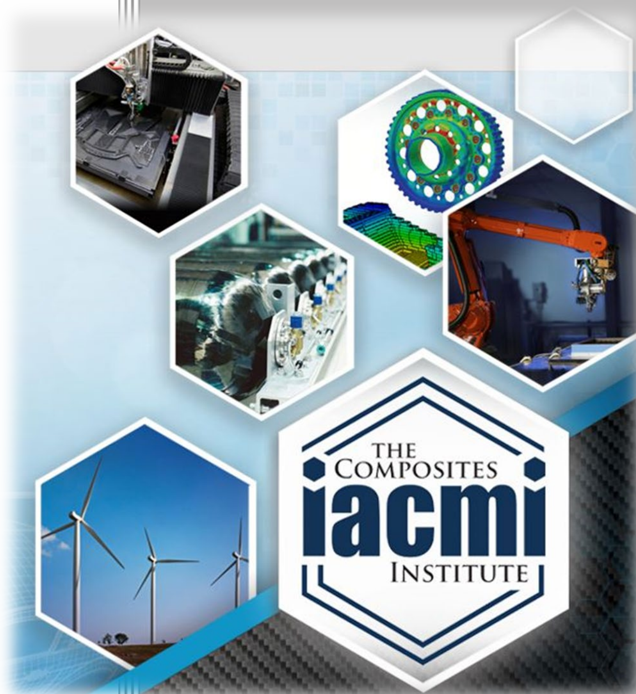
RapidClave® Technology Demonstrations – II Hat Stiffener



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RapidClave® Technology Demonstrations – II Hat Stiffener

Principal Investigator: Scott Huelskamp

Organization: University of Dayton Research Institute

Address: 300 College Park Ave Dayton, Ohio 45420

Phone: 937-229-3045

Email: Matthew.Cameron@udri.udayton.edu

Co-authors: Brian Rice, Scott Huelskamp, Matthew Cameron, Eric Lang, Caleb Tanner

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1. LIST OF ACRONYMS

UDRI	University of Dayton Research Institute
AM	Additive Manufacturing
PEI	Polyetherimide
RTD	Resistance Temperature Detector
Tg	Glass Transition Temperature
DoC	Degree of Cure

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1.4 Acknowledgements

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2. EXECUTIVE SUMMARY

This project sought to evaluate the cost and performance of both polymeric and metallic tooling for use with the RapidClave® composite process. Teijin's rapid cure carbon/epoxy prepreg, Q183, was selected to fabricate demonstration components, of aerospace design, which currently are fabricated via compression molding using matched steel tooling. The ability to fabricate components using this prepreg in the RapidClave®, and using low cost single sided tooling, could significantly reduce the cost of part manufacture and shorten production lead times for tooling fabrication.

The component demonstration article was a "hat stiffener" geometry typically used to reinforce fuselage or wing skins of an aircraft. A rapid preforming process was demonstrated and rapid process cycle times similar to compression molding were achieved by placing the preform on hot tooling, thus avoiding the time and energy associated with typical thermal cycling.

A 90% reduction in tooling cost was achieved through the use of single sided aluminum or polymeric additive tooling when compared to compression molding matched steel tooling. In addition to rapid cycle times, RapidClave® offers the ability to change out tooling in minutes such that multiple part geometries can be fabricated in one shift.

3. INTRODUCTION

Compression molding and autoclave processing have been standard methods of manufacturing both automotive and aerospace components for several decades. Each process possesses its own set of drawbacks and advantages. Compression molding allows for quick cycle times, however the matched tooling costs can be prohibitively expensive for low production runs and prototyping. Autoclave processing requires much longer cycle times due to slow temperature and pressurization ramp rates, however, it benefits from inexpensive single sided tooling. The RapidClave® process aims to incorporate the advantages of both compression molding and autoclave process to achieve rapid cycle times with inexpensive tooling.

Introduced to the market in 2007, RapidClave® offers an innovative composite process/curing approach that enables cycle times approaching that of compression molding with the added benefit of rapidly produced, low-cost tooling that delivers part quality typical of autoclave processing. The RapidClave® design utilizes a low profile rectangular pressurized shroud which raises up and down over the part to be consolidated and cured. Specialized for relatively flat parts, the shroud can be pressurized to 100 psi in approximately 1 minute. An autoclave sized to process a similar sized part has a larger volume to pressurize and heat, thus requiring nearly ten times as long to complete the consolidation and cure cycle.

The RapidClave® process in this demonstration takes advantage of low-cost aluminum tooling paired with a preforming approach and a reusable silicone vacuum bag to achieve cycle times comparable to compression molding and tooling costs comparable to autoclave processing. Teijin's Q183 carbon/epoxy rapid cure prepreg was selected for this demonstration because it is currently used to produce aerospace structures such as hat stiffeners processed by compression molding. The prepreg provides a Tg of approximately 360°F with a cure time of only 20 minutes at 320°F. The prepreg tack and drape characteristics offer the ability to lay-up flat sheets of prepreg and then vacuum form at ambient temperature to the desired shape, thus creating a stable preform that can readily be placed on a preheated tool for rapid consolidation and cure.

4. BACKGROUND

The RapidClave® has previously been demonstrated in composite production environments. Specifically, it was in use at Plasan Carbon Composites until recently to produce Corvette, C7 exterior, carbon fiber body panels [1]. Although capable of meeting the required production rate, the legacy equipment required integrally-heated tooling that was very expensive to manufacture. Figure 1shows the plumbing in a legacy RapidClave® tool. Previous IACMI investment retrofitted the current RapidClave® to remove the need for integrally heated tooling. This was done by installing a hot tool plate with heated oil channels embedded within the plate. Individual tooling without need for integral heating could be placed on the plate and heat would conduct into the tool from the hot plate. This approach requires only one initial investment in the tool plate, rather than a recurring investment every time a new tool was required, saving more than $100-200k on each tool. This concept of keeping the tooling heated during consolidation and cure is consistent with compression molding, where a preform is placed on the heated tool, the matched tool is closed to consolidate and cure the part, then the tool is opened and the part is removed hot.

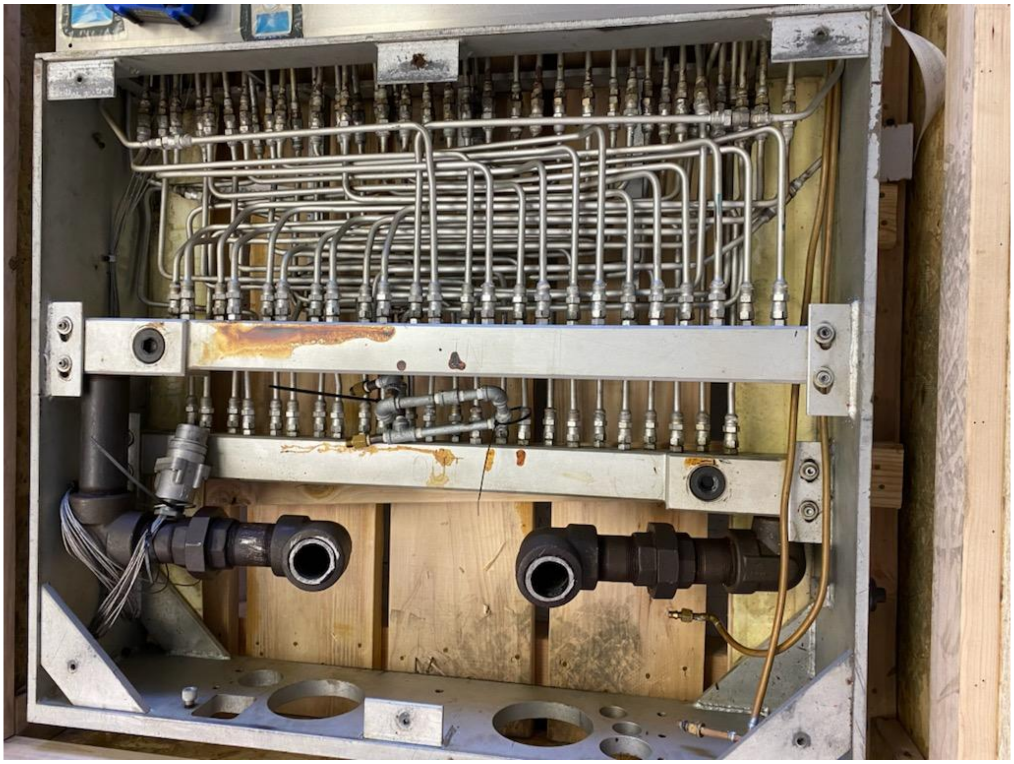

Figure 1 Typical Plumbing for an Integrally-Heated Tool

The modified RapidClave® was also retrofitted with a hot air blower in the shroud to supplement the hot oil heated tool plate. This allowed for heated air to impinge on the cure tool from the top simultaneously to the heat conducting into the bottom of the tool through the hot tool plate.

This project demonstration sought to validate that the changes to the operational structure of RapidClave® would enable use of simplified low cost tooling. Rather than tools cycling from hot to cold between cycles (similar to an autoclave operation), the process would be more analogous to compression molding. The tools would be kept at mostly a constant temperature, and pre-shaped ply stacks would be dropped onto a preheated plate and rapidly cured. Parts would be demolded hot, and the machine would be ready to accept the second ply stack. The result is faster cycle times and far less energy consumption.

5. RESULTS AND DISCUSSION

Hat Stiffener Demonstration

The hat stiffener geometry was selected as a benchmark to compare against the Teijin compression molding prior work. The demonstration sought to evaluate a range of tooling concepts including carbon filled thermoplastics processed by “pellets to part” additive manufacturing and CNC machining from M1 aluminum alloy billet. Given the low molding pressures of 100 psi the aluminum tool would be expected to last at least 1000 molding cycles, if a longer service life were required Invar or tool steel would have been selected, with the understanding the cost and lead time could be nearly double.

The hat stiffener geometry used for this demonstration is currently produced on matched steel tooling for compression molding, resulting in low cycle times but high upfront tooling cost. The RapidClave® approach aimed to achieve similar cycle times to compression molding with low cost single sided tooling. The project objective was to demonstrate a 50% cost savings as compared to baseline compression tooling. These tooling demonstrations were intended to reduce the cost of low volume parts that require high rate of production. Teijin produces a rapid cure carbon epoxy prepreg suitable for both aerospace and high performance automotive applications, and its’ compatibility with the RapidClave® process was evaluated in this demonstration.

The first step in this demonstration was to design a single sided tool to match the hat stiffener geometry currently produced using matched tooling for compression molding with Teijin Q183 rapid cure carbon epoxy prepreg. The single sided tool geometry was generated from part geometry provided by Teijin as presented in Figure 2 where the part geometry and mold details are specified. The tool fabricated was similar to the lower mold geometry while the silicon vacuum bag would conform to the part and act as the upper mold half. An upper tool or caul was not used so as to minimize thermal lag and minimize tooling cost. The prepreg preforming process helped to ensure proper fit and consolidation without need for a caul.

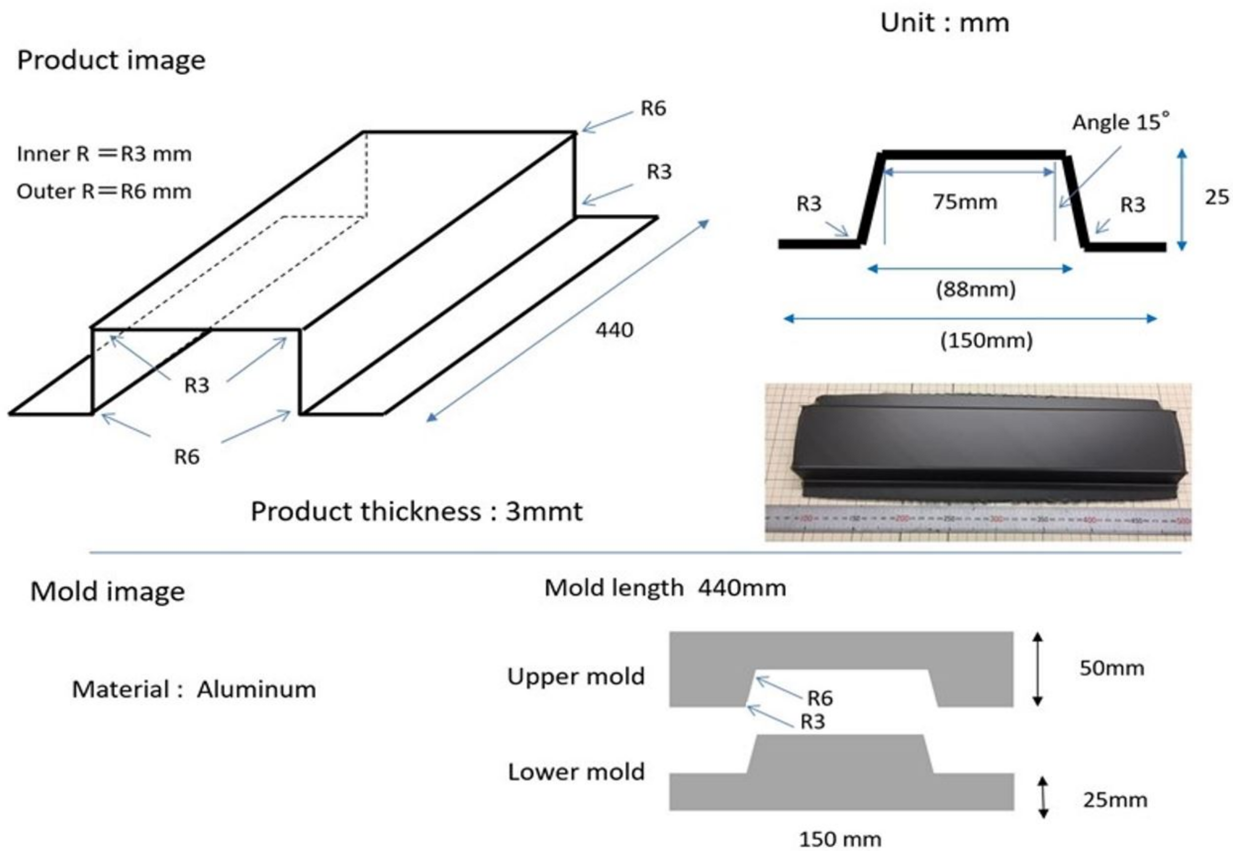

Figure 2 Tooling Geometry Provided by Teijin

Given the focus on tooling cost and cycle time, the tooling geometry design did not account for any spring back in the laminate. Two versions of the tooling geometry were designed. The first tooling geometry was the net shape of the tool to be used for a single-sided aluminum CNC machined tool, and an additively manufactured preforming tool. The second tooling geometry included an additional ½" of material added to the surface. This tool was to be additively manufactured, and the additional material was machined off resulting in the same final geometry and similar surface finish to the aluminum tool. Both of these CAD models can be seen in Figure 3.

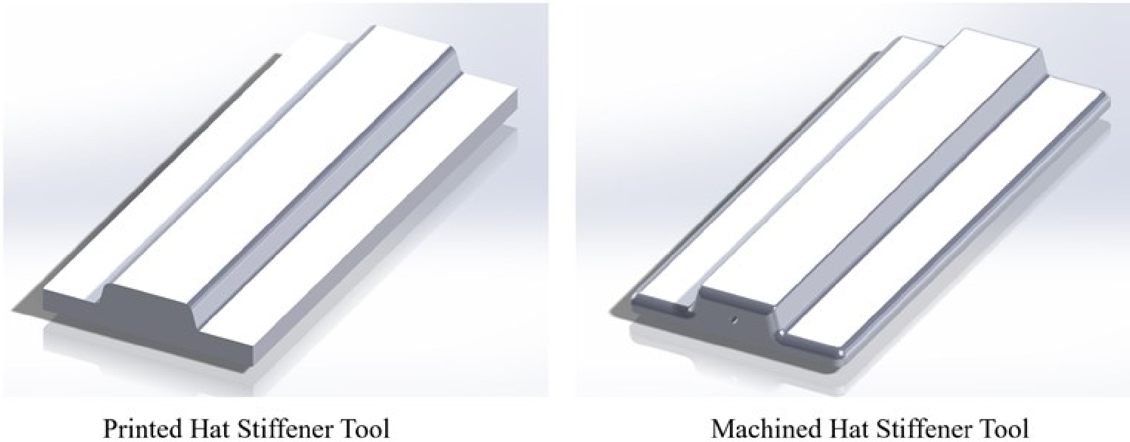

Figure 3 CAD Models of Hat Stiffener Tooling

Three hat stiffener tools were produced. The first hat stiffener tool was a CNC machined M1 aluminum tool. The second and third tools were both printed on UDRI's Titan Robotics Atlas large format 3D printer with a 20% carbon fiber-filled polyetherimide (PEI) (Thermocomp™ EX004EXAR1 Ultem®) feedstock. The additive tool intended for RapidClave® processing was printed vertically. This allowed the additional ½" of material to be printed as increased wall thickness and minimized additional print time. This printed tool was used for a direct comparison to the machined aluminum tool for processing. The third tool was printed horizontally to the net shape, and used only for preforming the Teijin snap-cure prepreg. These tools can be referenced in Figure 4. The additive processing tool required a small amount of bench work after machining away the additional ½" of material. Small surface imperfections and voids were present on the machined surface. This is largely due to the nature of printing with carbon filled high temperature thermoplastics. In order to achieve cost-competitive additive tooling, faster printing speeds were used that resulted in small interlayer imperfections. These small imperfections and voids were filled with Loctite EA 9394, high temperature, epoxy paste adhesive, which was then cured in an oven, and sanded down to a smooth surface. The grey areas on the tools seen in Figure 5 result from the adhesive filler.

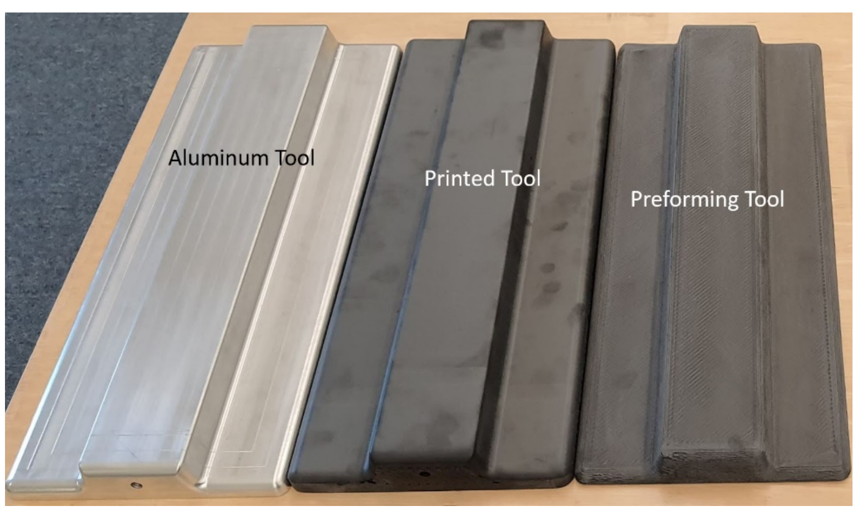

Figure 4 Hat Stiffener Tools

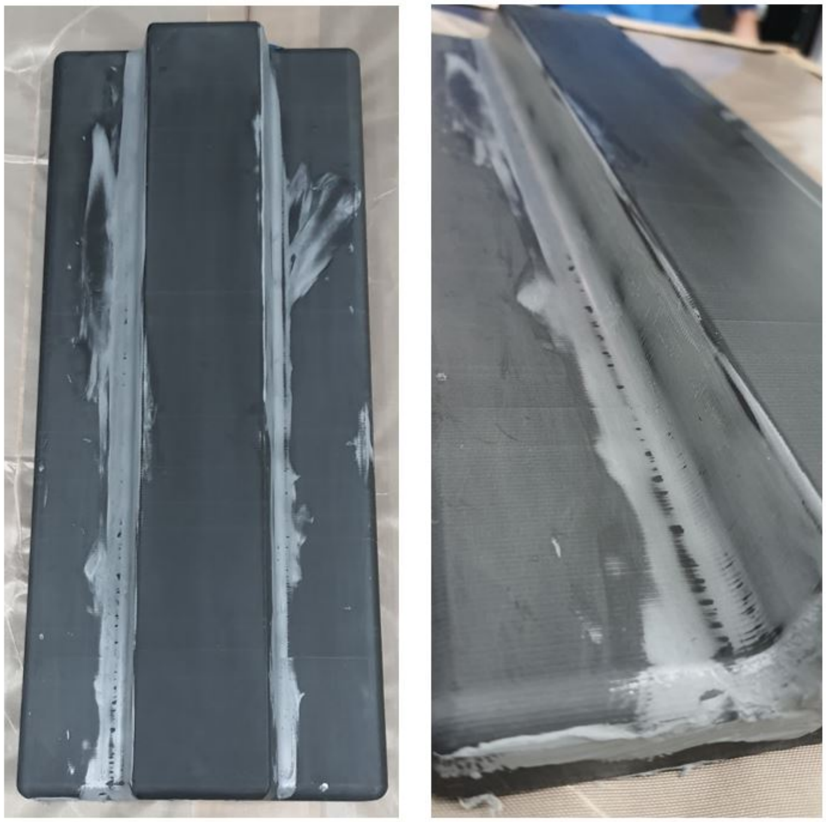

Figure 5 Photo of Additive Tool Post Adhesive Application and Sanding

Baseline hat stiffener parts were cured on both the aluminum and polymeric printed tools using an autoclave process as a conventional aerospace process benchmark. The layup for all hat stiffeners produced was 16 ply symmetric, quasi-isotropic. The bagging scheme involved: reinforcement, oversized porous Teflon release film, nonporous Teflon release film, N10 breather, and Stretchlon 400 bagging film. No caul was used, as only the tool side geometry would be used for comparison and the preforming step was deemed sufficient to drive the prepreg into the tool radii. The autoclave cure cycle recommended by Teijin was 180 minutes to allow for the autoclave's lower heating and cooling rates as shown in Figure 6. Both hat stiffeners cured in the autoclave (Figure 7) had noticeable tool side surface porosity at the radii indicating the preform did not fit as tightly onto the tool as required. The additive tool visually had a better tool side surface finish as compared to the aluminum tool, however we don't have a rationalization for this observation. Given that the autoclave run was intended as an initial screening process, prior to curing in the RapidClave®, no further effort was made to remanufacture a part in the autoclave.

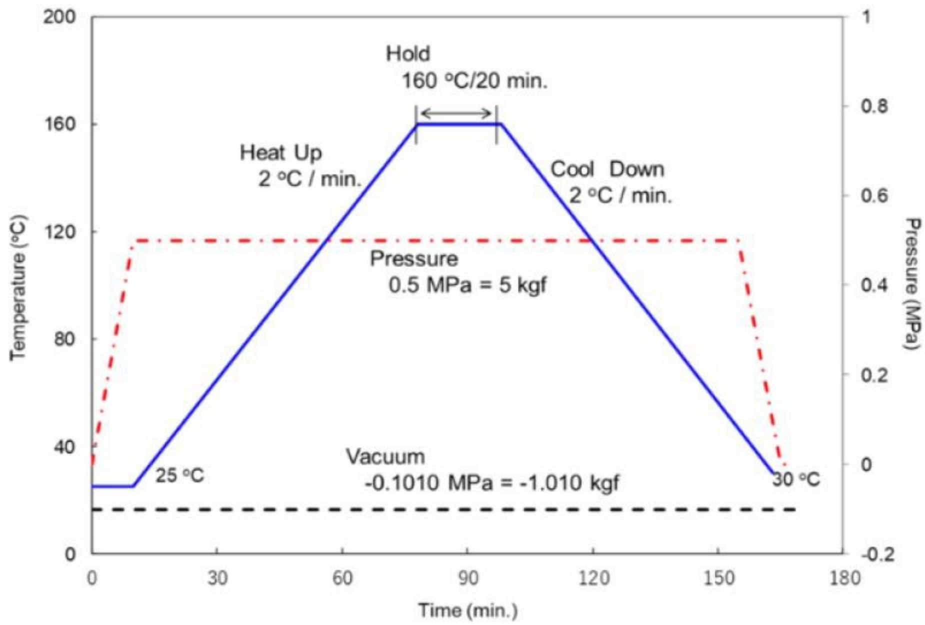

Figure 6 Recommended Teijin Q183 Autoclave Cycle

Figure 7 Baseline Hat Stiffeners Processed in Autoclave

RapidClave® Processing Trials

Processing laminates in the RapidClave® is slightly different than compression molding as a result of differences in pressure application and tooling configuration. The revised RapidClave® process embodies a pre-heated tool, upon which a prepreg preform is positioned. A Torr reusable silicone rubber vacuum bag is applied (Figure 8), then the tool is drawn into the RapidClave® shroud, which then closes. Once closed the system begins to heat to the cure temperature and pressurized nitrogen is applied. The time elapsed from prepreg placement on the hot tool to achieving full pressure is approximately 3 minutes, whereas in compression molding the closure time is approximately 30 seconds. Care must be taken to ensure that the prepreg does not gel on the tool before pressure is applied. DSC and rheology experiments were conducted to simulate process conditions to understand the processing window at various initial tool temperatures. Although rheology data suggests that gelation should not occur for 7 minutes with a tool temperature of 320°F, in practice premature gelation was observed. Substantially lower tool temperatures approaching 200°F to prevent premature gelation would require longer heating times to recover the desired set-point. Other considerations that drive optimized process conditions include prepreg thickness where a thick laminate could result in excess exotherm temperature, and tooling construction which could result in thermal lag.

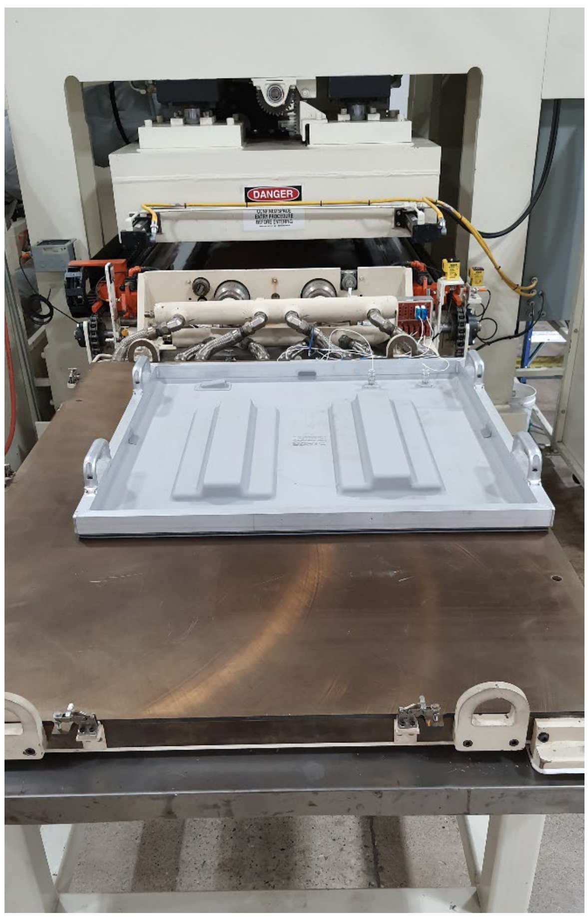

Figure 8 Torr Bag Vacuumed Down to Hat Stiffener Tools on RapidClave® Platen

Several processing trials were conducted on the Q183 prepreg to explore these conditions. Initial RapidClave® runs were conducted on 10 and 35 ply quasi-isotropic flat panels to determine appropriate processing parameters. These runs utilized a 320°F tool fully preheated to simulate Teijin's recommended press cure profile shown in Figure 9. The resulting laminates had some surface porosity, similar to the autoclave parts, as shown in 10. During the run there were some pressure and vacuum variations that may have caused the poor surface quality.

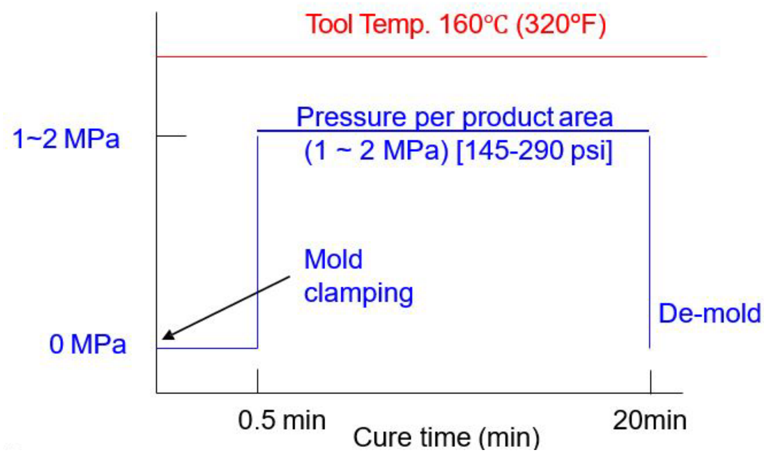

Figure 9 Teijin Q183 Press Cure Profile

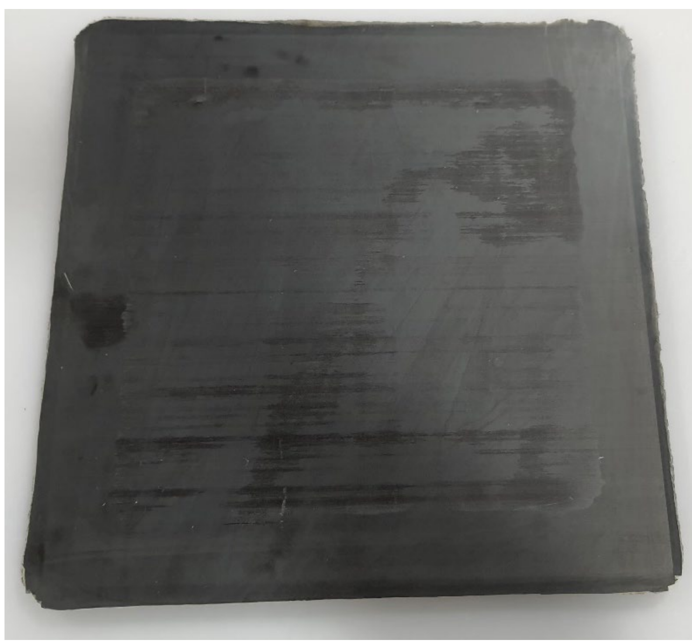

Figure 10 35 Ply Teijin Q183 Flat Panel Tool Side Surface Finish

Subsequent trials were conducted on the hat stiffener tool using an initial pre-heat tool temperature of 260°F. This trial resulted in improved surface finish on both bag and tool side as shown in Figure 11. Reducing the preheat temperature from 320°F to 260°F and ramping to the 320°F cure temperature increased the cycle time from around 20 minutes to 40 minutes.

Figure 11 260°F Preheat Hat Stiffener

DSC results conducted on prepreg, shown in Table 1, indicate the cure onset temperature is 272°F and peak exotherm occurs at 326°F during a rapid heating rate of 41°F. This kinetics data suggests the rate of cure at 260°F should be minimal and premature gelation at this temperature is not a concern.

Table 1 Teijin Q183 Raw Material DSC Data

DSC: Teijin Q183 Raw Material Temperature Sweep Data	
Temperature ramp rate (°F/minute)	41
Onset temperature (°F)	272
Peak temperature (°F)	326
Enthalpy Normalized (J/g)	138

Two additional hat stiffener process trials were completed with a 200°F preheat cycle, and a 250°F preheat cycle, both using the polymeric additive tool. A temperature of 250°F was determined to be a safer preheat temperature, being well below the reaction onset temperature. The 200°F preheat was used as an extreme lower temperature for comparison. Both DSC and DMA tests were completed on the cured hat stiffener laminates as presented in Table 2 and Table 3. The DSC glass transition temperature (Tg) was determined using the enthalpic relaxation peak. The DSC degree of cure (DoC) was determined using the remaining heat of reaction. The DMA Tg was measured by tangent delta peak. Overall, the degree of cure and Tg met targets of 95% and 350°F respectively.

Table 2 Teijin Q183 Cured Hat Stiffener DSC Data

Panel	Coupon	Tg (°F)	DoC (%)	Panel Average Tg (°F)	Average DoC (%)
200°F Pre-heat	20210401_MCJF_1_3	372	94	371	95
	20210401_MCJF_1_4	370	97		
250°F Pre-heat	20210401_MCJF_4_5	372	93	372	95
	20210401_MCJF_4_6	371	98		

Table 3 Teijin Q183 Cured Hat Stiffener DMA Data

Panel	Coupon	Tg (°F) (Tan Δ)	Ave. Tg (°F)
200°F Pre-heat	20210401_MCJF_1_DMA_1	366	366
	20210401_MCJF_1_DMA_2	366	
	20210401_MCJF_1_DMA_3	366	
250°F Pre-heat	20210401_MC_2_DMA_1	368	352
	20210401_MC_2_DMA_2	344	
	20210401_MC_2_DMA_3	344	

Tool side surface quality was improved on both the 200°F preheat and 250°F preheat hat stiffener laminates as shown in Figure 12. The RapidClave® process cycles for both 200°F and 250°F pre-heat conditions are presented in Figures 13 and 14 respectively. The process cycle times of 68 and 44 minutes for 200°F and 250°F pre-heats respectively are longer than desired. The principle cause of the longer than optimal cycle is that the heater which drives the chamber air temperature shown as the green curve in Figures 13 and 14 reduces power too early at 16 and 12 minutes respectively resulting in a sinusoidal time temperature response. Ideally the chamber air would be kept hotter for a longer period of time to drive up the part temperature sooner. Through revised tuning of parameters in the hot air system we expect the heating time could be reduced by approximately15 minutes, the time it took the chamber air to settle. To prevent overheating the surface of either bagging film or the reusable Torr bag, the maximum allowable power of the 50kW process air heater was reduced. We also expect the tool preheat temperature can be increased as the time required to apply the vacuum bag and pull the tool into the shroud is reduced. Through discussions with aerospace industry partners a cycle time of 30 minutes is desired and believed to be achievable.

Figure 12 Additional Hat Stiffeners: 200°F and 250°F Preheats

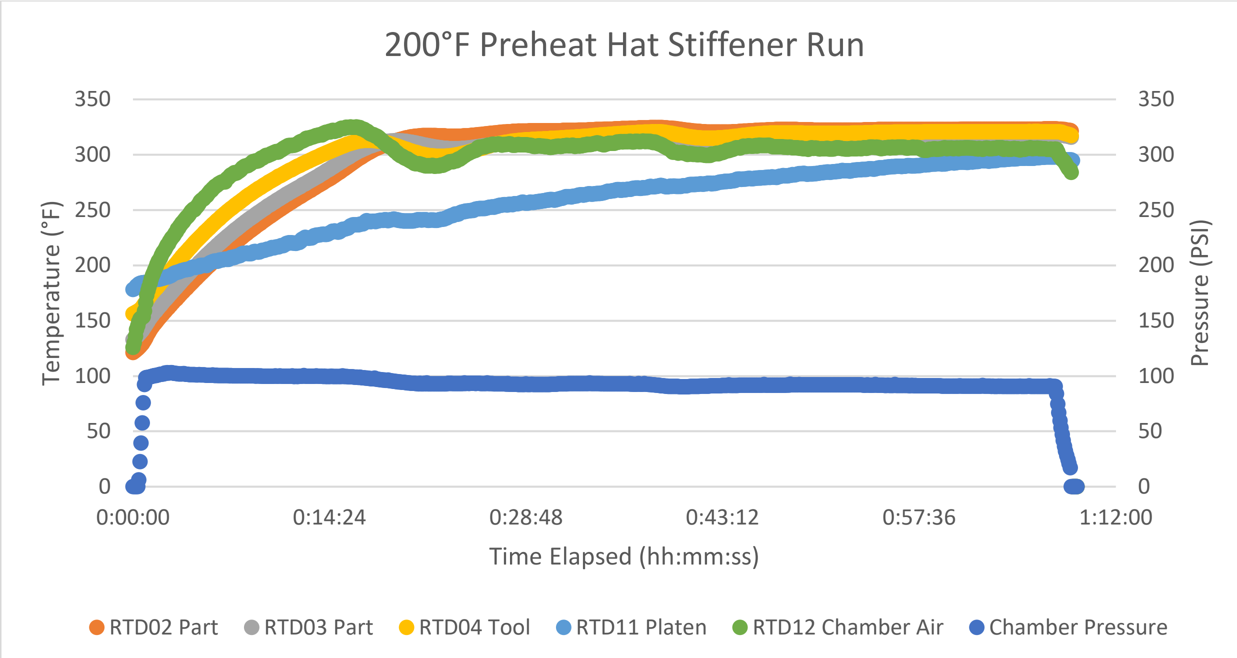

Figure 13 200°F Preheat Hat Stiffener Run

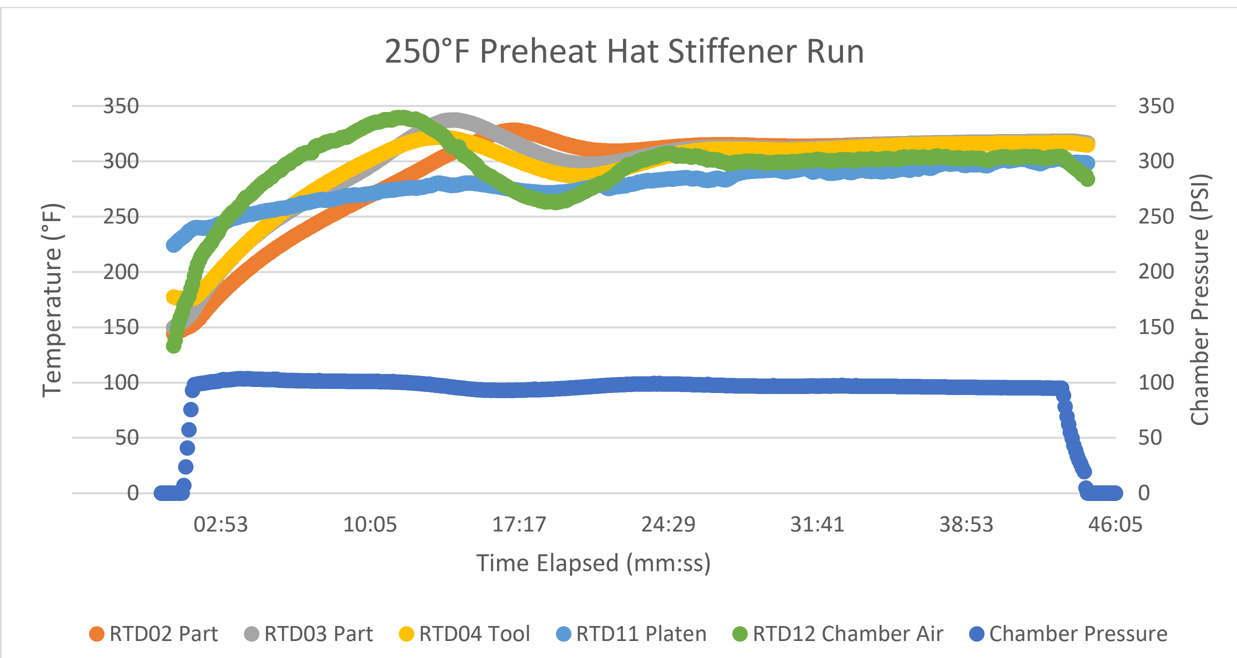

Figure 14 250°F Preheat Hat Stiffener Run

A Creaform 3D scanner was used to scan the tool side of the composite hat stiffener part which was cured at 250°F and compared to dimensions to the top of the hat stiffener aluminum tool. A best fit alignment was used to compare the bottom of the demolded part to the surface of the aluminum tool. The aluminum tool served as the net geometrical reference for the part. The allowable profile tolerances for this scan comparison were set at +/- 0.005. The error distribution histogram shown in Figure 15 showed that 58.70% of the scanned part was within that acceptable profile tolerance region on the heat map. Most of the out-of-tolerance areas were high spots that appeared to be visible on the top surface of the part. The hat stiffener tools did not account for spring-back when designed. This also could have contributed to the top surface showing more movement. The dimensional scan was conducted for benchmarking and learning purposes and there was no particular tolerance set for this demonstration.

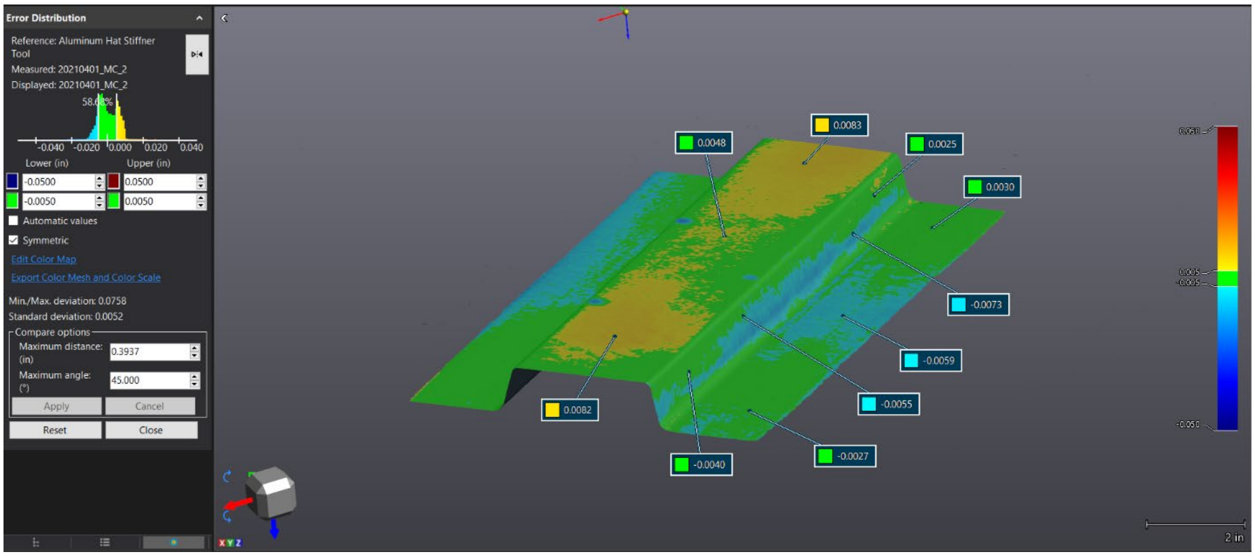

Figure 15 3D Scan Comparison of 250°F Preheat Hat Stiffener and Tool Surface

6. COST ANALYSIS/BENEFITS ASSESSMENT

All tooling costs were tracked throughout the duration of the project. Some tooling had additional costs such as bench work or sanding before it could be used for processing parts. Machine and labor rates were standardized across all tooling for direct comparison. Not all contracted work could be broken down into labor and machine rate categories. For these instances, only the total invoiced amount was used. Additive tooling costs were broken down into four categories: tool print, machining, benching, and sealing. These categories help to clearly show where the cost benefit from additive tooling arises as detailed in Table 4.

The tooling concepts in this project are intended for a limited run of parts, reducing the cost and lead time of innovation rather than high volume production. The additive hat stiffener tool achieved a cost savings of approximately 90% compared to matched steel compression molding tooling. While the single sided machined aluminum tool cost was comparable to the additive tool, further development to reduce labor and optimizing printing parameters to reduce both material usage and machine time would reduce the total cost of additive tooling. Compression molding tooling is based on matched steel tooling with no internal fluid channels used for temperature control. Future processing trials need to be conducted to evaluate effects on aluminum, which has higher mass and higher thermal conductivity as compared to carbon/polymeric tooling. The aluminum tool is expected to have a longer service life. Tooling lead time is likely to drive the selection process. Single sided steel or Invar tooling could be utilized for high volume production at an expected cost reduction of 50%.

Table 4 Hat Stiffener Cost Analysis

Hat Stiffener			
Material	Compression Molding	M1 Aluminum	**Titan Atlas – 20% CF PEI (ULTEM)**
Total Costs	$24,000	$2,530	**$2,435**

Task	Labor Hours	Labor Costs ($75/hr)	Machine Hours	Machine Usage Costs ($80/hr)	Material (lbs)	Material Costs ($25/lb)	Total Costs	Notes
AM Tool Print	4	$300	15.75	$1,260	8	$200	$1,760	Costs $80/hr for print time on a Titan printer (as quoted by Titan Robotics).
Machining	N/A	$	N/A	$	N/A	N/A	$600	Machine usage hourly rate will need adjusted appropriately depending on commercial rate (assumed $80/hr).
Benching	1	$75	N/A	N/A	N/A	N/A	$75	This could vary depending on the individual and how much of this cost is rolled into the total machining costs.
Sealing	N/A	$0	N/A	N/A	N/A	$0	$0	Labor hours reported by operator. 600g of sealer used on the tool set.
						Total:	$2,435	Labor hour cost was set at $75 but could vary depending on the individual performing the work.

7. COMMERCIALIZATION

Reformatting of the RapidClave® process to utilize autoclave type single-sided tooling while achieving shortened process cycles competitive with compression molding has generated substantial interest in the aerospace community where eight hour process cycles are typical. UDRI and Globe Machine have partnered on multiple Air Force programs to further refine and demonstrate this approach to achieve low cost aerostructures at high production rates. The processing approach has also found great interest in the e-VTOL and UAV vehicles area.

8. ACCOMPLISHMENTS

This project helped to validate that it is possible to process a composite part with low cost tooling and comparable processing rate to compression molding. The RapidClave® achieved a cycle time of 44 minutes and over a 90% degree of cure with no post cure required. The RapidClave® cycle time is only 14 minutes longer than the desired cycle time of aerospace industry partners, 24 minutes longer than compression molding, and 136 minutes shorter than autoclave processing. Further process optimization is planned to reduce the process cycle time including installation of a higher capacity oil heater for the tool plate and improved tuning for the hot air system controller. Despite several challenges incurred during new RapidClave® process several key accomplishments were achieved 1) Low cost tooling was demonstrated through use of the new hybrid heating concept utilizing a hot tool plate augmented with heated pressurized nitrogen. 2) A preformed prepreg blank was positioned on a hot tool and cured in a similar manner as compression molding. This approach minimizes energy of the process by avoiding heating and cooling of the tool, simplifies tool design requiring CTE compensation, and reduces cycle time.

9. CONCLUSIONS

The RapidClave® process shows great potential to reduce tooling costs for small volume production of aero structures that require a fast rate of production. This project began at a Manufacturing Readiness Level 4 and completed at a Manufacturing Readiness Level 5 where-by the basic capability was demonstrated. Although cycle times did not reach that of compression molding, the significant cost savings for tooling is considered a success. Further optimization the RapidClave® programing and hardware has potential to reach cycle times comparable to compression molding.

10. RECOMMENDATIONS

With further time and additional funding, improvements to the RapidClave® software and hardware would benefit cycle time and efficiency. For example, improving the PID tuning for the air heat system and a more powerful oil heater would greatly improve heating ramp rates. A Mokon system with both heated and cooled reservoirs would improve fidelity of control over the tool temperature. An automated gantry or robotic arm to raise and lower the reusable bag system would remove a manual step for operators. Tooling designed to accommodate spring back in the material would improve the part tolerances.

11. REFERENCES AND/OR BIBLIOGRAPHY

[1] P. Malnati, "Sub-8-minute cycle times on carbon/epoxy prepreg," CompositesWorld, 6 January 2015. [Online]. Available: https://www.compositesworld.com/articles/sub-8-minute-cycle-times-on-carbonepoxy-prepreg. [Accessed 21 January 2021].

[2] Emergen Research, "Globe News Wire," 15 December 2020. [Online]. Available: https://www.globenewswire.com/news-release/2020/12/15/2145151/0/en/Urban-Air-Mobility-Market-To-Be-Worth-USD-15-54-Billion-by-2030-Emergen-Research.html. [Accessed 21 January 2021].

12. APPENDICES

N/A