THERMOFORMING HIGH DENSITY POLYETHYLENE SHEET USING TEMPERATURE-CONTROLLED ALUMINUM TOOLING

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Abstract

Previous research has shown that thermoforming high density polyethylene (HDPE) is something that has been shied away from in the plastics industry. This paper will show the differences of thermoforming HDPE using temperature-controlled and non temperature-controlled tooling. In doing that, it will aim to prove that HDPE can be used with success in the thermoforming industry, as long as temperature controlled aluminum tooling is used.

Individual Performance Objectives

1. Show the importance of temperature-controlled molding in thermoforming.

2. Prove that HDPE can be a relevant material to use in thermoforming, instead of just amorphous materials.

Introduction

High density polyethylene isn't usually thought of as a usable material when thermoforming is talked about. It is not a material that seems like it would work with that type of process. Companies in industry have shied away from HDPE, because of its crystallinity and shrinkage rate. The thermoforming industry almost always uses amorphous materials, because they are a lot easier to control than crystalline materials.

Also, a lot of companies use wooden or urethane tooling to run their parts, because it is a lot cheaper to do that than to get aluminum or steel tooling. Instead of heating up their mold with water or oil, and keeping it at a constant temperature, they will just let the heat of the machine and material heat up the mold over time, but will run into problems at the start and end of their runs. The mold will either be too cold for the material and cool it too quickly, or be too hot, which will lengthen cycle time, and increase the chances of part defects.

Increased cycle times and part defects will cost the company a lot of money in the long run, when they could've just used a temperature-controlled aluminum mold. A temperature-controlled mold will stabilize mold temperature from the start, and will not have the variation a non temperature-controlled mold will. This will give the company much needed control of the tooling to help give them a chance at producing better quality parts for their customers. With better quality parts coming off of the temperature-controlled mold, there will be much less scrap sheet, stabilized cycle times and oven temperatures, and the company will be paying the cost of the tooling off with material savings.

Temperature-controlled tooling opens the doors to numerous materials that were once thought to never have a place in the thermoforming industry. It minimizes the increase in percent crystallinity that a material goes through when it is heated up and let to relax.

Material

Black HDPE sheet was used for this project. The sheet was 40 inches wide (machine direction), 22.5 inches long (transverse direction), and 0.125 inches thick. The material has a levant finish on one side and a smooth finish on the other, which would be the side used to touch the mold. The HDPE should be formed in between 285 and 385 degrees Fahrenheit, with the optimum forming temperature being 330 degrees Fahrenheit. The optimum temperature to take the sheet out of the mold is 170 degrees Fahrenheit.

Thermoformable high density polyethylene sheet has an average density of 0.0345 pounds per inch cubed (0.955 grams per cubic centimeter). It also has a 66.3 average Shore D Hardness, an average ultimate tensile strength of 3,800 pounds per square inch (psi), and an average tensile yield stress of 3,829 psi. The average deflection temperature with 66 psi is 166.5 degrees Fahrenheit.

Procedure

This project started when the material was received from the manufacturer. The first step after receiving the material was to put a grid system on the smooth side of the sheet, so that it could be measured to show the stretching that the material goes through when it is formed. With help from the Printing Department at Penn College, the sheet was screen printed with an inch by inch silver grid system (shown in Figure 1). After the gridding was complete on the 50 HDPE sheets that were available for the project, they were ready to be thermoformed. The first mold that was to be used on the project was a replica mold of the main aluminum mold for the project, and it was made out of Renshape 472 medium-density Polyurethane Modeling Board. The mold has a wooden base, and then the machined polyurethane is made to be exactly the same

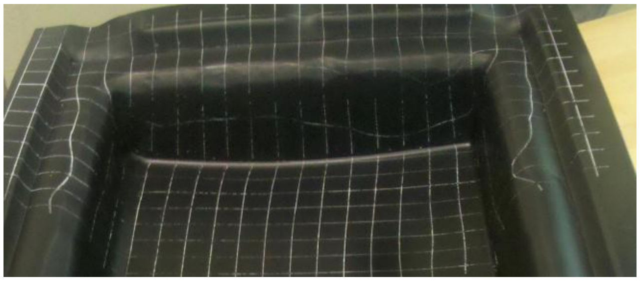

Figure 1 (gridding system on sheet after being formed)

dimensionally as the aluminum mold, which in relation to the material, is 15.25 inches long, 33.125 inches wide, and 4.2 inches high.

The mold was first set on the lower platen (shown in Figure 2) of the MAAC Thermoformer that was used on the project. The first set of parts that were made on the machine was to try and help set up a process that would produce a quality part, so that a production-style run could be started. After a few parts were formed, it was easily determined that the mold should be hung from the top platen rather than the bottom platen.

Figure 2 (Renshape mold on bottom platen)

The mold was switched from being set on the bottom platen to being hung from the top platen, because the sag in the pliable material coming from the oven coinciding with the top of the cool mold would cause a build-up of material in the four corners where the material would drape over the side of the mold. Switching to the top platen (shown in Figure 3) would eliminate the build-up of material in the corners, and create a better quality part.

Also by switching to the top platen, counter material sag stretching was eliminated. When a material is run in a thermoforming machine with the mold set on the bottom platen, the sag of the material as it comes out of the oven is met by the mold coming up into the pliable sheet and going through it to help create a seal to be able to vacuum the sheet around the dimensions of the mold. This phenomenon stretches the material twice, which could lessen some of the material's important physical properties. If the properties are compromised, the part has a possibility of failing once it gets out to its customer and starts being used. Hanging the mold from the top platen eliminates this from happening to the material. With the mold coming from the top of the sagging material, there is only one stretch on the material, which is in the same direction of the sag, and then the vacuum created by the seal between material and mold sucks the material back to the shape of the mold. This type of molding minimizes the stress on the material and theoretically eliminates the extra physical property damage done by double stretching with molds set on the bottom platen.

Figure 3 (Renshape mold on top platen)

After the urethane mold was hung from the top platen, the machine settings were altered so that they were the exact same as the bottom platen settings and it was time again to try and find the correct settings and cycle to produce quality parts repeatedly. Once they were found, a production-style run could be performed.

A few problems were run into when trying to find the "perfect" cycle. The first problem was that the rails that hold the sheet in place were set too close to the mold and the mold was going too far through the rails. This caused the back of the sheet to rip out completely. After this, the rails were moved out to about one-half inch from the mold and the mold was programmed so that it didn't go through the rails as far. The top of the mold was then set to go down 5.5 inches from the sheet in the rails. The sheet didn't rip completely when the mold came down through it, but it did leave a few small tear spots, which were a sign of the side of the sheet closest to the oven being too hot when it came out to be formed (shown in Figure 4). This problem was fixed by lowering the oven percentages in the back of the oven so that part of the sheet wouldn't be as hot as it exited the oven. After the cycle was finalized, the production-style run was ready to be started. A production-style run is basically just a certain number of sheets run one right after another. This production run was set for 10 sheets, and there were a number of variables that were measured related to the machine during the production run. They were: temperature of the front of the mold, the top of the mold, and the back of the mold (all of which were taken right before the next sheet in the run was loaded in the rails), sheet temperature as it came out of the oven right before forming, and temperature of the sheet after the rails opened after cooling and the formed part was ready to be taken out of the machine. Room temperature and humidity were also measured before every sheet was loaded.

Figure 4 (Tears in back of formed sheet)

After the formed sheet came out of the mold, it was set into the measuring jig that was made for the dimensions of what the sheet should be as it comes off the mold. The aluminum jig (shown in Figure 5) is 33.500 inches wide and 15.875 inches long. The sheet was placed in the jig the exact same way every time, and measured in 10 different places along the lengths and widths of the part (shown in Figure 6) using dial calipers set at the edge of the jig and being extended into the formed sheet.

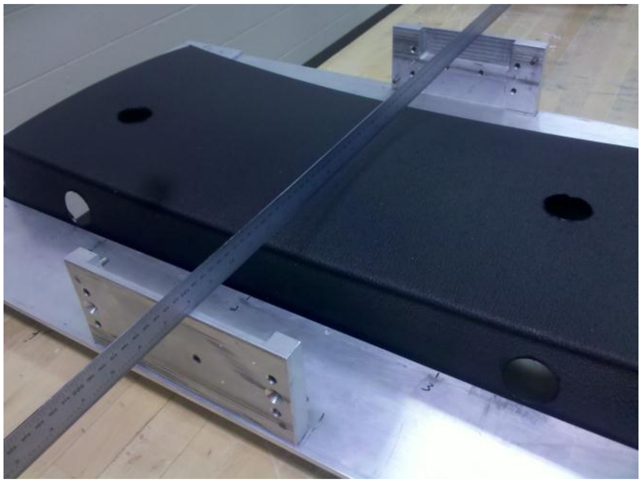

Figure 5 (HDPE sheet in aluminum jig)

Also shown in Figure 5 is how thickness measurements were taken on each of the sheets after they had been measured using the jig. A drill and hole saw attachment were used to cut one-inch holes in the top, front, left, back, and right sides of the sheet. The discs that were produced were then measured for thickness. Figure 5 also shows that the holes were drilled in the left side of each side immediately after the sheet was taken out of the machine. Measurements taken 24 or more hours later were drilled out of the right side of each side.

Also shown in Figure 5 is how the height measurement was taken for each part after the 10 jig measurements were taken. Two aluminum blocks were placed on the long sides of the aluminum jig, and an aluminum meter stick was placed on top of the blocks. The dial calipers were then extended from the top of the meter stick to the top of the formed sheet. That number was then plugged into a formula (5.5625 – x = height) to obtain the actual height of the part. The number 5.5625 comes from the jig thickness, aluminum block height, and meter stick height.

After all of the measurements were taken, they could be plugged into formulas that would give the formed sheet lengths and widths at the given measurement points. The original measurement points and their corresponding formula labels are shown in Figure 6.

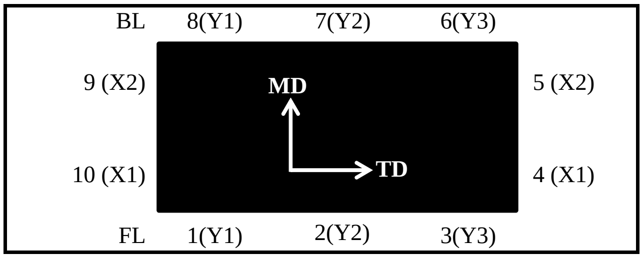

Figure 6 (Measurement points and formula labels)

The formulas were calculated by taking the original jig Y (machine) direction (15.875 inches) or the original jig X (transverse) direction (33.500 inches) and subtracting the two measurement points that go together (1-8, 3-6, 5-9, etc.). An example for the Y1 measurement would be 15.875 inches minus the combination of measurements 1 and 8 (0.1025 and 0.4865), measured with the dial calipers, which would equal out to a Y1 length of 15.2860 inches. The caliper measurements help show the warpage of the formed part and the formulas for the length and width help show the overall shrinkage.

After the production style run was completed with the Renshape urethane mold, the aluminum mold needed to be prepared so that it too could be hung in the machine and used for a production-style run to compare with the production run performed with the Renshape mold. The aluminum mold was sealed and then was switched out with the Renshape mold so that a production-style run could be performed. The aluminum mold has water lines inside of it, so a circulator was used to send hot water into the mold to control the temperature of the sheets, so that there wouldn't be an increase in mold temperature as there was in the Renshape production run. All of the same measurements were performed during the aluminum production-style run, with the only additions being the circulator temperature and the inlet and outlet temperatures to and from the mold and circulator.

A Design of Experiment (DOE) was also performed for the project using the temperature-controlled aluminum mold. The main purpose of the DOE was to show if extreme high and low values were mixed and used in a cycle could produce quality parts like the production-style run. The three factors used in the DOE were cooling time, circulator temperature, and infrared (I.R.) eye temperature. The infrared eye is a laser that measures the temperature of the sheet in the oven. Figure 7 shows all the different set-ups ran for the DOE. The MAAC thermoforming machine allows for either a time or temperature-based oven time. The cycle that was used in this project was temperature-based. The high and low values for cooling time were 150 and 90 seconds, respectively. The high and low values for circulator temperature were 205 and 170 degrees Fahrenheit, respectively, and the high and low values for I.R. eye temperature were 330 and 400 degrees Fahrenheit, respectively.

Run	**Cooling Time**	**Circulator Temp**	**I.R. Eye Temp**
1	-	-	-
2	-	-	+
3	-	+	-
4	-	+	+
5	+	-	-
6	+	+	-
7	+	-	+
8	+	+	+

Figure 7 (DOE Table)

Results and Discussion

The first results that were obtained were from the production-style run of the Renshape (REN) mold. When the machine was first heated up, five parts were run to solidify the cycle so there wouldn't be a lot of variation during the production run. Since the five parts were ran, the mold already started to heat up. Appendix A shows the temperatures measured during the production style run. The graph shows that every measured mold temperature increased by at least 10 percent and up to 25 percent, and the forming temperature increased by 6 percent without any parameters being changed. The ejection temperature also increased by 12 percent in 7 runs until cooling time was increased to help make the parts easier to handle out of the mold.

The measurements that were taken on the REN mold parts right after forming and 72 hours after forming are shown in Figure 8. The most noticeable thing about the REN mold measurements was how much the part shrank in only three days. The length of the formed sheet shrank about one-half inch in three days and the width shrank about one-quarter inch in three days. The standard deviation of the length averages about 80 thousandths of an inch and the width's standard deviation averages 64 thousandths of an inch. The height shrank about one-sixteenth of an inch in three days.

The thickness of the sheet also shrank dramatically after three days. The front thickness shrank about 12 percent, the right shrank 23 percent, the back shrank 15 percent, the left shrank 27 percent, and the top shrank 6 percent. The standard deviation for the thicknesses averages around 8 thousandths of an inch right after forming, but only around 5 thousandths of an inch after 72 hours. This shows that the thicknesses vary a lot right off of the mold, but get to a more stable state after they shrink.

REN	**2 mins**	**72 hrs**	**2 mins**	**72 hrs**
Dimensions	**Average**	**Average**	**St. Dev.**	**St. Dev.**
Y1	15.2772	14.7679	0.0737	0.0817
Y2	15.2703	14.6292	0.0916	0.1319
Y3	15.2146	14.6189	0.1027	0.1786
X1	32.8077	32.5823	0.0680	0.0540
X2	32.7825	32.5545	0.0604	0.0547
Z	3.6531	3.5861	0.1874	0.0854
Thickness	**Average**	**Average**	**St. Dev.**	**St. Dev.**
Front	0.0728	0.0640	0.0066	0.0063
Right	0.0699	0.0541	0.0072	0.0036
Back	0.0693	0.0590	0.0086	0.0056
Left	0.0733	0.0536	0.0105	0.0034
Top	0.1280	0.1207	0.0068	0.0037

Figure 8 (REN mold measurements)

Aluminum	**Al 2 mins**	**Al 72 hrs**	**Al 2 mins**	**Al 72 hrs**
Dimensions	**Average**	**Average**	**St. Dev.**	**St. Dev.**
Y1	15.1864	15.0772	0.0532	0.0629
Y2	15.3429	15.2224	0.0556	0.0498
Y3	15.2405	15.1412	0.0387	0.0494
X1	32.7307	32.4864	0.0815	0.0799
X2	32.6969	32.5176	0.0234	0.0627
Z	3.5513	3.5266	0.0566	0.0451
Thickness	**Average**	**Average**	**St. Dev.**	**St. Dev.**
Front	0.0939	0.0903	0.0021	0.0047
Right	0.0838	0.0807	0.0064	0.0054
Back	0.0846	0.0918	0.0028	0.0055
Left	0.0810	0.0835	0.0021	0.0044
Top	0.1029	0.1083	0.0017	0.0055

Figure 9 (Aluminum mold measurements)

After all of the data was collected and measured for the urethane mold, the temperature-controlled aluminum mold was ready to be switched out. Appendix B shows the forming temperatures during the production-style run using the aluminum mold. This mold required a few more measurements: rail temperature, circulator temperature, and inlet and outlet temperature of the circulator.

The production-style run was started with a 100 second cooling time and a 370 degree Fahrenheit I.R. eye. Before sheet 4 was loaded, the cooling time was extended to 120 seconds, because the sheet was consistently coming out at around 200 degrees. It came down to about 190 degrees, and then before sheet 5 was loaded, the cooling was increased to 150 seconds and the I.R. eye was changed to 360 degrees Fahrenheit, because at 370 degrees the sheet was coming out in a consistent pattern of 343 and 330 degrees Fahrenheit. Before sheets 7, 8, and 9 were loaded, the cooling time was decreased to 130 seconds, 120 seconds, and 110 seconds respectively to see what kind of effect it would have on the ejection temperature. This can also be seen in Appendix B. As seen on Appendix B, the top of the mold barely changed at all during the production run, while the front and back of the mold increased slightly, with the back increasing the most, because it is closest to the oven (which reaches upwards of 700 degrees Fahrenheit). The rails, circulator, and inlet and outlet temperatures all stayed virtually the same throughout the production run.

Appendix C-1 shows the part lengths after 72 hours over the course of the production run. The REN mold parts have a downward sloping trend for the lengths. The temperature-controlled aluminum mold parts basically stayed the same overall, but have a slight upwards undulation in the middle of the run.

Appendix C-2 shows the part widths after 72 hours over the course of the production run. The REN mold part widths both have downward sloping trends, while the temperature-controlled aluminum mold part widths have one upward and one slightly downward sloping trend. This shows that even though the aluminum has differing trends, it is still closer to staying the same than the REN mold part widths.

The measurements of the formed sheets (shown in Figure 9) showed much better results than the REN mold. While the REN mold widths shrank an average of one-half inch in 3days, the aluminum mold widths only shrank about one-tenth of an inch. The REN mold and aluminum mold lengths both shrank about one-quarter inch. The REN mold height shrank about one-sixteenth of an inch and the aluminum mold shrank less than one-thirty second.

The aluminum thicknesses only changed at most 8.5 percent, and averaged about 3.5 percent, while the REN mold thicknesses changed up to 27 percent and averaged 16.5 percent.

OVERALL SHRINKAGE			
REN	72 hrs	***Aluminum***	72 hrs
Width	3.816%	Width	0.719%
Length	0.691%	Length	0.647%
Height	1.836%	Height	0.696%

Figure 10 (Overall Shrinkage)

Figure 10 shows the overall shrinkage percentages for the REN and aluminum mold. The REN mold widths shrank over 5 times more than the aluminum, the lengths shrank only one-half percent more, and the heights shrank over 3 times more than the aluminum.

Warpage was also a key factor in the REN mold parts after 72 hours (shown in Figure 11). These measurements come directly from the aluminum jig, and show the difference from the edge of the jig to the edge of the part. Each formed sheet that was brought off of the thermoformer and placed in the jig was pushed in the bottom right hand corner (in between measurement point 3 and 4 as seen in Figure 6. Points 1, 2, and 3 made up the front of the part. The REN mold seems to be better on the front as it only changed about 34 thousandths while the aluminum changed 100 thousandths from point 1 to 2, but that is the only instance of the REN being slightly better than the aluminum. Points 4 and 5 make up the right side of the part, and the warpage was about six thousandths for both the REN and aluminum mold.

Warpage	**REN 72hrs**	**Al 72hrs**	**REN 72hrs**	**Al 72hrs**
Measurement Pt.	**Average**	**Average**	**St. Dev.**	**St. Dev.**
1	0.2195	0.2134	0.0551	0.0687
2	0.2342	0.1188	0.0719	0.0131
3	0.2000	0.1339	0.0481	0.0192
4	0.2427	0.1639	0.0281	0.0686
5	0.2485	0.1583	0.0394	0.0278
6	1.0562	0.5999	0.1765	0.0538
7	1.0117	0.5339	0.1038	0.0514
8	0.8877	0.5845	0.0681	0.0609
9	0.6971	0.8242	0.0510	0.0454
10	0.6751	0.8498	0.0659	0.0605

Figure 11 (Warpage measurements)

The back is where the REN mold really warped. It varied about 75 thousandths where the aluminum mold only varied about 65 thousandths. The left sides of the parts both varied about 20 thousandths. The standard deviation for the REN mold show how much the warpage varied on any one part. The front varied an average of 60 thousandths on the REN mold and only about 40 thousandths on the aluminum. The right sides were about the same, with the aluminum having a slightly higher standard deviation. The back of the REN mold parts varied an average of 110 thousandths of an inch, while the aluminum only varied an average of 53 thousandths of an inch. The left sides of the REN mold parts varied an average of 58 thousandths, while the aluminum only varied an average of 52 thousandths. All these averages show that the REN mold was much more unpredictable when it was measured in the jig, because every part shrank and warped differently, while the aluminum mold was much more consistent.

The grid that was placed on the bottom of the sheets was to show stretching in the machine and transverse direction. The grid on the Renshape mold expanded an average of 10 thousandths of an inch on the top of the mold in the machine direction and shrank an average of 20 thousandths in the transverse direction. On the drawn part of the sheet, the material expanded an average of 1.500 inches over the original inch in the machine direction and shrank an average of 25 thousandths in the transverse direction. The aluminum mold expanded an average of 100 thousandths in the machine direction and 120 thousandths in the transverse direction on the top of the part. On the drawn section of the part, the material expanded an additional inch in the machine direction and shrank an average of 20 thousandths in the transverse direction. All grid measurements were taken after 72 hours. These measurements show that the temperature-controlled aluminum mold parts held their dimensions a lot more than the Renshape mold parts, as the Renshape mold parts stretched and then shrank back down below the original grid measurements after 72 hours.

The Design of Experiment results showed that only a couple parts off of the aluminum temperature-controlled mold would be deemed quality. Run 1 with all the low settings, Run 3 with just a high circulator temperature, Run 5 especially with just a high cooling time, and Run 6 with high cooling time and circulator temperature, all produced a part that was too cold when it was ejected. The top of the part stuck to the top of the mold, and permanently deformed the part by stretching it (shown in Figure 1). Run 2 with just a high I.R. eye temperature and Run 7 with a high I.R. eye and high cooling time, produced full parts that ended up with a lot of warpage. Run 4 with a high circulator temperature and high I.R. eye temperature produced a full part that only exhibited a small amount of warpage, and Run 8, which had all high settings, produced the best part of the DOE. This shows that the cycle that was set up for the production run is the best for this material.

Tensile tests were run on a number of the parts, with samples being cut out of the front, back, left, and right portions of the formed sheet. The results are shown in Appendix D. Unfortunately, the data that was collected from the temperature-controlled aluminum tool parts was too random to determine whether one mold produced tougher parts than the other. Overall, the results look similar. The yield and maximum stresses, yield and maximum elongation percentages, and maximum energy were all similar. The modulus measurements from the parts of the temperature-controlled aluminum mold were very random and ranged from 3410 to 1.2 million, so it was deemed irrelevant for the comparison.

Conclusion

Overall, the temperature-controlled aluminum mold showed a much more consistent process than the Renshape mold did. It shrank less, warped less, and had a much higher dimensional stability. With that, this project proves that there is a huge importance in temperature-controlled aluminum tooling in the thermoforming industry. This also shows that HDPE can be a relevant material in the thermoforming industry, instead of just amorphous polymers. In conclusion, if a company wants to run a crystalline material that has a high shrinkage rate, then they need to use a temperature-controlled aluminum tool if they want to continuously make quality parts.

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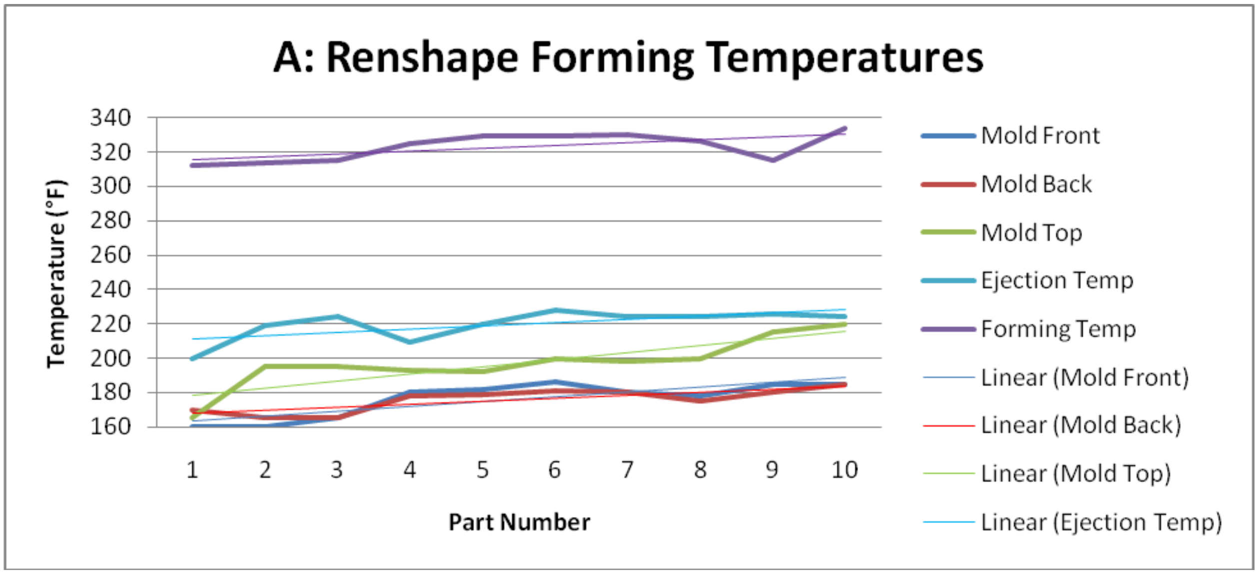
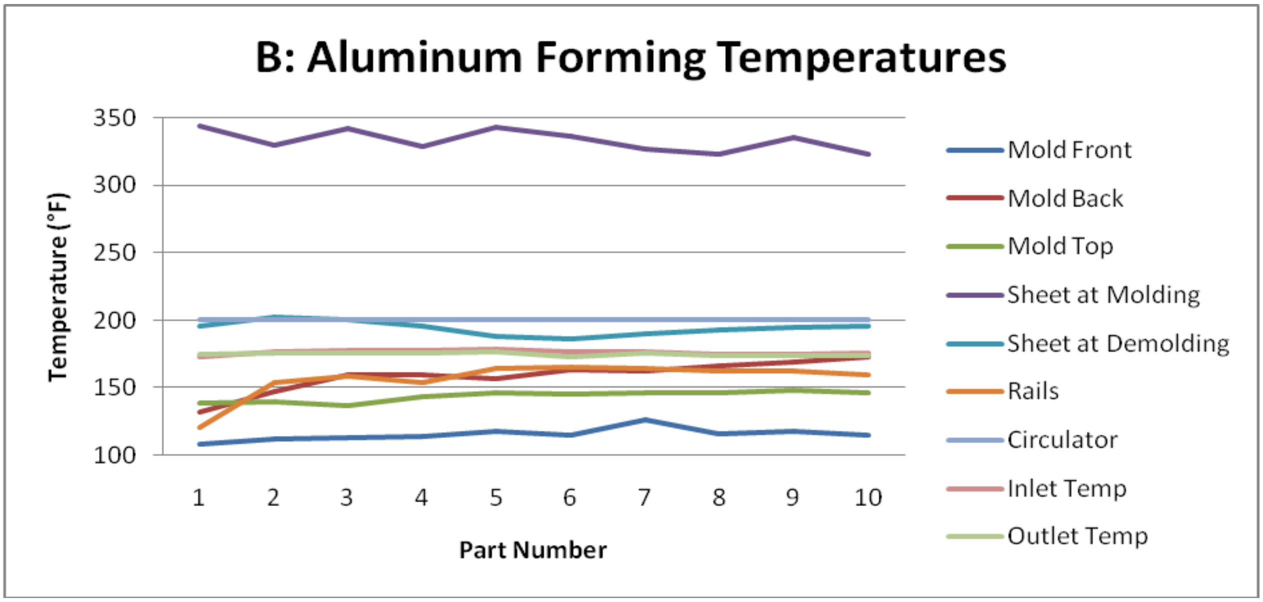
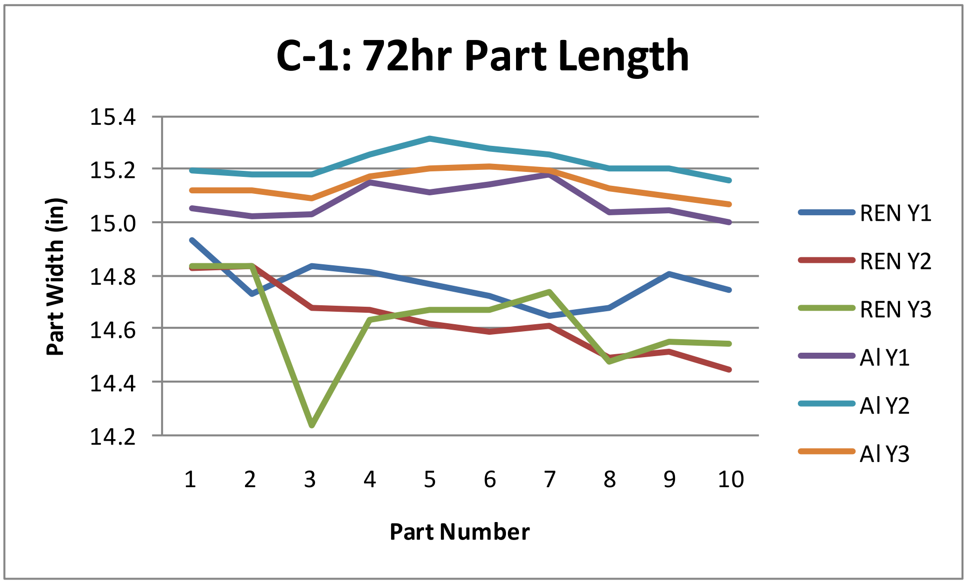
Appendices

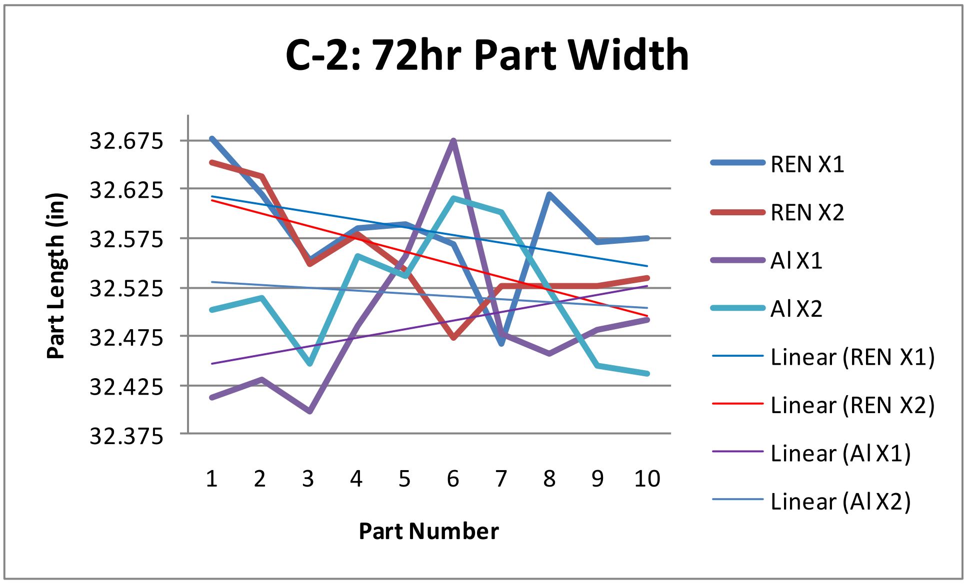


A: Renshape Forming Temperatures
Temperature (°F)
340
320
300
280
260
240
220
200
180
160
1
2
3
4
5
6
7
8
9
10
Part Number
Mold Front
Mold Back
Mold Top
Ejection Temp
Forming Temp
Linear (Mold Front)
Linear (Mold Back)
Linear (Mold Top)
Linear (Ejection Temp)



B: Aluminum Forming Temperatures
Temperature (°F)
350
300
250
200
150
100
1
2
3
4
5
6
7
8
9
10
Part Number
Mold Front
Mold Back
Mold Top
Sheet at Molding
Sheet at Demolding
Rails
Circulator
Inlet Temp
Outlet Temp





D: TENSILE TESTING

Type	Yield Stress (psi)	Max Stress (psi)	Yield Elongation (%)	Break Stress (psi)	Modulus (psi)	Max Energy (in*lb/in^3)	Max Elongation (%)	TE Auto (%)
REN front	2830.00	2830.00	14.23	1157.23	53133.33	275.33	13.79	664.00
Al front	2610.00	2610.00	13.74	760.50	514600.00	276.50	13.47	270.60
REN back	2860.00	2860.00	13.72	1142.50	65250.00	278.75	12.88	486.25
Al back	3086.67	3086.67	14.78	806.20	456900.00	351.67	14.40	249.33
REN left	2835.00	2835.00	12.82	2169.67	42125.00	310.25	15.69	853.00
Al left	1809.67	1813.33	17.89	899.33	19570.00	198.00	16.83	1040.67
REN right	2765.00	2765.00	16.06	2109.25	31950.00	283.00	15.53	1032.50
Al right	2776.67	2783.33	17.43	2032.33	131100.00	313.67	16.73	1039.00