FABRICATION OF A COMPLEX PART WITH DEEP-DRAW SECTIONS BY RESIN TRANSFER MOLDING

Thomas K. Tsotsis[1], Gilbert Cespedes-Gonzalez[2], Mario Wiener[2], Leslie Cohen[3], Dominic Calamito[3], Stephan Costantino[4], Florian Klunker[4]
[1]The Boeing Company, Huntington Beach, CA, 92647 USA
[2]SGL Composites GmbH, Ried im Innkreis, Austria 4910
[3]HITCO Carbon Composites, Inc., Gardena, CA 90249 USA
[4]Huntsman Advanced Materials, Basel, Switzerland

ABSTRACT

One of the three processing tracks within the RApid high-Performance Molding (RAPM) for Small Parts program performed under the DARPA Tailorable Feedstock and Forming (TFF) initiative focused on resin-infused composites. Lessons learned from previous preforming and part-fabrication trials were used to produce a complex-shaped part containing two deep-draw sections. A preforming approach to enable fabrication of the part without fiber distortion was developed. Furthermore, a low-cost tooling approach was applied to creating the preforms. Unlike earlier work in the program, low-pressure resin transfer molding (LPRTM), instead of high-pressure RTM (HPRTM) was used to ease the requirements on tooling pressures to enable lower-costs in tooling materials and tooling fabrication. The details of the tool designs, preform, and part fabrication will be discussed.

1. INTRODUCTION

One of the Tasks in RAPM [1] focused on the use of resin infusion to form aerospace-relevant parts. In the early stages of the program, three different geometries, shown in Figure 1, were used to determine the capabilities of using an automotive-derived, non-crimp fabric (NCF) in conjunction with resin transfer molding (RTM) for fabricating these aerospace-relevant shapes. The parts were selected because they incorporated different features common to aerospace parts that can cause manufacturing challenges. For example, the beaded panel had multiple out-of-plane features along with pad-ups, pad-downs, and a vertical edge. The rib panel had a pad-up with multiple 90° edges and a joggle in one of the edges and the C-channel had varying curvatures, differing radii, varying web height, and varying thickness. Later, the lessons learned from these parts were applied to a challenge part that will be described later.

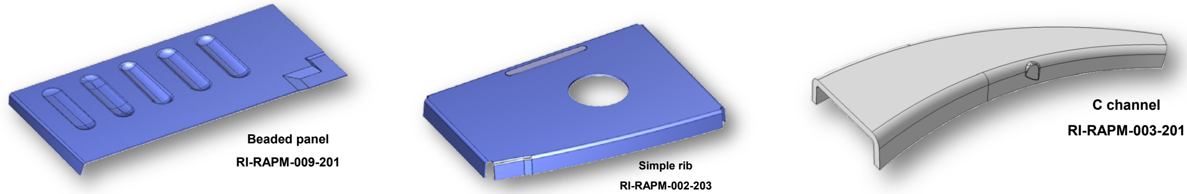

Figure 1. Pathfinder parts used in RAPM. Left, beaded panel; center, rib; right, C-channel.

In order to determine the best procedure for infusing the C-channel, and later the challenge part, it was determined to use computational flow modeling to better understand the problem. The objectives of the analyses were to:

- Analyze process behavior by computer simulation to provide guidelines for process parameters (injection rate, temperature etc.) to steer trials at SGL
- Evaluate potential risks of the current process solution by outlining different injection scenarios
- Demonstrate relationships of material and process parameters to process behavior

The details and results of this flow modeling are given below.

In addition to introducing flow modeling earlier into the design of the tooling for the challenge part mentioned above, the challenge part had several other goals. First was to leverage the knowledge developed during the fabrication of the pathfinder parts and apply lessons learned. In particular, methods to lower the cost of tooling were implemented, as will be discussed below. Second, the challenge part represented a realistic, difficult-to-fabricate part based on a part on a production platform. Improvements in preforming were developed to show a pathway to much more efficient part fabrication using resin infusion than possible with the previous state of the art for this type of part.

2. FLOW MODELING

For the challenge part, shown in Figure 2, an existing fabrication cell at SGL Composites GmbH (Ried im Innkreis, Austria) was used in order to establish the boundary conditions, resin inlet, and vacuum outlet locations of the computational model. Resin was introduced using low-pressure RTM (LPRTM). Huntsman's (The Woodlands, TX) FAF2 two-part epoxy was used in the modeling. The solid model for the challenge part was provided by Boeing; Huntsman (Basel, Switzerland) performed the flow modeling using PAM RTM (ESI Group, Paris, France). The preform fabrics were biaxial 150 gsm/ply and uniaxial 190 gsm/ply NCFs from SGL ACF (Wackersdorf, Germany). Preform permeabilities were estimated [2, 3] using literature techniques and were not measured. These values are shown in Table 1. Prior to the present work, modeling had been applied to the C-channel shown in Figure 1 and lessons from that effort were incorporated into modeling the challenge part shown in Figure 2.

Figure 2. Depiction of pan-assembly challenge part (RI-RAPM-004). Dimensions, approximately: 760 mm (30 in) wide; height of left side, 760 mm (26.5 in); height of right side, 500 mm (20 in); rectangular deep-draw section 57 mm (2.25 in) deep; and the triangular deep-draw section 114 mm (4.5 in) deep.

Table 1. Preform permeability values used in flow modeling

	Kx [m²]	Ky [m²]	Kz [m²]
Preform	1e-11	1e-11	5e-13
Compressed Preform	1e-14 1e-13 1e-12	1e-14 1e-13 1e-12	1e-14 1e-13 1e-12
Neat resin area	5e-8	5e-8	5e-8
Potential "Top Layers" (Front/All)	1e-9 1e-7	1e-9 1e-7	1e-9 1e-7

The geometry used for the challenge part was inspired by a pan assembly that has two deep-draw sections as well as pad-ups around the deep-draw sections and the access hole. These features ensure that the flow path will not be uniform, so the model was created to determine the optimum strategy for infusion, resin exit, and flow channeling.

The preform was broken up into multiple sub-elements, as shown in Figure 3. There were separate elements for the skin, deep-draw sections, and build-up areas, both for the skin and the deep-draw sections. Different layups were used for the different elements as needed to match the designed panel thicknesses. Unlike the C-channel pathfinder part, which also used computational flow modeling and had no resin outlet, the challenge-part model included a resin exit and used low-pressure RTM (LPRTM, *e.g.* 30 bar) instead of HPRTM (*e.g.* 300 bar). The resin, preform, and modeling software used were the same as for the C-channel.

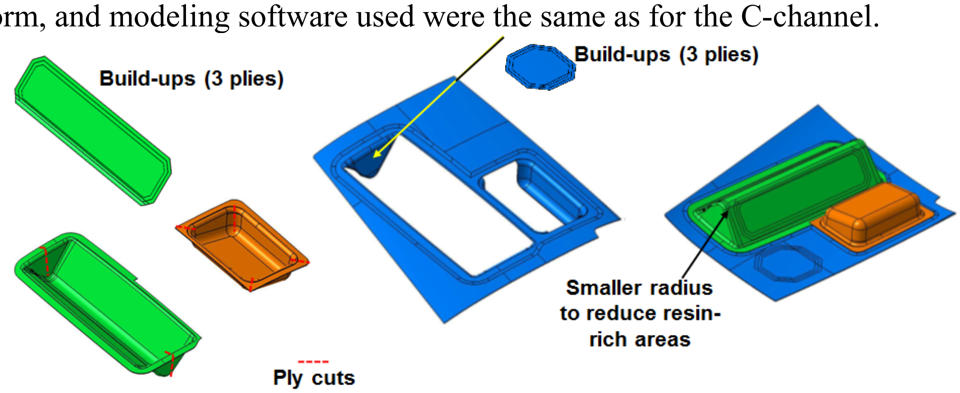

Figure 3. Model elements for challenge part (RI-RAPM-004)

3. TOOLING

3.1 Low-cost tooling approaches

The pathfinder parts shown in Figure 1 were all fabricated using HPRTM and all-steel tooling, which are typical for the types of automotive parts produced by SGL. Because automotive-part production rates and volumes tend to be much higher than for aerospace and because the RAPM program is further targeting manufacturing for defense applications having variable rate and part mix, per-part fabrication costs and per-part tooling costs can only be amortized over a much smaller number than would be the case in the automotive industry. For these reasons, much-lower-cost tooling solutions were sought for the RI-RAPM-004 challenge part.

In order to enable lower costs of mold tooling, it was determined to move away from HPRTM to LPRTM. This processing change dramatically lowered the amount of load on the tool, meaning that it could be made both lower in mass and from less-stiff materials. In this specific instance, it meant using aluminum (see Figure 4) instead of steel for the mold tool, which made tool machining significantly easier.

Figure 4. Image of one of the mold faces for the challenge part (RI-RAPM-004), made from Al5083.

In addition to the mold tool, tools for forming the preforms and trimming finished parts were also made from lower-cost materials. As can be seen in Figure 5, the preform tools were made from Raku-Tool, a polyurethane based manufactured material made by company RAMPF Tooling Solutions GmbH & Co (Grafenberg, Germany). Some of the advantages of the Raku-Tool, include an extremely fine surface structure, very easy milling, excellent dimensional stability, and heat resistance up to 110°C, which was more than sufficient for heat-setting of the preforms in the fabrication of the challenge part. Additionally, as is seen in the images at the left and center of Figure 5, simple, hand-operated clamping mechanisms along with a simple metal detail (left) and a fiberglass casting (center) were also utilized in forming the preform fabric to the desired shape. The trim tool, also made from Raku-Tool, is shown in Figure 6. It should be noted that, although all preform handling was done manually for the challenge part, all steps were designed such that each could be automated if rates warranted.

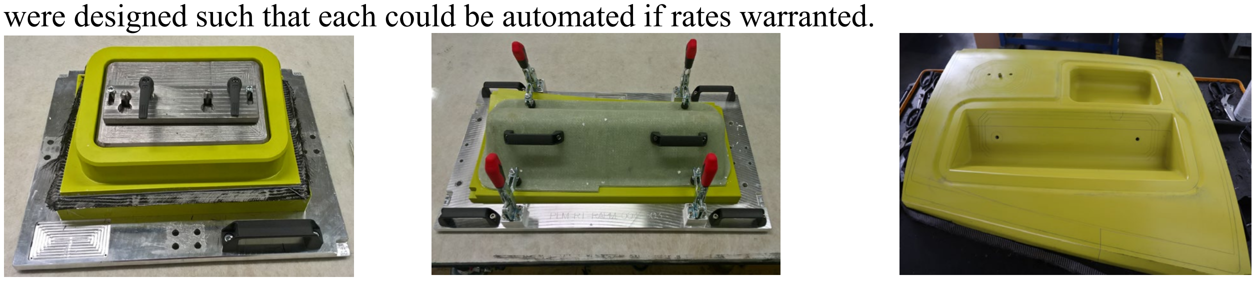

Figure 5. Preform tools for rectangular deep-draw section (left), triangular deep-draw section (middle), and full part assembly (right) for challenge part, RI-RAPM-004.

Figure 6. Trim fixture for milling of challenge part (RI-RAPM-004).

4. RESULTS

4.1 Challenge-part flow modeling

Using the lessons learned from the modelling of the C-channel, a similar approach was used to model the challenge part. The preform subelements shown in Figure 3 were used to construct the model shown in Figure 7. The model assumed that the base plies all had a fiber-volume fraction of 50% and that pad-ups had fiber-volume fractions of 54.8%. The maximum pressure was constrained to 30 bar as this part was processed using LPRTM instead of HPRTM.

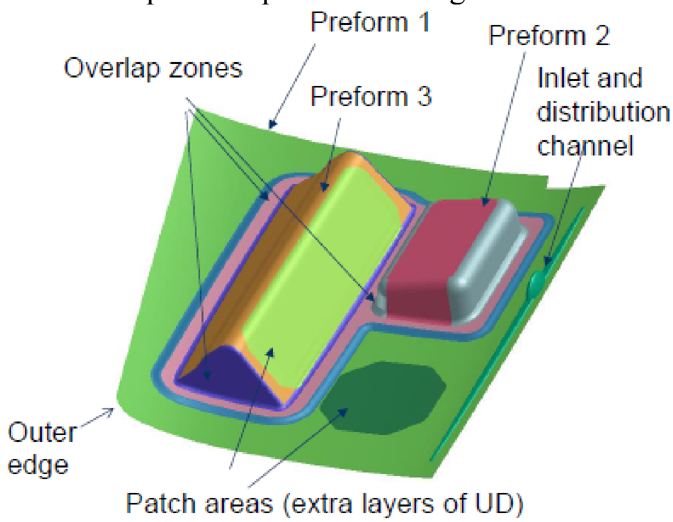

Figure 7. Model set-up for challenge part

Computational trials were performed to determine the filling pattern based on the resin-inlet location and initial resin-distribution strategy. In Figure 8, the effect of the deep-draw sections is seen in changing the flow pattern as the length of the resin flow path increases in these areas. As a result, at 95% of filling the preform, it may be seen that the lower right corner of the preform fills last. Thus, it was recommended that the resin outlet be located in this area as shown in Figure 9.

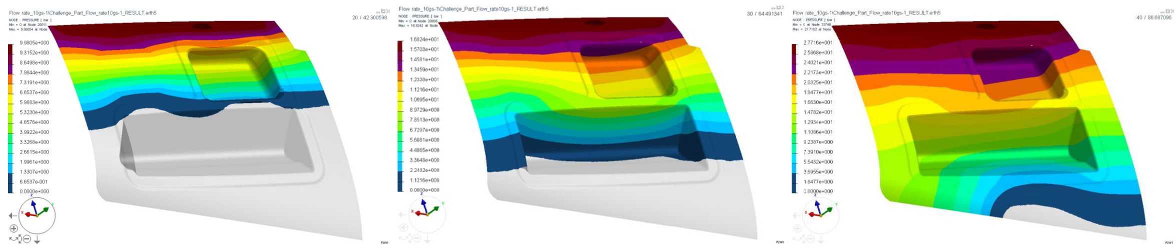

Figure 8. Resin filling flow pattern at 50% (left), 75% (center), and 95% (right) at 10 g/sec resin flow rate.

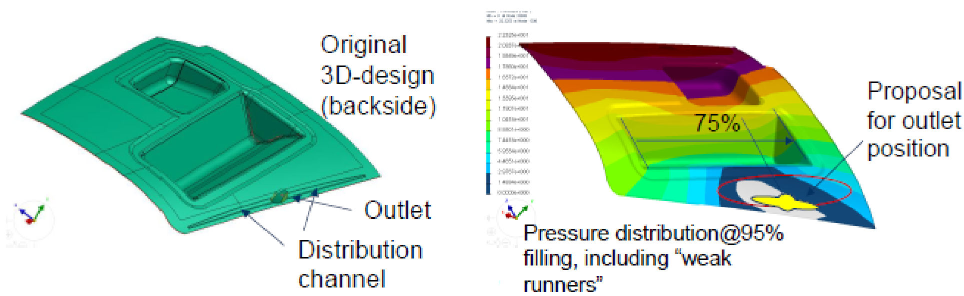

Figure 9. Original flow scheme, left, and recommended flow scheme, right.

In addition to the relocation of the resin outlet, the size of the resin distribution channel near the outlet was reduced. The location of the resin outlet was placed approximately 75% along the length of the preform, as shown in Figure 9. Robustness trials were performed to examine the effects of high resin flow along the preform edges. The results, shown in Figure 10, indicate that strong runners would cause the second deep-draw section to fill last, giving a high potential for creating a dry spot in this area of the part after filling. Thus, it was determined that this type of flow pattern should be restricted to ensure full preform wetout.

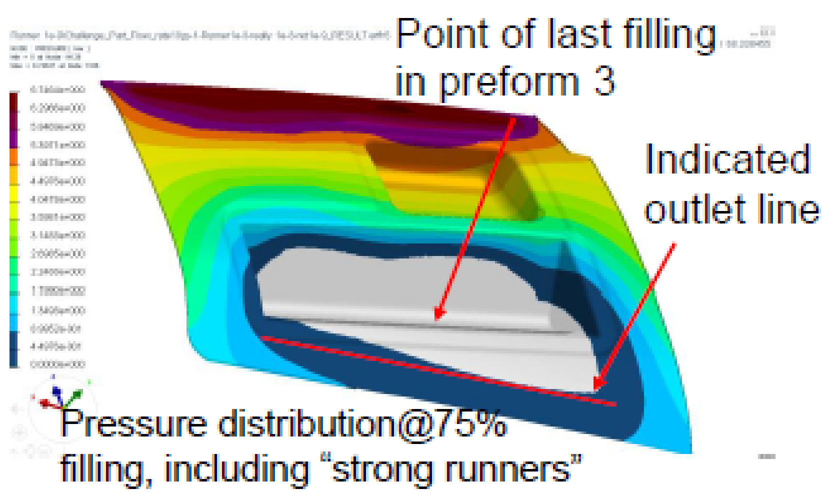

Figure 10. Effect of high resin flow (*e.g.* "strong runners") along preform edges.

4.2 **Challenge-part fabrication**

The preforming approach shown in Figure 3 was used, with a fully assembled preform shown in Figure 11. Each part detail was preformed to near-net shape prior to assembly by preheating the details and then forming them using low-cost tools, as shown in Figure 5.

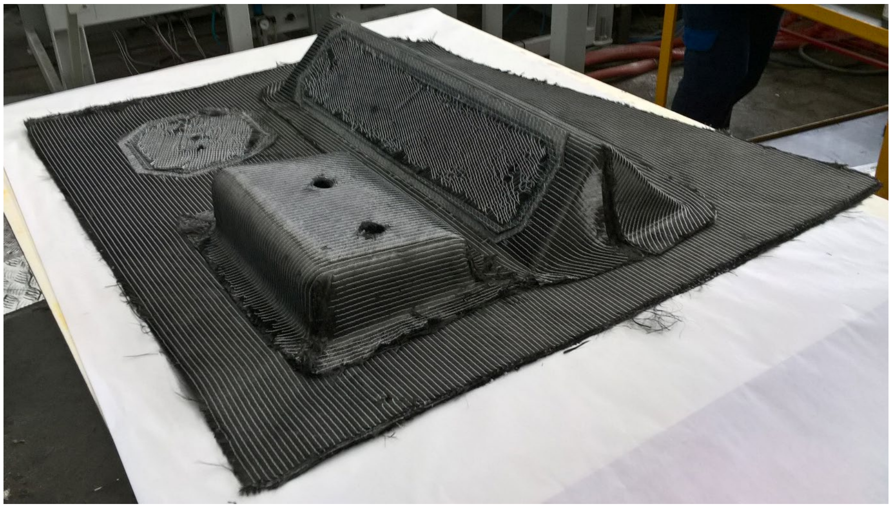

Figure 11. Fully assembled preform prior to infusion for RI-RAPM-004-201.

The modeling approach described above was implemented in the fabrication of RI-RAPM-004-201. Initial trials showed an unexpected anomaly in the flow near the exit that acted to lift the surface plies, causing fiber distortion. For this reason, the inlet and outlet were reversed, which eliminated the fiber distortion and resulted in repeatable, high-quality panels, as shown in Figure 12. After infusion and initial cure in a 130°C tool, all parts were post-cured at 180°C according to guidelines provided by Huntsman and then machined to net shape. Once all process parameters had been fixed, ten parts (see Figure 13) were fabricated for delivery to Boeing for full evaluation.

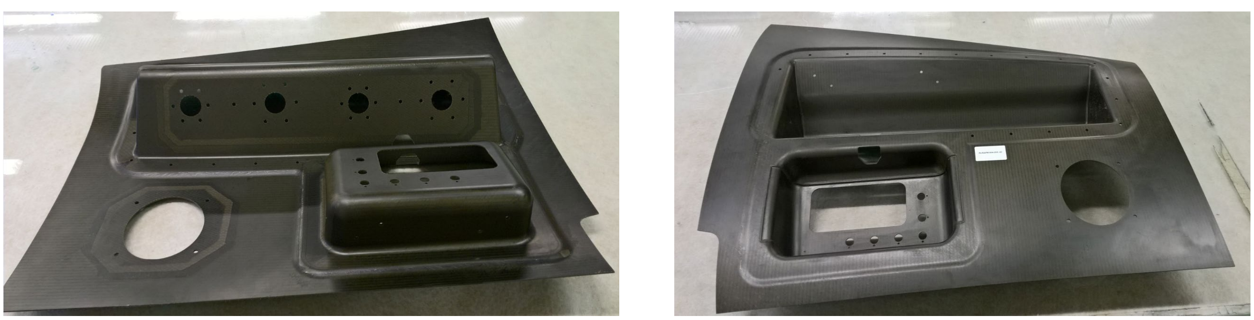

Figure 12. Bottom (left) and top (right) of RI-RAPM-004-201.

Figure 13. Ten RI-RAPM-004-201 parts delivered to Boeing.

4.3 **Challenge-part analyses**

All of the parts shown in Figure 12 were ultrasonically C-scanned, as seen in Figure 14. A typical result for the C-scanning is shown in Figure 15, where it is seen that, due to the complex part geometry, there are areas inaccessible to the ultrasonic transducer during C-scanning.

Figure 14. Automated ultrasonic scanning system (AUSS) used for C-scans of challenge parts (RI-RAPM-004).

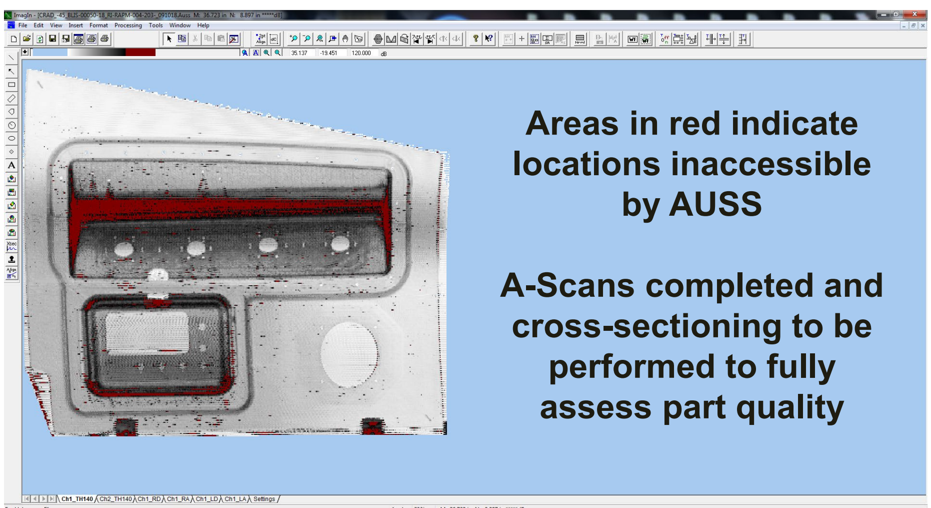

Figure 15. Typical ultrasonic C-scan of challenge parts.

Because the AUSS could not access certain areas on the challenge parts, it was necessary to complete non-destructive examination (NDE) using hand-held ultrasonic A-scanning. During these tests, it was seen that some of to the challenge parts exhibited some anomalous areas in some of the radii of the deep-draw sections. It was determined via subsequent cross sectioning of these areas that the anomalies were delaminations, likely induced by out-of-plane stresses in the radii generated thermally or mechanically during part removal from the tool. It is believed that either a modified cure cycle with full cure on the tool or the use or a resin system with improved interlaminar toughness would eliminate this type of flaw from the fabrication of this part. Note that the tooling system used in the present study could not operate higher than 130°C, so full cure within the desired processing time was not possible at the facility where these parts were fabricated.

The parts exhibited a glass transition temperature of 197°C dry and 176°C wet after a 14-day soak in 71°C distilled water with a fiber-volume fraction of 49.5% (this value is typical for the ACF fabric used herein). Cross-sectional analyses showed full consolidation, as seen in Figure 16. Subsequent CT scans (not shown) also showed excellent fiber alignment and good part quality.

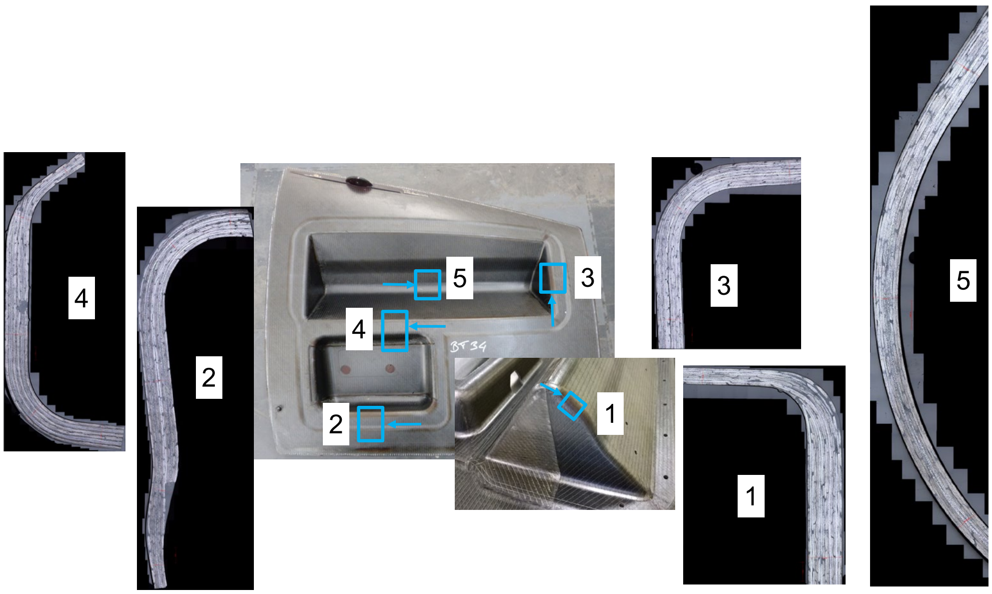

Figure 16. Cross sections from various locations of pan assembly challenge part, RI-RAPM-004-201

Greater detail of the typical quality of part cross sections is shown in Figure 17, which shows no porosity or unwanted fiber distortions. As seen in Figure 16, such quality is largely consistent throughout the part with the exception of the anomalous areas noted above in some of the radii.

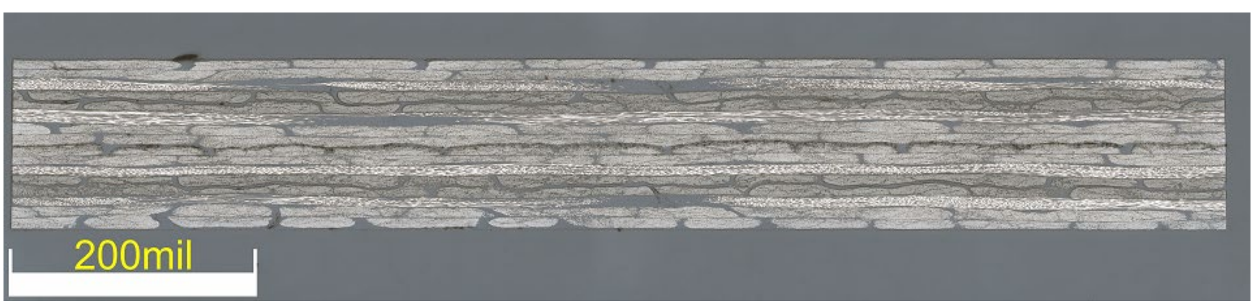

Figure 17. Representative cross section of challenge part taken from pad-up around V-shaped deep-draw section

When comparing the complexity of the fabrication of the part geometry that inspired the challenge part described herein, the approach demonstrated above enabled over a two-thirds reduction in piece count in part layup as well as an estimated 90% reduction in touch labor vs. the current state-of-the-art process. Thus, the approach shown in the present work shows that the use of low-cost materials and processes do indeed have significant benefits outside simply the lower acquisition costs of raw materials in enabling simpler and easier part fabrication to capture further cost benefits.

There are plans under RAPM to fabricate the challenge-part geometry using aerospace-qualified resins and fabrics, which will show how well adapted the tools and processes described above are to different materials and materials combinations. Additionally, these trials will help to show how the technologies developed under RAPM can be used to help transition resin-infusion approaches to part manufacturing to existing and future Defense programs.

5. CONCLUSIONS

Flow modeling was used successfully to characterize the flow of resin for a complex-shaped preforms to fabricate a complex-shaped pan assembly with two deep-draw sections and with areas with a high radius of curvature. Processing parameters and the mold design (inlet and exit) were adjusted according to the model calculations to reduce the chances of dry fibers from incomplete wet-out. Fabrication trials showed that application of the approach from the model results produced preforms that had completely infused.

Furthermore, the tools demonstrated herein provide a framework for low-cost, early-stage process modeling to reduce the risk of producing parts of substandard quality and dramatically reducing or eliminating the costs associated with tooling and/or process rework. It is highly recommended that such an approach be used prior to any detailed design is performed to capture cost and schedule savings while assuring higher part quality.

Resin infusion was shown to be capable of producing high-quality parts with very complex geometries in a way that enables significant reductions in both the number of piece parts needed during layup and in the amount of touch labor needed during part fabrication versus current state-of-the-art aerospace composite manufacturing methods using conventional prepreg materials and processes. Incorporation of the materials and methods described herein, when applied to appropriate parts and part types, offers significant potential benefits in lowering manufacturing costs, if implemented correctly, thereby demonstrating one of the key goals of both RAPM and TFF.

6. ACKNOWLEDGMENTS

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