COMPRESSION MOLDING OF COMPLEX THERMOSET LAMINATES

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ABSTRACT

Traditionally, high-rate small parts have been fabricated out of metal due to low cost, and high producibility. Following after trends in the automotive sector, certain aerospace-grade resins have shown processing flexibility while maintaining high mechanical and physical performance. The ability to fabricate complex composite laminates with a compression molding process using aerospace resins is essential for achieving low cost, structurally efficient components. The reduction in composites processing time through compression molding also enables favorable economic trades against metallic baselines, while providing increased component performance and providing weight savings. Challenges exist as the laminate thickness increases, tight radius of curvature are incorporated, and unidirectional tape is utilized. An undulating part was fabricated using aerospace prepregs and compression molding techniques. This shows that unidirectional tape can be used to fabricate constant cross section laminates with thick complex features in an automated process with direct forming. The demonstration article was fabricated using CYCOM® 5320-1 carbon fiber tape and fabric prepregs utilizing an on tool cycle time of 30 minutes to enable high throughput. The fabrication of this article will lead to further development of structure that requires quasi-isotropic properties coupled with complex, stiffening geometry. In addition, the ability to compression mold this geometry opens the option of geometrically stiffened structure where previously cost prohibitive.

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1. INTRODUCTION

Recently, there has been expanded interest in developing processes that enable the fabrication of high-rate (>1000 parts per year), high quality, thermoset components, [1] and [2]. Thermosets traditionally have a wide variety of product forms that lend themselves to complex forming and isothermal processing. Combined with these product forms, technology has been developed that allows the compression molding of aerospace grade thermoset materials [3].

Compression molding of thermosets offers an out-of-autoclave solution to traditional, autoclave baselines. Utilizing a closed mold tooling concept [3] and isothermal temperatures, on-tool times of 30 minutes or less can be achieved. When paired with a free-standing post-cure, mechanical and physical properties can be attained that compare well with those from an autoclave, or vacuum bag processes.

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As the utilization of composites continues to grow outside of traditional aerospace fixed wing applications, the need for rate capable processes increases. New applications are continually being explored in commercial applications like urban air mobility platforms and defense applications like high performance weapons. These applications require the performance characteristics and weight savings offered by carbon fiber composites with the rapid cycle times traditionally targeted by industrial applications. Aerospace incumbent materials have shown promise in this area as well as developmental materials being researched by the traditional aerospace supply base.

1.1 Component Definition

A multifunctional team including Design, Materials and Process, and Strength Engineers developed an experimental laminate, referred to as TS-RAPM-012. This laminate was created to meet a set of mechanical performance requirements and hit a set of processing milestones in the RAPM program [3-8], in conjunction with the Tailorable Feedstock and Forming (TFF) initiative [1]. This part has several characteristics that are of interest when a high stiffness, buckle resistant laminate is desired. Of note, it has a nominal thickness of 6.3 mm, tight 12.7 mm radii which are formed in a corrugated pattern. Figure 1 shows a modeled representation of this component. In its untrimmed state (not shown), 44mm of excess material extends past the outer curves, and beyond its length.

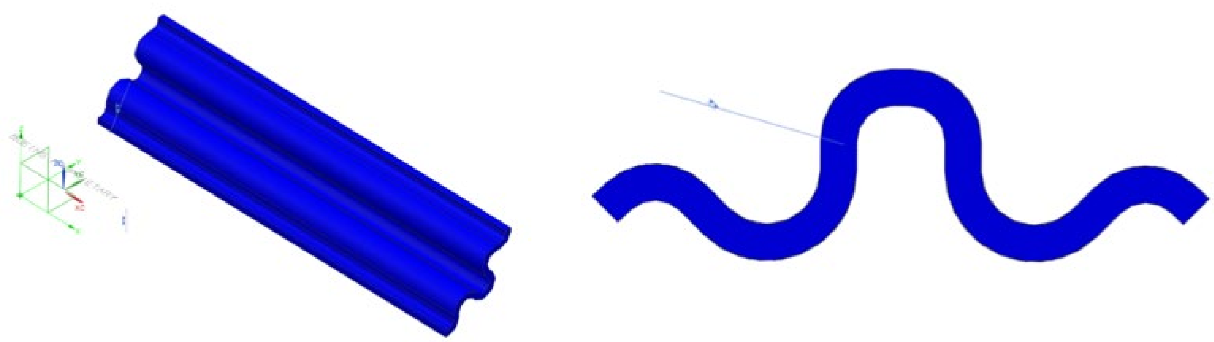


Figure 1 - TS-RAPM-012

To meet the performance requirements, a blend of multiple textile variants (Table 1) was used. A quasi-isotropic layup was used utilizing primarily intermediate modulus, sandwiched between fabric and glass plies. TS-RAPM-012 utilizes the CYCOM® 5320-1 resin system, which has shown the flexibility required for shorter length, isothermal cure cycles [3].

Table 1 - TS-RAPM-012 Material Composition

Material Designation	Resin System	Fiber Type	Weave
1	CYCOM® 5320-1	Glass	Style 108
2	CYCOM® 5320-1	T650	8 Harness Satin
3	CYCOM® 5320-1	IM7	Unidirectional

1.2 Compression Molding of Complex Geometry

Compression molding of thermosets is the process of placing a planar, collated blank of material into a two part mold installed in a hydraulic, heated press. Under hydraulic pressure and temperature, the liquid thermoset material is allowed to cure. This process is capable of high-volume fabrication of high-quality laminates [3]. Utilizing prior development in the RAPM program [3], it has been shown that a 30 minute, isothermal cure cycle at 177 °C, followed by a free standing 177 °C post cure for 2 hours provides adequate mechanical and physical properties for the CYCOM® 5320-1 resin system. The short on-tool cure cycle provides a laminate enough green strength for extraction from the tool in order to be subsequently batch processed in an oven at a later time. In addition to these thermal parameters, several other decisions must be made which are dependent on part geometry and tooling used. These parameters include the need to perform a pre-consolidation, and if a pre-heat processes is needed. Pre-consolidation is the process of using heat and vacuum to remove bulk from a collated ply-stack; this is essentially a hot-debulk. Pre-heating a blank provides improved formability of the blank by quickly reducing resin viscosity. An example of the planned TS-RAPM-012 process flow is shown in Figure 2.

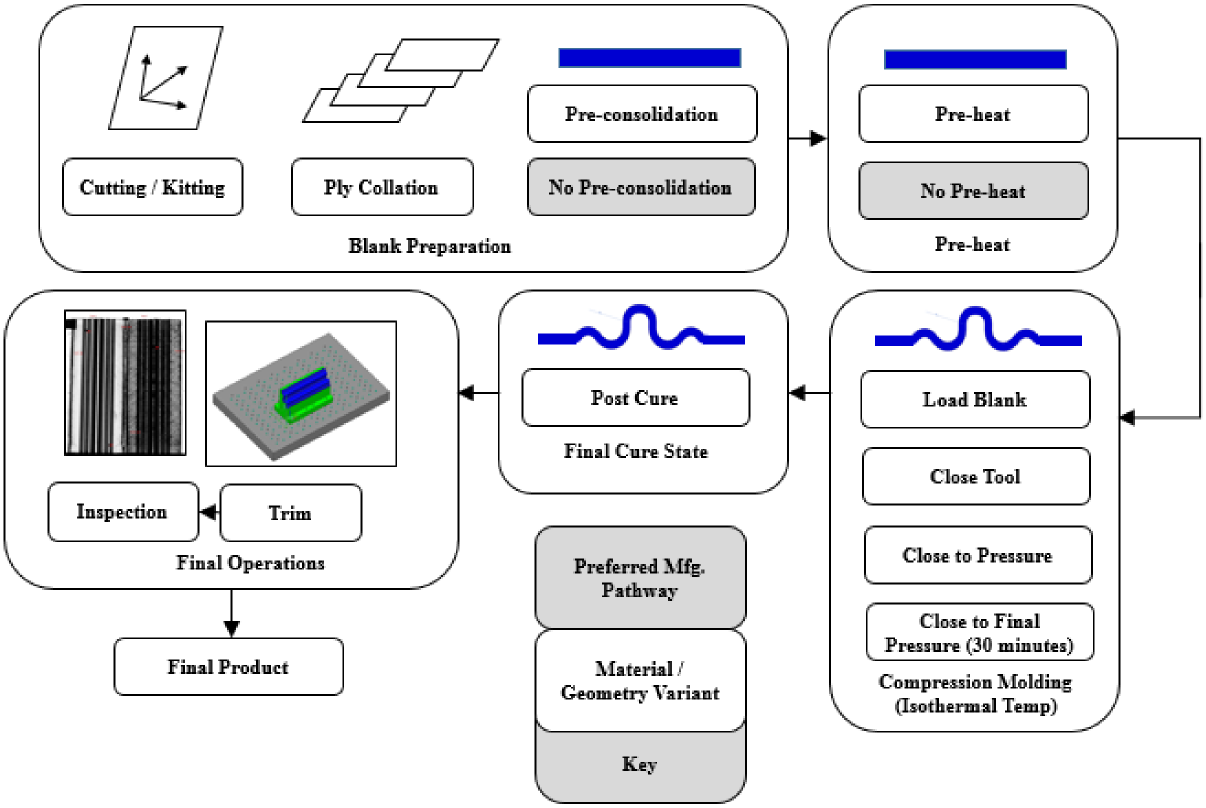


Figure 2 - Compression Molding Process for TS-RAPM-012

2. EXPERIMENTATION

2.1 Tooling

2.1.1 Clamp Fixture

A Surface Generation clamp fixture with Performance to Functional Specification (PtFS™) heating/cooling control technology was selected for the fabrication of TS-RAPM-012. The purpose of this advanced press is to tightly control the thermal input into the laminate using a pixelated tooling approach [4]. Being able to control individual pixels allows for consistent and uniform heat flow into the laminate. In addition, this press offers the flexibility to control consolidation pressure as a desired set point, or by controlling the mold gap by adjusting the platen offset, effectively creating a desired gap between mold faces. This press has 150 tonne clamping capacity, with a temperature ceiling of over 400°C. The design and build of this manufacturing cell is shown in Figure 3.

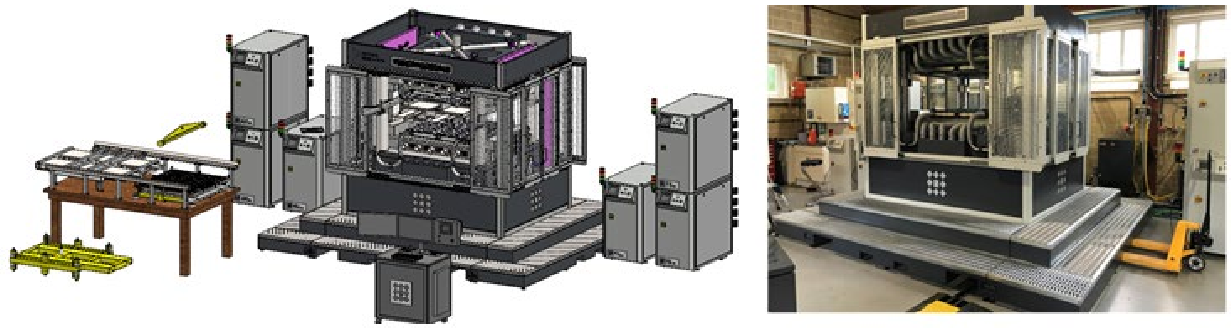


Figure 3 – CF-OaO-RAPM PtFS Manufacturing Cell

2.1.2 Laminate Mold

The mold for this laminate, designated CMD-TS-RAPM-012-501, was specifically designed for use on CF-OaO-RAPM with PtFS [4]. Fabricated from P20 steel, the mold utilizes both integrated resin and vacuum seals. Given the overall concave shape of the female-side mold, the vacuum seal allows the tool cavity to be evacuated during consolidation. The resin seal is designed to keep the resin from migrating out of the molding cavity, allowing the laminate to retain internal hydrostatic pressure, a key component to the fabrication of a quality compression molded laminate. As a process mitigation, the tool cavity was purposely fabricated thinner than nominal laminate thickness. The purpose of this was account for statistical variation in the resin content of the material. If resin content is below nominal, this "thinned out" cavity will still allow the laminate to maintain internal hydrostatic pressure. A representation of the mold faces is shown in Figure 4.

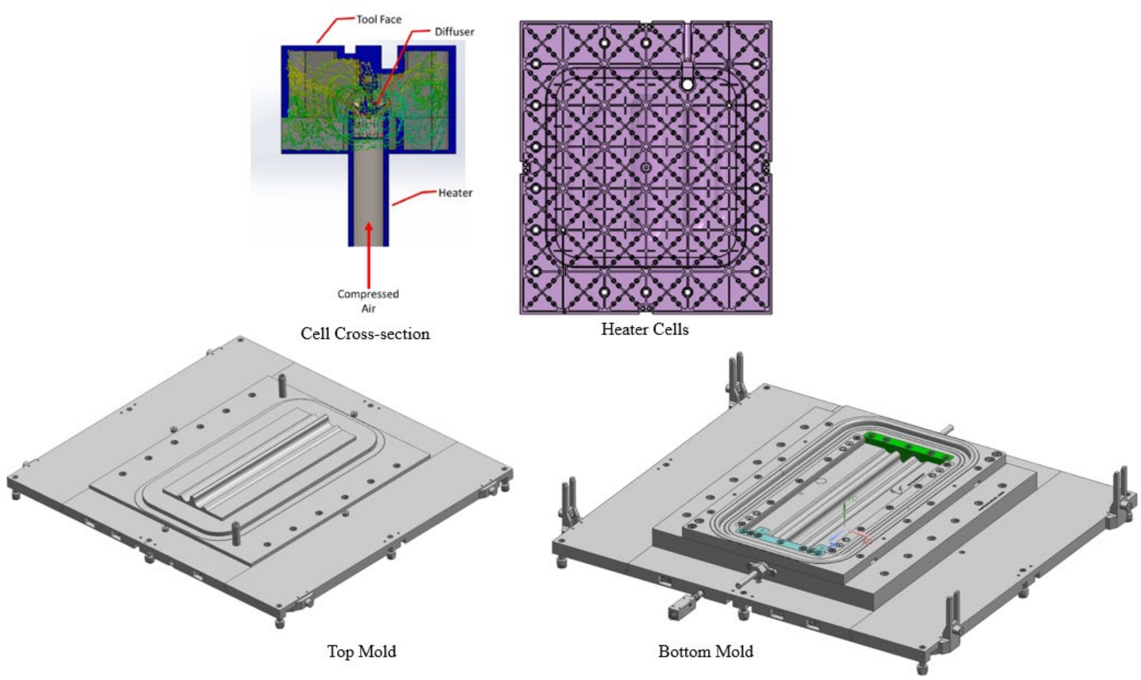
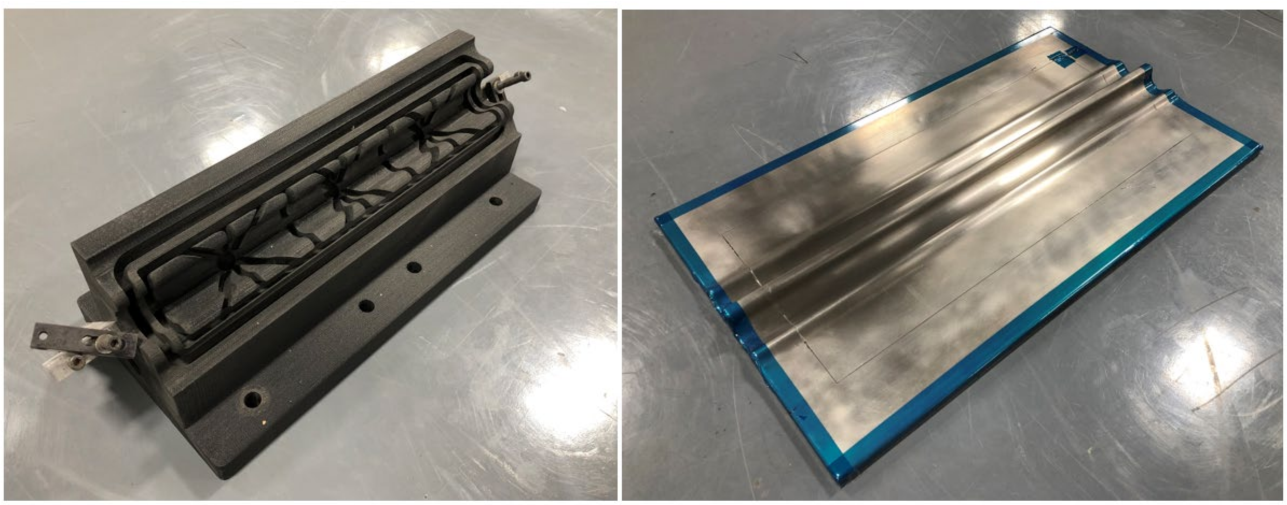


Figure 4 - CMD-TS-RAPM-012-501 Mold Configuration

A tool thermal uniformity survey was conducted on these mold faces to properly tune the thermal input into each of these tooling cells, or pixels. The hot and cold areas were also important to identify as these were locations that would be tested for degree of cure and glass transition temperature.

2.1.3 Supplemental tooling

During the development of TS-RAPM-012 it was determined that additional tools outside of the mold and clamping fixture would be required. The first was an additively manufactured trim fixture. This tool is designed with integral vacuums to hold the part in place. It was machined using a 5-axis Hurco. In addition, while the final CMD-TS-RAPM-012-501 mold was being manufactured, an autoclave mold was machined to create risk reduction articles in an autoclave. The purpose was to develop a baseline for part quality as well as understand the labor benefits achieved using a compression molding process against a traditional hand lay-up. These tools are shown in Figure 5.



Additive Trim Fixture | Autoclave Mold

Figure 5 - Supplemental Tooling

2.2 Part Trials

2.2.1 Autoclave Baseline

To understand what traditional hand lay-up laminate would look like, and to compare labor differences to a compression molding process, several laminates were fabricated as risk reduction articles. Important information regarding time to fabricate was collected.

First, because of the deep, sudden changes in the geometry of this part, getting acceptable bag side quality was difficult. Multiple bagging schemes were utilized in order to achieve a smooth bag-side surface, and wrinkle-free laminates. Woven and nonwoven breather, as well as a flexible rubber caul were used. Because this was a trial tool, a caul sheet was not fabricated. The best part was fabricated using non-woven breather during processing. However, this laminate took three shifts to complete the hand lay-up operation, meaning it is not a feasible solution to high rate applications. This information is valuable when deciding if a compression molding process is an appropriate for a laminate of this complexity.

2.2.2 Forming Trials

An appreciable amount of work on the compression molding of continuous fiber thermosets had been accomplished prior to the fabrication of this component. Using previous process development and lessons learned, a solid baseline process was already in place as a starting point [3]. The difference from previous experiences are the aggressive geometry, and the use of a quasi-isotropic lay-up. The CF-OAO-RAPM PtFS controller was programmed to apply a minimal amount of pressure on the laminate until a proper viscosity was achieved. After this initial step, final pressure was applied to finish out the cure of the laminate. Only one trial was post-cured in a batch oven, and the rest post-cured in the clamping fixture to reduce time between trials. Very little was changed in regards to the press programming between trials. Several trials were completed building off of what was observed from visual, dimensional, and ultrasonic C-Scan inspections. Select laminates were subsequently dissected and chosen to undergo additional tests including photo-microscopy, degree of cure, and glass transition temperature. Table 2 outlines the trials that were completed in this exercise. After an acceptable laminate was fabricated, four additional laminates were fabricated using the same process. These additional laminates prove the consistency of the process parameters.

Table 2 - TS-RAPM-012 Trial Run Parameters

Trial	Cold Form	Pre-Consolidation (min / °C)	Pre-Heat	Cure Time (min)	Run Notes
0	Yes	No	No	30	First run - Cork Dam used; no release film
1	Yes	No	No	30	Release film used to aid in extraction: (2) layers on bottom, (1) on top; No cork dam
2	Yes	No	No	30	No release film; no cork dam
3	Yes	Attempted	No	N/A	Part destroyed during run
4	No	No	No	30	First part without cold form; no release film; no cork dam
5	No	40 / 116	3 / 179	30	Blank pre-consolidated flat; new release film scheme; cork dams used
6	Yes	No	No	N/A	Test part for new release film scheme. Part not cured
7	No	No	No	30	New release film scheme; cork dams were used
8	No	40 / 116	3 / 179	30	Blank pre-consolidated flat; cork dams used; no release film

In regards to the process parameters noted, several warrant discussion. First, the idea of cold-forming a previously collated ply-stack was derived from a desire to see if the plies would suffer damage during the actual pressing operation. After this was done the first time (Trial 0), it was thought that cold-forming could provide some benefit in order to pre-shape the charges. This was abandoned after Trial 3 due to being too cumbersome, time consuming, and the blank relaxing back to a flat shape. The other reason this was being done was to fill the mold cavity. The ply kits were designed to completely fill the mold cavity; trying to press a full sized flat charge into a fully assembled tool resulted in the tool shear wall clamping down on the ply stack, destroying it. After this was discovered, the side walls were removed in order to cold-form a whole stack of plies. When the cold-forming was abandoned, the blanks were trimmed down to just fit within the periphery of the assembled tool. Consequently, the blank would stop short of completely filling the mold, causing resin loss. Cork dams were inserted into the press to provide mass to fill volume.

Next, pre-consolidation (or hot-debulk), is a process that has been utilized with thick laminates to increase part quality. The process is performed in an oven, under full vacuum (>20inHg). The laminate is placed on a plate and bagged with woven fiberglass breather, and pre-consolidated in an oven for a determined amount of time. For this part, the parameters are shown in Table 2. It is preferred to not perform this step in order to reduce processing time, and keep a low thermal history on the resin. It must be observed that a pre-heat process is highly recommended when a blank is pre-consolidated. If placed in a press cold, the materials ability to form complex geometry is hampered by the high resin viscosity of the staged part. For these trials, the blank was simply placed into the hot mold, and closed as close as possible to the flat blank thickness without touching. After 3 minutes, the press operation proceeded as normal. It is recommended that an automated infrared pre-heat be used in a production scenario to reduce variability and part handling [3].

Last, in order to aid in laminate removal after cure or improve hydrostatic pressure, two configurations of release film was used. The first configuration used in Trial 1, was simply sandwiching the blank in 3 layers of film; 2 on the female side, 1 on male. The thought was the side with 2 layers would create a slip plane to help with forming. This was ultimately abandoned because of surface wrinkles in the cured laminate. The second configuration stretched two layers taut across the mold, with the blank in-between. This provided good results, but caused an unacceptably thin laminate.

2.2.3 Trial Evaluation

Two criteria were used during the part forming trials to evaluate acceptability. All parts were submitted for ultrasonic inspection utilizing a 1MHz and 5MHz scan, while several parts were chosen for dissection. This second group of parts were evaluated for laminate thickness. Figure 6 shows both the 1Mhz and 5Mhz scan. It is important to note that only the 5MHz would be an acceptable frequency to correlate an attenuation level to porosity. However, the 1MHz scan was able to more reliable penetrate the aggressive curvature. This was used to verify that the parts were consistent visually across most geometry of the laminate.

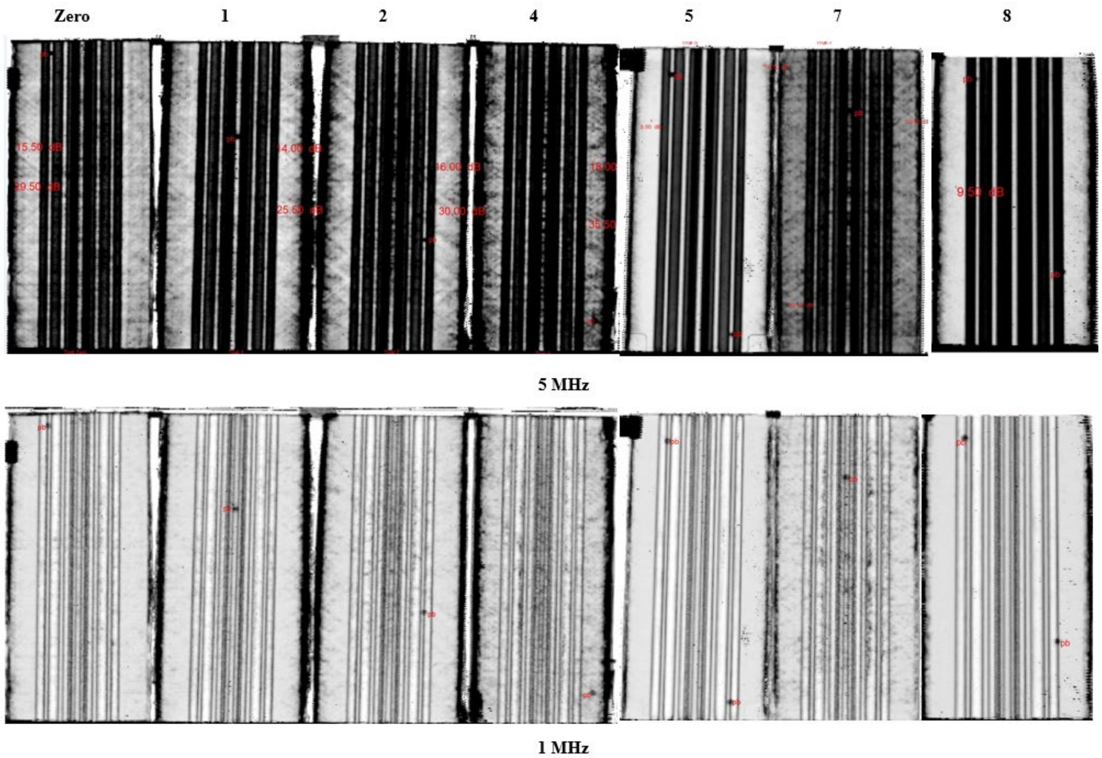


Figure 6 - TS-RAPM-012 Trial NDT Inspection Results

It is important to note that the dark regions around the radii will show increased attenuation. This is due to the ultrasonic system used only scanning on a 2D plane. However, a few observations should be made from evaluating these images. First, pre-consolidation has a large impact on perceived part quality. The drop in attenuation levels in Trials 5 and 8 are evidence of this. Second, the cold forming appears to have correlation to lower attenuation, meaning that the shaping of the plies prior to cure may have reduced the laminate porosity.

In addition to ultrasonic inspection, thickness measurements were taken on several parts, and is shown in Table 3.

Table 3 - TS-RAPM-012 Thickness Results

Trial	Thickness min/max (mm)[1]
0	5.8/6.4
1	N/A
2	N/A
3	N/A
4	5.8/6.4
5	5.6/6.3
6	
7	5.6/6.0
8	5.8/6.0

Notes:

1 - Nominal thickness is 6.3mm; permissible minimum is 5.7mm

The key take-away from the thickness data is the impact of both the pre-consolidation and the "new release film scheme" had on the overall part thickness. Both appeared to have created a thinner part, although the pre-consolidation appears to have abated this problem when combined with the release film. Trial 8 was an effort to fine tune the process, and was successful. A part with low attenuation levels, and desirable thickness was manufactured.

3. RESULTS

3.1 Non-Destructive Evaluation

In addition to the trial parts detailed above, four additional parts were successfully fabricated using an identical process to Trial 8. The NDT results are shown in Figure 7.

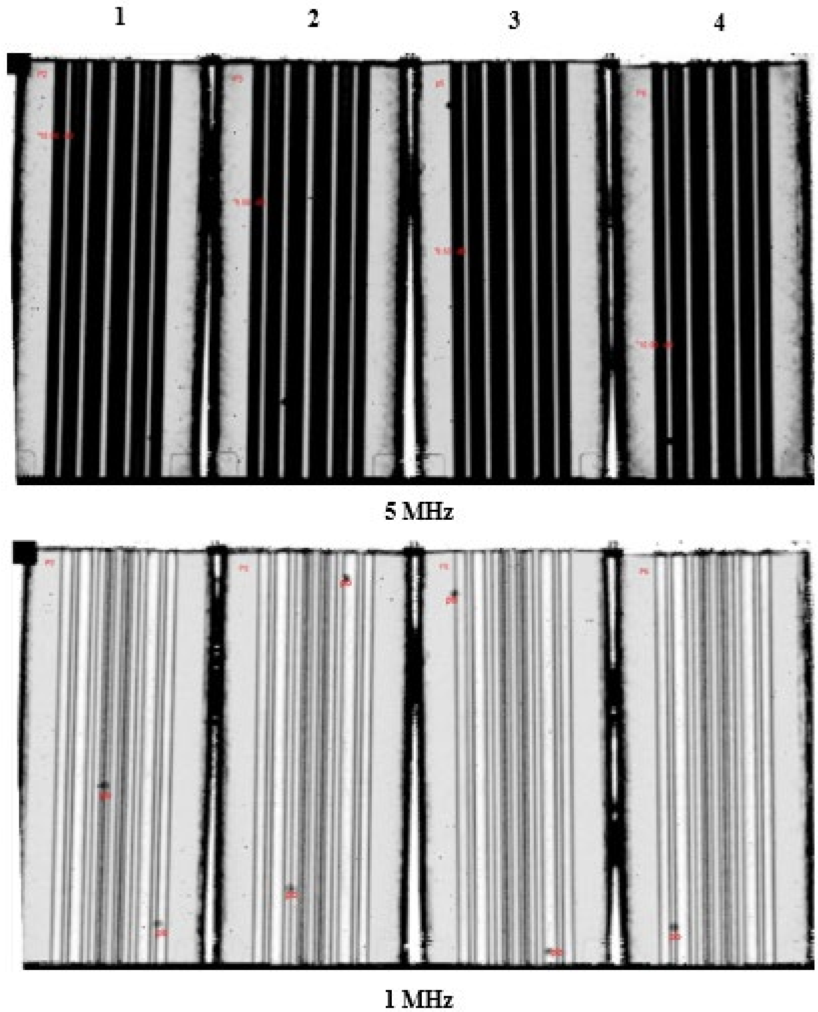


Figure 7 - TS-RAPM-012 Final NDT Results

All subsequent parts show excellent consistency with Trial 8 and each other; each part ranges between 9.5 and 10 dB with the 5MHz scan. Visually, the 1 MHz scans are nearly identical. These scans were later correlated with photo-microscopy and void content analysis to ensure the reliability of the scan method. It is important to note that the flat excess material was left on for inspection purposes. It was later trimmed off during the final trim operation. A complete laminate is shown in Figure 8.

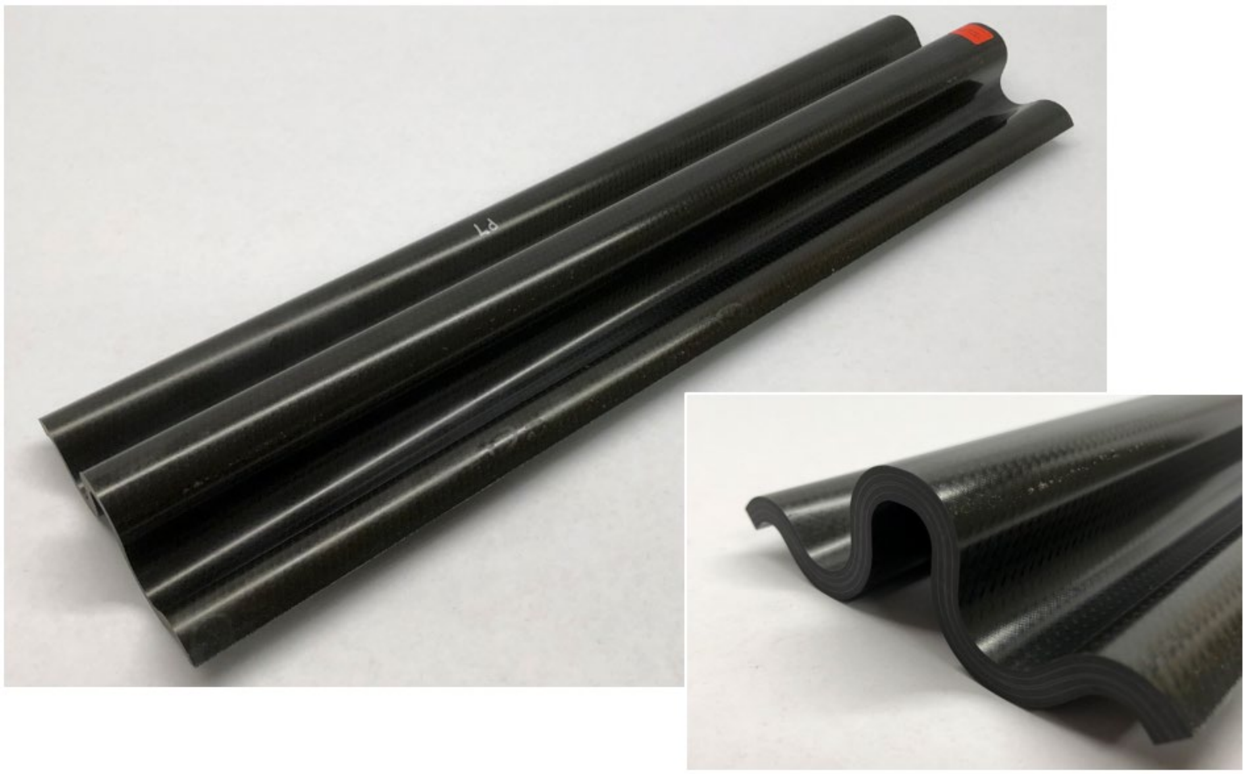


Figure 8 - Completed TS-RAPM-012 Laminate

3.2 Photo-Microscopy

In addition to the ultrasonic inspection, the quality of the laminate internally was also of great interest. Particularly, how much the fibers were disturbed during the forming from a flat blank, and any other anomalies. A dissection map is shown in Figure 9.

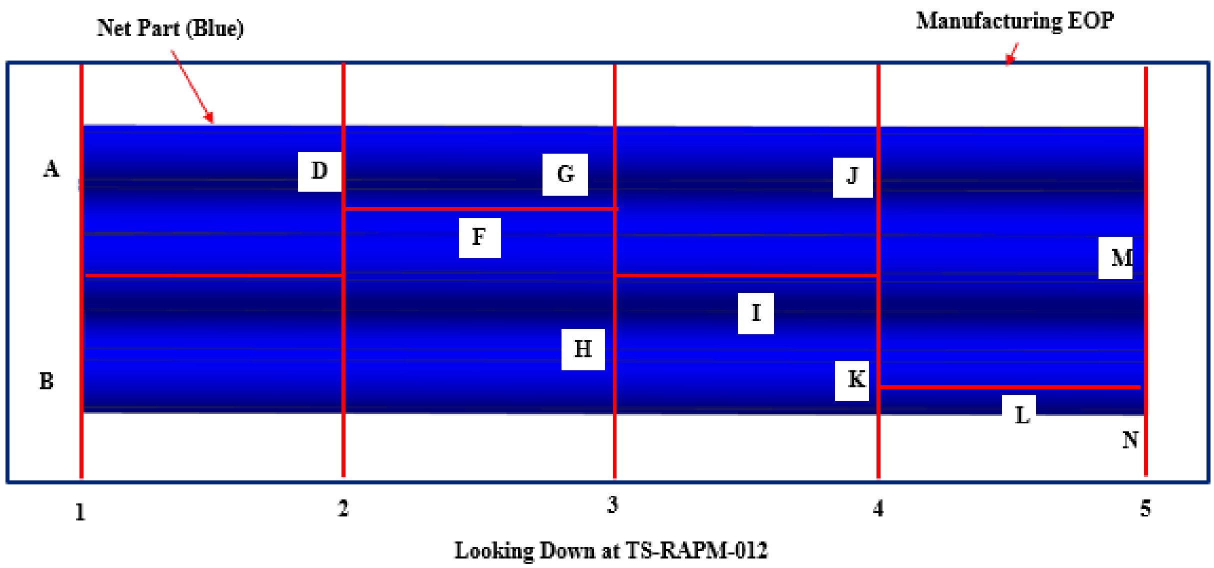


Figure 9 - TS-RAPM-012 Dissection Locations

Four trials were completely dissected, and Trial 8 was partially dissected as to retain the laminate whole. Figure 10 shows a sampling of the images taken of Trial 8, as it represents the final process used.

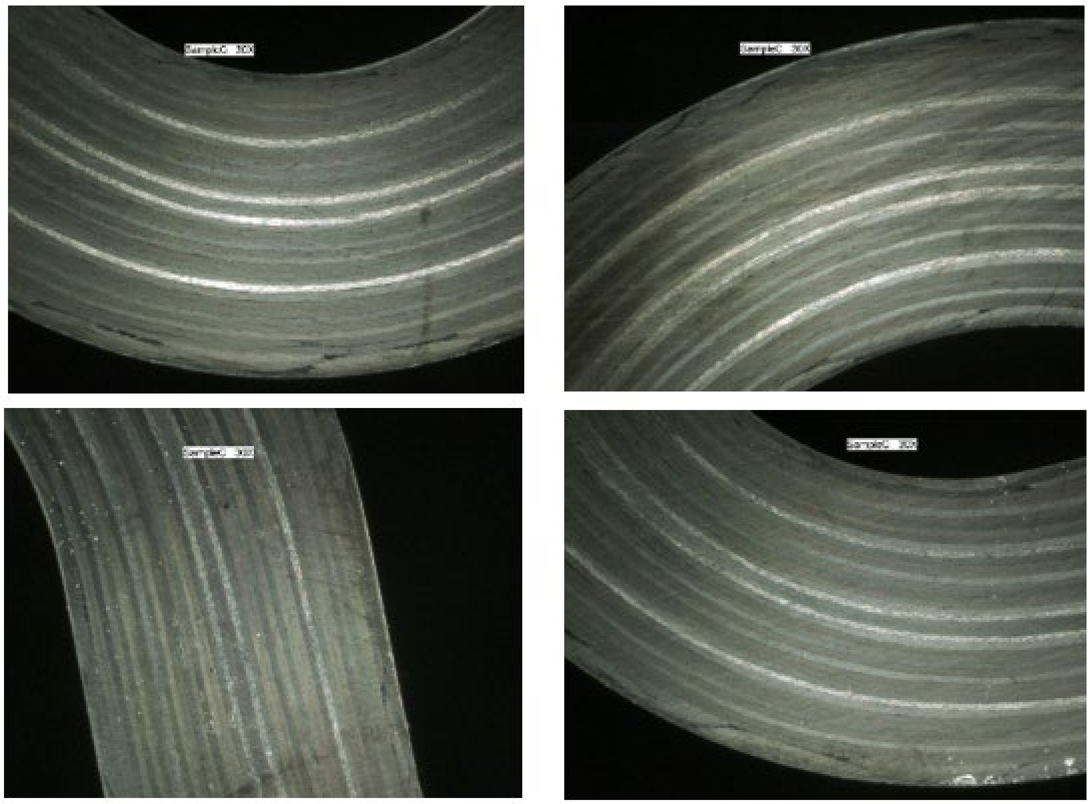


Figure 10 - TS-RAPM-012 Curved Geometry

Overall, the quality of laminate is acceptable. For the majority of sections observed, the fibers remain true and without disruption. Occasionally, small amounts of porosity were observed but as documented later, only in low levels.

3.3 Physical Testing

The last verification of the process was to verify degree of cure, glass transition temperature, void content, and fiber volume fraction.

Table 4 - TS-RAPM-012 Degree of Cure Results

Sample	Mass	Tg half height (2nd Heat)	Residual exotherm	Degree of cure	Exotherm Peak
	(mg)	(C)	(J/g)	(%)	(C)
Prepreg	21.41	214.0	143.7		233.39
T5 DOC 1	13.5	215.9	6.8	95.3%	243.01
T5 DOC 2	11.02	217.1	7.3	94.9%	243.27
T5 DOC 3	11.79	215.4	8.3	94.2%	245.69
T7 DOC 1	12.74	221.2	5.7	96.0%	244.35
T7 DOC 2	13.27	220.9	4.7	96.7%	243.45
T7 DOC 3	11.52	218.6	5.0	96.5%	241.46

Using Differential Scanning Calorimetry (DSC), the degree of cure was determined for six samples; three from Trial 5 and three from Trial 7. Trial 5 was used as a proxy for Trial 8 due to it having identical thermal history. Trial 7 was chosen to see how much difference there would be between a laminate that was pre-consolidated and one that was not. As shown in Table 4, there is very little difference, and the degree of cure is within the expected range of this resin system.

Table 5 - TS-RAPM-012 Glass Transition Temperature Results

Sample	Tg
	(C)
T5-1	207
T5-2	203
T5-3	205
T7-1	205
T7-2	202
T7-3	203

The dry glass transition temperature was determined using Dynamic Mechanical Analysis (DMA), and the results are shown in Table 5. The rational for using Trial's 5 and 7 remain the same. The glass transition temperature is within the expected range of this resin system.

Table 6 - TS-RAPM-012 Fiber Volume and Void Content

Sample	Resin Volume Content	Fiber Volume Content	Void Volume Content
T5-C-1	41.81%	58.40%	-0.21%
T5-C-2	40.63%	59.32%	0.06%
T5-C-3	38.81%	60.79%	0.39%
T5-C-4	38.69%	60.85%	0.46%
T5-C-5	37.96%	61.56%	0.48%
T5-C-6	37.29%	62.04%	0.67%
T5-C-7	38.32%	61.31%	0.36%
T5-C-8	37.90%	61.56%	0.54%
T8-1	38.64%	61.06%	0.31%
T8-2	37.71%	61.89%	0.40%
T8-3	37.27%	62.37%	0.36%
T8-4	37.53%	61.87%	0.60%
T8-5	39.38%	60.80%	-0.18%
T8-6	41.18%	59.11%	-0.29%
T8-7	39.06%	60.84%	0.10%
T8-8	37.11%	62.58%	0.31%

Several samples were taken from Trials 5 and 8 to evaluate fiber volume and void content, with results shown in Table 6. Trial 5 originally had sixteen samples taken from the laminate, but due to specimen error, eight samples were discarded. Of the remaining sixteen samples, three samples show negative values. It is suspected that specimen preparation was to blame as the outer fiberglass ply needed to be mechanically removed. Overall, fiber volume content and void content are within acceptable ranges.

4. CONCLUSIONS

The results indicate that after a rapid sprint controlling the relevant processing variables, a high quality, direct stamped, thermoset composite prepreg laminate with complex curvature can be manufactured that enables new high part volume applications. The results show that this is a viable process meeting standard quality requirements and helped to highlight new tooling and equipment approaches. These findings are consistent with the findings completed in other RAPM [3-8] technology tracks and show novel approaches for structural composite fabrication.

5. ACKNOWLEDGEMENTS

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