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RapidClave® Technology Demonstrations - I

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RapidClave® Technology Demonstrations -1

Principal Investigator: Scott Huelskamp

Organization: University of Dayton Research Institute

Address: 300 College Park, Dayton, OH 45469

Phone: 937-229-3045

Email: scott.huelskamp@udri.udayton.edu

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LIST OF ACRONYMS

CAD	Computer Aided Drafting
UDRI	University of Dayton Research Institute
DSC	Differential Scanning Calorimetry
DMA	Dynamic Mechanical Analysis

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1. EXECUTIVE SUMMARY

This demonstration sought to show a dramatic reduction in tool cost for RapidClave® tooling, taking advantage of recent modifications made on the RapidClave® system. Instead of building tools with complex internal heating, simple aluminum tools would be produced and heated externally through the recently added hot plate and air blower inside the RapidClave® system. Baselining against this tooling is the legacy RapidClave® tooling, as well as compression tooling, which would be the incumbent processing technique that the RapidClave® is displacing.

Both an automotive and aerospace application were used to evaluate the tooling and process. Specifically, a four-piece Volkswagen hood structure was selected as an appropriate automotive geometry, while a wing structure representative of a current wing entering limited production was provided by Cornerstone Research Group for evaluating aerospace applications. In total, six tools were fabricated, and costs were compared against compression tooling quotes of the same tool geometry. A cost savings of over 80% was shown on all the tools.

This demonstration also produced parts in the RapidClave® using the abovementioned tools to validate the low-cost tooling and the machine modifications. Solvay recommended two prepreg systems, CYCOM® EP2750 and SolvaLite™ 712, as appropriate for aerospace and automotive applications, respectively. Flat panels of each material were fabricated to verify cure parameters before proceeding with actual part fabrication. On-tool cycle times of approximately 30 minutes was achieved, with modifications identified to lower the time further.

2. INTRODUCTION

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.

RapidClave® technology challenged legacy thought processes and now has established a new paradigm for advanced composites curing technology. This innovative approach has been a key influence for material suppliers to innovate aerospace type polymer chemistries for even greater curing efficiencies that as recent as 10 years ago were simply viewed as “future state”. These new and innovative polymer systems are now finding application in mainstream, high volume applications in the automotive industry, yet opportunities remain.

The legacy tooling approach for RapidClave® resulted in long lead times and high costs, limiting the application of RapidClave® technology in markets outside of the high-volume automotive industry. Recent proof-of-concept efforts to demonstrate a rapidly produced, low-cost tooling approach indicate a significant opportunity to open-the-door to RapidClave® production application in the aerospace market with tooling costs comparable to typical aerospace tooling and a fraction of the cost for automotive application. This effort seeks to expand on these early demonstrations for a real world automotive application by taking advantage of previous lessons learned and new rapid-cure resins to establish a RapidClave®

manufacturing process more suitable for lower volume production.

3. BACKGROUND

The RapidClave® has 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. Previous IACMI investment retrofitted the current UDRI RapidClave® to remove the need for integrally heated tooling. This was done by installing a hot plate with heated oil channels embedded within the plate. Individual tooling without 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 since the integral heating can be omitted on future tools. Figure 1 shows the plumbing in a legacy integrally heated RapidClave® tool.

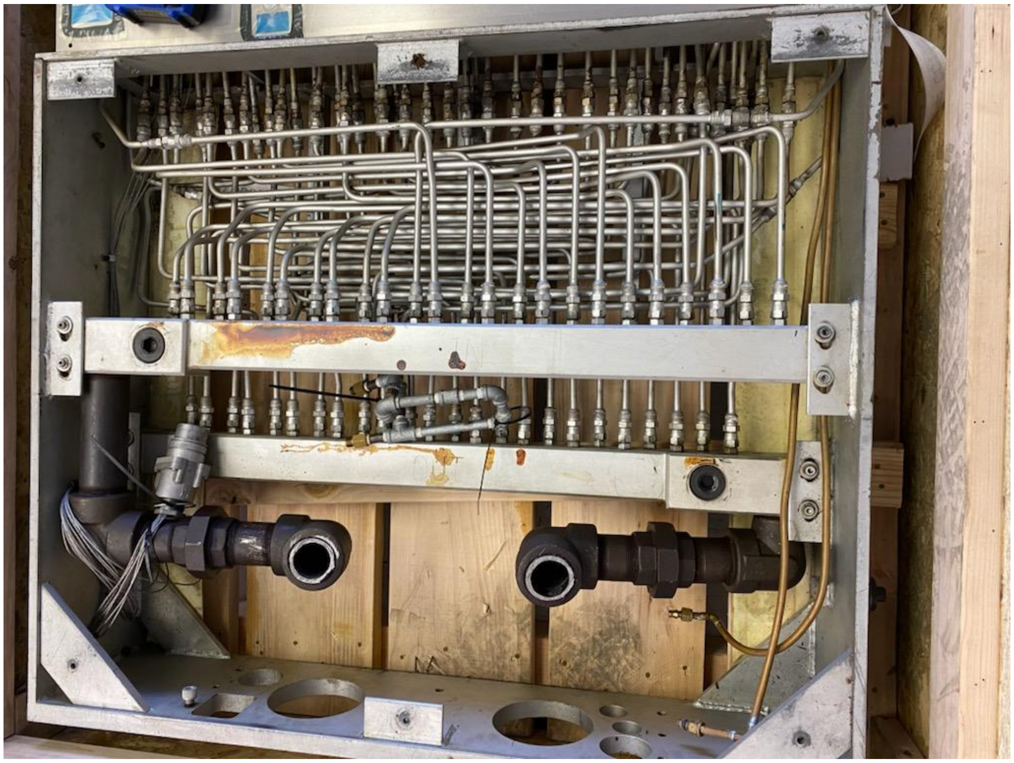


Figure 1. Typical plumbing for an integrally-heated tool

Also done during the retrofit was the inclusion of a hot air blower to supplement the hot oil heat. This allows 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 plate. This additional heating capability more than offset the efficiency lost by moving the integral heating channels to the hot plate rather than directly in the tooling.

The retrofit was done to address the high tool costs associated with the legacy tooling approach. This project demonstration sought to validate that these deficiencies had been addressed, and in doing so, changed the operational structure of RapidClave®. 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 positioned onto a preheated plate and rapidly cured. Parts would be demolded hot, and the machine would then be ready to accept the second ply stack. The result expected was faster cycle times and far less energy consumption.

4. RESULTS AND DISCUSSION

4.1 Material Selection

Solvay helped to identify two snap-cure prepregs that would serve the aerospace and automotive industry. CYCOM ® EP2750 is a toughened epoxy prepreg system well-suited for aerospace applications with an on-tool time of 30 minutes. SolvaLite™ 712 was selected for automotive applications, primarily due to its three to six minute on-tool cure time. Both materials have been used in press and autoclave processing and were expected to process well in the RapidClave®.

A rapidly curing paste adhesive was also selected for the aerospace wing section fabricated in this program. AeroPaste® 1006 (Solvay) was chosen because it provided a large processing window, allowing for a low-temperature cure (160 °F) for 4 hours or an accelerated cure of 1 hour when the cure temperature is raised to 250 °F. The optimal balance between cure speed and performance is still under investigation by Solvay, and this program will explore these trade-offs as well.

4.2 Tool Design

Volkswagen identified four hood components as parts of interest and provided CAD to UDRI. Single-sided tools were designed for each part, to be CNC machined from aluminum billets. Only one of the four tools are available for release in this report)(Figure 2).

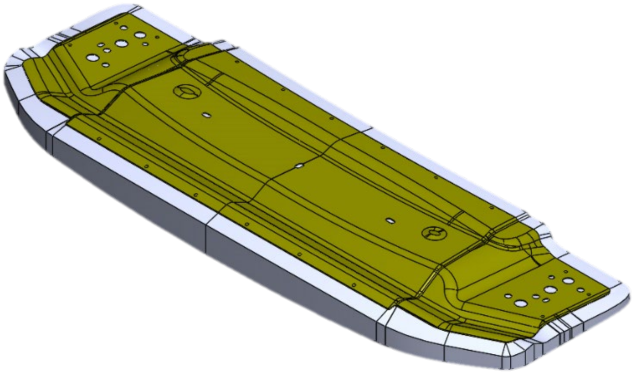


Figure 2. CAD rendering of Volkswagen tool and part (approx. 24" x 8" x 1")

The tools were designed without pocketing on the back so that maximum contact could be made with the heated tool plate, thus improving thermal performance and reducing machining costs. Figure 3 shows the integrally heated hot plate with a removable tooling plate to protect the hot plate surface. The tool plate measured 61" x 44". Cure tools were designed to rest on the tooling plate surface and be heated by the hot air blower as well as by the hot oil in the hot plate.

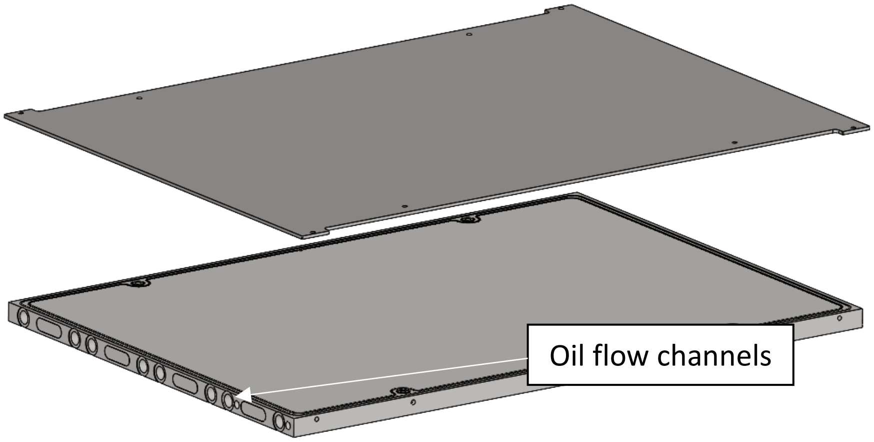


Figure 3. Schematic of RapidClave® tool plate

Similar tooling was also designed for the wing demonstrator, although the tooling was more complicated due to the multi-component nature of the wing. The wing was split into a top and bottom half, and tools were designed for both. The top half (Figure 4) included provisions for co-curing the front and rear spar onto the top skin. This entailed two removable mandrels that would allow for lay-up of the spar prepreg plies. The mandrels would then be placed into the mold cavity, on top of the wing plies, and allowed to "float" so that consolidation would not be prevented during the cure. A floating caul was included on the trailing edge to better form the edge.

A detachable section of the leading edge of the tool was also included. When removed after cure, this would expose the leading edge and allow for mechanical trimming of the edge without demolding the part, thus streamlining the post-bonding step.

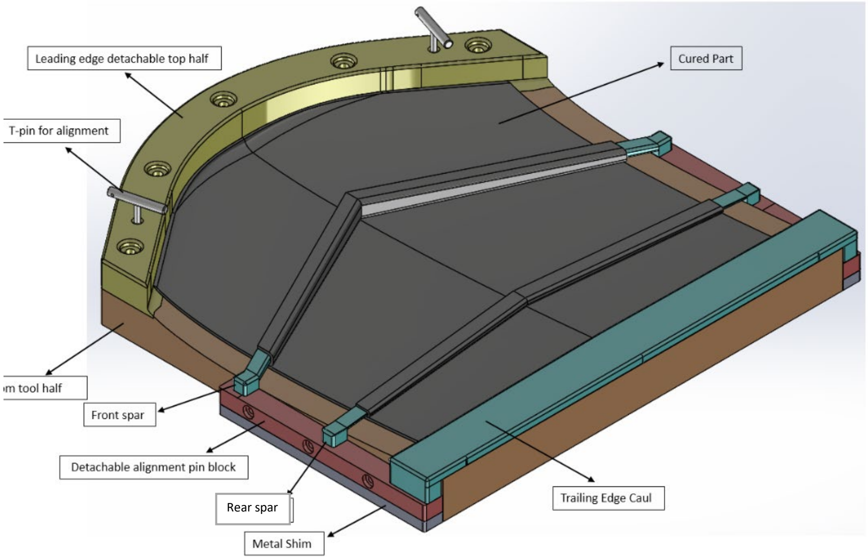


Figure 4. Wing demonstrator tooling, top half

The bottom tool half (Figure 5) was designed similarly, although no provisions for spars were included. The detachable leading edge was also omitted. The bottom wing skin was to be fully demolded for bonding, so trimming could be done off-tool.

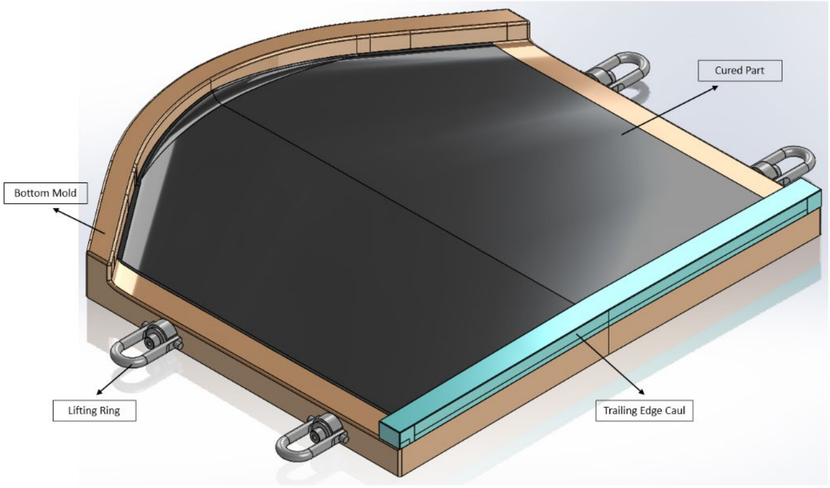


Figure 5. Wing demonstrator tooling, bottom half

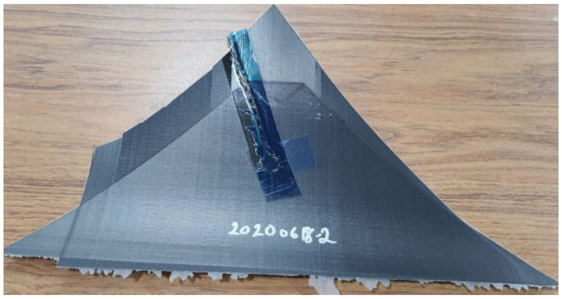
4.3 Part Fabrication

Flat panels of each prepreg material were made to validate that the correct cure parameters were being used. These are listed for both prepregs in Table 1 and Table 2.

Table 1. CYCOM EP2750 prepreg cure parameters

Cure Parameters for EP2750 Prepreg • Tool preheat to 350 °F • Hot air preset to 375 °F • Tool and air temperature lowered to 330 °F once lay-up shuttled into RapidClave® • 100 psi applied in 2 minutes • 30 minute soak at 330 °F (350 °F post cure off-tool) Total on-tool time: 36 minutes	

Table 2. Solvalite 712 prepreg cure parameters

Cure Parameters for Solvalite 712 Prepreg • Tool preheat to 200 °F • Hot air preset to 400 °F • Tool temperature ramped to 285 °F as rapidly as possible • 100 psi applied in 1 minute • 6 minute hold at 285 °F Ramp time: 6 minutes Total on-tool time: 15 minutes	

One of the flat panels made with SolvaLite™ 712 was selected for further investigation. The 25-ply panel was cut and pieces were subject to fiber volume analysis, microscopy, and T_g determination. Fiber volume, determined with the acid digestion method ASTM D3171 Procedure B, was found to be 60%. Void content was found to be -0.38%. This negative value is caused by the error in the test method and obviously not a real number, but it does indicate the void content is very low. Microscopy also confirmed the absence of voids (Figure 6).

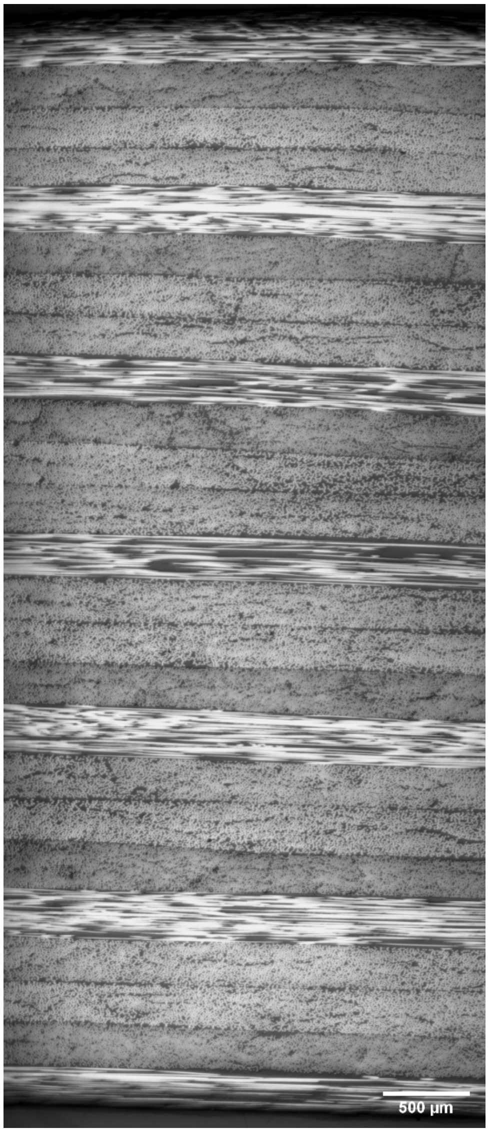


Figure 6. Microscopy of cured Solvalite 712 flat panel

Differential scanning calorimetry (DSC) was used to determine T_g of the cured panel. A value of 329 °F was determined, very close to the predicted T_g of 338 °F as recorded on the datasheet using dynamic modulus analysis (DMA).

After validating the cure parameters, the team moved on to fabrication of the Volkswagen parts. Prepreg was cut and kitted according to the part specifications provided by Volkswagen. These kits were preshaped so that they could be placed immediately onto a preheated tool. Two methods were investigated for this preshaping activity. The first involved building up the four-ply stack ply-by-ply, in the traditional manner (Figure 7). This worked well, but was time consuming.

Figure 7. Preshaped ply stack fabricated ply-by-ply

The second approach was similar to how material would be loaded into a press. The plies were stacked in the correct orientation, then debulked to the tool as a single stack. Approximately 50% time saving was demonstrated during the preliminary trials using this approach for the CYCOM EP2750 (Figure 8). Some wrinkling was present in the material, but optimizing the process should lead to no wrinkles (e.g. adding some tension and/or adjusting temperature and forming pressure). This has previously been demonstrated by Solvay with this material for compression molding applications, so it should not be a large future effort.

The same approach was also taken with the 712 material, but the unidirectional fiber architecture did not lend itself well to this approach. The fibers tended to split apart from one another in the fill (transverse) direction, leaving large gaps within the plies. Large wrinkles also occurred because the unidirectional material has no ability to stretch around contours. With a more drapable weave, the approach would have likely been successful.

Figure 8. Preshaped ply stack fabricated in a single debulk operation

Preshaping the ply stack allowed the lay-up time to be decoupled from the cure tool and RapidClave®, increasing throughput and lowering capital expense in a production environment. To further improve the cost efficiency of this approach, one of the parts used an additively manufactured draping tool (Figure 9) to demonstrate a non-metallic tooling approach. The AM tool was over 50% cheaper than its milled aluminum counterpart because it could be made with low-cost, commodity feedstock and needed no substantial post-processing. Using an AM draping tool would allow a manufacturer to essentially get two tools for the price of one, doubling the lay-up rate of the parts.

Figure 9. Additively manufactured draping tool

The preshaped ply stacks were positioned onto tools that had been preheated to the appropriate temperatures, depending on the prepreg used (Figure 10). A reusable silicone vacuum bag, obtained from Torr Technologies, was placed over the part and tool, and the hot plate was shuttled into the RapidClave® for cure. After cure, the parts were demolded and inspected for quality (Figure 11).

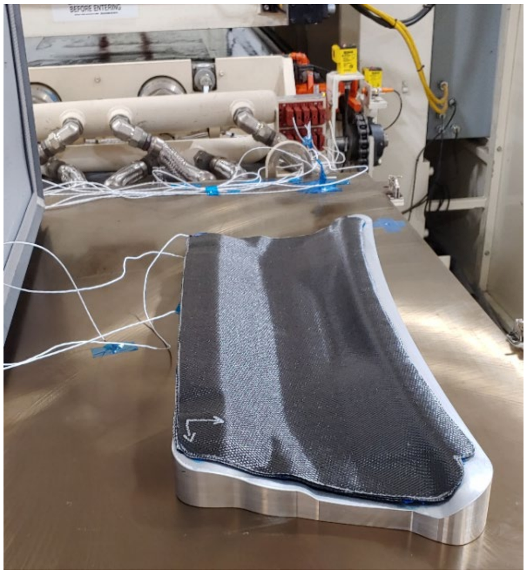


Figure 10. CYCOM 2750 ply stack on preheated Volkswagen tool

Figure 11. Cured CYCOM EP2750 Volkswagen part

One of the Volkswagen parts fabricated with CYCOM EP2750 was selected for a more thorough quality investigation. Trimmed areas of the part were used for fiber volume determination, T_g check, and microscopy. Fiber volume, determined with the acid digestion method ASTM D3171 Procedure B, was found to be 58% with only 0.5% void content. Both of these numbers indicate a well consolidated composite. This was further confirmed through microscopy, with little to no voids evident (Figure 12).

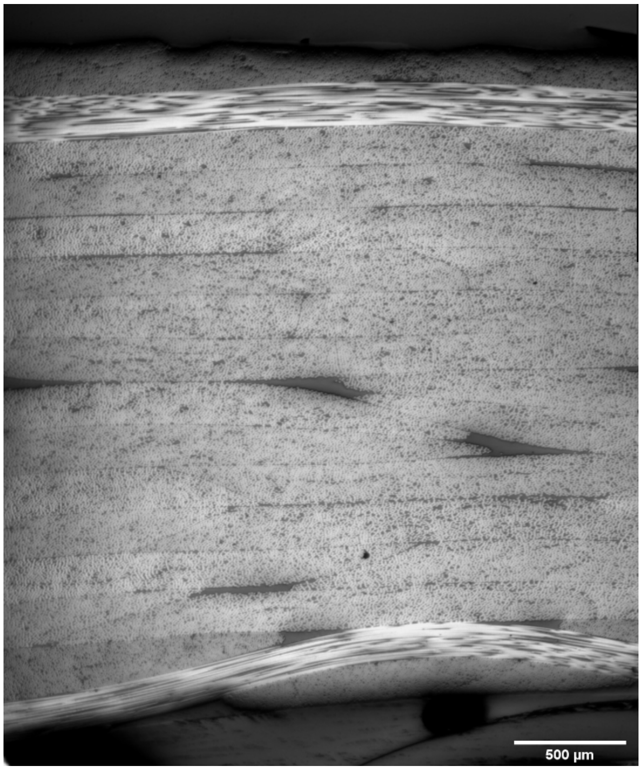


Figure 12. Microscopy of Volkswagen part made with CYCOM 2750

As previously mentioned, the CYCOM 2750 was cured using a two-step process. The initial 30 minute cure at 330 °F achieved an approximate 80% degree of cure and was sufficient to allow a freestanding post cure of 375 °F for 30 minutes. The post cure was conducted off-tool in a batch oven so as to make better use of the cure tool and RapidClave®. DSC was conducted before and after the post cure. Prior to the post cure, a substantial energy release is observed to occur, beginning just prior to the initial cure temperature of 330 °F (165 °C on chart) (Figure 13). After the post cure, a T_g of 365 °F (180 °C on chart) was recorded (Figure 14). This is slightly lower than the 380 °F reported on the datasheet, but is well within the differences between test equipment and parameters used.

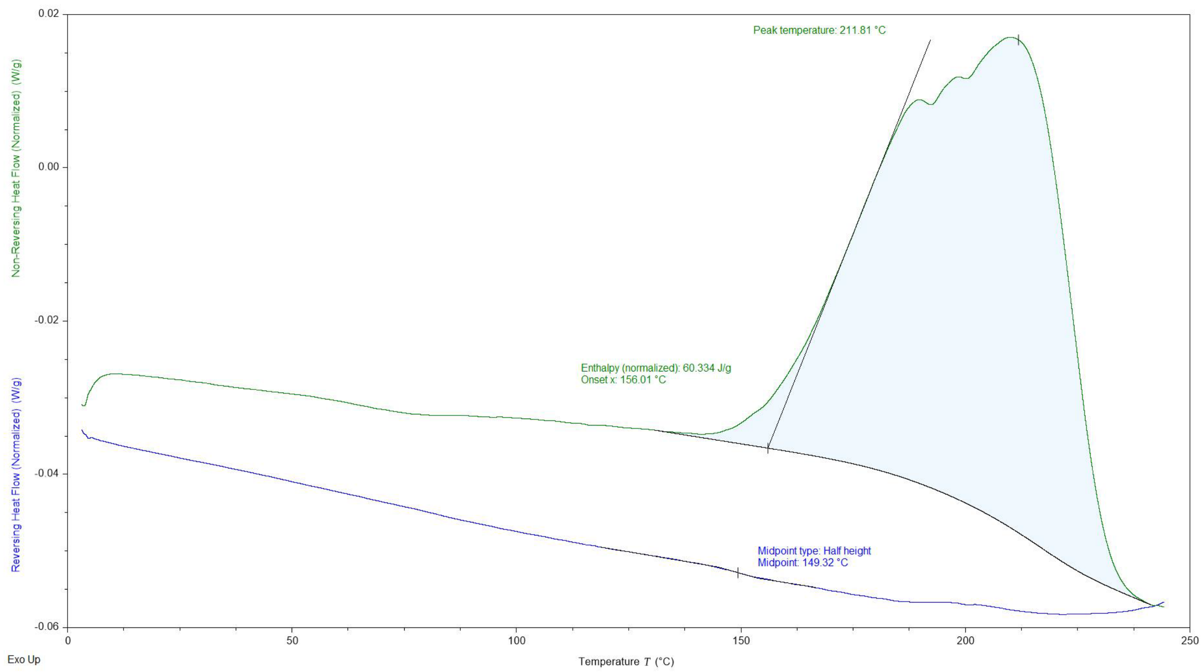


Figure 13. DSC of CYCOM EP2750 composite prior to post cure

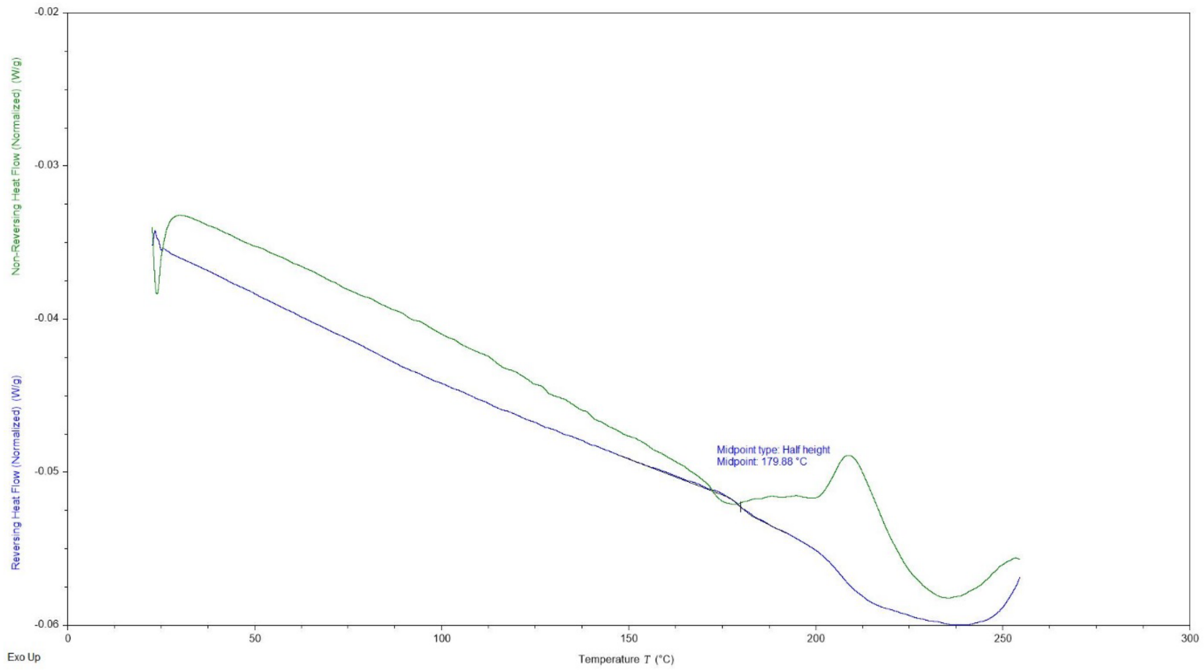


Figure 14. DSC of CYCOM EP2750 composite after post cure

Tooling for the wing section was fabricated and is shown in Figure 15 and Figure 16. Due to budget and time constraints, parts were not able to be made on the wing tools. This was not necessary in meeting the project milestones. It is expected that parts will be made from the tools in follow-on RapidClave® work outside of this project in 2021.

Figure 15. Bottom wing skin tool

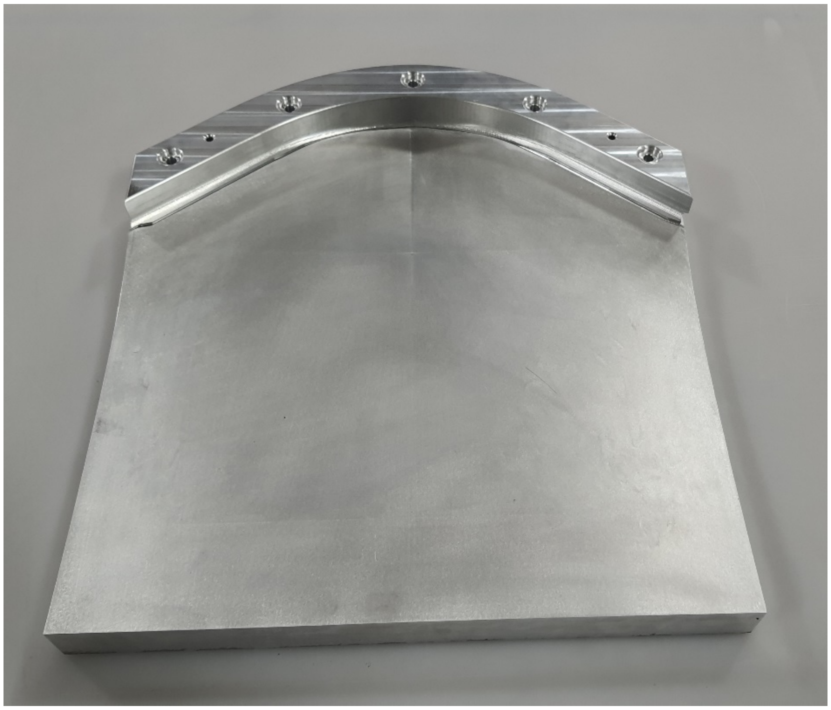


Figure 16. Top wing skin tool

4.4 Cost Analysis

Dramco Tool Company (Grand Island, Nebraska) was contracted to fabricate the Volkswagen RapidClave® tooling. They also supplied quotes to make compression molding tools with the same geometry. These costs are tabulated in Table 3. The costs for the RapidClave® tooling is drastically lower, representing almost a 90% cost savings compared to a compression tooling for the entire set. This is largely due to the fact that compression molding tools are two-piece, match set tools that are tightly toleranced to ensure good mating. They are also constructed from steel and are stoutly built to survive the high compressive forces. The RapidClave® tools are single-sided, aluminum tools that don't require the same level of tolerancing. The low cost of the RapidClave® tooling was also possible because of the equipment retrofit that negated the need for integral heating, reducing the tool cost by 50% or more. This cost study fulfilled the requirements for meeting Milestone 5.1.15.

Milestone 5.1.15 RapidClave Low-Cost Tooling: Demonstrate a 50% cost reduction in prototype tooling supporting the RapidClave process compared to conventional machined steel tooling. Complete report on tooling design, performance, and cost.

Table 3. Volkswagen tooling costs

	Compression Tool	RapidClave® Tool
Tool #1	$92,000	$12,100
Tool #2	$65,500	$6,600
Tool #3	$65,500	$6,300
Tool #4	$54,000	$4,500
TOTAL	**$277,000**	**$29,500**

The same cost study was conducted for the wing skin tooling as well. To make for a more direct cost comparison, only the main tool of the top and bottom wing skin tools were compared. The removable spar mandrels and detachable leading edge were omitted because these would not be present for compression molding. The cost of a steel, match-set tool that would be used for production compression molding was quoted by Dramco at $42,500 for the upper skin and $40,500 for the lower skin. This totals to $83,000. The quoted cost for a single-sided upper skin tool and a lower skin tool to be used in the RapidClave® was $6,400 for each tool, totaling $12,800. This represents a cost savings of over 80%, well beyond the requirement for meeting Milestone 5.1.15.D1.1. This cost data is presented in Table 4.

Table 4. Wing skin tooling costs

	Compression Tool	RapidClave® Tool
Upper wing skin tool	$45,500	$6,400
Lower wing skin tool	$40,500	$6,400
TOTAL	**$83,000**	**$12,800**

5. BENEFITS ASSESSMENT

The effectiveness of the low cost tooling, in conjunction with the RapidClave® retrofit, allows for this processing technique to be a preferable alternative to autoclave processing. Since its inception, RapidClave® has boasted significant cycle time reductions compared to autoclave processing, but the need to build custom tooling that costs five to ten times more than an autoclave tool limited its acceptance. With this new tooling approach, tooling identical to that used in autoclave processing can be used.

The improved processing approach also allows RapidClave® to be a strong alternative to compression molding. Cycle times are now similar to compression molding, and tool costs are 80% less than match-set compression tooling. Before this project, RapidClave® tool costs were still twice that of compression molding, offering little incentive for manufacturer's to make the switch.

Tool cost is an important consideration in comparing these processes, but machine operation cannot be overlooked. Drawing on Globe's experience in manufacturing and running presses, as well as the RapidClave®, the team compared the hourly cost of running comparable equipment. The RapidClave® at UDRI's facility costs approximately $100 per hour to run, accounting for electricity, compressed gas, and amortized maintenance costs. By comparison, a 2000-ton press capable of producing similarly sized parts costs $225 to run. Autoclave processing is higher still, approximately double that cost.

In summary, adoption of this technology and the improvements made during this investigation, would allow manufacturers to match the cycle times of compression molding with tool costs matching that of autoclave processing, all while improving hourly processing costs by at least 50%. Widespread adoption would have a profound effect on energy consumption in composite manufacturing.

6. COMMERCIALIZATION

Although many markets would benefit from RapidClave® processing, the urban air mobility (UAM) market perhaps stand to gain the most. Within the next ten years, the market is projected to be worth over $15B [2]. This represents tens or hundreds of thousands of new vehicles being manufactured, all heavily reliant on composites to meet weight and performance requirements. This fleet size places the manufacturing, in terms of volume, somewhere between aerospace and automotive. This is a somewhat awkward position that outstrips the capabilities of conventional autoclave processing, typical of aerospace manufacturing, but does not necessarily rise to the level of investment needed for full-rate automotive production lines. In addition, the part quality must meet that of aerospace standards, further reducing the opportunity to pull automotive processes into this market.

The RapidClave® is uniquely positioned to address this gap in production capability, allowing for the production of aerospace-quality composite structures at a rate previously not possible. This investigation has laid the groundwork for its adoption.

7. CONCLUSIONS

This program set out to demonstrate a low-cost tooling option for RapidClave® that would make the technology even more competitive against incumbent technologies and offer the aerospace and automotive industries a processing solution capable of meeting required cycle times and part cost. Perhaps more pertinently, it gives manufacturers of urban air mobility vehicles a processing solution that yields aerospace-quality in a cycle time comparable to automotive requirements. Given the size that this industry is expected to grow to over the next decade, this has the potential to be extremely impactful. As reported, the milestones were easily achieved during this work, and high quality parts were fabricated, paving the way for future RapidClave® development and setting the stage for widespread commercialization.

One topic worth discussing further is that the parts examined in this effort were relatively flat, with little z-height variation. Parts with more significant height variation will exhibit more temperature variation since the hot plate heat must travel through thicker tool areas to reach the composite (Figure 17). This may be offset by the fact that the blown hot air will be striking these same high areas with more intensity. At a minimum, it will require more effort to thermally map a tool with a large z-component and fine tune a thermal profile to match the intended cure cycle. This will need to be investigated further in future work.

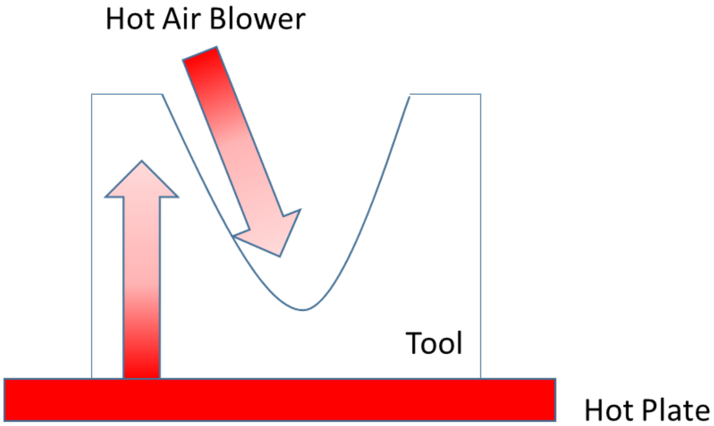


Figure 17. Example tool with large z-component

8. RECOMMENDATIONS

Further reducing the mass of the tooling will both lower the tool cost and provide for more responsive tooling, allowing for faster ramp up and cool down times. These transient periods offer the largest potential for reducing cycle times. Future modifications planned for the RapidClave® are likely to allow for a very thin tool shell that is exposed directly to a hot oil bath on the backside of the tool. This should have a dramatic effect on tool ramps rates and allow for lighter tools that require less material and machining. This would be a natural continuation of the work started in this effort.

Also, this program was hampered by the under-powered heat exchanger used to heat the circulating hot oil. Preheating cycles and ramp up rates were greatly extended as a result. This was a known issue at the beginning of the program and was driven by equipment budget constraints. Replication of the tool trial runs with a correctly-sized heat exchanger should show increased performance. This is slated to occur outside of this program in early 2021.

9. REFERENCES

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