RAPID HIGH PERFORMANCE MOLDING OF STRUCTURAL THERMOPLASTIC COMPOSITE PARTS

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ABSTRACT

Manufacturing small composite parts that are relatively insensitive to part and material mix is challenging. When thermoplastic material is introduced to that scenario, creativity is needed for the tooling approach and the processing capabilities of the work cell. The high processing temperatures of thermoplastics limit the available tooling materials while increasing the need to consider the coefficient of thermal expansion (CTE) of the tooling material. The thermoplastic material itself has an order of magnitude higher CTE out-of-plane versus in-plane. This CTE mismatch of the thermoplastic material to the tooling material causes it to shrink away from tooling faces during the critical crystallization temperature and leads to a lack of uniform pressure that may impact the part consolidation quality. High processing temperatures compared to other materials also affects cycle time, tool face temperature uniformity, and de-mold temperature. This paper addresses the challenges, the mitigation plan and tooling design approach to overcome CTE shrinkage, pressure application normal to the part surface, and temperature uniformity across the part to ensure successful and rapid part fabrication.

1. INTRODUCTION

The thermoplastic portion of Rapid High Performance Molding (RAPM) for Small Parts [1] is to investigate rapid molding of small complex thermoplastic parts within a given work cell. The TP-RAPM-002 rib configuration was chosen to showcase the challenge of compression molding a thermoplastic composite from a raw material to a finished complex geometry in a single step. The forming process needs novel tooling to create horizontal pressure on the thermoplastic part during the consolidation cycle.

The TP-RAPM-003 curved channel configuration was chosen to showcase a two-step approach to creating a complex small part. The first step is to consolidate the thermoplastic layup into a flat blank. This flat blank will be further processed in a stamp forming system to completely form the part to final dimensions.

2. EXPERIMENTATION

2.1. Challenges of Thermoplastic Consolidation

Thermoplastic composites have a much higher processing temperatures than thermoset materials. Common matrix material that we will be covering in this paper for thermoplastics are polyetheretherketone (PEEK) and polyetherketoneketone (PEKK). Their typical processing temperatures are 390 °C and 375 °C, respectively. This high processing temperatures limits the use of tooling materials available for direct part contact during processing and consolidation. The

challenges and the issues associated with PEEK and PEKK thermoplastics are summarized and discussed in Table 1.

Table 1 Processing Challenges with Thermoplastic Composites

Challenge	Issues
High Processing Temperatures	• Limits use of tooling materials • Increases CTE concerns - affects laminate pressure • Adds to difficulty maintaining uniform temperature
Non-linear CTE and volume change for thermoplastic laminates	• Order of magnitude higher for out-of-plane vs. in-plane • Large CTE Mismatch (tooling vs. TP) • Leads to lack of uniform pressure during critical stages of cycle • Impacts part consolidation quality
Temperature Uniformity	• Large temperature delta impacts part consolidation quality and geometry • Longer cycle times required to allow tool/machine to heat and cool more evenly when using conventional heating/cooling
Setup and cycle times for complex parts have not been optimized	• Time required to bring tools/machines to high processing temperatures and back to room temp • Tools need to be cooled prior to removal for next job • Sometimes requires a couple of "setup parts" to ensure tooling and holding devices are positioned correctly
Material Bulk Factor	• Large material bulk factor leads to additional challenges for introducing charges into tooling • Higher risk of wrinkles during consolidation

The first thing one must consider is the much higher processing temperatures associated with high performance thermoplastics. These are generally in excess of 375 °C. This elevated temperature impacts tool surface thermal uniformity as well as increasing the tool thermal growth and shrinkage due to the coefficient of thermal expansion (CTE) of the tooling material.

Next, thermoplastic laminates experience a non-linear CTE as well as a volume change when the material changes phases. Not only is there a non-linear CTE but there is a different CTE value associated with in-plane properties versus out-of-plane properties. A mismatch in the thermoplastic CTE to the tooling CTE can cause the material to shrink away from the tooling during a critical phase change transition. This causes the pressure applied to the laminate to drop which can negatively impact the consolidation quality.

Another impact to consolidation quality is the lack of thermal uniformity across a tool face at these elevated temperatures. Couple this with a large temperature delta from de-mold temperature, to melt, and back to de-mold temperature causes cycle times to increase. Allowing the tools to heat soak and become more uniform requires longer cycle times than are ideal for rapid manufacturing.

Finally, the bulk factor of the material at room temperature must be considered in the tooling approach. Thermoplastic composite unidirectional tape generally has a bulk factor around 30% of consolidated thickness. This bulk factor greatly increases for thermoplastic fabrics and can be as high as 200% to 300% or more.

A thermoplastic material undergoes three distinct phase changes during a thermal cycle. Figure 1 is a Differential Scanning Calorimetric (DSC) plot of a sample of PEKK composite.

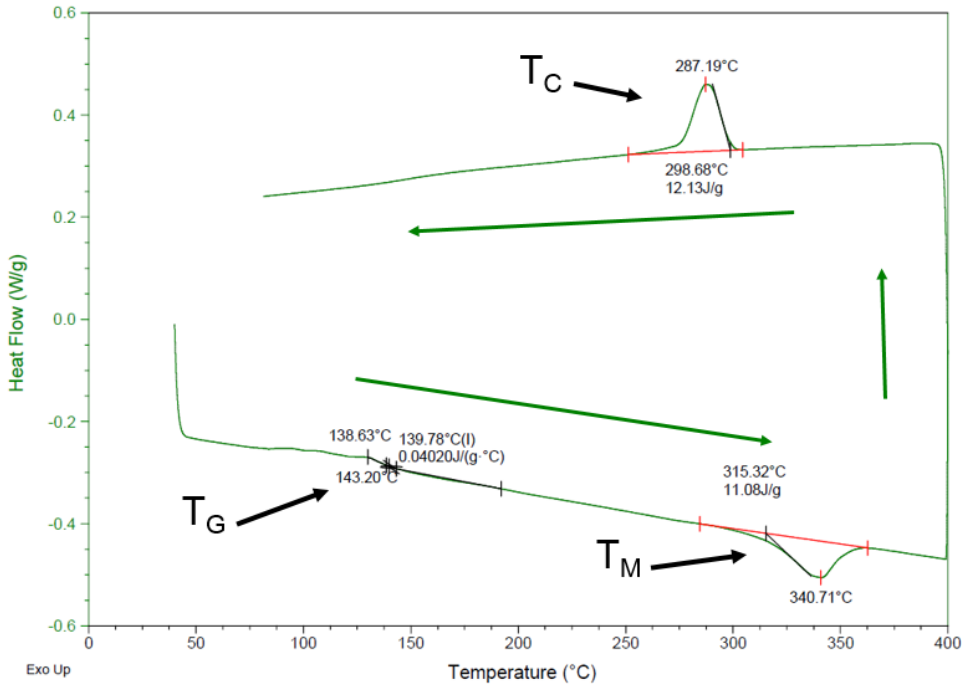


Figure 1. DSC Heat-Cool Scan of PEKK Composite showing Phase Changes.

Figure 1 shows exothermic heat flow as a positive value on the y-axis and the temperature of the material is the x-axis. The plot begins in lower left portion of the graph near room temperature and as heat is added to the system the material experiences a glass transition (T_G). This is the temperature at which the glassy polymer transitions into a rubbery state due to the segmental mobility of the main chain atoms. As heat is added to the system, the material transitions into a melt state (T_M) around 340 °C. Once at melt, the system will begin to remove energy to cool the material. This begins in the top right portion of the graph and trends down towards the left as heat is removed from the system. The material will experience a crucial phase change from a liquid to a solid during this cool down and is known as the crystallization temperature (T_C). In Figure 1, this temperature for the PEKK unidirectional tape is around 288 °C. This is the critical point in processing thermoplastic composites that requires accurate control over thermal uniformity and laminate pressure as the material transitions through this phase change.

There is a significant specific volume decrease in the material during crystallization which causes the laminate to shrink away from the tooling surface and can decrease the pressure on the laminate at this critical time.

Another factor contributing to laminate pressure loss is the CTE mismatch between the tool steel and the thermoplastic material. The CTE of the thermoplastic materials is dominated by the matrix and any thermal expansion in the direction of carbon fibers is approximately constant. Through the thickness of the laminate and perpendicular to the fibers the CTE is approximated by a bi-linear curve. The CTE of the matrix is a temperature dependent value and must be accounted for in the tool design to keep the tool surface in contact with the material through crystallization. If the laminate pressure drops during crystallization or thermal uniformity is poor then the resulting laminate will not achieve full consolidation and will fail non-destructive inspection (NDI).

2.2. Forming of Ribs and Channels with Side Walls

The primary challenge of the RAPM program is utilizing a vertical direction only hydraulic press or a clamping fixture to process small complex part configurations. These parts have vertical elements in them that require horizontal pressure application during forming. With only vertical actuation available, tool design needs to be creative in the approach for applying horizontal pressure to the laminate, Figure 2.

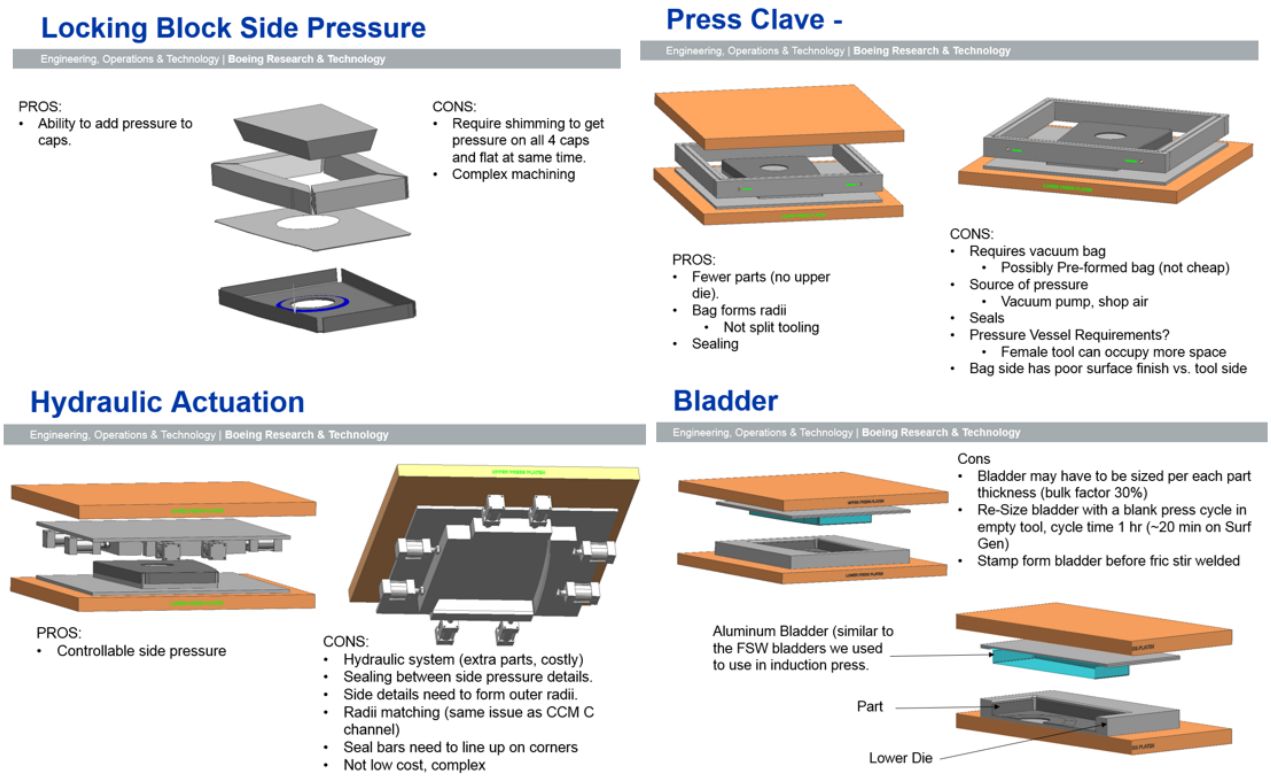


Figure 2. Four Approaches to Apply Horizontal Pressure in a Vertical Acting Press

The concept in the top left of Figure 2 showcases chamfered surfaces on the tools that interact with each other. As the top tool comes down the chamfers engage and the side tools are pushed out into the laminate flanges. The timing of the tools and how the faces fit together is critical to ensure equal pressure on all vertical surfaces as well as the horizontal surface of the web of the part. This would be rather complex to ensure all parts work in perfect time and expensive to machine.

The top right tooling approach in Figure 2 is a press clave style tool. This would utilize a vacuum pump and high temperature bagging material to ensure uniform pressure across the part face. This was not possible at the beginning of the program as the clamping fixture would not have press clave capabilities.

The bottom left in Figure 2 is a common approach that is currently in work with another consolidation technology. This tooling approach utilizes hydraulic actuators that act horizontal to the press direction. This allows the horizontal tools to apply pressure to the vertical flanges of the part. This is an expensive technology to add to presses that do not already have horizontal hydraulic system and controls incorporated.

Finally, in the bottom right of Figure 2 is a bladder type tool. This tool utilizes a thin aluminum bladder that can be pressurized with inert gas at high temperatures. The bladder would then expand and apply even pressure to all part surfaces during the consolidation cycle, resulting in a hydrostatic pressure while using a vertical acting press. This was the tooling direction chosen for the two thermoplastic part configurations.

2.3. TP-RAPM-002 Rib Fabrication

With the tool concept decided the design work and details fell in place quickly, Figure 3.

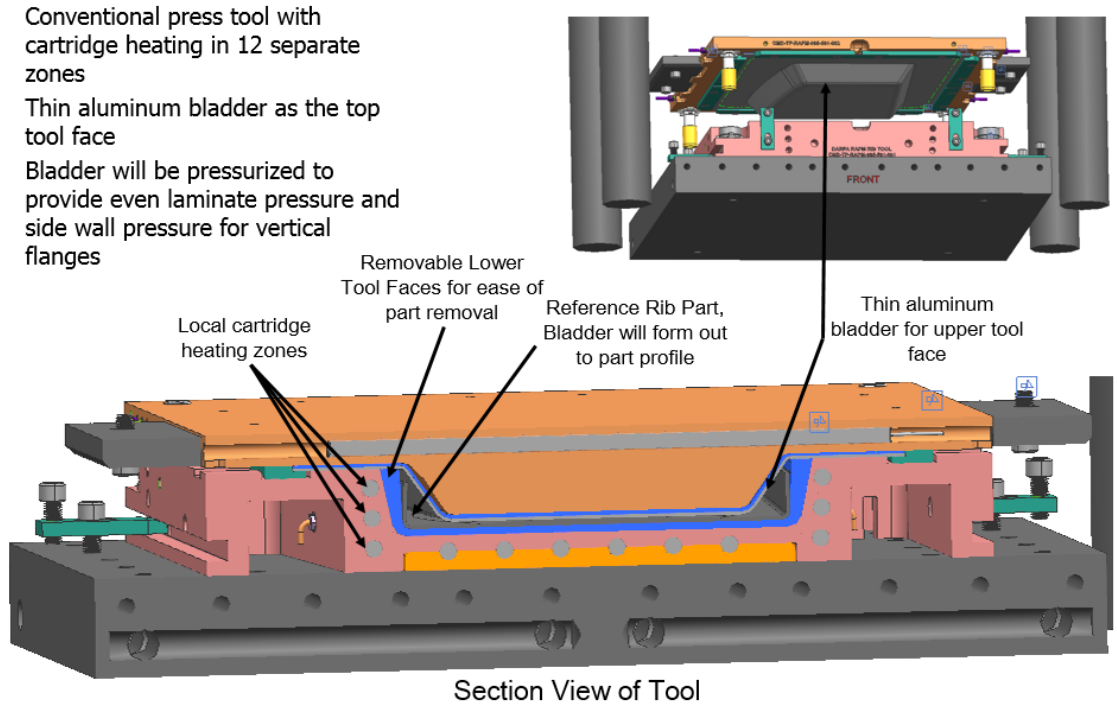


Figure 3. CMD-TP-RAPM-002 Rib Tool for Thermoplastic Materials and Processing.

The top and bottom tools shown in Figure 3 in orange and pink are both 410 stainless steel. The 410 stainless is an excellent match to the in-plane CTE of PEKK unidirectional tape composite material. As the web of the part grows laterally, the tool will expand or contract a similar amount. The lower tool also incorporates removable lower tool faces, shown in blue, so that the completed part can be extracted at the end of the cycle and it is not locked into the tool cavity.

This tool is mounted in a conventional press that is heated through electric heating cartridges. These were placed around the tool as close to the laminate as possible. They are wired in 12 separate zones that our press can control independently as well as the 6 main zones of the press platen. The 12 zones were chosen to maximize control over the tool surface temperature around the flanges and web of the rib.

In order to apply pressure to the vertical flanges the prototype aluminum bladder was designed. This first iteration used two sheets of aluminum that would be incrementally sheet formed (ISF) in a CNC mill to 50% of final shape. The two sheets are then be friction stir welded around the

perimeter with a nozzle feature to create a pressure cavity and an inlet. The 2024 aluminum was chosen as the best candidate for ISF and friction stir welding. The final forming of the bladder would rely on super plastic forming the aluminum within the tool to final shape.

One difficulty encountered after the first trial was failure of the bladder under pressure around the friction stir weld. It was determined the tooling was not making good contact over the weld and the hydraulics of the press were not holding the bladder closed around the edges. To solve this leak, a perimeter of high temperature graphite gasket was utilized between the tool and bladder that would pinch the bladder closed before the gas could reach the weld.

Once the welds were relieved of pressure the next issue encountered was drastically thinning of the aluminum bladder in the corners. To find the root cause and a solution to this issue we connected with an internal expert in super plastic forming. This expert was able to evaluate the design and material choices and recommended the use of 5083 aluminum which has the ability to be super plastically formed compared to the 2024 aluminum that was initially chosen. It was confirmed that the temperatures and pressures of thermoplastic composite are suitable for this type of super plastic aluminum forming.

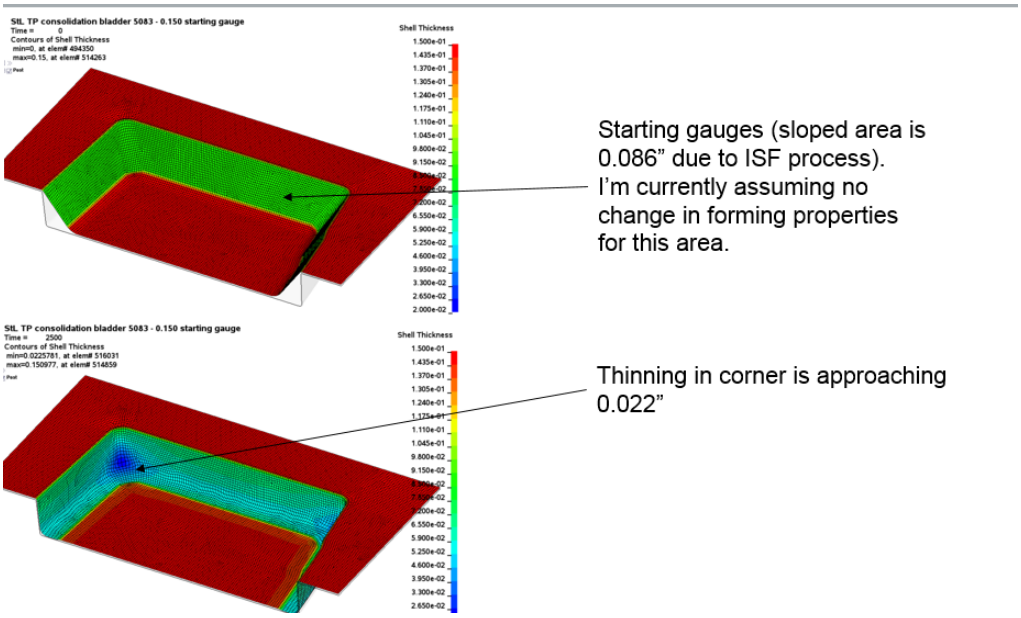


Figure 4. TP-RAPM-002 Rib Bladder Super Plastic Forming (SPF) Finite Element Analysis (FEA)

A Finite Element Evaluation (FEA) shown in Figure 4, was performed at the temperature and pressure schedule of the thermoplastic cycle to simulate the yield of the aluminum bladder within the tool cavity. The results of this study reveal that incremental sheet forming as well as the super plastic forming had thinned out the aluminum sheet over 85% of its original thickness. This is beyond the limit of 5083 Aluminum and reveals why the 2024 series aluminum bladder failed as well. It was ultimately determined that super plastic forming the aluminum bladders was not feasible with the depth and inner radii of the rib part.

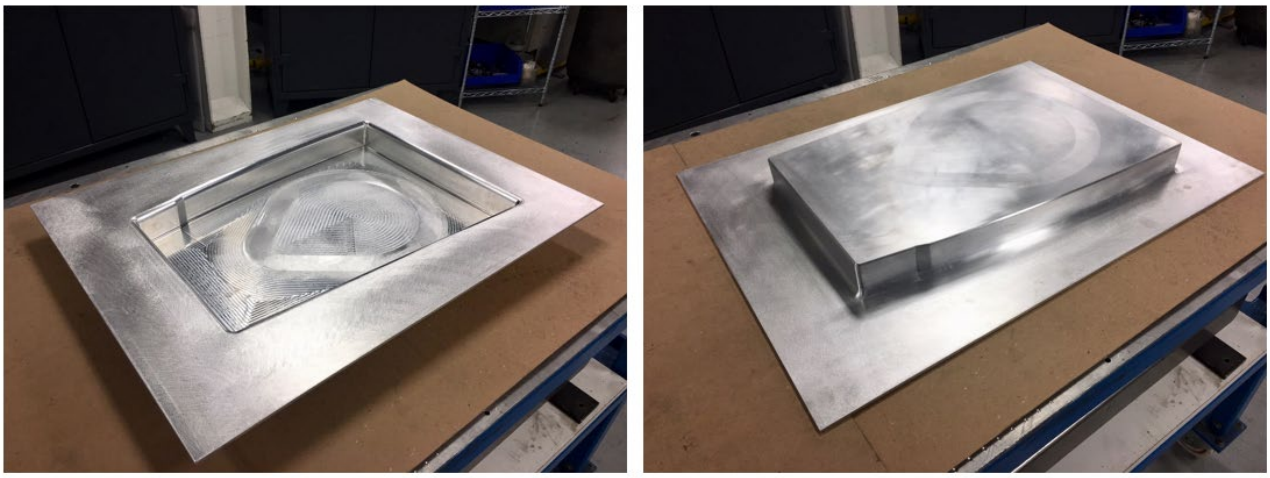


Figure 5. TP-RAPM-002 Rib Bladder for Processing Thermoplastic Composites.

The final iteration of the aluminum bladder is shown in Figure 5. A single sided bladder was chosen to eliminate the friction stir welding of two sheets together. This bladder was milled from a single billet of aluminum and is undersized 30% from the final part thickness. This 30% comes from the bulk thickness of the thermoplastic unidirectional tape in an un-consolidated laminate. The material choice was 2024 aluminum as the bladder would not need the ability to super plastic form since it was near net size.

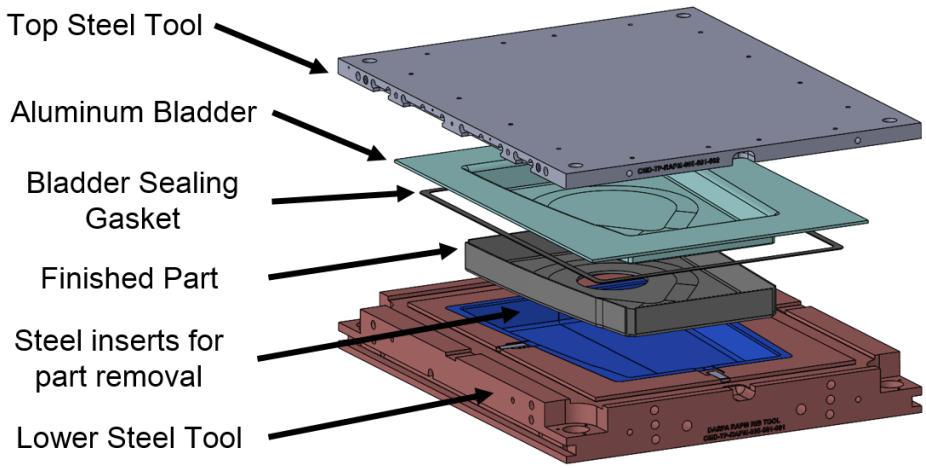


Figure 6. TP-RAPM-002 Rib Tool Assembly.

Figure 6 shows an exploded view of the full tool assembly. This shows the single sided bladder in green. Just below that is a bladder sealing gasket that runs the full perimeter of the bladder. The top and bottom steel tooling remains 410 stainless and again in blue you can see the tooling inserts that allows the removal of the final part. Overall, this second tooling iteration involves less complex assemblies by eliminating the need to incrementally sheet form a bladder as well as eliminating the friction stir welding.

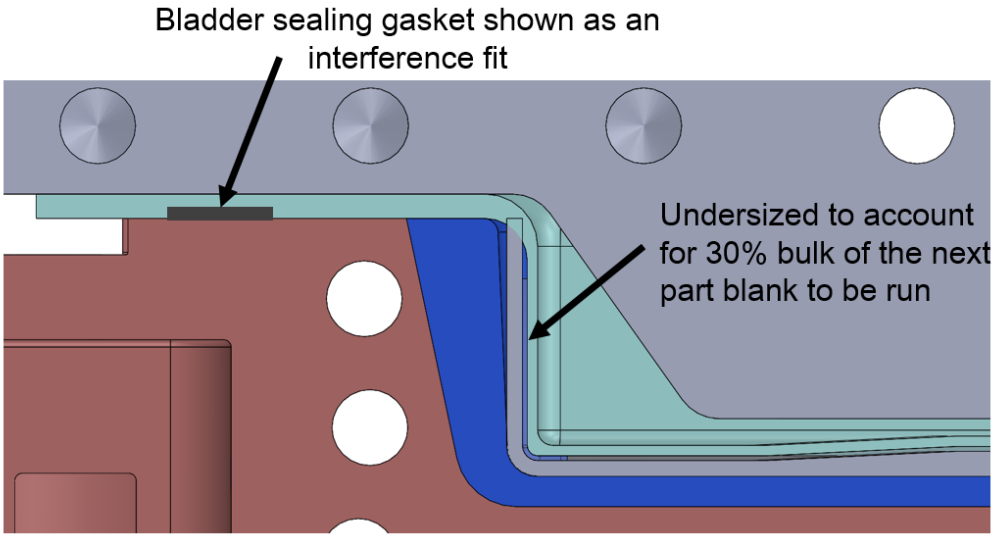


Figure 7. TP-RAPM-002 Rib Bladder Details.

In Figure 7, a cross section view of the tool shows two features that are critical to processing the thermoplastic composite. At the top left is a continuous high temperature graphite sealing gasket. This is shown as an interference fit between the bladder and the lower steel tool. The idea behind the gasket is the press hydraulics will bottom out on this gasket feature and will apply a force through this gasket. This force will seal the argon gas within the bladder. The press hydraulics do not apply any pressure to the material laminate itself. When everything is closed up there remains a gap between the bladder and a completed part.

This gap is calculated to allow an additional 30% of the consolidated part thickness. This is necessary to fit the next bulk layup into the tool. In order to do that the bladder will need to shrink away from the surfaces. The shrinking factor will come from the CTE retraction in the web across the temperature change from the stress-free temperature of 288 °C to room temperature.

In order to pressurize the bladder a pressure inlet was added to the top steel tool. This allows argon gas to be supplied from a cylinder which will pressurize the bladder cavity while the press hydraulics seals the bladder and keeps the tool closed. If the capacity of the hydraulics are not high enough, the gas will react to a larger surface area and can actually overpower the hydraulic actuator and open up the tooling. The capacity of the conventional press that is operating with this tool is enough to overpower the gas pressure 2 to 1.

When the press cycle is started, the upper tool with the aluminum bladder will come down and slowly press the bulk layup into the female cavity of the lower tool. This is where the additional 30% bulk factor in the aluminum tool at room temperature is key to fitting a bulk layup into the tool without interference.

The pressure application of the aluminum bladder to the thermoplastic material is critical to achieve proper consolidation. As the material experiences a volume change and CTE shrinking, this is overcome by the pressure application of the aluminum bladder normal to the surfaces of the part.

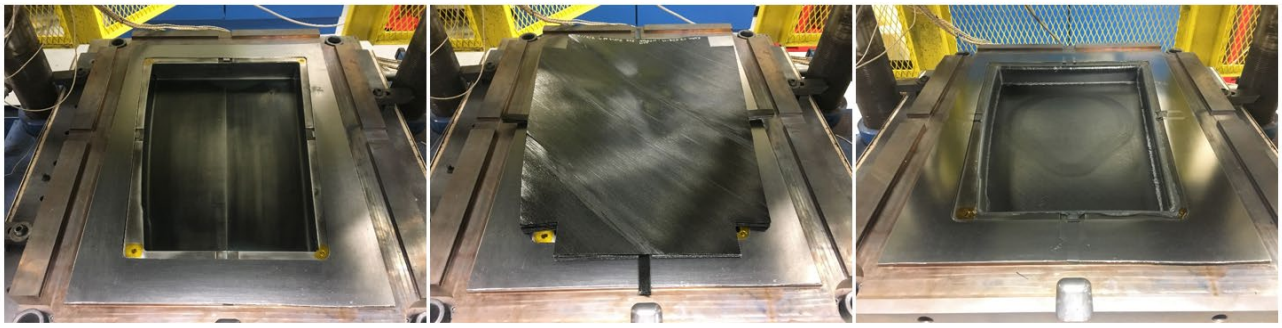


Figure 8. TP-RAPM-002 Rib Tool Part Run.

Figure 8 shows an empty tool cavity, followed by the raw material laminate placed on top. The laminate utilizes alignment tabs to locate it to the lower tool. Finally on the right is the conoslidated laminate after the full heat and pressure cycle. The pad-up in the center of the laminate is clearly formed.

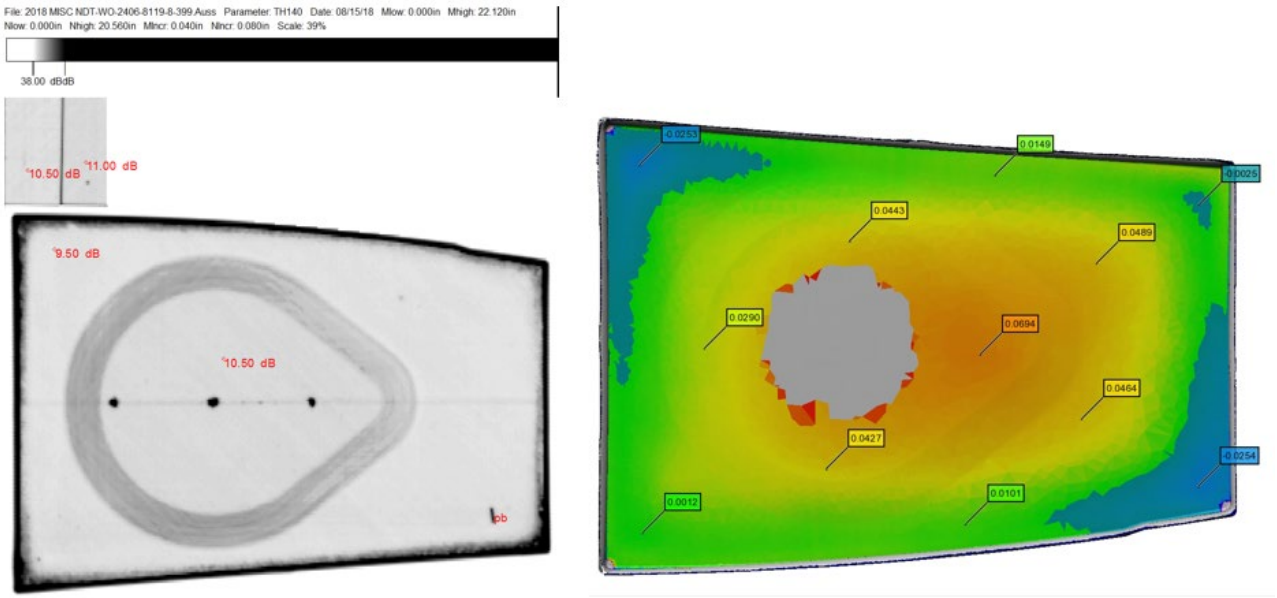


Figure 9. TP-RAPM-002 Rib Non-Destructive Inspection Results.

Non-destructive Inspection (NDI) data of the first part to be processed is shown above in Figure 9. The dB attenuation is excellent through the web of the part. The pad-up shows tack weld locations that were moved to the trim of the part in subsequent layups. The right image shows a dimensional scan of the part. It is noted that the web of the part varies from thick and thin across its face. This dimensional variance is one of the major difficulties with bladder tools. A similar result is shown for the vertical wall of the part flanges in Figure 10.

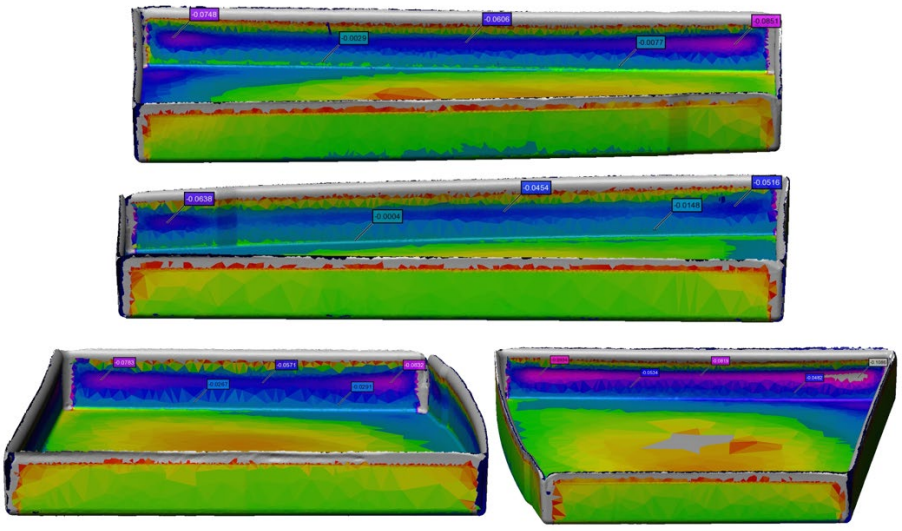


Figure 10. TP-RAPM-002 Rib Thickness.

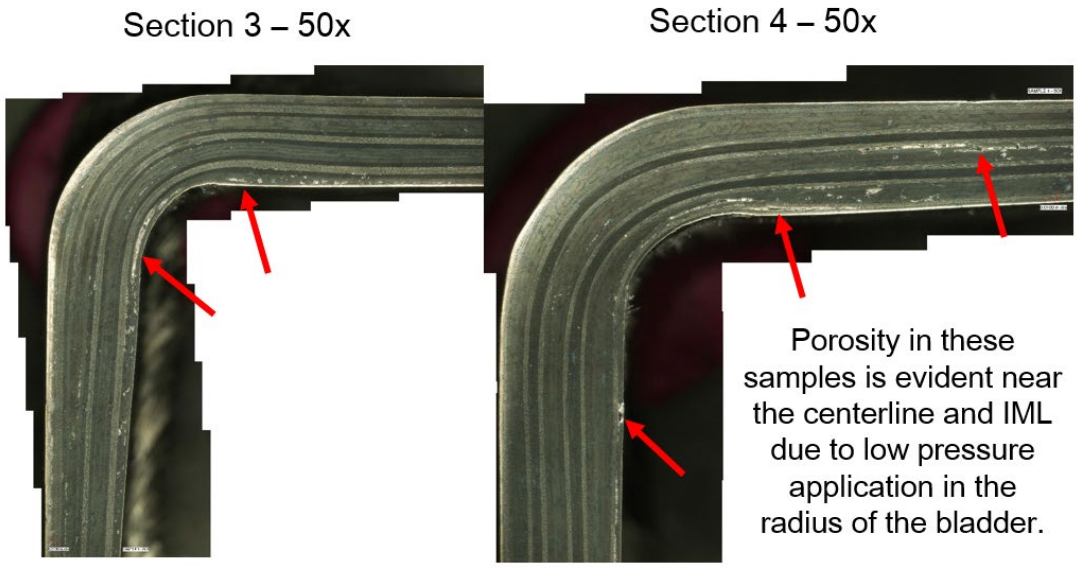


Figure 11. TP-RAPM-002 Rib Cross Section Photomicrographs.

Manual A-scan NDI was taken of the inner radii and they were shown to have poor consolidation. The radii were cross-sectioned and polished to confirm the NDI results. Figure 11 shows porosity within the center and inner mold-line (IML) side of the radii of the rib part.

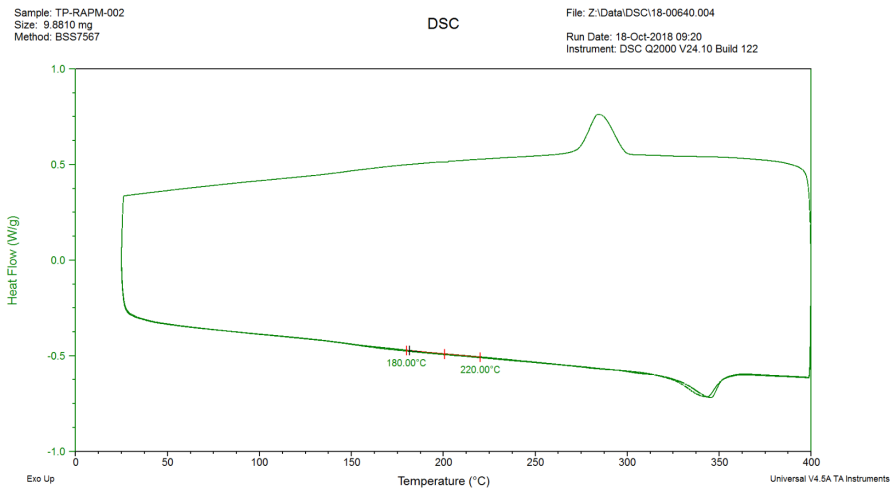


Figure 12. Differential Scanning Calorimetry (DSC) Sample 1.

Differential Scanning Calorimetry (DSC) samples were taken from three different locations on the rib. Samples 2 and 3 exhibit no cold crystallization. Sample location 1, Figure 12, shows a small cold crystallization peak. Sample location 1 was taken near a tack weld in the layup that is visible in NDI and expected to have poor thermal history.

The conformal nature of the bladder as well as its sectional rigidity create a difficult to control tool. The bladder allows the part to consolidate to various thicknesses while making it difficult to apply even pressure to the internal radius of the part. The locations where the bladder made intimate contact with the laminate resulted in excellent NDI and DSC data.

2.4. TP-RAPM-003 Representative Curved C-Channel Blank Consolidation.

The rib is a single step process, from a bulk layup at room temperature, through the heat and pressure cycle, and into a completed part. The C-Channel is different as an additional step is added to this process. It begins the same as a bulk layup at room temperature. This layup includes ply drops through the cross-sectional thickness. The tapered thickness comes from internal ply drops from 32 plies down to 24 plies along the length of the part. That layup will be consolidated into a flat blank with the tapered cross-sectional thickness. The final forming step is to stamp form the consolidated blank into the final part shape. This stamp forming creates the vertical flanges shown in the final part to the right. The material chosen is a 2x2 twill woven fabric that is partially pre-impregnated with powder coat applied PEKK thermoplastic.

The first step is to consolidate the tapered layup into a flat blank. To do this we again incorporated a superplastic forming bladder style tool. The exploded view shown in Figure 13 shows the top and bottom tools that are flat and made of steel. The material choice for CTE of these steels is not critical in this design. In yellow section is a flat sheet of 5083 aluminum. Below that in pink is a volume reducing frame that includes the pressure sealing gasket.

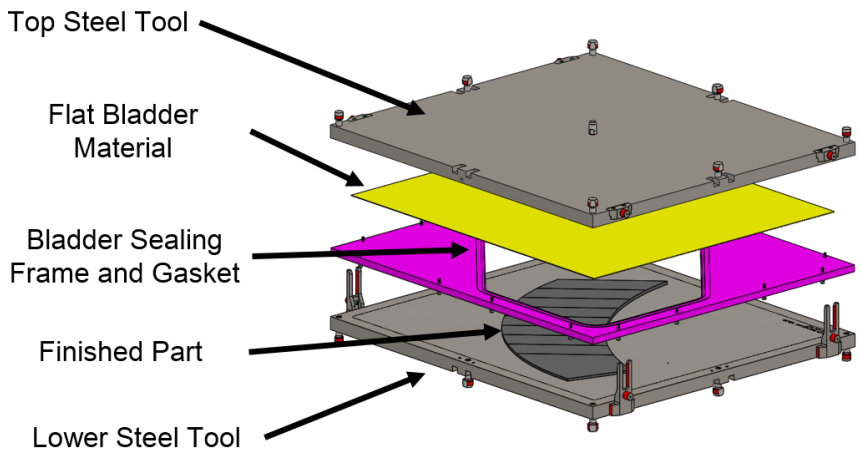


Figure 13. TP-RAPM-003 Curved Channel Tool Assembly.

The intent of this tool is to have the flat layup housed within the section of the frame and to close the tool. Heat and hydraulic pressure will then be applied to an aluminum sheet through the top tool. Once at forming temperature argon gas is applied to the back side of the aluminum. The bottom tool will be held around the glass transition temperature of the material. This way the material is pliable but is not in a melt state. Once the aluminum is at process temperature the argon gas is applied to its top face. This gas pressure will form the aluminum down into frame cavity and apply laminate pressure to the tapered blank. Once pressure is applied, the lower tool temperature is increased through the melt phase of the material. The pressure of the bladder needs to be applied so that the material does not flow around the lower tool when at a melt state.

This tool could have been created with a matched metal molding approach. However, that tool would only be able to consolidate one part configuration. The approach shown in Figure 13 is much more flexible for future parts. One can simply change out the aluminum bladder to a fresh sheet of 5083 aluminum and form over an entirely different part shape.

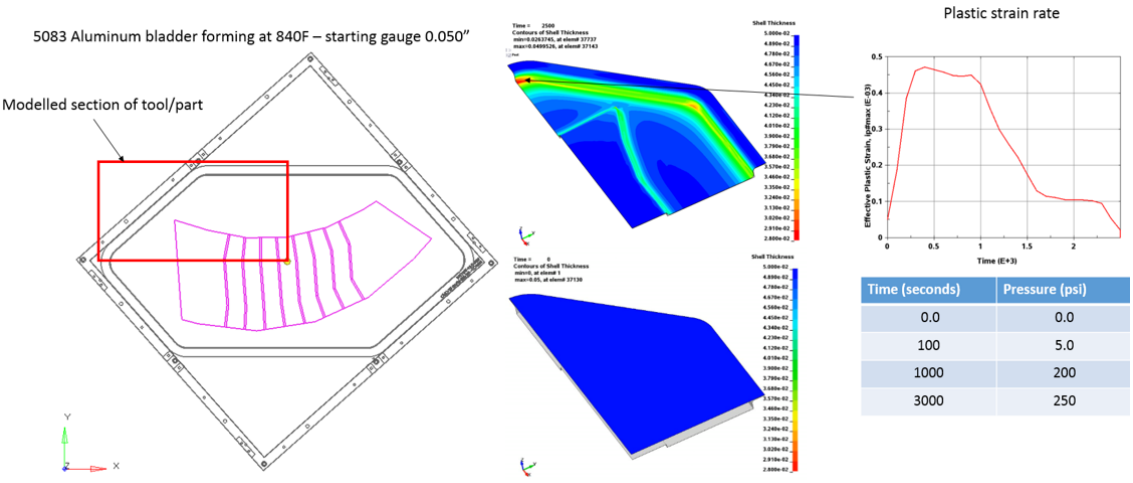


Figure 14. TP-RAPM-003 Bladder Super Plastic Forming (SPF) Finite Element Analysis (FEA).

Again, an FEA evaluation of the 5083 aluminum in this configuration was performed, Figure 14. The results show that forming the aluminum into the part cavity does not critically yield the material. A pressure application schedule was also generated to form the aluminum at an ideal plastic strain rate. Critical thinning of the bladder around the edges of the frame is not predicted and the bladder should hold pressure for multiple part runs.

The rib tool utilized electric cartridge heaters to apply heat to the laminate. These are rather slow to heat up and the tooling mass is difficult to cool down quickly, which leads to increased cycle times. The C-Channel tool is designed to operate within a Surface Generation system. This system utilizes individual thermal cells that can be independently heated and cooled at variable rates. The cells are heated through convective heat transfer and the tool faces are designed as thin as structurally possible to allow a rapid heat transfer to the thermoplastic material. Further, these cells can be controlled to act together so all sections of the tool go through the consolidation program simultaneously. In Figure 15, one can see the back face of the tool and how it is divided into multiple individual thermal cells. Further details on the Surface Generation Performance to Functional Specification (PtFS) CF-OaO-RAPM work cell are available in [2].

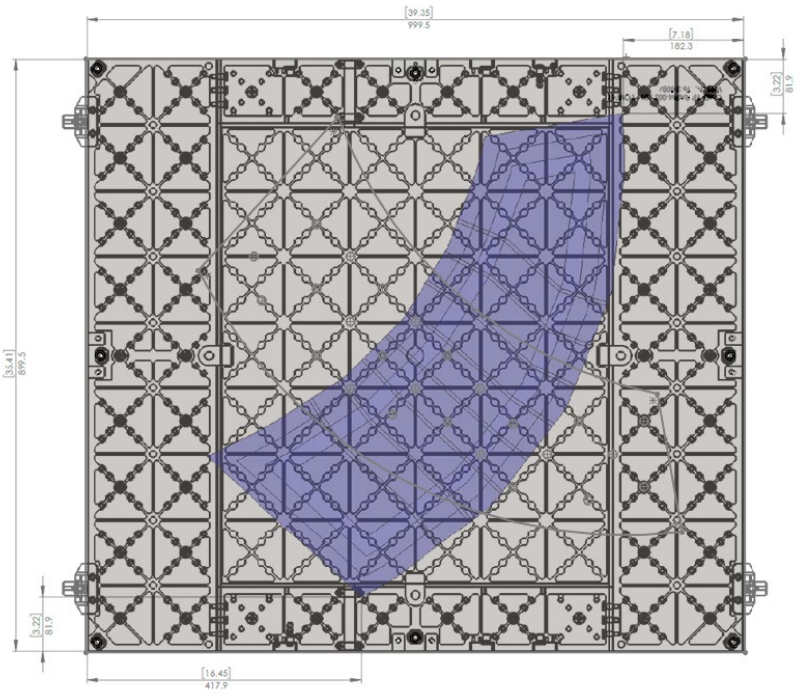


Figure 15. TP-RAPM-003 Curved Channel Blank Mold Face on Surface Generation Heater Base.

The first step to creating a part on the Surface Generation system is optimizing the cells. The part perimeter is overlaid on the thermal cells. The operator of the system can use this diagram to group cells into certain zones. These zones enable the operator to uniformly control the tool surface temperatures. The cells that are directly under the part or adjacent to it can be grouped together and controlled to optimally step through the thermal cycle of the material. The perimeter cells can be heated at a different rate and to a lower temperature to minimize thermal loss from the central cells.

This type of precise control and rapid heat up and cool down is critical to reducing the cycle times of thermoplastics. With such a large delta of temperature in the thermal cycle, conventionally heated tools take far to long for rapid part creation.

A PEEK/Carbon fabric was used for the TP-RAPM-003 C-Channel which has a relatively high bulk factor. The first cycle on the 5083 aluminum would be to form it over a milled aluminum blank that was at the 200% bulk thickness of the thermoplastic laminate. The milled aluminum blank did not have the corners relieved of sharp radii like a laminate would. When the aluminum bladder formed over this blank the corners over yielded the aluminum and it ruptured, Figure 16. When investigating additional 5083 aluminum, it was discovered that AZ31 magnesium is a suitable replacement and offers excellent super plastic forming properties at similar temperature and pressure ranges as the thermoplastic composite.

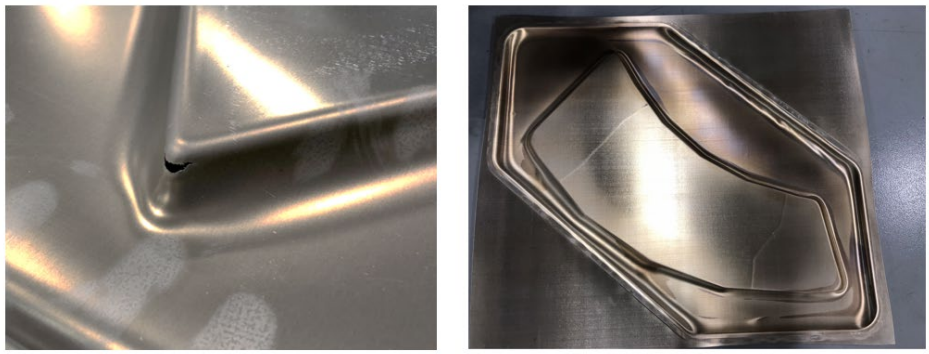


Figure 16. Lesson Learned: Pre-forming the bladder over aluminum over-strained the corners.

The magnesium bladders proved to be successful in forming into the tool cavity and over the thermoplastic laminate. The bladder was able to successfully seal around the edge of the part and prevent the polymer matrix from excessively leaking out of the laminate. NDI results of the first four parts are shown in Figure 17. There is currently not an NDI reference standard to compare this material to, however the blanks are consistent in the NDI results when compared to each other. The dB attenuation noted is a similar magnitude for comparable PEEK thermoplastic composites in a similar thickness range. Thicknesses were measured along 6 locations of the blank along its taper. The thicknesses measured are within ±5% of the reported nominal thickness of the PEEK composite fabric.

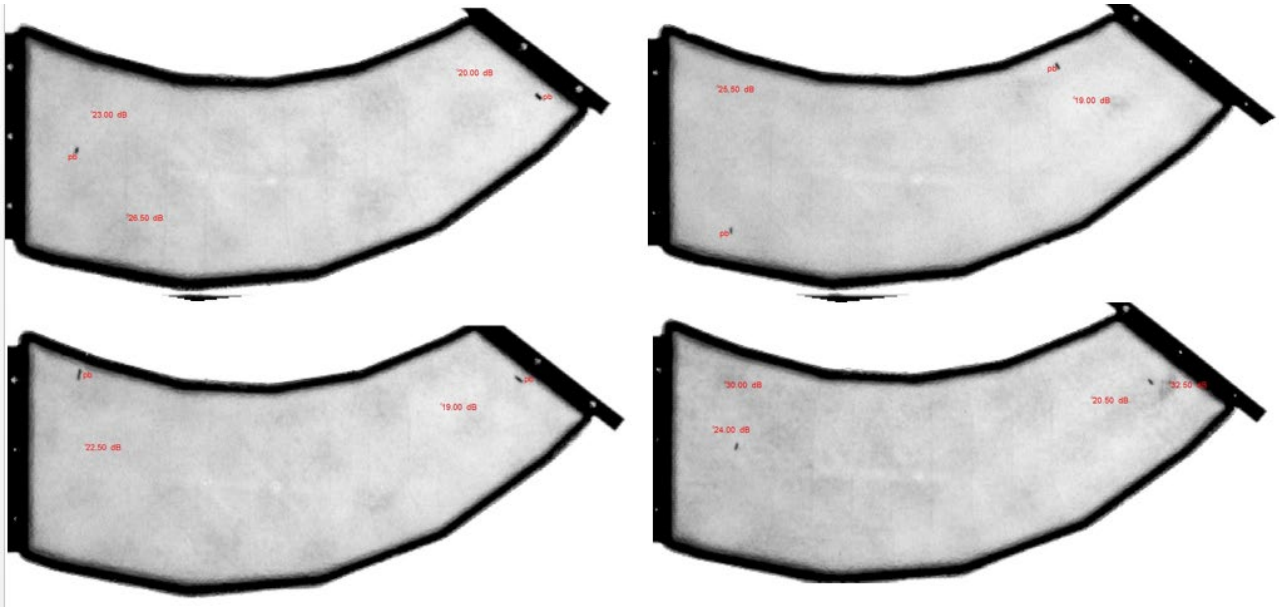


Figure 17. Non-destructive inspection of consolidated blanks showed even consolidation throughout.

In our initial approach each blank required a new, unformed sheet of magnesium to superplastic form into the bladder. In order to lower the recurring costs and decrease overall cycle time, a bladder was reused for multiple blanks. The single bladder was used to consolidate a total of 6 blanks, meaning 5 of those blanks were re-using the bladder in a formed configuration. Figure 18 shows the initial NDI results of re-using a bladder to consolidate the blanks. These are promising results and indicate it is possible to achieve full consolidation without needing a new bladder every run.

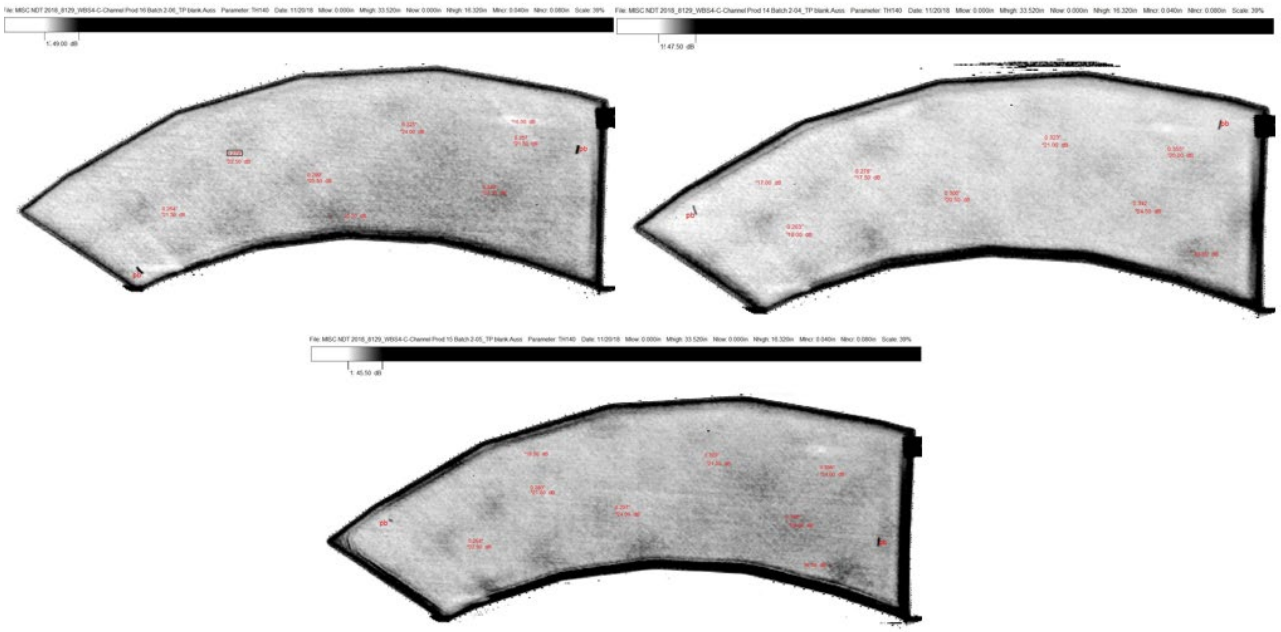


Figure 18. Non-destructive inspection results of blanks formed with re-use of the same magnesium bladder.

Further charaterization and thickness measurements are on-going for the blanks created by re-using a single bladder. Noticable visual indications, persist between the blanks as shown in Figure 19. Digital scanning and measurements will be taken of the blanks and compared to a baseline part created with a fresh bladder.

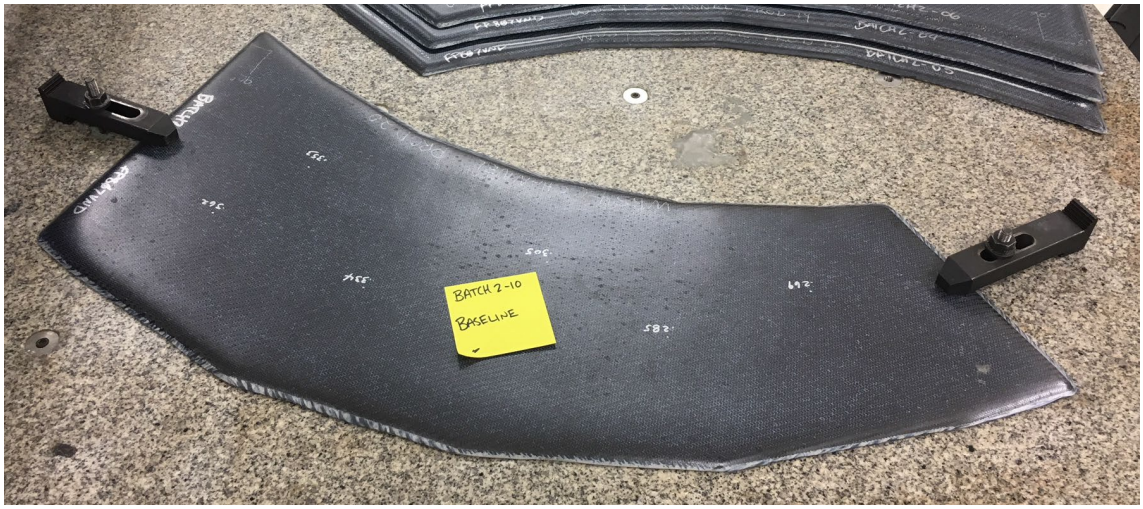


Figure 19. Example of pre-consolidated blank made with re-used magnesium bladder.

With the blank processing completed, single-bladder-use consolidated blanks were shipped to Advanced Thermoplastic Composites (ATC) Manufacturing, in Idaho for stamp forming to final shape.

2.5. ATC Manufacturing. Stamp Forming of C-Channel.

Figure 20 provides a schematic of the press forming die configuration to the TP-RAPM-003 curved channel based on the press forming assessment in Figure 21. Stamp forming is a rapid forming process in which the pre-consolidated blank is heated to the process temperature in a short time and then shuttled to a rapidly closing press to form the part quickly. The forming tool is maintained at a constant temperature which enables rapid cycle times as the tool is not heat cycled. The tool temperature is selected to enable controlled forming of the part while it is cooling, the development of the correct level of crystallinity in the polymer and to ensure that the part will become form stable while on the tool. Therefore, the part can be removed from the tool without any deformation. A series of blanks with implanted thermocouples was used to evaluate and validate the complete process thermal cycle through heating and forming.

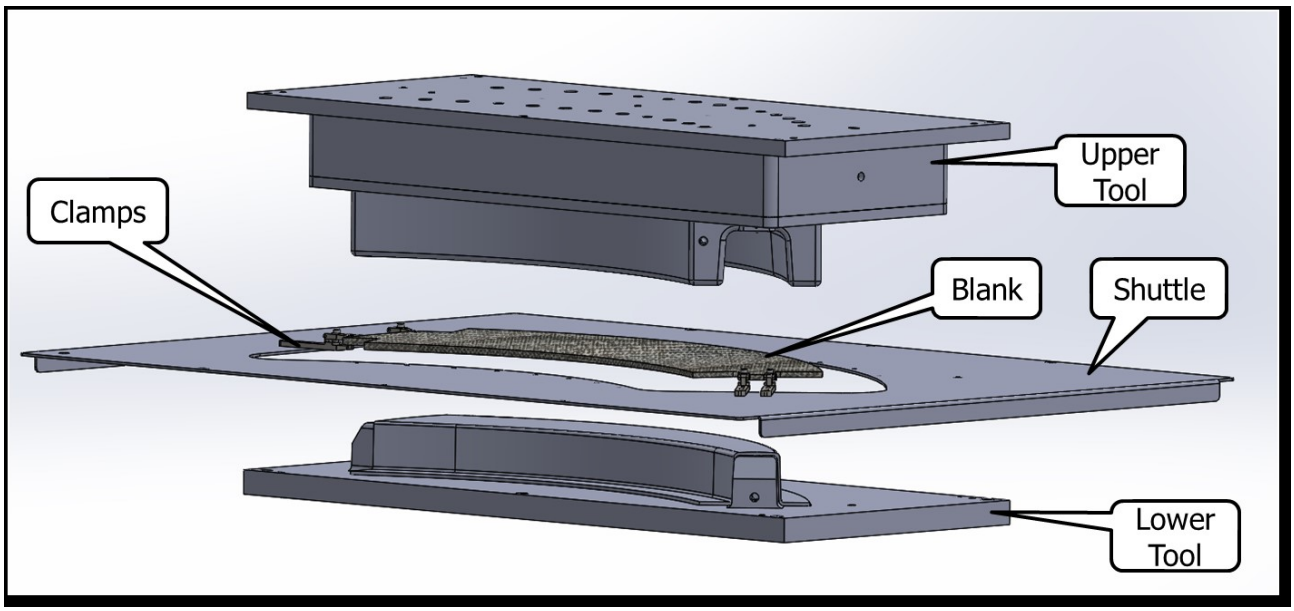


Figure 20. Press Forming Die Configuration for TP-RAPM-003 Curved Channel.

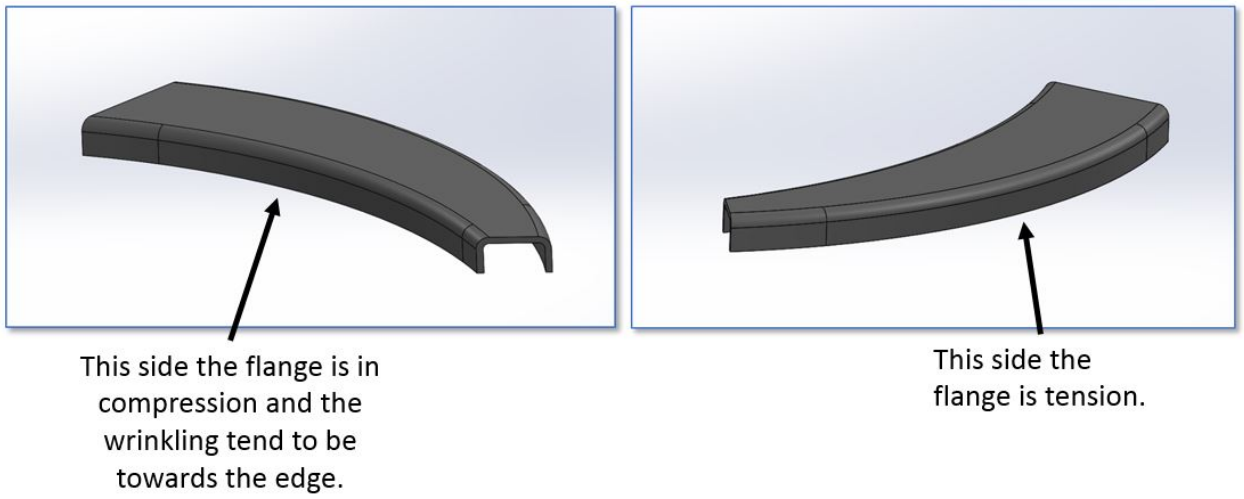


Figure 21. Press Forming Assessment.

Process steps are shown in Figure 23. The stamp forming tooling was designed to include thermal compensations allowing for the volumetric changes in the PEEK/carbon fabric discussed in section 2.1, including crystallization, in-plane and out-of-plane CTE changes with temperature. The tooling must be precisely designed and fabricated to ensure that pressure is maintained across the ply drops in the part. In addition, the forming pressure around the curved flanges and sidewalls must be managed to avoid wrinkling of the reinforcement and maintain good consolidation pressure. In order to achieve all these requirements a tool set with one steel face and a compliant material on the other face was used. Detailed evaluation of the parts produced is underway at the time this paper is being submitted.

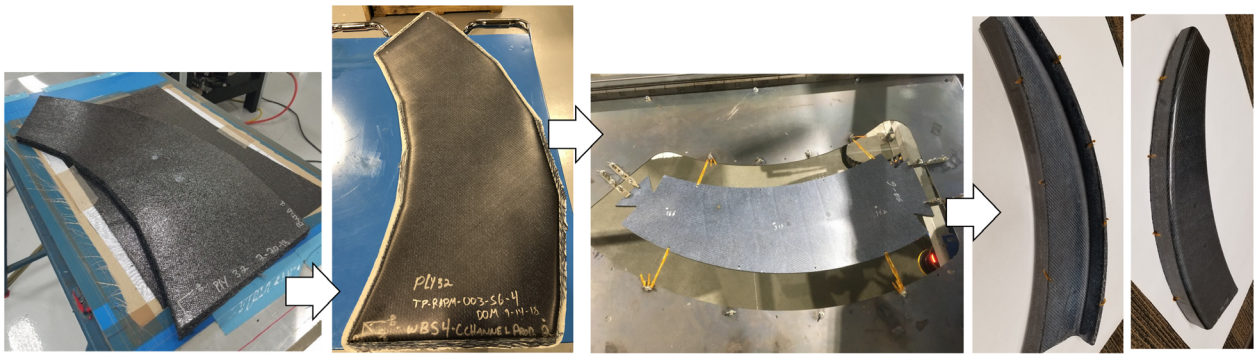


Figure 22. Manufacturing Process for TP-RAPM-003 Thermoplastic Curved Channel.

3. CONCLUSIONS

The thermoplastic forming portion of the RAPM program is to develop rapid molding of small, complex thermoplastic parts for aerospace and other defense applications. The TP-RAPM-002 rib configuration demonstrated the complexities of forming thermoplastic parts within a press system that only applies pressure in one axis. The bladder tool design to overcome this limitation showed promise but ultimately requires more analysis to be successful in compression molding the rib. Difficulty in forming the bladder into the tight inner radii of the part as well as surface thickness uniformity were the primary failure mode of this forming method. The forming experiments were successful in proving that a thin aluminum bladder can apply enough sustained pressure to consolidate a PEKK thermoplastic composite part with passable NDI results.

The flat bladder tool utilized in the Surface Generation system proved to be successful in consolidating thermoplastic tapered parts into a flat blank for the TP-RAPM-003 curved channel configuration. The consolidated blanks are suitable for further processing in a stamp forming cycle to form to the final part configuration. The two processes together overcome the limitations imposed on the rib part and show that complex geometries are attainable with stamp forming for configurations for which compression molding might not be possible.

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