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Rapid Carbon Fiber Prepreg Molding Technology for Automobile Structural Parts – "SEAHAWKS"

Felix N. Nguyen, Toray Composites (America), Inc.

December 18, 2016

PROJECT FINAL REPORT
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- Michigan State University ('MSU')
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ABSTRACT

Carbon fiber reinforced plastics (CFRP) offer a variety of potential benefits to automotive parts vs. metals, mainly in the form of light-weighting, part consolidation, and corrosion resistance. However, complexities of composite manufacturing and lack of robust supply chain evolution and integration have hindered technological advancements to overcome high manufacturing costs, slow production rates and prolonged time to market. As a result, the use of CFRP in automotive structural parts has been limited to expensive "low to medium" volume platforms.

The project overall investigates a concept of ecosystem-based composite manufacturing that enables rapid implementation of an integrated manufacturing system. Through partnering with individual organizations in the prepreg supply chain along with their respective technological advancements in materials, part designs, tool, equipment, recycling and repair, this project's objective is to integrate these technologies into a manufacturing system through optimizing them individually and as a whole.

Upon a successful delivery of a finished composite component to market, all associated technologies are evolved to production readiness levels not only individually but also in part of the integrated manufacturing system itself. Risks are mitigated effectively, as development costs and successes (and/or failures) are shared among all organizations. As a result, further cost reduction of the finished component is anticipated.

Toray Composites (America) Inc. led the effort along with 13 other organizations to investigate and validate the concept. Phase I of this project via flat panel demonstrations focused on molding aspects of the integrated manufacturing system from several combinations of prepreg materials and molding methods used such as hydraulic press, RapidClave®, heated composite light tool (HCLT), light induction tool (LIT) and Quickstep. Other aspects such as automation equipment, recycling and component identification to further investigate and validate the concept via component demonstration in Phase II were also explored. It was found that several prepreg/process combinations could achieve a 3-6 min cure cycle time with panel thickness from 0.8 to 2.4 mm. This can be achieved under compaction pressure as low as vacuum, leading to composite panels that are void free, have good to excellent molded surfaces, Tg (by G'onset of DMA) ranging from 120-190 ^{o}C, and mechanical performance comparable to conventional autoclave cure.

1.1 Rapid Prepreg Molding for Automobile Structural Parts

Project type: Automotive
Start date: April 18th, 2016
End date: December 18th, 2016

Partner organizations and classification (large or SME)

1. **Toray Composites (America), Inc., ('TCA', large)**
2. Zoltek Corporation ('Zoltek', SME)
3. Reichhold LLC 2 ('Reichhold', large)
4. Janicki Industries, Inc. ('Janicki', large)
5. Globe Machine Manufacturing Company ('Globe', SME)
6. Composite Recycling Technology Center ('CRTC', SME)
7. American Composites Manufacturers Association ('ACMA', SME)
8. Michigan State University ('MSU', large)

1.2 BACKGROUND

Lux Research in 2015[i] forecasted the CFRP automobile market could reach six billion dollars by 2020. Structural parts such as floors, pillars, sills and roofs are growing at a rapid rate and take about 50 % of the market share. Roland Berger in 2012[ii] estimated that CFRP parts of the same function were about 4 times lighter than steel but 8 times more expensive than steel. They further anticipated about 30 % cost reduction of the finished part cost by 2020. Process costs and raw material contributed to 40 % and 20 % of the reduction, respectively.

Several efforts have been made to adopt CFRP for automotive applications. However, complexity of composite manufacturing coupled with an underdeveloped mass-infrastructure for integration in-practices have imposed numerous risks for a wider implementation of composites. An improved composite manufacturing system while integrating recent advancements of technologies in raw materials, automation, tool, molding, trimming and painting, as well as recycling technologies is essential to an evolved supply chain to support further reduction of cost and promotion to achieve production rate targets of at least 100,000 units per year, allowing automobile OEM/Tier 1 justification of CFRP parts in high volume platforms.

Toray (Composites) America, Inc. ("TCA") has realized a CFRP ecosystem concept originally applied widely in IT companies such as Apple and Google, which involves a network of organizations – including suppliers, distributors, customers, competitors, government agencies, and so on – involved in the delivery of a specific product or service through both competition and cooperation. Since the CFRP ecosystem is scaled up as a whole from the design concept of a part to commercialization of the part, organizations in the prepreg supply chain could mitigate their risks by utilizing and leveraging resources from other organizations to evaluate and improve own technologies and/or products to meet the common goal of delivering a cost effective CFRP structural part. TCA is leading the effort for developing and validating the concept of ecosystem-based CFRP manufacturing in the U.S. using prepreg materials. In this report TCA discusses results of Phase I for developing and validating the concept via flat panel demonstrations. Critical technological and financial information as well as a proposed manufacturing work cell set up for serial production of a component at a high production rate are presented.

1.3 TECHNICAL RESULTS

Results of this project are the culmination of a composite ecosystem combining several project partners and supporting project partners who are collaboratively working to provide a solution for the challenge of high costs and cycle times currently limiting the use of CFRP in automotive structural parts. Our approach to reduce costs and panel cycle times includes an integration of material selection, molding methods, preform design patterns, together with waste stream utilization. It is anticipated that an impact of at least 15 % cost reduction for target components could be achieved.

The scope of this report is limited to Phase I, as described below.

1.3.1 Theoretical Framework

Ultimately, this project is focused on an ecosystem-based solution for CFRP manufacturing for automobiles not only for high speed, energy efficiency, waste stream utilization but also time reduction to commercialization. It is understood that not all automobile parts could be converted from metal to composite economically, and there is no universal composite manufacturing process for a candidate composite part. Efforts were placed on developing an automatic composite manufacturing work cell as shown in Fig. 1, targeting structural automobile parts by optimizing state-of-the-art prepreg material and processing technologies individually and as a whole when they are integrated in a serial production.

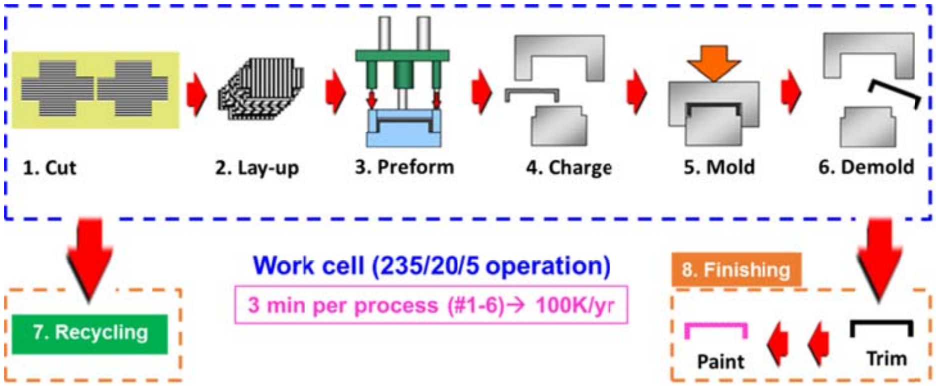

Figure 1. Prepreg molding work cell. Based on an integrated manufacturing process consisting of steps 1-6, working 235 days a year, 20 hours a day, 5 days a week, it is necessary for each of the above steps to be completed in less than 3 min, which would yield approximately 100,000 parts per year. Recycling and finishing steps are also incorporated and optimized as a whole to achieve competitive finished part costs.

The team investigates the followings to demonstrate the concept of an ecosystem-based composite manufacturing solution for structural light-weight parts achieving competitive finished part cost, the required performance, and an annual production rate exceeding 100,000 parts suitable for low-to-mid-end automobiles.

i. *Target platform*: Autodata/Markilines estimated in 2014 and 2015 in the U.S. more than 50 % of cars on the road are tall and heavy cars including light duty trucks, SUVs and vans.

ii. *Target structural parts*: Several structural metal parts above the mid-plane of a car are responsible for a high center of gravity causing potential rollover. Parts such as roofs and pillars are targeted for composite replacement to achieve maximum weight reduction with the thinnest and lightest designs without penalizing performance and safety. In addition, to present a compelling business case against aluminum (more than just weight savings), carbon fiber composites can provide improved cost competitiveness by part consolidation, potential cost saving with optimized CFRP manufacturing and/or new designs, and green composite manufacturing. This will be further investigated in Phase II of the project.

iii. *Material*: The thinnest and lightest structural components favor a design space for prepregs and their molding methods versus resin transfer molding/resin infusion. High performance premium prepregs when compared to low cost prepregs are also in favor because a lesser amount is used for equivalent or better performance. This allows thinner parts to consistently obtain high performance qualities through better exotherm control and void minimization.

Thermosetting resin is favored when compared to thermoplastic resins due to low temperature consolidation, hence reduced CFRP embodied energy consumption. In addition, for medium and larger surface area parts such as a Cadillac Escalade outer roof panel with approximate dimensions of 3 m x 1 m, thermoplastic resins might not meet the minimum resin modulus requirement for the resulting carbon fiber reinforced thermoplastic composites that provide the maximum fiber volume for the thinnest and lightest designs vs. thermosetting materials. Furthermore, since thermoplastic materials have to be molded at extremely high temperatures over 300 ^{o}C due to extremely high melting viscosity, more than 500 psi compaction pressure is needed to compensate for cooling effects after the materials are taken out of an oven. For parts larger than 2m^2, it will be a great challenge. Additional features of thermosetting materials such as rapid curability, fiber areal weight (FAW) as low as 50 gsm, excellent control of cured ply thickness, and long out time at room temperature allow composite parts to be cured less than 3 min, less than 2 min, and even less than 1 min, achieving the compelling out-of-the mold quality similar-to or better than thermoplastic materials. For this study Torayca® T700S carbon fibers are standard but also low cost carbon fibers such as Zoltek™ PX35 along with epoxy-based and vinyl hybrid-based (Advalite™) resins are investigated. Table 2 summarizes all prepreg systems for Phase I of the project (the present study).

iv. *Molding method*: Another advantageous feature of thermosetting over thermoplastic materials is substantially lower resin viscosity during molding, requiring only vacuum pressure for part consolidation. Recent advancements in hydraulic press as well as other prepreg molding methods with ramped-heating such as RapidClave®, HCLT, LIT broke the 3-min molding cycle time barrier of rapid cure thermosetting prepregs. Figure 2 summarizes all molding methods for the present study.

v. *Automated cutting/ Lay up/Preforming*: Optimal design patterns allow minimal prepreg wastes and rapid press preforming. Slit tape for AFP/ATL could be an option. The present study estimates lay up speed vs. tape width.

vi. *Waste minimization/Recyclability*: Molding of secondary parts from prepreg scraps. The present study documents scrap rates and initially evaluates moldability of chopped scrap prepregs for flat panels from fiber distribution and void content.

vii. *Finishing*: The present study documents surface defects and methods to characterize class A finish.

viii. *Hybrid/ multi-material form molding*: co-cured between long carbon fiber prepreg and its scrap or SMC. This will be investigated in Phase II.

ix. *Serial production:* automatic work cell comprising of cutting → laying up → preforming → charging → curing → demolding. This present study investigates a method to determine average panel cycle time based on daily production rate.

x. *Part cost variant*: part cost vs. cure cycle time (or average panel cycle time), prepreg material effective cost (total prepreg cost including scrap). The present study explores part cost variant tendencies using a cost model on a large panel of 3 m x 1 m.

The project is broken into two phases. Phase I as shown in Table 1 constitutes a benchmarking study with an objective to validate the concept of an ecosystem-based solution to reduce cycle time/cost of prepreg molding via flat panel demonstrations. The anticipated deliveries include identification of supply chain partners and database build for materials combined with processes suitable for the most cost-effective automatic work cell and performance. Phase II is a continuation of Phase I for a component demonstration study with an objective to utilize lessons learned from Phase I not only from technologies but also from the collaborative partnership framework working to further validate the ecosystem-based solution with an extended and more complete supply chain integration. The anticipated deliverables include manufacturability and financial viability to indentify a path for commercialization.

Table 1. Summary of Phase I including number of tasks, responsible organizations and project timeline. The performance period was originally set from April-October but later was extended to December to consider approval process for public release of this report. Official project partners include TCA, Zoltek, Reichhold, Globe, Janicki, CRTC, MSU, ACMA while supporting project partners include CFA, Huntsman, RocTool, KTX, and Quickstep. *Zoltek, CFA, Huntsman, and Reichhold provided materials to TCA and support to make prepregs.

Task	Primary responsibility	Task description	2016								
			Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1		**Flat panel study with material and molding method**									
	TCA	Prepreg manufacturing*									
	Reichhold	Hydraulic press molding									
	(RocTool/KTX)	Light Induction Tool molding									
	Globe Machine	RapidClave® molding									
	Janicki	Heated Composite Light Tool molding									
	(Quickstep)	Quickstep molding									
	MSU	Panel evaluation (void, class A, thermal/mechanical properties)									
2		**Documentation of recycling method for prepreg scrap**									
	TCA	Scrap from hand layup vs. automation									
	CRTC	Scrap processing and molding trial									
3		**Documentation of ATL/AFP**									
	TCA	Flat tool ATL/AFP estimation									
4		**Phase II planning**									
	All	Component identification									
	All	Baseline component cost estimation									
5	TCA, ACMA	**Final report**									

1.3.1.1 Test Matrix

Five prepreg materials and five manufacturing processes were investigated in Phase I, as seen in Table 2, resulting in up to 15 unique manufacturing conditions. However, only 10 out of 15 conditions were fully executed due to time constraint. The following criteria were implemented for Go/ No Go decisions:

1. The prepreg material must have a cure cycle time (defined as cumulative time once heat is applied to the uncured panel until cooling to demolding temperature) less than 5 min.
2. The cured composite part must have less than 1 % void. Selected mechanical properties are evaluated. In addition, it must have a Tg greater than 130 °C with a degree of cure (DoC) measured by a differential scanning calorimetry (DSC) of at least 90 %. Heat deflection feature is also documented.
3. Minimal rework is required for the finishing step, judgement based on the best quality panels representing each integrated manufacturing condition, and quantified based on selected class A characterization methods.
4. Qualitative projection of individually critical cost factors such as average panel cycle time, material effective cost on finished part cost.

Table 2. Test matrix showing up to 15 manufacturing conditions to be investigated. However, at the end of Phase I, only 10 conditions were fully completed.

Material	**FAC-01**	**FAC-02**	**FAC-03**	**FAC-04**	**FAC-05**
Resin type	Epoxy	Epoxy	Epoxy	Epoxy	Vinyl hybrid
Resin	G-83C	G-83C	**G-83C mod 1**	**G-83C mod 2**	**ADVALITE™**
Fiber	T700S-12K-60E	**PX35-50K-13**	T700S-12K-60E	T700S-12K-60E	**T700S-12K-F0E**
Commercial	**Yes**	**R&D**	**R&D (Prod ready)**	**R&D**	**R&D**
Advantage	**[Baseline]**	**[Lower cost CF]**	**[Faster cure]**	**[Faster cure] [Improved processing]**	**[Faster cure] [Long out time]**
Hydraulic Press	x	x	x	x	x
RapidClave®	x	x	x	x	x
Quickstep	x	-	-	-	-
Heated Composite Light Tool	x	-	x	-	x
Light Induction Tool	x	-	-	-	-

Postponed Completed

1.3.1.2 Material Selection

FAC-01 material is G-83C prepreg commercially available from TCA (Fiber areal weight (FAW) 190 gsm, resin content 37.5 %, Torayca® T700S-12k-60E carbon fiber) and is currently used by several automobile programs. This material was selected for all molding methods, to provide a baseline for comparison among processes. Four other materials at R&D scale, except FAC-03 ready for production, were also initially included, to further explore material cost vs. manufacturability and performance, offering users an option to select the right material for the right molding method for their business case reasons. These materials focused on advantages over the baseline material, including reduced cure time, lower material cost, improved processing, and higher Tg. The advantages for FAC-02, FAC-03, FAC-04, FAC-05 are summarized in Table 2. These systems also have FAW of 190 gsm and resin content of 37.5 %, except FAC-05 having resin content of about 34 %. All resins have a baseline cure condition of 163 ^{o}C (325 ^{o}F) for 3 min to achieve a DoC of at least 90 %.

1.3.1.3 Molding Process Selection

There is a wide range of prepreg molding state-of-the art (SOTA) processes comprising both compaction pressure and heating rate that are critical processing parameters to produce thermosetting composite parts for production rate vs. quality, as shown in Fig. 2. These methods include hydraulic press (e.g., Wabash), RapidClave® (manufactured by Globe), Heated Composite Light Tool or HCLT (manufactured by Janicki), Light Induction Tool or LIT (manufactured RocTool and KTX) and Quickstep (manufactured by Quickstep). Their key advantages and disadvantages are summarized in Table 3 and further elaborated on the following pages.

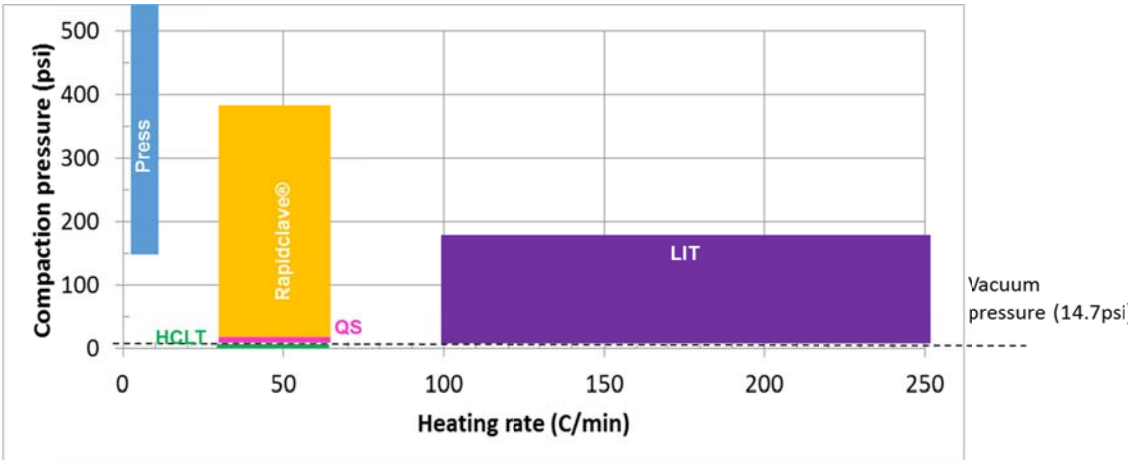

Figure 2. Pressure and heating rate comparison of molding processes

Table 3. Molding method overview

Molding	Press	RapidClave®	QS	HCLT	LIT
Pressure	**Highest**	Low to High	**Lowest**	**Lowest**	Low to medium
Ramp rate	**Lowest**	High	Moderate	High	**Highest**
Key advantage	Fastest molding	Right size for part family Low energy consumption	Processing flexibility Low energy consumption	Low cost tool Small footprint Low energy consumption	Processing flexibility Small footprint Low investment Low energy consumption
Key disadvantage	Largest footprint High energy consumption	Medium footprint	Medium footprint	Tool life Tool surf. finish Atm. pressure	One side heating (both sides optional)

For this study, available laboratory-scaled machines from project partners were utilized to demonstrate baseline processing capabilities of these machines over selected prepreg materials, i.e., to establish baseline cure cycle times. Project partners then projected improved cure cycle times if either commercially available production-scaled machines or optimized machines would have been used.

1 Hydraulic Press

Current state-of-the-art. Hydraulic presses have been known for their extremely high tonnages, extremely fast closing speed, and high level of customization for the right size of part family. For these reasons, they are often selected to meet a production rate of at least 100,000 parts per year, especially to process thermoplastic materials. In such a process, typically a thermoplastic part is heated in a nearby oven at its softening temperature typically in the range of 250-400 °C and quickly transferred into the press with preheated massive platens or matched die tool at a temperature substantially lower, e.g. 160-200 °C. In addition, after removed from the oven, since the heated part tends to lose heat very quickly, extremely fast closing speeds (>200 ipm) and extremely high pressures (>4000 tonnages) are required to compress the part while it is still flowable into the final shape.

In order to accommodate such high pressure, large footprint and ceiling height are needed; hence large infrastructure to accommodate the press is required. As a result, both non-recurring (capital investment for machine and tool) and recurring costs (labor, energy consumption, machine/building maintenance, etc.) could be the highest for this process compared to the other competing processes.

Processing a thermosetting material for the same part design does not require as much high tonnage and cure temperature because of its substantially lower viscosity and cure kinetics. However, other processing difficulties arise such that to isothermally mold the thermosetting material, a charge at room temperature or slightly elevated temperature has to be transferred to the press heated at a temperature closer to the cure temperature as possible and the platens have to be closed as quickly as a few seconds to avoid the surface of the charge being cured right after it is placed on the bottom die and the material has enough flow time to ensure desired surface finish and part quality before fully cured. Often the charge is preformed (i.e., press molded at an elevated temperature to a certain degree of cure (i.e., partially cured or B-staged) to provide near net shape and stiffness to the charge so that it can be transferred to a different tool in another press for final cure.

Present study. The press used in this study was manufactured by Wabash as shown in Fig. 3, capable of 300 tons and 180 °C cure temperature. Reichhold provided this press and a tool for the present study. The 14" x 14" tool is a matched die tool made of steel with chromed surfaces for class A.

The tool was preheated in the press at 163 °C. A mold release provided by Chem Trend was sprayed on the hot tool surfaces and allowed to evaporate before molding. A pre-laid up flat charge with different thicknesses provided by TCA was placed onto the bottom die and the tool was closed and 10 tons of pressure (i.e., up to 140 psi on the charge) was reached. The charge was molded at 163 °C for 3 min after the press was closed. Temperature was monitored by thermocouples attached to the tool surfaces.

The tool has an air popper located on the bottom die slightly extruded above the cavity surface, leaving an indent in the center of the part and deforming a region around it. The air popper was originally designed to blow air into the tool cavity so that the cured panel could be popped up. In addition, there is a minimal gap requirement for the tool of about 0.8 mm such that when molding a 4-ply panel, compaction pressure was not applied evenly on the panel, resulting in edge distortions and as well as warpage. These will be discussed in detail in the results section.

Figure 3. Wabash hydraulic press provided by Reichhold

Anticipated production. Minor improvements include fixing the air popper and minimum gap requirements to obtain higher quality thin panels. Major improvements are not related to the press itself but the overall molding process such that the charge could be preformed or B-staged at a certain degree of cure to allow easier transfer and positioning the charge in the center of the tool's cavity. A robot could be used to support the charging process and improve overall panel cycle time.

2 RapidClave®

Current state-of-the-art. The first generation "RapidClave® Classic" is currently used for the production of several Corvette C-7 body panels by Tier-1 automotive supplier Plasan Carbon Composites. RapidClave® employs an isobaric chamber integrated into a press type environment with fully automated-programmable control of process temperatures & pressures. Tool temperature ramp up is achieved by utilizing fluid heated tool. Material compaction is provided by pressurizing the top chamber cavity which encloses the tool. RapidClave® Classic allows for controlled molding temperatures up to 288 °C, ramp rate up to 80 °C/min, up to 150 psi pressure, 28 in/hg vacuum, and rapid cooling. RapidClave® 2 & 3 enable the fastest temperature ramp and cool down capability with peak temperatures up to 480 °C via hot air impingement heating and induction tool heating (Globe-RocTool partnership) technologies. Chamber pressures capable up to 350 psi are also realized. In addition, the machine can be optioned with an automatic tool-change system allowing rapid transfer of one tool in and out the machine while another tool is prepped and waiting for the curing process, enabling minimal machine idle time. RapidClave® enables low energy consumption vs. hydraulic press but might require similar footprint with reduced ceiling height requirements.

Present study. This study utilizes a lab-scaled RapidClave® with a molding surface of 18.5" x 18.5" as shown in Fig. 4. Globes Lab machine is designed for plaque production and includes the capability to introduce air into the heated pressurized chamber. This machine is equipped with heating oil up to 288 °C, providing a ramp rate up to 80 °C/min, an air pressure of up to 150 psi while the maximum cooling rate by water is around 40 °C/min. This machine was not designed nor intended to support state-of-the-art (SOTA) cycle time demonstrations.

For molding, the lower platen was initially heated to 50 °C. A mold release was wiped onto the surface of the flat tool and allowed to evaporate. A pre-laid up laminate was placed onto the tool surface, and thermocouples were taped to the four outer edge surfaces to monitor the part temperature during cure. Instead of using a reusable silicone bag as seen with production machine, manual bagging was carried out with a peel ply film and bleeder applied overtop, before the part was sealed with a vacuum bag and sealant tape. The tool was then loaded manually onto the lower heated platen, and thermocouples were manually connected to the machine ports. After the tool was loaded, vacuum was applied (28 in/hg), and the chamber was lowered (taking around 30 seconds). Upon sealing of the chamber, temperature was applied by circulating heated oil in the platen, but no heated air on the bag-side surface of the part. In order to control temperature variance from the setpoint, two heating rates were used. Using a heating rate of approximately 80 °C/min, the temperature was raised to 140 °C where the heating rate switched over to 55 °C/min until reaching the dwell temperature. The chamber was pressurized during the ramp, reaching 85 psi before ramping up to the dwell temperature of 163 °C. Temperature was held at 163 °C for 3 min, before the tool was cooled down to 70 °C at around 40 °C/min and removed from the chamber.

Figure 4. Globe lab-scaled RapidClave®

Anticipated production. Future RapidClave® models employ faster, more-controllable heating and cooling methods, helping further reduce cure cycle time. For today's state-of-the-art epoxy resin systems, RapidClave® 3 can achieve cycle time directly comparable to a matched metal die "press" type process. Potential target rates would be more than 140 °C/minute heating and cooling. Use of higher quality tool materials will further improved surface finishes.

3 Heated Composite Light Tool

Current state-of-the-art. Currently, this technology is in development stages. A light composite tool incorporates a structural carbon fiber fabric layer as a conductive heating element underneath the molded resin surface, providing temperature by applying an electrical voltage to the carbon fiber layer. This tool has the lowest cost among participating molding processes and provides a very low footprint and low energy consumption, as no large processing equipment is required outside of the tool itself and the voltage applier. This technology also takes advantage of the low thermal mass of the tool, allowing for higher heat transfer rates to be achieved. However, tool surface might not provide an ideal smooth molded surface, and the tool life could be short (depending on molding temperatures). Vacuum pressure is applied through a standard bagging method as compaction pressure, which could result in high void content in the molded panels with increased lateral dimensions, thickness and geometric complexity.

Present study. The tool utilized for the present study was a flat composite laminate with an approximate molding surface of 15" x 20". A backing structure was incorporated to provide additional stiffness and prevent any deflection when applying vacuum during cure. A majority of the composite tool was fiberglass fabric reinforced BMI resin, with one layer including multiple strips of carbon fiber fabric positioned in parallel with a certain gap between two strips. A voltage meter was connected to the carbon fiber strips, whereby controlling the voltage applied increased the current and corresponding heat within the strips. Maximum heating rate was up to 80 ^{o}C/min while cooling rate was up to 65 ^{o}C/min by forced air.

In preparation for part curing, a PTFE coated release film was adhered to the composite tool surface. A pre-laid up laminate was placed onto the PTFE film, while the tool was at a temperature slightly above room temperature (27 °C). Thermocouples were placed on the bottom and top edge of the part. A 2 inch wide plain weave fiberglass tape as edge breather was placed around the top surface edges of the laminate. A release film and breather were placed on top, with the part lastly vacuum bagged using Airtech general sealant tape and vacuum bag material. Once vacuum was applied (around 30 in/hg) for 10 min, heat was applied at a ramp rate of approximately 60 °C/min. This temperature was manually controlled by varying the voltage applied to the carbon fiber layer.

Upon reaching 163 °C, temperature was held for 3 min before cooling the part by blowing compressed air onto the outer bag-side surface, at a cooling rate of approximately 50 °C/min. Upon reaching a temperature of 65 °C, the part was demolded.

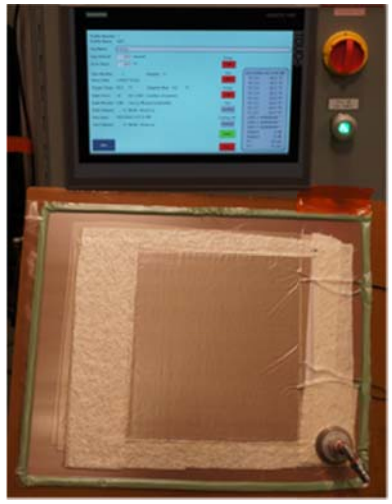

Figure 5. Janicki heated composite light tool

Anticipated production. Current technology has implemented a controller, as seen in Fig. 5 above. This will greatly reduce variation in heating rates and dwell temperatures from operator error and inconsistency. Additional, further improvement of the system may yield faster ramp rates, through controller advances as well as carbon fiber heating strip placement optimization. For bagging, a reusable composite caul with rubber seals may be utilized to eliminate the timely manual bagging process. Due to the use of an adhesively bonded release film, there are some limitations for potential part surface finishes achievable. Potential surface finish quality and mold durability at high part production rates are still to be determined. In the current state, the technology is well suited for preform and pre-process steps which utilize low pressures, to improve the life cycle and molded surface quality concerns.

4 Light Induction Tool

Current state-of-the-art. This turn-key solution provided by RocTool comprises a small footprint tool structure (foundation), above which is placed a thin metal shell (the tool, manufactured by KTX). The RocTool induction technology is fitted within the shell, and enables conformal heating and cooling with heat rates up to 200 °C/min, leading to rapid heat transfer to the part. For the demonstration tool used for this study, two zones were independently controlled using thermocouples fitted very close to the molding surface for higher accuracy control. For each zone, the induction coils are powered with a unique RocTool Double-Zone generator, thus enabling a relatively low energy consumption, below 2 kW.h/part. The tool is also capable of applying vacuum, with a reusable membrane incorporated on the B-face providing an additional isotropic pressure up to 150 psi (with pressurized air). The technology is also available in a metal/metal configuration without the reusable membrane, and is recommended for thicker laminates or sandwich panels. Due to its heating and cooling capabilities, low pressures are usually considered and the use of large infrastructure expenses for autoclaves and presses becomes redundant. The complete solution is already commercially available through RocTool, and is currently in use globally to transform thermoplastic materials, in productions for major brands in a wide range of industries including automotive, aerospace, consumer products and electronics.

Present study. Molding utilizing light induction tool technology was conducted using a 1:2 scale hood tool, as seen in Fig. 6, with approximate dimensions of 30 in x 20 in. In this configuration, the tool shell was produced with a nickel alloy. A flexible membrane was located on the upper side of the system, which conformed to the part geometry and applied pressure during the curing cycle. Temperature was controlled only on the tool shell in this demonstration system.

A pre-laid up laminate was placed on to the tool surface, after the surface was prepared with a mold release through a manual wipe application. After 10 min under vacuum at 38 °C, pressure and elevated temperatures were applied. 100 psi was applied by the end of the pre-cure vacuum, and temperature was ramped at a rate of 85 °C/min to an intermediate dwell temperature of 105 °C. After one minute, temperature was ramped to 163 °C at 50 °C/min. Temperature was held at 163 °C for 2 min before cooling down to 40 °C with a cooling rate of 120 °C/min. Additional panels were molded successfully with a ramp rate of 120 °C/min from 38 °C to 163°C with a three minute dwell before cooling down. These panels were found void free and excellent surface finish but were not sent to MSU for further evaluation.

Figure 6. RocTool Light induction tool

Anticipated production. RocTool continues to widen the range of LIT solutions with different induction and tool technologies. A few tool materials are considered and being optimized. RocTool processing experts can now provide a thorough technical evaluation for each application, considering part's size, the complexity of the geometry and the common process parameters for the selected material. Two sided heating is also available, for optimized heat transfer during curing.

5 Quickstep

Current state-of-the-art. The Quickstep Process uses a unique fluid-based technology for curing the composite materials. Design is flexible to meet, or where required, improve material properties of the end product. It works by positioning the laminate between a free floating rigid (or semi-rigid) mold that floats in a Heat Transfer Fluid (HTF). The mold and laminate are separated from the circulating HTF by a flexible membrane or bladder. The HTF can then be rapidly heated and then cooled to cure the laminate. This solution lowers energy consumption for heating/cooling of the laminate, provides additional compaction pressure in addition to vacuum pressure from the weight of the fluid onto the part. The process is currently employed to produce parts for F-35 Joint Striker Fighters[iii]. Quickstep produced a machine as big as 6 m x 4 m[iv].

Present study. A composite laminate is placed on a tool encompassed by two bladders filled with a heat transfer fluid, as seen in Fig. 7. Details of processing are available upon a request to Quickstep, Australia.

Figure 7. Quickstep molding process

Anticipated production. Details are available upon a request to Quickstep, Australia.

1.3.2 Results

Table 4 summarizes the data obtained for the present study against the Go/No Go criteria below

1. The prepreg material must have a cure cycle time (defined as cumulative time once heat is applied to the uncured panel until cooling to demolding temperature) less than 5 min.
2. The cured composite part must have less than 1 % void. Selected mechanical properties are evaluated. In addition, it must have a Tg greater than 130 °C with a degree of cure (DoC) measured by a differential scanning calorimetry (DSC) of at least 90 %. Heat deflection feature is also documented.
3. Minimal rework is required for the finishing step, judgement based on the best quality panels representing each integrated manufacturing condition, and quantified based on selected class A characterization methods.
4. Qualitative projection of individually critical cost factors such as average panel cycle time, material effective cost on finished part cost.

Table 4. Phase I data summary

Manufacturing condition					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
			No.		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
			Material		FAC-01 (Baseline)					FAC-02		FAC-03			FAC-04		FAC-05		
			Molding		Press	RC	HCLT	LIT	QS	Press	RC	Press	RC	HCLT	Press	RC	Press	RC	HCLT
Go/No Go Criteria	1. Cure cycle	Cure time < 5min	Current Lab-scaled		3.0	6.0	6.3	6.0	**	3.0	6.0	3.0	6.0				3.0		6.3
			Once optimized		3.0	4.4	5.0	5.0		3.0	4.4	2.5	3.9				2.5		
	2. Performance	Void < 1%	NDI	4-6 ply	1.4	0.1	0.9	0.1		0.5	0.1	0.2	0.1				1.8		
				8 ply	2.3	0.1	0.3	0.3		2.3	0.1	0.4	0.2				2.2		
				12 ply	0.3	0.1	**	0.0		1.1	0.2	0.5	0.2				1.0		**
		Thermal DoC > 90 % Tg > 130°C	MDSC	DoC %)	94.1	92.8	95.3	94.8		94.2	95.1	98.2	96.5				98.2		
				Tg °C)	147	152	148	147	**	147	147	195	191				145		
			DMA	Tg @ G' (°C)	135	134	130	135		128	127	187	178				119		
				Tg @ tan δ °C)	162	161	159	160		158	157	206	199				159		
		Mechanical			**												**		
	3. Class A	Minimal rework	4-6 ply thick		E.D.*					E.D.*		E.D.*					E.D.*		
			8-12 ply thick														Surf.		
	4. Cost Comparison	12”x12” panel time (min)	Current Lab-scaled (cumulative)		10.8	24.5	26.1	24.0											**
			Once optimized (cumulative)		10.8	12.3	16.4	13.0											
			Est. Serial Operation in production (ave.)		4.5	5.2	8.0	7.0											

>+/-(100 %) +/-(10-100 %) Meet/ Exceed

*E.D. = edge distortion ** See text for details

1.3.2.1 Cure Time

Cure time is defined in the study as the time when heat is applied to the uncured panel until cooling to demolding temperature. Starting with FAC-01 (the baseline material for comparison among different manufacturing conditions), it was previously observed that a glass transition temperature (Tg) measured from storage modulus (G') onset of dynamic mechanical analysis (DMA) method could achieve as high as 140 ^{o}C if it was cured at 143 ^{o} C (290 ^{o}F) for 15 min in an autoclave to achieve a degree of cure (DoC) measured by modulated differential scanning calorimetry (MDSC) method of at least 90 %. In order to achieve a shorter cure time with a similar DoC, FAC-01 was targeted to be cured at 163 ^{o}C (325 ^{o}F) for 3 min. Tg was set at a minimum of 130 ^{o}C to ensure minimal penalty for subsequent thermal processing and mechanical properties, if any. It was observed excessive cure at a temperature higher than 163 ^{o}C to achieve a shorter cure time could lead to adverse performance.

While isothermal molding at 163 ^{o}C and demolding at this temperature to achieve the shortest cure cycle time was attempted, it was anticipated that in order to achieve a quality molded surface finish, i.e., minimal rework from surface defects and voids, additional time from a heating up rate from a starting temperature to the cure temperature and cooling rate to a demolding temperature might be needed. For this reason, a cure cycle time was targeted to 5 min, pushing efforts to investigate combinations of reasonably doable starting temperature, heating/ cooling rates and demolding temperature vs. isothermal cure.

Figure 8 summarizes cure cycle time for all molding processes for FAC-01. For each process, the first bar represents the possibly achievable cure cycle time after a reasonable investigation while the second bar projects an improved cure cycle time if the molding parameters would have been further optimized in the current laboratory-scaled machine and/or in a production ready machine.

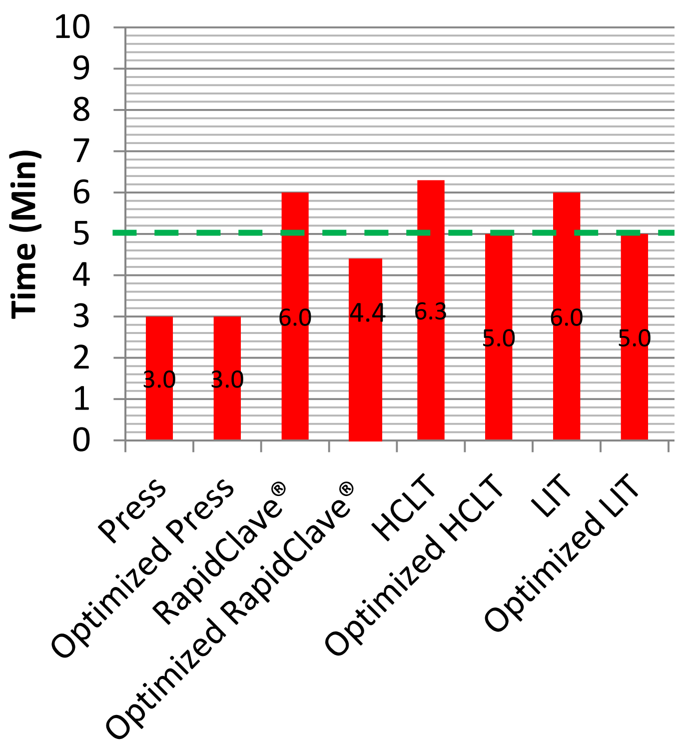

Figure 8. Cure time chart for FAC-01 molding

1. *Hydraulic Press*. The three minute requirement at 163 °C was successfully achieved by isothermal molding in the press and demolding at this temperature without compromising molded surface finish and void free (to be discussed in details below). Due to the shear edges of the compression mold, it was not possible to place thermocouples onto the part surface during the cure. The tool was kept at a consistent temperature, 163 °C, throughout the molding process.

   It was anticipated that no further optimization of molding parameters could shorten the cure cycle time less than 3 min unless a lower DoC could be targeted and the panels could be free-standing post cured during subsequently thermal processes such as primer applications and painting. However, post cure processing is not in the scope of the present study.

2. *RapidClave®*. The RapidClave® cure time is the result from starting at an initial mold temperature of 50 °C-75 °C , ramp rate of 85 °C/min to 140 °C, with a reduced heating rate of 50 °C/min to the final dwell temperature of 163 °C, which was held for 3 min, cool down rate of 50 °C/min and a demolding temperature of 70 °C.

   Globe anticipates they could bring the current cure cycle time from 6 min to 4.4 min (3 min cure plus 1.4 min for ramp up and down) by implementing advanced elements for more-rapid heating and cooling rates to their laboratory machine and/or production machines. Further time reduction could be done by raising starting mold temperature and demolding temperature. An example cure plot can be seen in Fig. 9. Thermocouples were placed on the top surface (bag side) of the panels, 1 inch in from each corner of the laminate.

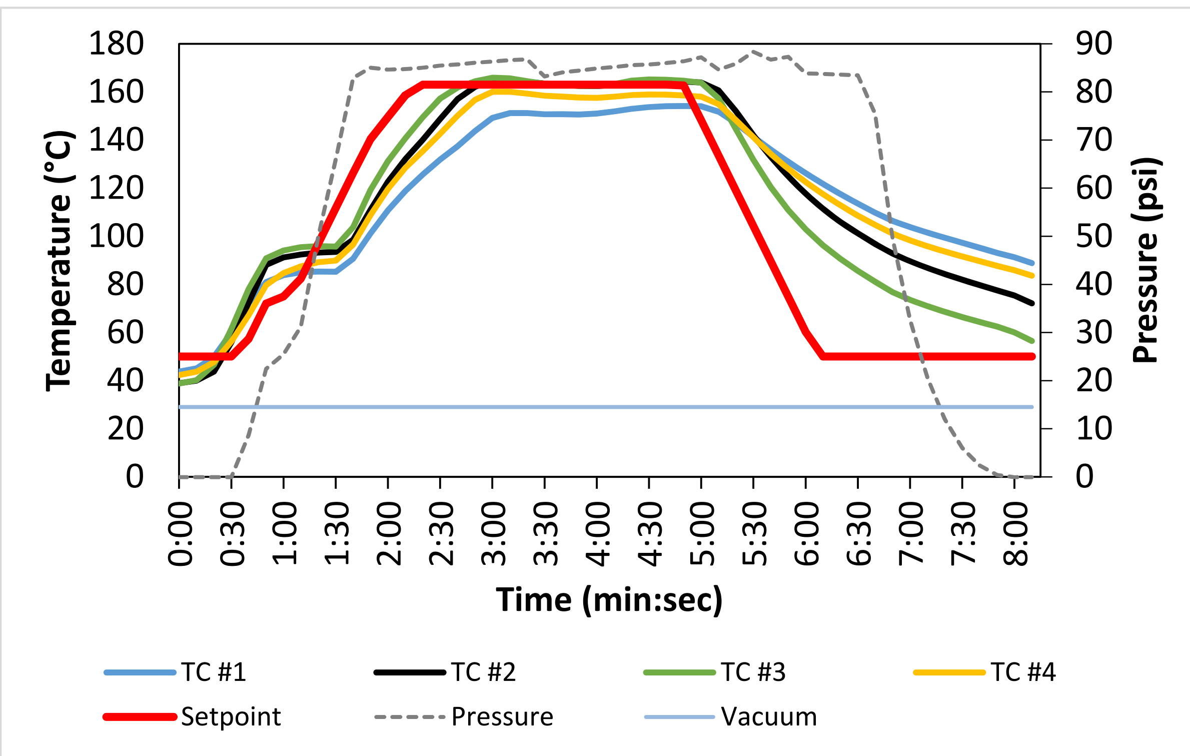

Figure 9. Example Rapidclave® cure profile

3. *HCLT*. The HCLT cure time is the result from starting at an initial mold temperature of 25 °C, ramp rate of 65 °C/min to 163 °C and hold for 3 min, cool down rate of 65 °C/min, and a demolding temperature of 65 °C. A brief hold at around 140 °C was utilized to control temperature overshoot. An example cure plot can be seen in Fig. 10.

Janicki anticipated that they could bring the current cure cycle time from 6.3 min to 5 min by further optimizing the heating and cooling rates, as well as starting cure at a temperature above ambient.

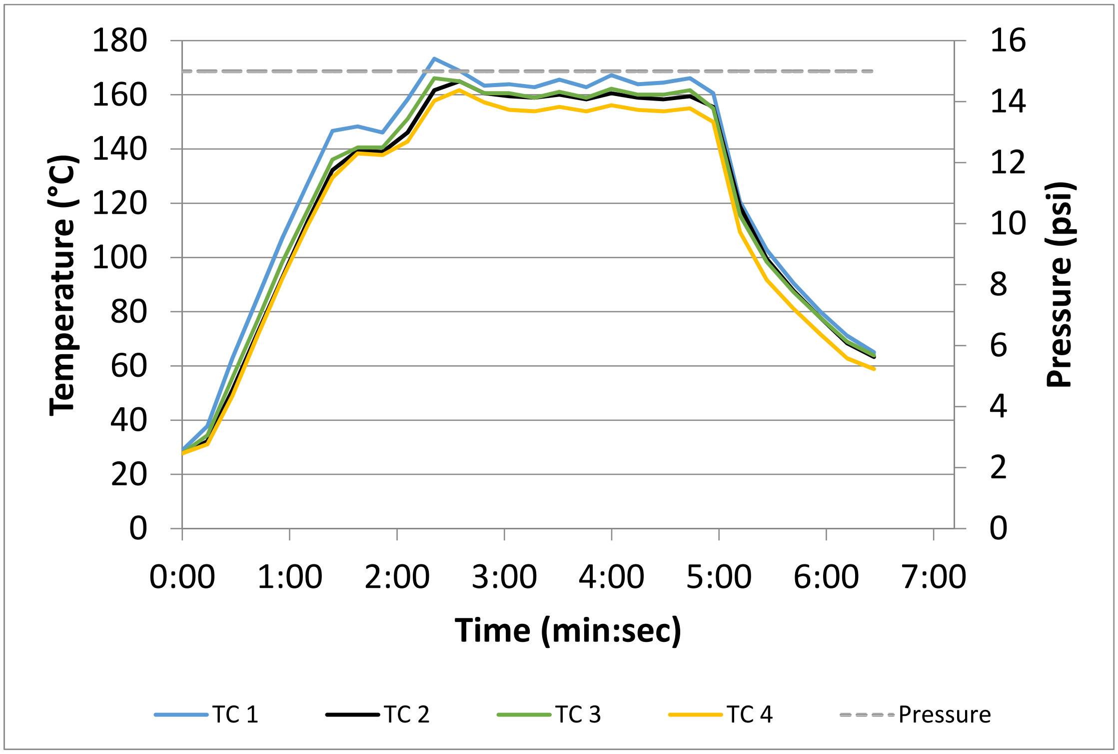

Figure 10. Example HCLT cure profile

4. *LIT*. The LIT cure time is the result from a two-step cure, from starting at an initial mold temperature of 38 °C, ramp up rate of 85 °C/min to an intermediate dwell at 105 °C for 1 min, and a second ramp rate of 50 °C/min to 163°C for 2 min, a cooling rate of 120 °C/min and a demolding temperature of 40 ^{o}C. It was noticed that the actual temperature followed the set-point pretty well. However, the current machine did not allow export temperature data.

   RocTool anticipated that they could bring the current cure cycle time from 6 min to 5 min by increasing the heating rate to at least 120 ^{o}C/min, as well as increasing the initial mold temperature and the demold temperature. A successful demonstration with a heating rate of 120 ^{o}C/min resulted in similar panel quality as other panels that were evaluated at MSU.

5. *Quickstep*. Details are available upon a request to Quickstep, Australia

For FAC-02 identical cure cycle times for each participating molding process for both the present experiment and further optimization were achieved because it comprises G-83C resin, which is the same resin as in FAC-01.

For FAC-03, a modified G-83C resin for faster cure at 163 ^{o}C was utilized. However, for the present experiment for each participating molding process a 3 min cure was investigated for comparison with G-83C resin. A reduction in cure cycle times could be achieved if desired since it was found that when cured for 2 min, at least a DoC of 90 % was obtained. In order to ensure the properties 2.5 min cure was proposed. The summary is shown in Fig. 11.

For FAC-05, Advalite™ vinyl hybrid resins from Reichhold were utilized. For the present experiment for each participating molding process 3 min cure was investigated for comparison with G-83C resin. A reduction in cure cycle times could be achieved if desired since it was found that when cured for at least 2 min, at least a DoC of 90 % was resulted. In order to ensure the properties 2.5 min cure was proposed.

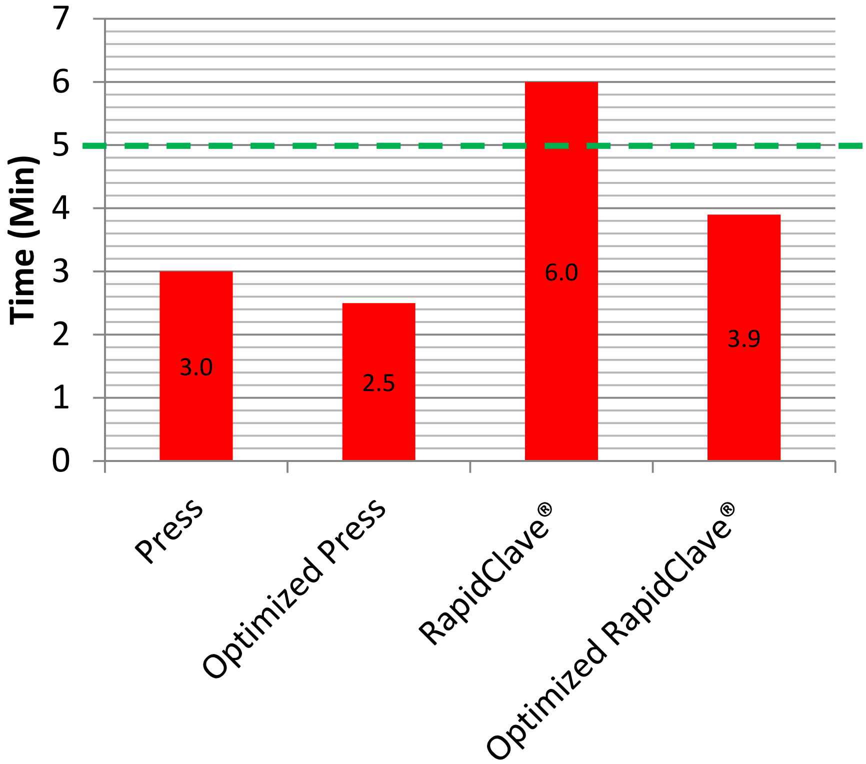

Figure 11. Cure time chart for FAC-03 molding

1.3.2.2 Void Content

The present study set a void content target of less than 1 % as higher amounts adversely affect mechanical properties of cured structural parts. Ideally, the average void content would be below 1 %, with no regions exceeding much higher than that target, as localized voids would likely create failure zones in the part.

Two techniques were used to measure void content of each cured panel. Panels were first evaluated using Ultrasonic C-scan Non-Destructive Inspection by TCA. Panels were scanned in comparison to autoclave cured specimens of similar thickness and known void content. This method served as a quick, qualitative assessment of part consolidation and overall void content. The other evaluation technique used was microscopy conducted by MSU, which provided a more quantitative average void content value to be obtained as spot checks. Eight specimens from various locations (marked by *) from each panel of the entire cross-section were cut, polished, and observed under a microscope. Images were captured, and sent to TCA to determine average void content based on the eight specimen locations using imaging software. For the following tables, the microscopy image (from the location marked by a yellow star) is representative of the average void content per the eight specimens extracted from a panel, with the reported void content value reflecting the actual average of all eight specimens.

1 Hydraulic Press

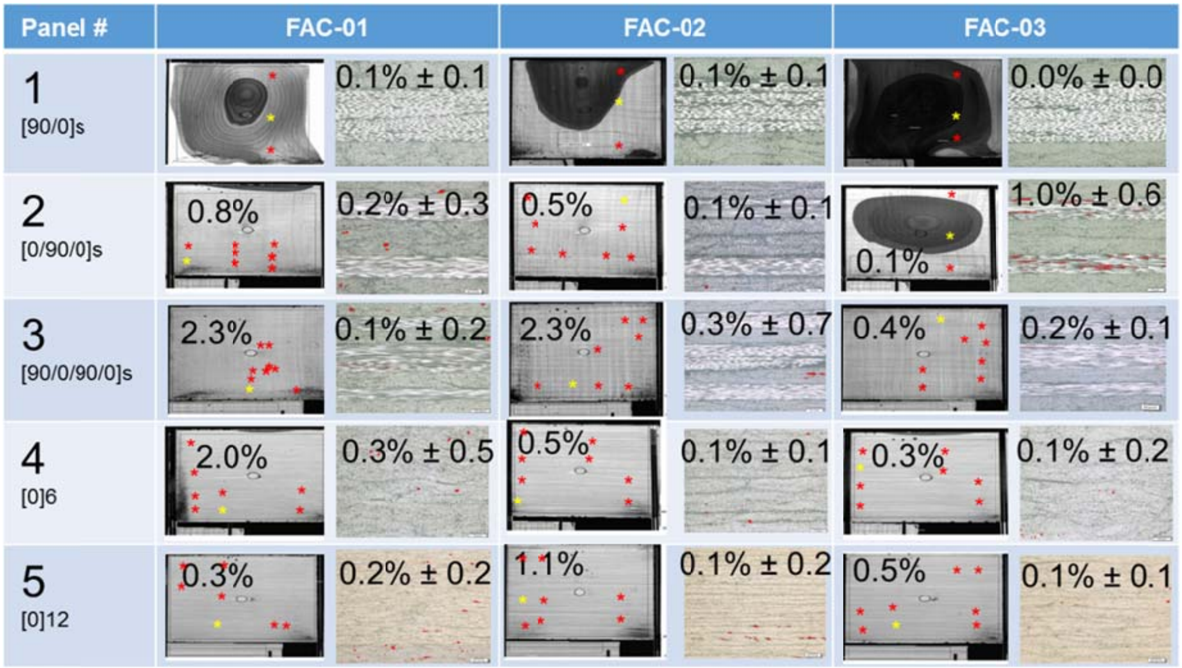

Figure 12. Hydraulic press panels void content analysis (NDI on left, and microscopy on right) Yellow star (*) denotes the location where the microscopic image was taken.

All panels analyzed with microscopy were on average well below the target void content of 1 % or less for the press cured panels, as shown in Fig. 12. Some initial void content values from NDI were above 1 % (FAC-01 panels 2 and 3, FAC-02 panels 3 and 4), but all passed microscopy analysis in every location checked (eight locations randomly spaced out). Variation between NDI and microscopy was the result of two likely causes, the first being a consistent localized defect at the center of the panel, due to the 'air popper' in the female mold, which was slightly extruded above the mold cavity. Secondly, some defect regions can be observed in the lower left and right corners of each panel. This is theorized to be due to a slightly uneven distribution of pressure on the panels from the mold, either due to the popper, or difficulty arising from molding fairly thin panels with the press (minimum gap in the mold was set very close to 0.8 mm, which is similar thickness of panel 1). These two factors led to very thin panels (FAC-01 to -03 panel 1 and FAC-03 panel 2) warping during molding, as seen by the large dark distortion regions from the NDI scan. These regions, when observed with microscopy, showed very little to no void content, confirming these regions appeared as artifacts from NDI due to variation in panel height in relation to the transducer, instead of from void content. During normal operation, with these factors corrected, it is expected that void content and ply consolidation should be easily obtained and controlled due to the very high pressure hydraulic presses can provide, upwards of 150 psi. As such, all panels molded passed the void content requirement based on microscopy analysis.

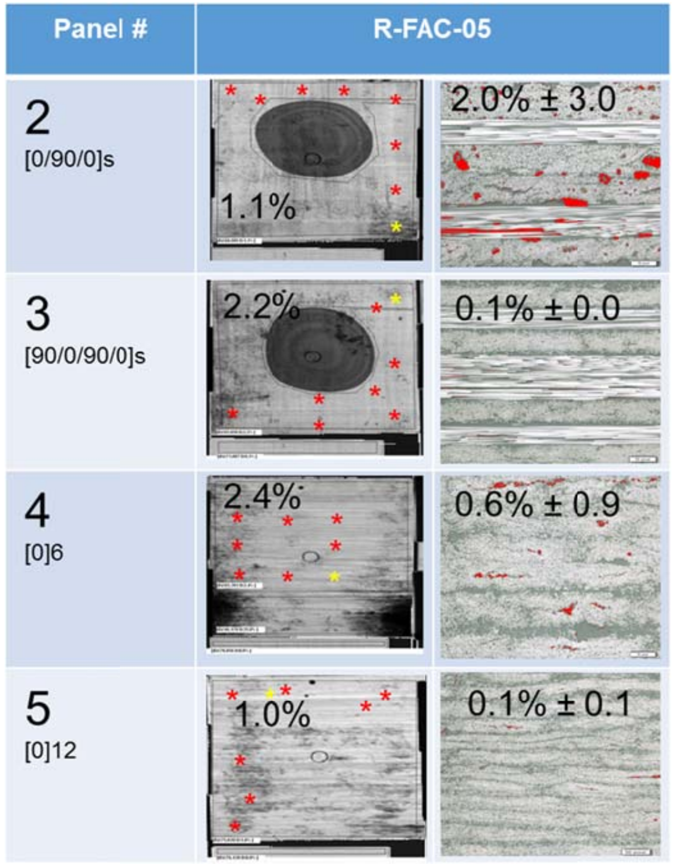

Figure 13. Hydraulic press FAC-05 panels void content analysis
Yellow star (*) denotes the location where the microscopic image was taken.

For FAC-05 panels a shown in Fig. 13, slightly higher void content was observed from the same molding process as the panels previously discussed. Localized deformation in the center of the panels can be observed in panels 2 and 3 (due to the air popper). These regions were not included in the NDI void content calculation, as they indicate inconsistency in panel distance to the transducer while scanning rather than defects due to void content. Similar to the previous panels, higher void content was observed in the corners of the panels, indicated by the darker regions in the NDI images. From microscopy, it was observed that void content still remained below the target of 1 %, with the exception of panel 2. The average void content from microscopy was skewed by two specimens taken near the right corner of the panel, which did not receive consistent pressure during cure, and yielded specific void content of 9.01 and 4.53 % respectively. The average value between the other 6 specimens taken away from this region yielded a much lower average void content (0.39 %). Based on microscopy, FAC-05 panels were also well consolidated and below the target average void content.

2 RapidClave®

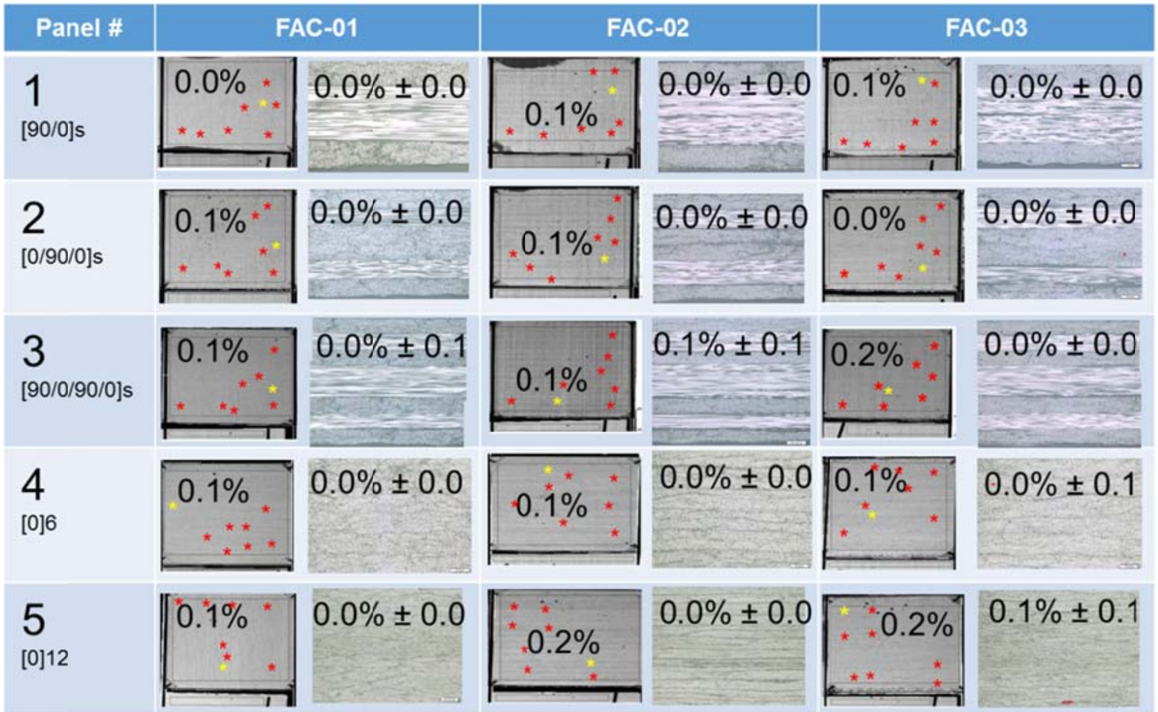

Figure 14. RapidClave® panels void content analysis
Yellow star (*) denotes the location where the microscopic image was taken.

All panels manufactured using the RapidClave® process yielded very consistent and excellent low-void content (<0.2 % for all panels), as shown in Fig. 14. Actual void regions were infrequently observed in all microscopy specimens, supporting the low void content values obtained from initial NDI scanning. Parts were well consolidated using approximately 85 psi (and vacuum), applied by a pressurized air chamber in the RapidClave® during molding.

3 Heated Composite Light Tool

As shown in Fig. 15 for panels 1-3 from heated composite light tool, NDI and microscopy analysis show acceptable consolidation and void content. However, for the uni-directional 6 ply and 12 ply lay-up (no accurate NDI value could be obtained), much higher void content values were observed. For this process, only vacuum pressure was utilized, which was unable to consolidate the larger uni-directional panels during the short cure. All panels were placed under vacuum for 10 min prior to applying the cure cycle, which appears to have helped achieve successful ply consolidation for thinner panels. Some streaked regions can be observed from the c-scans (particular panels 4 and 5), due to the spacing between carbon fiber fabric heating strips, causing a slightly uneven heat distribution on the part during cure. This issue can be addressed by adjusting the heater spacing in the mold to a tighter gap tolerance, which would also improve heat transfer during curing. However, without additional pressure, this process may not be able to consistently yield high consolidated parts above 2 mm thick, based on the large increase in void content for the 12 ply panel.

Five panels of FAC-05 were also molded using HCLT. Only one panel yielded positive results from NDI scanning, which showed no void content (excluding the wrinkles formed from the placement of thermocouples to monitor cure temperature, on the right of the panel above). This panel, however, received a pre-cure vacuum time of 3 weeks. The other panels, which only received 5-10 min of vacuum time before the cure cycle showed no response. Upon visually inspecting the cross section, large delamination regions were observable across the entire width, regardless of panel thickness. Panels were not able to be consolidated because the resin produced a higher degree of off-gassing during cure vs. other resins systems.

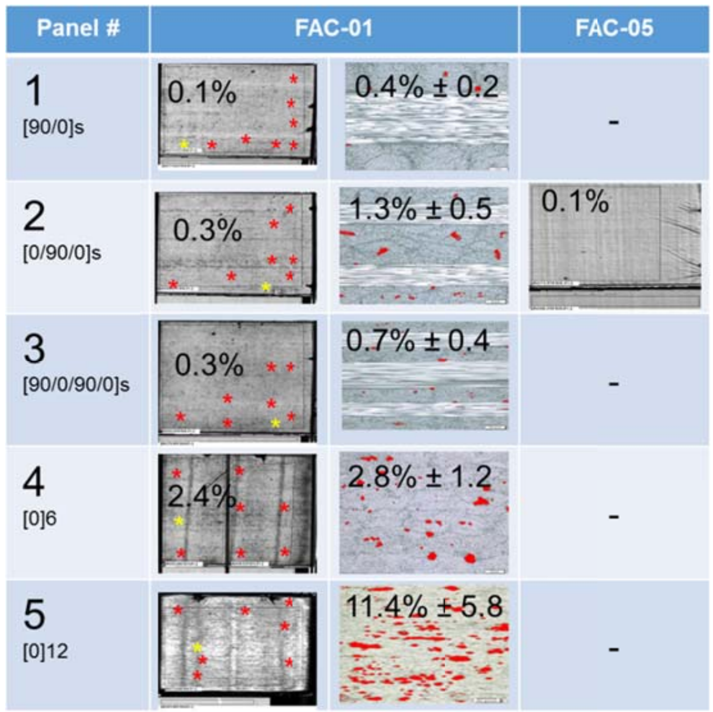

Figure 15. Heated composite light tool panels void content analysis
Yellow star (*) denotes the location where the microscopic image was taken.

4 Light Induction Tool

LIT panels were molded on a small scale hood tool, which was 30 in x 20 in, with multiple curved regions and height variation. The actual part dimensions, to be trimmed out from the rectangular laminate after cured, can be observed from the dark regions of the 'trim line'. Due to variation in relative part height, multiple scans were required in order to capture the entire panel using NDI analysis, as shown in Fig. 16. All panels were well consolidated and void free. A few locations were slightly warped, which show up as the dark regions in the NDI scans, however they do not represent necessarily a high void region. The only exception was the average void content observed from the microscopy specimens for panel 3, which was slightly above 1 %. Specimens for panel 3 were primarily taken from bottom edge of the part, beyond the trim line, and from the left flange, with the higher void content values coming from the bottom edge (specimens from the edge of the part averaged 2 % void content, whereas specimens taken from within the part had an average void content of 0.65 %). Based on microscopy of the other panels, the average void content was well below the target value, and high quality consolidated parts were obtained.

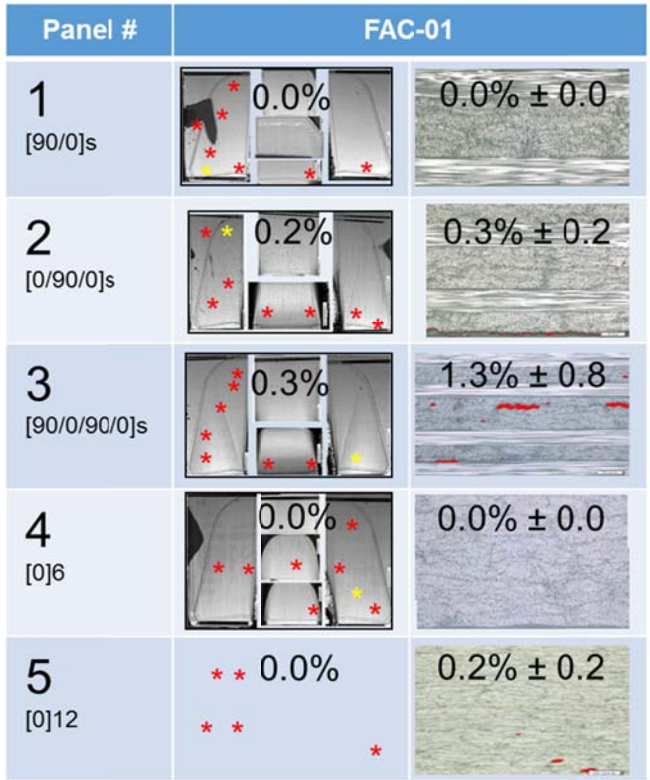

Figure 16. Light induction tool panels void content analysis
Yellow star (*) denotes the location where the microscopic image was taken.

5 Quickstep

Data is available upon a request to TCA.

1.3.2.3 Thermal Properties

Table 4 summarizes the thermal properties collected in this study, including glass transition temperature, degree of cure and G' retention. Degree of cure, measured by MDSC, indicates the completion of the materials cure reaction, and a fully crosslinked network, yielding the desired mechanical and thermal properties. This target was set to 90 %, where a majority of the reaction has completed to achieve a Tg of at least 130 ^{o}C. All panels yielded a degree of cure well above the target of 90 % cured, as seen in Table 4.

Tg and G' retention at a temperature of interest are both indicative of the temperature range the material can be safely handled at for elevated temperature processes such as primer application and painting, without jeopardizing dimensional stability from the desired final part geometry. Multiple techniques are available for determining Tg of a material, and depending on the manufacturer or application, a particular method may be more relevant. The present study reports Tg determined as shown in Fig. 17 by the non-reversible heat flow from MDSC (from the half width of the inflection point), G' onset and tan delta peak from DMA (a dual cantilever, 3 °C/min, 12 ply UD coupons). G' retention was calculated from the ratio of G' at room temperature to G' value at a specific temperature from the same DMA test. G' retention is also a measure of heat deflection behavior of the composite.

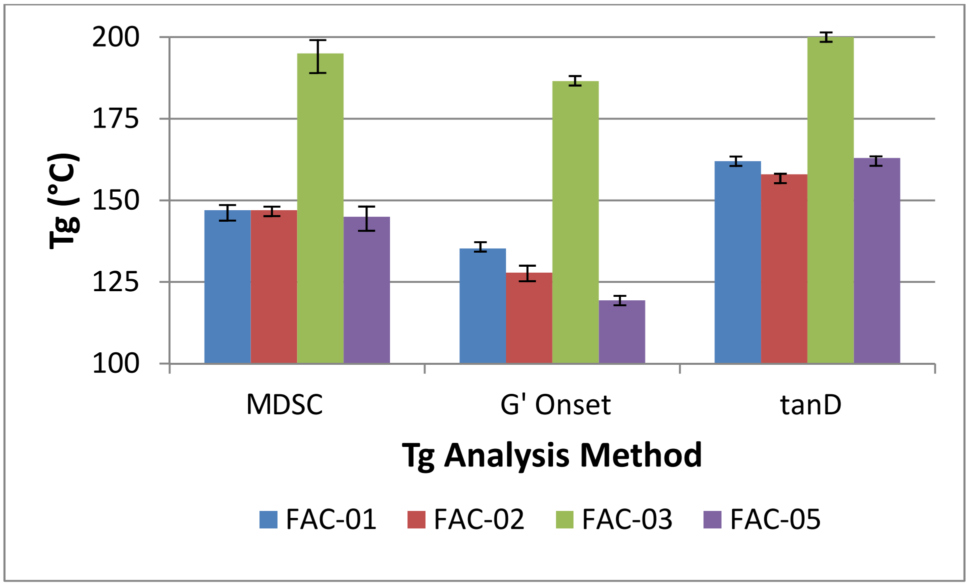

Figure 17. Tg comparison of press molded panels

For MDSC, the average Tg of FAC-01 and FAC-02 (same baseline G-83C resin system) was near 150 °C. The FAC-03 system, with a modified G-83C composition, yielded a much higher Tg, upwards of 190 °C. FAC-05 was also well above the target DoC, with a Tg comparable to FAC-01, as measured by MDSC.

For DMA, Tg values determined by G’ onset of FAC-01 and FAC-02 panels fell on average right around 130 °C. A large increase in Tg was again observed in FAC-03, averaging around 170 °C. Tg of FAC-05 was slightly under the target, averaging 120°C. A similar pattern can be observed in Tg determined from tan delta.

As shown in Fig.18 G’ retention for FAC-01 and FAC-02 followed a consistent pattern, starting at around 70 % retention at 120 °C, dropping to ~50 % at 135 °C, with a steep drop occurring at 160 °C, (~15 % retention). 60-70 % G’ retention was noted to be suitable for handling during thermal processing such as primer application and paint. For FAC-05, despite having a lower Tg than FAC-01, some improvements were observed in retention beyond 100°C. FAC-03 showed large improvements in overall G’ retention, as its Tg was much higher than FAC-01, FAC-02, or FAC-05. G’ retention remained above 90 %, until 160 °C, where retention dropped to around 80 % of its initial value and reduced to 60-70 % at 190 ^{o}C. As a result thermal processing for FAC-03 after cured could be performed up to 190 ^{0}C, which is probably the best automobile material system currently in the market.

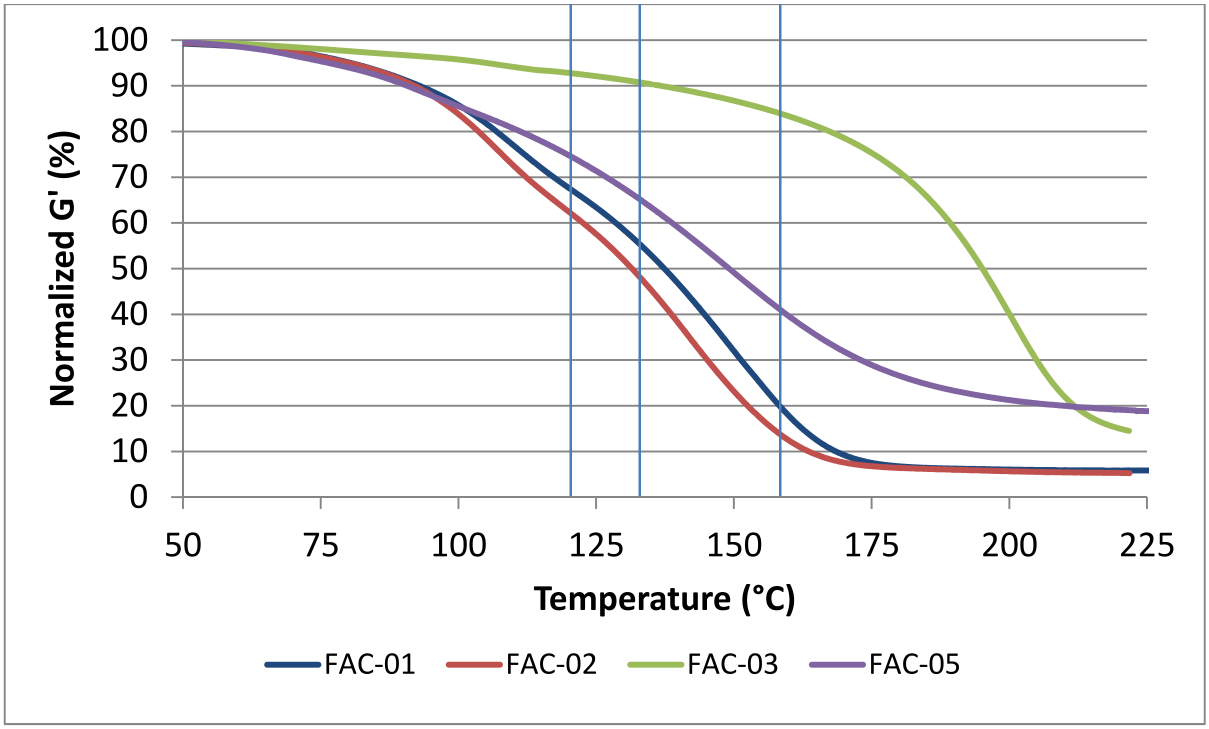

Figure 18. G' Retention comparison of press molded panels

1.3.2.4 Mechanical Properties

Table 5 summarizes tested mechanical properties for each manufacturing condition. There is no set target, database, or standards to which performance of molded panels can be compared. However, when compared to available data from conventional autoclave cure (known to produce the highest quality panels) for interrogated combination of material and molding process, similar values were observed. Also, noted that processing parameters (pressure, time, temperature and ramp rate) could skew data. As a result, collected data is best used as reference(s) for particular combination(s) of material/ molding method of interest for further optimization. It was decided that data would not be included in this report but made available to project partners. For other parties who might have an interest, upon a request to TCA, data might be released.

Table 5. Panel ply orientation and mechanical tests

Panel Number	Lay-up	Mechanical Tests	Test condition	ASTM
1	[0/90]s	0° Flex	RT	ASTM D7264
		90° Flex	RT	ASTM D7264
2	[0/90/0]s	0° Flex	RT	ASTM D7264
		90° Flex	RT	ASTM D7264
3	[0/90/0/90]s	0° Flex	RT	ASTM D7264
		90° Flex	RT	ASTM D7264
4	[0]6	0° Tension	RT	ASTM D3039
		0° Compression	RT	ASTM D3410
5	[0]12	ILSS	RT	ASTM D2344
		0° Flex	RT	ASTM D7264
		90° Flex	RT	ASTM D7264

1.3.2.5 Surface Finish Analysis

1.3.2.5.1 Defects and Rework

It was found that press molding could suffer from surface defects from several processing issues such as charging prepreg stack onto a hot tool surface leading to the contact surface to be cured before the tool is closed and/or lack of resin flow during cure, centering the stack in the mold cavity, and uneven pressure distribution especially around the edges. Figure 19 shows examples of fiber distortion and dry spots. These panels could not be reworked and would have to be discarded in production.

Figure 19. Fiber distortion and dry spots on surfaces of press molded panels

Hairline dry spots are common for prepreg molding due to various reasons such as non-contact areas of surface ply to the tool surface due to uneven pressure distribution or not enough applied pressure, uneven temperature distribution, resin bleeding out during cure, uneven mold release applications. These were found in some panels from all participating molding processes. Figure 20 shows an example from a press molded panel. These hairline dry spots could be reworked by sanding. However, if they create deep craters, the panel would have to be discarded as well. Certainly, further optimizing processing conditions would minimize these defects.

Figure 20. Hairline dry spots on surface of press molded panel

Most of the panels molded from Rapidclave®, LIT and some from press molding showed none to minimal rework required. Figures 21-22 show an example of press molded 12-ply panels FAC-01, FAC-02 and FAC-03 and LIT molded panels. Note that FAC-02 panel produced a substantial amount of fuzzes on the surface. However, after sanded and applied a primer, the primed surface appeared similar to those from FAC-01 and FAC-03 panels.

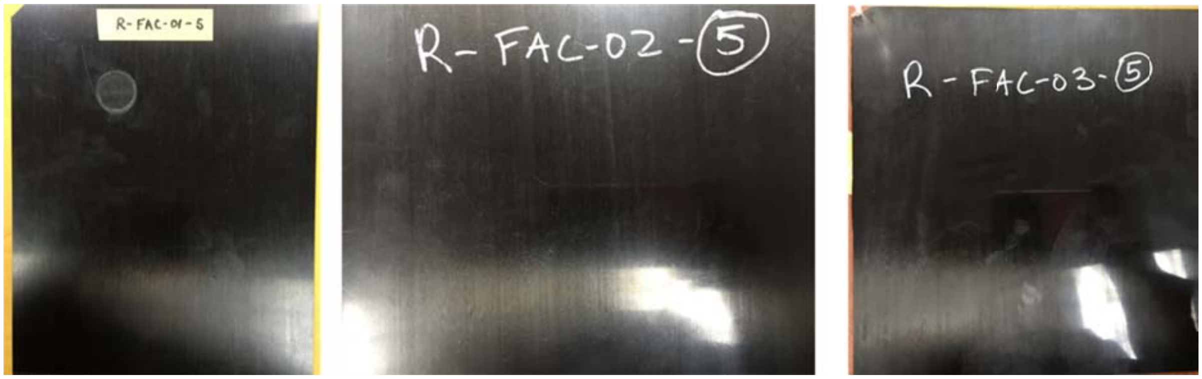

Figure 21. Examples of minimal rework pressed molded panels (highest surface quality)

Figure 22. Examples of minimal rework LIT molded panel (untrimmed)

1.3.2.5.2 Class A Characterization Methods

In the automotive industry, typically all exterior and quite a few interior surfaces are designated as Class A. These surfaces need to have little to no surface defects, uniform curvature and tangency, and no orange peel appearance. Another term often used when involving class A finishes is the distinctiveness of image (DOI), which is a measurement of the sharpness of a reflected image. A class A surface is often referred to a painted (final finish) surface provided that the corresponding out-of-the mold panel consists of little to none blemishes and can be re-worked .

In this study, deflectometry and wavescan were briefly explored and documented as potential surface analysis techniques applicable for class A finish characterization through demonstrations on the selected best quality panels. Deflectometry determines the local curvature of a surface by measuring distortion of a projected grid pattern (see Fig. 23) while wavescan uses a laser light source to detect the optical profile of a surface, for long and short characteristic wavelengths. In deflectometry an interrogated surface is scanned based on defined raster vectors, and compared to a reference class A surface. Wavescan offers a more quantitative analysis, and is a more common industry standard to determine key surface finish parameters such as dullness, DOI, and orange peel, depending on the range of wavelengths and their responses.

Figure 23. Deflectometry set-up. The grid pattern is projected from the top screen onto a panel below. The reflected pattern on the panel is captured and analyzed by a computer for deformations in the reflections to conclude topography of the surface.

Table 6 shows examples of data collected from deflectometry from selected press molded panels of highest quality. Scans were made in both the axial (aligned with top ply fiber direction) and transverse (perpendicular to top ply fiber direction). Panels were compared to the results obtained with a reference panel of stated 'Class A' quality, labeled Control in the table below. Values below this threshold (near or less than 1.0 for both directions), were considered passing for these surfaces based on this comparative analysis of surface quality. Only two panels were near or at the control threshold for both scan directions, which were FAC-03 panel #3 (8 plies) and #5 (12 plies).

Table 6. Surface finish analysis by deflectometry

Panel		Scan Direction	
Material	Lay-up	Axial	Transverse
FAC-01	[0]12	3.66	0.59
FAC-02	[0]12	5.21	0.62
FAC-03	[0/90/0]s	3.16	2.21
FAC-03	[90/0/90/0]s	1.44	0.81
FAC-03	[0]6	3.71	0.43
FAC-03	[0]12	1.13	0.30
Control		1.2	0.94

>+/-(100 %) +/-(10-100 %) Meet/ Exceed

BYK Wavescan-Dual was also conducted on a few selected panels to evaluate the surface appearance of as molded panels. Wavescan data offers a multitude of data to analyze a variety of surface finish characteristics, depending on the specific wave length region investigated. Typically, the dullness of a surface is determined by the lower wave lengths, whereas a feature such as waviness may be determined by the response measured by long wavelengths. The wavescan data was collected on a few panels with and without a primer. The data is still being processed and might be available upon request.

In addition to the above methods, another technique utilized to analyze surface finish was spectral gloss. Spectral gloss measures the reflectance of a test sample compared to a calibrated standard (ASTM D523 Standard Test Method for Specular Gloss), measured using a BYK-Gardner Micro

Gloss with a 60° incident angle reflectometer. It is important to note that spectral gloss is not considered an indicator of class A. The units of the spectral gloss values (GU) are relative to the reference specimen used, with 100 GU meaning the surface had the same surface reflectance as the reference.

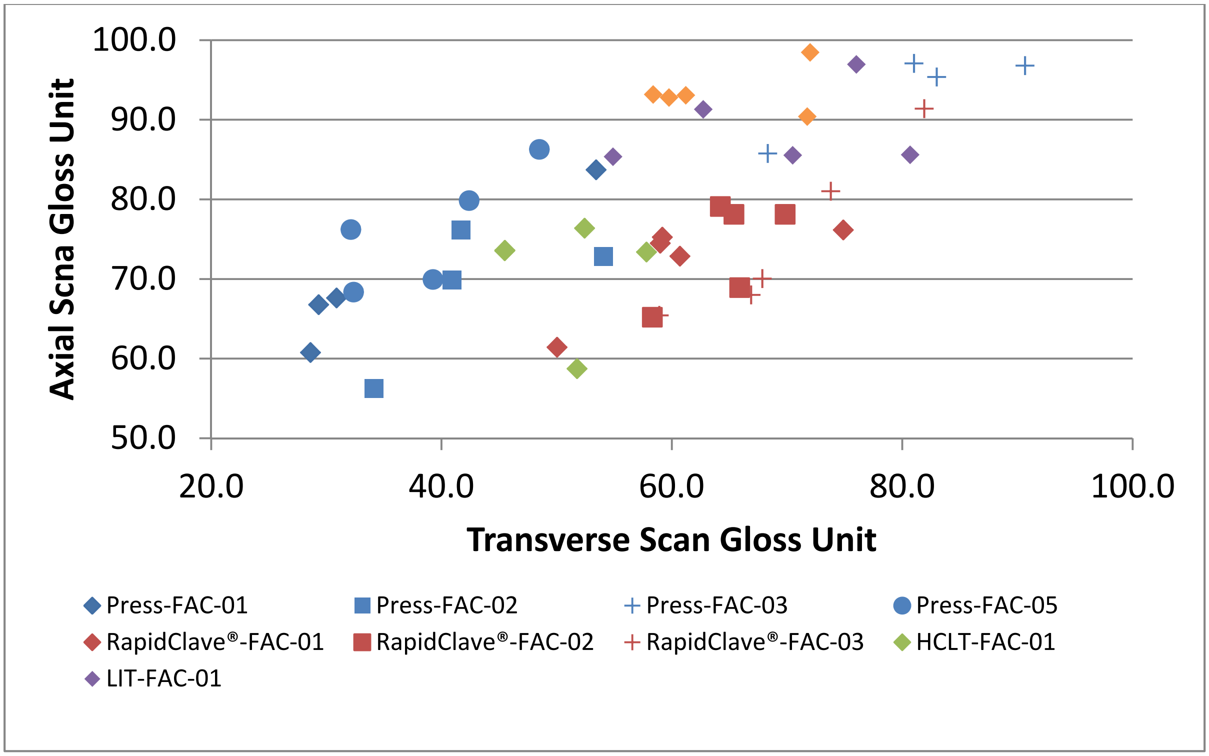

Figure 24. Spectral gloss data for selected molded panels

Spectral gloss data was collected for selected panels as shown in Fig. 24. One RapidClave® panel had relatively high quality results for both axial and transverse scans, which was the FAC-03 4 ply panel. The material and process yielding the highest surface quality was pressed molded FAC-03 panels, which yielded three of the highest GU values for both transverse and axial scans, which also yielded the best results based on deflectometry analysis. A typical low limit threshold for gloss is above 60, which nearly all of the panels surpassed in axial scans, with less consistency for the transverse scans. The highest quality panels from all manufacturing conditions indicated a high gloss surface could be achieved.

1.3.2.6 Cost Analysis

The present study also explored critical factors responsible finished panel costs. Average panel cycle time and material effective cost were explored and summarized as below

1.3.2.6.1 Cumulative and Average Panel Cycle Time

Cumulative panel cycle time in the present study is defined as the total time it takes from (0) cleaning/ preparation → (1) cutting → (2) laying up → (3) preforming → (4) charging → (5) curing → (6) demolding. Figure 25 summarizes panel cycle time for the participating molding processes using FAC-01 for 6-ply panels. Note molding process includes charging, curing and demolding. The time for each process was adjusted to a 12”x12” panel for comparison. For each process, the first bar represents the potentially achievable cumulative panel cycle time after a reasonable investigation while the second bar projects an improved cumulative panel cycle time if the processes #1-6 and their processing parameters would have been further optimized in the current laboratory-scaled machine and/or in a production ready machine. Quickstep process was excluded from this analysis.

(0) Cleaning and preparation process in the present study includes placement of an external mold release on the tool surfaces initially and subsequently after each molding and preparing the tool for the next molding. Project partners performed this process and documented the time. Time was adjusted to that of 12"x12" 6-ply panel in the panel cycle time calculation in Fig. 25.

(1) Ply cutting process was performed by TCA using an automatic cutter for three different panel sizes of 14"x14" (press), 30"x20" (LIT) and 12"x12" (RapidClave®, HCLT). Time was adjusted to that of 12"x12" 6-ply panel in the panel cycle time calculation in Fig. 25. This process took about 1 min.

(2) Hand lay-up process was also performed by TCA with debulking every other ply for 30 sec and final debulk of 1 min. Time was adjusted to that of 12"x12" 6-ply panel in the panel cycle time calculation in Fig. 25. This process took about 5 min.

(3) Preforming process in the present study includes bagging of a prepreg stack on a tool and additional debulking time after bagged but before temperature is ramped up to the cure temperature. This process is more applicable to RapidClave®, HCLT, and LIT. Project partners performed this process and documented the time. No adjustment to accommodate for different panel sizes was made in the panel cycle time calculation in Fig. 25.

(4) Charging process in the present study is part of the molding process including placement of the ready-to-go panel in a machine for molding. It is more applicable to press, RapidClave® and LIT. Project partners performed this process and documented the time. No adjustment to accommodate for different panel sizes was made in the panel cycle time calculation in Fig. 25.

(5) Curing process in the present study is part of the molding process including ramping the temperature up to the cure temperature and cooling down to demolding temperature. This process was described in detail previously. Project partners performed this process and documented the time. No adjustment to accommodate for different panel sizes was made in the panel cycle time calculation in Fig. 25.

(6) Demolding process in the present study is part of the molding process including physically taking the cured panel out of the tool and removing of bagging materials. Project partners performed this process and documented the time. No adjustment to accommodate for different panel sizes was made in the panel cycle time calculation in Fig. 25.

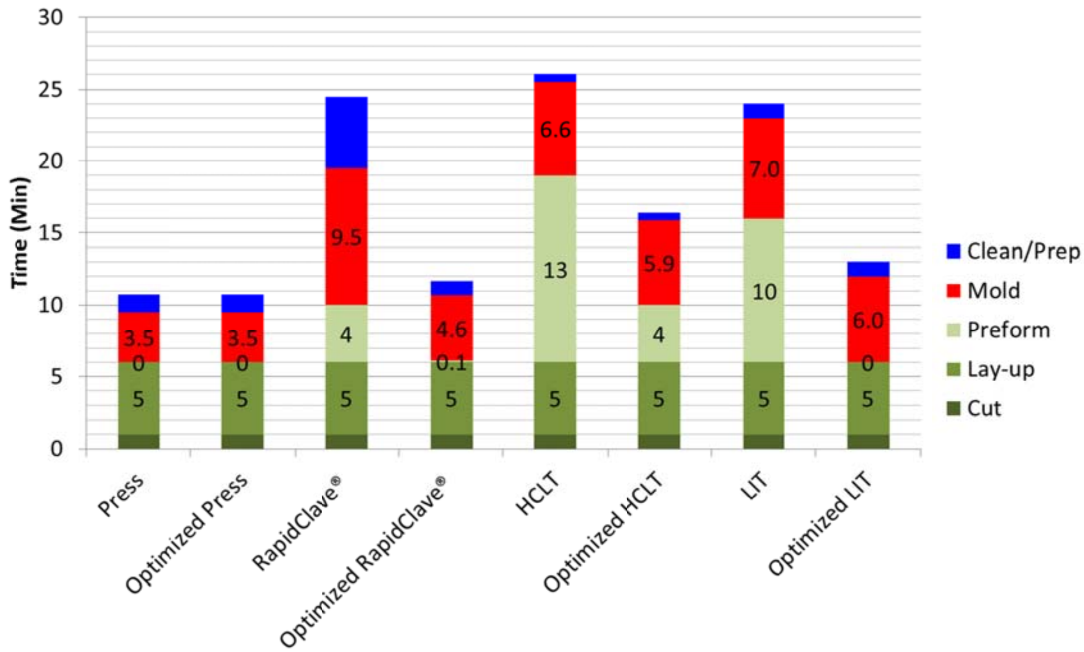

Figure 25. FAC-01 cumulative panel cycle time.

The cumulative panel time presented in Fig. 25 is the time to complete molding of one panel. The present study also explores average panel cycle time if the panels would have been produced in a serial production. Assuming a work cell comprising one cutting station, one lay-up station, one preforming station, one molding station with two tools, the resulting average panel time based on daily panel rate was approximated to be the average of time accumulating in processes #2-4 when the part is being prepped on the tool outside of the molding machine and time accumulating in processes #5-6 when the part is molding in the molding machine until demolded. Table 7 summarizes the estimated average panel cycle time for the molding processes using time steps from once optimized assumptions, except cutting and hand-lay up processes were kept at 1 min and 5 min, respectively and corresponding annual volume (annual operation time 235 days, 20 hours per day, 5 days per week.) In order to achieve at least 100,000 panels per year in a serial production), the average panel cycle time would be about 3 min, prompting that further optimization of individual processes and the whole serial production including transfer mechanisms from one process to the next is critical to achieve the 3-min goal.

Table 7. Estimated average panel cycle time in an assumed serial production.

Process	Once optimized processes for FAC-01						Serial production	
	Cutting (min)	Lay-up (min)	Preform (min)	Charge (min)	Cure (min)	Demold (min)	Average Panel Time (min)	Annual panel volume
Press	1.00	5.00	0.00	0.30	3.00	0.20	4.25	62.35k
RapidClave®	1.00	5.00	0.10	0.15	4.40	0.02	4.84	58.26k
HCLT	1.00	5.00	4.00	1.00	6.00	1.00	8.50	33.17k
LIT	1.00	5.00	0.00	1.00	6.00	1.00	6.50	43.38k

1. *Hydraulic Press*. Individual processing times in the present study were presented in Fig. 25. The cumulative panel time was 10.8 min. No further optimization for press was needed to reduce the time. In serial production with the above work cell, the average panel cycle time would be approximately 4.25 min, leading to 66,352 panels per year.

2. *RapidClave®*. Individual processing times in the present study were presented in Fig. 25. The cumulative panel time was 24.5 min. Majority of additional time vs. press came from clean/ preparation, preforming, charging, curing and demolding processes. Globe anticipated that they could reduce the panel cycle time to 12.3 min, taking into account of further optimization of the performing, charging, and demolding processes similar to those in their production machine in addition to the curing process with implemented technologies described above. In serial production with the above work cell, the average panel cycle time would be 4.84 min, leading to 58,264 panels per year.
3. *HCLT*. Individual processing times were presented in Fig. 25. The total panel time was 26.1 min. Majority of additional time vs. press came from preforming process since only vacuum pressure was used. Janicki anticipated that they could reduce the panel cycle time to 16.4 min, taking into account of further optimization of the performing process in addition to the curing process with implemented technologies described above. In serial production with the above work cell, the average panel cycle time would be 8.5 min, leading to 33,176 panels per year.
4. *LIT*. Individual processing times were presented in Fig. 25. The total panel time was 24 min. Majority of additional time vs. press came from preforming process since only vacuum pressure was used. Roctool anticipated that they could reduce the panel cycle time to 13 min, taking into account of further optimization of the performing process and the curing process. In serial production with the above work cell, the average panel cycle time would be 6.50 min, leading to 43,384 panels per year.

1.3.2.6.2 Part Cost Variance vs. Average Part Cycle Time (Part Time)

Globe provided rough part cost estimation including prepreg material cost, direct cost with amortization and indirect cost vs. average part cycle time using their cost model with assumptions of 3 m x 1m panel, 1 RapidClave®, 2 tools, material effective cost of 200 % (i.e., the cost of total prepreg amount used to make the part including its scrap; see the below section for more details), and annual operation time of 235 days, 24 hours per day, 5 days per week. Figure 26 shows number of parts per year vs. part time and part cost vs. part time in that the part cost was normalized to cost from a 17-min part time process. As shown, a 3-min part time is needed to achieve at least 100,000 parts per year for this work cell. There is a modest part cost reduction of 20 % when the part time is reduced from 17 min to 8 min and very minimal part cost reduction for part time reduction less than 8 min. This indicates that the material effective cost assumption of 200 % is the extreme case, prompting that a substantial reduction of scrap to reduce overall part cost is critical. If the material effective cost is 100 % (a little scrap) combined with a 3-min part time process, there is about 57 % reduction in the resulting part cost.

Note that the part cost information in this section is just to show general tendencies for the purpose of this discussion. More accurate part cost information would come from part manufacturers.

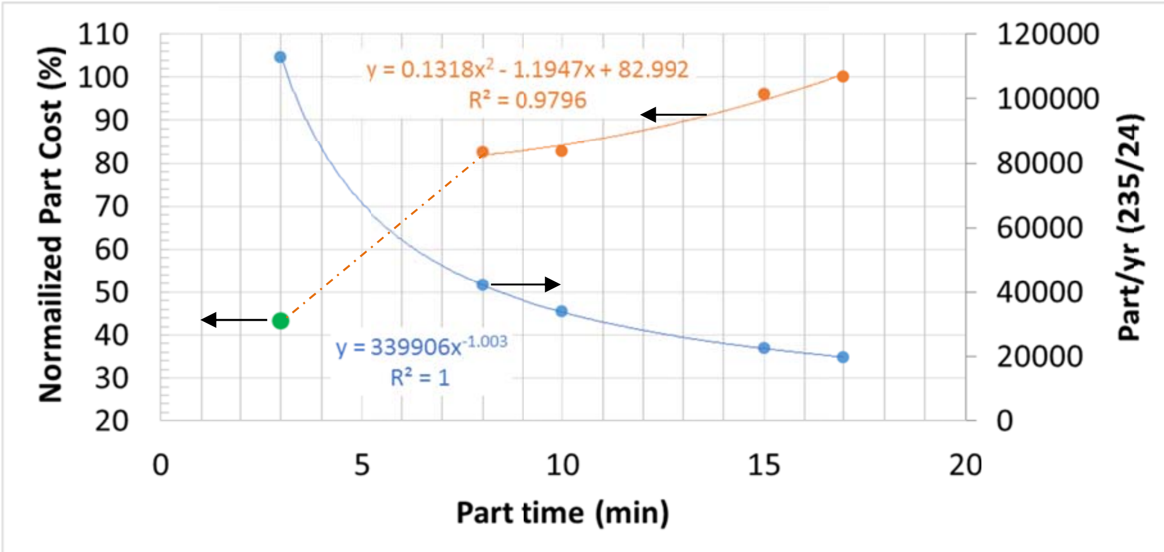

Figure 26. Part cost variance vs. part time analysis for 3m x 1m panel, 1 press, 2 tools, 6 plies of 300 gsm prepreg in a serial production work cell. Orange dots and green dot were calculated with material effective cost of 200 % and 100 %, respectively.

1.3.2.6.3 Part Cost Variance vs. Material Effective Cost

Globe provided rough part cost estimation including prepreg material cost, direct cost with amortization and indirect cost vs. material effective cost using their cost model with assumptions of 3m x 1m panel, 1 RapidClave®, 2 tools, 6 plies of 300 gsm prepreg and annual operation time of 235 days, 24 hours per day, 5 days per week. Material effective cost is defined the cost of total prepreg amount used to make the part including its scrap. 200 % is referred to a manufacturing case with a substantial scrap amount nearly as high as the prepreg amount is needed to make the part, hence the highest part cost is at 100 %. As shown in Fig. 27, for every one percent of material effective cost reduction either by a lower cost of the prepreg and/or a lower amount of scrap, part cost decreases 0.34 %. The latter certainly can be achieved by automatic lay-up machine such as AFP/ATL as discussed in the below section. If the part is stiffness driven, lower cost of prepreg could be achieved by using large tow cheaper carbon fibers such as Zoltek™ PX35 having the similar modulus as Torayca® T700 fibers.

Note that the part cost information in this section is just to show a general tendency for the purpose of this discussion. More accurate part cost information would come from part manufacturers.

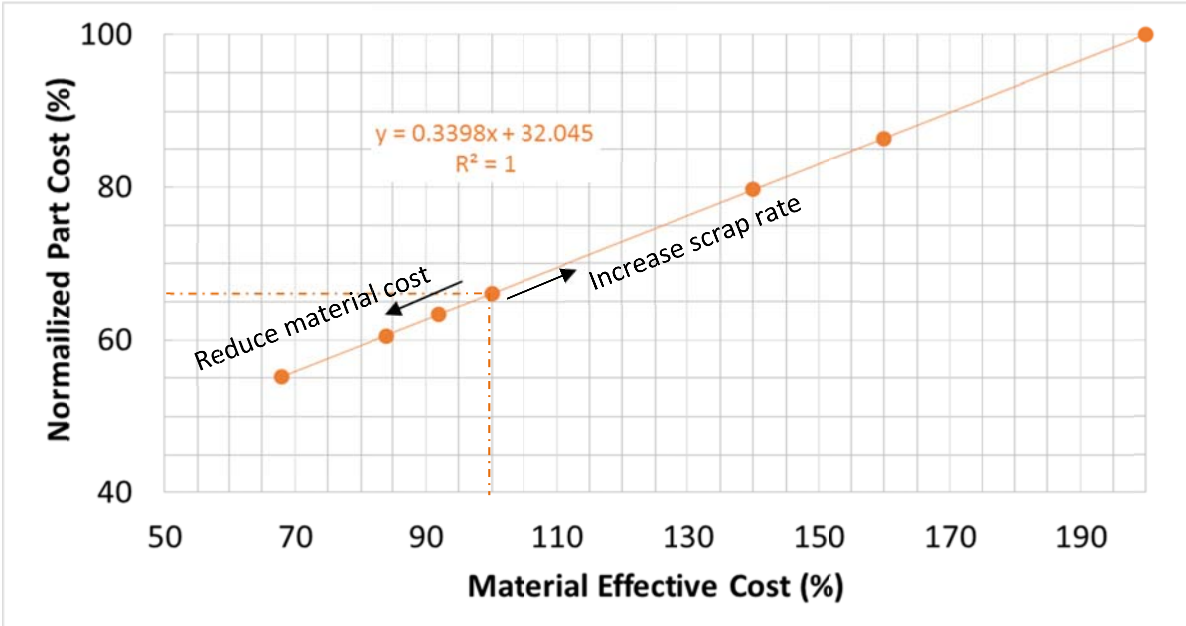

Figure 27. Part cost analysis for 3m x 1m panel, 1 press, 2 tools, 6 plies of 300 gsm prepreg in a serial production work cell

1.3.2.7 Recycled Prepreg Study

Plies for the flat panel study for the FAC-01 system were cut from a production 40" roll. The scrap leftover from cutting 12"x12" and 14"x14" panels were collected, and distributed to the Composite Recycling Technical Center (CRTC). Two methods of processing this material were investigated. One method took the recycled material and chopped it up, to be utilized as a sheet molding compound. Chopped material was distributed into a shear edge mold, and press cured. Another method took the various width pieces of uni-directional (UD) prepreg scrap, and recombined it into larger sheets of UD prepreg.

The panels were molded in a hot plated press, Wabash 150 ton, 24 x 24 platens with the temperature pre-set to 163 °C. Pressure only (no vacuum) was used for the molding, with estimated 3 min at 163 °C and a total of 6 min in the press. Moldings using controlled cavity thickness as well as free-edge were attempted, and ultimately a cavity mold pre-charge of about 90 % was used for the chopped panel samples. No issues were seen for molding the chopped samples, and subsequent work has shown continuing improvements in the panel qualities above the earlier ones shown below in the testing. Panels typically demonstrated surface defects (pitting, porosity) in the regions immediately above the worst void areas, with relatively good surface finish in the areas with lower void content. Continued improvements that have been seen in surface quality would indicate lower and/or more even distribution of the void content.

A rough analysis was performed of the potential use of the recycled (scrap) prepreg back into an automotive internal reinforcement for a roof panel, approximating a hat-section brace at 3 mm thick. This estimate indicates a potential cost reduction of the assembly of about 15 %, and the need for producing virgin fiber for the internals (assuming an SMC format) is reduced by approximately 35 %. The assumptions are that the prepreg scrap is generated by the skin tape-laying/placement machine scrap plus prepreg manufacturing scrap, with both of these steps being captive (internal) to the automotive production site. A near-vertical integration such as this would result in only the cured trim waste needing to be sent to secondary (pyrolysis/solvolysis) recycling.

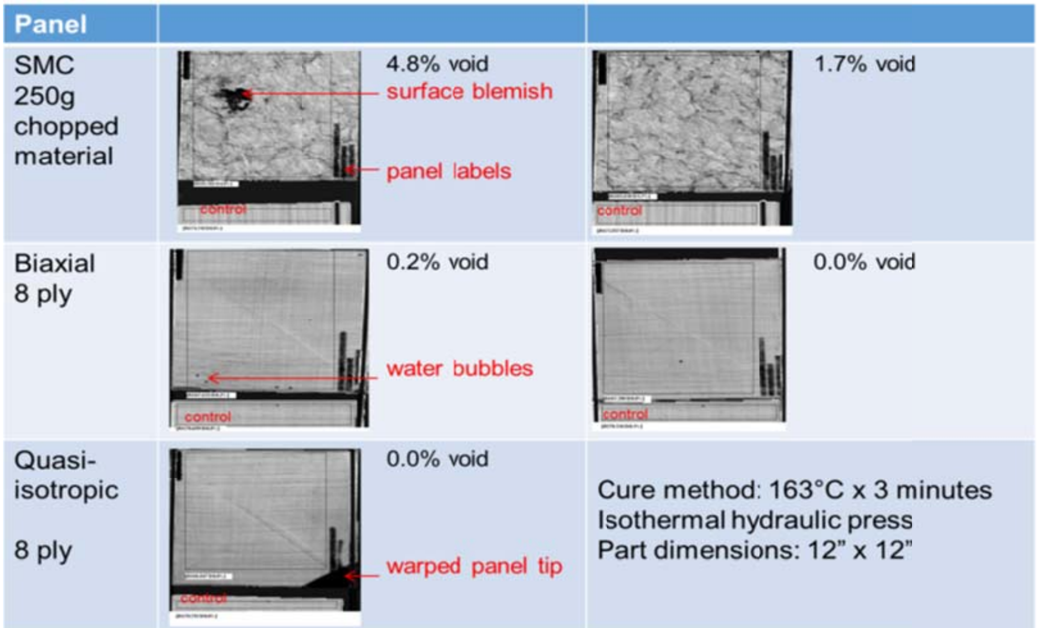

Figure 28. NDI scan of recycled FAC-01 prepreg panels

Based on the NDI results in Fig. 28, little to no voids were observed in the biaxial panels, where scrap material was recombined into a larger width pre-preg sheet before molding. For the chopped material, larger void content was observed. Inherent to the process, this method also yielded a large distribution of resin rich areas across the part.

1.3.2.8 Automation Study

A major hindrance on composite manufacturing rates is the speed at which technicians are able to lay-up plies, especially for large structures. AFP (automated fiber placement) and ATL (automated tape laying) are technologies that have emerged as a replacement for time consuming manual lay-up, allowing more material at greater consistency to be laid up in a short amount of time.

During the flat panel study, the average time for one operator to lay up a 12" x 12" panel was around 5 min. The graph in Fig. 29 compares theoretical lay-up times for different tape widths using an automated process.

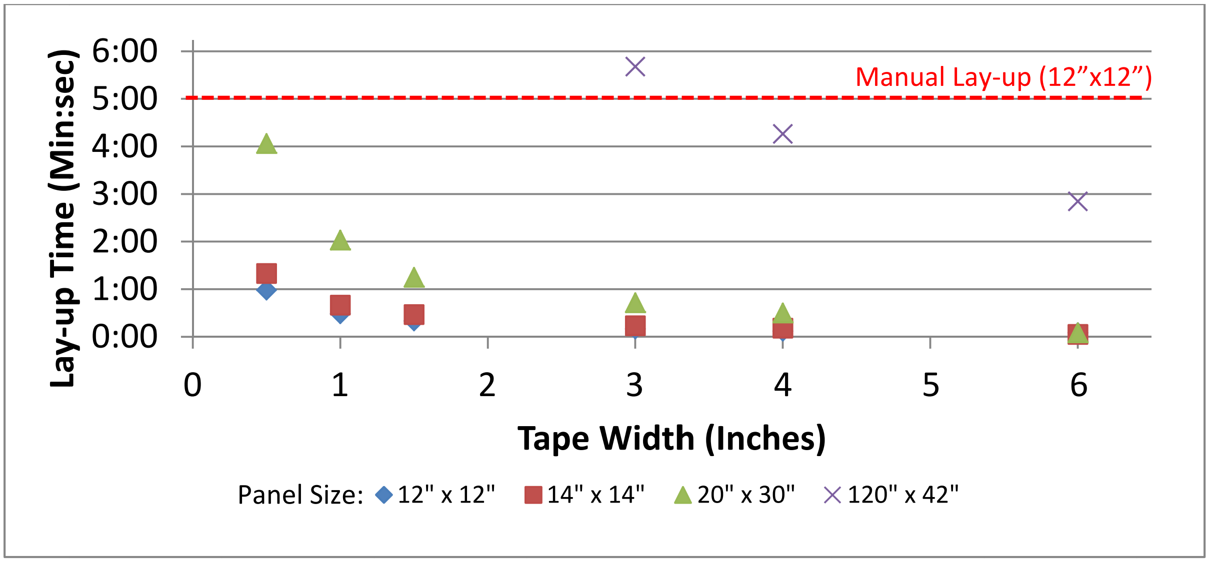

Figure 29. Lay-up time vs tape width

The calculations made above were assuming an average feed rate of 45 m/min[v] was being used, and only one tow was laid down at a time. An automated process laying down 3 inch wide tape can potential lay-up a 120" x 42" part in the same time it takes one operator to manually lay up a 12" x 12" part.

In addition to reducing lay-up time, automated processes can affect the scrap rate, (amount of prepreg that does not end up as a functional part). The information from the table below was gathered from the manual process of cutting and laying up the flat panels, with theoretical scrap calculations for the same panels being manufactured with an automated process.

Table 8. Scrap rate from various panel sizes, [0]6 layup.

	Panel size	Lay-up size	Pre-preg Scrap (%)	Trim Scrap[3] (%)	Total (%)
Manual	12" x 12"	12" x 12"	10.5[1]	30.6	41.1
	14" x 14"	14" x 14"	31.4[1]	26.5	57.9
	Small hood	30" x 20"	12.8[1]	25	37.8
ATL	12" x 12"	15" x 13"	26.2[2]	30.6	56.8
	14" x 14"	15" x 15"	12.9[2]	26.5	39.4
	Small hood	30" x 21"	4.8[2]	25	29.8

The prepreg scrap values from cutting for the manual process, were calculated based on cutting from a 40" wide roll. The prepreg scrap from the ATL process as shown in Fig. 30 is based on using 3-inch wide tape, and the assumption that an additional 0.5" width and length beyond the target panel size was laid down.

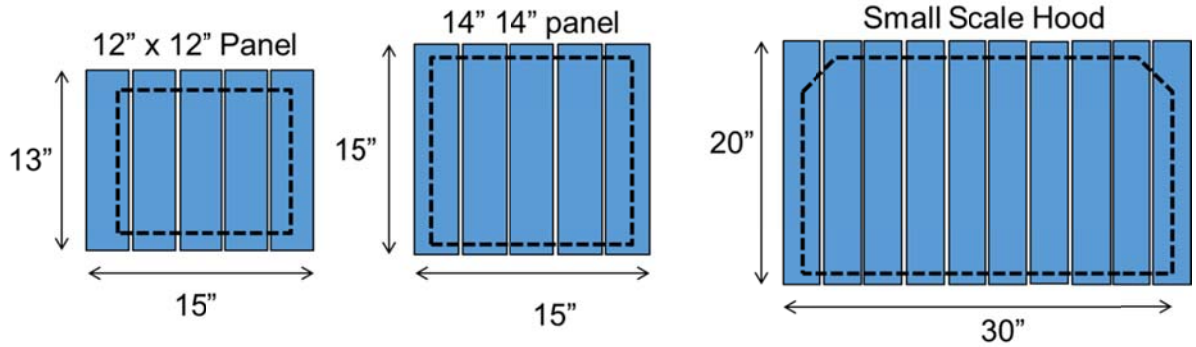

Figure 30. ATL tape paths for various panel sizes

Lastly, scrap from the cured panels would be generated when the edges must be trimmed away. Scrap was based on the assumption that 1 in around all edges would be trimmed away for the square panels, and up to the trim line for the small scale hood part.

Using an automated process could help significantly reduce the amount of prepreg that does not end up on the final part, with the largest influence coming from precise control on using the material for a specific area. For manual processes, the amount of uncured prepreg scrap is highly dependent on the ply dimensions and the width of the roll being used, thus how efficiently plies can be cut from the roll.

1.3.3 Sample Production (if project results include part production)

The present study did not include a part production.

1.4 IMPACTS

The present study has proven that 14 organizations (8 project partners and 6 supporting partners) in the prepreg supply chain are willing to collaboratively work together using their own resources on a program endorsed by IACMI. Without IACMI, this might not have been possible.

The study accumulated molding knowledge from flat panel demonstrations using several prepreg materials and several molding methods in a systematic approach. Several successful combinations of prepreg and molding method as well as know-hows to achieve cure cycle time, surface quality, void free, thermal/ mechanical performance were accomplished. In addition, the study also explored several aspects of an automatic work cell in a serial production plus recycling and finishing processes to maximize production rate and effective part cost. Lessons learned and experiences from the study are tremendously helpful for the team to move onto a component demonstration of interest, or support a part manufacturer to build a compelling business case for a component of interest using prepregs and/or to optimize their existing manufacturing process using prepregs for more cost effective.

More specifically, the outcome of this study has several impacts on large scale manufacturing of composite components

- Prepreg materials in the study were shown to be robust to be processed by several current state-of-the art molding technologies to achieve 2-5 min cure cycle time for flat panel as well as moderately curved panel with thickness from 0.8 to 2.4 mm (and thicker than 2.4 mm to be further explored), VOID FREE, good to excellent molded surface, Tg (by G' of DMA) from 120-190 ^{o}C, and comparable performance to slow autoclave cured composites. Selection of a combination of prepreg and molding method for large-scaled component demonstration will depend on one's reference and/or budget.

- Meeting the 3-min or less cure cycle time requirement enables prepregs to be the ideal candidate for thinnest, lightest and largest structural parts such as an Escalade roof outer panel at high production rate vs. RTM and thermoplastic material. However, in a serial production automatic lay-up, preforming, and charging/ transferring processes should be considered not only to further reduce the average panel cycle time, but also provide ease of handle-ability. In order to meet at least 100,000 per year a 3-min average part cycle time is needed, which requires a work cell to be set up with optimized processes and minimal capital investment.
- Conventional hydraulic press is not the only solution to mold thermosetting prepregs since compaction pressure as low as vacuum to 150 psi were shown to be adequate. One might consider other processes such as RapidClave®, HCLT and LIT having desired rapid heating/cooling and substantially lower energy consumption as alternative molding methods.
- Recycling can reduce cost further and should be considered.

1.5 CONCLUSIONS

The followings were found during execution of the present study

- Established a collaborative working framework
- Set up a dynamic, passionate team with 14 organizations
- FAC-03/hydraulic press as the best combination for the fastest cure (≤ 3 min) and the highest Tg (~190 ^{o}C)
- Completed database build from flat panels
    - Achieved cure time 3-6 min with isothermal and fast ramp up to 120 ^{o}C/min. Fastest cure cycle time provided by hydraulic press.
    - Applied pressure from vacuum to 150 psi
    - Achieved Tg (G' from DMA) from 120-190 ^{o}C
    - RapidClave® and LIT provided consistently best molded surfaces with minimal rework and low to very low void content
    - HCLT might be more suitable for preforming process
    - Quickstep process might be more suitable mid-volume automobile
    - Projections indicate that long hand-up time can be substantially reduced with ATL/AFP
    - Projections indicate that high scrap rate with manual/ hand lay up and scrap rate can be substantially reduced with ATL/AFP
    - Successfully molded flat panels with scrap prepreg
    - Completed rough part cost estimation of GM Escalade roof outer panel

LEAD PARTNER BACKGROUND

Toray Composites (America), Inc. ("TCA") was first established in 1992 to enable an efficient supply stream of Toray's carbon fiber composite materials. First used on the Boeing 777, Toray's advanced Carbon Fiber composite materials are now incorporated into the 777 and 787 primary structure and will be used on the new 777X wing. TCA supplies a diverse customer base both domestically and internationally and is a major exporter from Washington State. TCA is a wholly owned subsidiary of Toray Industries, Inc., located in Tacoma, WA.

TCA with support from Toray Industries (Japan) has resources and capabilities for being the center of the ecosystem of prepreg supply chain for the automobile industry for the following reasons:

(1) Over 30 year experiences of high and stable quality prepreg manufacturing evidenced by stable cured thickness. TCA has established capacities and capabilities to support mass-scale production of carbon fiber prepregs for aerospace, automotive, industrial, and sporting goods applications. We are ahead of the competition in terms of both quality and capacity.
(2) Over 30 years of prepreg R&D focusing on performance improvements as well as quick cure abilities, based on the experiences from aerospace and automotive markets and inputs from customers and potential partners
(3) Over 20 year experiences working with prepreg supply chain for aerospace such as Boeing 777, 787, 777X aircraft programs
(4) Toray and TCA has led several successful automobile programs including Nissan Skyline GT-R's hoods, drive shafts[vi], Teewave AR1 composite car from Toray's own materials and processes[vii]
(5) TCA has already supplied fast-cure prepregs such as G-83C to automobile market. G-83C is one of the best performing products in the current automotive market for both autoclave and advanced fast-cycle processing methods. Plasan Carbon Composites (PCC) has been using it for both Chevrolet Corvette and Viper sports car programs[viii].

PARTNER INTRODUCTION (SEE APPENDIX)

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[viii] Composites World 2005. http://www.compositesworld.com/articles/corvette-z06-adds-carbon-fiber-fenders

APPENDIX: PARTNER INTRODUCTION

1. Zoltek Corporation (‘Zoltek’)
2. Reichhold LLC 2 (‘Reichhold’)
3. Janicki Industries, Inc. (‘Janicki’)
4. Globe Machine Manufacturing Company (‘Globe’)
5. Composite Recycling Technology Center (‘CRTC’)
6. American Composites Manufacturers Association (‘ACMA’)
7. Michigan State University (‘MSU’)
8. Huntsman (“Huntsman”) – not available
9. RocTool (“RocTool”)
10. KTX Corporation (“KTX”)
11. ChemTrend (“Chem Trend”)
12. Quickstep (“Quickstep”) – not available
13. Toray Carbon Fibers (America), Inc. (“CFA”)

ZOLTEK
Toray Group

Date: 11 October 2016

From: Philip L. Schell, Ph.D.

Company Overview

Zoltek Corporation is a subsidiary of The Toray Group of Japan based in St. Louis, MO. Zoltek is focused on research, development, production, marketing and sales of a large tow carbon fiber product for the composites market.

The large tow product that Zoltek produces is a 50K (50,000 filament) tow or roving. The company focuses on high throughput, large tow products and low cost of production. With this focus, it is possible to produce and sell profitably a carbon fiber product at a much lower cost than conventional aerospace carbon fiber producers. Zoltek's focus is on the industrial and commercial markets for carbon fiber such as i) wind energy, ii) automotive, iii) infrastructure and iv) other markets such as oil/gas and sporting goods where possible.

Contribution to "Seahawks" project

Zoltek's contribution to the "Seahawks" project was to provide samples of PX35-13 50K tow product for prepreg production and comparison to Toray's standard product T700. In addition, Zoltek provide a technical service visit by a fiber processing expert to Toray Composites America (TCA) facility in Tacoma, WA.

Current Technology

The current technology at Zoltek is to produce a low cost 50K carbon fiber tow. Zoltek believes that in most markets, including automotive, that cost will play a very important role. Especially in a prepreg product for compression molding where the carbon fiber can account for >70% of the material cost and likely >50% of the final product cost.

Further Development

Zoltek is continually seeking to drive down the cost of producing carbon fiber and improving the quality of our 50K tow product. There are also project in place to develop new sizing chemistry technology for improved adhesion and performance in both epoxy and vinyl ester composites.

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Web Site: www.ZOLTEK.com

Reichhold LLC2 is a leading resin manufacturer, specializing in the composites and coatings markets. Reichhold enjoys a global footprint, with 19 manufacturing sites and 5 Technology Centers, located in 12 countries. Reichhold has a nearly ninety year track record of innovation in thermosetting resin and coating markets, on a broad, international basis. Over the past thirty years, Reichhold has supplied several unsaturated polyester and vinylester resins into the automotive composites market. These resins have historically been used by SMC & BMC compounders and fabricators, to produce many different structural, "under-the-hood" and Class A automotive composite components. As a result, Reichhold has extensive experience, know-how, and industry contacts within the automotive market.

Through October 1, 2016, for Phase I of the IACMI / Toray SEAHAWKS Project, Reichhold has contributed about $30,000 (direct cost), for tooling modifications, raw resin materials, formulation support to TCA, compression molding (of four different prepregs) and analytical testing, versus an original commitment of $15,000. The project has required more Technical support and testing than was originally planned.

Current Technology used in making Cost-Effective, Light Weight Automotive Parts

Reichhold currently supplies snap-curing **ADVALITE™** Vinyl Hybrid resins for use in the Chevrolet Spark and Corvette programs. Vinyl Hybrid resins are monomer-free, styrene-free systems that use a free radical mechanism for cure. **ADVALITE™** Vinyl Hybrid technology enables fabricators to utilize "snap curing" processes (i.e., press molding in 60-90 seconds) that are based on prepregs, resins and molding compounds that do NOT require refrigeration, either in shipping or storage.

The Chevy Spark composite battery tray is manufactured using a fiberglass mat prepreg made with a "hot melt" version of **ADVALITE™** Vinyl Hybrid resin. The 40 kg battery tray is compression molded in two parts, using oil-heated, matched metal tools kept hot, at 150° C. The unique resin chemistry allows pre-stacked layups (3mm thick) to be loaded into hot presses, cured completely (using dielectric sensors in each mold), in less than 90 seconds, and then de-molded "hot", which dramatically shortens overall cycle time, and allows rate production of hundreds of thousands of parts per year. Composite sandwich main floor panels for the Chevy Corvette are also compression molded, using a liquid version of **ADVALITE™** Vinyl Hybrid resin that is injected into a dry preform made of fiberglass mat and low-cost core material. These panels are also snap cured, in a process that allows very rapid production cycles.

Phase I - Applying ADVALITE™ Technology to other Fiber Forms and Processes

Based on success using Vinyl Hybrids in fiberglass prepregs and liquid injection molding, Reichhold recently introduced these fast-curing, room temperature storage resins into additional markets, on other forms of carbon fabrics, and carbon roving, for making composite structures that are a) vacuum-bag molded, b) filament wound, c) infused into dry carbon preforms, and d) processed into carbon SMC. As a result, **ADVALITE™** resin systems are now being used on woven carbon prepreg fabrics, unidirectional CF prepreg tape, and in innovative carbon SMC formulations, with applications in aerospace, defense, energy, communications, recreation and other industrial markets. Like the FAC-05 and 06 prepregs made at TCA, many of these systems are blended and formulated with special additives to achieve specific goals for viscosity, tack level, toughness and performance at various temperatures.

With completion of Phase I of the SEAHAWKS Project, Reichhold is confident that low-risk carbon prepregs and SMC made with **ADVALITE™** Vinyl Hybrid resins will produce high quality, high strength automotive parts that provide dramatically faster manufacturing cycle times versus known epoxies. The goal for Phase II will be confirmation of the fastest possible cycle times on larger, more realistic panels.

719 Metcalf Street
Sedro-Woolley, WA 98284

TO: Felix Nguyen
FROM: Andy Bridge
SUBJECT: Janicki Introduction
DATE: 10-10-2016

Janicki Industries Inc.

Janicki Industries is a privately owned Engineering and Manufacturing company, specializing in advanced composite materials and exotic metals, with large-scale facilities and high precision equipment that produces tooling and parts for a myriad of industries ranging from aerospace, marine, defense, transportation, space and infrastructure. Janicki was established in 1993 with 1.5 employees and $25,000, and today employees 690, of which 140+ have engineering degrees. Janicki has successfully developed a rapid Heated Composite Light Tool (HCLT) technology to cure prepreg material out of autoclave. Heating is achieved by integrating a structural carbon layer as a conductive heating element which reduces cost over conventional heating systems. Using a thin composite shell tool has the added benefit of a low thermal mass when compared to metal resulting in fast ramp rates with low energy usage. By applying heat directly to the HCLT coupled with the low thermal mass, ramp rates up to 200°F/min can consistently be achieved. The HCLT can also be utilized as a lay-up tool, vacuum forming tool and a cure tool in one for less than half the cost of a metallic approach.

Limitations are surface finish (print) and longevity (durability for high cycles). Potentially these limitations are overcome with non-cosmetic critical parts (hood liner, floor panels, etc.) and the low cost to repetitively fabricate low cost disposable thin shell tools that utilize a common vacuum chuck.

An ideal application may be for preform tooling using vacuum pressure only (<2 bar) as surface finish is not critical, pressures are low and temperatures are typically not as high. Multiple HCLT tools could shuttle between ATL/ATP prepreg laydown, preforming stages, and final molding press all in a highly automated work cell.

END

GLOBE
MACHINE MANUFACTURING COMPANY

September 20, 2016

IACMI/0007-2016/3.3

DE-EE0006926

IACMI PROJECT: Rapid Carbon Fiber Prepreg Molding Technology for Automobile Structural Parts – SEAHAWKS

GLOBE MACHINE MANUFACTURING COMPANY: INTRODUCTION

Globe Machine is an innovative supplier of engineered, custom-designed and built, fully-integrated composite manufacturing and material handling equipment.

Globe Machine serves automotive, aerospace, defense and industrial customers with patented RapidClave2® technology for highly accelerated out-of-autoclave composite curing.

Globe Machine also offers automated tape/fiber placement technologies and unique, creative material handling and process solutions for both thermoset and thermoplastic composites.

For almost 100 years, Globe Machine has produced automated production systems for high-volume, cost-sensitive industries with all services located under one roof.

SEAHAWKS PROJECT: GLOBE MACHINE MANUFACTURING COMPANY: TECHNOLOGY CONTRIBUTION

In this project, Globe provided RapidClave2® machine-time and other resources to facilitate cure of material-sample plaques made from CF/Epoxy prepreg and CF/Monomer-free Vinyl Ester prepreg materials.

The Globe RapidClave2® creates controlled-heating temperatures to 550° F, 200 psi pressure, 28 inches of vacuum, and rapid cooling. Temperature-rise rates of 50° C/minute are possible, with full control over ramps and dwell-times as needed.

With RapidClave® control of heating, cooling, pressure, and vacuum conditions within the curing tool, Globe attains uniform void-free resin-cure results in about 6-minutes.

Physical-property evaluation of cured plaques shows performance equivalent to that obtained by longer conventional autoclave cures. Also, surface-finish properties approximating “Class A” quality were demonstrated.

This technology has already been proven in a production setting where 50,000+ part-sets a year are made supporting a major automotive program, replacing conventional autoclave technology.

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GLOBE LABORATORY RAPIDCLAVE2®

GLOBE RAPIDCLAVE3®: CONTINUING TECHNOLOGY IMPROVEMENTS

As Globe Machine Manufacturing Company improves on the original RapidClave® concept, there are ready plans to employ faster, more-controllable heating and cooling methods while supporting better surface-finishes, energy conservation and waste-reduction.

Improved tooling materials, design and construction will allow making more-complex shapes. Automated fiber/tape placement technology will reduce touch-labor and lay-up errors, contributing accuracy to the process. Between process technology and Globe material-handling expertise, rapid and economical automotive composite assembly production becomes possible.

CRTC
COMPOSITE RECYCLING TECHNOLOGY CENTER

2220 West 18th Street, Port Angeles, WA 98363

Company Overview: The mission of the CRTC is to inspire and grow the global composite recycling community through innovation in technology and manufacturing that transforms carbon fiber scrap into products that positively impact people's lives and our environment. Toward that end the CRTC started operations with equipment donated from Profile Composites and materials donated by Toray Composites America and moved into a 25,000 ft^2 purpose-built facility in August of 2016. Their first commercial product was launched in November 2016 utilizing compression molding technologies with scrap TCA aerospace carbon/epoxy pre-preg. The CRTC will continue to focus on new product development and launch and has 4 additional products in the pipeline for 2017, including two in transportation applications.

Contribution to "Seahawks" Project: The CRTC's contribution to the Seahawks project was to provide experimental molding with both continuous and chopped formats of scrap pre-preg that was generated in the molding sample panel trials. CRTC's compression molding trials used a high-temperature hot-platen press (from Wabash-MPI), and proved that very low void content could be achieved at a 6-minute cycle time. The CRTC additionally generated input for the project on potential cost reductions to a large volume automotive component through utilizing the scrap in non-appearance internals.

Current Technology: The current technology at CRTC consists of compression molding at sizes up to 60" x 30" 650F platen presses, waterjet trim and 5-axis machining, and large oven/vacuum bag operations. The CRTC additionally has complete steel tool-making in-house and will be outfitting one or more of the presses with Roc-Tool induction heating systems for rapid cycle times.

Further Development: CRTC is expanding both the size and volume of the pre-preg scrap usage into value-added products, and is engaged in several transportation application developments at this time. Systems capability to handle up to 500 TPY is planned during 2017, and we are partnering with IACMI for development that would support high-volume automotive manufacturing (using pre-preg) with systems designed to capture and reuse all scrap internally in a vertically integrated operation.

American Composites Manufacturers Association

YOUR VOICE. YOUR RESOURCE. YOUR ASSOCIATION.

Date: December 19, 2016

From: Tom Dobbins, President, ACMA

ACMA Overview

The American Composites Manufacturers Association (ACMA) is the composites industry's largest trade group in the world. The American composites industry is made up of approximately 3,000 companies.

ACMA provides a forum for members of the composites industry to come together to develop shared market opportunities and deal with common challenges. It is recognized as an unmatched source of up-to-date information about the composites industry as well as the premier provider of educational resources relating to the field.

ACMA advocates for the interests of the composites community, proactively and positively affecting regulatory and legislative outcomes on a wide range of policy issues, including energy and environment, worker health/safety, trade policy and job creation. ACMA works to develop and expand markets for composite products in the U.S. and around the globe.

Contribution to "Seahawks" project

ACMA provided support to organize project team meetings, to bring members into the project, and to provide outreach into automotive OEM's to get feedback and support.

Further Development

ACMA supports the continuation of this project with the support of an end-user/OEM. We are reaching out to possible collaborators to create market pull for the technology developed.

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Michigan State University Capabilities and Facilities

The Vehicles Application Center is organized around Michigan State University (MSU) Composite Materials and Structures Center and the Composite Vehicles Research Center as well as the Composites Manufacturing Scale-up facility (SUF) in Detroit, Michigan. The SUF facility is being staffed with composite manufacturing experts and will house state of the art equipment at production scale for industry-defined processes (e.g., HP-RTM, injection overmolding, prepreg stamping/forming, etc.) with flexibility to accommodate glass and carbon reinforcements, and thermoset and thermoplastic matrices. MSU houses smaller pre-manufacturing facility for liquid molding, injection molding, lay stitch fiber preforming and compression molding on-site at MSU to develop process and manufacturing protocols to be the basis for manufacturing scale-up. In addition the MSU facility has a full time technical staff and extensive fabrication, processing, characterization and analysis instrumentation for composite materials.

Areas of expertise include polymer composite processing and modeling; process development, modeling and manufacturing of liquid resin systems; additive manufacturing of thermoplastic composites; multifunctional composites (nano-particles); composite joining adhesive bonding and reversible thermoplastic adhesive bonding; mechanical fastening and bolt design; surface treatments and sizing of reinforcing fibers and adherents; bio-based structural composites; modeling and structural analysis (static, crash, impact, fire, fatigue); dynamic characterization and design; NDI, NDE in-situ and remote sensing; design and manufacturability; and modeling and simulation of liquid molding and thermo-hydroforming. Recent relevant technology developed at MSU includes: a robust, 60-second UV carbon fiber surface treatment; design optimization software (HEEDS-MDO) for structural optimization of composites commercialized in 2013 by CD-Adapco; invention and commercialization of multifunctional graphene nanoplatelets for modifying the mechanical, thermal, electrical and flammability properties of composites (XG Sciences, Inc.); new low-cost NDI sensors with high sensitivity for composite flaw detection using electromagnetic (magnetic flux, eddy current, microwave)

methods; process simulation models for vacuum bag–autoclave cure, thermoplastic composite consolidation, filament winding, advanced fiber placement, injection molding, compression molding and sheet forming and including liquid molding processes such as RTM, VARTM, and RFI using commercial codes; models for extrusion of long chopped fiber thermoplastic compounds; improved models for prediction of fiber attrition during melt compounding, extrusion, and injection molding; a patented mechanical fastener with polymer inserts for joining composites.

In this TORAY COMPOSITES AMERICA Phase 1 project, MSU conducted the testing and evaluation of the composite panels manufactured by the five different methods. The testing and evaluation included: composite panel sample preparation and measurement of the Flexural, Tensile, Compression and Interlaminar properties; failure surface documentation using microscopy; Thermal Analysis using Differential Scanning Calorimetry (DSC); NDI inspection using C-scan and microscopy for void presence and origin; surface characterization using Profilometry and Wave Scan;

IACMI Project #PA16-0349-3.3-01

October 14, 2016

This document can be used by Dr. Felix Nguyen, Principal Research Scientist at TCA, for his presentation on the "Seahawks" project, looking at Rapid Prepreg Molding for Automobile Structural Parts.

Company introduction

Created in 2000, RocTool is a Technology & Manufacturing solutions provider offering Engineering services and systems. RocTool induction process is fully adapted to composite molding and plastic injection, including multiple configurations to fit with tier manufacturer's requirements. RocTool's Research and Development team is constantly adapting the technologies to more materials including metal.

As a Heat and Cool technology leader, RocTool offers now **Light Induction Tooling™** to composite part suppliers and **High Definition Plastics™** capabilities to plastic molders. The processes developed by RocTool are used in production by major brands in innovative industries such as automotive, aerospace, consumer products & electronics. They hold many advantages including reduced cycle times, surface quality, light-weighting and performance, therefore resulting in an overall cost reduction of the produced parts for manufacturers.

RocTool is listed on the Alternext Paris stock market. Its headquarters and R&D center is situated at Le Bourget du Lac (France). RocTool also has offices and molding platforms in North America, Japan, Taiwan and Germany.

Current technology used in the project

"Resulting of 3 years of R&D, the Light Induction Tooling™ (LIT™) will allow RocTool to develop its offer in key segments, such as **aerospace, automotive and transport**" explains Mathieu Boulanger, RocTool CEO.

The LIT™ technology is fully adapted to thermoplastic and thermoset composites; it enables **the production of very large parts** and allows manufacturers to improve their existing production capabilities.

RocTool LIT™ addresses OEM challenges to make **cost effective composite parts with quick cycle times**. LIT™ technology does not require any compression press machines or special large forming press that only few manufacturers can afford globally. A light tooling structure integrates RocTool state of the art induction heat technology and is connected to RocTool Performance Cooling units.

"With this new **Out Of Press and Out Of Autoclave** (OOA) technique, manufacturers can now increase their capabilities without investing in large tonnage machines and the OEM can extend their supply chain for such composite parts. Making large composite parts without compression machines, with light tooling configurations and precise temperature control is a game changer" says Mathieu Boulanger.

With this new innovative process, RocTool reduces the thickness of the tools; and shortens the heating and cooling times achieving cycles below 3 minutes for various materials. The LIT™ enables an **accurate control over heat ramps**, from very fast heating to defined heat rates for aeronautical certified resin systems which require an overall longer cycle.

"The energy cost is very low and we obtain an exceptional return. Globally speaking, this new RocTool process allows the end user to obtain **massive energy savings** compared to conventional manufacturing processes! For the JEC World demo mold, the energy consumption remains below 2 kW.h, and a cost per part below 15 cents, therefore much less than using an autoclave." highlights Dr. Jose Feigenblum, RocTool CTO.

Future improvements of the technology

Since its release on the market, the collaboration between RocTool and KTX continues in order to widen the range of LIT™ solutions, with different induction and tooling technologies. A few tooling materials are considered and being optimized by the engineering teams, since the **turn-key solution is offered as custom** to exceed OEM's requirements. Based on their experience from LIT™ productions, RocTool processing experts can now provide a thorough technical evaluation for each application, considering part's size, the complexity of the geometry and the common process parameters for the selected material.

KTX Corporation

Corporation

Profile

Head Quarter: Konan Aichi (Japan)
Oversea Bases: Detroit (USA), Bangkok (Thai), Seoul (Korea), Shanghai (China)
Main product: Ni Electroforming
IMG mold, Slush mold, Injection mold, Compression mold
Vacuum forming machine, Mold carrier
Website: www.ktx.co.jp

For SEAHAWKS project

Mold for LIT (Light-Induction Tooling), Mold carrier and Molding

10/25/2016

Chem Trend
Release Innovation™

Dr. Felix Nguyen
Toray Composites America, Inc.
19002 50th Ave. E
Tacoma, WA 98446

IACMI Project Phase I Final Report

Company Overview

For more than 50 years, Chem-Trend has been a global leader in the development, production and supply of specialized mold release systems. We have a singular focus on developing mold release systems and because we are so focused, we can deliver exceptional value, performance and dependability in all we do. Chemlease® and Zyvax®, Chem-Trend brands, offer a complete range of mold release systems developed to improve composites molding processes. Our superior products are rooted in our manufacturing and technical expertise, understanding of molding operations, deep insight and specialized laboratory resources. Our expertise goes well beyond just the products that we develop and manufacture, it reaches into the production processes of the industries that we serve. Each year, we spend thousands of hours on the plant floors of composites processors, giving our technical experts insight into the industry's toughest production challenges. In our world-class laboratories dedicated to the composites industry, we apply this insight to developing solutions that improve your operating efficiency.

Contribution to IACMI Project Phase I

Chem-Trend has supported Phase I of the IACMI project in the following ways:

- Provided technical insight on product selection considerations for mold release systems based on:
  - Process: Compression Molding vs. Rapid Clave
  - Material form and chemistry: Prepreg vs. SMC, Epoxy vs. Vinyl Ester
  - Tool medium: Chrome finish, Tool Steel, Aluminum, etc.
  - Molding temperatures
  - Cycle times
  - Spray equipment and investment level
  - Post finishing requirements prior to painting and secondary bonding
  - Release System Component Mix: External mold release, internal mold release, sealers, etc.
- Furnished various IACMI partner facilities with product samples for continued testing, evaluation and process optimization.
- Generated analytical data pertaining to :
  - External mold release transfer data
  - Internal mold release thermal property characterization

Toray Carbon Fibers America, Inc.
P.O. Box 248
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Decatur, AL 35602-0489
TEL : (256) 260-2626

Toray Carbon Fibers America was incorporated in 1997 and began production of Torayca® brand carbon fibers in 1999. The production facility in Decatur, AL was designed specifically for fiber production and has expanded to a multiple line facility with approximately 7900 MT/year capacity. The fibers produced at our facility services the aerospace market as well as a variety of industrial and recreational applications.

Toray Carbon Fibers America is pleased to support the Seahawks project by providing continuous filament carbon fiber tow as well as technical support from our Technical Center which is also located at the Decatur, AL plant site.