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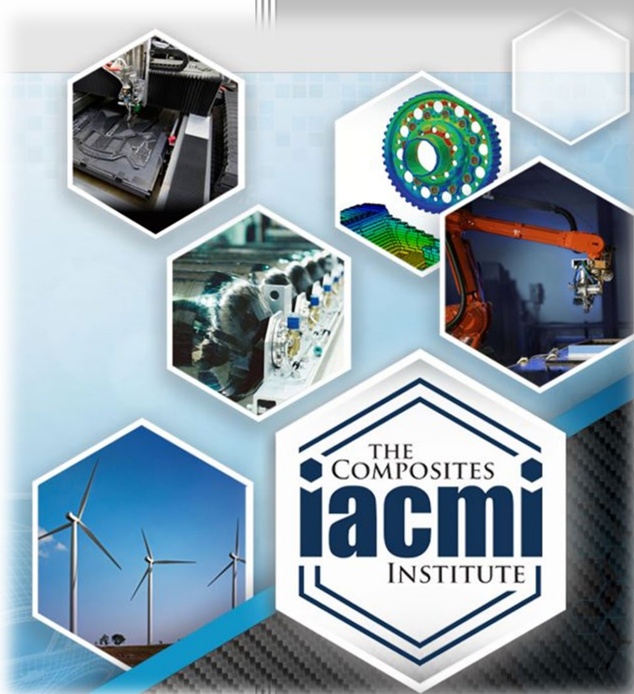
5.4 Injection Overmolding of Continuous Carbon Fiber Preforms



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Injection Overmolding of Continuous Carbon Fiber Preforms

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List of Acronyms

ASTM	American Society for Testing and Materials
CAD	Computer Aided Design
CTE	Coefficient of Thermal Expansion
FEA	Finite Element Analysis
FST	Flame Smoke and Toxicity
FVC	Fiber Volume Content
GNG	Go No Go
PAEK	Polyaryletherketone
PEEK	Polyetheretherketone
PEI	Polyetherimide
PP	Polypropylene
PPS	Polyphenylene sulfide
TFP	Tailored Fiber Placement
VF	Volume Fraction

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Acknowledgements

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1. EXECUTIVE SUMMARY

This project explored and developed a process to injection overmold continuous carbon fiber preforms fabricated with tailored fiber placement. Much early work was focused on the ability to infuse dry carbon fiber tow, fully wetting out the fibers, in an injection molding process. Various approaches were explored, including using commingled fiber and pre-consolidated flexible preforms. The commingled fiber was a blend of carbon fiber and polymer fiber matching the injecting polymer. This approach showed some merit but required an extremely high quality homogeneous mixing of the polymer fibers with the carbon fibers to wet out the carbon fiber tow. Therefore, the project focused on pre-consolidated preforms.

The pre-consolidated preform manufacturing method was first developed using compression molded flat plates that were cut into tensile specimen for testing. Work then progressed to an injection molded simplified corner fitting bracket. It was shown that a viable manufacturing method for overmolding continuous carbon fiber preforms could be developed.

2. INTRODUCTION

Traditional plastic injection molded parts lack the mechanical properties and durability to be used in highly loaded structural applications. This project focused on the development and commercialization of a new injection overmolding process as an improvement to current processes to enable low cost, lightweight, structural composite parts. The proposed technology incorporated dry fiber preforms, manufactured with tailored fiber placement (TFP) technology, into the injection molding process with the objective to make highly loaded structural thermoplastic composite brackets with cost and cycle time targets attractive to the aerospace industry. With further modifications, this technology also has direct application to automotive manufacturing, transferring a high-volume manufacturing process from one industry to another.

The enabling technology for the proposed overmolding process was TFP preforms. The approach was to take advantage of TFP to build a highly fiber-aligned preform that has built-in resin distribution channels to allow resin to flow unrestricted through the preform. This allowed thermoplastic resin to permeate the preform and surround each individual tow. As pressure built in the mold, the resin wet-out each tow from the entire external surface, drastically decreasing the distance resin must flow through carbon. In addition, z-stitching in the preform held tows in place and helped to prevent fiber wash during the injection.

3. BACKGROUND

Traditional plastic injection molded parts lack the mechanical properties and durability to be used in structural applications. The feedstocks contain short, discontinuous fibers that only modestly increase the strength and stiffness of the component. The mostly random distribution in the injection molded part guarantees that a large percentage of the fibers are not aligned in the direction of the loading of the component, thus failing to take advantage of their full strength. The fiber length further limits the load that the component can carry. Although some fiber alignment may occur during resin injection, it does not align fibers cross-flow, limiting how a part can be reinforced and making it difficult to control the fiber orientation.

Alternative processing methods address the shortcomings of traditional injection molding. One process, known as insert overmolding, uses a pre-impregnated insert that is loaded into the injection molding die prior to injection. The insert is reinforced with oriented fiber and made with a separate molding process. During injection, molten resin flows over and around the insert, creating a single component that features oriented fiber reinforcement. Newer technologies, such as the Organomelt system from Engel, utilize a thermoplastic prepreg that is heated and formed to an initial shape, then overmolded with molten resin.

Both of these methods successfully introduce aligned, long fibers into injection molded parts, but they fail to do so at the low costs and cycle times desired by automotive and aerospace manufacturers. In insert overmolding, a second manufacturing process is required to consolidate the insert. This adds additional cost, requires longer cycle times, and potential supply chain issues. Overmolding technology like Organomelt requires expensive, specialized equipment and uses costly thermoplastic prepregs. It also fails to take full advantage of fiber alignment since the prepregs are unidirectional or biaxially woven and cannot be entirely aligned with the load path of component. Both overmolding operations also have technical challenges to overcome, such as good bonding between the preconsolidated insert/prepreg and the injected polymer and coefficient of thermal expansion (CTE) mismatch between the injected polymer and the carbon fiber.

ENGEL, a global leader in injection molding equipment, has worked on several hybrid injection molding processes[1]. Previous attempts by industry to fully wet-out dry preforms during the injection molding process have failed. However, these have been done with preforms not readily suited for thermoplastic processing. They have featured woven or uni-directional fabrics stacked to fill most of the injection mold cavity.
These fiber stacks act as a dam to the high viscosity thermoplastic resins, race-tracking the resin away from the preform rather than through it.

The goal of this project was to advance the injection overmolding process to include dry, carbon-fiber TFP into the mold and inject a carbon fiber filled Polyetherimide (PEI) thermoplastic. The PEI family of amorphous thermoplastics has high temperature stability, good flame, smoke, toxicity (FST), and heat release properties. The results expected were a manufacturing methodology for strength and stiffness optimized small parts (brackets) with minimal material waste, lower part weight, and costs. This manufacturing cycle time is greatly reduced compared to traditional autoclave-cured parts, and the embodied energy costs will be reduced due to the net-shape performs implemented. A targeted cycle of time of 3 minutes or less will be the goal once the technology is proven to produce quality parts.

The initial parts (brackets) targeted aerospace applications. Current aerospace brackets are either formed aluminum or titanium. Various clips and cleats are fabricated from carbon fiber reinforced (FVC = 55%) PPS organosheets via hot-press forming. Other candidate parts for this technology, such as corner fittings, are machined aluminum. These are the materials and manufacturing processes that this project targeted to replace.

Existing injection molding solutions (e.g. short fiber reinforced PEI with 40% wt. carbon fiber filled) served as a baseline for comparison for this injection overmolding technology for airframe structures. The technology developed will potentially transfer to other vehicle markets or industries requiring high strength, low cost brackets or other structural parts. This project contains partners that have strong presence in these other markets as well and are therefore well placed to support translation of this technology beyond the aerospace market.

4. RESULTS AND DISCUSSION

The project was initially broken into three main tasks, each containing several milestones. First, the project focus was on flat plate geometry with low melt temperature polymers. Then the complexity of the geometry was increased to a simple bracket. The last task took those learnings and applied them to even more complex geometry with higher melt temperature polymers and applicable manufacturing processes.

However, after considerable work had been done, the project was re-scoped in order to streamline the effort and prevent work being performed that would not be applicable to the final objectives of the project. This re-scope broke the project up into two main tasks. Both tasks used the same high melt temperature polymer. The first task focused on compression molded flat plates and then final task used a simplified injection molded bracket geometry provided by Airbus.

4.1 Initial Work

Much of the initial work on the project focused on options available to place TFP preforms into injections molds, holding them in place during the injection cycle, and fully wetting out the fiber bundle of the continuous carbon fiber.

4.1.1 Holding Tailored Fiber Placement Preforms in Injection Molding Tool

A significant amount of work was done determining how to hold TFP preforms in place during injection molding. As shown in Figure 1, early preforms were very simple straight rows of dry carbon fiber with thick sections of built up tow on two edges. This build up was intended to be clamped between the tool halves to hold the preform in place during the injection molding cycle.

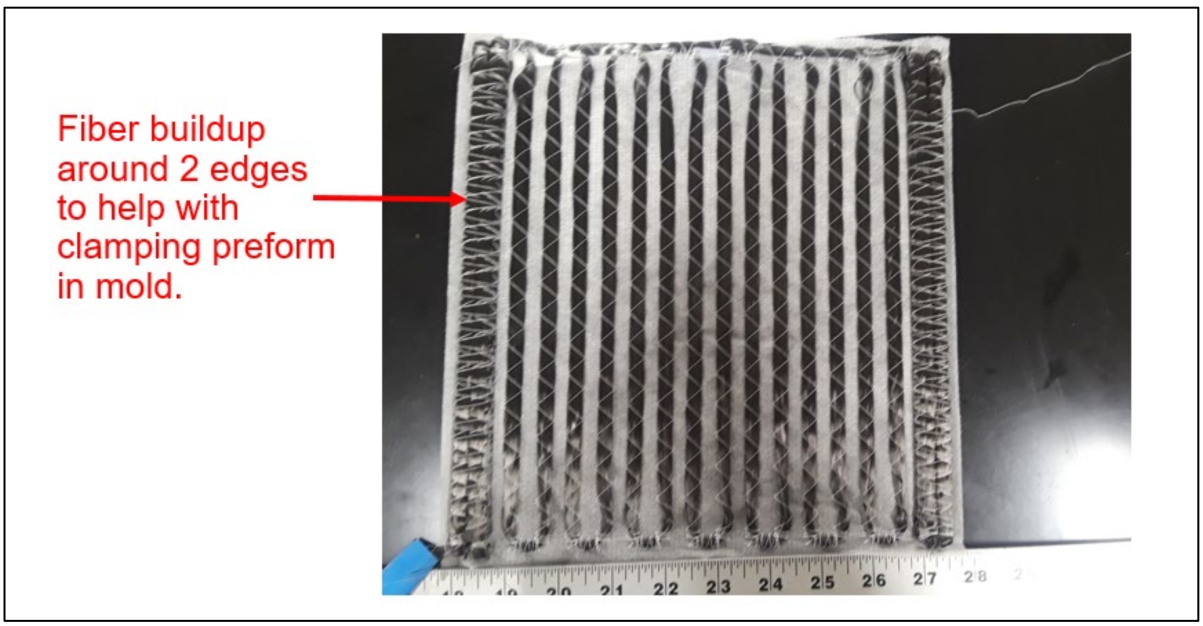


Figure 1 - Initial TFP Preform Design

Preform backing materials varied using polypropylene film, woven fiberglass, and non-woven nylon fabric. Carbon fiber tow was also varied using Zoltek 50k tow sized for polypropylene as well as 12k carbon fiber tow that Concordia Fibers commingled with polypropylene fiber. All preforms were stitched using polyester thread on the Tajima TFP equipment at UDRI.

When these early preforms were placed into a flat plate injection mold and overmolded with a high flow polypropylene (Sabic FPC100), the continuous carbon fiber tows and backing material were washed to the far end of the tool away from the injection molding inlet gate. This varied from part to part based on the backing material, but none were sufficient (Figures 2) to avoid distortion. The parts also had a great deal of warpage due to the carbon fiber being pushed to one side of the part and not held in the mid-plane of the molded geometry.

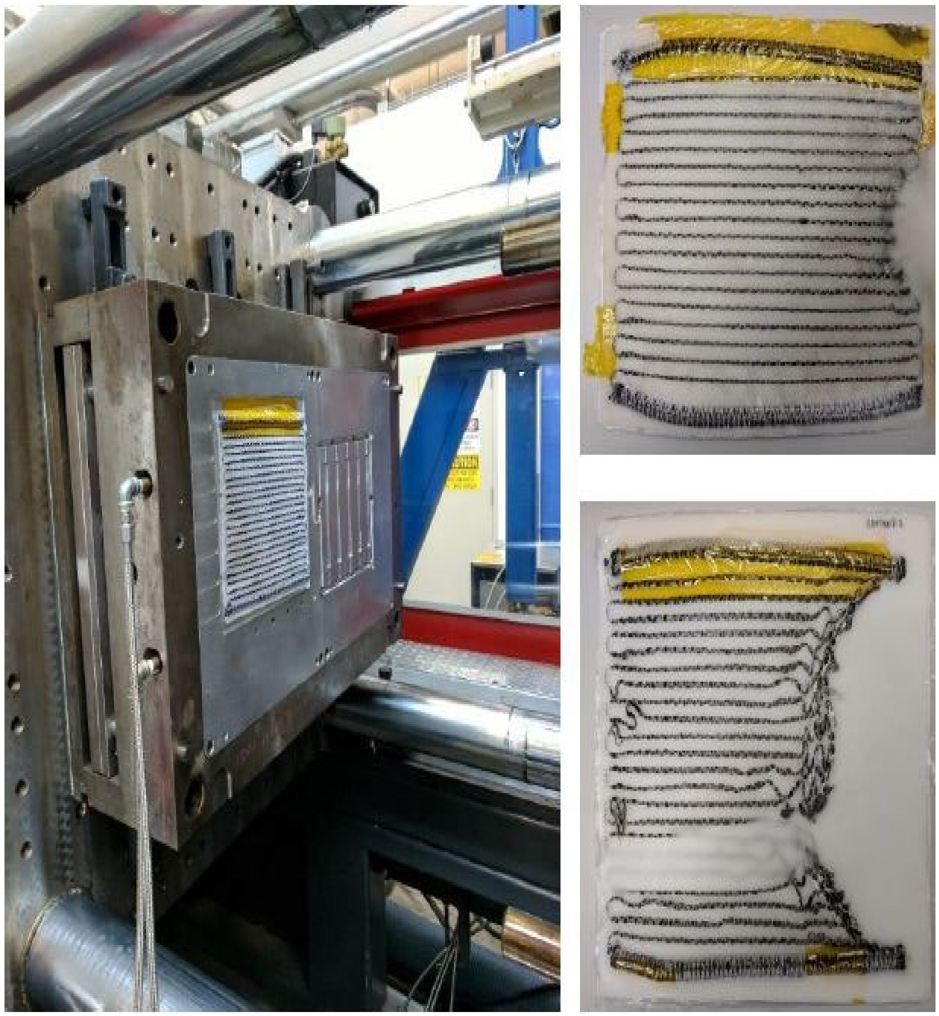


Figure 2 - Preform Placed in Injection Mold (Left), Preform Shift / Fiber Wash Caused by Injection Molding (Right)

A method for holding the preforms during the injection cycle needed to be designed into the injection molding tool. UDRI developed a small tool insert (Figure 3 and Figure 4) that allowed for the preform to be held centered in the part by the perimeter of the preform that extended beyond the injection molded part. This small insert tooling approach also allowed UDRI to iterate much more easily to determine the best method to hold the preform during injection molding.

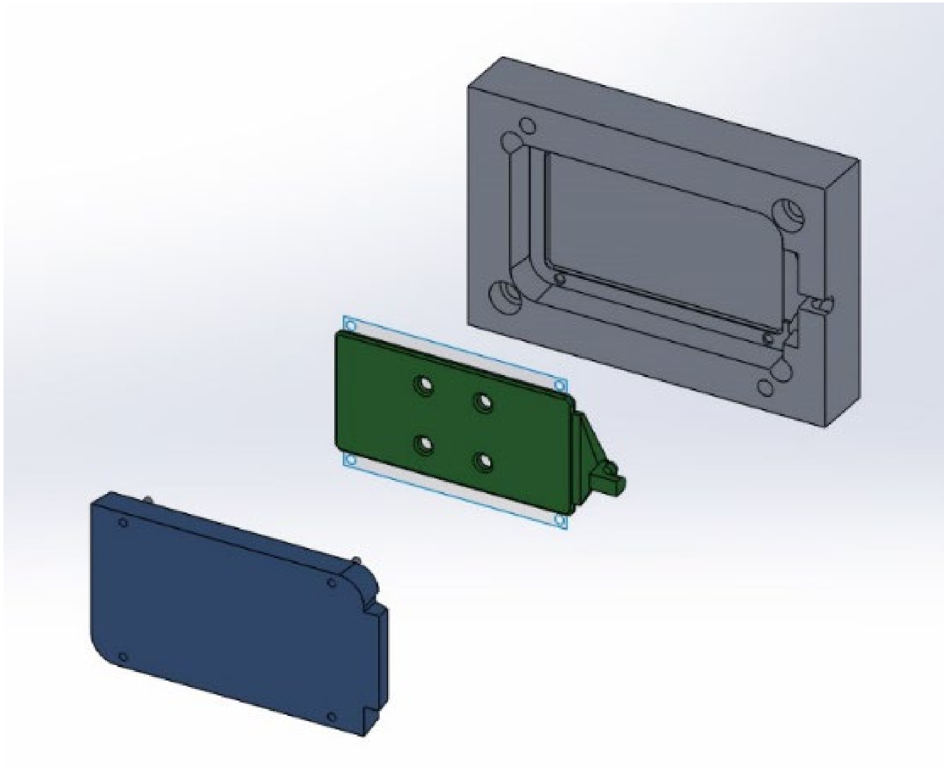


Figure 3 - Small Insert Tool

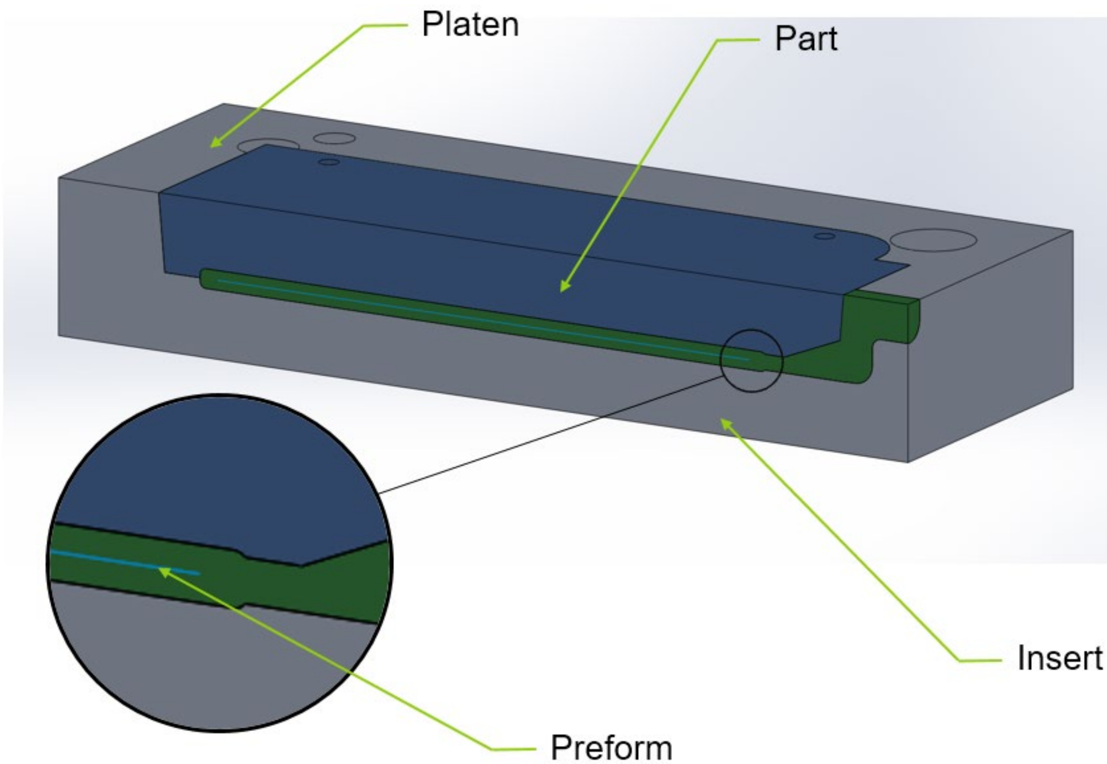


Figure 4 - Cross Section of Small Tool Insert

Small simple preforms were designed and made using several different backing materials and carbon fibers tows (Figure 5 & 6).

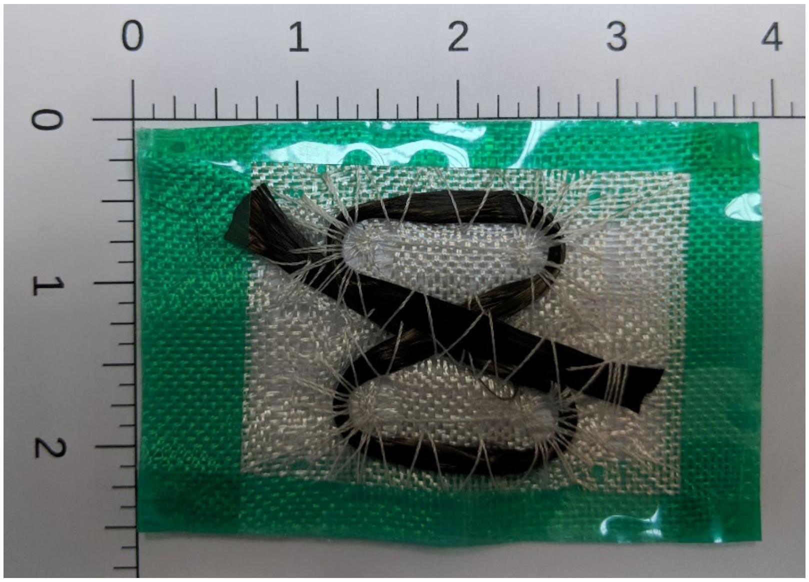


Figure 5 - Small Preform Design

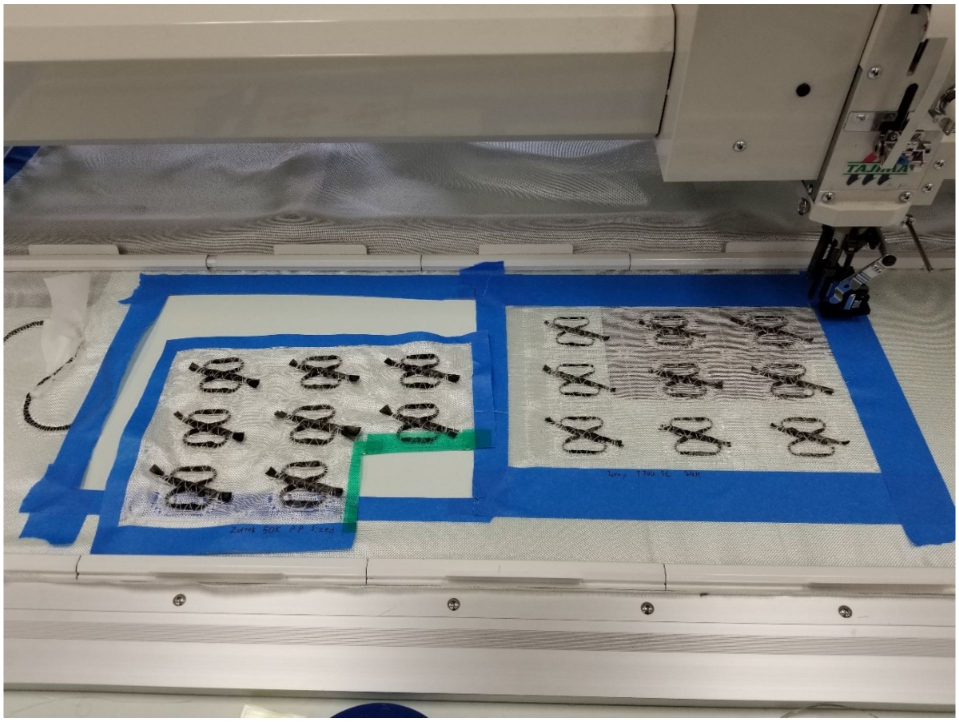


Figure 6 - Multiple Small Preforms Stitched at Once

Table 1 - Various Constructions of Small Preforms

Tow Material	Backing Material	Thread material
Zoltek 50K PP Sized	5 Mil PP	Polypropylene
Zoltek 50K PP Sized	4 oz fiberglass	Polypropylene
Toray T700SC 24K	5 Mil PP	Polypropylene
Toray T700SC 24K	4 oz fiberglass	Polypropylene
TC 35 12K PP Comingled	5 Mil PP	Polypropylene
TC 35 12K PP Comingled	4 oz fiberglass	Polypropylene

When these preforms were overmolded, the flow front did not wash the preform to one end of the part as the previous trials had (Figure 7); however, the flow front did force the preform to one side of the tool. This occurred with both backing materials being used. Additional iterations to the tool would need to be considered to improve preform holding during the injection cycle. Additionally, new backing materials that impede flow less would be needed.

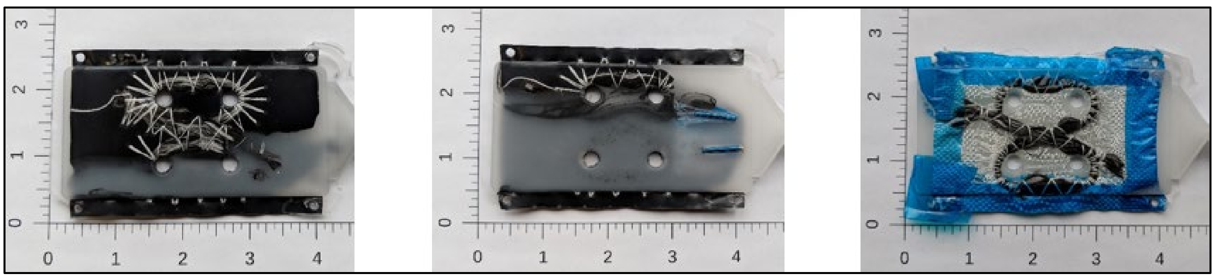


Figure 7 - Small Preform Overmolding Samples

Several additional designs were looked at that would involve a two-shot injection molding process. The first shot stiffened and gave more support to the TFP preform while being able to hold the preform in place in a more controlled manner. The second shot filled out the rest of the part geometry and finish the infusion of the dry fiber in one version (Figure 8). In the other version the fiber was infused in the first step (Figure 9).

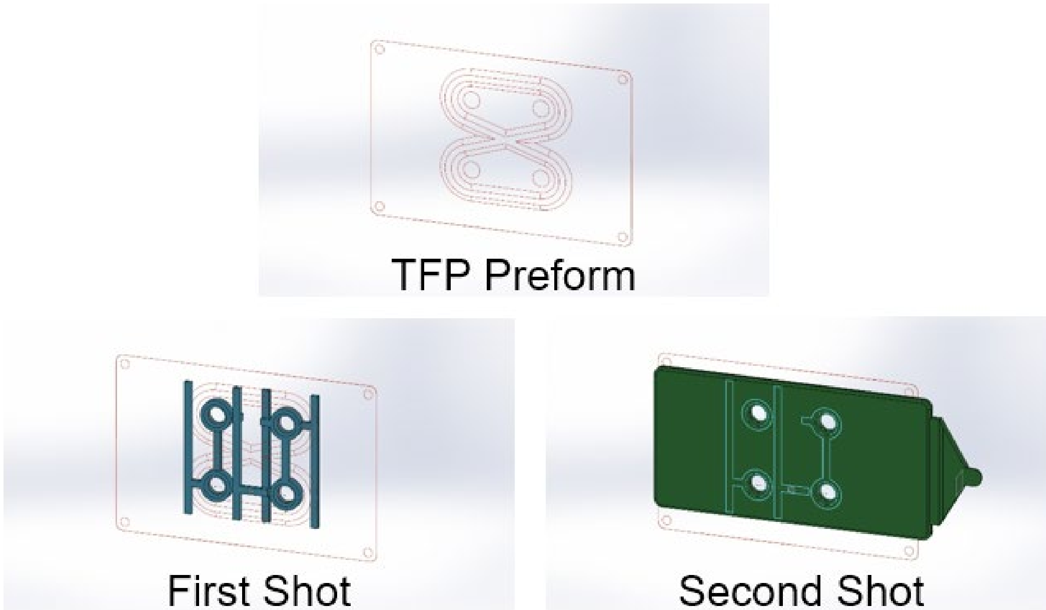


Figure 8 - Two Shot Tool Version 1: Fiber held in place by first shot creating a baffle system to help infuse fiber in second shot.

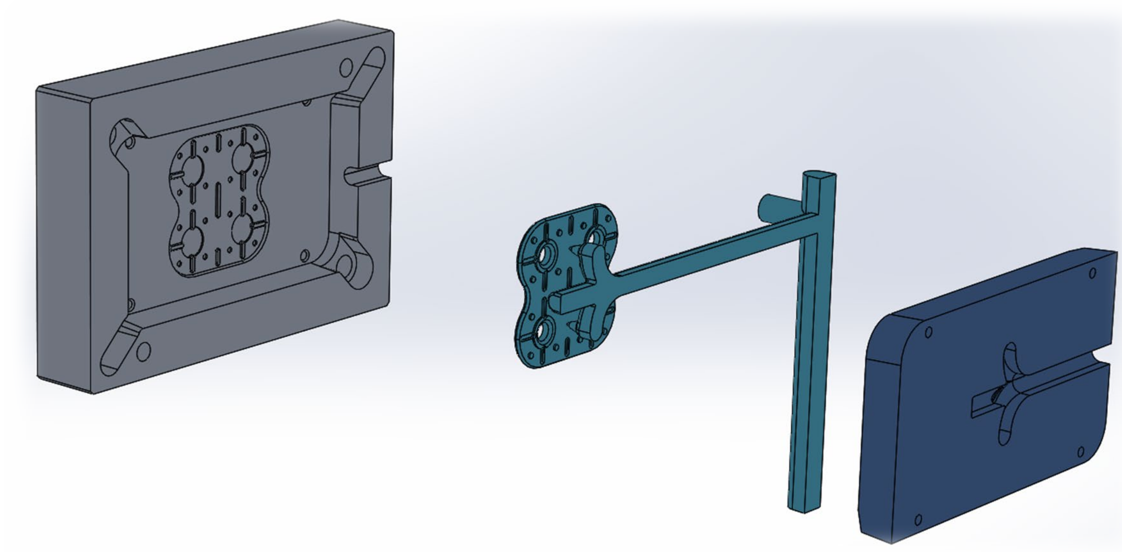


Figure 9 - Two Shot Tool Version 2: Fiber held in place by pins and bars in tool geometry

These preforms were also stitched to an open mesh polypropylene backing material (Airtech Greenflow 75). This allowed for the flow of the injection molding shot to not be blocked by the backing material allowing the preform to stay centered in the mold tool as intended.

The first tool version caused a lot of the carbon fiber to break due to the way the preform was held in the tool (Figure 10). However, the preform did stay in place much better than previous attempts.

Figure 10 - Injection Overmolded First Shot with Broken Fibers

The second version of the two shot tool (Figure 11 & 12) worked very well by holding the preform in place during the injection molding cycle.

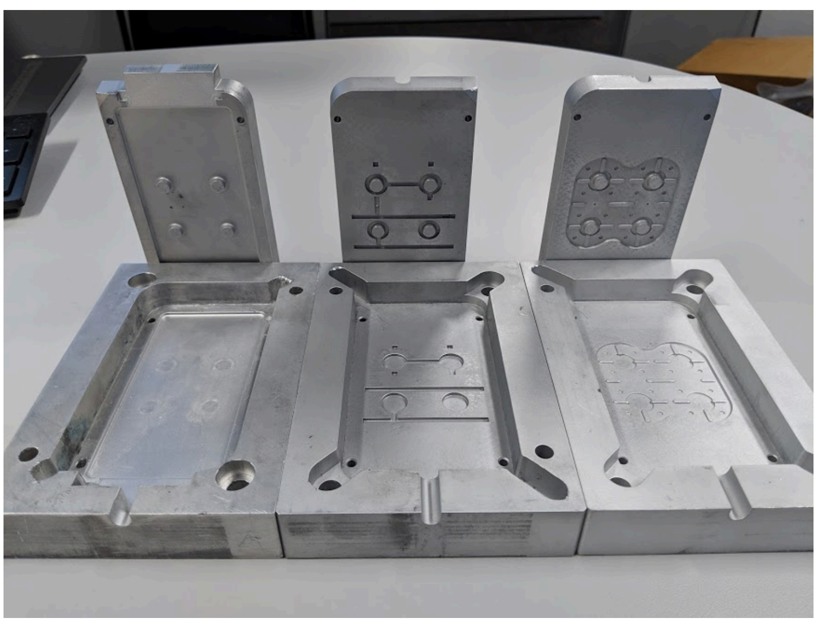


Figure 11 - Flat Plate Tool, 1st Shot Tool Version 1, 1st Shot Tool Version 2 (Left to Right)

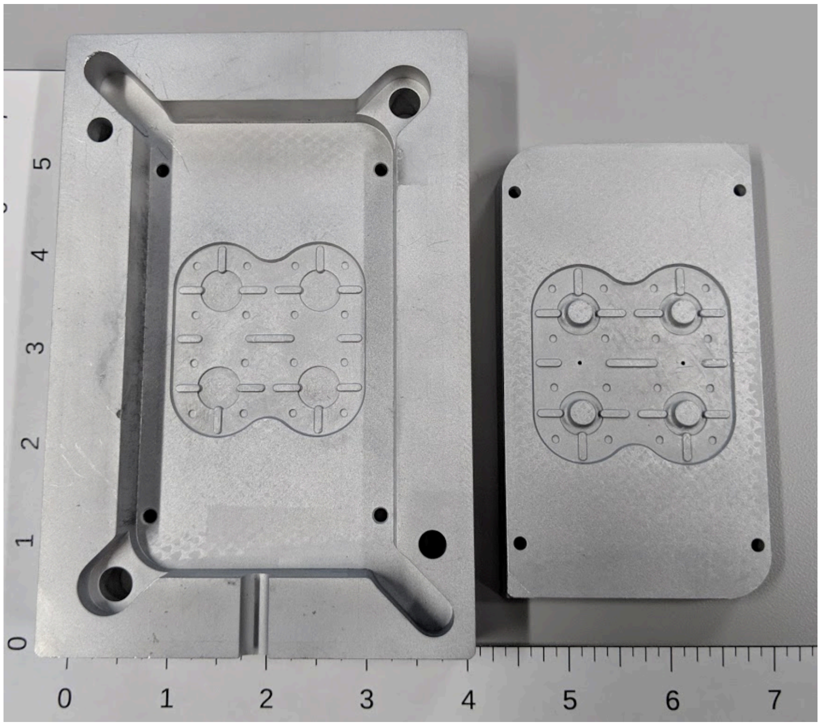


Figure 12 - 1st Shot Tool Version 2

The dual gate design of the tool (Figure 13) helped to fill the mold cavity effectively while keeping the fiber from moving much during the injection cycle.

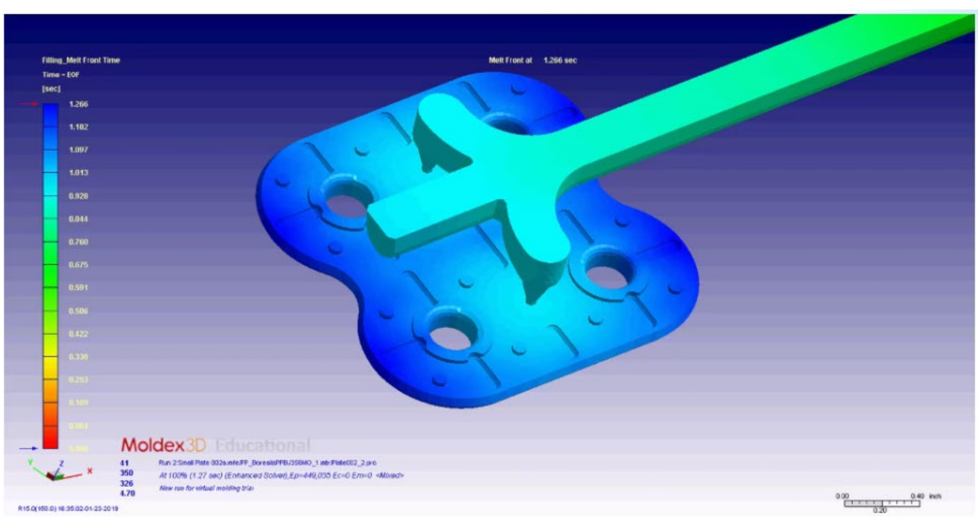


Figure 13 - Moldex3D Mold Filling Analysis of Injection Molding Tool Design

The results of this initial work led UDRI to design decisions for the Simplified Bracket (Section 5.3) tool design. Understanding how best to hold a flexible, or semi-flexible, TFP preform in an injection molding tool during the injection cycle was critical to completing later milestones in this project.

4.1.2 Dry Carbon Fiber Overmolding Infusion

Another challenge of this project was to determine if it was possible to infuse dry carbon fiber tow in an injection molding process. Alternate options that would be pursued if this was not feasible included carbon fiber tow commingled with polymer fiber and pre-consolidated flexible preforms. The ultimate goal was to be able to infuse a TFP preform using dry 50k carbon fiber tow by injection overmolding the preform with a carbon filed PEI material.

In order to try to infuse tow, especially 50k tow, it was desirable to spread the tow as wide as possible. On the Tajima machine, the current limit of the stitch width is 0.5” (13mm). The current foot design is only 0.3” wide. A 3D printed foot was designed that was 0.5” wide to try to maximize the width that the tow was stitched. When stitching with this foot configuration, it was noted that although there was a slight improvement on straight sections, any radius or curved section resulted in the tow bunching up on the inner side of the curve, negating the benefit.

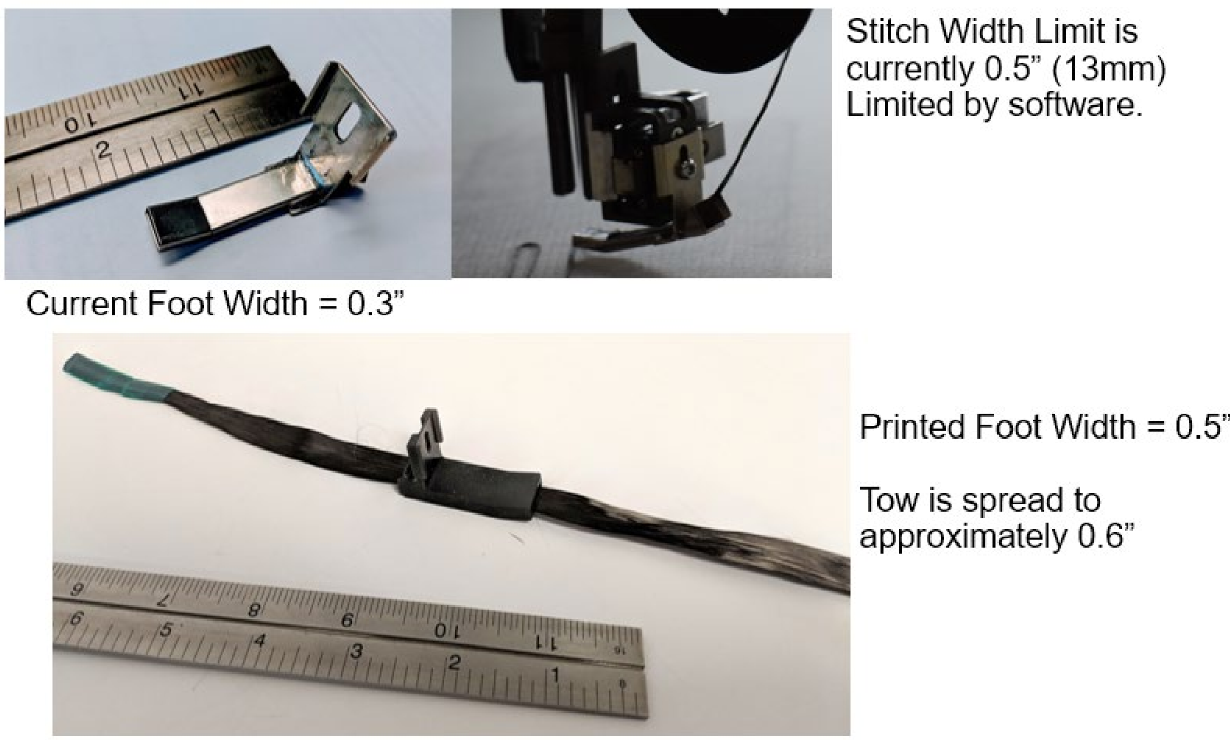


Figure 14 – Limited by the Current Machine a 3D Printed Foot was designed to spread tow

During initial molding trials, it was thought that if the injection polymer was kept near the top of the operating window while in the barrel and if the tool was kept hotter than the melt temperature and then cooled after injection, the viscosity would be kept as low as possible to better wet out the fiber bundle. Unfortunately, some of the materials planned to be used increase in viscosity as they are raised much above their operation window (Figure 15). This is exacerbated by the shear heating during injection further raising the polymer temperature. Also, by keeping the tool temperature hotter than the recommended operating window and cooling the tool after the injection cycle, the material was cooled slowly and degraded significantly prior to the part cooling enough to eject from the tool. Thus it was determined that raising the barrel and tool temperatures did not have the desired outcome and did not provide a viable path forward.

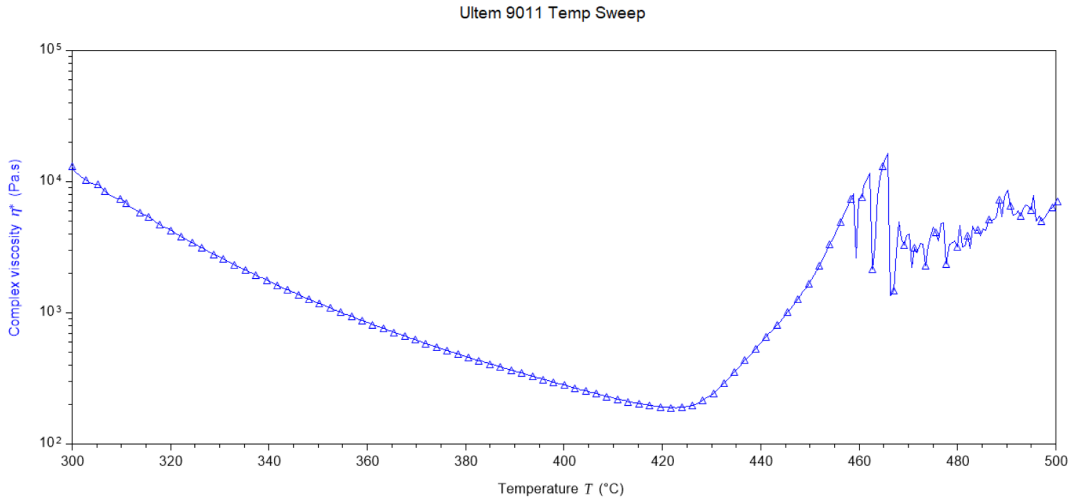


Figure 15 - Graph of viscosity plotted against temperature for Ultem 9011

Another factor that was looked at in determining if wetting out dry fiber in an injection molding process would be possible was comparing standard injection molding tool vent sizing to the interstitial space in hexagonal close packed carbon fiber tow. In standard injection molding tool design, vents placed around the parting line of the tool core and cavity are designed with an opening between 0.013 – 0.05 mm to allow for air to escape the cavity while the injecting polymer fills the cavity. This exact size is determined by the specific polymer being used. A properly sized vent will allow air to flow out but will not allow any flow of the injecting polymer. In a hexagonal close packed bundle of carbon fiber with a fiber diameter of approximately 0.007 mm, the interstitial space between the fibers is on the order of 0.001 mm (Figure 16). For the materials used in this project, the ideal vent size ranges from 0.0254 mm for polypropylene to 0.0381 mm for Polyetherimide. Therefore, the space between the fibers is an order of magnitude smaller than the standard vent size which is used commonly in tooling and does not allow for material flow.

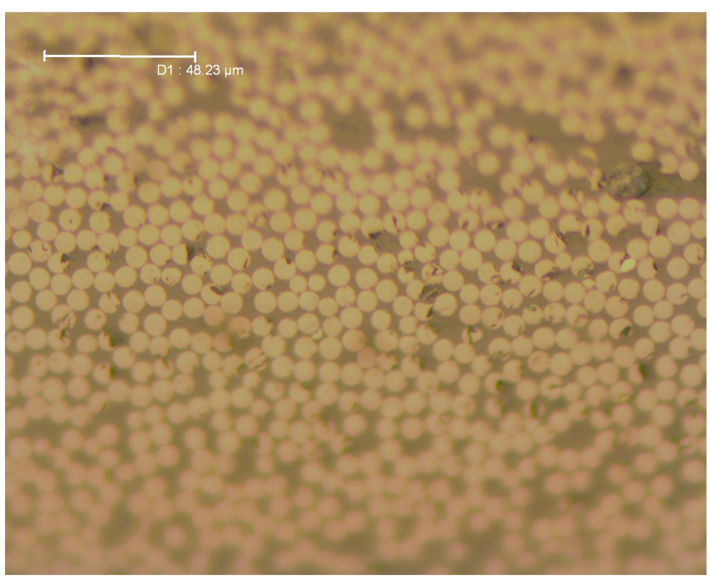


Figure 16 - Photomicrograph of infused carbon fiber showing genarally hexagonal close packed fiber arrangement

Additional challenges in using injection molding to infuse dry carbon fiber tow include the lack of pressure at the flow front and the nature of the flow front freezing and beginning to solidify as it contacts the preform in the tool cavity. While the injecting polymer fills the tool cavity, the pressure is very low as the air freely escapes the tool cavity. Due to the nature of this, the pressure at the flow front is very low. Pressure in the mold cavity only increases as the cavity is mostly filled with the injecting polymer. However, by this point the polymer has already formed a skin encasing most of the carbon fiber tow and will not penetrate deeper into the tow. To alleviate this, increasing the tool temperature and preheating the preform may help, but this causes the problems of significant material degradation as previously discussed.

4.1.3 Commingled Fiber

As an alternative to infusing dry carbon fiber, infusing carbon fiber tow that had been commingled was investigated. Carbon fiber tow could be commingled with polymer fiber in the tow bundle. By this, it would not be necessary to flow polymer as much as melt the polymer that was already in place.

Concordia Fibers, who specializes in engineered yarns and fibers, was able to provide assistance in commingling various carbon fibers with different polymer fibers. Polypropylene fibers were commingled with 12k AS4A carbon fiber, and with 50k Zoltek Sagrfil carbon fiber (Figure 17). PEI fiber would also be commingled with these carbon fibers. The Polypropylene versions could be tested in the UDRI injection molding machine while the PEI could not due to the high process temperatures exceeding the capability of the equipment.

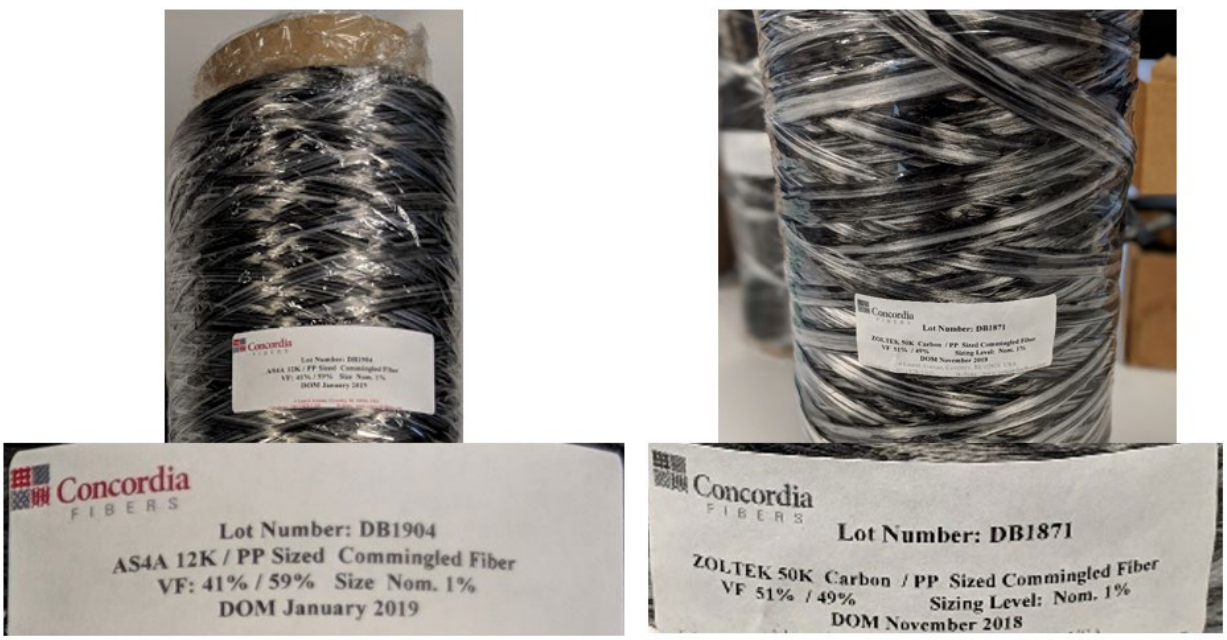


Figure 17 - AS4A 12 Carbon Fiber Commingled with Polypropylene Fiber (Left), Zoltek 50k Carbon Fiber Commingled with Polypropylene Fiber (Right)

One main concern with commingling was that in order to fully wet out the injection overmolded preform a high level of homogeneous mingling is desired. Concordia spent a considerable effort to try to achieve this high quality of commingling by refining their processes and improving the equipment used. With the effort to try to better mix the polymer fiber and carbon fiber, UDRI looked at methods to verify and quantify the quality of the commingling. Sections of the, as manufactured, commingled tow were potted carefully and photomicrographs were taken (Figure 18). Using Fiji ImageJ software the image was segmented and machine learning was used to recognize the polypropylene fibers. Once recognized, the particle distribution of the fibers could be analyzed, allowing quantification of the quality of the commingling of the polymer fiber and the carbon fiber (Figure 19).

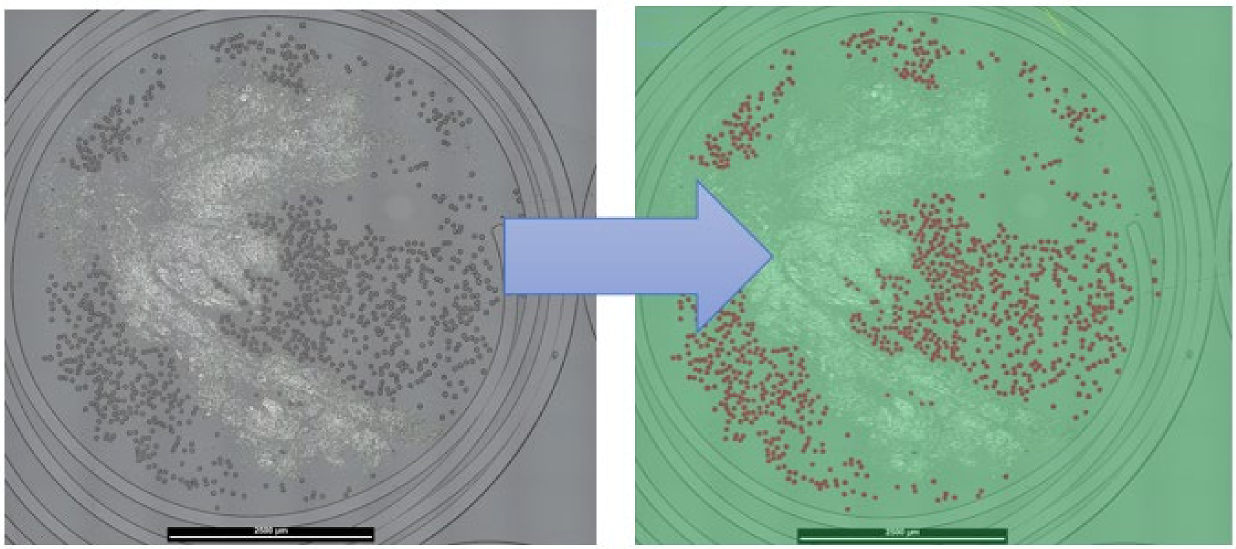


Figure 18 - Photomicrograph of Zoltek 50K Carbon/PP Commingled Tow VF 51% / 49% Cross Section (Left), Fiji (ImageJ) Software Used to process and segment photomicrograph to recognize PP fibers, PP Fiber in Red, Carbon Fiber appear as small white dots (Right)

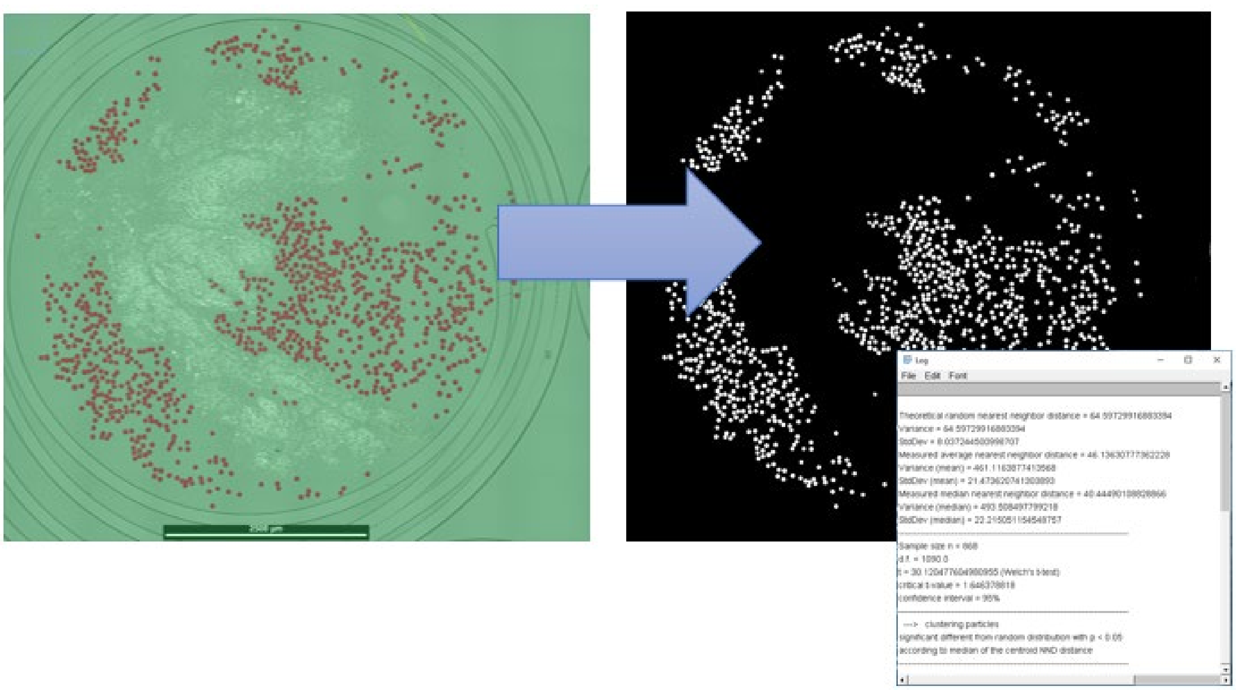


Figure 19 - Particle Distribution Analysis of PP Fibers in PP / Carbon Fiber Commingled Tow

Another main concern with the commingled fiber was how well the carbon fiber could be wet out using injection molding and commingled fiber. TFP preforms were constructed using the green mesh backing

(Figure 10) to allow as much molten material to flow around the commingled fiber as possible. Initial results were very promising with the polymer fiber mostly melting during the injection cycle (Figure 20).

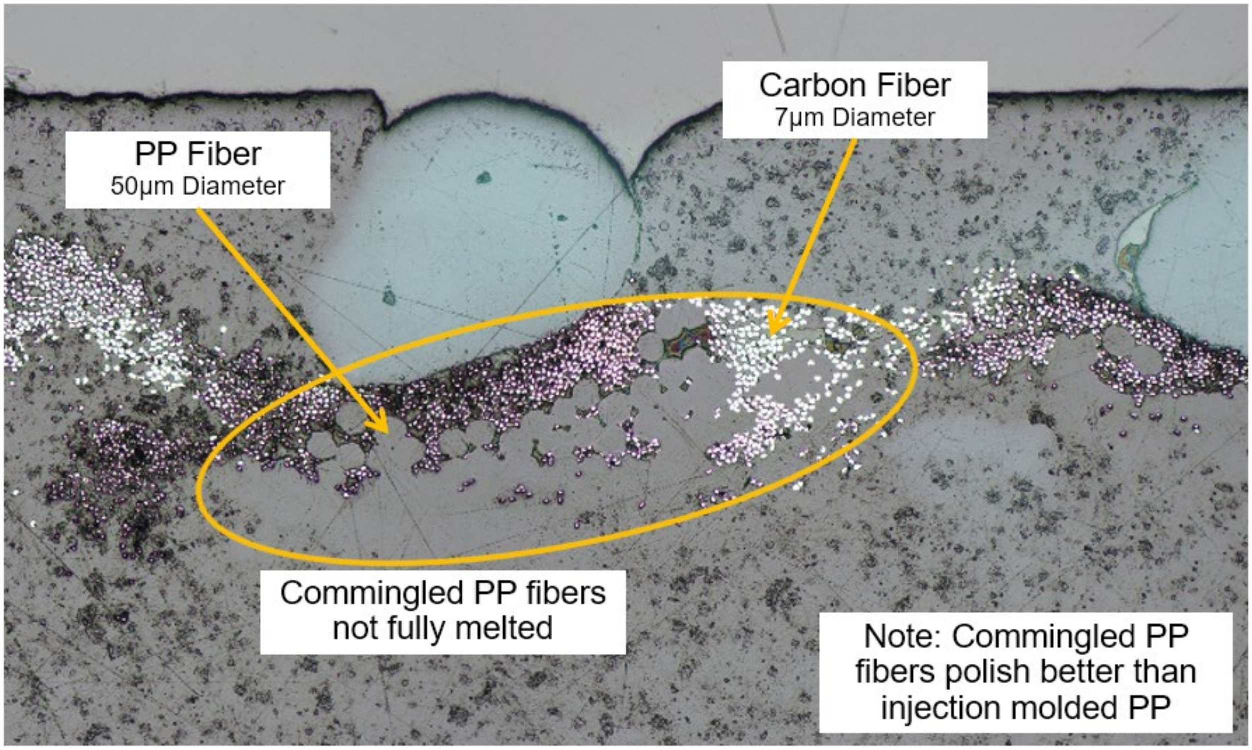


Figure 20 - Photomicrograph of Injection Overmolded TFP Preform with Commingled Carbon Fiber (AS4A 12k Commingled with PP Fiber)

With additional work to refine the process, commingled polymer fibers were fully melted and flowed better. In areas where the tow was commingled well, carbon fibers were fully wet out. However, in areas where there was not a good mix of fibers, there were areas of dry carbon fiber that was not infused during the injection molding process (Figures 21 & 22). With additional work on improving commingled quality this would likely be a viable option for injection overmolding continuous carbon fiber TFP reinforced parts.

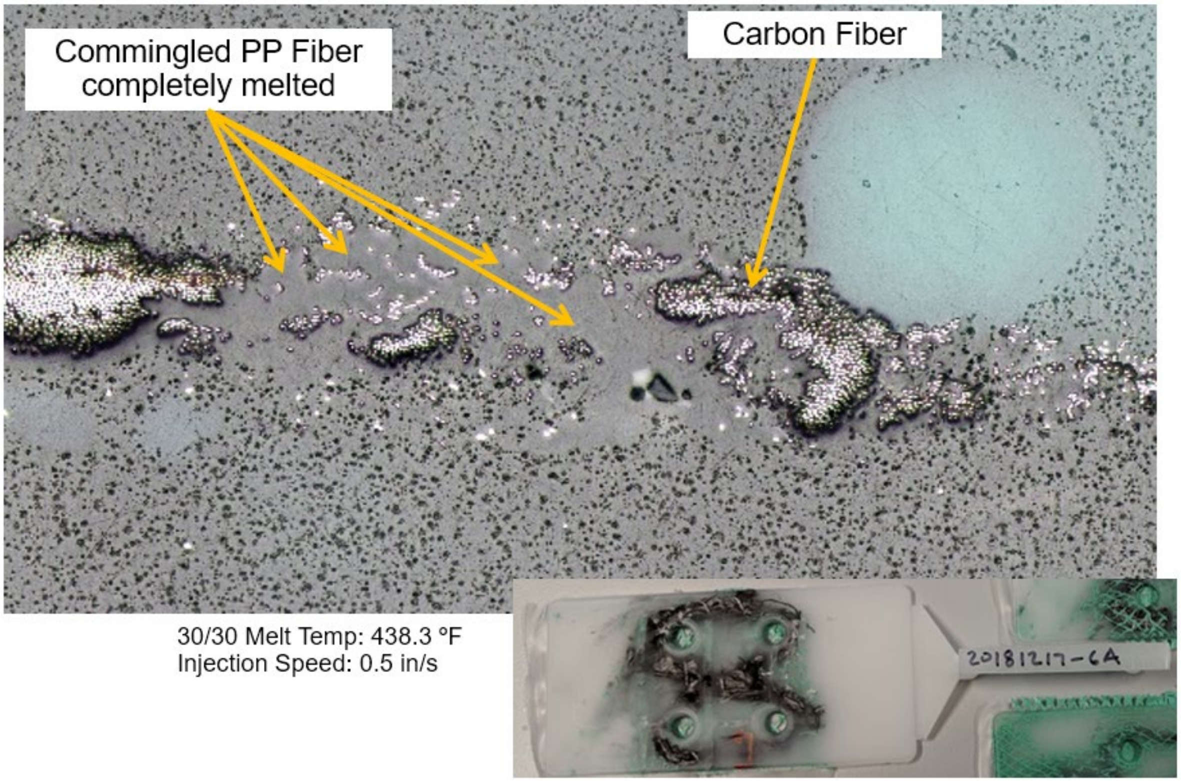


Figure 21 - Photomicrograph of Injection Overmolded TFP Preform with Commingled Carbon Fiber

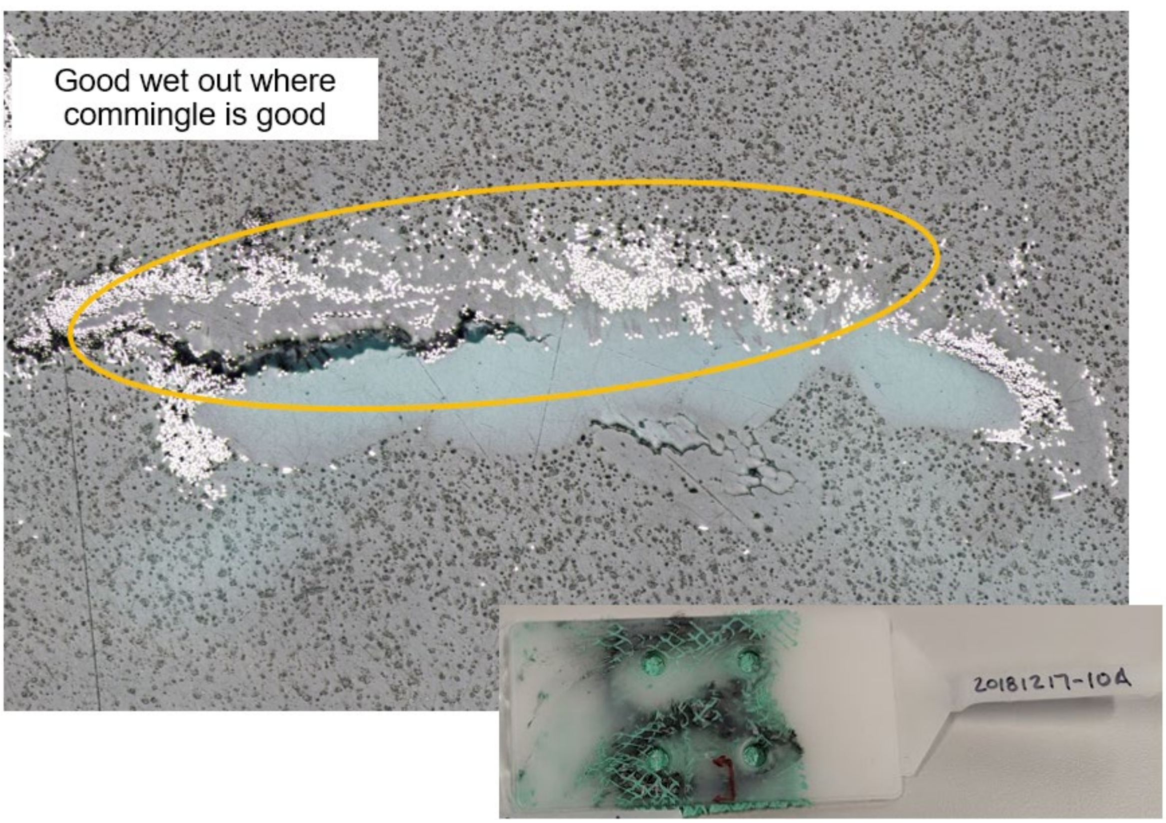


Figure 22 - Photomicrograph of Injection Overmolded TFP Preform with Commingled Carbon Fiber

Work was also done to infuse 50k Zoltek Sagrafil carbon fiber tow that had been commingled with PEI fibers. This was done in a heated press by placing straight rows of TFP stitched tow in a 6" x 6" flat plate mold. The TFP was placed between flat sheets of short carbon fiber filled PEI material (Sabic EC004APQ). As heat and pressure was applied, the fiber was infused and the commingled fiber was melted to aid in the infusion. However, due to the thicker tow bundle, not all of the fiber was able to be wet out fully. This can be in the microscopy as dark void area in the middle of the carbon fiber bundles (Figure 23).

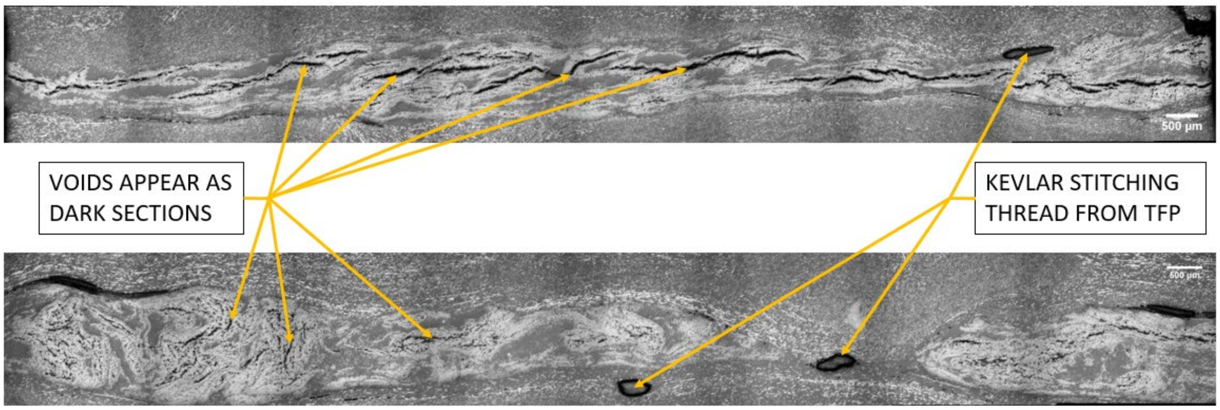


Figure 23 - Microscopy of Infused Commingled 50k Zoltek Sagrafil and PEI Fiber

4.2 Flat Plate Work

After much initial background work and alternative approaches, it was decided that the best way to proceed was to create pre-consolidated preforms. This work would also be performed using PEI instead of PP. From the initial work it was evident that, with PEI being the desired material to use for aerospace designs, PEI needed to be used for development work going forward since it has a much different mold temperature and is an amorphous polymer as opposed to the semi-crystalline structure of PP. The construction of these preforms included a layer of film on top of a TFP preform. The preform itself was 12k tow stitched with Kevlar thread to a PEI film. Due to working with PEI (Sabic Ultem 9011), the layers would need to be heated and pressed together to create flat plate samples that could be cut into test specimen (Figure 24). This construction would mimic the intent to injection overmold parts without having to design and build specialized tooling for the flat plate.

Figure 24 – Film and TFP Layers Pressed Into Pre-consolidated Preforms

The preforms would consist of straight continuous carbon fiber tows infused between layers of PEI (Figure 25). The PEI layers were 6” x 6” film sheets made by compression molding PEI pellets in a heated press with a 6” x 6” flat plate tool. Carbon fiber tow could be stitched to one sheet and a second sheet would be placed on top of the tow. This layered configuration was then placed into a 6” x 6” flat plate tool again and compression molded to pre-consolidate the preform.

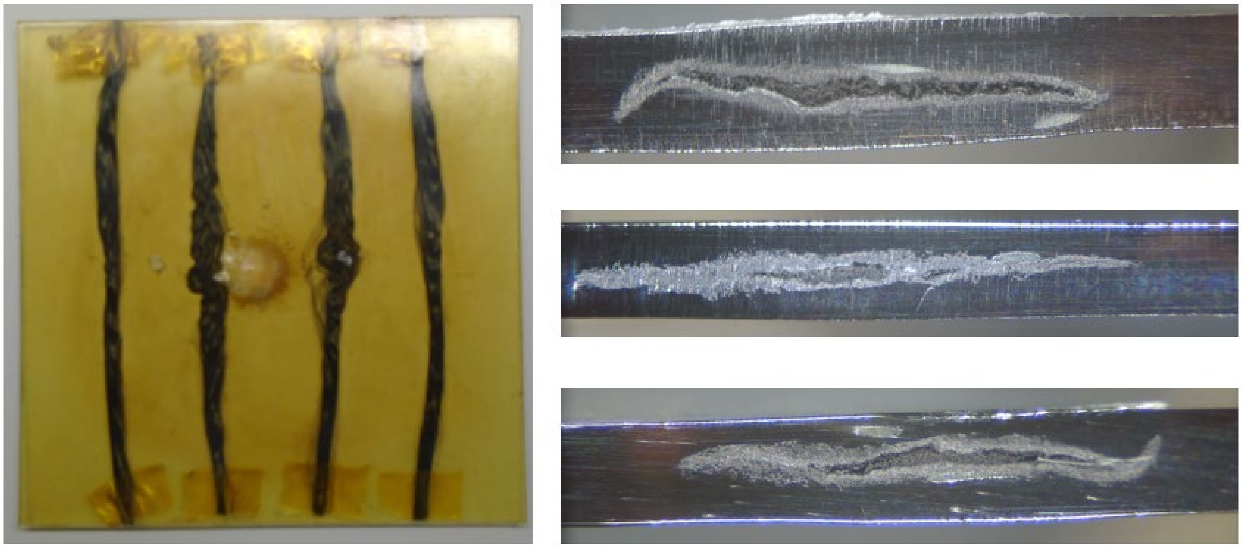


Figure 25 - Ultem 9011 (PEI) Film Preform with 12k Carbon Fiber Tow (Left), Cross Sections of Pre-consolidated Tow (Right)

The preforms would then be overmolded with short carbon filed PEI material (Sabic EC004APQ) (Figure 26).

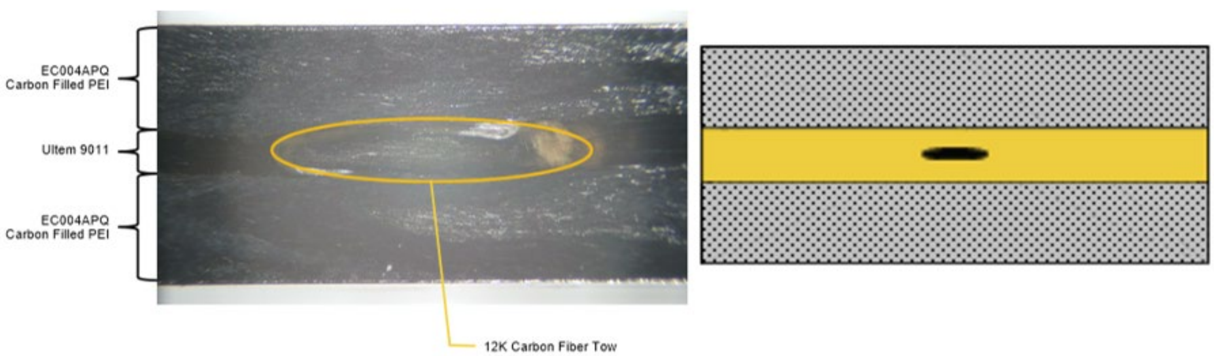


Figure 26 - Photomicrograph of Flat Plate Layer Construction (Left), Diagram of Flat Plate Layer Construction (Right)

Overmolded samples were sectioned and microscopy was performed to verify that the fiber bundle was fully infused (Figure 27). It was seen that the fiber bundle was completely wet out with little to no void content. Upon verifications of this, samples would be created using this same method to complete Milestone 5.4.2.1.

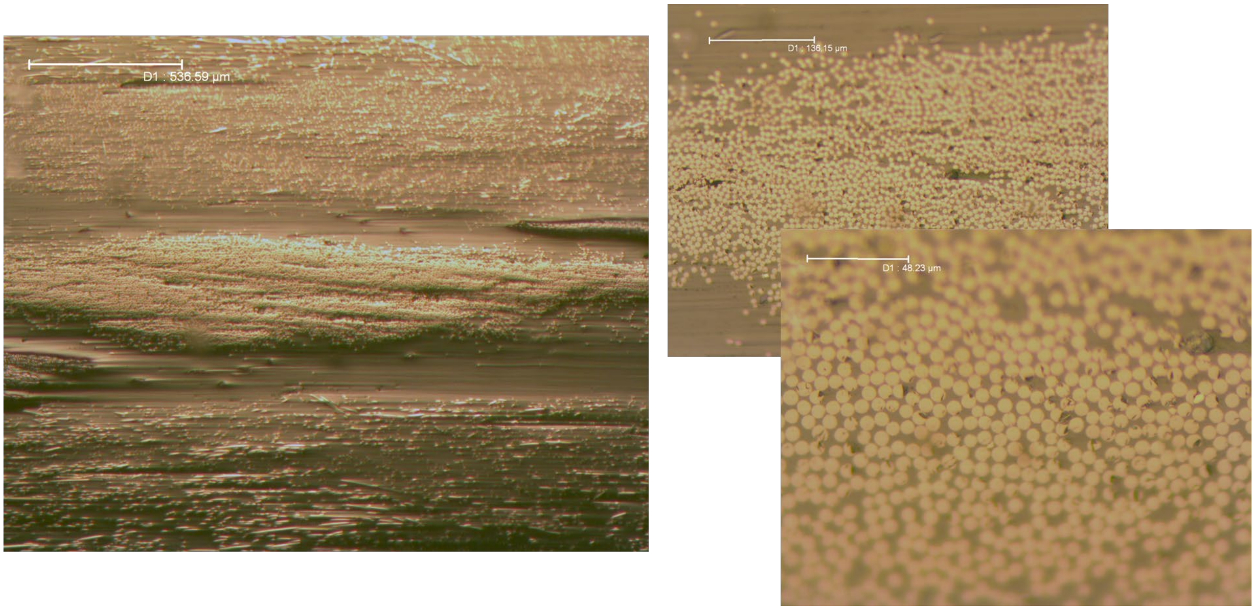


Figure 27 - Photomicrograph Shows Fibers Fully Wet Out in Overmolded Sample

Milestone 5.4.2.1 Demonstrate flat panel preforms can be fully wetted out via compression molding and show a consistent carbon and void content. This will be shown by a less than 5% bulk density deviation between preforms.

Samples were cut from three sections, each including a tow section (Figure 28). These sections were each measured to determine the bulk density of the section. The densities of the samples were 1.334 g/cm^3, 1.333 g/cm^3, and 1.329 g/cm^3. The results demonstrated that the density varied by less than 5% ensuring consistent void content and quality of the panel. This also was compared to the baseline density of 1.33 g/cm^3 of the overmolded material.

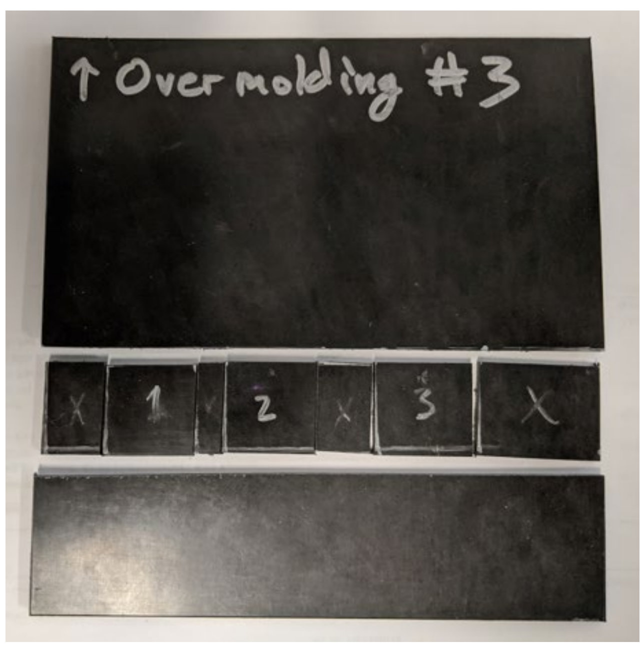


Figure 28 - Samples for Void Content

Additional samples were created with the same construction methods to verify Milestone 5.4.2.2.

Milestone 5.4.2.2 Demonstrate that the analytical tools used to design and analyze the TFP preform molded panels correlates with the measured test results within +/- 15%.

Modified ASTM D3039 tabbed tensile specimen were made for tensile testing (Figure 29). This construction would allow for the full tow to be captured within the specimen width and ensure consistency in testing.

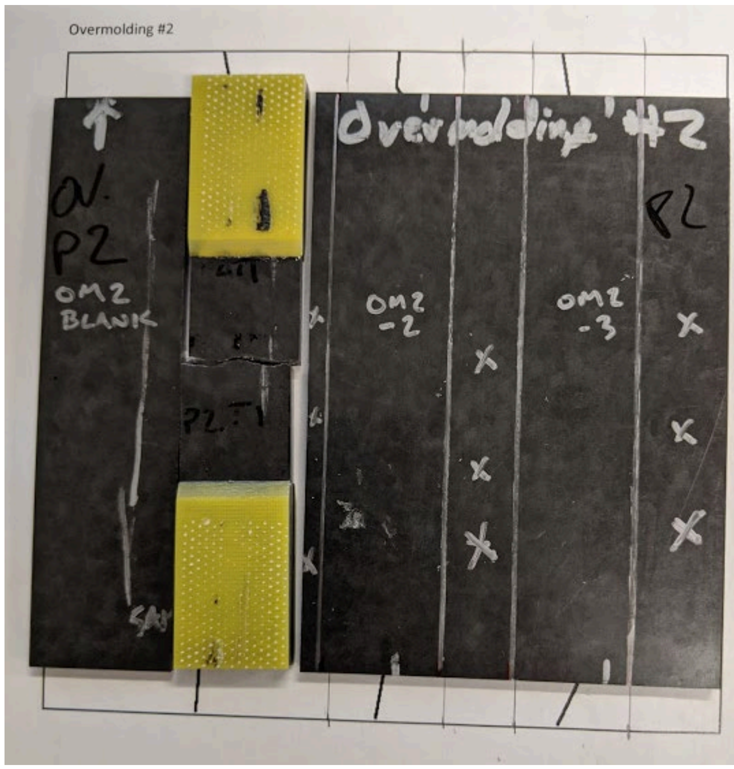


Figure 29 – Sample of Modified ASTM D3039 Tabbed Tensile Specimen Cut from Flat Plate

Along with developing the physical testing, predictive modeling was developed to be used later as a design tool. Modeling work was done by UDRI using BSAM-FEA. Material definitions were developed based on the material data sheets and known best practices regarding fiber orientation. The layered construction of the test specimen was matched in the predictive model with a different material model based on each layer. The preform layer was approximated based on the fiber volume of the construction.

All of the specimens tested, other than neat Ultem 9011, broke in the gage section and matched predictive analysis results. These tests were all performed with extensometers (Figure 30) to be able to compare and verify correlation to predictive modeling.

Customer	CVM
Job Number	CVM
Banner No.	LUN1C1
Laboratory Name	Composites Manufacturing & Testing
Instron Test Method	ASTM D638 Tensile Properties w/ Extensometry Controlled 10.4.19
PI Work Request	N/A
Operator ID	J. Lotz
Panel I.D.	OM2
Material	Carbon Filled PEI w/ single tow of 12K CF
Test Speed (in/min.)	0.05
Test Conditions	RTA
Temperature (°F)	75.
Humidity RH (%)	38.
Load Cell FS (lbs)	5,000 lbf
Test Frame ID	5SR1123CP7351
Test Date	10/14/2019

Figure 30 – Load Frame Test Setup for Tensile Tests of Flat Plate Specimen

For correlating to the predictive modeling and comparing to the baseline of a carbon fiber filled PEI sample various constructions were created and tested (Figure 31). Samples included neat PEI preforms overmolded with carbon fiber filled PEI, baseline carbon fiber filled PEI, and carbon fiber filled preforms overmolded with carbon fiber filled PEI.

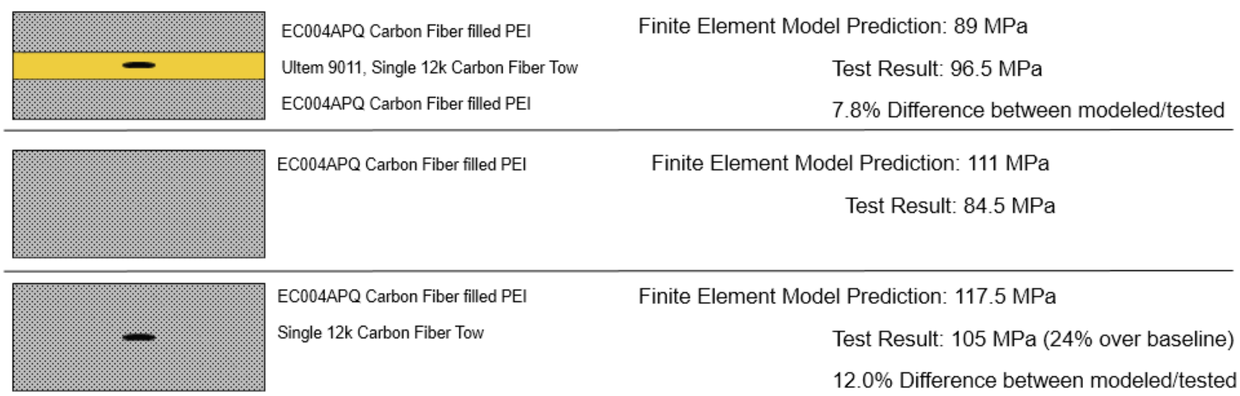


Figure 31 – Tensile Test Results of Various Constructions

The results of these tests were within the allowable error and met the criteria for Milestone 5.4.2.2.

To meet GNG 5.4.1 more tows would need to be added to each tensile specimen. It was determined that 7 tows in each inch wide specimen would meet the requirement.

GNG 5.4.1 Technology concept shows that the TFP-reinforced panels have a greater than 25% increase in tensile strength (ASTM D638) compared to short fiber reinforced Polyetherimide thermoplastic specimens.

With the close spacing of the carbon fiber tow in the preforms with 7 tows per inch, PEI film backing material would not work well. The material would perforate and begin to fall apart with that many needle holes from adjacent carbon fiber tow. It was determined that a non-woven carbon fiber veil could be used as a backing material (Figure 32).

Figure 32 - Non-Woven Carbon Fiber Veil

With this material used as the backing there would also no longer be a layer of neat PEI material in the construction. This would help create less discrepancy in the elastic modulus of the materials and would allow the composite structure to transfer load better to adjacent fibers and in turn carry more load.

Flat panel construction now would consist of a TFP preform, with carbon fiber veil, that was pre-consolidated by placing sheets of carbon filled PEI film above and below and forming them in the heated press. This would then be overmolded in the heated press by placing it between layers of carbon filled PEI (Figure 33).

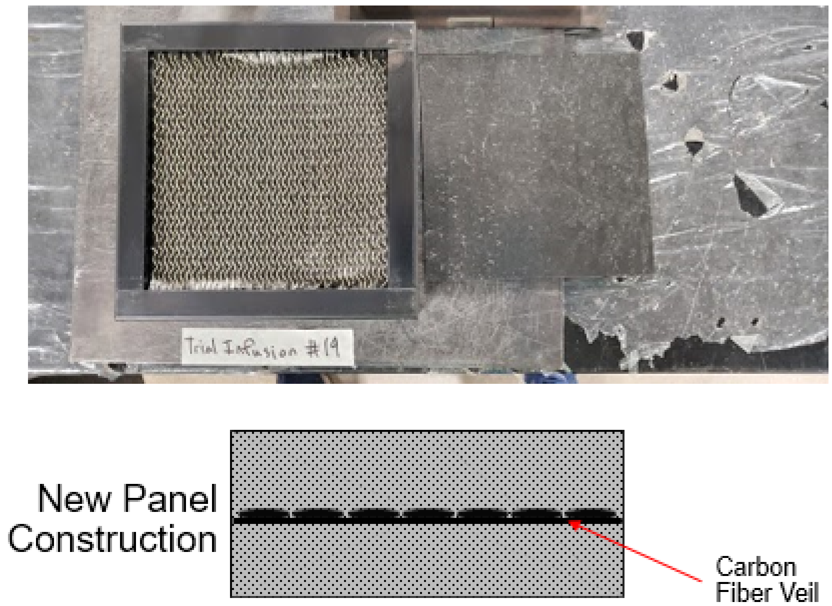


Figure 33 – 7 Tows per Inch Preform Placed in Mold for Pre-consolidation (Top), Panel with Carbon Fiber Veil (Bottom)

Panels manufactured with this constructions showed very good infusion of the carbon fiber tow (Figure 34).

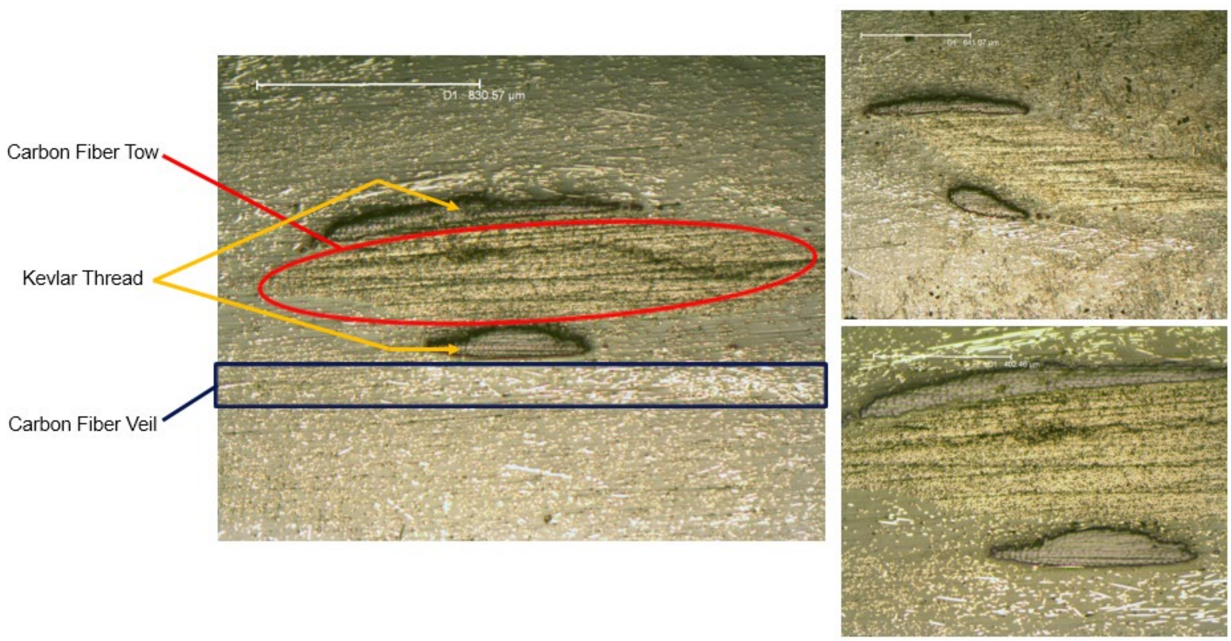


Figure 34 - Photomicrographs of Flat Plate Constructed Using TFP with Carbon Fiber Veil Backing

Tensile specimens were constructed and prepared for testing (Figure 35).

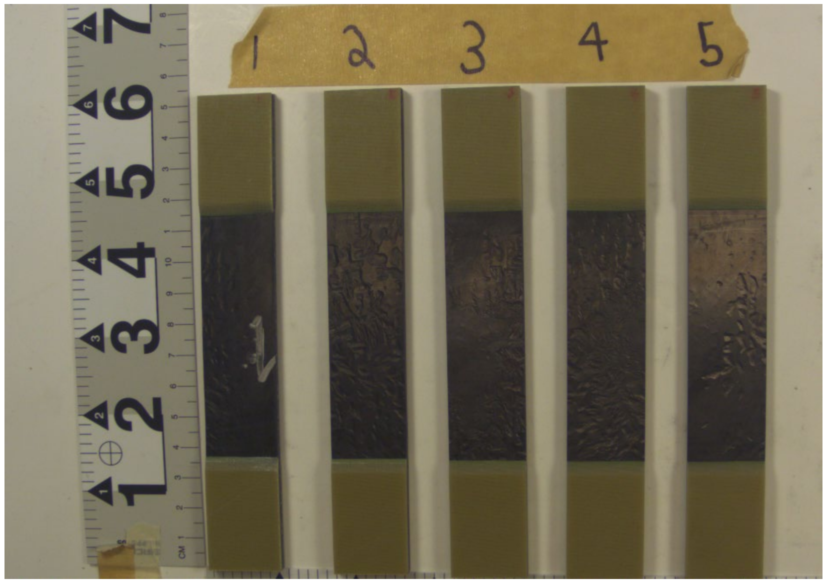


Figure 35 - 7 Tow per Inch Tensile Specimen

Test results (Figure 36) showed a significant increase over the baseline panel. Compared to the baseline, all carbon fiber filled PEI there was a 130% increase in tensile strength meeting GNG 5.4.1.

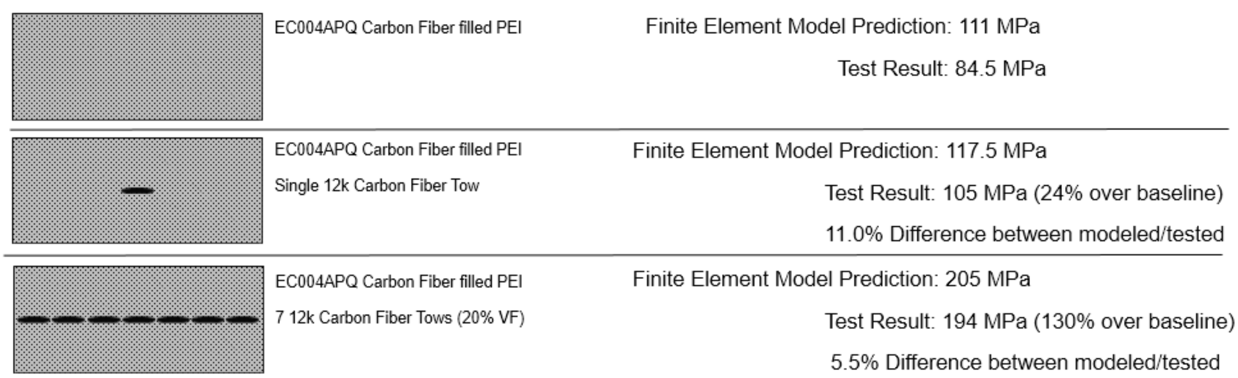


Figure 36 - Test Results of Flat Plate Tensile Samples

4.3 Simplified Bracket Work

UDRI proposed using a simplification to a short fiber filled injection molded corner fitting bracket (Figure 37). This was a bracket that Airbus had previously investigated for replacing machined aluminum fuselage corner fitting brackets. However, to simplify the tool design the bracket would essentially be cut down to half the full size. The proposed UDRI simplification would make the bracket smaller, in turn keeping the TFP preform and injection mold smaller. This would keep the cost and complexity significantly lower. Simplifying the bracket was also intended to keep the design of the TFP preform more manageable. The original bracket as designed is not shown due to proprietary concerns.

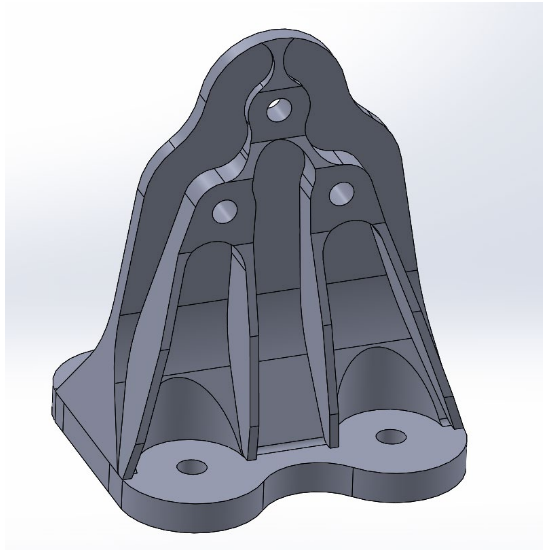


Figure 37 - Simplified Corner fitting Bracket

The TFP preform was designed to increase the tensile load carrying capability of the bracket. To do this, once the bracket geometry was complete, a topology analysis and a structural analysis of the bracket were performed (Figures 38 & 39). By looking at the results of the topology analysis, the load paths through the part can clearly be seen. These load paths are where continuous carbon fiber placed in the part will have the most effect on improving the load carrying capability of the part.

Figure 38 – Topology Analysis Results Used to Determine Fiber Placement for TFP

Comparing these load paths to the high stress and high strain areas of the part also helps determine the areas most likely to fail in the unreinforced part which need to be reinforced by the TFP preform.

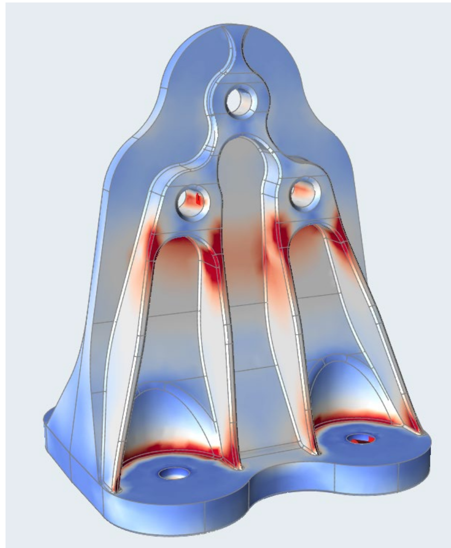


Figure 39 - Structural Analysis Results Used to Determine Weak Areas to be reinforced with TFP

All of this information was weighed with the results of the flat plate work. Based upon this it was decided that designing a preform should target the same fiber loading in high stress areas that was used in the 7 tows per inch flat plate samples. It was also necessary to design front and back preforms that would be stitched flat and then be formed to fit along the mid-plane of the bracket geometry (Figure 40).

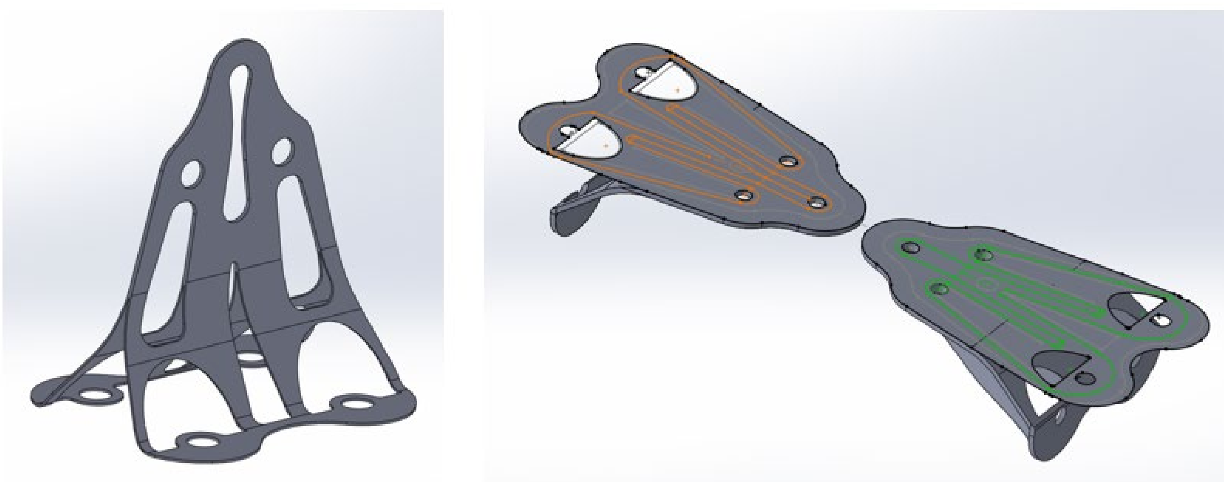


Figure 40 - Formed TFP Preform CAD Design (Left), Flat CAD Patterns for TFP Preforms (Right)

Once the design of the TFP preform had been determined, the TFP was stitched using the same construction as the flat plate work, 12k carbon fiber with Kevlar thread and non-woven carbon fiber backing material (Figure 41).

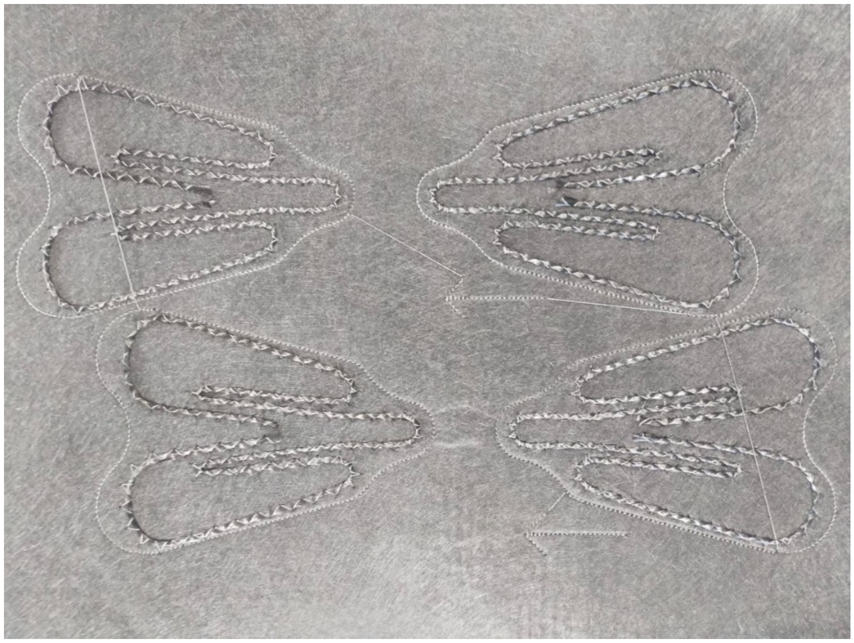


Figure 41 - TFP for Simplified Corner Fitting Bracket

The TFP was then pre-consolidated in the same construction as the flat plate preforms using the carbon fiber filled PEI material film to infuse the TFP (Figure 42).

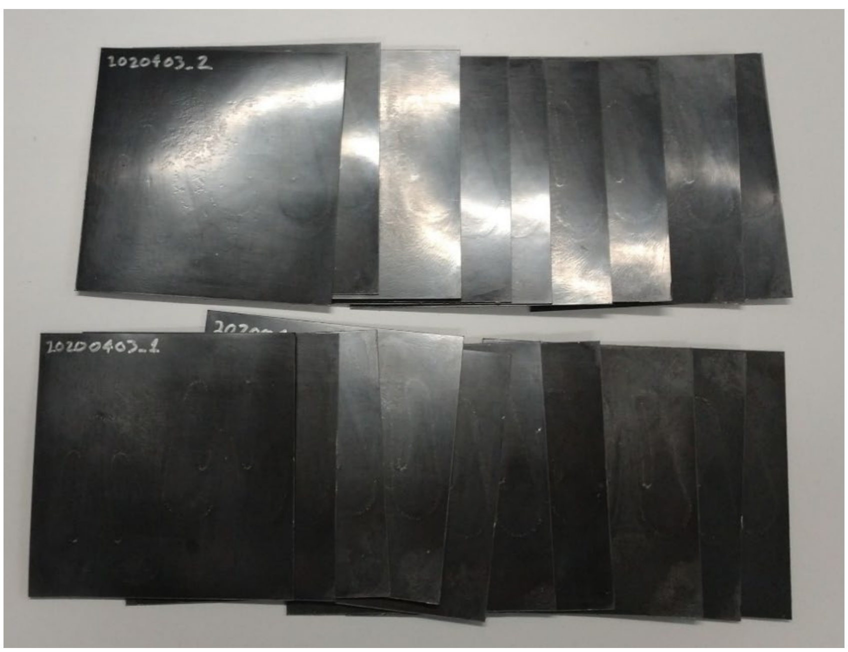


Figure 42 - Front and Back Pre-consolidated Prefroms

Preforms were then cut out and formed by hand. During the cutting and forming process a front and back preform were melted to each other to form the pre-consolidated TFP preform design (Figure 43).

Figure 43 - Hand Cut and Formed Pre-consolidated TFP Preform, Front and Side View

The cut and formed preforms would later be hand loaded into the bracket injection molding tool and overmolded to create continuous fiber reinforced brackets.

Milestone 5.4.4.1 Bracket preforms yielded during injection molding are fully wetted and have a bulk density deviation of less than 5%.

Samples were also cut and measured to verify the wet out and bulk density variation. Densities were found to vary from 1.254 – 1.362 g/cm^3, meeting the Milestone 5.4.4.1 of less than 5% variation. This ensured that UDRI was able to manufacture the TFP preforms with consistent, low void content and good fiber infusion.

Based on the bracket part design and the design of the TFP preforms, UDRI worked with Velocity Group, LLC to design and build an injection molding tool for the bracket (Figure 44). This tool was designed to be able to be run without a preform to mold baseline parts. The tool also had holding features designed in based on some of the early work done by UDRI on holding preforms in place during injection molding.

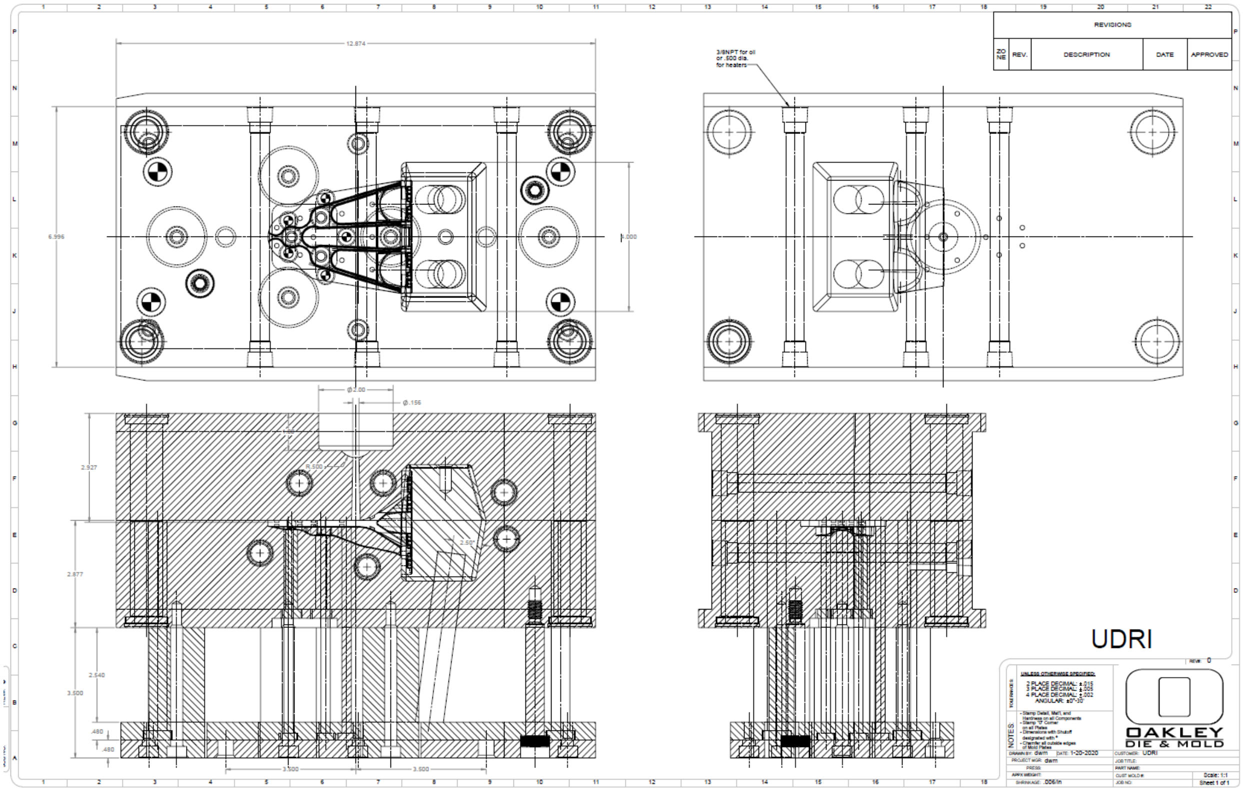


Figure 44 - Drawing of Injection Mold for Bracket

Once the tool was built, Velocity installed the tool in a 40 ton injection molding machine that would be able to run the carbon filled PEI material to mold both baseline brackets and reinforced brackets (Figure 45).

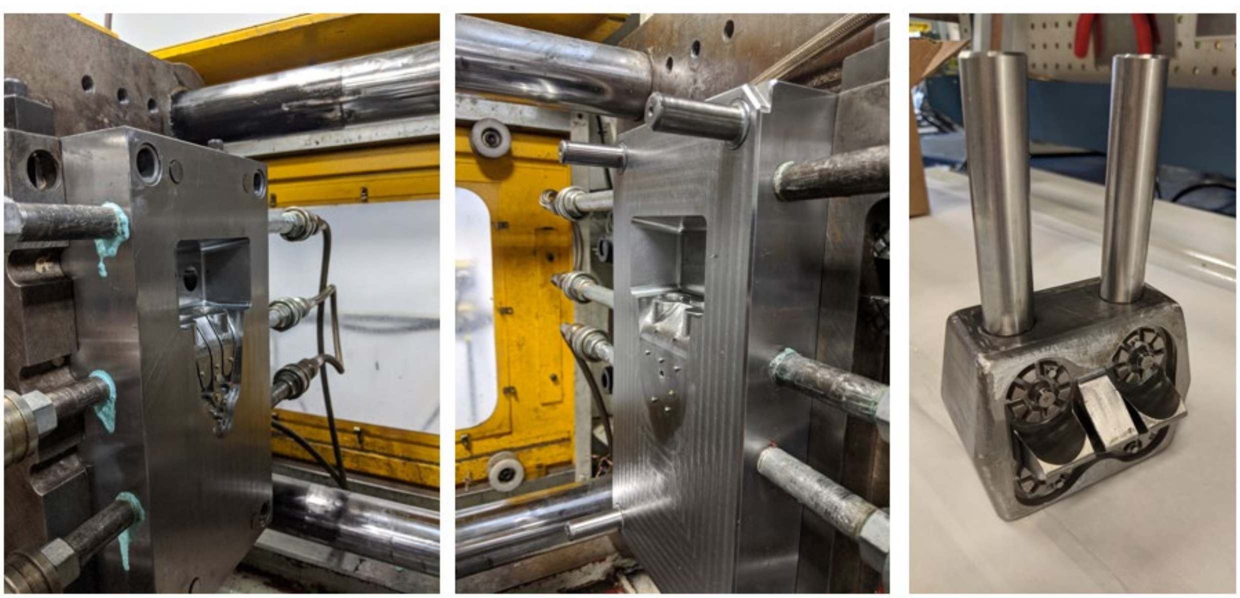


Figure 45 - Bracket Injection Molding Tool Installed in Injection Molding Machine (Left and Middle), Hand Loaded Insert for Bracket Mold (Right)

The injection molding tool ran very well when molding baseline parts using carbon fiber filled PEI with no TFP preform (Figure 46).

Figure 46 - Injection Molded Baseline Parts (No Overmolded Preform)

Due to the preforms being manufactured by hand, and the inconsistencies caused by a hand process, hand loading the preforms into the injection molding die was very difficult (Figure 47). If preforms were formed and cut with production equipment the variation from part to part and overall conformance to the design intent would ease the loading issues. Due to the time it took to hand load preforms, and then thin design of the preforms, the preforms had dropped to room temperature prior to the start of the injection cycle even when they had been heated to near the Tg of 217ºC.

Figure 47 - Preform Loaded into Injection Molding Tool

Baseline parts without preforms, fiber reinforced preform parts, and blank preform (no fiber, but overmolded preform) were all molded and then tensile tested on a custom designed fixture (Figure 48).

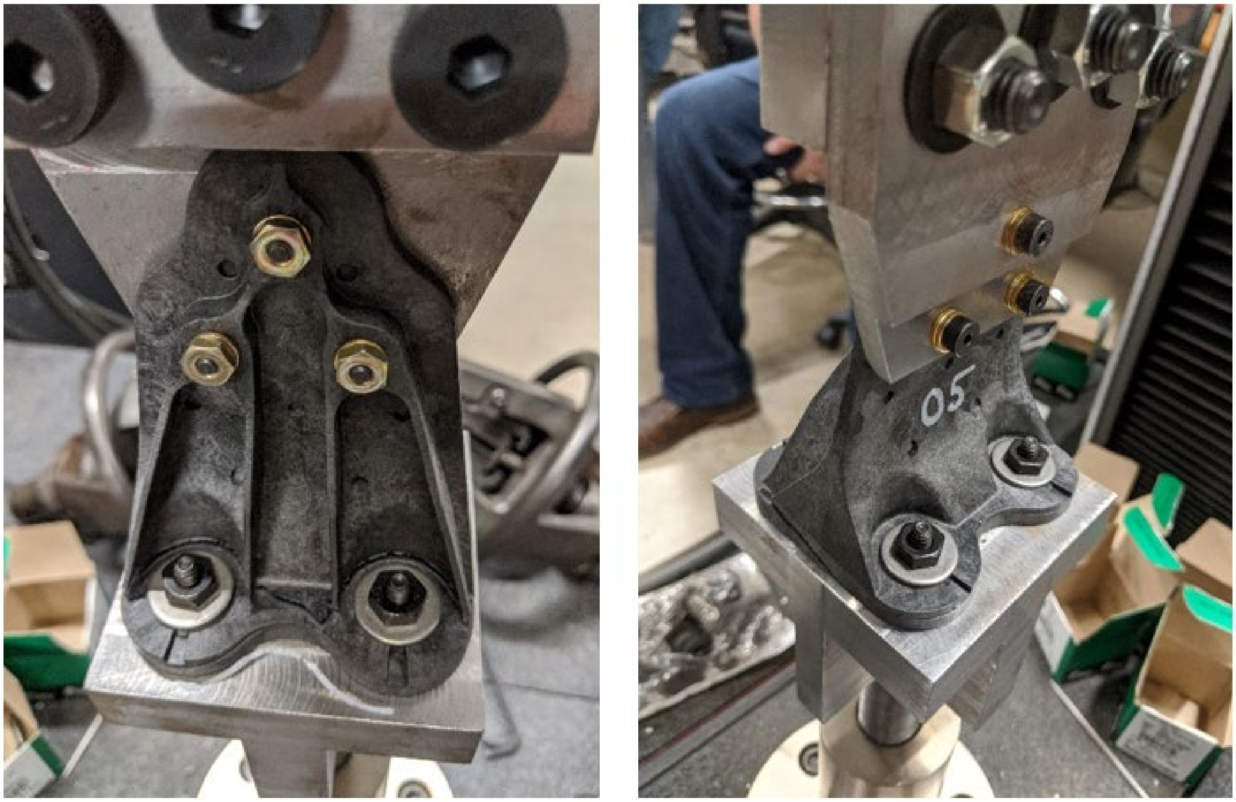


Figure 48 - Sample Bracket Loaded in Custom Test Fixture

There were several outliers in the test data. The outliers exhibited different failure modes which likely was due to the bonding issues with the overmolding not being consistent. When looking at the results without any outliers, baseline parts (parts without inserts) failed at 4274 lbf. Unreinforced preform overmolded parts (parts with polymer films but no TFP carbon fiber included) failed at 3859 lbf, and TFP fiber reinforced parts (parts with polymer film and TFP carbon fiber reinforcement) failed at 4434 lbf (Tables 2-4).

Table 2 - Baseline Bracket Tensile Results

Baseline Results Table

Specimen ID	Peak Load (lbf)	Displacement at Break (in.)	Effective Stiffness (lbs/in)	Fixture bolt torque (in-lbs)	Failure Description	Notes
BL1	4365	0.0818	6.50E+04	20	Top of part, along bottom 2 bolt holes	Complete fracture (2 pieces) at bolt holes
BL2	4178	0.0781	5.99E+04	20	Top of part, along bottom 2 bolt holes	Complete fracture (2 pieces) at bolt holes
BL3	4280	0.0778	5.98E+04	20	Top of part, along bottom 2 bolt holes	Complete fracture (2 pieces) at bolt holes
BL4	4471	0.0795	6.05E+04	20	Top of part, along bottom 2 bolt holes	Complete fracture (2 pieces) at bolt holes
BL5	5324	0.098	5.99E+04	20	Bottom of part, at base flange	Partially Fractured, still held together
BL6	4077	0.0716	6.06E+04	20	Top of part, along bottom 2 bolt holes	Complete fracture (2 pieces) at bolt holes
Mean	**4449**	**0.0811**	**60976**			
Std. Dev.	**450.2**	**0.0089**	**2.02E+03**			
%COV	**10.12%**	**11.01%**	**3.31%**			

Table 3 - Unreinforced Preform Bracket Tensile Results

Unreinforced Preform Results Table

Specimen ID	Peak Load (lbf)	Displacement at Break (in.)	Effective Stiffness (lbs/in)	Fixture bolt torque (in-lbs)	Failure Description	Notes
P02	4093	0.075	5.23E+04	20	Top of part, along bottom 2 bolt holes	Complete fracture (2 pieces) at bolt holes
P03	3624	0.067	5.87E+04	20	Top of part, along bottom 2 bolt holes	Complete fracture (2 pieces) at bolt holes
Mean	3859	0.0710	55504			
Std. Dev.	331.6	0.0057	4.54E+03			
%COV	8.59%	7.97%	8.18%			

Table 4 - TFP Reinforced Preform Bracket Tensile Results

TFP Reinforced Preform Results Table

Specimen ID	Peak Load (lbf)	Displacement at Break (in.)	Effective Stiffness (lbs/in)	Fixture bolt torque (in-lbs)	Failure Description	Notes
P02	4769	0.0839	6.32E+04	20	Top of part, along bottom 2 bolt holes	Audibles heard at 3700 & 4300 lbs
P03	4210	0.0765	6.08E+04	20	Bottom of part, at base flange	Component fractured but held together by preform
P05	4497	0.0806	6.35E+04	20	Bottom of part, at base flange	Component fractured but held together by preform
P06	4603	0.0817	6.20E+04	20	Bottom of part, at base flange	Component fractured but held together by preform
P09	4318	0.0765	6.45E+04	20	Bottom of part, at base flange	Component fractured but held together by preform
P10	4525	0.0763	6.47E+04	20	Bottom of part, at base flange	Component fractured but held together by preform
Mean	4487	0.0793	63114			
Std. Dev.	200.1	0.0033	1.50E+03			
%COV	4.46%	4.12%	2.37%			

These results did not match the predicted failure load and also failed in a different location in the fiber reinforced parts (Figure 49). This made comparison to the predictive model difficult. The difference appears to have come from poor bonding of the overmolded material to the preform material. Additional parts would be run and tested with a new preform design.

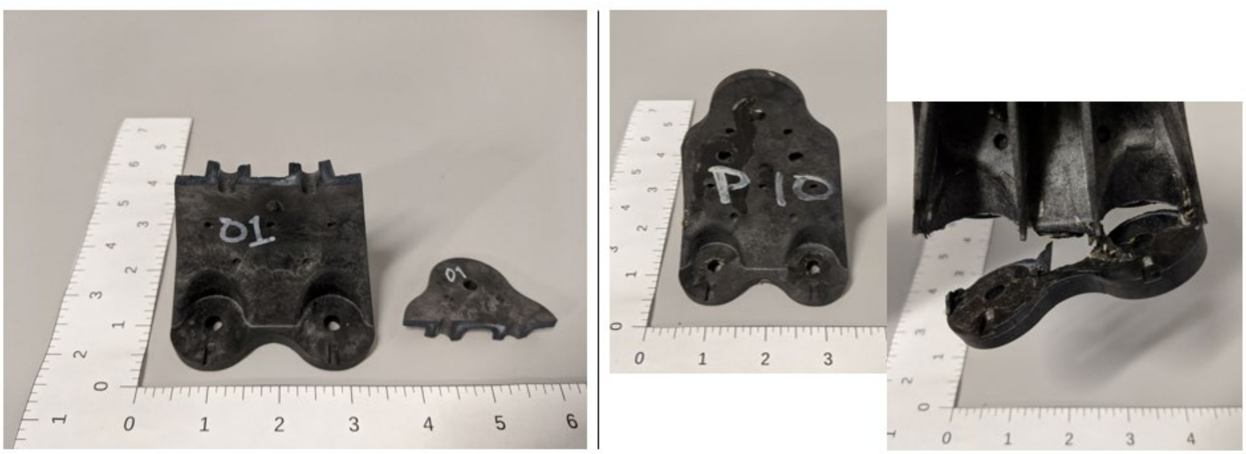


Figure 49 - Baseline Bracket Post Test (Left), Fiber Reinforced TFP Preform Bracket Post Test (Right)

New preforms were designed to only reinforce the top section of the bracket and not introduce any preform in the lower section of the part to eliminate any poor bonding in the lower section of the part (Figure 50). The top only preforms would also eliminate many of the issues of hand loading the preform into the injection molding tool. Preforms were also designed that would double the amount of carbon fiber reinforcement in the lower part of the bracket.

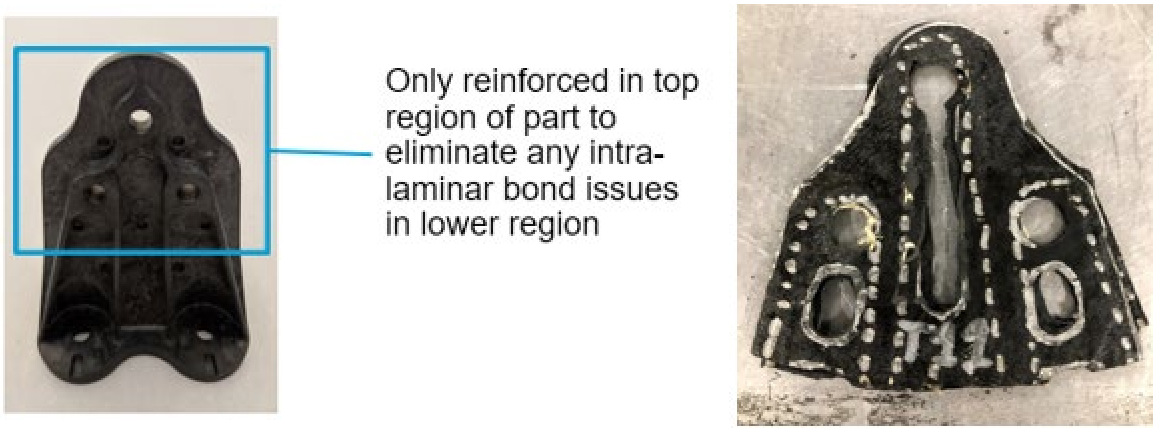


Figure 50 - Design of New Top Only Preform

Parts were molded and tested with the new top only preform design (Table 5 & 6).

Table 5 - Top Only Preform Tensile Results

Specimen ID	Peak Load (lbf)	Displacement at Break (in.)	Fixture bolt torque (in-lbs)	Failure Description	Notes
T11	3846	0.096	20	Top of part, along bottom 2 bolt holes	Complete fracture (2 pieces) at bolt holes
T12	3978	0.096	20	Top of part, along bottom 2 bolt holes	Complete fracture (2 pieces) at bolt holes
T13	4781	0.111	20	Top of part, along bottom 2 bolt holes	Audible heard at 3000 lbs
T14	4148	0.094	20	Top of part, along bottom 2 bolt holes	Complete fracture (2 pieces) at bolt holes
T15	3791	0.091	20	Top of part, along bottom 2 bolt holes	Audible heard at 2700 lbs
Mean	4109	0.0976			
Std. Dev.	357.9	0.0069			
%COV	8.71%	7.12%			

Parts molded with the top only preform failed at the top holes in the same failure mode as the baseline parts.

Parts were molded and tested with the doubled lower area (Figure 51).

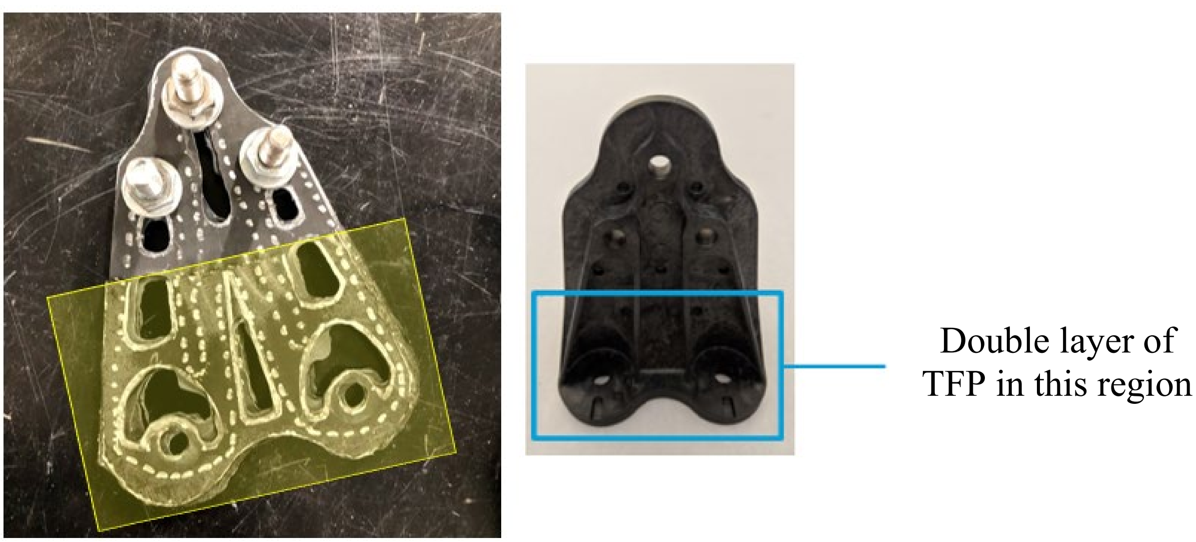


Figure 51 - Doubled Lower Section Preform Design

Table 6 - Doubled Lower Preform Tensile Results

Specimen ID	Peak Load (lbf)	Displacement at Break (in.)	Fixture bolt torque (in-lbs)	Failure Description	Notes
D01	4203	0.11	20	Top of part, along bottom 2 bolt holes	Complete fracture (2 pieces) at bolt holes
D05	4635	0.117	20	Bottom of part, at base flange	Audibles heard at 2500 lbs
D06	4714	0.112	20	Bottom of part, at base flange	Audible heard at 3000 lbs.
Mean	4517	0.1130			
Std. Dev.	224.6	0.0029			
%COV	4.97%	2.61%			

The parts molded with the doubled lower preform all failed at the bottom of the part.

Looking at the tensile test data without outliers we see:

- Baseline 4274 lbf
- Unreinforced Preform 3859 lbf
- TFP Reinforced 4431 lbf
- Top Only TFP 4109 lbf
- Double Thick Lower TFP 4517 lbf

It appears that all of the overmolded parts are experiencing some delamination.

Milestone 5.4.4.2 Mechanical performance of the bracket with the LayStitch preform has greater than a 25% improvement over the baseline materials of 20% wt. carbon filled PEI "T" brackets.

Compared to the baseline part, the best tensile performance increase was only a 5% increase. If we use the unreinforced preform as a baseline to account for the performance decrease due to the poor bonding, we see a 17% increase in tensile load. It is difficult to determine how these translate to performance if the bonding issue was not present.

A clear path forward to eliminate the poor bonding is to design the preform from a lower melt temperature but compatible material. This has been demonstrated with continuously-reinforced Victrex polyaryletherketone (PAEK) composite substrates over molded with polyetheretherketone (PEEK) [2]. With PEI as the injection overmolding polymer, lower melt temperature but compatible polymers such as polycarbonate could be investigated to make preforms. The design of the part can also contribute to improved molding conditions along with better mechanical interlocking of the preform to the overmolded polymer.

Milestone 5.4.4.3 Demonstrate that the analytical tools used to design and analyze the TFP preform molded brackets correlate with the measured test results within +/- 15%.

Predictive modeling predictions ended up giving very accurate results, especially based on the complexity of the model. Both the baseline model and TFP reinforced model ended up meeting the goal of Milestone 5.4.4.3. The baseline predictive analysis showed failure initiation at 4498.2 lbf within 6% of the 4274 lbf of the test data. The TFP reinforced model showed failure at 5132 lbf compared to the predicted 4517 lbf of the tested samples, a 14% difference.

5. BENEFITS ASSESSMENT

By using injection overmolding with continuous carbon fiber TFP preforms, brackets can be designed and manufactured at lower weight and cost. Brackets have the potential to be half the weight of aluminum brackets and manufacturing cost can be significantly lower.

Time studies indicated that 10 minutes is needed to stitch one complete bracket preform, although this is expected to be significantly less when ran on a more production-appropriate machine. Per ZSK, one technician can run an 8-head machine independently, meaning one technician can produce 48 preform sets per hour. If a fully burdened hourly rate of $80/hr is assumed, the 48 preform sets made on one machine per hour would cost $1.67 per preform for labor. In a single shift, the equipment could make almost 100,000 preforms in a year.

Preconsolidation and trimming of the preforms would also be needed. If a roll-to-roll TFP machine is used (Figure 52), the roll of preforms could be placed between layers of polymer (also in roll form) and fed through heated rollers. Once infused/consolidated, a second set of rollers, equipped with die cutters, could be used to trim preforms to final shape. These production costs are estimated at $0.84 per part, given that production throughput should be at least twice as fast as the TFP preform manufacture and that the equipment would be very low tech.

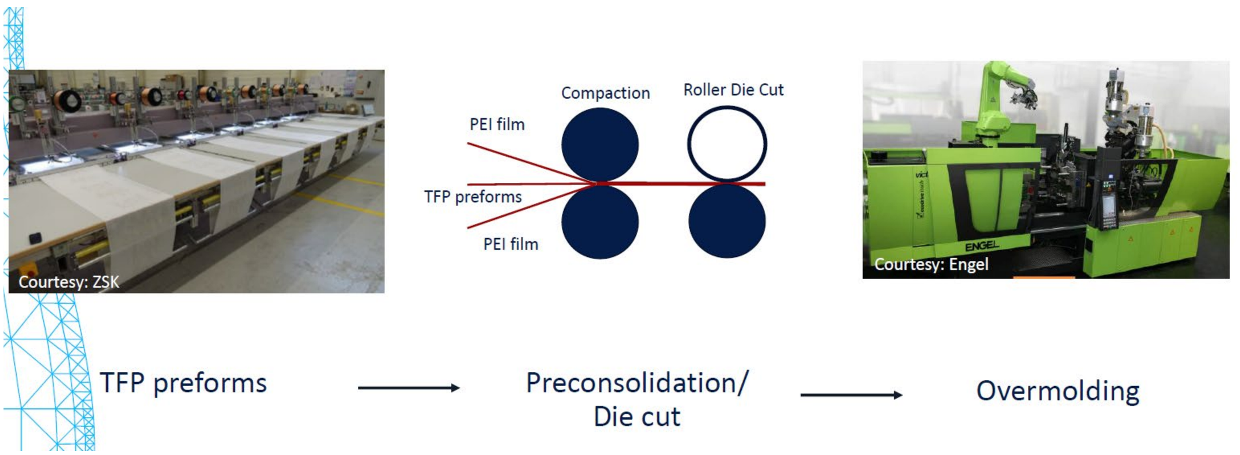


Figure 52 - Manufacturing Concept for Production

Other manufacturing costs, such as overhead, equipment depreciation, operational costs, maintenance, etc. are not well understood by the team. An estimate of $200,000 annually for the work cell was used for the sake of this study. At roughly 100,000 preforms per year, this cost amortizes to $2 per part set.

Cost of the carbon and Ultem sheets are estimated at $0.25 per preform set in volume. Per Velocity's quote (see Appendix), injection molding costs, including feedstock, are $5.60 per part in volumes of 100,000.

Totaling these expenses, a final bracket cost of $10.36 is shown for the injection overmolded part. The price of the aluminum version at production level was not available to the team, although at low volumes, it was quoted as $300. For the sake of this cost study, the team used an aluminum bracket from Airbus that did have production-level pricing information (Figure 53). This bracket costs $150 in volumes of 100,000, although it is substantially smaller and less complex than the bracket made in this program. Even at this reduced size and complexity, the injection overmolded part provides an order of magnitude cost reduction.

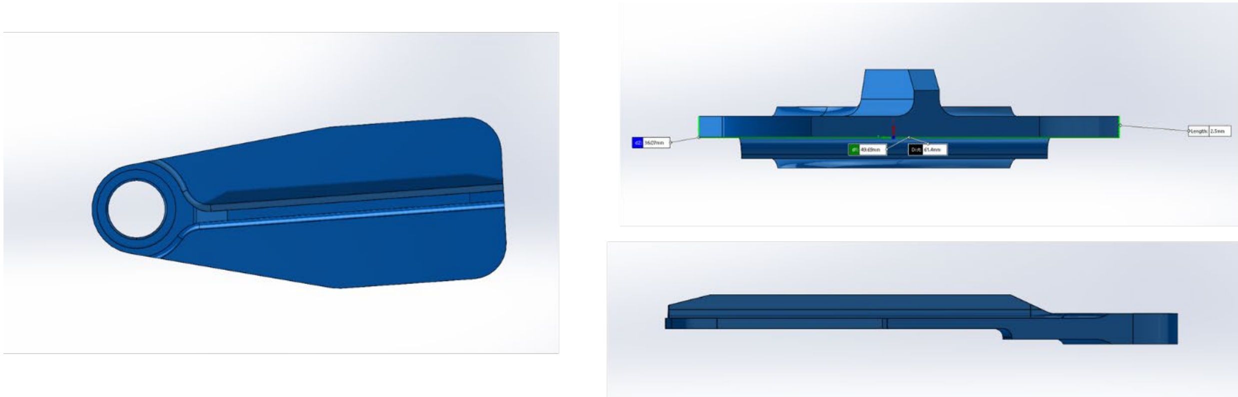


Figure 53. Alternate Airbus bracket used for cost study, approximately 5" x 2"

6. COMMERCIALIZATION

In order to move forward with commercialization, a specific bracket would need to be identified. Once identified, load cases and specific requirements would need to be known. Upon laying out the design requirements for a specific bracket, UDRI is prepared to work closely with Velocity Group, LLC to design a part that will both be optimized for the injection overmolding process and the specific requirements of the part function. Velocity Group has the ability to work through this at all stages of early development through final production. UDRI has the design and analysis skills to develop a part that will meet or exceed the design requirements.

Potential barriers to commercialization could include selection of an appropriate preform film material and development of manufacturing equipment to pre-consolidate and cut preforms. Material selection to enable sufficient bonding between the preform and the injecting polymer is critical. The preform material needs to have a lower melting temperature to enable bonding but also needs to have a similar modulus of elasticity to be able to transfer loads to adjacent fibers in the composite. Custom equipment also will need to be built and proven to work seamlessly with the TFP stitching and film roll pre-consolidation along with the cutting of the preforms.

7. CONCLUSIONS

This project set out to develop a design methodology and manufacturing process to demonstrate the potential for injection overmolding continuous carbon fiber TFP preforms to produce high strength brackets that could replace aluminum or traditional composite parts. The project was able to demonstrate the potential for this type of part and made many steps toward a viable manufacturing process. The design methodology was also demonstrated to be able to predict performance of such parts. Continuous carbon fiber reinforced injection overmolded parts in PEI have great potential in the aerospace industry. The processes developed in this project could extend to other polymers, fibers, and industries.

8. RECOMMENDATIONS

Further work with refining the design process, material selection, tool design and the injection molding process will be able to yield a viable manufacturing solution for aerospace brackets along with countless other applications. There is also considerable work that should continue around commingled fiber for use in injection overmolding applications. Much of this work could be accelerated through the selection or real world use cases with known requirements. Existing brackets with known engineering requirements and design constraints would be good candidates to move this technology forward.

Additionally, follow up work in matching preform film materials to the overmolding polymer can be investigated to optimize material bonding. This will allow for parts to meet the loading requirements. Also, considerable follow up on developing the continuous manufacturing process of TFP pre-consolidated preforms should be explored.

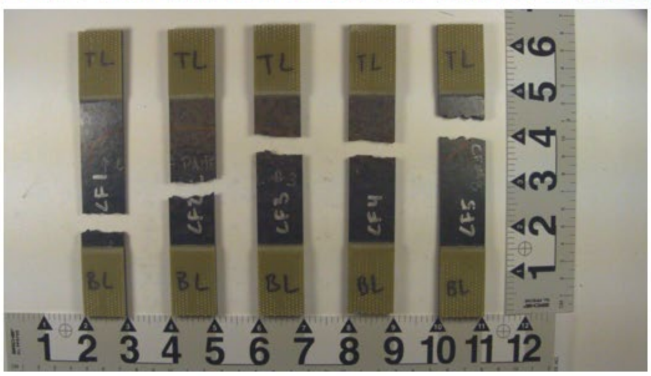
9. REFERENCES

1. https://www.ptonline.com/articles/the-new-lightweights-injection-molded-hybrid-composites-spur-automotive-innovation

2. https://www.compositesworld.com/articles/overmolding-expands-peeks-range-in-composites

10. Appendix

PEI Flat Short Carbon Fiber Filled Panel Initial Results



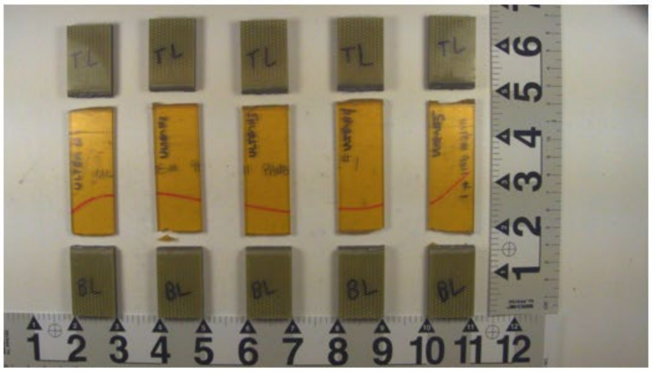
- EC004APQ 20% Carbon Fiber Filled Ultem
- Tensile strength at break:
  - From data sheet 35.5 ksi
  - From test 10.025 ksi

Results Table 1

	Specimen label	Area (in^2)	Extension @ Max. Load (in)	Maximum Load (lbf)	Maximum Tensile stress (ksi)	Modulus (ksi)	Strain to Failure %	Failure Mode	Test Time
1	CF1	0.1259	0.092	1,300.7	10.331	924.09	1.24	LGB	10/25/2019 10:22 AM
2	CF2	0.1288	0.089	1,246.2	9.675	886.13	1.29	LGM	10/25/2019 10:30 AM
3	CF3	0.1297	0.086	1,234.8	9.520	776.99	1.42	LGT	10/25/2019 10:38 AM
4	CF4	0.1313	0.060	1,186.2	9.034	797.58	1.24	LGT	10/25/2019 10:54 AM
5	Cf5	0.1337	0.087	1,546.0	11.563	884.10	1.50	LGT	10/25/2019 11:02 AM
Mean		0.1299	0.083	1,302.8	10.025	853.78	1.34		
Std Dev		0.003	0.013	141.918	0.977	63.177	0.116		
Coeff of Var %		2.23	15.75	10.89	9.75	7.40	8.69		

Figure A-1 - Flat Plate Tensile Test Results for Short Carbon Fiber Filled PEI

PEI Flat Neat Ultem Panel Initial Results



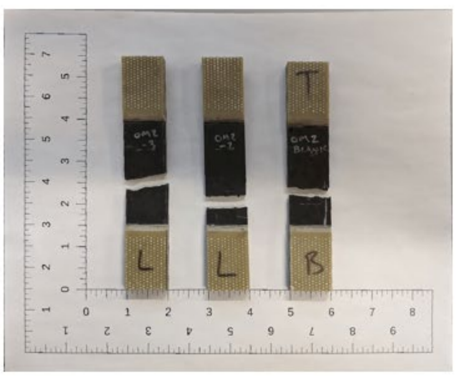
- Ultem 9011
- Tensile strength at break:
  - From data sheet 15.2 ksi
  - From test 10.6 ksi

Results Table 1

	Specimen label	Area (in^2)	Extension @ Max. Load (in)	Maximum Load (lbf)	Maximum Tensile stress (ksi)	Modulus (ksi)	Strain to Failure %	Failure Mode	Test Time
1	Ultem #1	0.1361	0.114	1,435.7	10.549	466.04	2.66	LMV	10/25/2019 11:17 AM
2	Ultem #2	0.1354	0.105	1,356.9	10.021	467.62	2.50	LMV	10/25/2019 11:26 AM
3	Ultem #3	0.1353	0.102	1,337.0	9.881	479.40	2.40	LMV	10/25/2019 11:34 AM
4	Ultem #4	0.1361	0.115	1,445.1	10.618	476.48	2.70	LMV	10/25/2019 11:41 AM
5	Ultem #5	0.1381	0.139	1,651.9	11.961	465.73	3.29	LMV	10/25/2019 11:49 AM
Mean		0.1362	0.115	1,445.3	10.606	471.05	2.71		
Std Dev		0.001	0.014	124.817	0.823	6.410	0.348		
Coeff of Var %		0.83	12.56	8.64	7.76	1.36	12.85		

Figure A-2 - Flat Plate Tensile Test Results for Neat PEI

PEI Flat "Overmolded" Panel Initial Results



Results Table 1

	Specimen label	Area (in^2)	Extension @ Max. Load (in)	Maximum Load (lbf)	Maximum Tensile stress (ksi)	Modulus (ksi)	Strain to Failure %	Failure Mode	Test Time
1	OM2-2	0.1401	0.109	1,970.4	14.064	1,256.48	1.04		10/14/2019 2:38 PM
2	OM2-3	0.1439	0.112	1,982.0	13.773	1,248.00	1.37		10/14/2019 2:44 PM
3	OM2 Blank	0.1384	0.123	1,971.8	14.247	1,074.07	1.66		10/14/2019 2:48 PM
Mean		0.1408	0.115	1,974.7	14.028	1,192.85	1.36		
Std Dev		0.003	0.007	6.342	0.239	102.954	0.308		
Coeff of Var %		2.00	6.49	0.32	1.70	8.63	22.73		

Figure A-3 - Flat Plate Tensile Test Results for "Overmolded" Single Tow Samples

D638 Tensile
Longitudinal Strain (Extensometer)

Customer	IACMI Airbus
Job Number	CVM
Banner No.	LUN1C1
Laboratory Name	Advanced Composites Group
Instron Test Method	ASTM D638 Tensile Properties w/ Extensometry Controlled 10.4.19
PI Work Request	CVM-AD-20-002
Operator ID	J. Lotz
Panel I.D.	Panel #8
Material	Overmolded
Test Speed (in/min.)	0.20
Test Conditions	RTA
Temperature (°F)	72.
Humidity RH (%)	47.
Load Cell FS (lbs)	1,000 lbs
Test Frame ID	55R1123CP7351
Test Date	2-7-2020

Sample note 1

Results Table 1

	Specimen label	Area (in^2)	Extension @ Max. Load (in)	Maximum Load (lbf)	Maximum Tensile stress (ksi)	Modulus (ksi)	Strain to Failure %	Failure Mode	Test Time
1	A-8-1	0.1191	0.075	3,478.2	29.204	2,405.62	1.24	AWB	2/7/2020 10:38 AM
2	A-8-2	0.1190	0.077	3,506.4	29.466	2,384.51	1.26	LWB	2/7/2020 10:59 AM
3	A-8-3	0.1206	0.070	3,139.4	26.031	2,053.77	1.38	LGM	2/7/2020 11:18 AM
4	A-8-4	0.1179	0.065	2,969.5	25.187	2,444.11	1.08	LGM	2/7/2020 11:37 AM
5	A-8-5	0.1209	0.082	3,793.7	31.379	2,751.79	1.29	LWB	2/7/2020 11:52 AM
Mean		0.1195	0.074	3,377.5	28.253	2,407.96	1.25		
Std Dev		0.001	0.007	325.245	2.573	247.755	0.111		
Coeff of Var %		1.04	8.93	9.63	9.11	10.29	8.89		

Figure A-4 - Flat Plate Tensile Test Results for Carbon Filled PEI with 7 Tows per Inch

VELOCITY GROUP

Velocity Concept Development Group, LLC

534 North First Street
Cambridge Ohio 43725
United States
1-740-432-2969

Quote Number: 13596

QUOTE

Quote To:	
UNIVERSITY OF DAYTON RESEARCH 1700 S PATTERSON BLVD DAYTON OH 45469 United States	Date: 12/7/2020 Expires: 12/21/2020 TermsDesc: Net 30 Days Reference: Sales Person: Adam Terpstra

USD

Line	Part / Description	Rev	Drawing	Quantity	Unit Price	Ext. Price
1	TOOL AIR BUS BRACKET 2 CAVITY TOOL			1.00	80,000.00	80,000.00

BUDGETARY PRICING TO DESIGN AND BUILD A H13 2 CAVITY TOOL

$70,000- $80,0000

- QUANTITY BREAKS -

Quantity	Unit Price	Ext Price
1.00 EA	80,000.00 /1	80,000.00

Line	Part / Description	Rev	Drawing	Quantity	Unit Price	Ext. Price
2	BRACKET AIR BUST BRACKET			0.00	0.00	0.00

PIECE PART PRICE TO MOLD AIRBUS BRACKET FROM ULTEM 2300

PRICE ASSUMES NO OVERMOLD

MOLD SET UP CHARGE 150.00 FOR ALL ORDERS LESS THAN 5,000 PARTS

- QUANTITY BREAKS -

Quantity	Unit Price	Ext Price
100,000.00 EA	5.60 /1	560,000.00

Quote Total	80,000.00

Delivery above is after receipt of purchase order. Quote does not include packaging, handling, consulting fees and other related expenses. Minimum finance charge: 2% / month on overdue invoices. Visit us at: www.velocityfast.com

Figure A- 5 - Quote for injection overmolding production quantities of simplified corner fitting bracket