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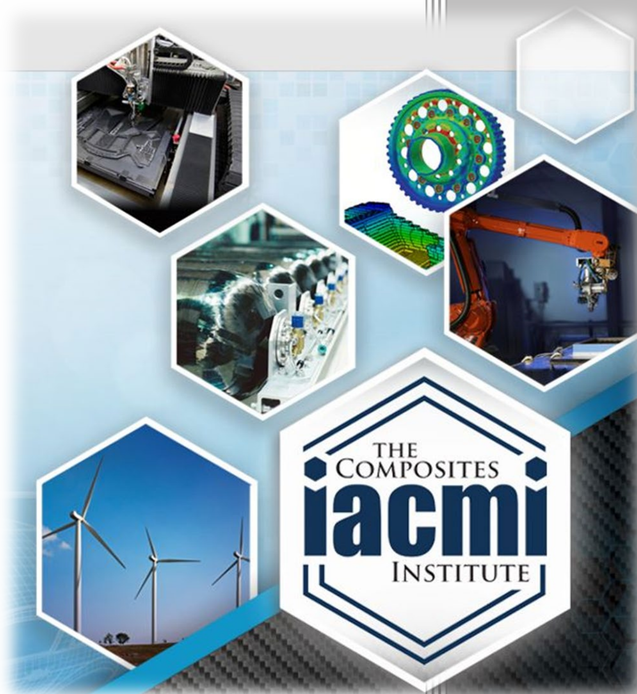
RapidClave Technology Demonstrations-II Kevlar Composite Vehicle Floor



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RapidClave Technology Demonstrations-II Kevlar Composite Vehicle Floor

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1. Lists

1.1 LIST OF ACRONYMS

UDRI	University of Dayton Research Institute
AM	Additive Manufacturing
TFP	Tailored Fiber Placement
PEI	Polyetherimide
CNC	Computer Numerical Control

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1.3 Acknowledgements

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2. EXECUTIVE SUMMARY

This Demonstration's objective was to develop enhanced methods to produce a complex preform comprised of Kevlar fabric and thermoplastic adhesive and rapidly consolidate the preform into the desired functional shape of a vehicular floor protection system. The approach and outcome goals were to reduce the tooling cost by 50% and shorten the processing time by 50% using the RapidClave® to consolidate the part rather than an autoclave.

UDRI partnered with O'Gara Armoring who currently produces one piece Kevlar floor composite laminates that offer enhanced impact resistance at lighter weights as compared to steel. These laminates are constructed by hand layup of 3000 denier K29 fiber in a plain weave architecture with a thermoplastic film adhesive layer manufactured by Barrday and will be referred to as semi-preg throughout this paper. The current process is labor intensive and costly. Current production rates are only about one per month but an improved process is expected to enable product growth.

A 50% reduction in tooling cost was achieved through the use of additive tooling, and the RapidClave® process enabled a 60% reduction in cycle time. Further cost savings were realized through the implementation of a preforming process that resulted in a 65% reduction in labor hours. This new approach for manufacturing reinforced vehicle floors has been partially implemented by O'Gara with plans to continue work on additional vehicle models. The cost savings has potential for increasing O'Gara's production to reach new markets, and lead to job creation.

3. INTRODUCTION

The objectives of this demonstration were to develop a tool fabrication strategy to exploit faster processing by the RapidClave® and to develop tooling and preforming concepts to minimize labor for arranging and consolidating a semi-preg preform. The semi-preg, manufactured by Barrday, is comprised of 3000 denier K29 fiber in a plain weave architecture with a thermoplastic film adhesive layer applied to one side of the fabric to allow for enhanced drapability. O'Gara's Kevlar floor composites require skilled technicians to drape rolls of Kevlar semi-preg to the complex tooling geometry and trim to shape. Several rectangular sections of Kevlar semi-preg of various sizes had to be precut before draping over the tooling and then cut by hand to the net shape. Five or more layers of the reinforcement is necessary for the vehicles. As layers build up the material can move around, requiring magnets and adhesive to tack the material in place. Also with limited tooling sets available, vehicle floor production is limited as the tooling is required for both lay-up and processing.

The project teams' approach to reducing cost and cycle time was to develop a preforming process in conjunction with low-cost additive tooling. Additionally, automation of labor intensive steps including cutting the Kevlar reinforcement further reduce manufacturing costs. Using this approach was estimated to reduce tooling cost by 50% when compared to traditional machined aluminum tooling for autoclave process, and reduce cycle time by 60% through use of

RapidClave technology.

4. BACKGROUND

This demonstration evaluates the cost and performance of both polymeric and metallic tooling for use with RapidClave®. The polymeric tooling is produced on UDRI's Titan Robotics printer as described below. Background information on the RapidClave® is provided in companion reports.

Part of UDRI's "Composite Production Work Cell" capability is additive manufacture (AM) of tooling. Polymeric tooling for this demonstration was fabricated using a 20% carbon fiber-filled polyetherimide (PEI) (Ultem®) pellets-to-part additive manufacturing extrusion process show in Figure 1.The Titan Robotics, Atlas printer has a build volume of 1m x1m x1.2m and uses various print nozzles ranging from 0.6 to 8mm, with an extrusion rate of 3-30lbs/hr. When large tools are fabricated, the part is broken into multiple pieces which are then glued together. In this demonstration the tooling that was fabricated fit within the printer's build volume. Further details may be found at the website https://titan3drobotics.com/.

Figure 1 Titan Robotics Atlas Printer

O'Gara Armoring produces a variety of specialty armored vehicles, some of which include a Kevlar reinforced floor. O'Gara produces these non-tactical armored vehicles in volumes of ranging from 10 to approximately 100 per year depending on the make and model. Manufacturing these reinforced Kevlar floors is both time and labor intensive. The complex floor geometry makes it difficult to create a consistent and repeatable composite structure. Prior to this project, there was no pattern or template for cutting the Kevlar pieces in the layup. O'Gara's layup involved draping several pre-cut rectangular sections of Kevlar over the metallic tooling. The sections of Kevlar were cut as needed and tacked down with a quick set adhesive to create mold-fitted preforms. The Kevlar semi-preg possesses limited drapability and is very difficult to cut by hand even with specialized tools. Consolidating the Kevlar semi-preg is also time intensive with long autoclave process cycles. Barrday's recommended process cycle for the Kevlar semi-preg calls for a 15-30 minute soak time at 290-330°F and 150-200psi. The laminate must be cooled under full pressure to between 120-140°F. O’Gara has modified this recommended process cycle by increasing the hold temperature to 375°F and cooling to ambient temperature before releasing pressure resulting in a longer cycle time. O’Gara’s autoclave process cycle is shown in Figure 2 and lasts nearly seven hours. The goal for this project was to increase O’Gara’s production efficiency of Kevlar reinforced vehicle flooring through new tooling and preforming approaches, paired with RapidClave® processing technology.

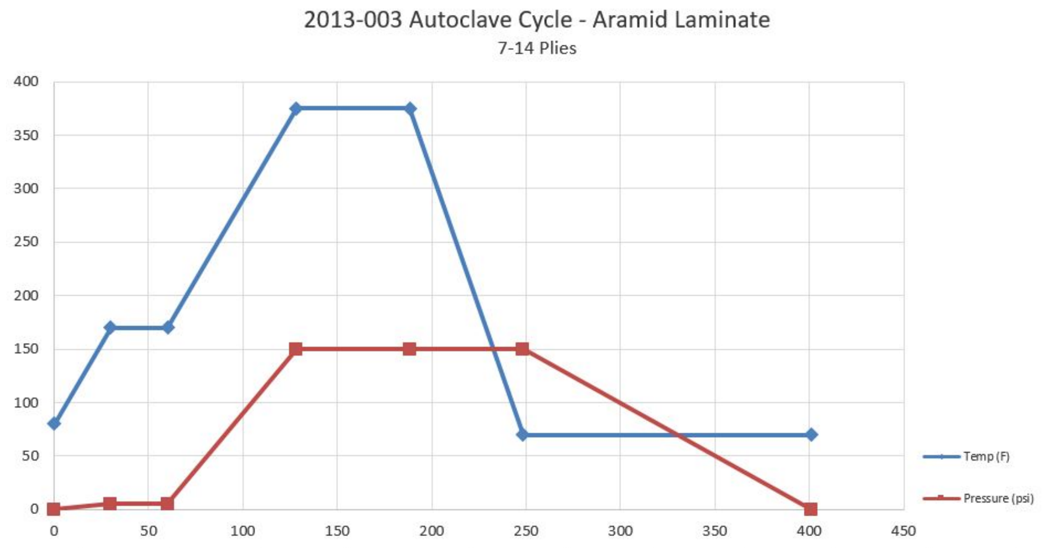

Figure 2 O'Gara Autoclave Process Cycle

5. RESULTS AND DISCUSSION

The approach toward fabricating the vehicle floor involved the pairing of a low-cost additive tool fabrication strategy with new preforming concepts to minimize the labor necessary for arranging the semi-preg. In order to reduce the amount of labor in producing the vehicle floor reinforcement, CNC cutting of the Kevlar semi-preg, and a repeatable preforming process were determined as the best path forward. Using CNC cutting creates a repeatable layer pattern that can simplify the layup process by reducing the total number of sections needed while minimizing post-processing labor such as trimming excess material. Small patches can also be CNC cut for any necessary splicing. Vehicle floor CAD models (Figure 3) were provided by O’Gara as starting point to create templates of the complex geometry.

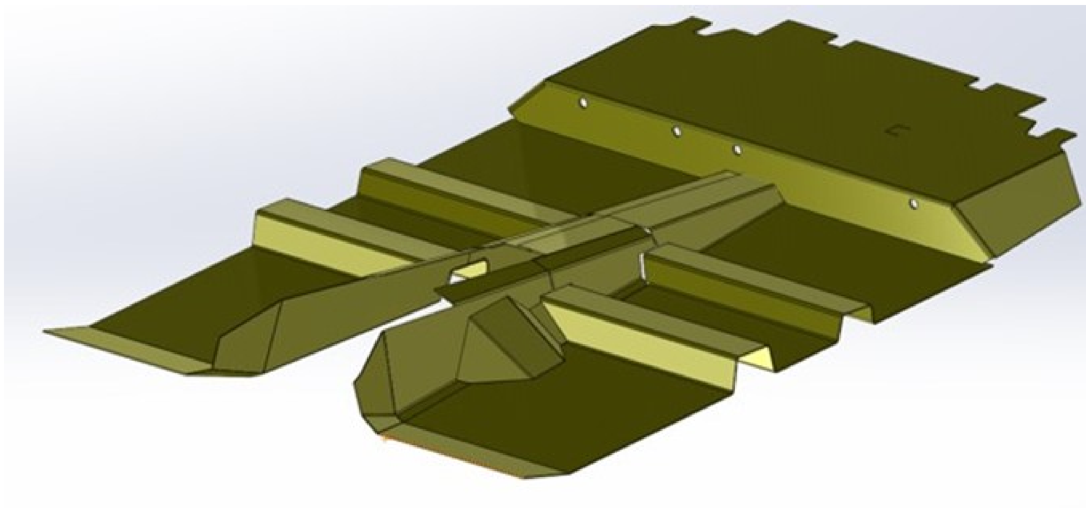

Figure 3 O'Gara CAD Model for Vehicle Floor

The provided floor model was comprised of three sections: driver side, passenger side, and rear. In order to CNC cut the Kevlar for these sections, each three dimensional section had to be converted into a two dimensional profile. This was accomplished using SOLIDWORKS flattening tools to generate .DXF templates as shown in Figure 4. These flattened templates were printed with paper and fitted to O'Gara's current tooling. O'Gara's current tooling is sheet metal welded together by hand (Figure 5). There were significant issues with the alignment of the templates on the existing tooling. Small differences between the model and the tooling led to the templates running off the tooling by several inches. It was decided to 3D scan the existing tooling to generate new templates. By 3D scanning the current tooling most of the differences between the CAD model and metal tool were be accounted for.

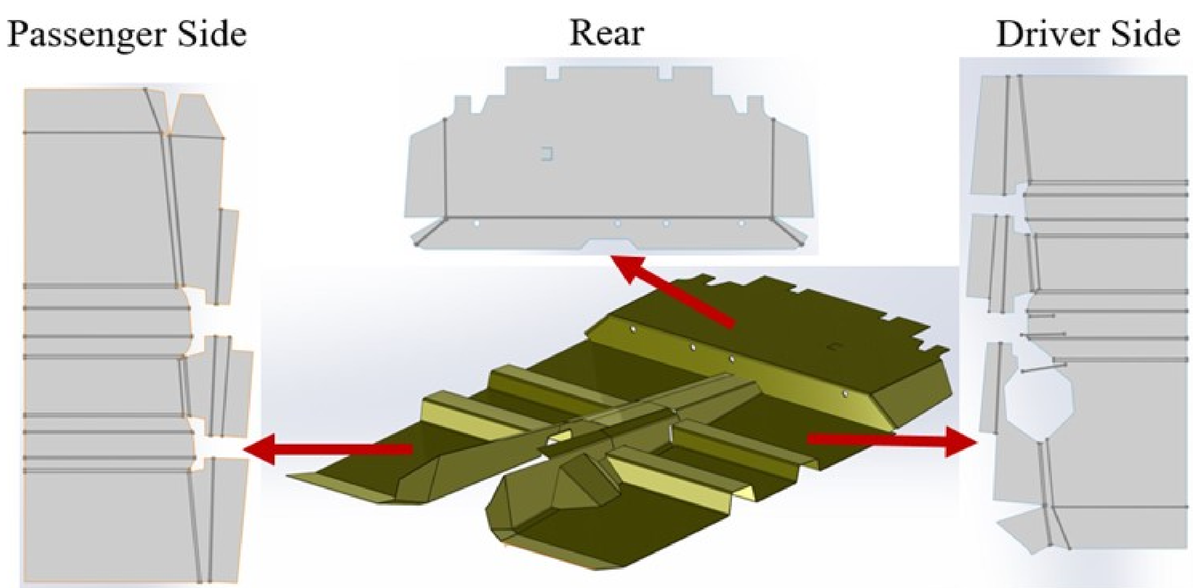

Figure 4 Floor Model .DXF Templates

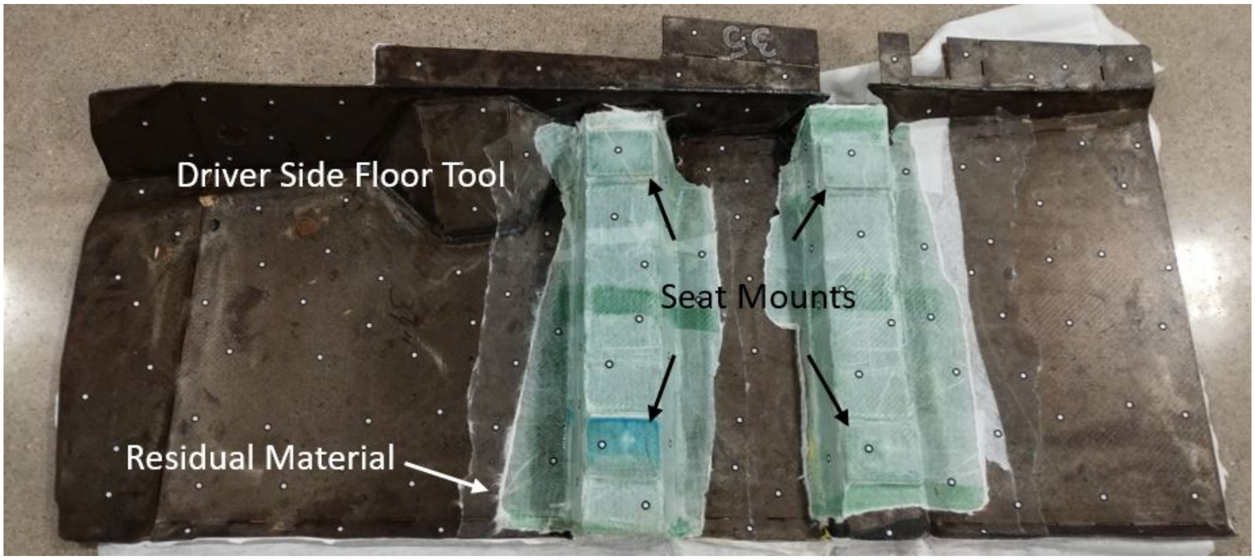

Figure 5 O'Gara's Current Sheet Metal Tooling

The 3D scans were generated with a Creaform Handyscan 700 3D scanner and imported to SOLIDWORKS. The scanned surfaces resulted in a complicated irregular surface (Figure 6) that needed to be simplified in order to create 2D templates. In order to simplify the irregular surfaces, a number of points were selected on significant edges and vertices to define new planar surfaces to reconstruct a model that could be flattened. Several iterations of these new templates were produced and printed with paper to test fitment. Kevlar was cut and fitment was tested after the paper templates appeared to fit the tooling well. Imperfections and residual material bonded to the existing tooling, along with the differences in drapability of the Kevlar and paper templates required several additional small changes to be made. With a working template for each of the 3 tooling sections (driver side, passenger side, and rear), additional updates were made to allow for a single template to be used for all five layers of reinforcement. With finalized templates the preforming process could be tested on the full geometry of the vehicle floor. This preforming process would later be used in conjuction with the AM tooling for a smaller section of the floor due to both print volume and RapidClave chamber volume limitations.

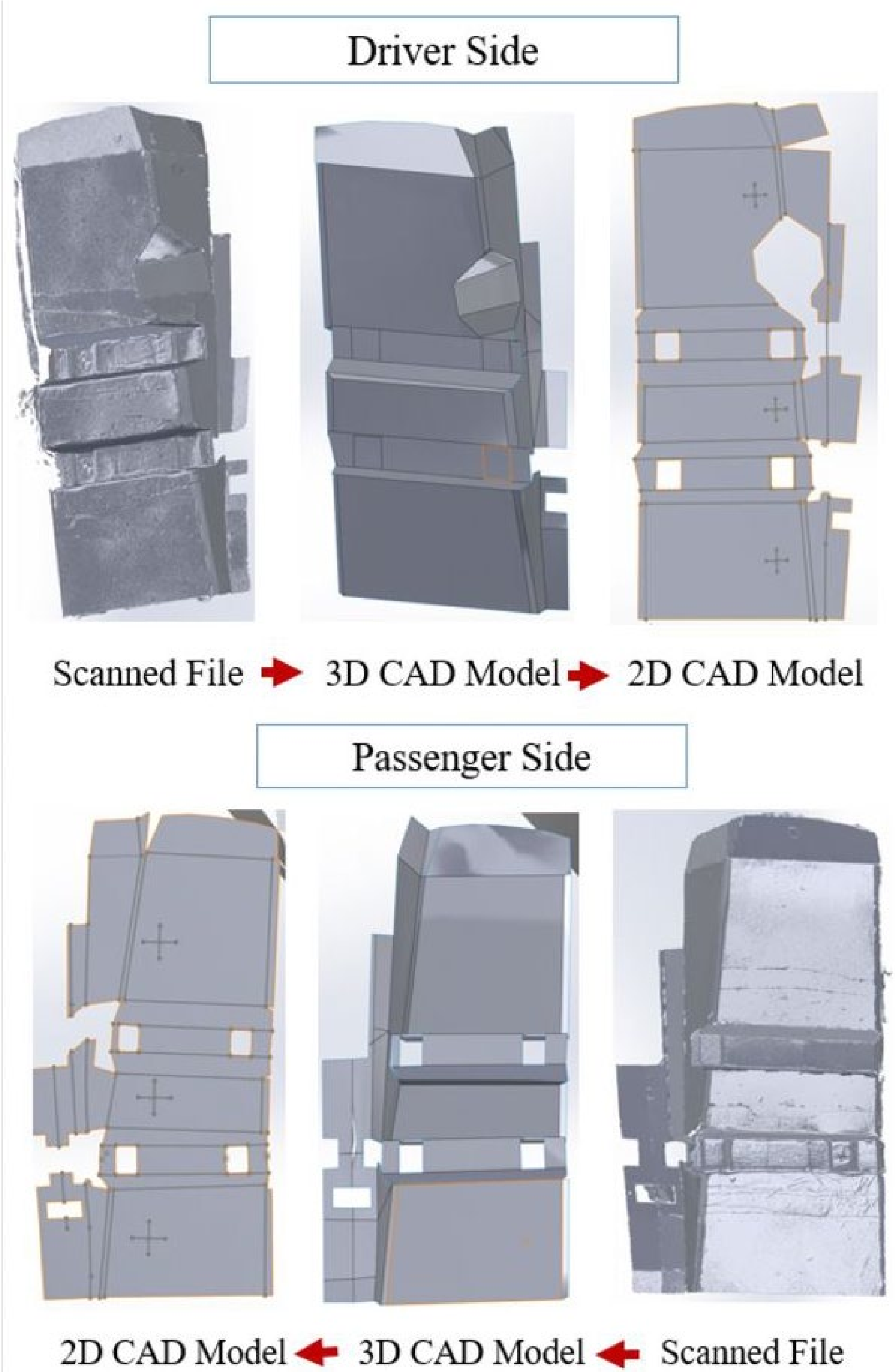

Figure 6 Floor Scans Rebuilt and Flattened

Initially, the goal was to use UDRI's Tailored Fiber Placement (TFP) equipment to quickly and precisely stitch all layers of the Kevlar semi-preg into a single drapable preform. However, due to the need for drapability across multiple contours, stitching the entire preform while flat would fix the position of the layers relative to each other. This lack of mobility would result in buckling and creasing on the inner layers of the preform when fit to the contours of the tool. This would also add an additional step and equipment requirement for O'Gara's preforming process so the implementation of TFP was abandoned. This led to an alternative preforming process: heating the semi-preg with an iron to tack the layers of reinforcement together by melting the thermoplastic film on the backside of each layer. O'Gara technicians currently use quick set adhesive to hold each new layer in place throughout the layup process, however, they would prefer to remove any additional materials from the final product. Tacking the thermoplastic film with heat not only removed the need for additional adhesive, but also allowed layers to be separated without affecting the woven Kevlar fabric if a misalignment occurred. Care was taken not to apply too much heat which would promote strong adhesion and prevent the layers from separating when required. This new preforming process (Figure 7) was tested with O'Gara's production team and received positive feedback. Floor sections produced (Figure 8) using the new templates reduced cut and layup hours from 18 hours to 13 hours. CNC cutting the Kevlar semi-preg was shown to further reduce the labor hours required to lay up each floor. This new preforming approach has been implemented into O'Gara's production, and has led to follow on work for addition vehicle models.

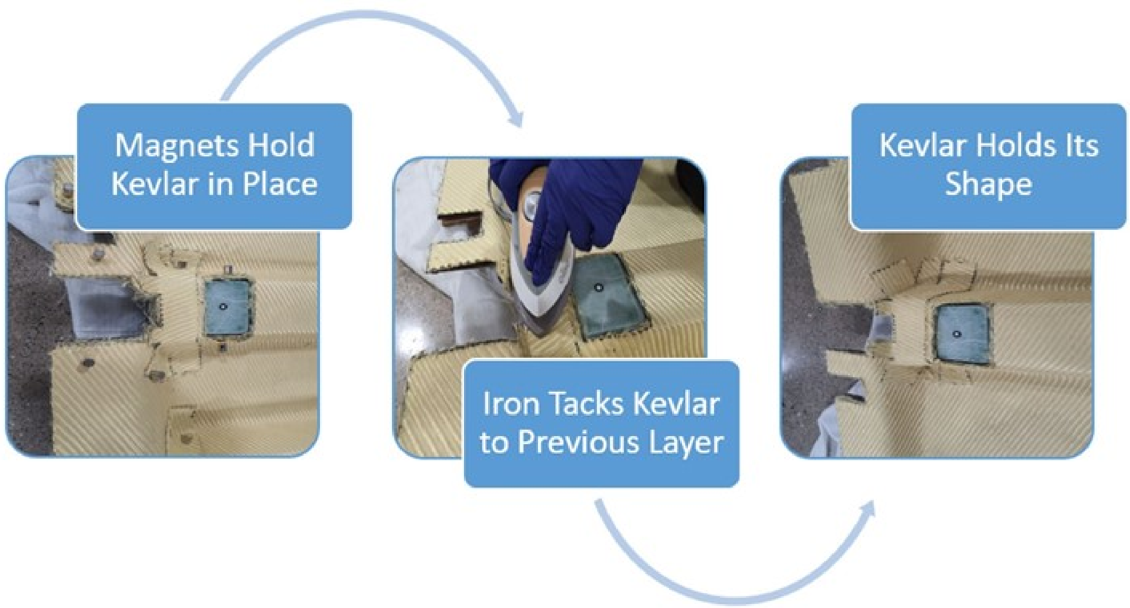

Figure 7 Kevlar Semi-Preg Preforming Process

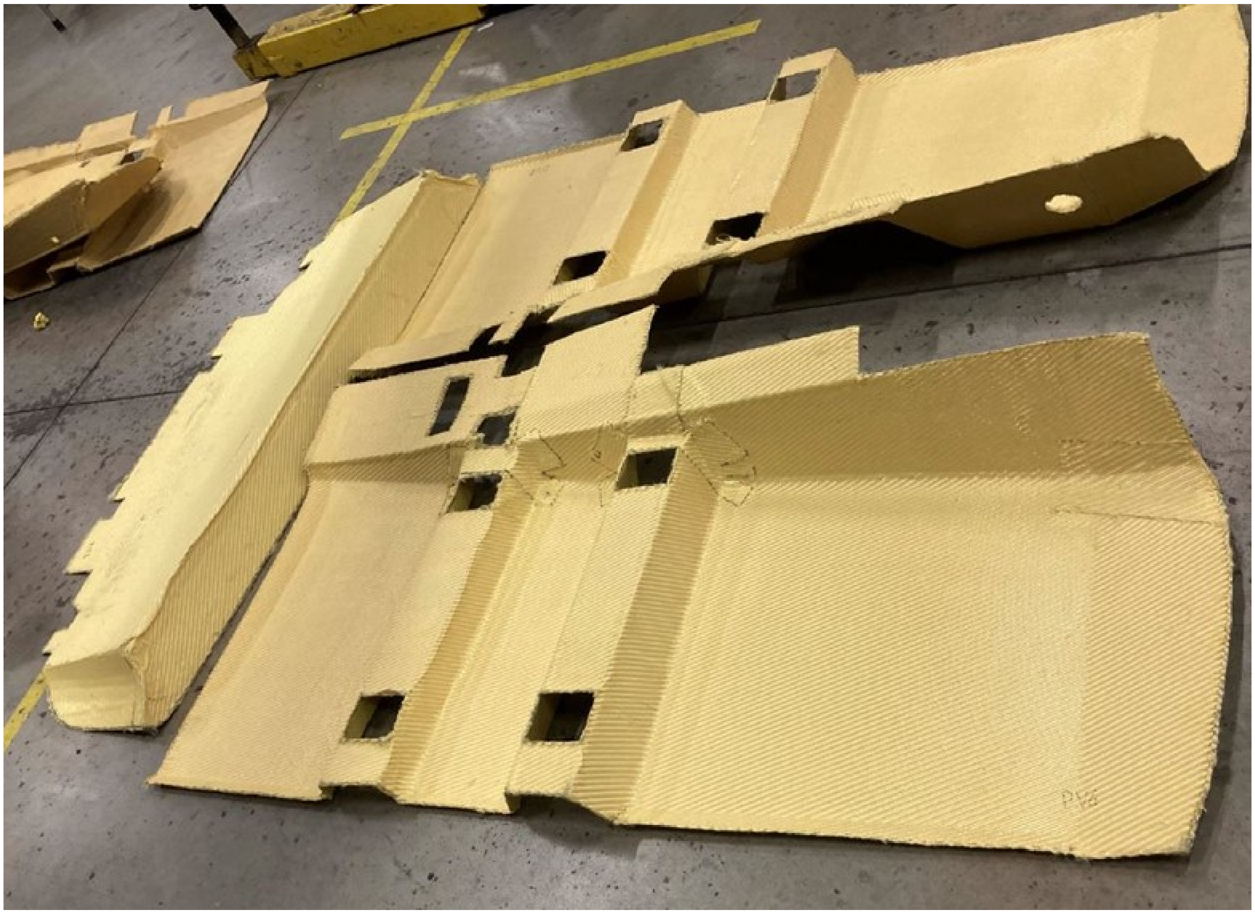

Figure 8 Kevlar Floor Manufactured with New Preforming Process

RapidClave® processing of the Kevlar semi-preg was also successful. A 12"x12", 5 ply flat panel was used as an initial test for the RapidClave®. Lay-up involved a Torr reusable vacuum bag with two layers of breather, and a release film on both sides of the Kevlar. The reinforcement was placed on the tool which was preheated to 290°F. The material was held at temperature for 30 minutes with 100 PSI of pressure, then cooled to 140°F before relieving pressure. Figure 9 displays a graph of the process cycle. The total run time was 102 minutes, while O'Gara's current autoclave process is 400 minutes. The 5 layers of material consolidated from an average of 3.78mm to 3.03mm (Figure 10) with the significantly reduced cycle time.

While the current configuration of the RapidClave® did not allow for process optimization during this study, there is a clear opportunity to reduce the process cycle as compared to the current autoclave cycle. The RapidClave® supports both bottom side temperature control using an oil thermal fluid and topside air temperature control that is discharged over the top of the part. Heating rates approaching 100°F/minute are possible when preheated oil is pumped into the base tool as shown in Figure 9 during process cycle start. Chilled oil from a second reservoir would be required to achieve a rapid cooling rate. This level of cooling is not typically required for thermosets and is not part of the current configuration.

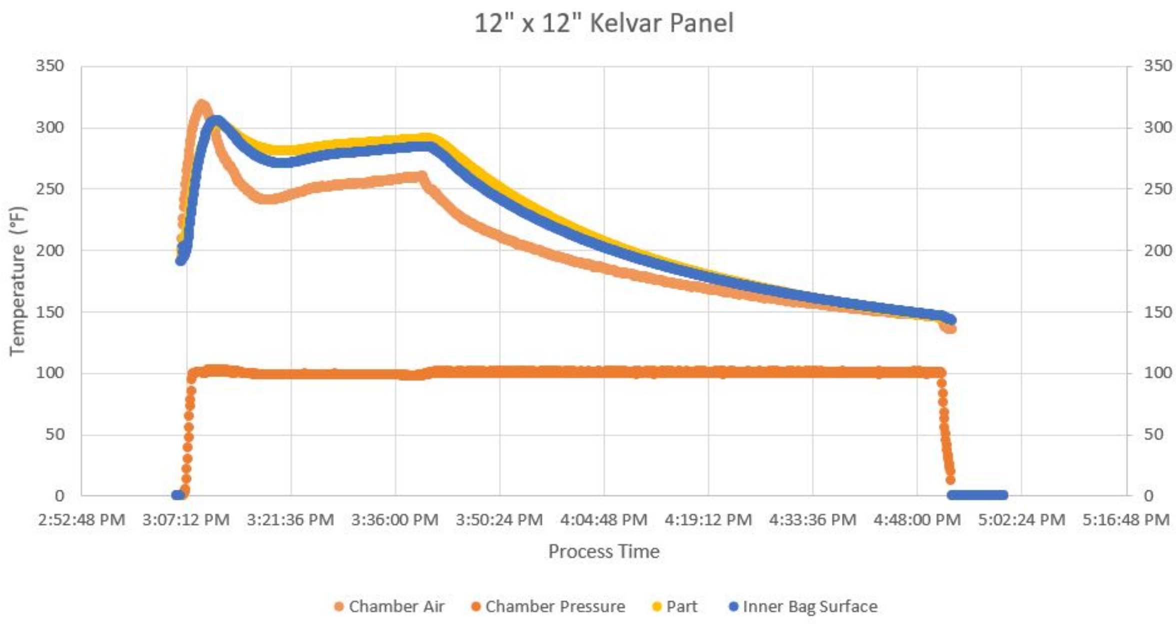

Figure 9 12" Kevlar Panel Process Cycle

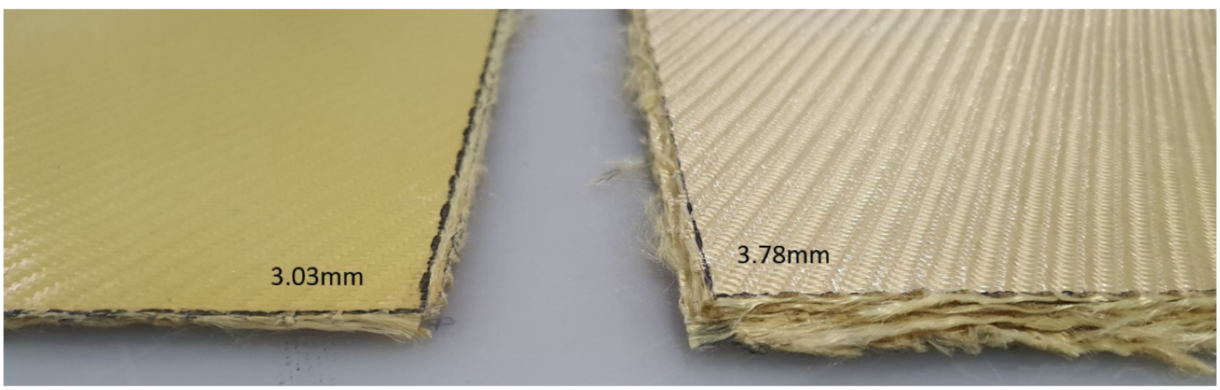

Figure 10 Kevlar Panel Consolidation

Due to the limited chamber height of UDRI's RapidClave®, only a section of the floor tooling could be tested. However, the cost analysis will examine the entire driver side tool. Figure 11 displays the section of driver side tooling that was printed. This portion of the driver side floor tooling was printed on UDRI's Titan Robotics Atlas large format 3D printer with a 20% carbon fiber-filled polyetherimide (PEI) (Ultem®) feedstock. The printed tool dimensions were 20"x20"x3.75" (LxWxH). The only bench work necessary for this application was light sanding (Figure 12). The Kevlar reinforced floors are not visible in the vehicles and thus have no surface finish requirements. This consideration allows the floor to be printed with a larger diameter nozzle resulting in faster print speeds.

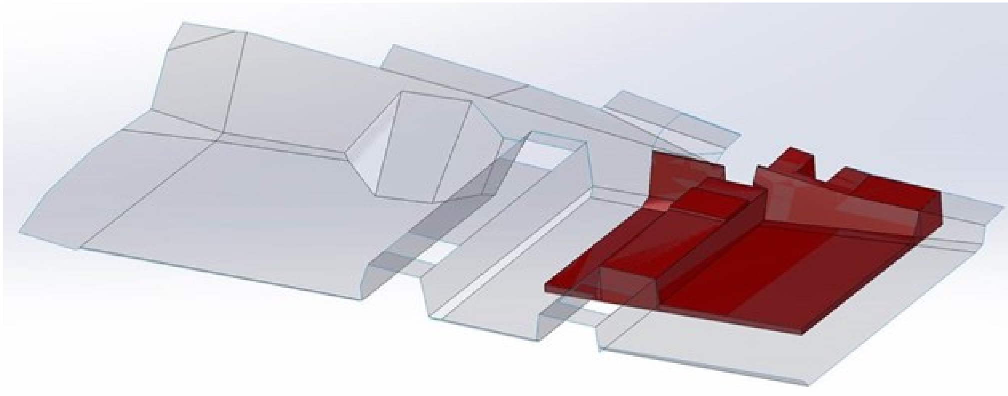

Figure 11 Section of Floor for RapidClave Processing

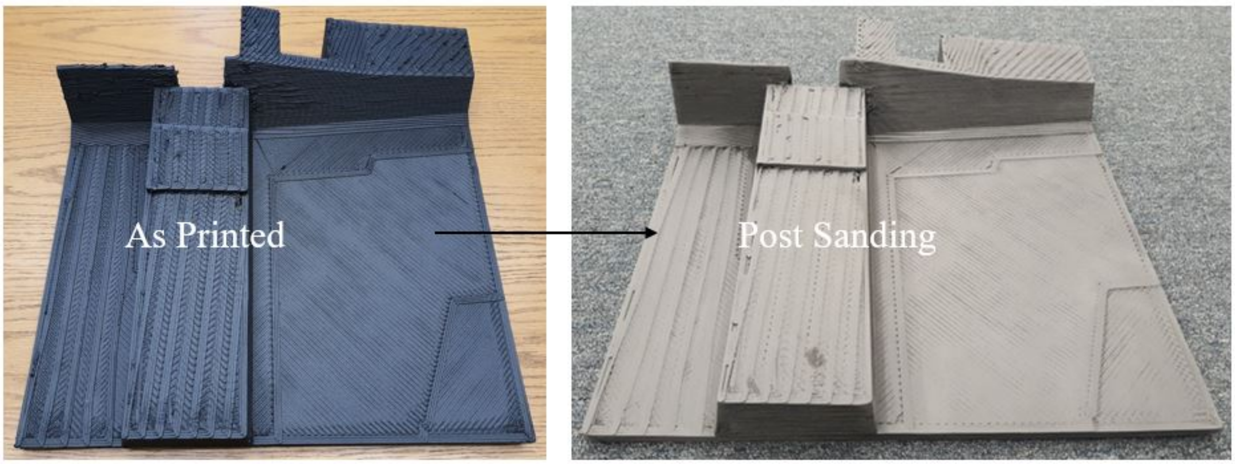

Figure 12 Printed Floor Tool Before and After Sanding (Apparent color change is due to lighting conditions)

The new preforming process used for the larger baseline part was used on this section of flooring (Figure 13). Preforming the semi-preg involved cutting the material by hand, and tacking the layers together with an iron. Layup was nearly identical to the flat panel, however the flooring section did not fit inside of the Torr reusable vacuum bag. Instead a Stretchlon 800 bagging film was used. This section was consolidated in the RapidClave® with no preheat due to schedule limitations. The semi-preg consolidated from 3.75mm to 2.95mm in thickness with a total cycle time of 170 minutes which represents a 60% time reduction. The process cycle can be referenced in Figure 14. The floor section produced had minimal frayed edges further reducing the amount of labor for post processing work (Figure 15). A further time reduction can be expected with the appropriate preheat of the RapidClave platen and chamber.

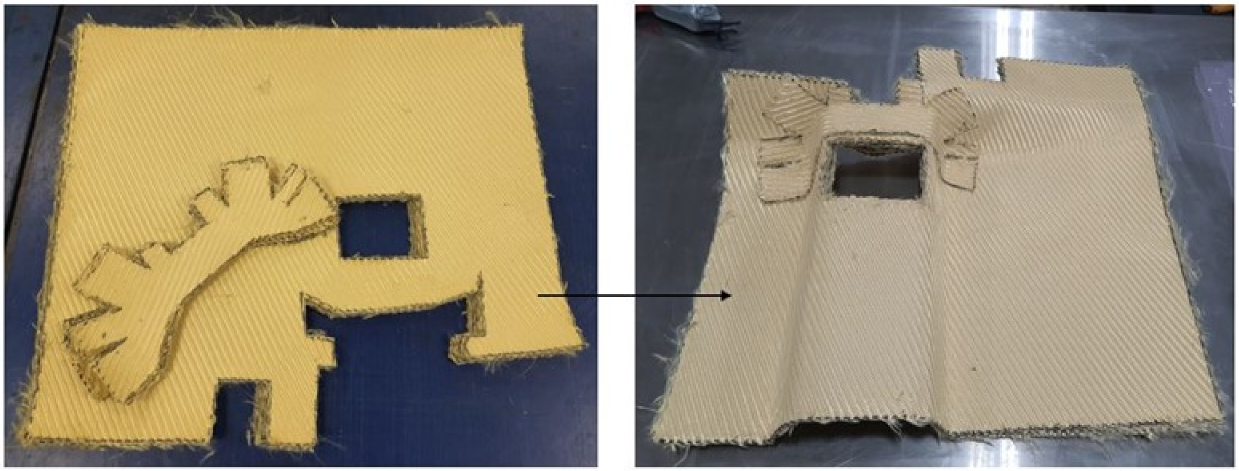

Figure 13 Floor Section Before Preforming (Left) and After Preforming (Right)

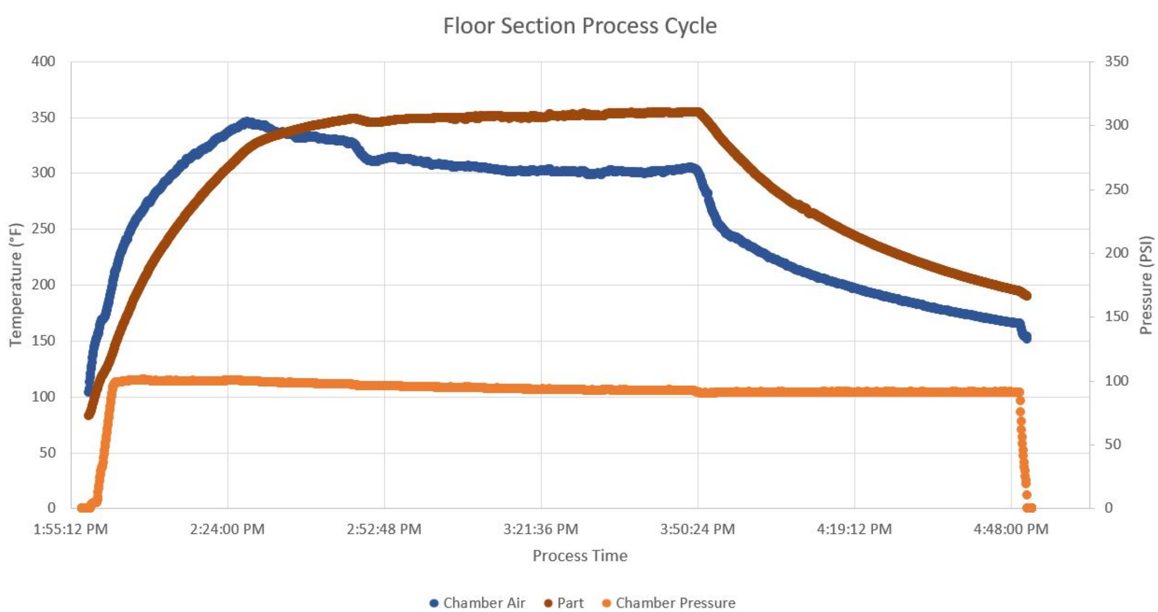

Figure 14 Floor Section Process Cycle

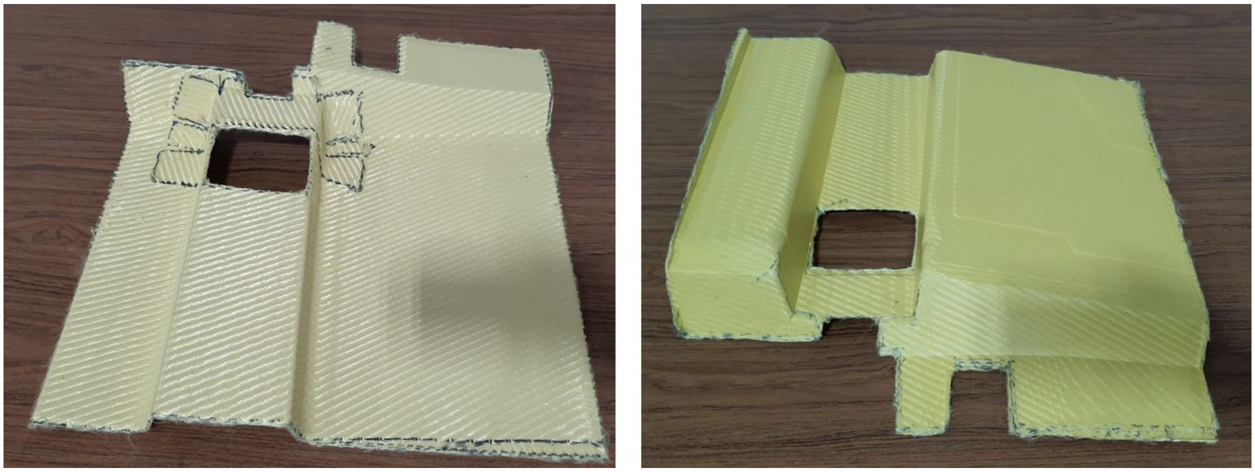

Figure 15 Floor Section Post RapidClave Processing: Left = Top of Part, Right = Bottom/Tool Side of Part

The floor tooling was laser scanned using a Creaform Handyscan 700 3D scanner post RapidClave® cycling (Figure 16). Slight curling (up to 0.04" or about 1mm) is apparent on the outer edges. This variance was present before RapidClave® processing, and may have been prevented with a higher chamber temperature during the print. This variance in the tooling is less apparent in the part due to the flexibility still present in the semi-preg post processing. Critical dimensions such as the width of the hump, and the square bump out are well within O'Gara's tolerances and helped to reduce post processing time and labor requirements.

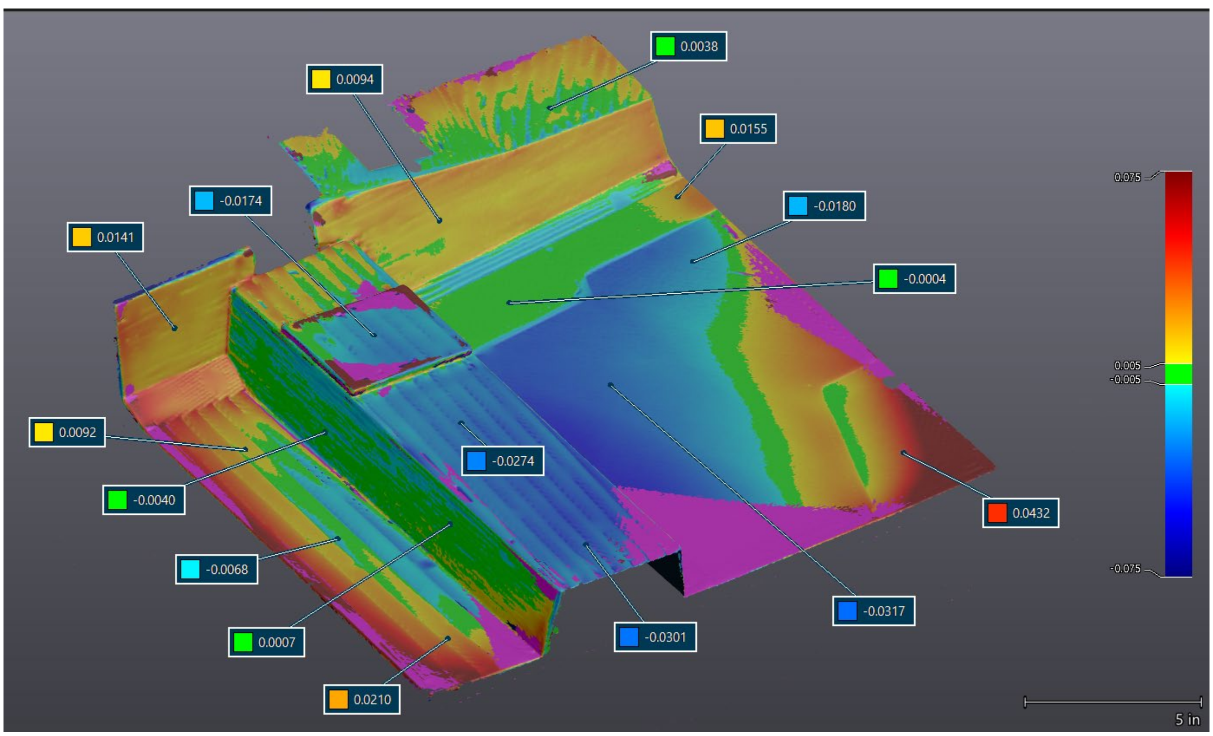

Figure 16 3D Scan of Floor Tooling

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.

Quotes for machined aluminum autoclave tooling were used as a baseline for comparison. The same tooling geometry was used in both cases. A full driver side section of the floor tooling was quoted using the same printing parameters as the section that was printed and processed with in the RapidClave for this demonstration. For the floor tooling, no machining or sealing steps were required. Removing these steps helped to drive down the total cost of additive tooling in this specific use case. This brought the estimated total cost for the driver side vehicle floor tool to $8,040 achieving a 50% reduction in cost when compared to a machined aluminum tool (Table 1).

Table 1 Vehicle Floor Tooling Cost Analysis

Vehicle Floor		
Material	M1 Aluminum	**Titan Atlas – 20% CF PEI (ULTEM)**
Total Costs	$16,500	**$8,040**

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	12	$900	68	$5440	62	$1550	$7890	Costs $80/hr for print time on a Titan printer (as quoted by Titan Robotics).
Benching	2	$150	N/A	N/A	N/A	N/A	$150	This could vary depending on the individual and how much of this cost is rolled into the total machining costs.
						Total:	$8,040	Labor hour cost was set at $75 but could vary depending on the individual performing the work.

Other improvements such as the preforming and RapidClave processes also contribute to cost savings in the form of labor and per part cost. O'Gara estimated a 65% labor savings for the pre-cut patterns in the preforming process. This does not include the additional savings that CNC cutting would provide. The 65% labor savings reduces that labor hours from 18 to 13 translating to an estimated $616 per vehicle. For larger vehicle models this would lead to even more savings. The RapidClave process reduced the cycle time by 60% and would O'Gara to increase production volume.

7. COMMERCIALIZATION

This demonstration in collaboration with O'Gara provided improvements in tooling, preforming, and consolidation which led to significant cost reduction of the finished vehicle floor.   The cost reduction not only helps O'Gara win more business for this specific part, but more importantly the technologies may be applied to part families supporting broader application and business development. While O'Gara specializes in armored vehicles the approaches demonstrated here could apply to conventional composites comprised of glass or carbon fiber. The preforming approach does not require any new equipment and has been implemented. Commercialization of the RapidClave® consolidation will require procurement of a large RapidClave. A large RapidClave design and procurement is underway with Air Force funding and will be made available to support DoD and industry needs in the future.

Table 2 O'Gara's Potential Job Growth with RapidClave Process

Program & Task	Sales # Units/Yr.	Future Jobs Added or Retained	Rationale for Job Growth and Updated Potential
Composite Vehicle Structures	**100**	**36**	*O'Gara continues to generate interest in this unique approach from various branches of the US Government currently buying armored vehicles. Thus far only small quantities (<10 ea.) have been ordered for specialty SUV units that require a raised roof or stretch door that utilize the composite technology explored under this program. In addition, some agencies have procured the conversion of a pickup truck into an SUV to accomodate weight of armoring. We believe this demand will increase as OEM's contiue to offer lighter, more fuel efficient platforms with lower GVWR. O'Gara is in ongoing discussions with US DOS (largest buyer of non-tactical armored vehicles) and while they have not yet committed to this type of product, they are interested. The gains made during this project further support the potential for larger awards based on the improved manufacturing efficiency, and overall quality. Job positions are calcualted based on estimated 100 units/year, 600 manufacturing hours per unit and 80% direct labor applied. Timing is probably 2022 for full design, validation and transition to production although smaller quantities may be possible in 2021.*
Design 3-D CAD Models door access panels			
Create evaluation matrix & provide materials			
Test samples for impact and environmental			
Provide prototype materials			
TOTAL			
Later Phases			
Design 3-D CAD models for full inner & outer doors			
Design 3-D CAD models for full body panels			

8. ACCOMPLISHMENTS

This demonstration met its intended objectives:

1) A new digital based process was developed and deployed to the shop floor that utilized CAD software and SOLIDWORKS to design a 3D printed polymeric tool and flatten the tooling geometry to yield a suitable cutting pattern to reduce labor and product variation. This process can now be applied to other complex tooling geometries to reduce the amount of labor required for layup. The additive tooling reduces the cost for both processing and preform tooling.

2) A new systematic approach was developed to build the preform and hold it in place by using the thermoplastic layer as a binder. Utilizing the thermoplastic layer improved part consistency, removed the need for an additional tackifier, and reduced the post processing work required for part fitment inside of the vehicle. This preforming approach has potential to improve process efficiency for e-VTOL and similar aerospace components where flexible semi-pregs are utilized.

3) A section of the floor was consolidated in the RapidClave with a 60% shorter process cycle while using polymeric AM tooling. The RapidClave's ability to preheat the tool plate provides a great advantage over autoclave processing by reducing the overall cycle times and increasing temperature ramp rates.

4) The processes developed throughout this project improve the manufacturability of custom low volume composite parts for manufacturers with limited resources, equipment, and software that aim to produce state of the art composite components. This process uses one CAD software package, utilizes a readily accessible and cost effective additive manufacturing process to

produce tooling, and processing with the RapidClave allows for double the part volume in the same shop floor footprint compared to a similar size autoclave.

9. CONCLUSIONS

The additive tooling and preforming process were able to produce quality vehicle components with a significant cost savings resulting from reduction in cycle time and labor required. The preforming process did, however, require a significant investment of time to design the templates. This was largely due to the discrepancies between the provided tooling CAD models and actual tooling geometry. If O'Gara were to adopt the additive tooling approach in conjunction with the preforming process this would minimize upfront design efforts, while maintaining the advantages in manufacturing labor and reduction of cycle time.

The RapidClave® was also successful in significantly reducing the process cycle. Adoption of RapidClave® technology would not only increase O'Gara's efficiency, but also their manufacturing capacity allowing them to potentially reach new markets such as state level law enforcement and OEM part manufacturing.

10. RECOMMENDATIONS

UDRI and O'Gara will seek opportunities to apply these technologies toward new products. Consolidation of the full-size floor will be demonstrated in 2022 with UDRI's new large scale RapidClave. We suggest these approaches be applied toward conventional composite large structures such as an automotive structural floor or an e-VTOL passenger cabin.