DEVELOPMENT OF SCALABLE DYNAMIC CONTROL ARCHITECTURES FOR FLEXIBLE COMPOSITES MANUFACTURING WORK CELLS

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ABSTRACT

A work center that has the ability to simultaneously micro-manage laminate temperature and pressure and the timing of each, as well as process or material specific inputs, necessitates digital control capability. Allowing material matrix choices in both thermoset and thermoset families increases the range of required thermal flexibility. A work center was physically produced to demonstrate efficient processing of thermoset, resin infusion, thermoplastic materials on a single asset with rapid process changeover.

The Production to Functional Specification (PtFS) equipment by Surface Generation is based on a high-frequency, synchronized process controller which integrates the timing of thermal changes (both heating and cooling), consolidation pressure changes, pixelated thermal control over the entire part area, process specific triggers (i.e. vacuum and consolidation gas pressure management), and positional control. All inputs and outputs are recorded and a consolidated data output is made available to the process engineer/user, creating a unique data record that can be subsequently characterized for both real-time and historic trends. The demonstrator's operational design and development will be discussed including lessons learned on topics such as process variable selection, rapid tool change out with pixelated thermal control, required process specific input controls, digital workspace management, thermal uniformity, and consolidation control.

1. INTRODUCTION

As a part of the RApid High Performance Molding (RAPM) for Small Parts program [1], heating equipment (CF-OaO-RAPM-001) called Performance to Functional Specification (PtFS) was evaluated for use with multiple configurations such as resin infusion (RI), thermoset composite (TS) cure, and thermoplastic composite (TP) consolidation. This system was selected for its zoned thermal control, rapid heating and cooling rates, smooth continuous cooling without coolant phase transitions and modular tooling design. The PtFS equipment used in this program has been integrated into a 150 tonne tool clamping fixture (CF-OaO-RAPM-001) with position and pressure control as well as a heating system that allows independent zoned heating across the tool face [2] shown in Figure 1.

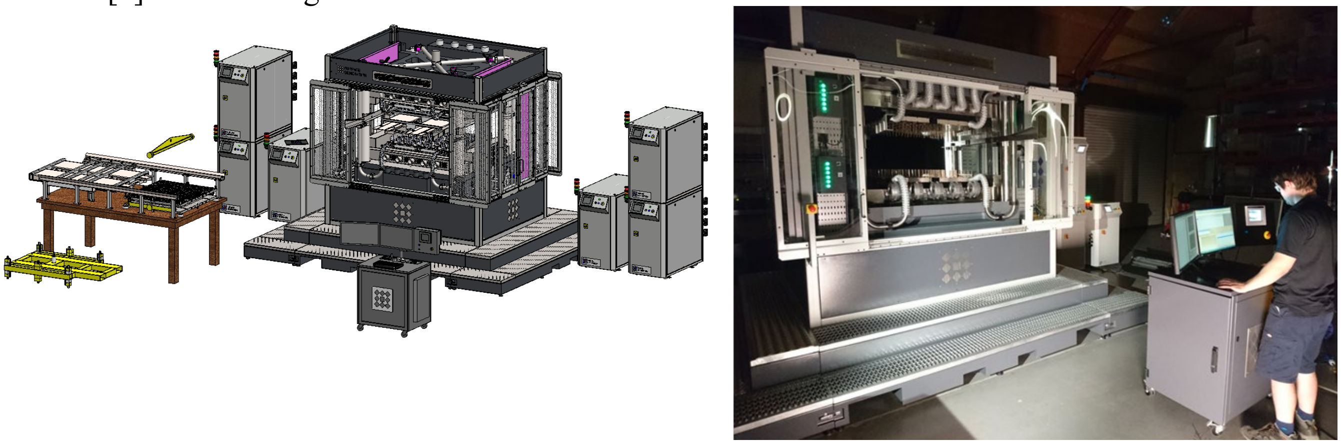

Figure 1 RAPM PtFS Manufacturing Cell Design and as Built

The PtFS Equipment

The PtFS equipment uses heated compressed air directed at the underside of a tool face. The heated air deflects off of an air diffuser before reaching the back side of the tool face. The tool faces are divided up into 180 individually controllable heating channels (90 per half). Each channel has two feedback thermocouples, a two stage compressed air source and a heater. The heater channels are arrayed across the top and bottom of the matched metal tools with channels spaced apart in a 10.0 cm (3.9 inch) grid. Figure 2 shows a cross section of an individual heater channel and the backside of the tool face.

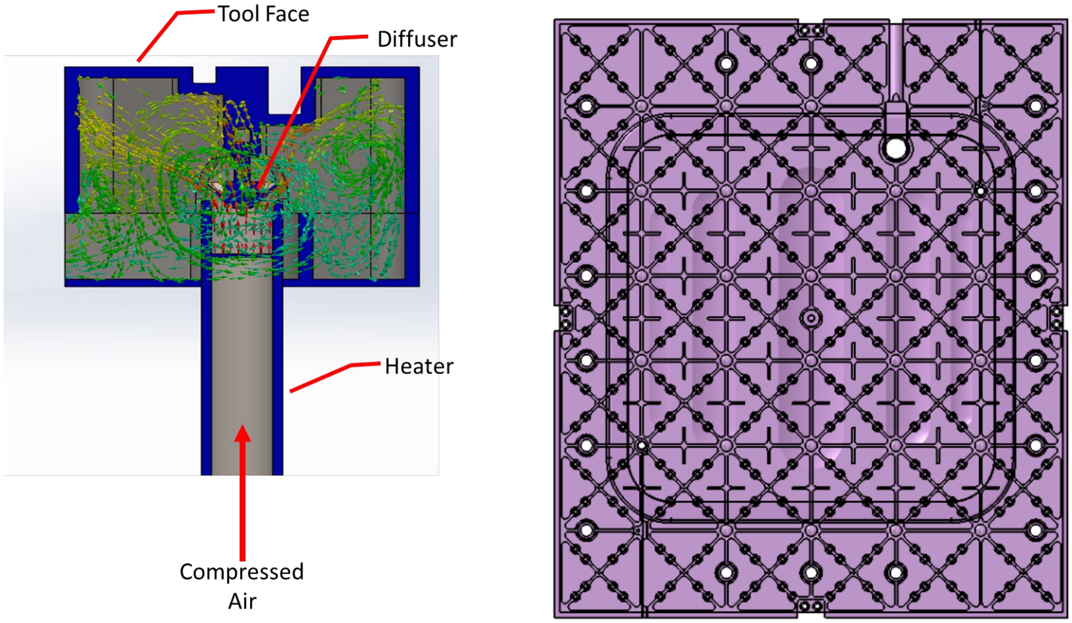

Figure 2 Individual Heater Channel (left) Transparent TS-RAPM-001-201 Tool to Show Cells (right)

Audience

This paper is written for individuals knowledgeable of composite processing and processing equipment. The intention is to provide individuals with knowledge of the architecture of the Surface Generation PtFS system used in the RAPM program as well as strengths, weaknesses and usage of the equipment during resin infusion, stamp forming, and bladder consolidation of composite materials.

Overview of Content

This paper introduces the PtFS system used in the RAPM program and its key features. This includes control systems, system use and tooling. The RAPM program uses the PtFS cell to fabricate isothermally processed thermoset parts, resin infused parts, and bladder formed thermoplastic parts. This starts with thermal profiling the tooling for temperature uniformity and transitions into part manufacturing using the system. Finally, potential usage scenarios are presented where the PtFS system would be beneficial.

Equipment Temperature Control

Each of the heater channels are grouped into a zone control scheme. Any amount of heater channels can be placed into each of these zones. Each zone has a heating profile associated with it and tolerances can be set within and between zones as required. This allows all of the heaters in each zone to heat, cool, or maintain temperature following the heater profile associated with the zone by dynamically varying heater power levels and compressed air flow rates [3]. The PtFS equipment control software has specific analogue and digital heating strategies that can be tailored to different heating scenarios. The strategy used in the RAPM program is analogue control which requires auto-tuning of the system near targeted usages temperatures to determine heater power levels. Power levels for each heater are set to prevent over or undershooting during heating/cooling ramps and to maintain temperature set points. [2] The auto-tune automatically determines constant values for a modified Proportional Integral Derivative control method for every heater channel at each specified temperature. Once the auto-tune is complete, heating profiles can be written for each zone. Figure 3 displays the hierarchy of control where each channel is placed into a zone, and each zone has its own heating profile.

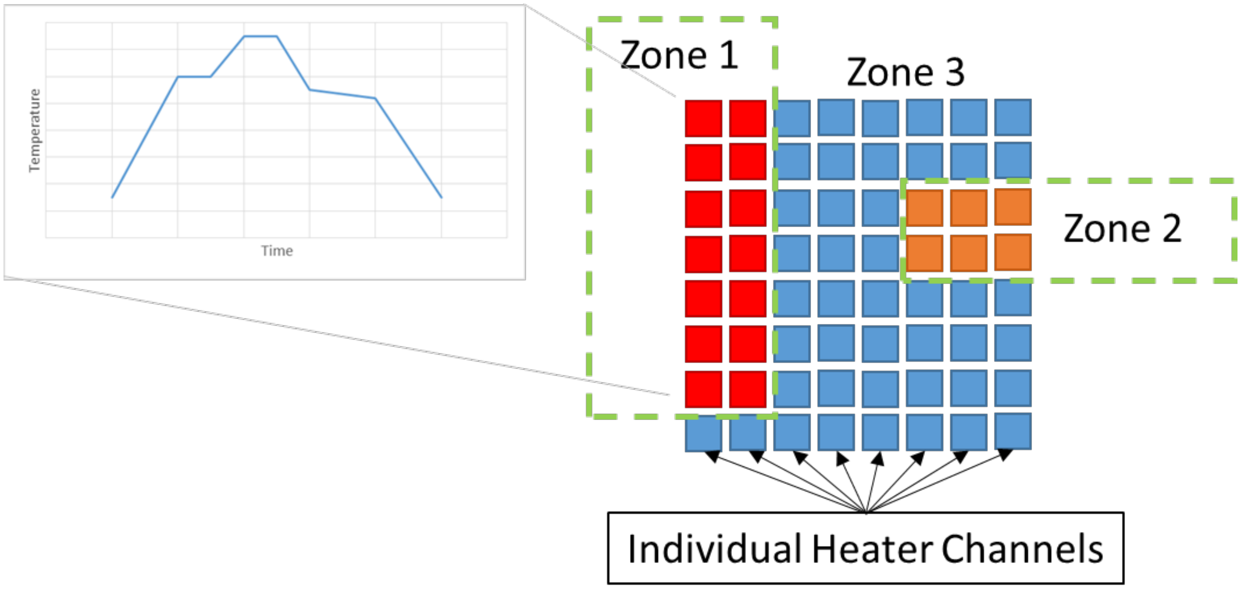

Figure 3 Zone Selection of Heater Channels

The PtFS system is modular in design and can be completely stand alone or use portions of existing infrastructure. The equipment can be designed to operate with a hydraulically actuated tool clamping fixture or an existing hydraulic press. The RAPM cell uses a 150 tonne clamping fixture designed by Surface Generation to only have 0.3mm (0.012 inches) of platen deflection at maximum pressure. The heater base with its standalone control cabinet provides the tool heating and accept various tool faces. All of the active heating and cooling is located in the heater base, meaning the interchangeable tool faces are entirely passive. The various pieces are shown in Figure 4.

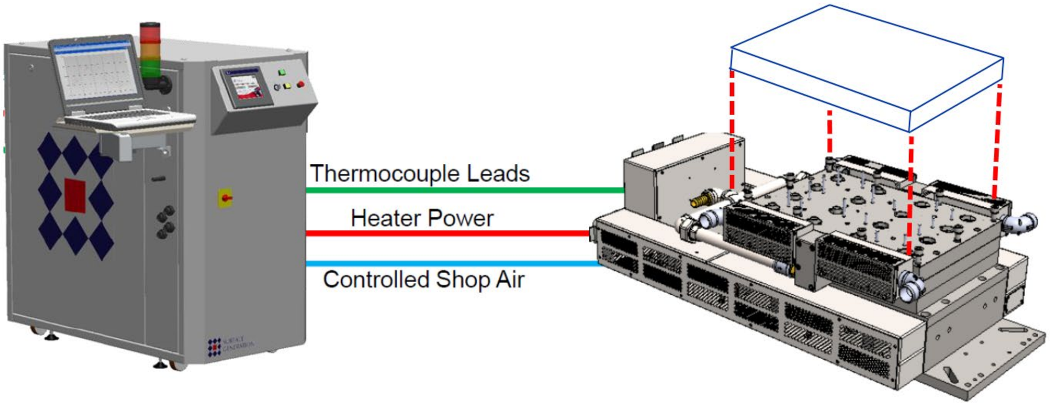

Figure 4 Heater Base with Control Cabinet

Heater Base

The heater base contains all of the heating components and operates in response to outputs from the control cabinets. The heater base is bolted to the top and bottom platen of the clamping fixture. The installed heater base is shown Figure 5 and contains all of the heaters, feedback thermocouples and the compressed air lines. These bases can hold multiple part configurations limited only by the heater base X/Y footprint. The feedback thermocouples are spring loaded to ensure intimate contact with the back side of the tool face with tool face depth limited by the spring length of travel. In the RAPM program, the main thermocouple configuration is 6.0 cm (2.3 inches) meaning parts that require more depth require extensions or heater base modification. In order to accommodate high aspect ratio geometries, longer spring loaded thermocouples will be added to the heater base by removing the heater base from the clamp fixture, disassembling parts of the heater base and replacing the thermocouples.

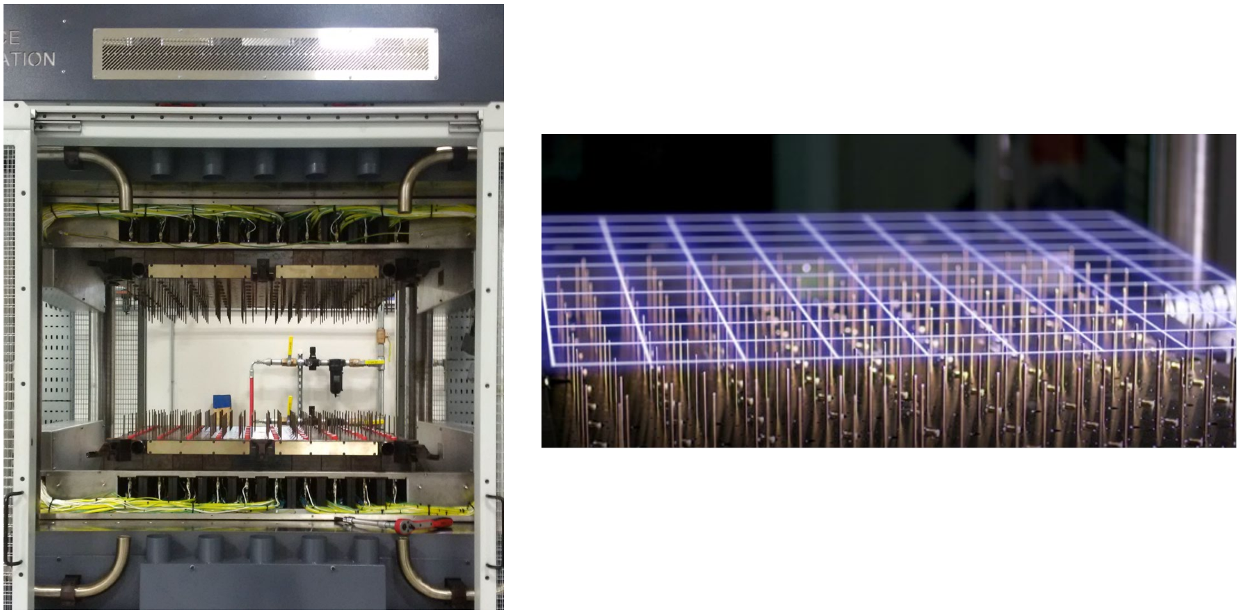

Figure 5 Installed Heater Base in the Clamping Fixture (Left) and Heater Base with Channel Grid (Right)

Tool faces of acceptable geometries can be changed out with other tool faces designed for the same heater base. The tool will need the same heater channel dimensions, approximate thermocouple placement and a depth that will fall within the spring-loaded thermocouple travel. To change a tool face on a compatible heater base, the tool faces are loaded onto the heater base using a rail and loading system which aligns all 360 spring loaded feedback thermocouples into sleeves on the back side of the tool face. Pins align the tool face and allow tool loading to be done without precise forklift control. The tool change processes can be completed in 2-4 hours with two operators including disassembling and reassembling the tool face into its picture frame.

Tool Face

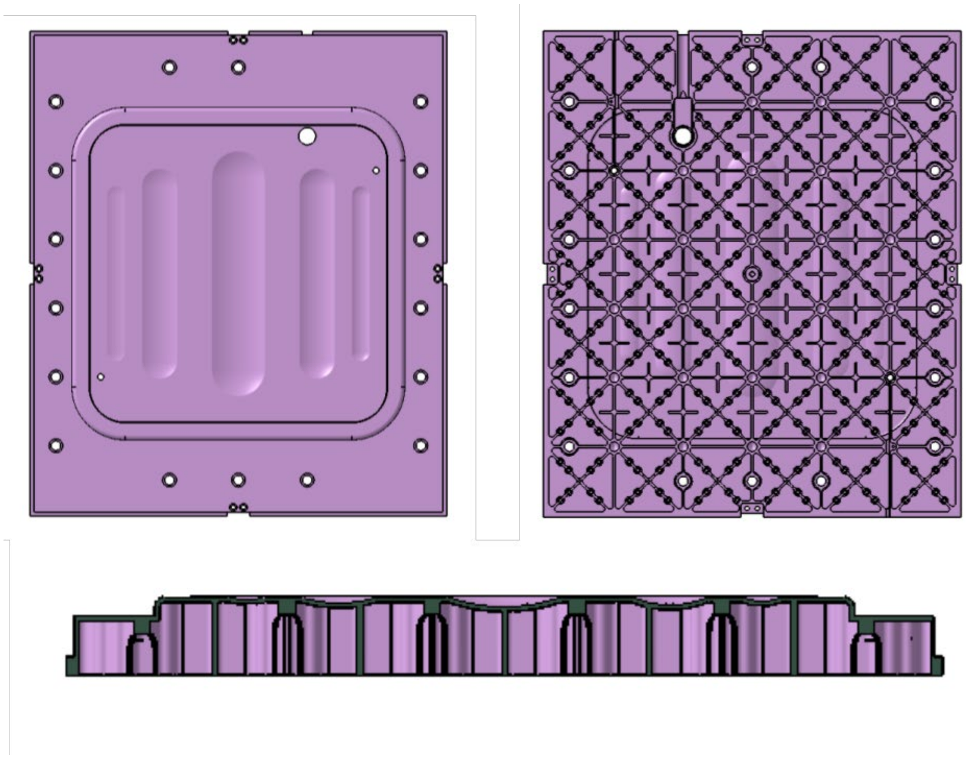

Figure 6 Tool Face Top (Top Left) Tool Face Bottom (Top Right) Tool Face Section Cut (Bottom)

Tool faces are machined from a solid block of P20 / DIN 1.2312 tool steel. The TS-RAPM-001-201 lower tool is shown in Figure 6. Looking from the top of the tool face, the tool looks like a standard stamp forming tool. Turning the tool face upside down, the tools look very different because any material not needed for structural support was machined away. This leaves a tool faces near 3 mm (0.120 inches) thick. In addition to the structural elements, each heater has its own pocket. This allows individual cells to be controlled without significantly effecting the cells around it. This geometric feature is what allows regions 10.0cm (3.9 inches) apart from each other to have differences in temperature of 28°C (50°F) or more.

The tool faces in the RAPM program have been performance optimized using linear and non-linear finite element analysis (FEA) as well as steady-state and transient computational fluid dynamics (CFD) thermal analysis. This iterative loop is used to tailor part geometries to help maintain a desired tool face temperature while maintaining the required factors of safety for tool face support.

2. EXPERIMENTATION

The PtFS equipment has been used in the fabrication of thermoset (TS) prepreg parts, thermoset resin infusion (RI) parts, and thermoplastic (TP) prepreg parts. Additional information on part processing completed in the RAPM program are availiable for RI [4], TS[5], and TP[6] processing. TEquipment use requires each tool and processing temperature complete a thermal profile. Following the completion of the thermal profile runs, each of the TS, RI, and TP composite processes were performed. The equipment was evaluated on its thermal uniformity, ability to maintain positional and pressure control.

3. RESULTS

Thermal Profiles

The PtFS system uses two thermocouples located on the underside of each pixel of the tool to control the temperature of the tool face. These thermocouples are in direct contact with the back side of the tool using spring loaded thermocouples that slide into a hole feature machined into the back of the tool. While the back side of the tool and the front side of the tool are similar in temperature, there is a difference between the temperatures on the front and back side of the tool and across the heater channel surface. A thermal profile is completed to verify that the composite part is exposed to temperatures within ±5.5°C (±10°F) of the desired set point.

The individual cells in the PtFS system have been heated to 440°C (824°F) during thermal profiling at 405°C (761°F) which is the upper end of our current desired temperature usage range. The lower temperature bound is ambient temperature. This is a result of using a large volume of ambient temperature compressed air as the cooling method. Near the top end of the temperature range the cooling is very fast but slows significantly as the temperature approaches 60°C (140°F). During heating to thermoplastic temperatures the tool face temperature has been recorded heating at an average rate of approximately 41°C/min (74°F/min). During cooling of the same run the peak average cooling rate of approximately 36°C/min (65°F/min). The benefit of using compressed air as the cooling media is a more continuous cooling ramp. Using active thermal management (i.e. heating when required), the temperature remains fairly linear during cool down. There are also no large discontinuities on cooling as the equipment switches from air cooling to water or as the temperature passes through the boiling point of the cooling media i.e. no risk of phase change.

Figure 7 Thermocouple locations on the Beaded Panel Thermal Profile

The RAPM PtFS equipment has 180 independently controlled channels. Of these 180 channels, the beaded panel configuration (RAPM-001) only falls in 112 of these channels. This includes 56 channels on the top tool and 56 channels on the bottom tool. Each of these channels needs 1 or more thermocouples in them to verify that the cell is within the desired tolerance. Figure 7 shows the thermocouple (TC) location on the tool face. The temperature was measured on both the top and bottom tool faces using the same TC pattern.

Each heater channel was adjusted until the thermocouples in each tool region were within the set point temperature tolerance. Currently, this is a manual process to move each heater channel from one zone to the next to bring the tool face thermocouple into tolerance. **Figure 8** shows the offsets given to each channel to maintain a uniform tool temperature during an isothermal run. The maximum channel offsets were +9.4°C / -8.3°C (+16.98°F / -14.88°F) to maintain the tool within the processing tolerance of ±5.5°C (±10°F).

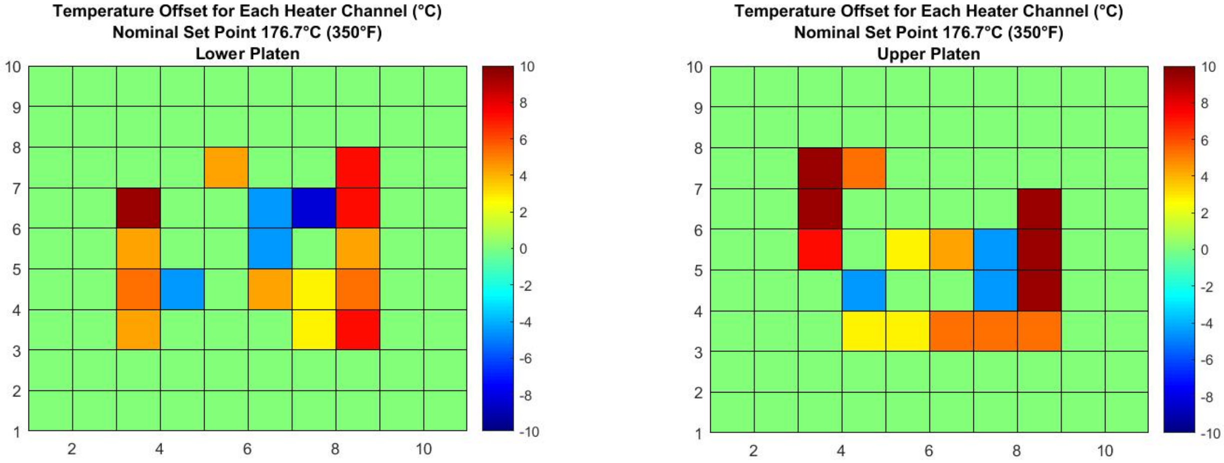

Figure 8 Channel Set Point Deviations From Nominal. (Left): Lower Platen (Right): Upper Platen

After the temperature was allowed to stabilize, each tool face thermocouple was recorded for 2-5 minutes. Temperature recordings were completed in batches due to a limited amount of external thermocouple recording equipment channels. For this program 176.7±5.5°C (350.0 ±10.0°F) was the target tool temperature to process one of the composite materials.

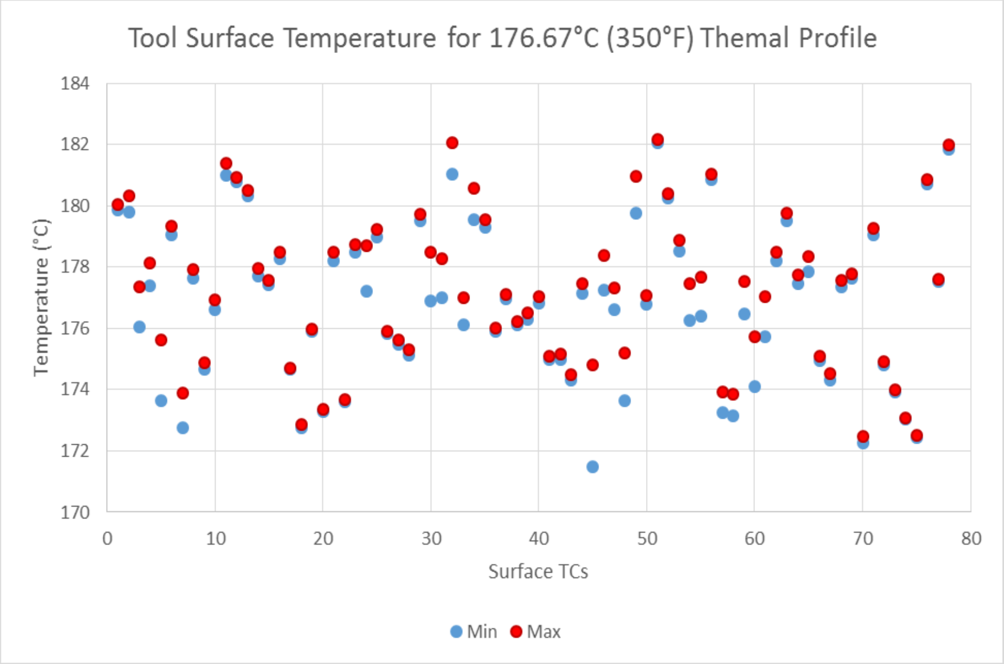

Figure 9 Initial 176.67°C (350.0°F) Tool Face Thermal Profile

After the 176.7°C (350.0°F) thermal profile was completed the equipment was cooled and re-run on two additional days. The tool temperature surface was re-measured and variability in the tool face temperature across the three runs was recorded. Table 1 shows maximum and minimum TC readings from two additional 176.7°C (350.0°F) tool face temperature recordings. During the second iteration, one thermocouple data point was discarded due to suspected poor contact with the tool surface from adhesion failure in the Kapton mounting tape.

Table 1 Thermal Profile Iterations at 176.6°C (350°F)

	Limits		Initial Thermal Profile		Second Look		Third Look	
	°C	°F	°C	°F	°C	°F	°C	°F
Min	171.1	340.0	171.5	340.7	170.4	338.7***	171.6	340.8
Max	182.2	360.0	182.2	359.9	181.3	358.3***	184.6	364.2

*** The lowest thermocouple reading was removed due to suspected poor tool surface contact.

Following the empty tool face temperature uniformity test, the test was repeated after imbedding thermocouples at the midpoint of a 16 ply thermoset carbon epoxy woven laminate as shown in **Figure 10** and **Table 2**. Initially the tool face thermal profile was completed to bring the tool face into the temperature tolerance. Once composite material is added, the temperature distribution becomes tighter as the composite itself acts as a heat transfer path. This also helps to bring the tool to the desired temperature without scrapping the composite material. The temperature uniformity within the composite laminate was tighter than the tool face readings. The single TC in Run 1 below that oscillated outside the desired temperature range was near the part edge and is suspected to be caused by temperature fluctuations of neighboring cells outside the part trim line.

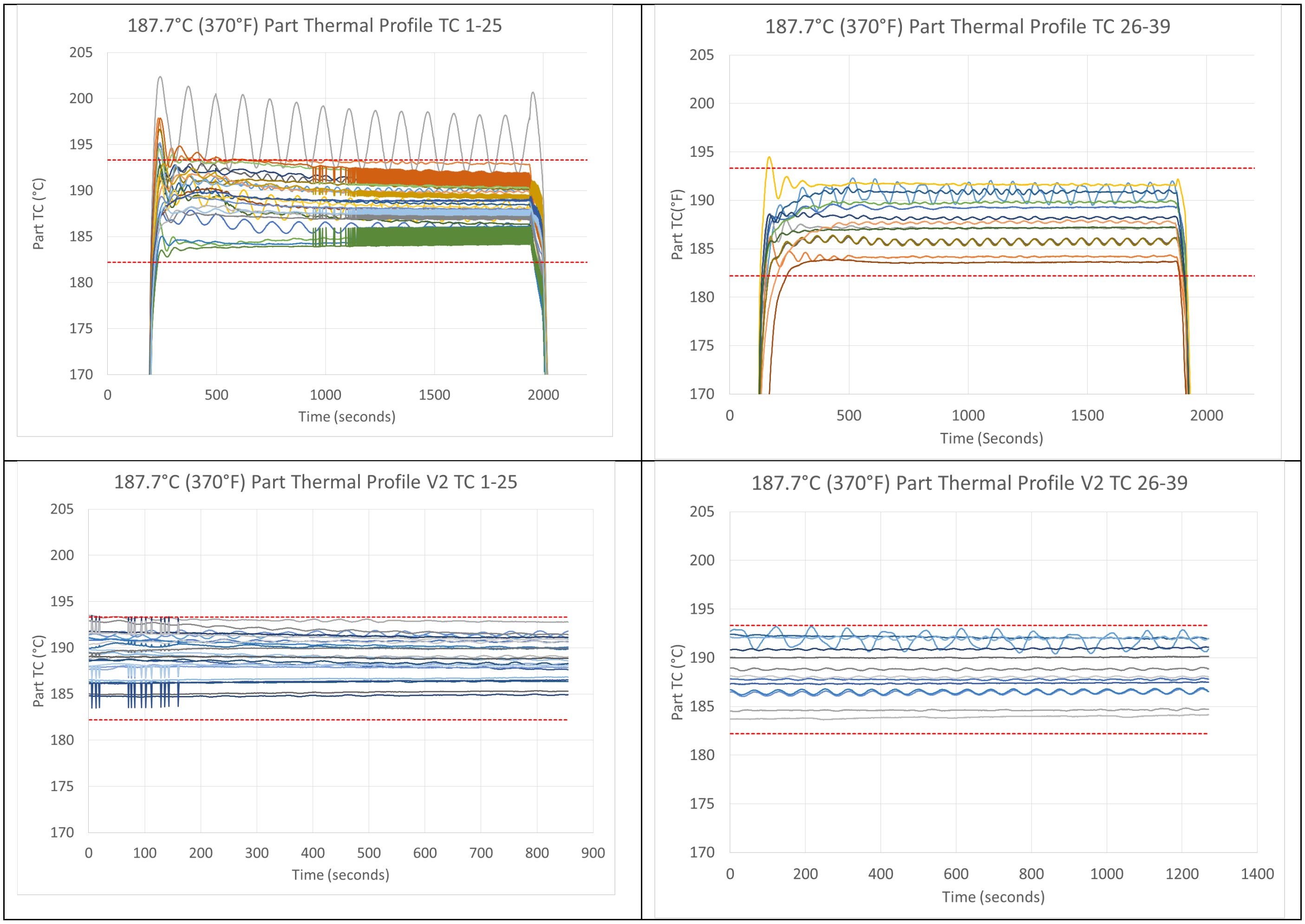

Figure 10 Isothermal Part Thermal Profile at 187.7°C with Imbedded TCs

Table 2 Min and Max Internal Part TCs at 187.7°C

	Run 1 *without oscillating TC	Run 2
Min Temperature After Stabilization	183.6°C (362.4°F)	183.9°C (363.0°F)
	192.9°C(379.3°F) Oscillated near 198.9°C (390.0°F)	193.1°C (379.5°F)

These thermal profiles with the composite material are the primary thermal uniformity requirement. The imbedded thermocouples are the verification thermocouples that will be used of establishing the heater set points.

Thermoset Isothermal Processing

The first processing methodology tested with this equipment was isothermal processing. This uses the set points from the thermal profile to ensure the tool surface temperatures is within the desire range. The goal of isothermal processing is to reduce material processing times on the clamp fixture tooling. The material is only on the tooling long enough to gel the matrix of the composite. Following gelation, the material is post- cured in an oven to drive reaction completion and increase the material glass transition temperature, Tg.

One major consideration with isothermal processing is the temperature selected in the processing. Higher temperatures can bring the material to gelation faster but too high a temperature causes material degradation and exotherm risk. This exotherm is a major concern during this processing method. Traditionally large thermal masses are used in the stamp forming process so the tooling can absorb the additional energy from the matrix reacting. The PtFS equipment uses active cooling on the back side of the tool to dissipate excess energy from the reaction.

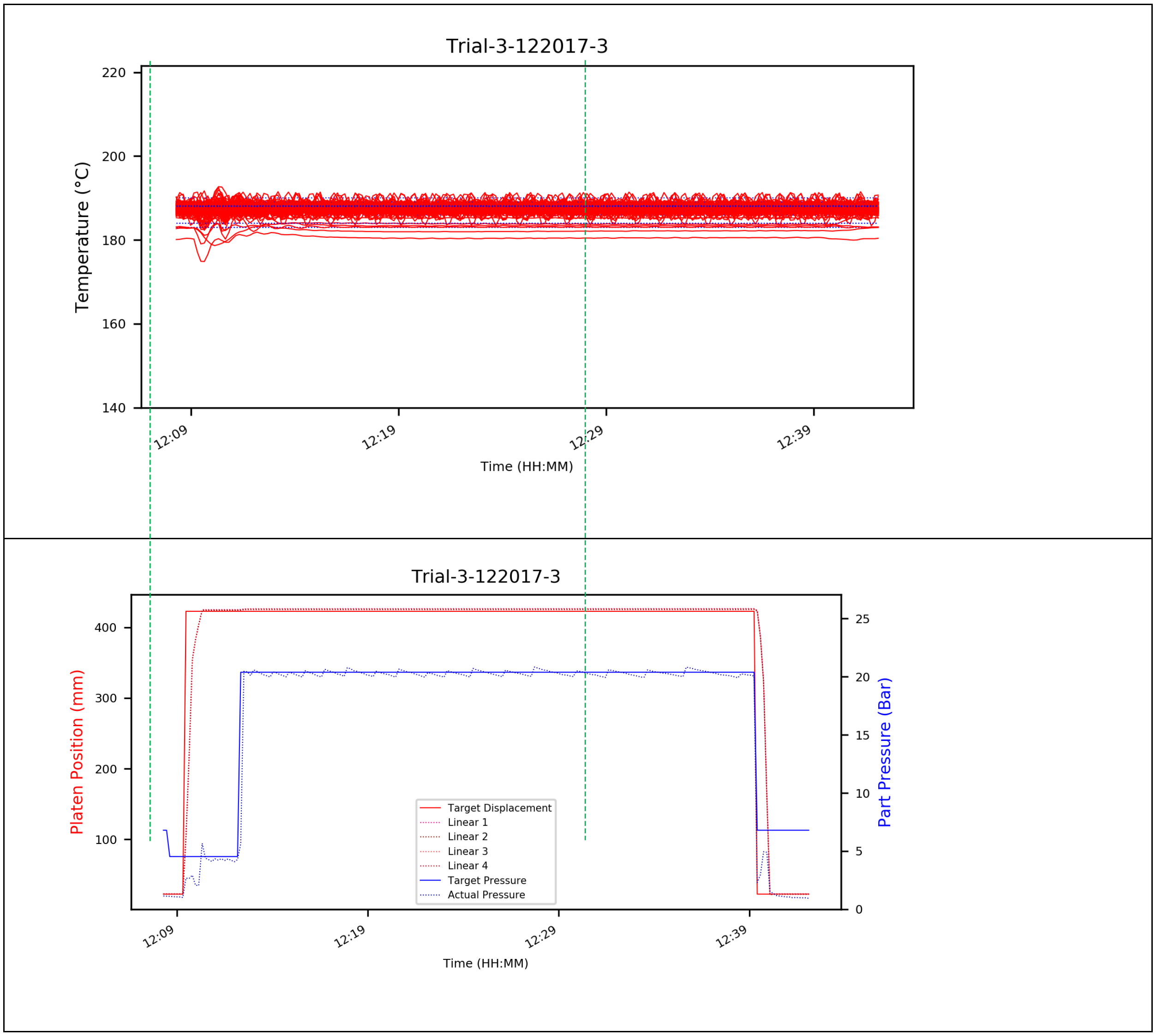

Figure 11 Representative Isothermal Processing Response

Figure 11 shows isothermal processing data from an early test with the PtFS equipment. The system rapidly heats to the isothermal processing temperature in approximately 8 minutes. The top image shows the tool temperature during the processing run. The tool closed at 12:09 starting the 30 minute processing cycle. In the first 2-3 minutes there is a slight temperature deviation. Following the brief stabilization period, the PtFS equipment is able to maintain stable tool temperatures.

Isothermal processing is cutting out significant amounts of time from the processing cycle by loading and unloading the composite at temperature. The process uses two pressure stages to ensure that the charge heats up quickly while minimizing resin squeeze out. After the initial heating, the composite is placed under elevated pressures up to 2.1 MPa (300.0 psi) to ensure good consolidation and prevent void growth in the material.

Resin Infusion Dynamic Temperature Cycles

Resin infused parts with using the PtFS equipment were infused at a low temperature of 60°C. The part geometry was the C-channel RI-RAPM-003. Following the infusion the material was ramped at 2°C/min to 125°C and held for 60 minutes before cooling. One resin used to test the PtFS equipment was an automotive style quick cure resin system with high reactivity. A benefit of the PtFS equipment was active cooling. As the exothermic reaction progressed the tool face was automatically actively cooled specific tool regions to maintain part temperatures.

Parts fabricated using the resin infusion manufacturing method used a gap infusion method. Before infusion, the tool was closed to an initial vacuum gasket. The vacuum gasket protruded above the tool surface allowing the tool to remain open an extra 1.3 mm. The resin was infused into this cavity with the tool faces 1.3mm from being fully closed. After the infusion was complete, the tool was closed the remaining distance to drive the resin into the preform. The PtFS equipment was able to provide the positional control to support this gap infusion process.

Thermoplastic Dynamic Temperature Cycles

The PtFS equipment was also used in the consolidation of thermoplastic composite materials. Processing of the material was completed using the rapid heating and cooling of the PtFS equipment to superplastic form AZ31 magnesium over a thermoplastic charge and cool the charge under magnesium bladder pressure. The equipment heats the charge and bladder to processing temperatures in approximately 55 minutes followed by a 30 minute cooling below the crystallization temperatures. **Figure 12** shows the processing conditions used by the PtFS system in processing the thermoplastic prepreg into a flat c-channel blank to be formed into the final geometry in a secondary operation.

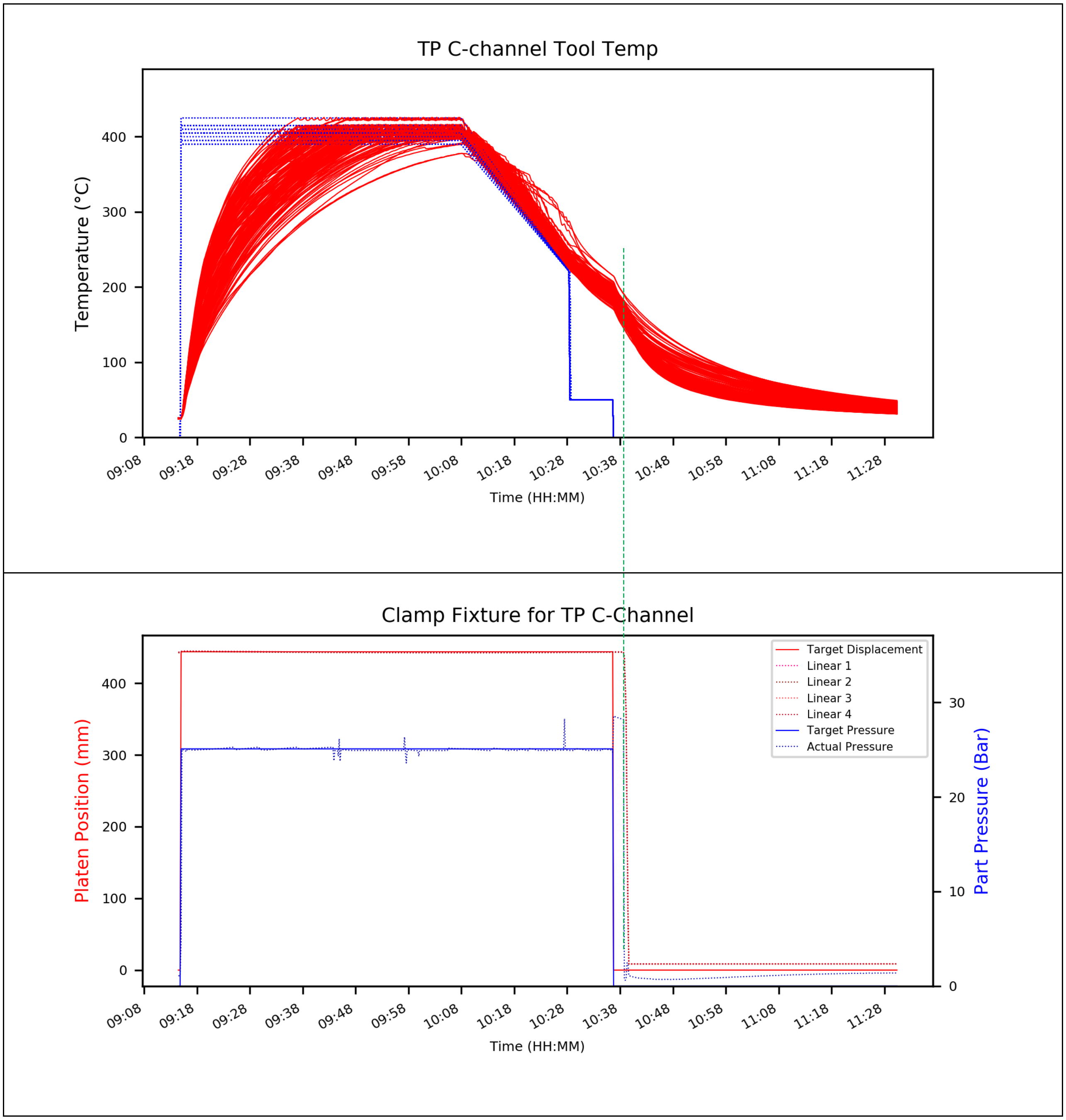

Figure 12 Sample Thermoplastic Bladder Forming Processing Conditions.

Currently, pressure control in the bladders is a manual process so that during each processing cycle, the equipment operator must adjust the pressure regulator while the PtFS control system maintains a constant clamp pressure of 25.16 Bar (365psi) over the projected consolidation area. Throughout the superplastic forming of the bladder and consolidation of the thermoplastic prepreg charge the bladder pressure is increased from a starting pressure of less than 1.37Bar (20 psi) to 9.65 Bar (140 psi) after the bladder reaches superplastic forming temperatures. This pressure is maintained throughout the cooling of the composite through its crystallization temperature and released at the end of the cycle. An integrated automatic pressure and vacuum control system module, the Pressclave system, has recently been incorporated into the RAPM cell. The Pressclave system will allow automatic pressure and vacuum control to the tooling in the future.

4. SUMMARY

The PtFS equipment has been able to process the three material types using isothermal processing, low temperature ramps and high temperature ramps. The PtFS equipment was able to heat and cool within the desired temperature ranges and apply the desired clamping forces to the materials.

Improvements to the PtFS system during the RAPM program include 2 feedback thermocouples, improved control software, and development of pressure and vacuum control into the control system. The backside of the tool face can accept 8 thermocouple locations. If needed, the heater base can have its feedback thermocouples moved to one of the 8 thermocouples in each tool. The software also allows the heater channel to be controlled by 1 or both of the backside thermocouples. This selection can help make sure that the feedback thermocouple fall within the projected area of the part in the heater cell. This provides a better correlations between the tool temperature reading and the part temperature. Through the RAPM program thermal improved thermal uniformity methods have been evaluated. Tool face sheet thickness has been varied and evaluated with simulation software as a method to reduce tool temperature deviation from set points. Unfortunately this reduces the heating and cooling rates the equipment can provide to the part. The tool thickness tradeoff is analyzed for each tool based off of the tools intended processing parameters. Another path forward toward improving thermal uniformity has been though, Surface Generation's development of alternative diffusers to better distribute the airflow around the heater cells. This helps reduce hot and cold spots in each heater channel. Preliminary testing showed the new diffuser design reducing thermal oscillations across the tool face.

5. CONCLUSIONS

The PtFS equipment has shown its ability to process various composite product forms. The equipment has potential to be used in isothermal processing when tool heating times are a concern. The sub 10 minute heating to 179.4°C (355°F) epoxy curing temperatures along with automated tool changes would allow for quick part changeovers on short manufacturing runs. High temperature dynamic runs can be completed quickly with the rapid heating and cooling of the tooling. These two usages cases are exceptionally suited for the PtFS equipment. Throughout the RAPM program the PtFS equipment has significantly increased it capability.

During processing, the PtFS system is generating and recording a significant amount of data each second. Every heater channel has the current set point, heater power levels, channel compressed air level, and the PID parameters. The data is available for inspection and post-processing following each processing cycle. It is also available for the operator to view during each cycle. The volume of data produced significantly exceeds conventional processing methods and provides additional opportunities using machine learning for quality control and process improvements. Further software enhancements would allow this data to identify processing anomalies such as if a specific tooling region is requiring more energy for a set responsiveness.

The PtFS equipment was selected for use in the RAPM program for its rapid heating and cooling [2], wide processing capabilities, thermal control and the substantial part processing data pedigree associated with each manufactured part. The equipment has been shown to be versatile in composite manufacturing and especially useful when continuous rapid heating and cooling is required.

6. ACKNOWLEDGMENTS

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7. REFERENCES

1. Hahn, G.L. and Tsotsis, T.K. Rapid High Performance Molding (RAPM) for Small Parts." SAMPE 2019 Conference Proceedings. Charlotte, NC, May 20-23, 2019.
2. Massey, Pete and Halford, Ben. "Symphony Suite Training Manual v2.pdf" 19 Sept 2017
3. Ryder, A. "Enhanced Thermal Control of Mould Tooling as an Enabler for Thermoplastic Overmoulding" *SAMPE Europe Conference 2018,* Southampton, UK
4. Tsotsis, T.K., Wiener, M., Cespedes-Gonzales, G., Kubitz, J., Calamito, D., and Cohen, L. J. "Fabrication of a Complex Part with Deep-Draw Sections by Resin Transfer Molding." SAMPE 2019 Conference Proceedings. Charlotte, NC, May 20-23, 2019.
5. Luchini, T.J., Rodriguez, A.J., Rogers, S.A. Hahn, G.L. "Spring Frame Press Fabrication of Aerospace Production Components." SAMPE 2019 Conference Proceedings. Charlotte, NC, May 20-23, 2019.
6. Schell, J.J., Shewchuk, S. M., Leach, D., McCrea, T., Mecham, S., Hahn, G. L. "Rapid High Performance Molding of Structural Thermoplastic Composite Parts." SAMPE 2019 Conference Proceedings. Charlotte, NC, May 20-23, 2019.