Test Report

Title: Markforged – Onyx^{TM} material temperature test
Date: 19th November 2021
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Test Conductor: Kenneth Jackson
Revision: A

Introduction

This report summarizes results of the testing conducted on the Markforged Onyx^{TM} material. The purpose of the test was to determine the suitability and expected life expectancy of a thermoforming tool printed using Onyx^{TM} material.

(Note! The life expected of the tool is in terms of forming cycles under typical thermoforming conditions.)

Equipment and tool design

- Forming machine
  - Standard desktop Formech 450DT machine (*see machine spec sheet in Appendix A*)
- Vacuum forming tool
  - Designed in line with good vacuum forming design principles, and manufactured on a Markforged Mark Two^{TM} printer using standard Onyx^{TM} material (*see general tool design in Appendix B*)
- Temperature measuring equipment
  - Perfect Prime Thermocouple 4 channel meter
  - 4 x Thermocouples, type K
  - Fluke VT04A Visual IR Thermometer
- Raw material
  - HIPS, 1mm thick, sheet size 17" x 12"

Test Set up (*see pictures below*)

- The Onyx^{TM} tool was mounted to an MDF baseboard, and each thermocouple inserted from the underside
  - The thermocouples were strategically placed around the tool so the median tool temperature could be recorded.
  - Each thermocouple was adjusted so that just the measuring tip was protruding from the upper face of the tool. (This was so the tool temperature was captured at the forming face.)
  - Note! The Fluke Visual IR Thermometer was used to support the temperatures reported by the thermo couples since none of the devices used were calibrated.

- The MDF baseboard was secured to the 450DT table using M6 fasteners, and the leads of the thermocouples threaded out of the side of the baseboard and over the edge of the table seal to the front panel of the machine. The leads were then thread out of the panel lower edge and connected to the 4-channel meter.
  - This set up allowed forms to be made throughout the test period without disturbing the equipment.

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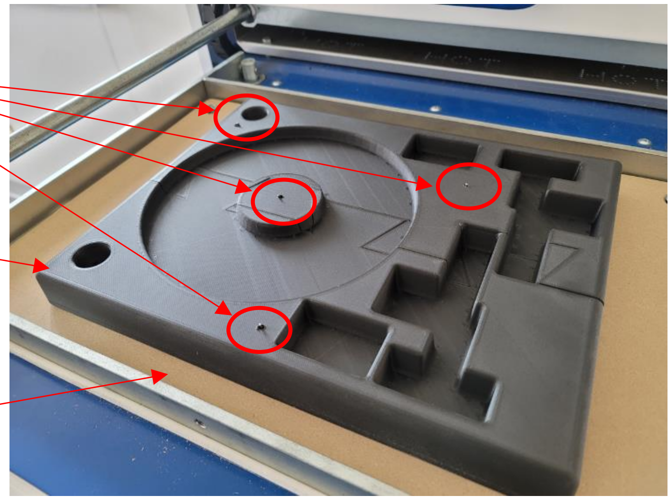
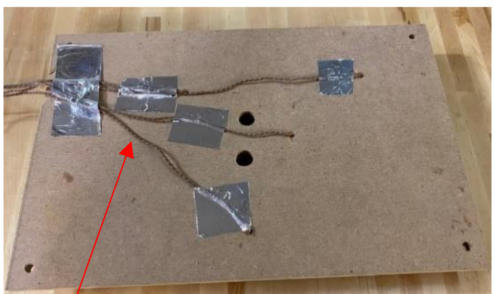
Thermocouples

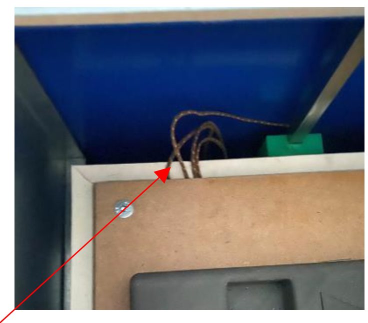
Onyx™ Tool (two part with dovetail interlock)

MDF Baseboard





Thermocouple leads inserted into the tool from the underside of the MDF baseboard



Thermocouple leads

Note! A small piece of silicone foam seal was placed over the thermocouple leads (not shown) to ensure an airtight seal was present when vacuum forming samples

Thermocouple leads shown exiting from the front panel bottom edge of the machine and connected to the 4-channel meter.

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Procedure

- After the equipment was set up and the machine powered on, initial sample were formed until acceptable forming's were being generated. Once this was achieved the cycle time and tool temperature were recorded, (and used later as a base line measurement for accelerated life testing).

- Accelerated life testing
  - To reduce the testing time, and also material, accelerated life testing was used to simulate vacuum forming cycles.
  - Accelerated life testing was achieved by adjusting the output heat of the heating elements until a set steady state tool temperature was achieved (typically 77.5°C and above). Once the tool temperature was set it was allowed to run at this temperature for a known period (typically 49 mins)
  - Vacuum formed samples were produced at the end of each 'test run' to visibly check the quality of the formed part to confirm that they were still acceptable, and to also inspect the tool for any obvious damage / changes.
  - The set steady state tool temperature mentioned above was used as a multiplier to calculate the simulated total cycles, (and subsequently the accumulated cycles).

Test Results

1) Initial Testing to determine cycle time and tool temperature (*see test results in Appendix C*)

   The following was determined from the initial
   - Tool Temperature = 77.5C
   - Heating Time = 55 seconds

   For the accelerated life testing calculation, the heating time was rounded up to the nearest minute, so the figures below were used for the accelerated life test calculation
   - Optimized Tool Temperature (OTT) = 77.5C
   - Heating Time = 1 minute*

   *Using 1 minute meant that for every minute of accelerated life testing = 1 forming cycle.

   Note! The Total cycle time noted in the tests results is for information only.

2) Accelerated life testing (*see test results in Appendix D*)

   For accelerated life testing the simulated forming cycles were calculated as follows.

   - [Tool Temperature (TT)[1] / Optimized Tool Temperature (OTT)[2]] x Run Time (RT)
   - A Test Form Cycle (TFC) was the sample vacuum formed at the end of each title and added to the Total Cycles (TC)

[1]*Actual tool temperature during the test run*
[2]*As determined from the initial testing i.e., 77.5*

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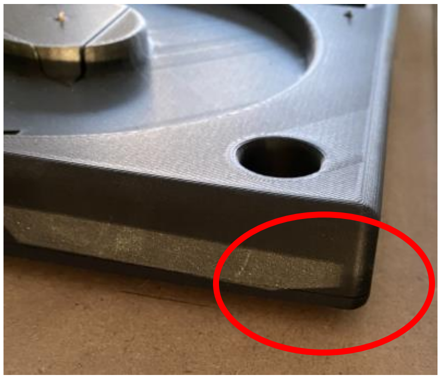
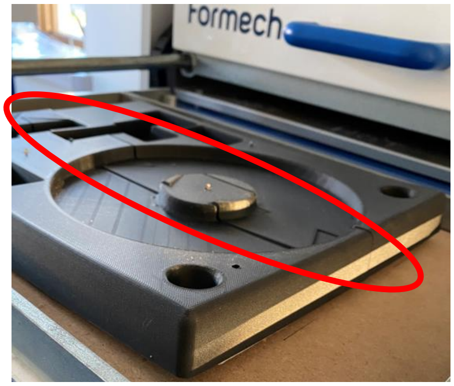
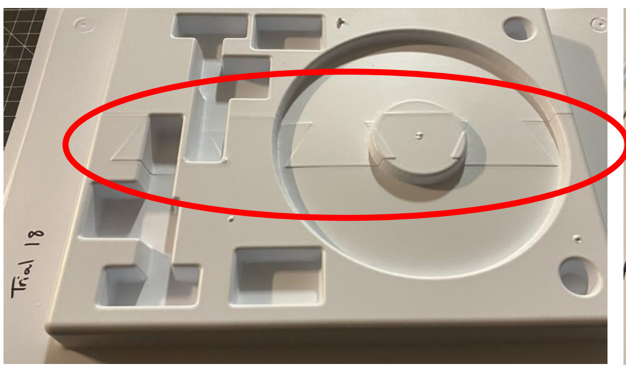
Observations

On Test Run 18, at approximately 1000 cycles, the warping on the Onyx™ tool was becoming more pronounced especially in the corners, where it was visibly starting to lift off the baseboard.

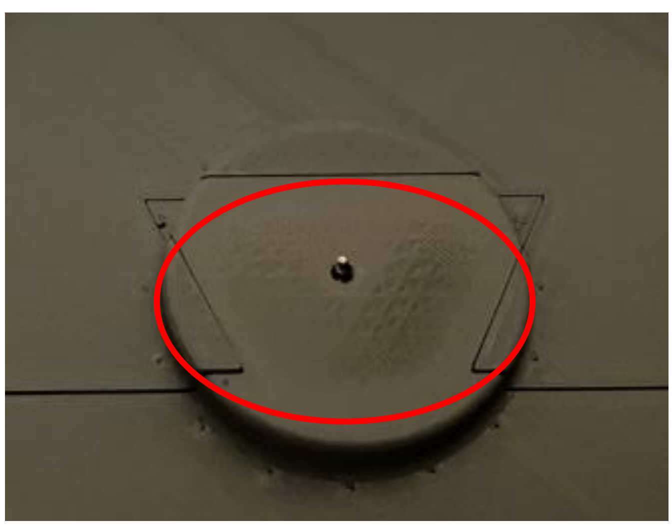




Also, on Test Run 18 the split line on the tool was beginning to distort, and separate. As a consequence, it was starting to become slightly more visibly on the vacuum formed sample, especially when compared to an early sample.



The accelerated life testing was stopped at Test Run 27 / 28, when the tool temperature was around 160C, and was visibly taking on a glossy appearance and obviously starting to melt.



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Test summary

The total accumulated cycles reached was 1318. However, defects started to be present on both the tool, and formed sample, at around 1000 cycles.

For amorphous materials, which are typically used in vacuum forming, and for a basic tool designed in accordance with good vacuum forming practices I think an Onyx^{TM} 3D printed tool would comfortably last for at least 500 cycles.

This is more than adequate for proof-of-concept work, or for even an exceptionally low sample run.

Important note!
The accumulated cycles were determined using accelerated life testing and measuring temperatures using uncalibrated equipment (although different devices were used for corroboration purposes). It is possible that in actual service the life expectancy is shorter.
However, it is believed a conservative approach was taken, since the tool was not allowed to cool down between cycles, and therefore allow potential recovery time. Using higher temperatures as a simple stress accelerator was also conservative.

Comments

- Tool geometry; undercuts and thin sections
  Tool geometry, in any material, has an impact on life expectancy. However, for a 3D printed tool the material strength is minimal, so any undercuts, or very thin sections would likely easily fail, possibly reduce the expected cycles to single digits.

- Material; hard to form, high temperature etc.,
  The material used for testing was high impact polystyrene (HIPS), which is a common amorphous material with a low melting point, and large reducing windows. Using other materials such as those with high melting points, or those that hold heat for an extended period of time, will likely reduce the expected cycles to maybe 10's.

- Material; thickness
  The material shrinks during the cooling process, and subsequently applies pressure on the tool. The excess stress applied to the tool during the mold ejection phase causes the tool to wear. Using thicker material, will increase the tool wear, and likely reduce the expected cycles to maybe a 100.

APPENDIX A

Formech 450DT specification

Formech 450DT

Desktop Vacuum Forming Machine

Our desktop models are the perfect first approach to vacuum forming. Easy to use, intuitive but yet very professional, they are the go-to models for creatives, hobbyists, students and chocolatiers.

Quiet and built-in vacuum system, energy efficient quartz heaters, safety interlock and Mono HMI operating interface for the bigger desktop models will help you achieve consistent formings.

Key Features

- Safety Interlock
- Vacuum & Release
- Vacuum Gauge
- PLC Control with 4" Mono Touch Screen
- 20 Programme Memory
- Independently Controllable Heating Zones

Options

- Reducing Windows
- Dedicated Trolley
- Reel Feed
- Starter Pack of Plastic
- Spare Parts Kit

Technical Specifications

Forming Area (mm / inches)	Sheet Size (mm / inches)	Max Depth of Draw	Max Material Thickness	Heater Type	Heating Zones	Width	Height	Depth	Weight
430 x 280mm / 17 x 11"	450 x 300mm / 18 x 12"	160mm / 6.3"	*6mm / 0.25"	Quartz	4	639mm / 25.2"	525mm / 20.7"	986mm / 38.8"	75kg / 165lbs

Single Phase Power Requirements	Other Voltage (USA)	Power Consumption	Vacuum Pump Type	Pump Flow (SCFM @ 0 in. / 60Hz) (Pump flow m3 /h @ 0mbar / 50Hz)"	Mould release method	Air Requirements
208-240V / 13A	110-120V / 15A	2.4kW (1.6kW USA)	Diaphragm	3.0 (4.9)	Pump exhaust	n/a

*certain materials over 4mm thick may require turning the sheet mid-cycle

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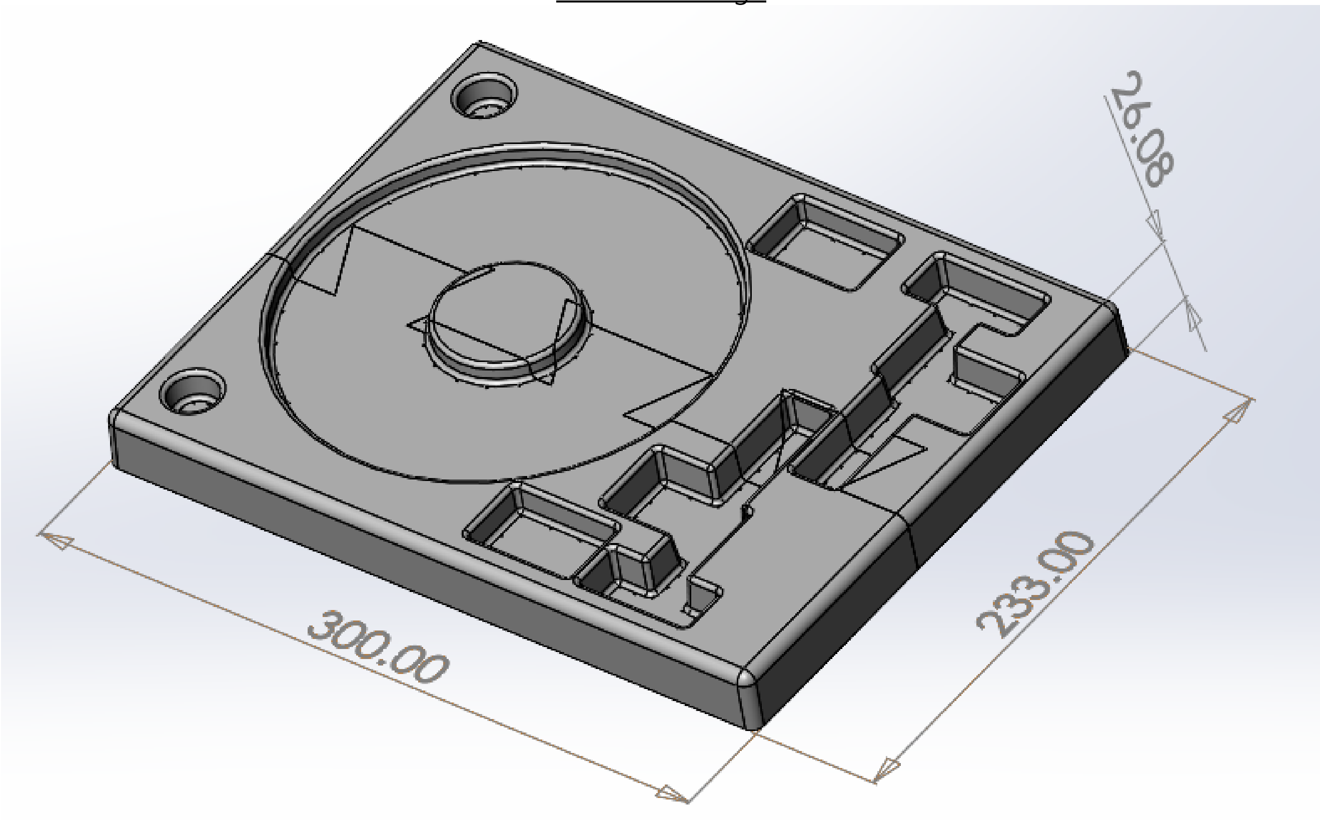
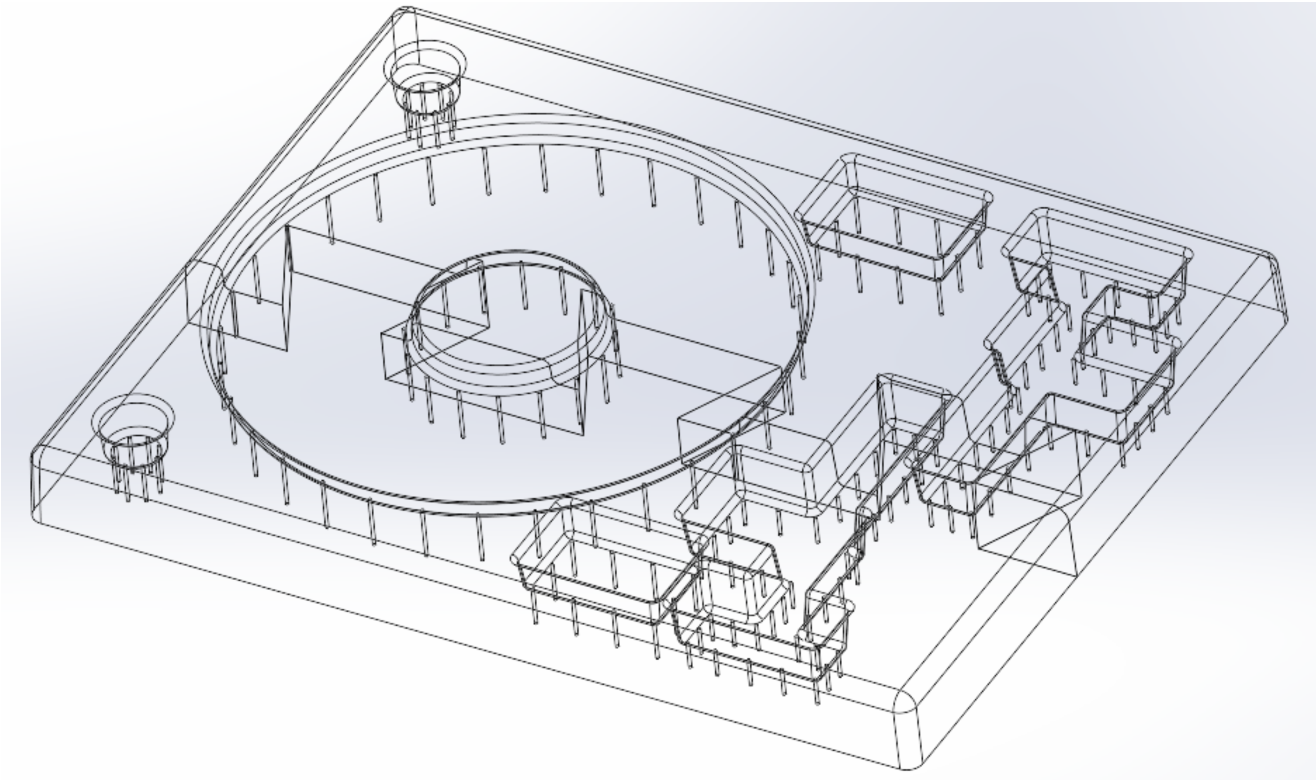
APPENDIX B

Test Tool Design





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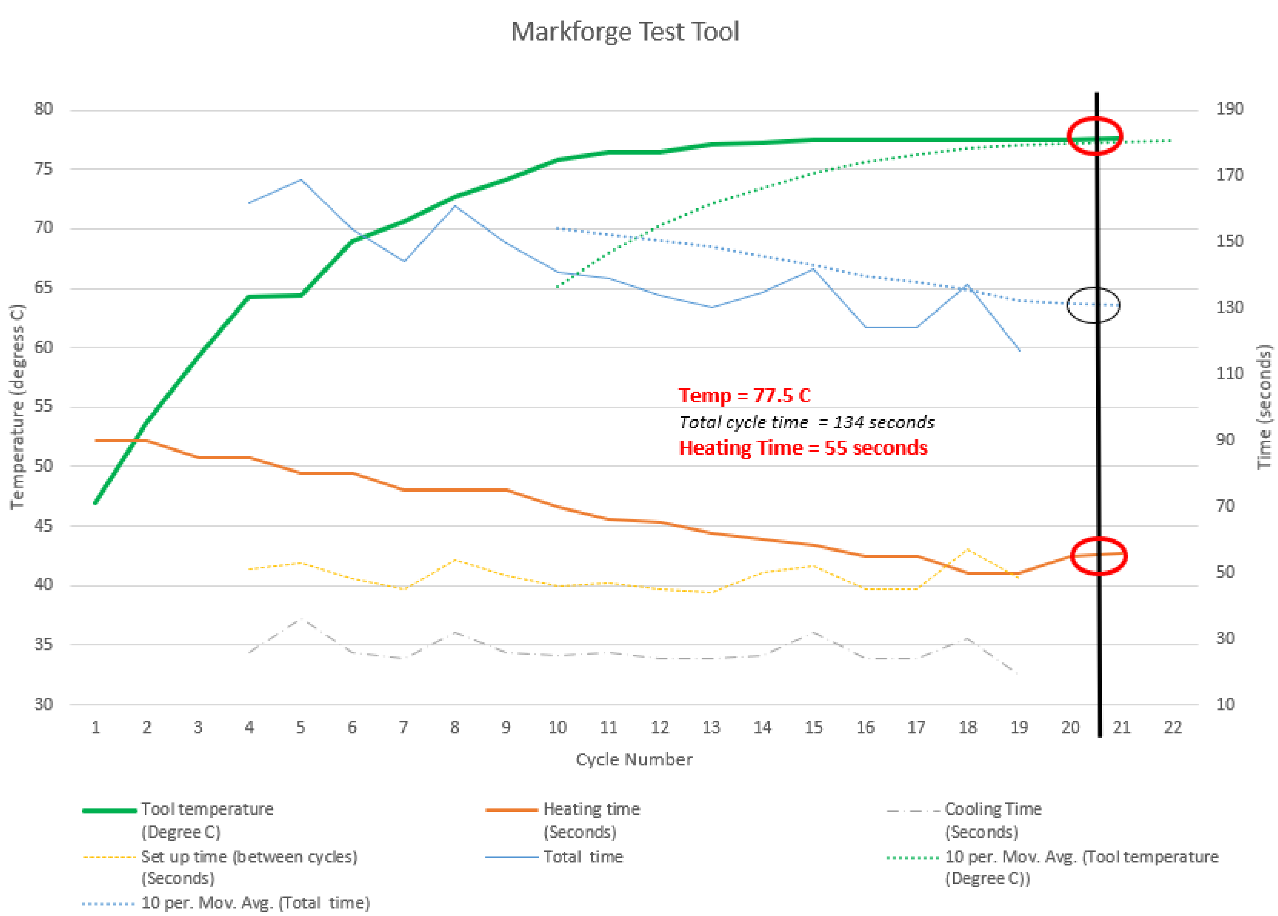
APPENDIX C

Initial Test Results

Heating time (Seconds)	Tool temperature (Degree C)	Cooling Time (Seconds)	Set up time (between cycles) (Seconds)	Total time
90	46.9			
90	53.8			
85	59.2			
85	64.3	26	51	162
80	64.4	36	53	169
80	68.9	26	48	154
75	70.7	24	45	144
75	72.7	32	54	161
75	74.2	26	49	150
70	75.8	25	46	141
66	76.5	26	47	139
65	76.5	24	45	134
62	77.1	24	44	130
60	77.2	25	50	135
58	77.5	32	52	142
55	77.5	24	45	124
55	77.5	24	45	124
50	77.5	30	57	137
50	77.5	19	48	117
55	77.5			
56	77.6	29	49	134



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APPENDIX D

Accelerated Life Testing Results

Test Run #	Run Time RT (mins)	Optimized Tool Temp OTT (Determined by Experiment) (Deg C)	Tool Temp TT (Deg C)	Equivalent forming cycles EFC [=(TT/OTT) * RT]	Test form cycles TFC	Total cycles TC [=EFC +TFC]	Accumulated Cycles
1	49.0	77.5	77.5	49	1	50	50
2	49.0	77.5	91.0	58	1	59	109
3	49.0	77.5	91.0	58	1	59	167
4	49.0	77.5	77.5	49	1	50	217
5	49.0	77.5	77.5	49	1	50	267
6	49.0	77.5	91.0	58	1	59	326
7	49.0	77.5	91.0	58	1	59	384
8	49.0	77.5	95.0	60	1	61	445
9	49.0	77.5	91.0	58	1	59	504
10	49.0	77.5	77.5	49	1	50	554
11	49.0	77.5	77.5	49	1	50	604
12	49.0	77.5	77.5	49	1	50	654
13	49.0	77.5	120.0	76	1	77	731
14	49.0	77.5	120.0	76	1	77	807
15	49.0	77.5	77.5	49	1	50	857
16	49.0	77.5	120.0	76	1	77	934
17	49.0	77.5	120.0	76	1	77	1011
18	49.0	77.5	77.5	49	1	50	1061
19	49.0	77.5	120.0	76	1	77	1138
20	49.0	77.5	120.0	76	1	77	1215
21	10.0	77.5	125.0	16	1	17	1232
22	10.0	77.5	130.0	17	1	18	1250
23	10.0	77.5	135.0	17	1	18	1268
24	5.0	77.5	140.0	9	1	10	1278
25	5.0	77.5	150.0	10	1	11	1289
26	5.0	77.5	150.0	10	1	11	1300
27	5.0	77.5	160.0	10	1	11	1311
28	3.0	77.5	160.0	6	1	7	1318