RAPID HIGH-PERFORMANCE MOLDING (RAPM) FOR SMALL PARTS

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ABSTRACT

RApid high-Performance Molding (RAPM) for Small Parts is a program under the Tailorable Feedstock and Forming (TFF) initiative of the Defense Advanced Research Projects Agency/Defense Science Office (DARPA/DSO) to revolutionize the cost paradigm for small composite parts enabling pervasive use in defense applications that are insensitive to part mix and rate fluctuation. Aerospace-capable, composite-material product forms and forming techniques inspired by industrial-automotive composite materials and manufacturing technologies are being developed by a Boeing-led team to achieve a reconfigurable manufacturing cell featuring modular tooling and rapid heating/cooling with pixelated zones to win design/manufacturing trades for composite small parts enabling transition of these technologies and their spinoff benefits across the supply network. Stakeholders are interested in improving "throughput" and gaining better understanding of small-part (and process) composite trade space and processing techniques for repeatable part quality. Defense customers are also interested in agility to deal with manufacturing rate because of the range of production quantities across defense applications and the frequent fluctuations in production/spares quantities across defense. Challenges, opportunities, and progress to date will be discussed for forming thermoset prepreg, thermoplastic prepreg, and resin-infused materials.

1. INTRODUCTION

RApid high-Performance Molding (RAPM, pronounced "wrap-em") for Small Parts is the forming program under the Defense Advanced Research Projects Agency (DARPA) Tailorable Feedstock and Forming [1] initiative. The objective of RAPM is to revolutionize the cost paradigm for small composite parts (size) enabling pervasive use in defense applications with manufacturing agility for part mix and rate fluctuation. Keys to meeting this objective are confirming aerospace structural performance and winning trade studies against machined aluminum for certain classes of aerospace-relevant structures. Past trade studies by Boeing showed that materials (or feedstocks) and their forming operations (forming) are pivotal to success in trades when considering different families of part types, geometries, and sizes. Additionally, when adding to those studies the constraints of defense systems, which have fluctuations in production/spares quantities, the agility and resilience of the factory and supply chain must be considered.

Industrial-automotive composite materials and manufacturing technologies are rapidly gaining prominence in the composites industry. In particular, work-cell developments have been highlighted in trade magazines [2-3] and at conferences – even the notable joining of SAMPE and American Composites Manufacturers Association (ACMA) for the creation of the annual Composites and Advanced Materials Expo (CAMX) is representative of the merging of aerospace and non-aerospace composites technologies in the marketplace. At CAMX 2017 in the Emerging Technologies for Affordable Composites Structures category, 11 papers and three education sessions highlighted materials, automation, material product forms developed for particular processing methods, and quality. The discussion by Koon et al. [4] was an example of the progression from the 1980s paperless factory to the Digital Factory of the Future (DFofF), the Programmable Powdered Preform Process for Aerospace (P4A) circa the early 2000s to the long-fiber injection processes presented in the paper. The automotive and industrial emphasis is often on high rate, although variable rate and agile manufacturing approaches are also seen in some discussions, most notably those with regard to defense applications such as the Low Cost Attritable Aircraft Technology also referred to in [4].

RAPM is developing and evaluating three primary material/process areas: resin infusion, which includes effort by HITCO and SGL Composites GmbH; thermoset prepreg forming, which includes effort by Cytec/Solvay/C-Con GmbH; and thermoplastic forming, which includes effort by Advanced Thermoplastic Composites (ATC) Manufacturing, Inc., to provide a rich trade space to better identify which materials and processes are best suited for different part types, geometries, sizes, and rates. Because the materials of Tailorable Universal Feedstock for Forming (TuFF) [5] were not available at the start of the TFF initiative, "surrogate" materials have been utilized – currently qualified aerospace materials, recently developed materials, and some from industrial roots.

To be considered aerospace capable, a material must maintain adequate properties when exposed to aerospace fluids. The mechanical properties must enable a competitive (comparable or better) trade position against machined aluminum. Key properties for small parts could include in-plane modulus, bearing, open-hole-tension/compression, shear, and inter-laminar tension. Key properties must be maintained over the use temperature range which can typically be from -100 F or – 65 F to 180 F or 300 F. Acceptable laminate quality is typically fiber volume of 54-60%, void content of less than 1-2%, and acceptable fiber alignment which is replicated part to part, demonstrating stable materials and processes with appropriate control.

This paper is one of a series [6-10] on the RAPM program, providing an overview of the effort, highlighting progress, and eliciting discussion of challenges and opportunities for currently qualified and emerging materials, work-cell development and equipment, including design guidelines which drive nondestructive testing approaches, challenging part features and technology-transition opportunities, manufacturing part mix and replication, and trade study approaches and datasets. There is relevance to material, tooling, equipment, and software providers as well as materials and process, manufacturing, and design and strength engineers.

1.1 Trade Space

Figure 1 summarizes recurring cost trends by component size compiled across many platforms. Resin infusion wins trade space for large components as seen with the example configuration near 45-kg (100-lb) part weight. RI-RAPM-004 is a double-pan challenge configuration which is being fabricated in the RAPM resin-infusion task and under consideration by TuFF [11]. Also, referring to Figure 1, the thermoset-forming curve has points for two RAPM configurations, a process-development beaded configuration, designated TS-RAPM-001, and a challenge configuration, designated TS-RAPM-012. The thermoplastics curve shows trade-space-winning applications on both ends of the curve, such as clips and brackets under 0.23 kg (0.5 lbs) and long parts, which win the trade space with Continuous Compression Molding

(CCM), near 11 kg (25 lbs). Configuration TP-RAPM-013 is a rib representing several potential transition opportunities for thermoplastics.

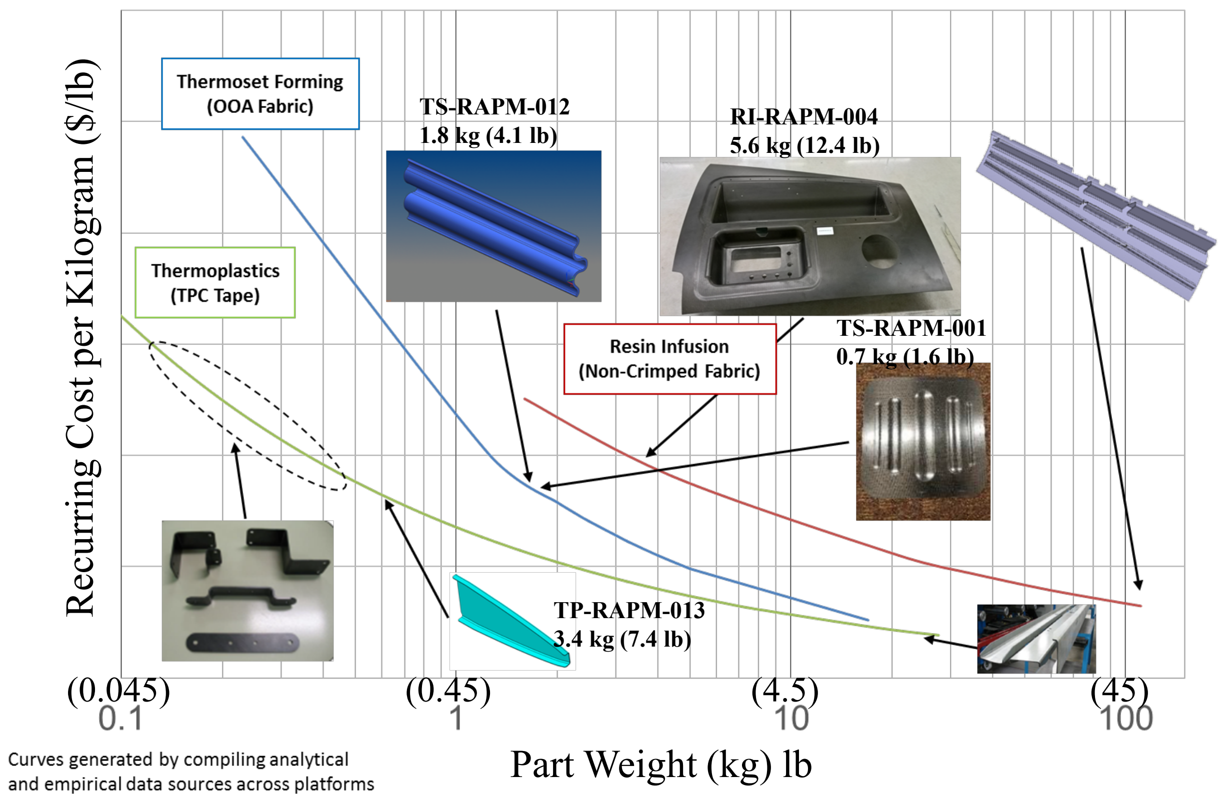


Figure 1. Recurring Cost Trends by Component Size

1.2 Design Optimization – Tying TuFF Feedstock and RAPM under TFF

Design Optimization for Short Fiber Parts is a RAPM task that was added in 2018 to address the feedstock portion of the Tailorable Feedstock and Forming (TFF) initiative [1, 5]. The task develops at framework for rapid modeling, analysis, and optimization of three-dimensional (3D) volumetric parts with non-uniform material properties. The approach being consider includes modeling of a parametric family of potential designs (3D volumetric modeling of non-isotropic, variable density materials), automated structural analysis of geometric models (develop and integrate capability for performing structural assessment), and design optimization (use of numerical optimization to evaluate parametric family of designs). Figure 2 provides an example of a geometric model for a C-channel which could be used in an application such as a rib or spar.

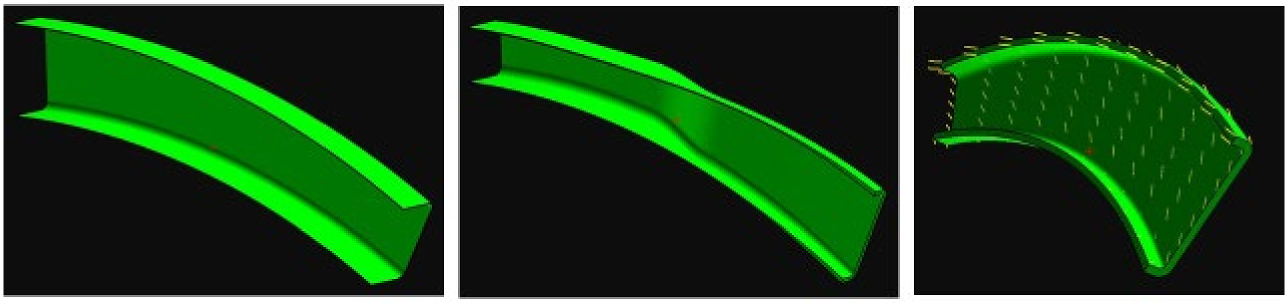


Figure 2. Geometric model adjusting thickness, height, width, and radius (initial configuration based on the RAPM-003 curved-channel)

Although further details of Design Optimization for Short Fiber Parts will not be covered in this paper or at SAMPE 2019, appropriate reporting through TFF and RAPM will be available within the year. This task provides the tie between the feedstock development, forming development, design and manufacturing trade studies, and potential applications that benefit from developments under the TFF initiative, and, in some cases, other developments in the DARPA portfolio.

2. EXPERIMENTATION

RAPM experimentation is in two primary categories:

1. Development - configurations for development of forming processes, manufacturing approaches, and trade studies and

2. Challenge and Transition – configurations to challenge the initial forming process developments and transition candidates with the potential to win the trade against a machined-aluminum approach.

2.1 Development

Figure 3 provides the initial development approach in RAPM with the three primary tracks of resin infusion, thermoset prepreg forming and thermoplastic forming for three primary part configurations – two beaded-panel configurations, a rib with pad-ups, and a C-channel.

	Resin Infusion*		Thermoset Prepreg		Thermoplastic Forming	
Part	HPRTM	Gap Infusion	Press-Forming	Surface Generation Press	Press	ATC Stamp-Forming
Beaded Panel (-001 or -009)	API DD3-84, Huntsman FAF2**		970/T300-3K-70-PW, 5320-1/T650, XEP2750/T650	5320-1/T650, XEP2750/T650		
Rib (-002)	API DD3-84, Huntsman FAF2		5320-1/T650, XEP2750/T650		AS4D/ PEKK-FC (Accudyne)	
Curved Channel (003)	API DD3-84, Huntsman FAF2	Huntsman FAF2, CYCOM 823	5320-1/T650, XEP2750/T650		Consolidate Preform (Surf Gen)	2×2 Twill AS4/PEEK, 5 HS AS4/PEEK

***Sigratex® C U170-0/ST UD Fabric, Sigrafil® T50-4.4/255E100 carbon fiber**

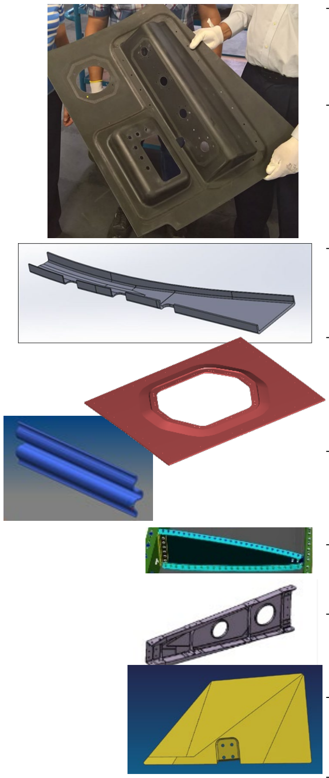
**** Huntsman FAF2 was formerly called PF**

Figure 3. RAPM Manufacturing Development Configurations

The goal of the Development category was to develop design and manufacturing guidelines for each of the three different material forming tracks. For example, forming trials using continuous-fiber, non-crimped fabrics from SGL in the resin-infusion task with the C-channel geometry were used to determine acceptable radii and part geometries that would produce parts without unwanted fiber distortion. A set of design rules was derived from these trials. Additionally, forming trials using double-diaphragm forming of thermoset prepreg were conducted to determine the combination of key process parameters (*e.g.* applied tension, processing temperature and pressure, and time on tool) that would lead to the highest part quality at the highest efficiency. Similarly, preforming and preconsolidation methods were developed for thermoplastics to identify those that produced the best quality with the least amount of processing. Lessons learned from the work performed in the three materials and processing tasks, in combination with calculated cost data as shown in Figure 1 were used inform the approaches used in the fabrication of various challenge and transition opportunities shown in Figure 4.

2.2 Challenge and Transition

Figure 4 provides a table of the challenge and transition configurations for RAPM forming with links to the different materials and processing tasks within RAPM. Note that LPRTM indicates low-pressure resin transfer molding and that press-forming means part fabrication at Solvay while any parts using the Surface Generation (SG) press will be processed by Boeing at its St. Louis facility. ATC stamp-forming designates parts made by ATC Manufacturing, Inc.



	Resin Infusion	Thermoset Prepreg		Thermoplastic Forming	
Part	LPRTM	Press-Forming	Surface Generation Press	Surface Generation Press	Stamp Forming
RTM Challenge RI-RAPM-004	SGL Sigratex® with FAF2 [1,2]				
	2 aero fabrics [3,4] with RTM 6-2 or RTM 6				
Solvay Challenge TS-RAPM-007		5320-1/T650, XEP2750/ T650			
Skin/Access Panel TS-RAPM-008 TP-RAPM-008		5320-1/T650, XEP2750/T650		*chopped AS4D/ PEKK-FC*	*AS4D/ PEKK-FC*
Boeing TS Challenge TS-RAPM-012			5320-1/T650, XEP2750/ T650		
Rib TP-RAPM-013					AS4D/ PEKK-FC
Motor Arm TS-RAPM-014		5320-1/T650/ XEP2750/ T650			
Fin TS-RAPM-015		5320-1/T650/ XEP2750/ T650			

1 Sigratex® C U170-0/ST UD Fabric, Sigrafil® T50-4.4/255E100 carbon fiber 2 Huntsman FAF2 was formerly called PF 3 3K-70-PW AS4 and HTS 40 2x2 twill with veil

Figure 4. RAPM Challenge and Transition Matrix

At the time of the writing of this paper, only the resin-infusion challenge part had been fabricated with the other parts in various different stages of progress. Updates on the results of these part-manufacturing studies will be presented in future forums.

3. RESULTS

Processing and forming trials were performed for resin infusion, thermoset prepreg stamp-forming, and thermoplastic stamp-forming. Some of the highlights of these trials are outlined below along with how these trials informed trade studies to evaluate the different approaches versus part type, geometry, size, and rate to establish metrics for enabling direct comparisons between these and machined aluminum for various applications.

3.1 Resin Infusion

Manufacturing development campaigns were performed using high-pressure resin transfer molding (HPRTM) to produce three different pathfinder parts (RI-RAPM-009, RI-RAPM-002, RI-RAPM-003 as shown in Figure 3). These campaigns identified key parameters for producing high-quality preforms that would permit the fabrication of high-quality finished parts. Key geometric features, such as the ratio of radius to thickness, part-curvature limits, the effects of out-of-plane features on fiber orientation, and flange effects were characterized and design rules were developed from these. Additionally, tooling approaches for how and when to apply tension to different types of preform geometries to limit or eliminate perform-fiber distortion were also identified and, where possible, implemented within the program. These design changes were implemented and validated via preform and part fabrication of a modified C-channel geometry, followed by computed tomography (CT) analyses. The lessons learned in these trials were applied subsequently in developing approaches to the RI-RAPM-004 challenge part, shown in Figure 4 and Figure 5.

Figure 5. RI-RAPM-004 Double Pan Deep Draw (10 cm) Challenge Configuration

To address a challenge configuration which could potentially lead to a transition candidate, a double-pan, deep-draw, 5-cm rectangular and 10-cm rectangular to a V shape (2 inches and 4 inches, respectively) configuration, designated RI-RAPM-004, was fabricated by low-pressure resin-transfer-molding. Flow process modeling was performed to facilitate tool design and improve the likelihood of acceptable part-quality outcomes. The details of tool designs, preforms, and part fabrication are discussed in [6], addressing tooling lead time and costs, which eroded trade-study benefits of resin infusion in the development phase of the program.

3.2 Thermoset Prepreg Forming

Manufacturing campaigns to develop processing and tooling approaches suitable for forming aerospace-capable thermoset prepregs were conducted for double diaphragm forming at Solvay using a spring frame with a conventional platen press spring-frame forming [7], and for press forming with the Boeing-Saint Louis Surface Generation press with pixelated heating elements which is discussed further in Section 3.3. Press-forming of thermoset prepreg composite components enables high-rate manufacturing of small and medium-sized parts.

Spring-frame forming was used to take advantage of tailorable charge-tensioning for ply-drop locating, low-cost stamp-forming tooling, rapid charge loading, and rate-enabling automation. A set of demonstrator articles was manufactured with complex ply drops and pad-ups using matched-mold tooling with Solvay resin prepregs based on CYCOM®5320-1, CYCOM®970, and XEP-2750 aerospace-capable formulated epoxy-based systems. Processing trials with these systems were used to develop processing parameters for additional part geometries along with guidelines for hot debulk cycles, preheat cycles, press consolidation, and post-cure steps for maximizing part quality and rate. Spring-frame press fabrication thermoset prepreg configurations shown in Figure 3 and Figure 4, are summarized in Figure 6 and are discussed in more detail in [7].

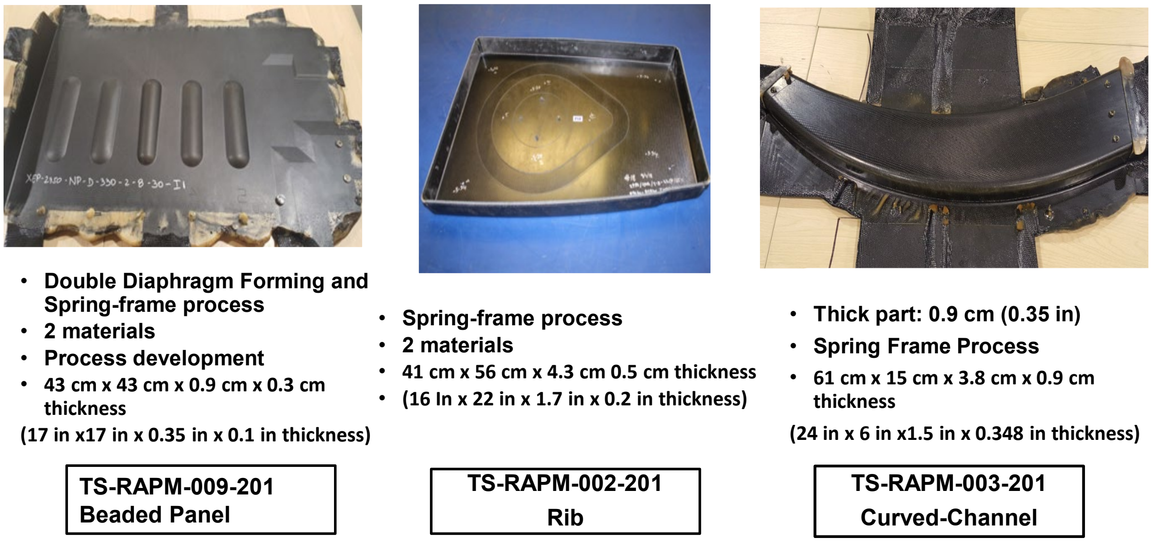
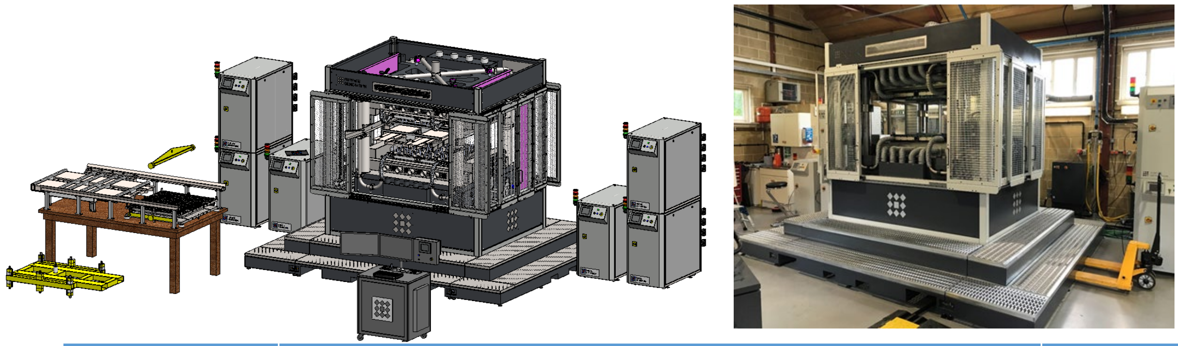


Figure 6 Forming Development for Thermoset Prepreg Approaches

3.3 Dynamic-Control Architectures – Rapid Heating/Cooling with Pixelated Zones

Boeing implemented a digitally controlled Surface Generation Production to Functional Specification (PtFS) pixelated-heating work center, designated CF-OaO-RAPM, Figure 7, at its St. Louis facility with the ability to simultaneously micro-manage laminate temperature and pressure and the timing of each, as well as process- or material-specific inputs across the planform of a tooled press. This equipment is based on a high-frequency, synchronized process controller which integrates the timing of thermal changes (both heating and cooling), consolidation pressure changes, pixelated thermal control over the entire part area, process-specific triggers (*i.e.* vacuum and consolidation gas pressure management), and positional control. All inputs and outputs are recorded and a consolidated data output is made available to the process engineer/user, creating a unique data record that can be subsequently characterized for both real-time and historic trends. This system was utilized for all three material and processing tracks within RAPM, as summarized in Figure 3 and Figure 4.



Item	Description	Quantity
Clamp Fixture	165 ton 0.9 m x 0.9 m (3 ft x 3 ft) hydraulic tool clamping fixture	1
Heater Base for maximum temperatures 440 °C (824 °F) intermittent use	Houses 180 independently controllable channel heaters and feedback thermocouples for the tool providing an effective part base of 76 cm x 76 cm (30 in x 30 in) The baseline unit at Boeing has effective part z-direction of 10 cm (4 in).	1
Control Cabinet	Control cabinets for the heaters in the heater base.	6
Control Computer	The control computer to control tool temperature, pressure, and position control.	1
Tool Loading Rack	A transfer rack to align the tool face onto the heater base.	1
Heater Base Loading Rack	A transfer rack to load the heater bases into the clamp fixture.	1
Tool Flipping Fixture	A flipping fixture to rotate the tool faces for maintenance and install into the clamp fixture.	1

Figure 7 Surface Generation Performance to Functional Specification (PtFS) CF-OaO-RAPM Work Cell

3.4 Thermoplastic Prepreg Forming

Thermoplastic prepregs, due to their higher processing temperatures and pressures, offer a different set of challenges than thermosets in the fabrication of small composite parts. The high processing temperatures of thermoplastics limit the available tooling materials while increasing the concerns for the coefficient of thermal expansion (CTE) of the material choices. Managing the CTE mismatch between the thermoplastic material and the tooling material that would cause it to shrink away from tooling faces during the critical crystallization temperature and lead to a lack of uniform pressure that would adversely impact part-consolidation quality needs to be recognized and be accounted for in establishing tooling dimensions and processing profiles. Developments in preforming and fabrication approaches for thermoplastics are detailed in [9] for the TP-RAPM-002 rib and the TP-RAPM-003 curved channel which are shown in Figure 3.

Figure 8 details the process for the TP-RAPM-003 curved channel which was made with a Cramer AS4-3K un-sized 2x2 twill fabric with fiber areal weight of 250 g/sq. m which was powder coated with PEEK polymer to a resin content of 42%. Boeing developed cutting and pick and place parameters for the raw material layup which was consolidated to a stepped thickness flat blank in the Surface Generation system discussed in Section 3.3. The consolidated blank was supplied to ATC Manufacturing, Inc. where shuttle system details and stamp forming tooling were developed and parts were fabricated.

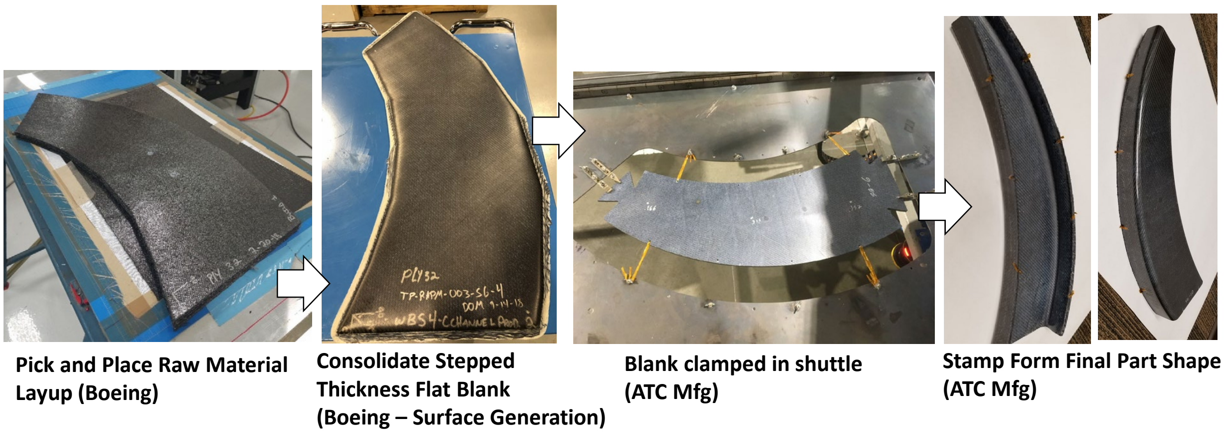


Figure 8 TP-RAPM-003 Thermoplastic Curved Channel

4. SUMMARY

4.1 Development Configurations

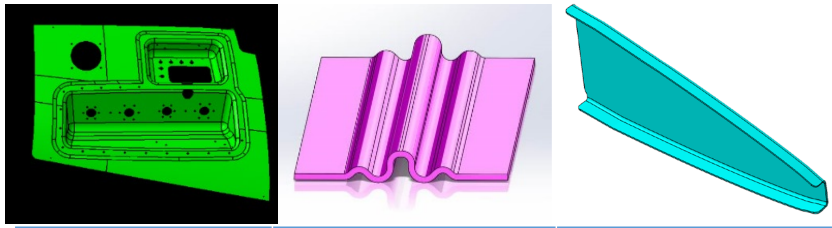
After the development configurations, Section 2.1, the following were identified:

- High-pressure resin transfer molding requires expensive tooling which erodes trade benefit for low-rate defense applications.
- Resin-infusion methods trade best for parts with complex geometry in the small part category.
- Thermoset forming methods can utilize currently qualified aerospace materials, but could also benefit from material products designed for methods and more automation.
- Thermoplastic forming can utilize currently qualified aerospace materials.
- Specialty-fabric thermoplastic products and tooling for thermoplastic processing are expensive.
- Surface Generation made significant software improvements to improve thermal uniformity and clamp fixture control for the RAPM PtFS system.
- A U.S. domestic source for Surface Generation PtFS compatible mold-face designs is desirable for situations in an agile defense-related manufacturing environment which require faster turn-around than international business arrangements.

4.2 Challenge and Transition Configurations

Examples of the trade results for some of the challenge and transition configurations, Section 2.2, are provided in Figure 9. Depending on the weight location and performance needs for TS-RAPM-012, the composite might win the program trade despite the initial trade with a recurring cost premium of 7%.

The recurring manufacturing costs (plus tool amortization) of select challenge part families were compared to machined aluminum



	RI-RAPM-004 Deep Draw	TS-RAPM-012 Wave	TP-RAPM-013 Rib
Related Part Family	5 per ship set	4 per ship set	18 per ship set
Weight Savings Per SS	5.6 kg (12.4 lbs)	1.8 kg (4.1 lbs)*	3.4 kg (7.4 lbs)
Recurring Cost Savings	67%	- 7%	12%
Potential Savings Over Life of Program	~ $3M	NA	~ $900K

* Opportunity exists to reduce weight additional 0.5 kg (1.1 lbs).

Figure 9 Examples of Challenge-Configuration Trade-Study Outcomes

4.3 Opportunities

4.3.1 Materials

The RAPM team considered rapidly processed resins with a goal of 30 minutes time on tool for resin infusion. However, these materials lacked interlaminar toughness. Approaches for interlaminar toughening would be beneficial to the aerospace small parts category.

The RAPM team was fortunate to have good success with existing aerospace-qualified materials in the thermoset prepreg and thermoplastic prepreg tracks. However, in some cases, bridge allowables are needed to confirm that the properties from the RAPM processes are the same as those of existing databases.

In addition, the RAPM team experienced the benefits of materials, such as the developmental material XEP-2750, which provide lower cost material option that is tailored to automated processes.

High temperature sealing materials and designs could still use improvement.

4.3.2 Equipment/Manufacturing Cell Approaches

Equipment and manufacturing cell approaches for high volume are not always compatible for the agility needed for part mix and rate mix of defense applications nor for the processing temperature requirements for aerospace capable thermosets and thermoplastics. However, there are also sometimes opportunities for dual use in manufacturing cell approaches given appropriate vision and planning.

4.3.3 Design Criteria/Non-destructive Evaluation

Among the goals for integration of inspection into manufacturing cell concepts are the following: inspection operation fits into the flow of the manufacturing cell thus saving time, is quick and low cost, ensures aerospace (or other stipulated) quality. Parts are classed as non-structural with no internal defect requirements, secondary structure with internal defect requirements, and primary structure with tighter internal defect requirements. The criteria and requirements placed on the part drive requirements. An example of this is when traditional thermoset porosity requirements are erroneously placed on thermoplastic parts which can prevent cost-effective methods, such as infrared thermography, from being used in the quality conformance process. Parts such as ribs, channels, and deep-draw configurations often require multiple scans for flat areas and radii which impacts the speed of part handling and the cost and complexity of positional tooling required for inspection in addition to the set up time considerations for multiple scans. Standardizing features such as radii and flange angles can help mitigate some of these cost drivers.

4.3.4 Modeling and Design Approaches Leading to New Part Configurations

While the RAPM task "Design Optimization for Short Fiber Parts" was incorporated into RAPM to enhance assessments of the TuFF [5] materials, 3D volumetric modeling does open up modeling and design for materials and part configurations when material properties vary throughout a solid. In addition, this capability, when coupled with the Surface Generation PtFS system which provides controlled heating and cooling within zoned cells could provide unique capabilities for part configurations that have not yet been explored.

4.3.5 Trade Studies

The RAPM team is interested in challenge part configurations, manufacturing scenarios for assessment, and approaches to extend or supplant our current protocols [10].

5. ACKNOWLEDGMENTS

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