the similar results with ABS, MetaPor performed in-between the two Aluminum conditions, yielding all 20 parts, low shrink CoV and good part inner and ridge detail. The highest cost of the study would most likely push the processor to choose traditional aluminum.
- **Syntactic Foam** – The Syntactic Foam tied for last place in the number of parts saved (9), had the highest non-metallic tooling cost, and the highest shrink rate CoV, indicating that this would not an ideal tool material for HMWPE. However, for part detail, Syntactic Foam was the clear winner for part detail in all 3 areas for non-metallic tools. Could be a potential consideration for detailed inserts in a rougher mold.
- **3-D Printed Silica** – As mentioned with the ABS portion of the study, the 3-D Printed Silica had the lowest tool cost and with the HMWPE, yielded the highest number of parts in the non-metallic options studied at 13. Shrink variation was lower than the non-temperature-controlled Aluminum tool, which is also favorable. Detail, as noted with ABS, was a noted tradeoff.

Acknowledgments

Special thanks to all involved with this study:

Patrick Castro Jr., Electro-General Plastics Corporation

Ian Munnoch, MSA Components, Inc.

Darrell Stafford, Catalysis Additive Tooling

Phil Troyer, PT Polymers LLC

James Alongi, MAAC Machinery

Matt Vandivier, Primex Plastics

Paul Uphaus, Primex Plastics

Dustin Wagner, Plastic Ingenuity

Fritz Borke, Borke Mold Specialists, Inc.

Eric Short, SIMONA PMC