2018

Manufacturing a Composite Wheel Prototype Using 3D Printed Molds

Steven Thuening
Minnesota State University, Mankato

Manufacturing a Composite Wheel Prototype Using 3D Printed Molds

By

Steven Thuening

A Thesis Submitted in Partial Fulfillment of the

Requirements for the Degree of

Masters of Science

In

Manufacturing Engineering Technology

Minnesota State University, Mankato

Mankato, Minnesota

April 2018

4/2/2018

Manufacturing a Composite Wheel Prototype Using 3D Printed Molds

Steven Thuening

This thesis has been examined and approved by the following members of the student's committee.

____
Advisor – Dr. Jones

____
Committee Member – Dr. Agarwal

____
Committee Member – Dr. Ahmed

Abstract

Title: Manufacturing a Composite Wheel Prototype Using 3D Printed Molds

Steven Thuening for the degree of Masters of Science in Manufacturing Engineering Technology from Minnesota State University, Mankato in April 2018

Throughout the evolution of high performance racing, a large emphasis has been on reducing the weight of the vehicle in order to improve its performance. Over the years, new designs and materials have been introduced reducing weight in a variety of different locations. Comparing weight reduced in different areas has shown that some areas are more valuable to reduce than others are. Perhaps one of the most beneficial locations are the wheels. This is because the mass of the wheel is considered unsprung and rotational. Because of this, large improvements towards the reduction of wheel mass have been developed in regards to design and material selection. Currently, the highest performance wheels are manufactured using carbon fiber reinforced in plastic.

Recently, manufacturing of a composite wheel has become more and more popular and is produced on a production car level all the way down to lower budgeted teams. Typically, to manufacture a composite wheel, expensive molds are machined out of large pieces of aluminum, and special tooling is required. This creates a poor environment for prototyping. If a flaw is found in the design, it can cost the manufacturer a considerable amount of time and money. For these reasons, a manufacturing method using inexpensive 3D printed molds was explored. This thesis will cover the development of the manufacturing process using 3D printed molds.

Table of Contents

Table of Figures

Chapter 1: Introduction

"Automobile racing began soon after the invention of the gasoline- (petrol-) fueled internal-combustion engine in the 1880s." (Britannica). Over 130 years later, automotive racing has turned into an extremely exciting, diverse and competitive sport. To win, it is simple, cross the finish line before your opponent does. This competition has provoked innovation from the drivers and teams to increase the performance of their vehicles whether it is: more power from the engine, better suspension or less vehicle mass. This has been accomplished by using new materials, radical designs and computer software.

In a racing series with fewer limitations and greater overall freedom, more unique designs and greater development can occur, an example of a series like this is the Formula SAE (FSAE) International Collegiate Design Series (SAE International). In the FSAE competition, students are challenged to design, manufacture and compete a single seat, open-wheeled racecar. Rules are in place to keep the cars relatively similar and competitive, and to meet safety standards, but other than that, anything is possible. This is a perfect condition where unique and innovative ideas can be cultivated. Figure 1 is an example of a typical vehicle competing within this series.

Figure 1 - MSU Motorsports FSAE Vehicle

Using the FSAE collegiate competition, this thesis will investigate the development and manufacturing of a composite wheel prototype using 3D printed molds. The composite wheel will be designed to be used within this series. In particular, the wheel was designed for the use on the Minnesota State University-Mankato (MSU Motorsports) FSAE vehicle. This will consist of a 10 inch x 7.5 inch wide wheel with an appropriate backspacing to work with the team's suspension design.

1.1 Objectives

The focus of this thesis will be on manufacturing a composite wheel using 3D printed molds and other resources available at Minnesota State University, Mankato (MSU). The process will consist of: prepreg carbon fiber reinforced in plastic, 3D printed molds using ABS plastic, a vacuum bag system, an oven, a CNC mill and a lathe. Throughout the exploration of the process, these are the major components needed, and they will be explained in greater detail later. There currently are composite wheels designed for the use in the FSAE series. Using these as examples, the manufacturing process was explored. Since the purpose of this thesis is not on the design and analysis of the wheel, the design of the wheel was generated using a collaboration of specific dimensional requirements from MSU Motorsports and other comparative composite wheel designs.

1.2 Limitations

The manufacturing process of this wheel design was to work with the equipment and resources available at the Minnesota State University – Mankato campus. The Mankato campus has an Engineering Projects Lab that would resemble a typical machine shop. The layup process was to be done manually on campus due to budget and time constraints.

1.3 General Requirements

The wheel was to be manufactured to meet all of the requirements needed for a wheel used on the MSU Motorsports' FSAE vehicle. In the FSAE rulebook, section T6.3.1 "The wheels of the car must be 203.2 mm (8.0 inches) or more in diameter" (FSAE 2018). Being that the team uses a 10 inch wheel, this is not an issue. The next requirement was to have a wheel to be used in conjunction to the team's current suspension design. This included a 5" backspacing, 4x100 bolt pattern and a hub-centric mounting design. Next, the packaging limitations of the components located within the wheel needed to be considered. These components include the upright, hub, control arms and brake assembly. Figure 2 demonstrates how these components are typically packaged. After taking all of these factors into consideration, the design for the wheel was generated. This will be discussed in a later chapter.

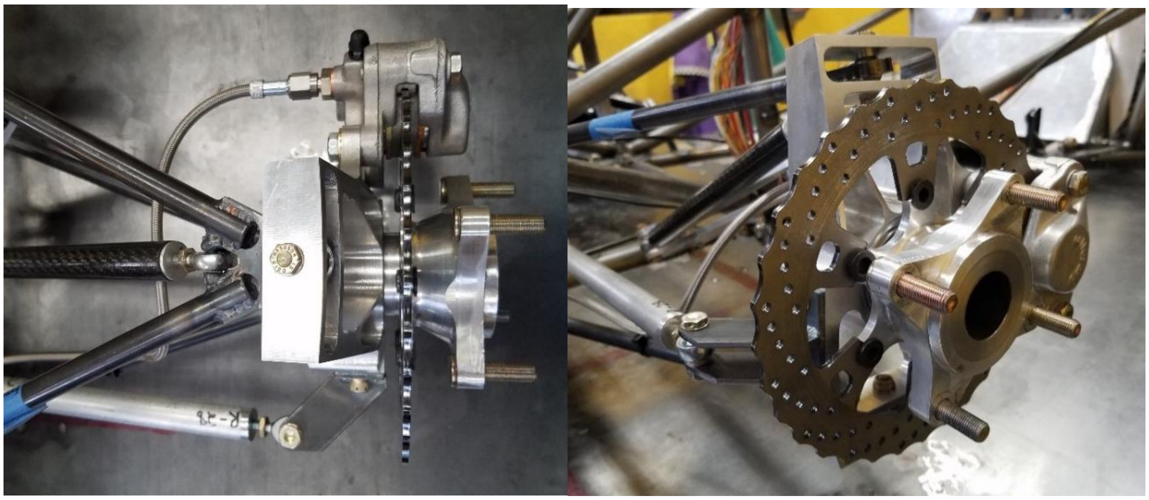


Figure 2 – Front suspension components

1.4 Significance of Wheel Mass

Through the development of racing, a large amount of time and energy has been focused on reducing the mass of each component. Because a vehicle is made up of so many components, mass can be reduced in a variety of different areas. Reducing the overall mass of the vehicle (while retaining the other characteristics) will always make the vehicle faster. By having less mass, the vehicle will be able to accelerate in any direction using less energy (acceleration, deceleration and cornering). However, reducing mass in certain areas such as: with the engine, a lighter rotating assembly; with the chassis, a tubular or monocoque design; with the suspension, reducing the unsprung mass will have a greater effect in regards to the vehicle's performance.

A large focus on mass reduction throughout the vehicle has been on the unsprung and rotational mass. The unsprung mass is any mass not supported by the springs. These components typically include tires, wheels, hub assemblies, brake assemblies, and part of the suspension arms. Everything else such as the chassis, engine and driver are all supported through the springs and dampening system. “Reducing unsprung weight is the key to improving handling” (Technical F1). Less unsprung mass means less work the springs and shocks have to exert to keep the tire in contact with the ground, thus increasing the possible grip available from the tires. Another benefit of reducing the unsprung mass is that it lowers the moment of inertia of the vehicle as a whole. This is because the unsprung mass is typically farthest from the axis (or pole) the vehicle rotates around. By reducing the moment of inertia, the vehicle will be able to rotate using less energy. Similarly, reducing rotating mass (wheels and tires) will have the same affect in regards to the axis the wheel and tire rotates about. The mass isn’t as far from the axis in the example of the vehicle as a whole, but the change in revolutions per minute is considerably higher (found during accelerating and braking). A simple example of this is a figure skater spinning on the ice. As the individual rotates, they can increase their angular velocity by pulling in their limbs or better centralizing their mass. In regards to a FSAE vehicle, reducing 2 pounds in the four corners will yield better performance when compared to reducing 8 pounds near the engine or driver (both typically located near the axis).

Chapter 2: General Design

The focus of this chapter will be towards the overall design of the wheel used in this research project, as well as the mold designs used for the wheel. Since the focus of this thesis is on exploring the manufacturing method, a computer simulated analysis of the loading characteristics was not done, even though they were considered. Instead, the design for the wheel was generated in regards to existing designs and research, for example, the design and analysis by Hans Walther for Jayhawk Motorsports (Figure 3) and the wheels developed by Tu Graz Racing (Figure 4 and Figure 5).

Figure 3 - Composite wheel developed by Hans Walther

Figure 4 - Composite wheel design developed by Tu Graz Racing


Figure 5 - Tu Graz Racing's hollow wheel section

2.1 Wheel Anatomy

Before going into the overall design of the wheel, a few terms need to be considered first, for example: drop center, bead seat, inner and outer flange, back spacing and offset. Figure 6 shows the different parts associated with a typical wheel. The drop center part of the wheel is used to aid in installing and removing the tire from the wheel. Without the drop center, the tire would need to be stretched drastically to fit over the flanges of the wheel possibly resulting in damage to the wheel or tire. This area allows the tire slip over the flanges with ease. Next, the bead seat and flanges are where the tire makes contact with the wheel. This is also where most of the loading is transferred from the tire to the rim. Finally, the back spacing or offset are used for fitment of the wheel to the vehicle. In regards to a FSAE vehicle, they are used to get the proper track width and clearance of the suspension components.

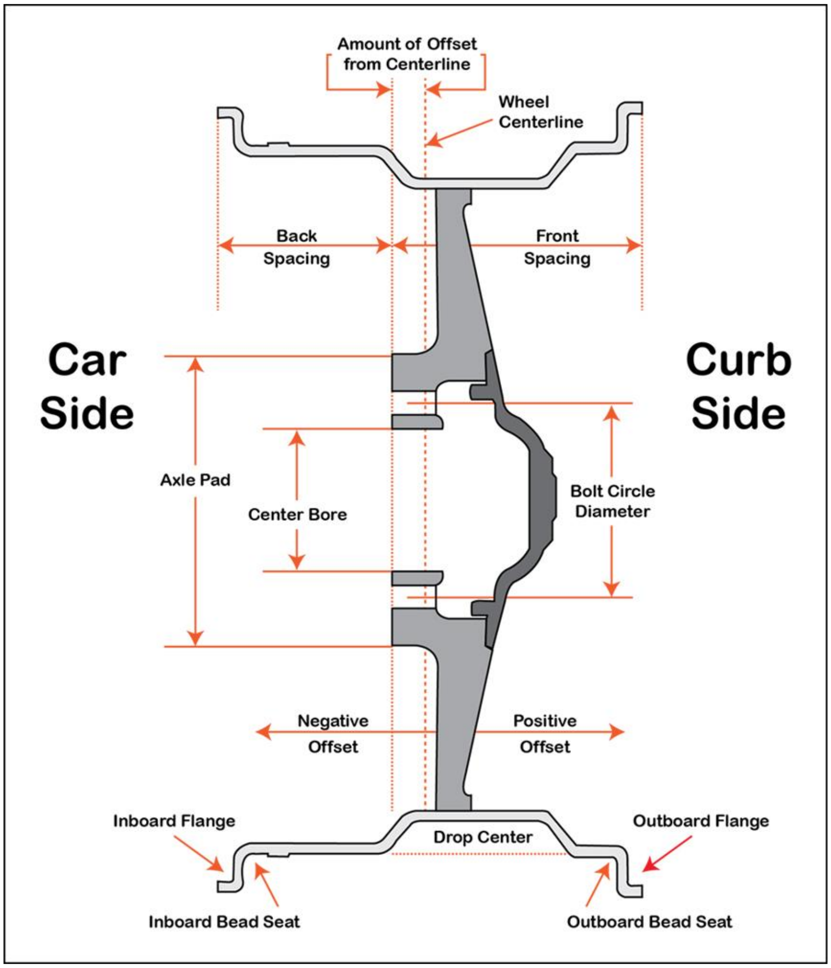


Figure 6 - Diagram of a Wheel

2.2 Design Requirements

Working with the 2018 Formula SAE team MSU Motorsports, the dimensions for the wheel design were implemented to fit their needs. The team was already using a three-piece aluminum wheel from Keizer that used a hub centric mount and a 4x100 bolt pattern. The tire they choose was an 18.0x7.5-10 from Hoosier. The manufacturer recommends a rim width of 7-8 inches. They designed their suspension to work with a 10”x7.5” wheel with a 5” backspacing. Their current wheel weighs 5.29lbs. Using the wheel and tire dimensions their suspension was designed for, the design for the composite wheel could begin.

The overall design of the wheel was to fit the team's needs and to be a four-spoke design. A four-spoke design was used, so the mold sections could be universal. This will be discussed in greater detail later. Figure 7 illustrates the revised wheel design used in this thesis. Next, the drop center and bead-flange profile was designed to replicate that of the 10" Keizer wheel. The drop center and flange must work in unison, if the flange is too large, or the drop center not deep enough, the tire will become extremely difficult to install or remove from the wheel, possibly causing damage to the wheel. The location of the drop center isn't as critical when compared to the depth of it. With that being said, the drop center was located so it would work in conjunction with the spoke design, as well as, the parting line required for the molding process. Through trial and error, the design was changed multiple times to fix issues that came up during tests and to aid in the manufacturing process.

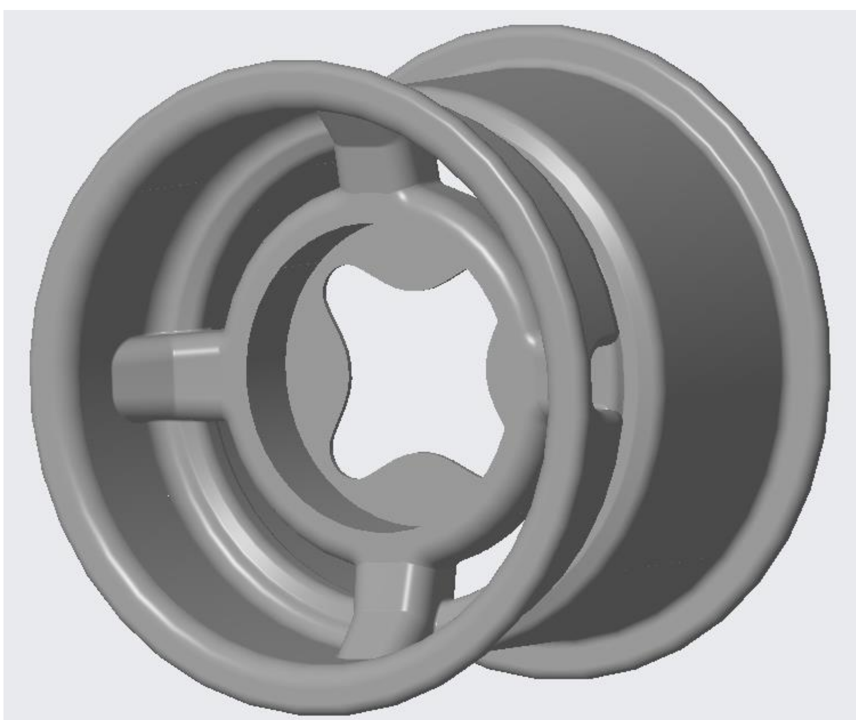


Figure 7 - Final design without the center section

Working with the four-spoke design, the composite wheel was design to use a center section. The center section was designed to be made separately out of aluminum and glued in afterwards using an epoxy. The reasoning for this was to reduce some of the overall complexity of the process. The center section is the portion of the wheel that will be in contact and secured to the face of the hub. This area of the wheel needs to hold very tight tolerances concerning the hub centric mount and bolt pattern. If these two areas have any discrepancies, there is a greater chance of the wheel not spinning true to the hub causing it to be unusable. After the aluminum section is glued in, the wheel will be put onto a lathe to remove any misalignments that might have developed during the layup process. This will be explained in detail in the manufacturing chapter.

To ensure there is sufficient strength between the center section and composite wheel, extra material was added to the composite to increase the bonding area between the aluminum and carbon fiber. In Figure 7, you can see the extra flange that will contact the back of the center section. There are few points to note, the cut out for the hub and the percent increase in contact area. First, this area was cut out to mimic the profile of the hub being used. By doing this, it will ensure an uninterrupted contact between the center section and hub face. Next, this flange will increase the amount of area for the epoxy to adhere to by 55%. This increased surface area will help to reduce the chance for the center section to shear from the outer composite section. Finally, this flange creates a positive stop for the center section reducing the chance of a misalignment of the two pieces during the bonding process. After the two pieces are joined together, the design will need some post processing to remove any misalignment that may have developed between the two. Once the post processing is done, the design of this composite wheel had a projected weight of 2.85 pounds, 2.35 pounds for the composite portion and 0.50 pounds for the aluminum center section. Figure 8 is a computer model of the two pieces, and how they are designed to be orientated.

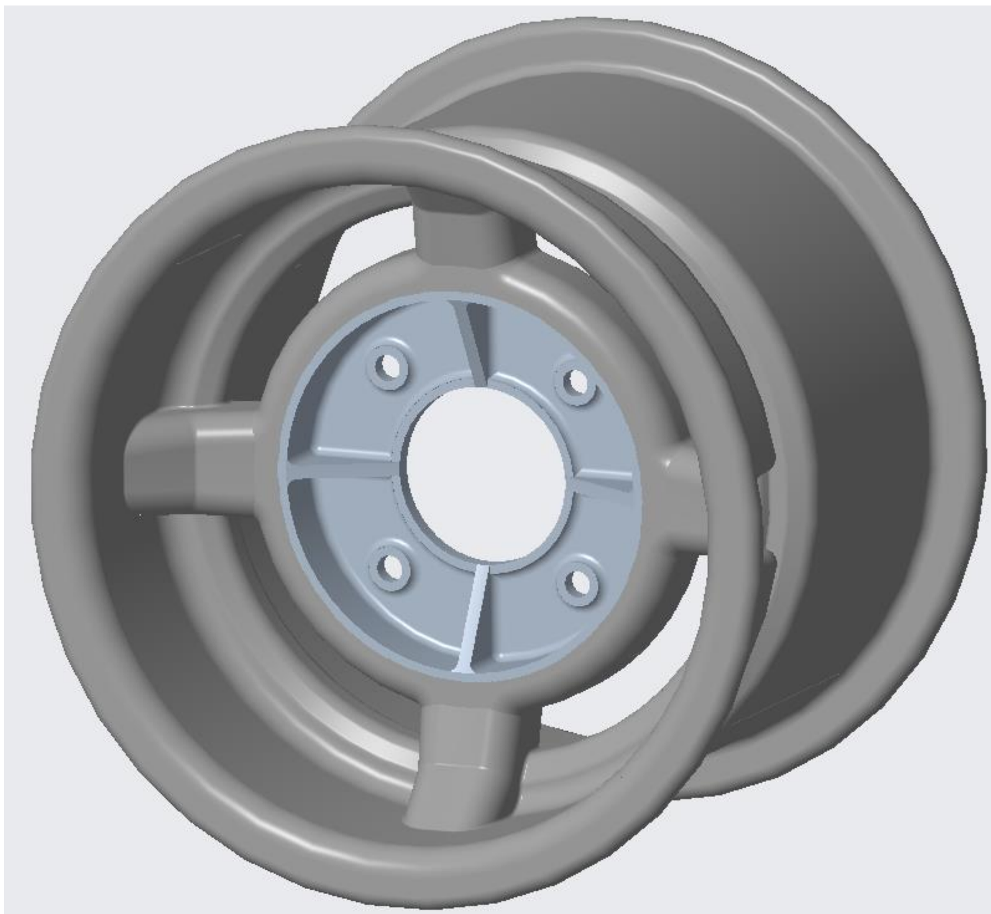


Figure 8 - Final design with aluminum center section

2.3 Material Selection

Throughout the growth of the automotive racing industry, wheels have been made from a variety of different materials. Early on, they were made out of steel and later aluminum, and they still are made from both of these materials. With the advancement of computer software, performance rims made from steel or aluminum have seen a reduction in weight due to computer aided designs and simulation software. By using a variety of different software packages, designers are able to keep material where it is needed and reduce material in areas where it is not. Recently, wheels made from these materials have begun to reach a plateau in regards to reducing material while safely retaining an appropriate strength and stiffness. Because of this, different materials were explored in attempts to surpass this plateau. At first, different metals, mainly magnesium, were used gaining some performance characteristics when compared to steel or aluminum. However, most of these were quiet costly compared to the weight savings and performance gains. As carbon fiber became more prevalent as a lightweight stiff material, it transitioned into a suitable material for manufacturing a wheel, an example of the weight savings by switching to carbon fiber can be seen by Koenigsegg. On one of their high performance production cars, they previously used a wheel that was 19”x10” made from forged aluminum that weighed 22lbs. A wheel with the same dimensional requirements made from carbon fiber weighed 13lbs. They would later state that the wheel made from carbon fiber was also stiffer than the forged aluminum wheel.

To manufacture a laminate such as this, the most common method is to use a fabric that is already pre-impregnated with a resin matrix, commonly known as prepreg. This allows multiple layers to be laid over a considerably longer working period. Unlike a typical wet-layup process, where the fabric and resin are separate and then later combined allowing to cure over a period of time. A prepreg fabric is infused with a resin that is cured using heat conventionally in an autoclave. Using a prepreg fabric, helps produce a laminate that has better resin saturation throughout while not over saturating causing an excess of weight. Different fabric materials can be pre-impregnated such as fiberglass or Kevlar, but perhaps the most common material is carbon fiber. Availability of prepreg carbon fiber has increased significantly over the past few years allowing a greater variety of components to be manufactured using carbon fiber reinforced in plastic.

2.3.1 Material Options

When choosing the specific prepreg carbon fiber, one will soon come to realize there is a large variety of different weaves or patterns to choose from. The weave or pattern of the fabric consists of how the carbon fiber strands (tow) are bundled together to create the fabric. The three most common patterns are perhaps the 1x1 plain pattern, 2x2 Twill weave (both seen in Figure 9) and a unidirectional pattern (Figure 10). Besides these three patterns, there is a large variety patterns giving different appearances and properties. An example of a different pattern is a hexagonal weave (Figure 10). Having a variety of different weaves, allows the strands to be orientated in a way that will give advantages and disadvantages. As an example, a 2x2 twill pattern will provide good strength and stiffness in a range of different directions; whereas, a unidirectional fabric is exceptionally strong along the direction of the fibers, and considerably weak if a load is applied perpendicular to the fibers. However, the unidirectional fabric can be significantly lighter than the 2x2 twill weave.

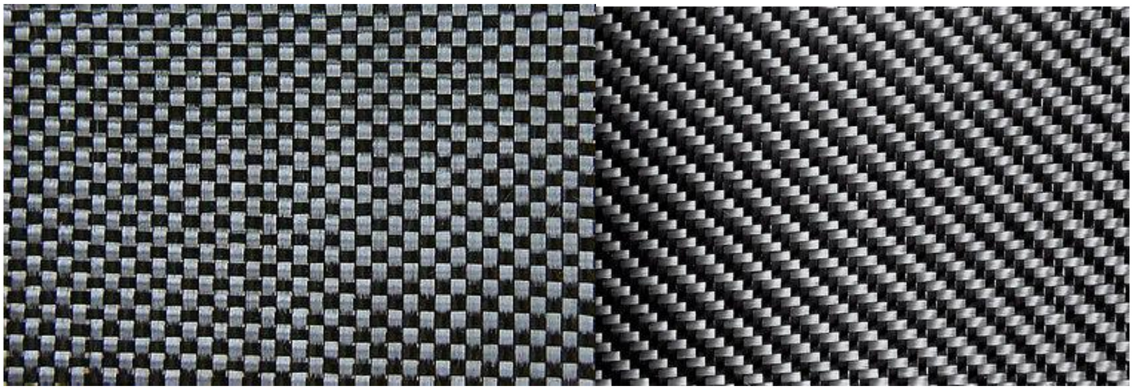


Figure 9 - Examples of 1x1 plain weave (left) and 2x2 twill weave (right)

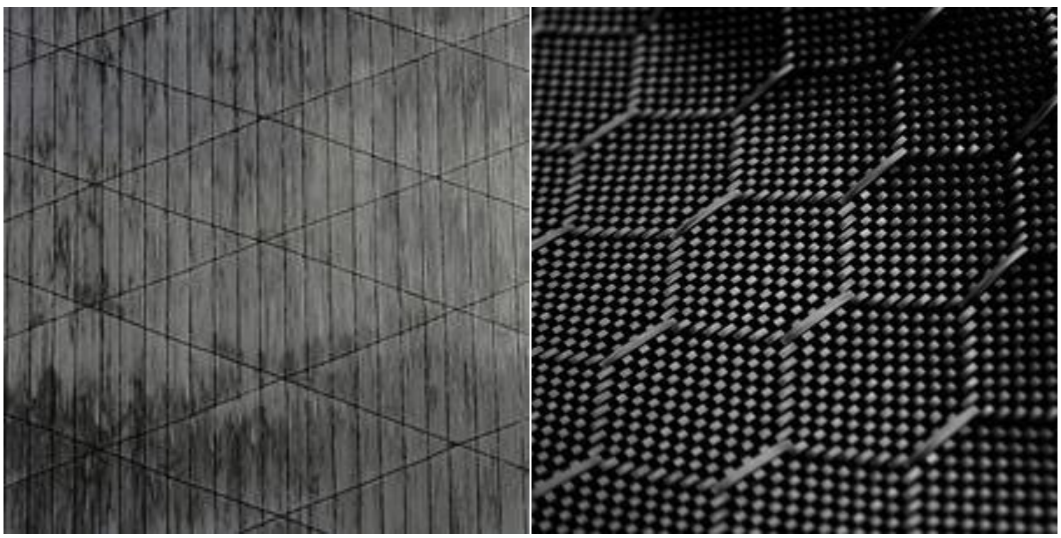


Figure 10 - Examples of unidirectional (left) and hexagonal (right) patterns

Depending on the weave or pattern, there can be different sizes available. For example, a 2x2 twill weave can come in sizes ranging from 1K-24K. The K refers to the number of thousands of individual carbon strands per bundle. Just like the different weaves, having a different amount of filaments per bundle, gives different characteristics. For example when comparing 3K to 12K, the 3K will be have a lower gsm (grams per square meter) with a thinner thickness. According to Carbon.ee, "3K carbon fiber is the most popular. It's light, relatively stiff and easy to get and make." The 12K carbon fiber, being heavier and thicker, is commonly used as backing plies behind layers such as 3K carbon fiber. This is because the material typically less expensive and appears robust with a larger pattern. Figure 11 illustrates the size comparison between the 12K and 3K tow.

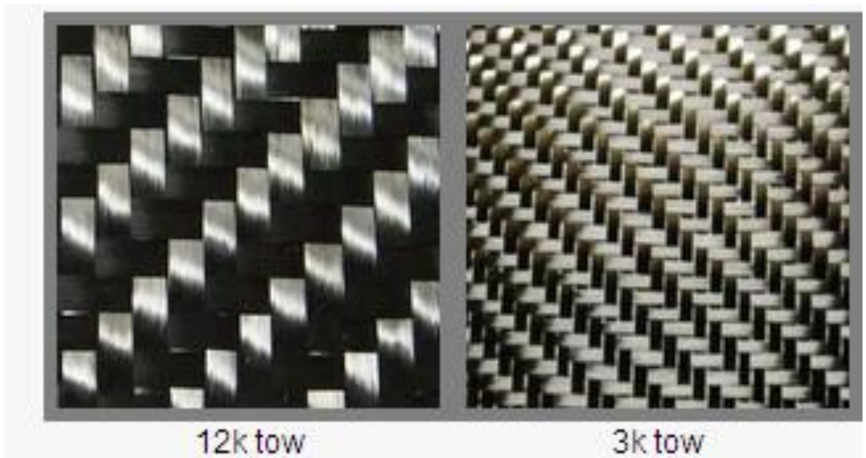


Figure 11 - Contrast between 12K and 3K tow

2.3.2 Selecting the Specific CFRP

The material selected for this thesis had a large consideration on manufacturability using the tools and resources available at MSU, as well as, compatibility with the 3D printed molds. Normally a prepreg carbon fiber material will require an autoclave reaching temperatures over 250° F or 120° C to cure; both the autoclave and curing temperature would be issues. First, since there was not an autoclave available at MSU, an out-of-autoclave procedure was explored. If an autoclave was not used to cure a conventional prepreg material, pinholes are commonly present on the surface and throughout the laminate. Next, the resin used in the prepreg needed to have the capability of curing at a temperature below the safe working temperature of the mold material. This will be covered in more detail during a later chapter. For these two reasons, the material chosen was the XPREG XC110 series from Easy Composites.

The XC110 is a type of prepreg carbon fiber with a 2x2 twill pattern. The XC110 uses a particular type of resin that could safely be used for this thesis (following the manufacturer's recommended processing guide and curing cycle). The XC110 series was designed to cure using an out-of-autoclave process. This material also had a 'Low Temp Cycle' available that would not bring the cure temperature (185° F or 85° C) higher than the molds could handle. Throughout this laminate, two different material options were used from the XC110 series: 3K, 210g and 12K, 450g.

2.3.3 Stacking Sequence

By following Easy Composites recommended stacking sequence and the analysis done by Hans Walther, a general stacking sequence was created. Using the XC110 material, Easy Composites recommends using two or more layers of the 3K as the surface plies and 12K as the backing plies. The 3K will give a good surface finish with minimal imperfections, and the 12K will provide good stiffness at a lower cost. The number of layers followed the number used by Hans Walther in "Development of a Lightweight Laminated Composite Wheel for Formula SAE Race Vehicles." His design and analysis of a carbon fiber wheel contained ten layers consisting of 1x1 3K plain weave and unidirectional material orientated in accordance to his simulations and analysis. Taking both of these into consideration, the stacking sequence for the wheel used in this thesis is as follows: three layers of 3K, five layers of 12K, and two layers of 3K.

2.4 Mold Design

Typically, when a wheel like this is manufactured, the molds are done in two pieces, an inner and outer half. Although this would be ideal, the printing area of the 3D printers available was not sufficient to print each half in one complete piece. Instead, both the inner and outer halves were to be made out of four sections each, eight sections total. As stated before, the molds used for the wheel were to be as universal as possible. This became a driving factor for the four-spoke design. Next, the parting line of the mold was placed in a particular location. This was to aid while applying the fabric and being released from the cured piece. Once the inner and outer portion of the complete mold were separated at the parting line, they were each broken down into four smaller sections. By doing this, the mold could be printed in manageable sections that would fit within the printing area of the particular printer that was used. The four spoke design worked in conjunction with this so only two separate mold designs were needed, one for the inner and one for the outer, both replicated 4 times. The molds were designed to be bolted together creating the inner and outer halves. Figure 12 illustrates a sectioned view of the mold consisting of four individual sections.

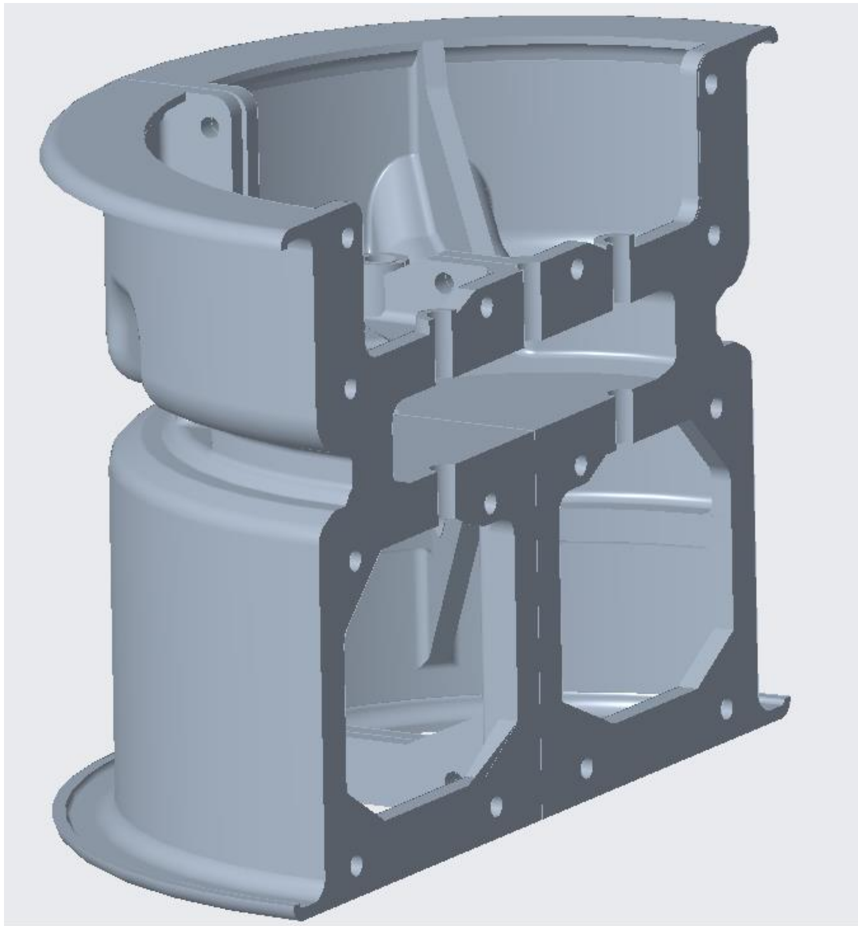


Figure 12 - Sectioned view of the mold design

The design for the mold can have a lot of different requirements that were not considered during the initial designing of the wheel. Perhaps the three most crucial requirements are: avoiding mechanical locks, the location of the parting line and reinforcement needed during the demolding process. Any piece that is to be made using a molding process needs to be able to be separated from the molds. Great consideration must be taken as to how each mold section will be separated from the piece being made. The more complex the shape, the more parting lines will be needed, so the mold is not locked onto the piece creating a mechanical lock. For the wheel, the locations of the drop center, center section, parting line and spoke design needed to work together to allow the molds to be released properly. During test #2, a mechanical lock was found, (an overview of each test sample is located in the appendix). There was difficulty removing the test piece from the mold, and the wheel design was reconsidered to remedy this issue. This was done by moving the drop center and the parting line accordingly.

By making the molds from printed plastic, it was found that the demolding process could apply a significant amount of strain to the molds; extra reinforcement was needed in particular areas. During test #3 the molds were attempted to be released in the manner as if it was a complete wheel. Meaning, they were to be pulled straight out from the laminate as opposed to removing it from the exposed edges. Two of the molds were destroyed during this process. This was thought partly because of two reasons: difficulty when pulling the mold since there was no area to sufficiently pull from, and not enough support in certain areas. Figure 13 is an example of an outer mold, and Figure 14 shows the revised mold design to accommodate what happened during the third test. Note the extra flange near the bead seat and the extra material near the parting line. Both of these areas were found to be weak after a layup was performed.

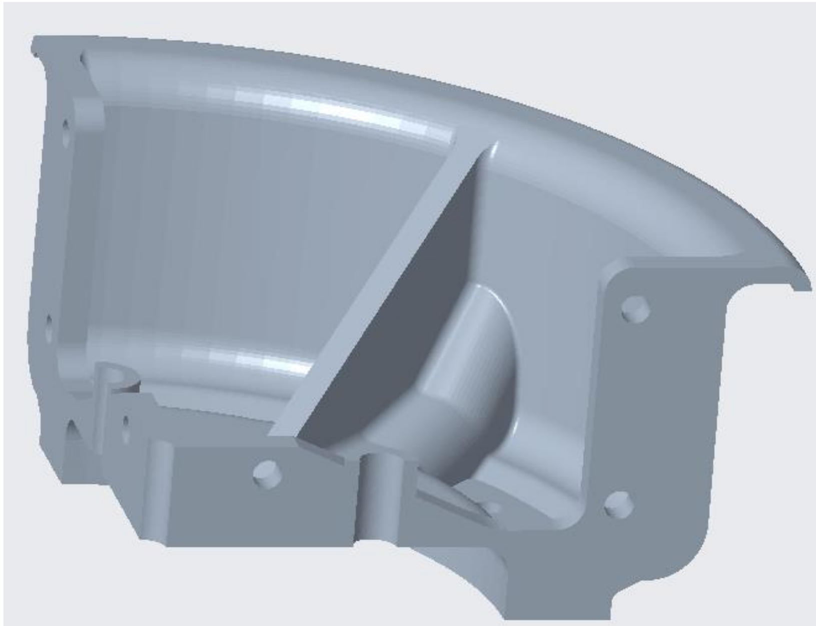


Figure 13: Outer mold used on test #3

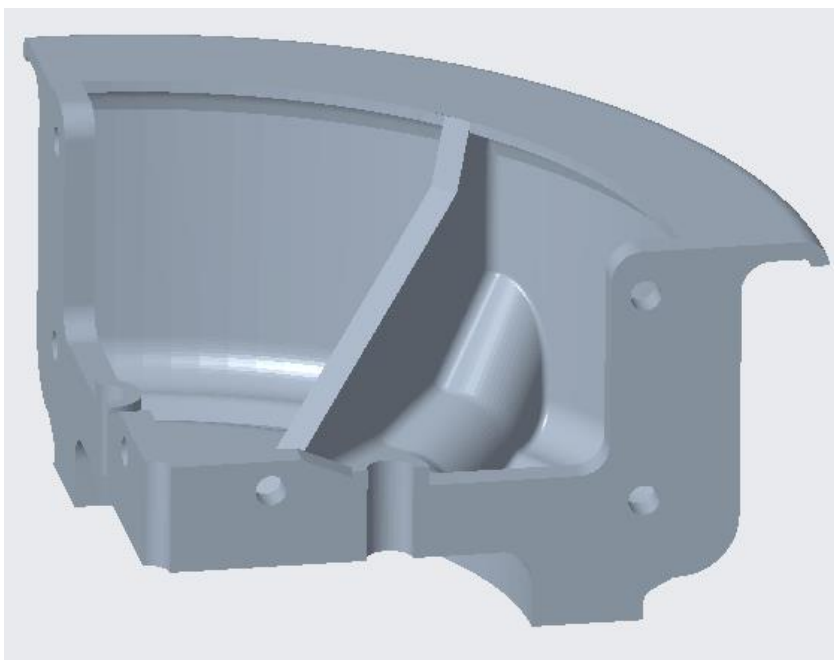


Figure 14: Revised outer mold from test #3

Chapter 3: Manufacturing Process

The Manufacturing Process chapter will cover the tools and techniques used during the development of this composite wheel. The topics that will be covered include: the molds and tooling, debulking, the layup process, curing cycle and post processing. Each one of these will be covered in greater detail in the following sections.

3.1 Molds and Tooling

3.1.1 Tooling

Many components made with composite materials achieve a high stiffness to weight ratio by increasing the thickness of the piece while having a low density, effectively increasing its section modulus. This is typically done by using a core material or by making hollow sections. A good example of this has been seen earlier in Figure 5. When making any composite piece that has a hollow section, the same problem always presents itself. How to apply sufficient pressure in areas where a vacuum bag system cannot.

Nearly all composite wheels have hollow spokes. This is how they retain their stiffness and still remain light. When manufacturing a composite wheel, the most difficult area to manufacture perhaps is this hollow spoke section. Like most manufacturing problems, there are many possible solutions. For manufacturing a hollow section within a composite piece, some type of tooling is used that can be removed later. Some of the methods for removable tooling consist of rubber tooling (with a high coefficient of thermal expansion), an air bladder system and even 3D printed soluble cores. For higher volume production, the rubber tooling and air bladder system are commonly used; both of these allow the tooling to be used multiple times. They do however, have higher initial costs and added complexity. This is from the need of manufacturing extra molds for forming the rubber inserts, and the complexity behind creating an intricate air bladder system. Figure 15 shows the use of rubber tooling being used to manufacture a carbon fiber motorcycle wheel by Blackstone Tek. The rubber is broken up into sections, so it can be easily removed after the laminate has been cured. Also, note the tooling is wrapped in fabric before the two halves are joined. This helps strengthen the joint at the parting line. As for the air bladder tooling, Figure 16 demonstrates how it can be used to create a bicycle head tube out of a composite material. Finally, the 3D printed cores made from a soluble material have been used more so in a prototyping or low volume situation. The low initial cost and ease of printing the tooling allows multiple revisions to be made, before a final design is found. Figure 17 shows an example by Champion Motorsport. They printed an inner mold using a soluble material to create an intake tube for a Porsche 997. After the intake tube has cured, a solution can be applied to remove the inner mold. All three of these methods can provide an excellent final product if done properly. They all can apply sufficient pressure to the composite from inside the mold during the curing process.

Figure 15 - Blackstone Tek manufacturing a carbon fiber wheel

Figure 16 - Sculpted Cycles' use of an air bladder system (left) and a cured head tube (right).

Figure 17 - Champion Motorsport's example of a printed soluble core

During the exploration of this project, all three of these methods were considered, and they were all found to be inadequate for this thesis. Either the method was too involved (the rubber tooling or air bladder), or it was unable to be made (printing soluble cores), so a different route was taken. During the design phase of the wheel, thought was given for this very issue. The hollow spoke section was designed, so it wouldn't need special tooling like the other three methods. Instead, the spokes were enlarged to allow room for the vacuum bag to supply adequate pressure while being cured. During tests #2 & #3, this was found to be an acceptable replacement for any special tooling such as those three methods; however, some tooling was reqired. An aluminum plug was used during the layup to hold the proper shape for the center section. This was to be removed after the laminate had cured. Then a lightweight aluminum center section could later be glued in. To create the hollow area located around the center section, a low-density fabric was used to apply pressure once the inner and outer halves were joined. This tooling would stay trapped within the final product. The material was Lantor Coremat from Easy Composites. The material was folded into long strips that resembled the inner portion of this section. Then the pieces were wrapped in a thin impermeable film so the resin would not soak into the Coremat. How they were used will be covered in greater detail in the Manufacturing chapter. During test #3, this proved to be an efficient replacement for any special tooling.

3.1.2 Mold Material

Using unconventional material for the mold making process can present many unknown issues. Typically, with a process such as this one, the molds would be made out of aluminum or wood using a CNC milling process, an example of this is the wheel designed and manufactured by Koenigsegg. Figure 18 shows an example of an outer mold half used to make one of their carbon fiber wheels. Using molds machined from aluminum, they are able to get a very accurate mold that leaves a near perfect surface finish. During Koenigsegg's documentary "Making 280mph Capable Carbon Fiber Wheels", they comment on the surface finish not needing any post processing such as extensive polishing or applying a clear coat of some kind. The aluminum molds and resin give a perfect gloss finish; however, making the molds from aluminum can be very expensive. The size of the molds needed to create a wheel presents three main issues. First, the size of the blanks needed for the inner and outer halves is considerably expensive. Second, the CNC machining necessary to process the blanks into molds would require a professional to set up the programing and have it machined. Third, if there are any issues with the mold designs that are found while doing test samples, there is a high probability the molds will be unusable. By manufacturing the molds using a 3D printer, it allows multiple, relatively low costing revisions to be made with the mold design before it is finalized. This creates an ideal environment for prototyping.

Figure 18 - An example of an aluminum mold from Koenigsegg

For making the molds, the 3D printing filament had to be a material that could be printed with the printers available at MSU. The printers that were available were an Ultimaker 3, a Markforged Mark Two and a Stratasys Uprint. Using these three printers, three different types of materials were considered PLA, Nylon and ABS. During the decision making process for the three materials, particular aspects to this project were reviewed. The material would have to be compatible with the curing cycle temperatures and pressure, chemicals used, and the overall manufacturing process.

PLA (poly lactic acid) was the first consideration of material for the molds. This is a very common material used for 3D printing. This filament has many desirable characteristics that are applicable with this project such as smoother appearance, minimal warping, low cost, and higher printing speeds. In addition, this filament could be printed by multiple printers that were available, reducing the time needed for printing. However, it also has a few undesirable characteristics in regards to this project.

PLA is certainly the weakest in regards to the other two choices for filament. Although this is not desirable, this could be worked around. The determining characteristic is the low glass transition temperature of 140° F or 60° C. As stated before, the prepreg material being used requires a temperature of at least 185° F or 85° C (on the 'Low Temp Cycle') to set the resin. This elevated temperature would be well beyond the glass transition temperature, and the molds would have a high risk of distortion during the curing cycle while under vacuum.

The next material of choice was a filament made from nylon. Comparing nylon to PLA, nylon was a considerably better material for this project for many different reasons. First, the strength of a mold printed using nylon is considerably stronger than one printed from PLA. This will help resisting damage to the print during the demolding process. Second, the printer capable of printing nylon (the Markforged Mark Two) can hold tighter tolerances with less dimensional discrepancies. Finally, the glass transition temperature of the nylon available was 285° F or 140° C. This would be well below the temperature needed throughout the cure cycle making it a very good choice. However, there are a few shortcomings of a mold printed with this material. First, the nylon filament needed is considerably more expensive than the other two material choices. Second, nylon has a high abrasion resistance characteristic. This would make any post processing more difficult such as sanding or removing printing lines and errors with the print. Third, there is only one printer available on campus that is capable of printing this material making the total printing time much greater. All of these aspects, although not ideal, are not ones that cannot be overcome.

ABS (acrylonitrile butadiene styrene) was the third choice of filament for the molds. Just like the other two material choices, ABS has its own adavantages and disadvantages in regards to this project. First off, for the advantages, the glass transition temperature of the ABS used was 220° F or 105° C. This temperature is relatively close to the highest temperature experienced during the 'Low Temp Cycle'. Since it was uncertain if the material wouldn't deform at that temperature while under vacuum a test was performed (test #1). Next, when compared to the nylon, this material is much easier to remove any imperfection in the print. For the disadvantages, ABS has a tendency to warp if the printing conditions are not set correctly (print bed and environment temperature). Finally, ABS isn't as robust as the nylon material, and this became more prevalent the more times a mold section was used throughout the tests. After reviewing these three materials and performing tests, it was found that ABS was the best choice for this project.

3.1.3 Mold Annealing

When certain types of material, typically metals, are heated to their melting point and then re-solidify, the physical and mechanical properties are changed. While the material is cooling, tension within the piece can develop from the uneven curing rates throughout the part. Annealing is one of many heat treatment processes used to help recover certain properties of the material. "During the annealing process, metals are heated evenly to return them to as close to their pre-cold worked state as possible" (Monarch Metal Fabrication). The material is heated just above its recrystallization temperature and cooled at a certain rate. By doing this, any internal irregularities (tensions or stored energy) can be relieved, and the piece can be uniform throughout.

During the printing process of 3D prints, the filament is extruded beyond its melting point and cools as the print continues. Once the next layer is printed, the filament is laid down on a variety of different temperatures located across the print. This means that between layers, different tensions can develop in different areas possibly causing poor bonding between layers, and prints typically fail between the layers. Using an annealing process, the print can be brought back to a uniform state improving the print's strength, durability and stiffness. According to Ed Tyson in "How to Anneal Your 3D Prints for Strength", both ABS and PLA can experience a 40% increase in strength and durability, and a 25% increase in stiffness. Knowing the molds would undergo punishment during the demolding process, all of the molds were annealed to increase their toughness.

To anneal a printed part, the part is placed into a preheated oven that is set just below the materials glass transition temperature. With the ABS used on the molds, the temperature was set to 212° F or 100° C. Once the oven is at the proper temperature, the part is placed into the oven on an oven-safe sheet and the oven is then turned off. The print is left in the oven allowing it to soak up the heat and cool slowly back to room temperature. This process is then repeated 3-4 times depending on the size of the print. Annealing the prints can cause them to expand and contract in certain areas. According to Ed Tyson, "you will notice that the object(s) will have shrunk slightly along the lines of its print layers" (X and Y coordinates) and "you will notice some expansion perpendicular to the print line" (Z coordinate). This was took into consideration while designing the molds.

3.2 Debulking Process

When working with a thermoset composite such as a prepreg laminate, it is important to ensure that each layer is completely pressed up against the mold and the previous layer. If the mold that is being used has complex shapes, dips or curves, the material can form what is called “bridging”. Bridging is the term when an unintentional air gap or void is formed during the hand layup. This can be between the first layer and the mold, or even between layers. It is very important to ensure that each layer has no bridging before the next layer is placed. Hand tools are often used to help encourage the fabric into the mold. This method usually works if the mold isn’t too complex and only a few layers are being used. With this project, this method alone would not work. As more and more layers are applied, it becomes very difficult to ensure no bridging had occurred. This is where debulking can help. Debulking is the process of applying a vacuum to a partial or full layup at room temperature for a short period, roughly 30 minutes. This will help the layers of the piece settle into the mold as well as remove any bridging that may have occurred. After the piece has been debulked, more layers can be applied knowing they are not covering any sections that may be bridged.

Throughout the manufacturing of this wheel, the layup was debulked multiple times. Originally, with test #1 & #2, the tests were only debulked before they went into the oven. This allowed a comparison with test #3, which had been debulked before and after the two halves were joined. Test #4 was debulked after layer 5, layer 10 and before it went into the oven. More information on the tests can be found in the appendix. Debulking proved to help the layup process significantly especially as more layer were applied.

3.3 Layup Process

The layup was done using typical techniques found while working with prepreg laminates. The molds were cleaned, mold release was applied, and the sections were bolted together creating the inner and outer half. As discussed earlier, the process consisted of 10 layers total laid in a particular manner in attempt to maximize appearance and stiffness. The layup process consisted of many different steps to achieve the final product. The two halves are partially laid up independently, debulked, the trapped tooling is inserted, then they are later joined, and the rest of the layers are applied.

Step #1: First layer orientation.

To get a good quality surface appearance, it is important to position the pieces of fabric, so a seamless appearance is achieved. Typically, the seams are placed, so they can be hidden such as in corners or places that will not be immediately seen. The first layer is placed giving extra care in this regards.

Step #2: Partial layup and debulking.

For the outer mold, the plug that will hold the shape for the center section is bolted in. Then the layers are applied. During this step, both the spoke and barrel part of the mold is laid up with five layers. Each piece and layer is overlapped or intertwined. All of the edges located at the parting line are left intentionally 0.25 inches long. This will provide good overlap once the two halves are joined later. This outer half is then debulked, and the remaining five layers are applied in any area that will be inaccessible once the two halves are joined, for instance the spoke area and center section. It is then debulked again. The inner half is done in the same manner, but only debulked once right before they are joined. Unlike the outer mold, the material near the parting line is trimmed at the parting line. This will help ensure no material is trapped between the two molds once they are joined. On both halves, the material at the bead and flange is left 0.50 inches long and trimmed before the final debulking.

Step #3: Final tooling and joining the halves.

Once the two halves have been debulked, the trapped tooling is then installed into the outer mold. On the outer mold, all of the material at the parting line that was left 0.25 inches long is then folded over away from the parting line. Around the center section, a ring of prepreg is laid on top of the pieces folded over the trapped tooling. This ring will help hold the pieces in place while the halves are joined. The inner and outer molds are then bolted together taking care no material has shifted onto the parting surface of the molds.

Step #4: Final layers, trimming and debulking.

Once the two halves are joined, the remaining five layers are applied using the same overlapping process as before. While these five layers are laid, extra material is added at the parting line to interlock the two halves. In the spoke section, extra material is placed between each layer giving this area more strength. Next, before it can be debulked for the final time, the material for the flange is trimmed following the profile of the mold. Finally, the full composite laminate can be debulked taking extra care to get the vacuum bag into the spokes as much as possible so no bridging occurs. The composite wheel is now ready for the oven.

3.4 Curing Cycle

Using the 3D printed molds would not allow for a curing cycle typically used when working with prepreg material. A typical cure cycle for prepreg like this, would call for an initial elevated temperature, a ramp rate of about 3-4° F/minute, a final temperature around 250° F or 120° C and a cure time of about 4-7 hours. An example of a cure cycle, can be seen with Figure 19. Looking at this cycle, there are a two main areas to note throughout the cycle such as the initial soak and post curing temperature. The initial soak (temperature held at 70° C for four hours) of the cycle is used to allow conditions for the resin to flow throughout the laminate. Next area is the post curing process (temperature held at 120° C for one hour). This area is to ensure the resin has been completely cured. The duration of both these area subject to change depending on the number of plies used and size of the molds. Extra time may need to be added accordingly.

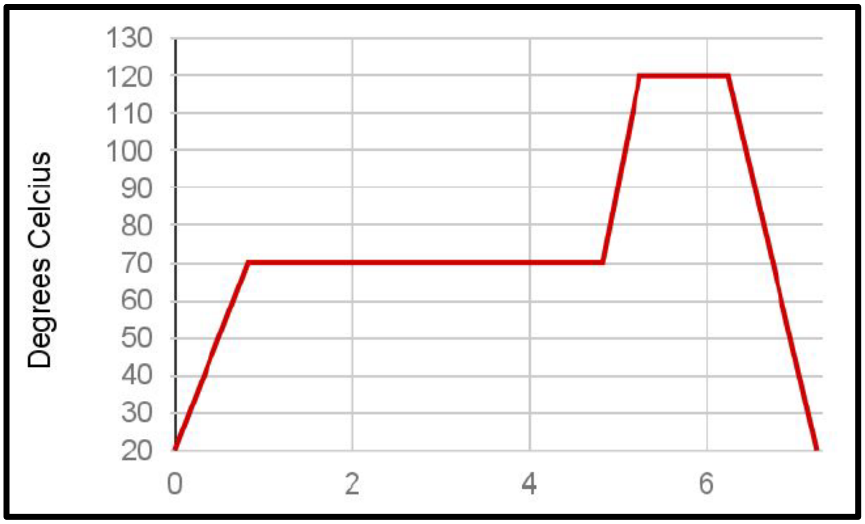


Figure 19 - Easy Composite's standard cure cycle

As stated before, having a cure temperature of 250° F would elevate the mold's temperature higher than what is acceptable and lose their form. By working with the material Easy Composites supplies, their 'Low Temp Cycle' could be used safely with the printed molds. Figure 20 illustrates this particular curing cycle. Their cycle does require a considerable amount of extra time in the oven when compared to a typical cycle, 15 hours. For the purpose of this thesis, the extended curing time was not an issue. After using this 'Low Temp Cycle' on all three tests, it proved to be a safe and effective cycle for the molds and curing the laminate.

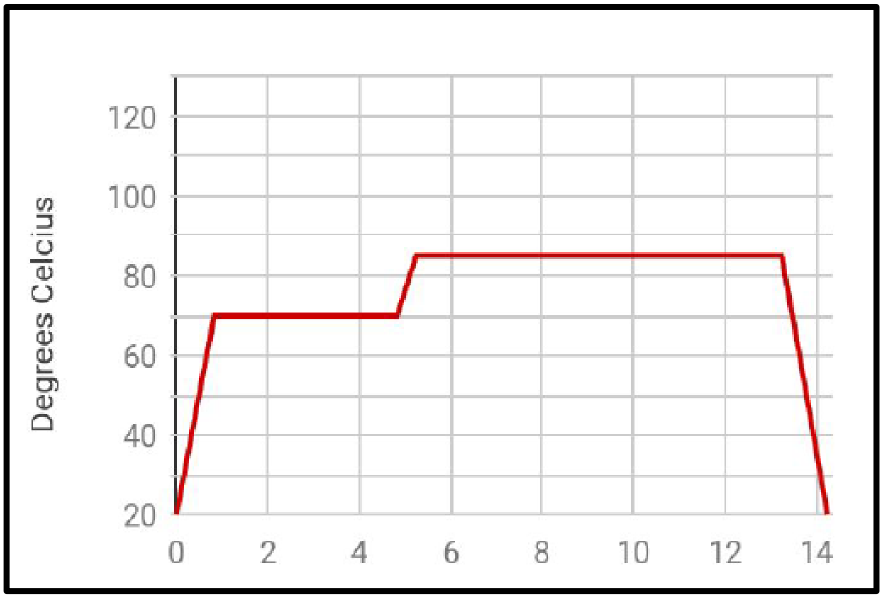


Figure 20 - Easy Composites' 'Low Temp Cycle'

3.5 Manufacturing the Center Section

In addition to manufacturing the composite wheel, the design used in this thesis required a center section that would be inserted and glued in during the post-processing period. The center section is an aluminum piece manufactured in house using a 3-axis CNC mill. This piece was to hold the tight tolerances required when the wheel was mounted to the vehicle.

3.6 Post Processing

After the piece has been cured and removed from the molds, the wheel needs additional work to become a finished product. The wheel will require four more steps. This will consist of finishing the surface, bonding the center section to the laminate, removing any misalignments that may have developed and installing the valve stem.

Once the piece has been removed from the molds, the surface finish is far from being considered ideal. This is entirely from the surface finish of the 3D printed molds.

Even though the molds were sanded considerably before the layup was preformed, a piece pulled from the molds still had small resin lines that mirrored the different printing layers of the molds. Another issue from the molds was the flashing that occurred. Flash or flashing is when excess material (resin) leaks between the parting lines of the mold. This did not prove to be that much of an issue since it was easily removed. Through the three tests, it was found that wet sanding with 500-grit paper could remove the resin lines and flashing easily. After the wet sanding, the finish was still dull and opaque. A clear coat was applied to bring back the gloss and fiber definition to the composite wheel. This proved to be a sufficient solution to the surface finish issue. Figure 21 is of test piece #1 and illustrates the effects of the clear coat.

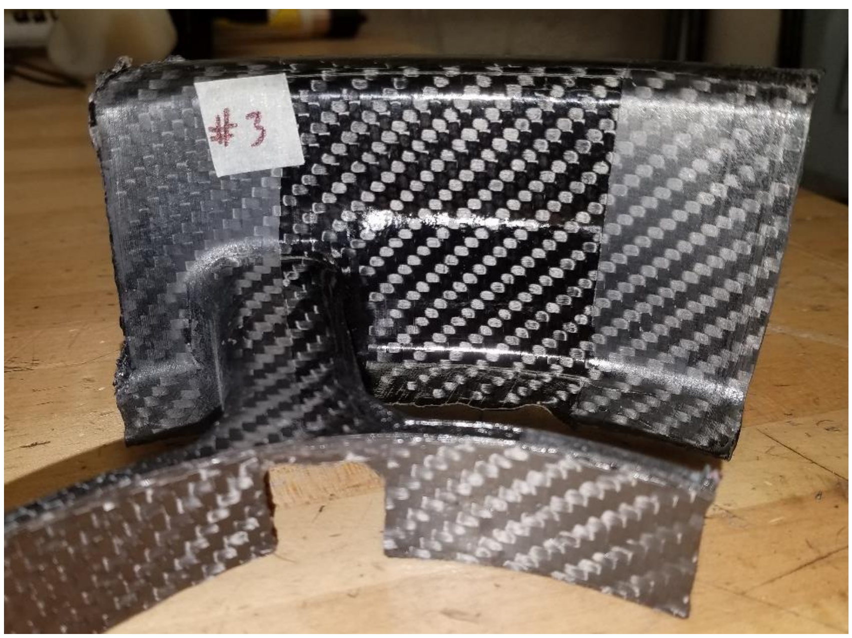


Figure 21 - Comparison between a coated and uncoated surface.

Once the sanding is done and a clear coat applied, the next step is bonding the center section to the wheel. This is certainly one of the most important steps while manufacturing this composite wheel and this is for two reasons. First, it is important to ensure good adhesion between the aluminum and carbon fiber. If the bond between the two pieces fails, there is a high probability of causing harm to the vehicle and more importantly the driver. To help with the bonding process, both the carbon fiber and the aluminum are sanded with 180-grit paper. This is to ensure the epoxy has a proper surface to adhere to. Loctite E-120hp was used as the epoxy. This epoxy has been used in the past at MSU with great success. Second, it is very important to set the center section properly. Any slight misalignment here will be exaggerated out at the bead and flange area.

After the center section is installed, the bead and flange profiles are machined to remove any misalignments that may have developed. This process is done by mounting the wheel to a lathe through a hub. First, an old hub is secured into a lathe and checking it for any runout. It is important to secure the hub so the axis of the lathe and hub are aligned. Next, bolt the wheel to the hub and begin machining the bead and flange profile. Using a carbide cutting tool, use a fine tool path to remove any imperfections. Take care not to overheat the resin within the laminate. Also, be sure to use some type of cleaning device, such as a vacuum, to collect the material as it is being removed. The machining process can create a significant amount of fine dust that could be hazardous to the operator or machine.

The final step is installing the valve stem onto the rim. For this process, the wheel is secured into a drill press, and a hole is drilled following the manufacturer's recommendation for the particular valve stem size used. Start with a pilot hole then finish with the final size. According to Composites World, a pecking motion should be used while drilling. This is to reduce the heat generated while drilling. Once the hole is drilled, the valve stem can be installed.

Chapter 4: Conclusion

Using the design and manufacturing process used in this thesis, it was found that a composite wheel could be made using 3D printed molds. At first, it was unclear if a printed material was capable of handling the chemicals and processes required to manufacture a composite piece such as this. Having the mold sections printed, certainly presented its own set of complications such as working limitations and mold preparation; however, it provided a good environment for prototyping. Having the molds printed allowed multiple revisions to be made during the course of the prototyping phase. This was done at a significantly quicker and less expensive pace if compared to the conventional method of using molds made from aluminum. Now that the designs and processes have been validated, the molds could be made from a more expensive and robust material to make multiple wheels.

Using this thesis as a basis for composite prototyping, the MSU Motorsports team can further explore manufacturing components using inexpensive 3D printed molds. Components previously thought to be too difficult or expensive to manufacture using a composite material, are now more achievable.

Chapter 5: Future Work

5.1 Conclusion

Due to unforeseen issues, setbacks, and time constraints, a finished composite wheel was not completed before this thesis was submitted. The steps still needed to complete the wheel include: sanding and coating the surface, securing the center section to the laminate, machining the bead and flange profiles, and installing the valve stem. Using test piece #4, it is anticipated to be completed soon after this thesis is submitted.

5.2 Testing and Comparing

Once the composite wheel is completed, a test could be performed comparing the composite wheel to the aluminum Keizer wheels currently used by MSU Motorsports. The main characteristic to compare is the stiffness to weight ratio. Using a test fixture, each wheel can be secured, and a load can be applied to measure the amount of deflection for both materials. If the wheel in test #4 is equal to or exceeds the stiffness of the Keizer wheel, it will be considered a success.

5.3 Material Selection

Throughout the development of this thesis, only the XC110 3K & 12K were currently available. Easy Composites was in the process of developing a unidirectional prepreg carbon fiber that would be compatible with the XC110 series. Having a greater selection of available weaves, could potentially allow a further reduction of wheel mass while retaining the same stiffness. Some of the heavier 12K material could be replaced by the lighter unidirectional orientated along the path of the loads.

References

The Editors of Encyclopædia Britannica. "Automobile Racing." *Encyclopædia Britannica*, Encyclopædia Britannica, Inc., 9 Dec. 2016, www.britannica.com/sports/automobile-racing

Einborn, Ben. "Carbon Fiber- What Is K?" *Carbon.ee*, 29 Mar. 2015, www.carbon.ee/en/n/carbon-fiber-what-is-k

The Drive. "Making 280mph Capable Carbon Fiber Wheels - /INSIDE KOENIGSEGG." *YouTube*, YouTube, 22 Apr. 2014, www.youtube.com/watch?v=PGGiuaQwcd8

"Carbon Fiber Vs Aluminum Frames." *Soyater*, 20 May 2014, soyater.wordpress.com/2014/04/24/130/

Cathcart, Alan. "Blackstone Tek/BST Factory | Black Gold." *Sport Rider*, 7 Apr. 2011, www.sportrider.com/sportbikes/blackstone-tek-bst-factory-black-gold#page-5

"Complex Mouldings Using Prepreg Carbon Fibre." *Easy Composites*, www.easycomposites.co.uk/#!/composites-tutorials/complex-mouldings-using-prepreg-carbon-fibre

Gardiner, Ginger. "Out-of-Autoclave Prepregs: Hype or Revolution?" *CompositesWorld*, CompositesWorld, 1 Jan. 2011, www.compositesworld.com/articles/out-of-autoclave-prepregs-hype-or-revolution

Korn, Derek. "Machining Composites By Conventional Means." *Modern Machine Shop*, Modern Machine Shop, 11 Nov. 2005, www.mmsonline.com/articles/machining-composites-by-conventional-means

Pratte, Dave. "PICKING WHEELS AND TIRES THAT FIT." *Speed Academy*, 8 Dec. 2015, www.creativemechanisms.com/blog/learn-about-polylactic-acid-pla-prototypes

Smith, Chris. "What Is Annealing and Why Is It Important?" *Monarch Metal*, 7 Sept. 2016, www.monarchmetal.com/blog/what-is-annealing-and-why-is-it-important/

Sloan, Jeff. "Machining Carbon Composites: Risky Business." *CompositesWorld*, CompositesWorld, 16 Apr. 2010, www.compositesworld.com/articles/machining-carbon-composites-risky-business

Soller, Jon. "Weave Definitions." *Soller Composites*, 2004, www.sollercomposites.com/fabricchoice.html

T, Devin. "Carbon Headtube: Part 2." *Sculpted Cycles*, 3 Feb. 2015, sculptedcycles.blogspot.com/2015/02/

"TEN THINGS YOU NEED TO KNOW ABOUT CARBON FIBER." *Motocross Action Magazine*, 6 Mar. 2017, motocrossactionmag.com/10-things-you-need-to-know-about-carbon-fiber-how-to-care-for-it/

Tyson, Ed. "How to Anneal Your 3d Prints for Strength." *Rigid.ink*, Rigid.ink, 16 Jan. 2017, rigid.ink/blogs/news/how-to-anneal-your-3d-prints-for-strength

"Unsprung Weight." *Unsprung Weight*, www.formula1-dictionary.net/unsprung_weight.html

Walther, Hans. *DEVELOPMENT OF A LIGHTWEIGHT LAMINATED COMPOSITE WHEEL FOR FORMULA SAE RACE VEHICLES*. 7 June 2016, kuscholarworks.ku.edu/bitstream/handle/1808/21984/Walther_ku_0099M_14767_DATA_1.pdf?sequence=1

Wyman, Carrie. "3D Printed Soluble Cores Keep Porsche Purring!" *Stratasys*, 8 Jan. 2015, blog.stratasys.com/2015/01/08/porsche-3d-printing-soluble-cores/

Appendix

Test Piece #1

Purpose: to check the compatibility of the chemicals used, the different mold materials, cure cycle, and mold preparation vs surface finish

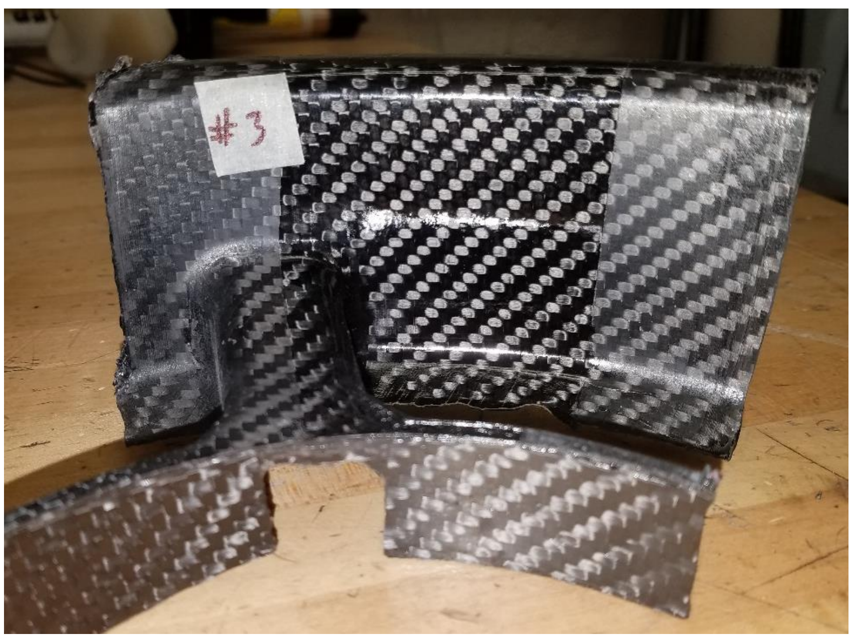
Overview: This test was performed with three outer mold sections. Two were printed using nylon filament (section #1 & #2), and one was printed using ABS filament (section #3). Two of the molds had complications during printing, but they still were sufficient for testing. The ABS and one of the nylon molds (sections #2 & #3) were initially sanded up to 500- grit paper pre-layup. The intention was to remove all imperfection in the mold. The other nylon mold was sanded using 200-grit paper. This was to remove just the major imperfections from the printing process. Two layers of the 3k fabric was laid over the molds. The test sample was then debulked and cured in an oven under vacuum using the 'Low Temp Cycle'. After the piece was demolded, all three sections were sanded to remove the flashing and resin lines. Section #1 was post sanded with 300-grit paper. Section #2 was post sanded with 500-grit paper, and section #3 was post sanded with 1200-grit paper. A clear coat was later applied to sections #2 & #3 to see the difference between sanding effort and surface finish.

<u>Results:</u> It was found that with this method, the chemicals and cure cycle would not have a negative effect on the molds or laminate. In addition, the ABS material worked better than the nylon material. The ABS mold was considerably easier to sand and achieve a better mold surface. The surface finish of section 3 proved to be preferable over the other two.

The Images below are of test piece #1

Layout of the mold materials, #1 & #2 are nylon and #3 is ABS

Comparing sanding preparation and surface finish



Comparing sanding preparation and surface finish

Test Piece #2

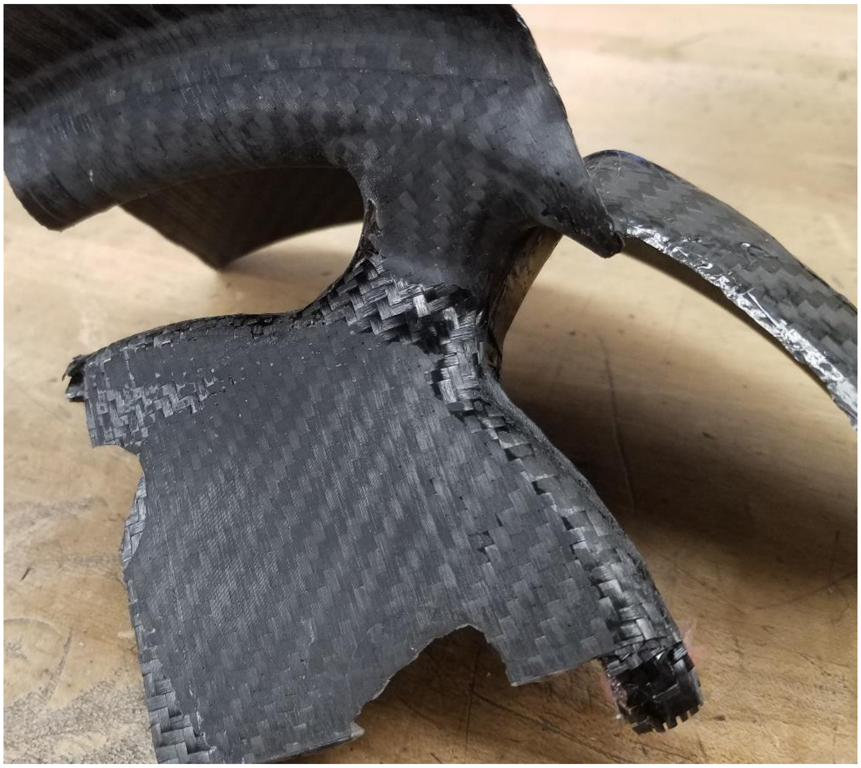
Purpose: to test the tooling and joining of the inner and outer halves.

Overview: Both of these molds were printed using ABS as the filament. The inner mold section had a complication while printing. It was still useable. Both halves consisted of four layers of the 3k material. After the halves were laid up, the trapped tooling was installed, and the halves were joined. The sample was then debulked and placed into the oven under vacuum.

Results: Demolding the test sample proved to be the first problem. It was found at this time an unintentional lock was in the mold design. This made demolding the piece difficult but not impossible. The trapped tooling proved to work nicely with the outer mold but not with the inner mold. This was from the location of the parting line, and how it worked with the rounded edge located around the center section. The tooling could not apply enough pressure, and a void occurred.

The Images below are of test piece #2

Configuration of test piece #2



A flaw in the mold design found. Insufficient pressure was applied to the laminate near the spoke and around the center section.

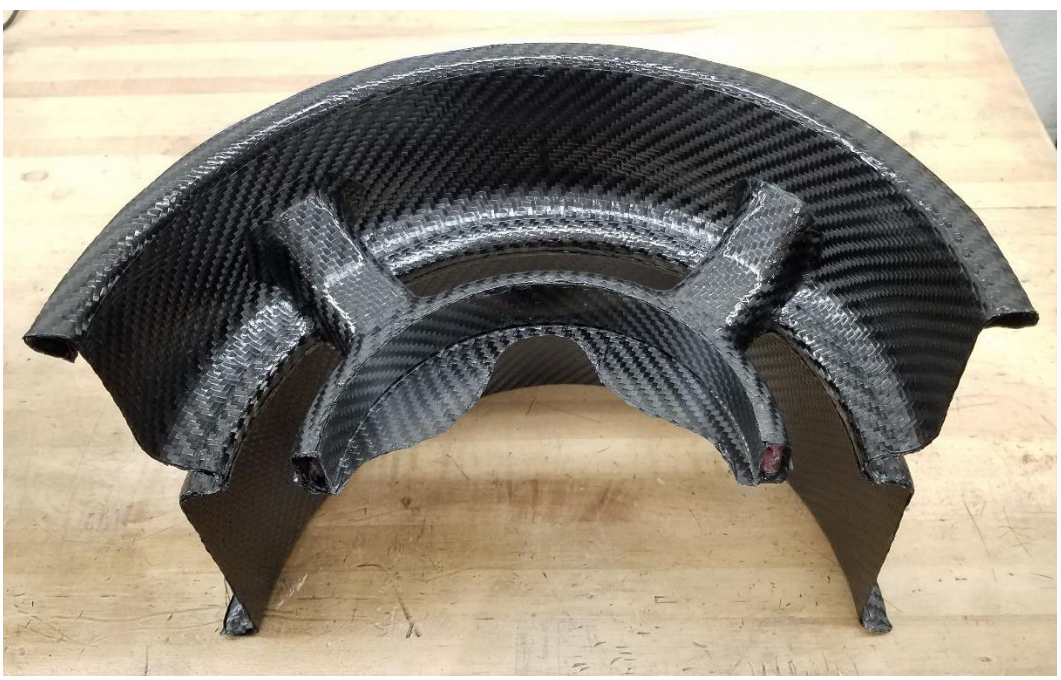
Test Piece #3

Purpose: to test the revised mold design, flange forming method and trapped tooling.

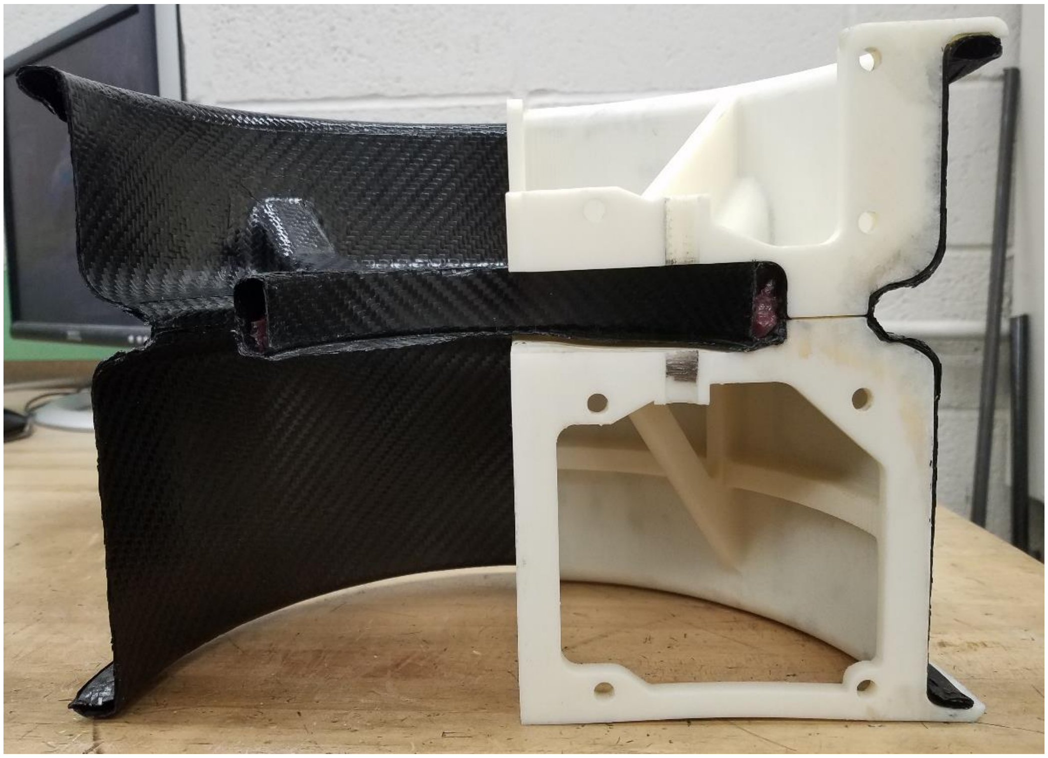
Overview: Four of the revised ABS mold sections were used to create half a wheel. Both the inner and outer halves consisted of five layers of the 3k material. Around the flange area, the material was left 0.50 inches long and later folded over creating the flange profile. Next, the trapped tooling was installed into the outer half. Extra prepreg was placed over the tooling to help apply extra pressure. Both halves were debulked before and after they were joined together. The test piece was then placed into the oven under vacuum. After removing the piece from the oven, it was found that the vacuum bag ruptured part way through the cure cycle.

Results: Having the vacuum bag fail during this test certainly caused issues. For instance, the material around the flange and spoke area unfolded slightly, as well as the material located near the drop center. However, the method used for forming the flange appeared to be an unreasonable option. The revised design around the trapped tooling proved to be effective. No imperfections were present around the trapped tooling and center section. It was found during the demolding process, the outer molds were difficult to remove since there was very little area to pull from. In addition, part of the mold design was found to be weak and needed reinforcement. These issues were later resolved with the next revision made to the mold design.

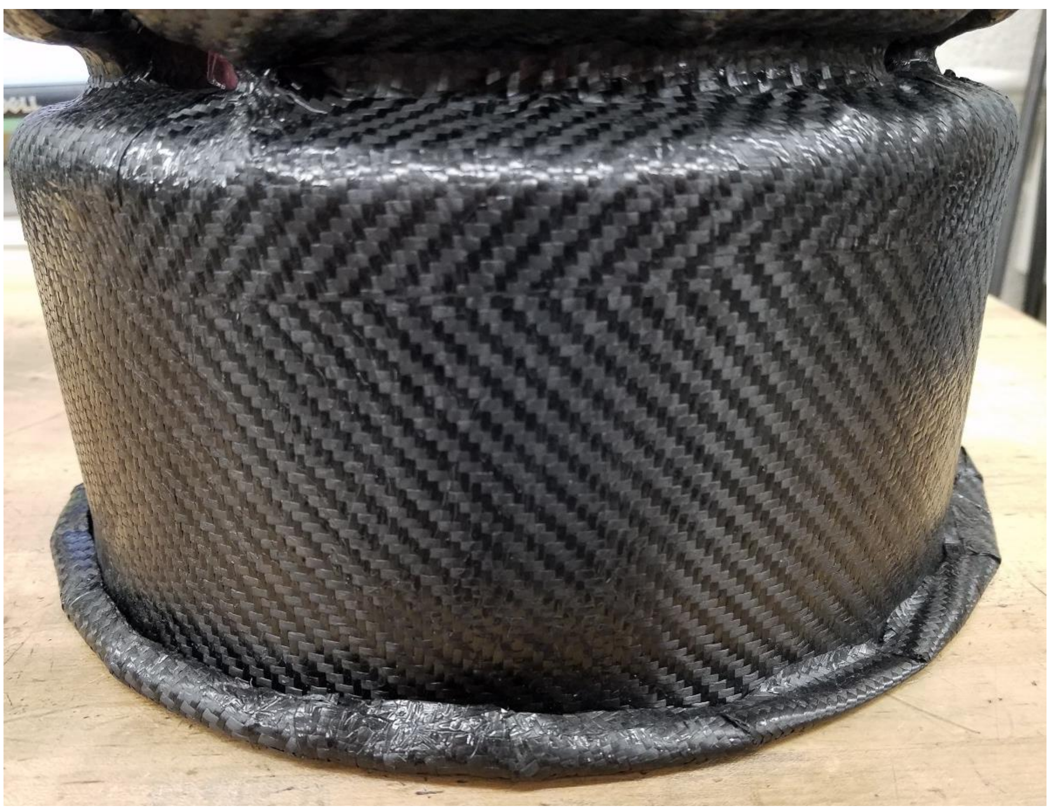
The Images below are of test piece #3



Surface finish after sanding and a clear coat was applied



Section view of the laminate and molds



Folded flange profile on inner half

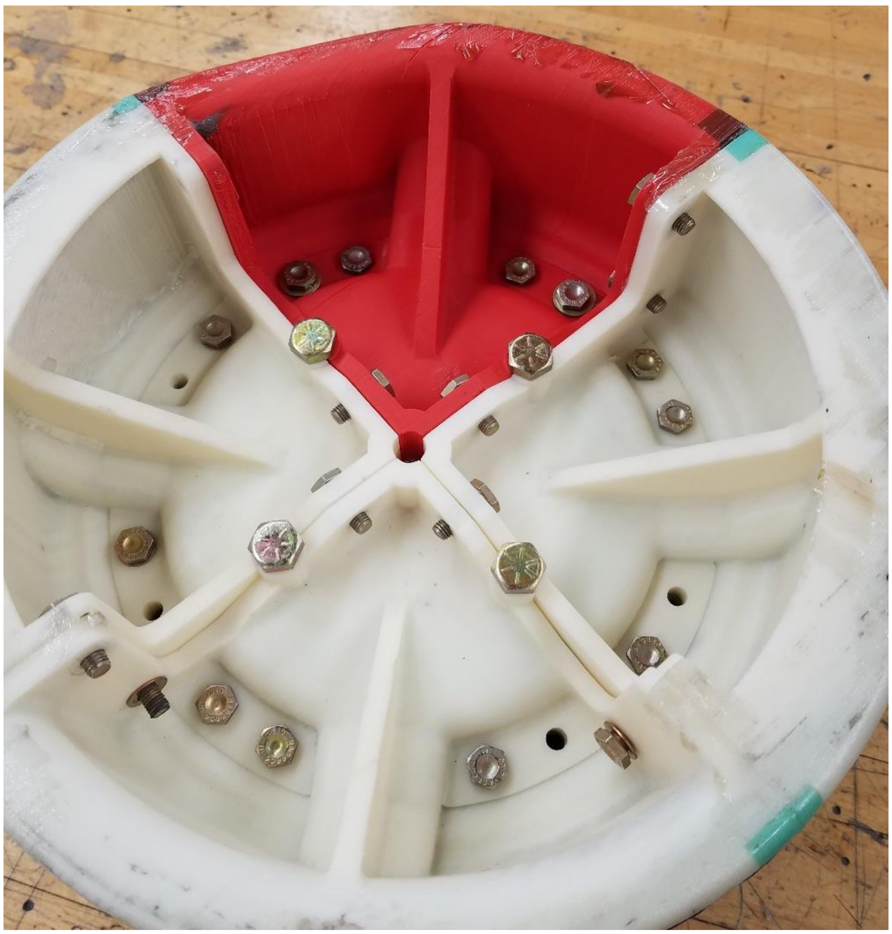
Test Piece #4

Purpose: to perform a full layup using the appropriate processes and stacking sequence, and to test a different flange forming method.

Overview: This test consisted of six ABS molds printed using the Stratasys and two ABS molds printed using the Ultimaker 3, one inner section and one outer. After the sections were bolted together creating each half, PET tape was used to cover all of the parting lines between each section. This was to reduce the amount of flashing between the mold sections. The layup process mimicked that of test piece #3 but with the full amount of layers using both 3K and 12K material. The outer mold half was debulked twice, once after five full layers, and again after the remaining ten layers were placed in areas inaccessible once the two halve were joined. The inner mold half was laid up the same way as outer half, but it was only debulked once after the respective five and ten layers were laid. Then the two halves were joined, and the remaining five layers were laid creating overlap between the two halves. While the five layers being laid, extra material was added near the spoke and parting line areas. This was in attempts to increase the overlap and strength in areas perceived to be weak. The material located round the flange area was again left 0.50” long and later trimmed to match the mold profile before it was debulked. After a final debulking of the piece, it was placed into an oven under vacuum. Once it was cured and removed from the oven, one of the mold sections had distorted. The section was the outer mold printed using the Ultimaker 3.

Results: the mold that distorted was thought to be caused by poor print quality. The distortion, not being ideal, will still allow the post processing steps to be performed such as inserting the center section and machining the bead and flange profiles. The method for forming the flange proved to be adequate. This method should be used on the next wheel. The weight of this composite without the center section was 2.50 lbs.

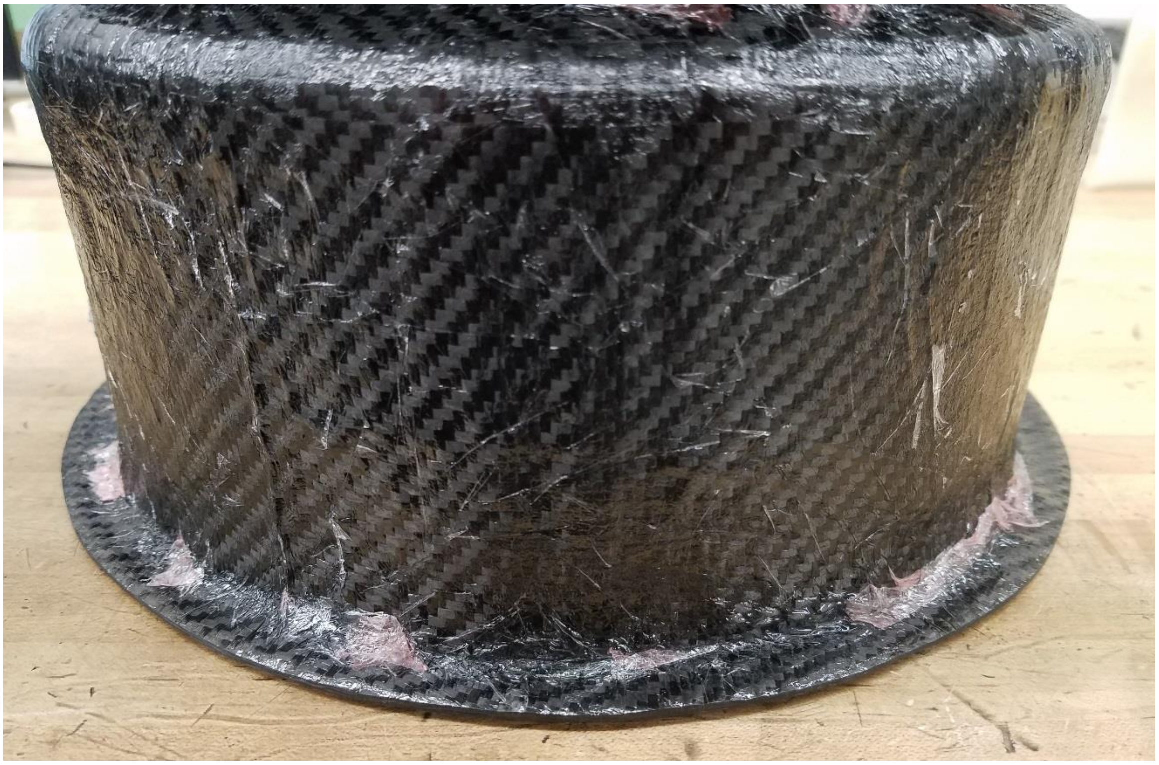
The Images below are of test piece #4



Layout of mold sections, cream colored molds were printed using the Stratasys and the red mold was printed using the Ultimaker 3

Test piece #4 once removed from the molds

Distorted section of the laminate



Trimmed flange profile on inner section

View of the inner half, laminate in the spoke area and around the center section have no apparent flaws.